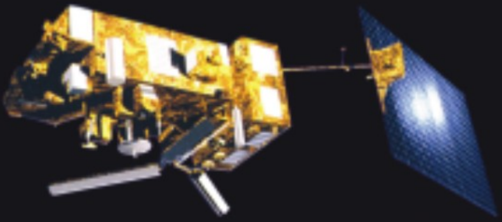

Austin Woods

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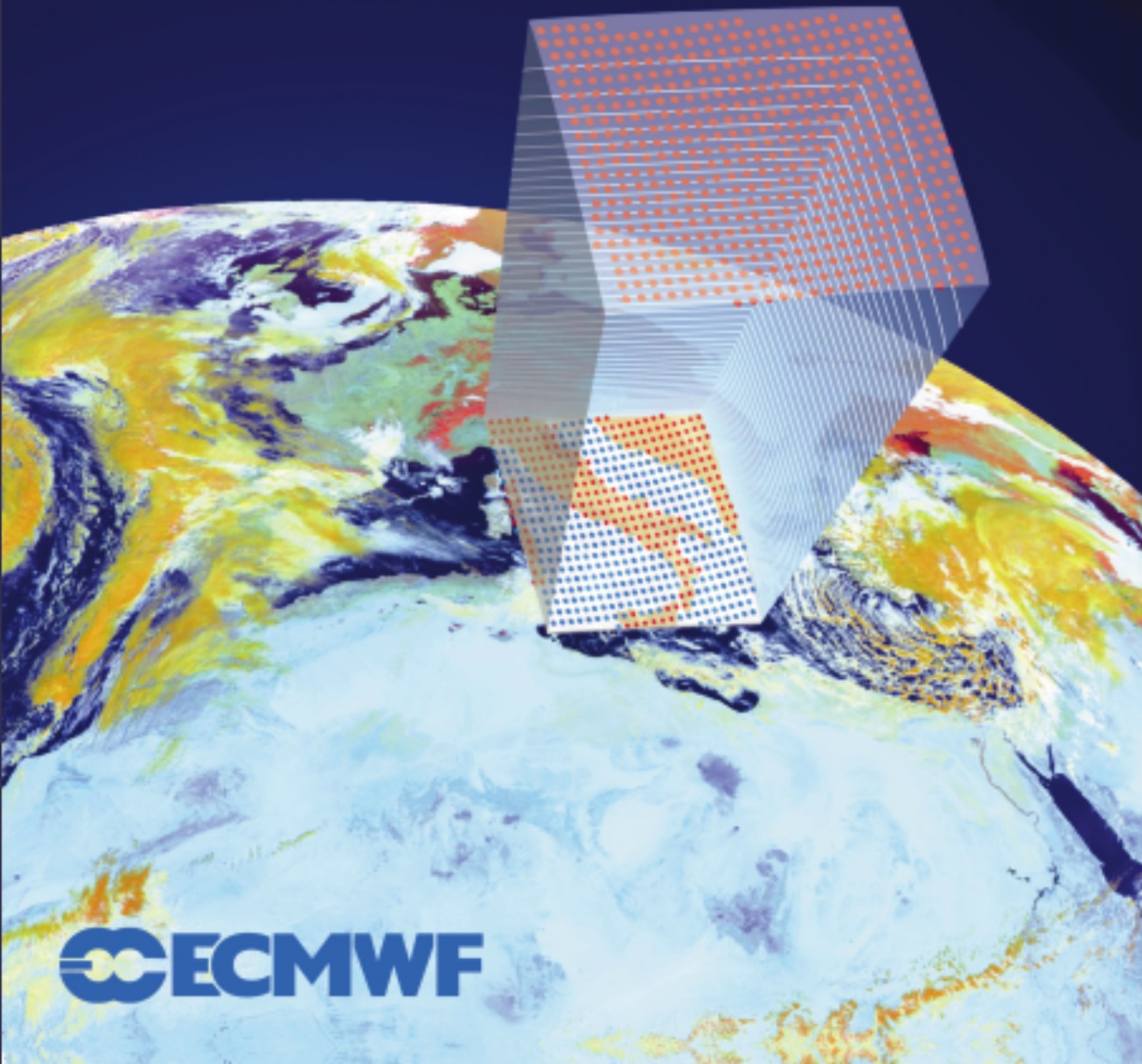
The European Approach

The story of the **European Centre for Medium-Range Weather Forecasts**



ECMWF

Medium-Range Weather Prediction

Austin Woods

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The European Approach

The story of the **European Centre for Medium-Range Weather Forecasts**

Forewords by Professor Anton Eliassen, President
of the ECMWF Council, Dominique Marbouty,
Director ECMWF, and Professor Francesco Fedi,
President of the COST Committee of Senior Officials

With 19 Figures, 9 in Full Color

Springer

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Foreword from the President of the ECMWF Council — Prof. Anton Eliassen

Meteorologists have long recognised the need for greater co-operation between the different European states. Eventually, in 1967, following an initiative from the Council of the Commission of the European Communities, at the time a community of only six countries, a group of visionaries drew up a list of scientific and technical challenges in which "the possibility of international co-operation could be discussed". By the end of that year, a proposal had been made for the establishment of a "European Meteorological Computing Centre". This far-sighted initiative lead to setting up the European Centre for Medium-Range Weather Forecasts (ECMWF), which on 1 November 2005 reaches its 30th anniversary.

I am proud of ECMWF. I can say with confidence that all those who have been associated with this most successful scientific and technical European organisation share this pride. Under the guidance of the Council and its Committees, and with the hard work of its talented and capable staff, the Centre has achieved much of what was envisaged. It has developed areas of research and applications that could not have been foreseen at the time of its establishment.

The public has become accustomed on Monday or Tuesday to being presented with a normally reliable outlook for the coming weekend's weather. Thirty years ago, this would not have been possible. The Centre's medium-range predictions have been of benefit at times of natural disaster, for commercial activities, in planning power supply, in planning sporting and marine activities, and much more.

ECMWF is a fine example of the advantages of international co-operation in science and technology. At the time of writing 25 countries support the Centre. We hope that our family of states will grow in the coming years.

I wish the Centre well in tackling the major scientific and technical challenges that it is facing.

Anton Eliassen

Prof. Anton Eliassen
President of the ECMWF Council

Foreword from the Director ECMWF

Early in 2003, Lars Prahm, then President of the Council of the European Centre for Medium-Range Weather Forecasts, proposed to David Burridge, then the Director, that with the 30th anniversary of the Centre coming up on 1 November 2005, it was time to record the history of the Centre. It has been the practice of other European scientific and technical organisations, such as CERN, JET and EUMETSAT, to record the story of their early days while those involved were able to contribute their memories.

In June 2003, the Centre's Council supported the proposal. David Burridge commissioned Austin Woods, who had been at the Centre since 1978 and served as Secretary to the Council since 1984, to carry out the work. The book was started with the intention of writing the history of a highly successful European scientific and technical organisation. It is however not that history.

In autumn 2003, the Centre's first Director Professor Aksel Wiin-Nielsen was informed of the intention to write the history of the Centre. He objected strongly! His objection was entirely reasonable. One cannot sensibly write the history of a relatively young, and active, institution. At the time of writing, major construction is under way to increase the size of the Centre's Computer Hall and to provide much-needed new office space. The Centre's work is expanding to include monitoring of the global environment for important, but non-meteorological, purposes. Current affairs cannot be treated as history.

The history of the Centre will undoubtedly be written sometime in the future, when in Wiin-Nielsen's words: 'the people concerned have left this planet'. Instead, in this book we have a record of the Centre's beginning and of its work during its first 30 or so years.

The Centre is widely acknowledged to be the world leader in its field. The contribution of the staff to the Centre's success has to be emphasised. Without names, this book would be a dry read. However is not possible to name all who contributed. Indeed we would have to name many in addition who were not on the staff at all, but in the Member States and even elsewhere. A quick calculation suggests that a minimum of well over 1,000 individuals should in justice be named, clearly an impossibility! To list the scientific awards granted to Centre staff, their work as journal editors, their efforts as members and Chairs of international committees, their publications in the scientific and technical literature . . . would leave us I think with an unexciting book. Thus, the omission of a name from this book cannot be seen as neglect, nor inclusion as recognition.

I thank Austin Woods for his work in putting this record on paper. I am confident that the record of the beginnings of this successful and exciting European co-operative enterprise will interest many outside the world of meteorology.

Dominique Marbouty, Director
European Centre for Medium-Range Weather Forecasts

Foreword from the President of the COST Committee of Senior Officials — Professor Francesco Fedi

COST — the acronym for European **CO**operation in the field of **S**cientific and **T**echnical Research — is the oldest and widest European intergovernmental network for cooperation in research. Established by a Ministerial Conference of 19 European states in November 1971, COST is at present serving the scientific communities of 35 European countries to co-operate in common research Actions supported by national funds.

"Bottom up approach" (the initiative of launching a COST Action comes from the European scientists themselves), "à la carte participation" (only countries interested in the Action participate), "equality of access" (participation is open also to European countries not belonging to the European Union) and "flexible structure" (easy implementation and light management of the research initiatives) are the main characteristics of COST.

As precursor of advanced multidisciplinary research COST has a very important role for the realisation of the European Research Area (ERA) anticipating and complementing the activities of the Framework Programmes, constituting a "bridge" towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of scientific excellence in many key domains such as: Physics, Chemistry, Telecommunications and Information Science, Nanotechnologies, Meteorology, Environment, Medicine and Health, Forests, Agriculture and Social Sciences.

Today there are more than 200 ongoing COST Actions and there have been many hundred of Actions over the years. The scientific importance and relevance of COST results is well recognised by scientific communities outside Europe and, in particular, in the USA, Canada and in Asia. The Actions have also contributed to European competitiveness through their many contributions to normative and standardisation bodies, the many small enterprises originating in Europe from COST activities at the frontiers of modern technology and by the many examples of transfer of results to the European industry.

COST Action 70 “European Centre for Medium-Range Weather Forecasts” is a very good example of such achievements through its evolution to become an independent international organisation with its own structure and headquarters.

COST is proud to have been associated with the success and the growing importance of this European Centre. The key roles played by COST in establishing ECMWF are reflected in the many files in our archives from the period 1970 to 1975. They included arranging the many meetings of working groups and expert groups that lead to the decision to establish the Centre. It was at these meetings that the text of the Convention was agreed, the United Kingdom chosen as host country and the Centre’s first Director appointed.

Therefore, in my capacity as President of the COST Committee of Senior Officials, I am particularly pleased, on the occasion of the 30th anniversary of its foundation, to be able to wish the Centre, its Director and its Council, the very best of luck for the future, especially in maintaining the outstanding traditions established in the past 30 years.

Francesco Fedi

Professor Francesco Fedi

Preface

About 450 million people live in the 18 States that set up the European Centre for Medium-Range Weather Forecasts. Thirty years ago, they established an independent institution with a clearly defined objective. It was not to be a university-type institute for research, neither was it to be an operational weather forecast office. It would combine the scientific and technical resources of its Member States to use the most powerful computers in order to extend the range of weather forecasts beyond two or three days, the limit of useful forecasts at that time.

It would be small; the work force was to be limited to about 150, including administrative and other support staff. In 2005, 30 years after the Convention was signed, the staff totalled about 160. The Centre attracted the best talent in its specific field of endeavour. Each year about ten scientists left, to be replaced by newcomers bringing younger minds and fresh ideas. It is not surprising that it quickly became a world leader in its field. It is widely recognised as having maintained its leading position.

This book considers how the Centre was conceived in the confusing and difficult political period of the 1960s in Europe. It summarises the political, scientific, technical and financial discussions that led to the drafting of its Convention, and how it came to be built 60 km west of London, England. It tries to convey to the reader how it was that with friendly help the Centre 'hit the ground running'. The Centre's early and formative years are reviewed in Chapters 1 to 7. The development of its science and technology over the following thirty years is reviewed in Chapters 8 to 17. Chapters 18 to 20 deal with commercial issues, staff and the outlook. I hope this book will convey a sense of what it was like to be a participant during the exciting time at the beginning, and over the years as the Centre matured.

In 1985 the Centre's Scientific Advisory Committee considered 'the reasons for the undoubted success of the Centre':

- The aims of the Centre were focused on a single objective, which was at the same time important, attainable and scientifically challenging.
- Scientists, including visiting scientists, of the necessary calibre, have been attracted by the challenge.

- The latest supercomputers and high quality computer scientists have been available at the Centre.
- Since the Centre did not grow out of an existing organisation, it could build on the best technology and techniques available and establish its own mode of operations.
- The size of the Centre and the juxtaposition of research and operational work have aided interaction, given a sense of unity and spurred the research effort.
- Its Member States consistently supported the Centre, in particular by the provision of trained staff, and regarded its work as complementary to that of their own weather services, rather than competing with them.

The reader will find out how this has worked in practise. You will note as well the long time required — many years, with more than a decade not unusual — to bring a well-formulated plan for a scientific and technical project to operational fruition. Examples include the establishment of the Centre itself, and the implementation of ensemble prediction, seasonal prediction, ocean wave forecasting and new methods of data assimilation.

The meteorological world has seen major, some would say astounding, technological advances in satellites and computers, hand in hand with impressive scientific advances, during the last decades. The Centre developed within the framework of that process. It has benefited greatly from, and has been a major contributor to, those advances. The wonderful tradition of international co-operation in meteorology is exemplified in the story of this European organisation.

The text of the Convention, and details of the Centre's models, forecasts, archives, data services and much more are available on www.ecmwf.int.

The European Centre is an interesting place with an interesting history. The fault is mine if the reader finds any part of its story uninteresting. This book is not a formal history of the Centre. While based on documents and interviews, it reflects my personal thoughts, memories and ideas.

Austin Woods

Acknowledgements

When summarising past events, one has to rely in large part on documents written at the time by others. Plagiarism is copying someone else's work. Using material from many contemporary documents can I hope be called 'research'. Much of this kind of research has gone into this book.

I could not have written this book without help. The enthusiasm of those associated with the Centre at the prospect that its story would be recorded was evident. I thank all those who gave of their time and otherwise assisted me. I thank Dr Lars Prahm, at whose suggestion I started to write this book. I hope that I have not disappointed anyone with the resulting work.

I express particular gratitude to Dr Erich Süssenberger who gave me a great deal of practical help and answered many queries. He was kind enough to extend his encouragement to my writing. He had reached the normal retirement age of 65 on 13 February 1976, but his continuing interest in and enthusiasm for the Centre was clear when we met in late 2004.

The Centre's past Directors Prof. Aksel Wiin-Nielsen, Mr Jean Labrousse, Prof. Dr Lennart Bengtsson and Dr Martin David Burridge CBE, and the current Director Mr Dominique Marbouty, were generous with their time and support, and patient in dealing with questions and queries. So also were Sir John Mason, Director-General of the UK Meteorological Office when the Centre was being established, and Mr Michel Jarraud, Secretary-General of the World Meteorological Organization and a former member of the Centre's staff.

The COST Secretariat in Brussels and the German Weather Service DWD kindly made their invaluable archives available to me. Detlev Frömming of DWD gave me a great deal of practical assistance. The UK Met Office also made contemporary documents available. Prof. Anton Eliassen and Mr Magnús Jónsson helped to clarify issues relating to Norway and Iceland respectively.

John Wilmot of the UK Ministry of Supply 1945-47 said: "What I like about scientists is that they are a team, so that one does not need to know their names." Many current and former staff members of the ECMWF team, delegates to the Centre's Council and its Committees, and others within and outside the Centre, allowed me to interview them or provided documentary material. Some gave particular help in supplying important and useful material, and improving the text as it progressed: Tony Hollingsworth, Adrian Simmons, Martin Miller, Walter Zwieflhofer, Philippe Bougeault, Gerd Schultes, David Anderson, Tim Stockdale, Sakari Uppala, Peter Janssen, Horst Böttger, Tim Palmer, Manfred Klöppel, John Hennessy, Roberto Buizza, Mariano Hortal, Bob Riddaway, Anabel Bowen and Rob Hine. I thank them all.

Austin Woods

Contents

Chapter 1

The first Director

Professor Aksel Wiin-Nielsen, the ideal candidate for Director of the soon-to-be-established European Centre for Medium-Range Weather Forecasts (ECMWF), was not particularly interested in the post. This was regrettable. However, it was understandable.

Wiin-Nielsen was in an enviable position. He had had an interesting and productive career. His working life started as a secondary-school teacher in his native Denmark, before joining the Danish Meteorological Institute in 1952. In 1955 he went to the International Meteorological Institute in Stockholm, Sweden as a student. Within six months of his arrival, he was invited to present lectures. One of his students was Lennart Bengtsson from Sweden, who was to become the first Head of Research of ECMWF and later its third Director.

Wiin-Nielsen went to the United States in 1959, first to Suitland, Maryland to join the staff of the Joint Numerical Weather Prediction unit. He moved to Boulder, Colorado as scientist at the new Laboratory for Atmospheric Science (LAS). This was part of the new National Center for Atmospheric Research (NCAR), which at the time owned neither buildings nor computers. Years later, he was to recall his time as Assistant Director of LAS: "there were so many practical things of building and changing and getting equipment and installing it . . . and we were all equally inexperienced in all these things". But what excellent experience for the future first Director of ECMWF!

Wiin-Nielsen had moved to Michigan in 1963. In 1969, when in his mid-40s, he first heard of the plans to establish the Centre. He was visiting professor at Copenhagen University for a year, on sabbatical leave from his post as Professor and Chairman of the prestigious Meteorological Department of the University of Ann Arbor, Michigan. The Department had several full Professors specializing in specific areas of atmospheric sciences.

His wife Bente and three daughters were settled in the USA. Life was pleasant in these American university towns in the 1960s. Schools were good; his daughters were progressing through the system. Cultural interests were well catered for, with visits from renowned European and American orchestras, artists and theatrical groups. Leisure activities included tennis, a favourite exercise for Wiin-Nielsen; he played tennis regularly with his grandchildren well into the new millennium, when he was in his late 70s.

He had an excellent professional and family life in the USA. The Beach Boys put it well: “This is the way I always dreamed it would be”. The activities concerning the planning for ECMWF had registered as only a small blip on Wiin-Nielsen’s personal radar, especially as progress was slow. Suggestions were tentatively made that he consider becoming Director of the planned Centre. He twice rather firmly turned them down.

The choice of Director was discussed on 8–9 May 1973 at the third informal conference of the Directors of the National Meteorological Services of the States interested in COST — European Cooperation in Scientific and Technical Research; we will discuss this further in Chapter 3. This was two months after the decision to site the Centre in the United Kingdom. At the invitation of Dr John Mason, later Sir John, the Director-General of the UK Meteorological Office, the conference was held at the Headquarters of the Meteorological Office at Bracknell. The conference expressed the wish that the Centre be set up quickly and efficiently. It was decided that a provisional Council of the Centre should be established, if possible before 1 August, to act as ruling body. This would remove responsibility for the Centre from the COST Senior Officials, who up to now had carried responsibility for establishing the Centre. The provisional Council could then make the decision on the Director, on the basis of technical and scientific criteria. If the Council had not been established, the COST Senior Officials would decide. Now who should be chosen, and how?

The world of meteorology has always been rather small, well informed and well connected. It had been recognised that “above all [of the other essential conditions which had to be fulfilled to establish a viable Centre], an outstanding and particularly energetic scientist had to be appointed Director of the planned institute”. All the researchers in the field, all conceivable candidates, were well known to COST. No advertisement of the vacancy was required.

Three possible candidates all well qualified in the field were considered: Prof B. Döös from Sweden and Prof F. Wippermann from Germany as well as Prof Wiin-Nielsen. However, the general opinion of the conference “was in favour of Professor Wiin-Nielsen”. There was agreement that a group should be set up as soon as possible to provide the nucleus of the staff of the Centre. This would comprise the provisional Director and four others. These would be experts in the fields of numerical prediction, computers, telecommunications and administration, also to be appointed provisionally.

Mr C. L. Silver, President of the COST Senior Officials, noted that the "support for Wiin-Nielsen was very much greater than that for the other two". Döös and Wippermann requested that their names be withdrawn.

Wiin-Nielsen's position now left those planning the Centre with a real problem. It was not simply that he was the best candidate. In a sense, we see that he was now in fact the only candidate.

It would appear that the choice of Wiin-Nielsen was made without any political considerations. Some readers may perhaps find it beyond credibility that any major European decision can be made without political considerations. For their benefit, we can find just a flavour, just the smallest hint, of politics. We will see in a later Chapter that in the vote on the site for the location of the Headquarters of the Centre, Denmark was in second place after the UK. Perhaps not entirely coincidentally, the decision was made that the Headquarters of another European organisation — the European Patent Office — would go to another hopeful contender, Germany. Now what about Denmark? Would it not be entirely appropriate that the first Director would come from Denmark?

Lennart Bengtsson, who was visiting the USA at this critical time, was aware of Wiin-Nielsen's reluctance. Knowing Wiin-Nielsen to be "a competent and born leader", he visited him in Ann Arbor. Bengtsson informed Wiin-Nielsen that he, Wiin-Nielsen, had been nominated for the post of Director of ECMWF, and frankly told him that one of the objectives of the visit was to encourage him to apply.

Meanwhile, for Wiin-Nielsen, times and circumstances were changing. In early summer 1973, he had been offered the position as Department Head at the National Center for Atmospheric Research in Boulder, a position created by the departure of Philip D. Thompson. In addition, George Benton, Deputy Director of the Environmental Science Services Administration (ESSA), successor to the US Weather Bureau, wanted Wiin-Nielsen as Director of the various research laboratories under ESSA, which would also have meant him moving back to Boulder.

Wiin-Nielsen had been at the University of Michigan for ten years. After much reflection, he decided that it was time to move on; there was now a growing sense of inevitability about it. He decided that "if I am going to move anywhere, it has to be to ECMWF".

He had always had a special interest in setting up new institutions: “in one way, it’s easier: you don’t have to fit in with something that already exists”. In addition, the new Director recruits his own staff. He does not have to “take over a group of people who have been used to someone else’s style”. Wiin-Nielsen felt that “you avoid having to take on the weight of the past, which can be hard to bear at old institutions”.

Not quite sure how best to proceed, on 31 July 1973, Wiin-Nielsen wrote to Mr Silver at COST. He informed him that he was aware that he had been nominated for the post of Director of the projected Centre. He expressed his great interest in being considered, being “fully inclined to accept the post if it was offered”. He was aware that it was planned that a group, including the Director-designate, would be established in late summer or early autumn 1973 to make initial plans for the Centre. Wiin-Nielsen enquired into the state of the project, and requested any other information judged useful.

The reply from Silver on 14 August was positive, and outlined the reason for the delay in completing the work on the Convention. Matters concerning the organisation, its programme and its financing had all been settled. What remained was without great significance to the Centre itself, but had assumed great importance to some future Member States, given the precedent that could be set for future organisations: the determination of the official and working languages of the Centre. [Some thirty years later, when consideration would be given to amending the Convention for the first time, the same question of languages was to prove the most difficult to resolve.] Since little would normally be accomplished in Europe in the summer period, the matter was unlikely to be resolved before mid-September at the earliest. The signing of the Convention could be expected soon after the problem was resolved, and the Director appointed provisionally a few weeks thereafter. He was not in the position to tell Wiin-Nielsen the date on which the post would be offered, nor even that it would be offered to him. However, he did inform Wiin-Nielsen that “you are held in very high esteem by all the experts in the field”, and that “they would be greatly disappointed if you would accept another post that would exclude the possibility of you taking on this important function”.

Soon after, Wiin-Nielsen was invited to go to Brussels for a meeting. From his sources, he was aware that the other two potential candidates had withdrawn their names from consideration. He knew that either they could nominate him or they would have to advertise the position. It also became clear that these were serious negotiations: he was told he should bring an assistant with him. The Danish mission to the European Economic

Community (EEC) in Brussels offered Mr Henrik R. Iversen to assist at the negotiations, an offer accepted by Wiin-Nielsen with gratitude. This would turn out to be a wise decision.

Dr John Mason of the UK Meteorological Office wrote asking Wiin-Nielsen to stop off in Britain en route to Belgium, so he could see where the new Centre would be built and the temporary offices that would be made available immediately.

The negotiations in Brussels lasted only a day. In the morning, Wiin-Nielsen met with Dr Süssenberger, Director of Deutcher Wetterdienst (DWD) — the German Weather Service, Dr Schregardus, Director of the Royal Netherlands Meteorological Institute (KNMI), Mr Gosset, Deputy Director of Météorologie Nationale, France, and Mr Zipcy, administrator of COST. They summarised: if terms could be agreed, the job was Wiin-Nielsen's. Iversen was well prepared. He had earlier briefed Wiin-Nielsen on the outcome of enquiries he had made on salaries given to others in comparable positions. When the question of the salary arose, Wiin-Nielsen produced a document stating the required salary, with reasons for the figure proposed. Eyebrows rose on the other side of the table. It was clear they had not thought of a figure of this magnitude. Iversen asked "So how much had you been thinking of?" When this much smaller figure was put forward, Wiin-Nielsen received a slip of paper from Iversen: "Say no". This he did. The parties agreed to have lunch separately, to give time to think things over.

Discussions started again after lunch. The negotiators were willing to accept the well-researched demands, and the remaining issues were quickly resolved. Wiin-Nielsen could say that he was ready to start in January 1974.

As the first person to be recruited for the Centre, Wiin-Nielsen now had to take on the task that would face many future staff members: making arrangements to move his family to the United Kingdom. The list of issues to be tackled would become familiar to many later recruits: temporary and later permanent housing, schooling for the children in a new system with the unusual British O and A Level examinations and where the "public" schools were very much private, separation of all the family members from their friends of long standing, and more. One difficult change had already been made: his family was already living in an English-speaking country.

The day after conclusion of the negotiations in Brussels, Wiin-Nielsen travelled to Denmark to visit his parents and his close family. He then returned to Ann Arbor, where he had many discussions with his wife Bente as to how to arrange the family move to the UK. Their eldest daughter Charlotte had already started university at Ann Arbor, and was in her first year.

Marianne their next daughter was in her last year at high school, and the youngest, Karen Margrete, was at the same school. It soon became clear that they would stay at Ann Arbor for the rest of the academic year at least. Bente would stay with them until they had sorted themselves out, after which she would join Wiin-Nielsen in England. She stayed with them until March, when she sold the house and rented an apartment their children could share.

On 9 January 1974, the COST secretariat was able to send a note to the COST Members:

> *On 21 December 1973, Professor Aksel C. Wiin-Nielsen informed the Secretariat that he agreed to take up the post of Director of the European Centre for Medium-Range Weather Forecasts on the basis of the terms of appointment dawn up by the Interim Committee and approved by the Committee of Senior Officials on Scientific and technical Research. He took up his duties on 1 January 1974.*

Wiin-Nielsen was at this stage the Director-designate; he did not formally become Director until 4 November 1975, when he was appointed by the first Council session. He spent his first few weeks in his new position in Brussels, to familiarise himself with the procedures of the COST secretariat. Initially the Centre would function under COST, since the new organisation would not come into existence as a legal entity until sufficient States had become Member States by ratifying, accepting or approving the Convention. This could take some time, and in fact was completed only on 1 November 1975, almost two years after Wiin-Nielsen's appointment. In the meantime, the future Member States were keen for preparations to proceed with deliberate speed. The different bodies, the steering committee — the precursor to the Council — and supporting advisory committees, were to be set up and running, with financial support coming officially through COST for the interim period.

While staying in Belgium, Wiin-Nielsen lived at the Hotel Metropole on the Place Brouckère. He knew when he arrived that he would be there for some weeks, and he insisted on choosing a room himself; he would need furniture that would allow him to work from the room. The hotel was well known in scientific circles, as it had been the location for many of the famous Solvay scientific conferences of the early decades of the 20th century, which brought together many distinguished physicists in Europe. The Solvay conferences on physics were particularly noted for their role in the development of theories on quantum mechanics and atomic structure. In this hotel, many important discussions between Bohr and Einstein had taken place. Pictures of the scientists who had attended the meetings were available for purchase in the hotel lobby.

During these few weeks, the Danish mission to the EEC, which was close to the building where COST was based, provided an office at its premises for Wiin-Nielsen's use.

Wiin-Nielsen's contact at COST, Mr Moys from the UK, acted as an administrator for the first few months until the Centre received its own budget during the course of 1974. Wiin-Nielsen found his knowledge and experience in dealing with the bureaucracy in Brussels to be most helpful. Wiin-Nielsen and Moys made rapid progress, and submitted budget proposals, which were considered at the first meeting of the interim Council, so that Wiin-Nielsen could start working from England.

In his first weeks in Brussels, Wiin-Nielsen and Moys arranged the first meeting of the temporary Scientific Advisory Committee, to which Dr Heinz Reiser of Germany was appointed Chairman. This was very helpful to the recruitment process Wiin-Nielsen was due to start once he moved to England. The Committee members could support him in a number of respects, especially since at this time Wiin-Nielsen was not that familiar with European meteorologists. He was glad to note that the Committee members were both highly interested and very helpful, even if some of them appeared at times to be rather upset. Wiin-Nielsen suspected that they would perhaps have liked to be considered for some of the posts themselves!

At the beginning of February, Wiin-Nielsen moved to Bracknell. This town is 15 km east of Shinfield Park, Reading, where the Centre building was to be constructed. The top two floors of Fitzwilliam House, an office building about 10 minutes' walk from the headquarters of the UK Meteorological Office, had been set aside for temporary use by the future staff of the Centre. At the beginning of course there was only Wiin-Nielsen. The accommodation was above the local government offices of the Department of Health and Social Security (DHSS), so there was constant activity in the building.

Wiin-Nielsen arrived in Britain in the middle of the first major oil crisis. There were restrictions on use of electricity and heat. Wiin-Nielsen remembered the DHSS caretaker keeping a close eye on his use of power! As it was winter, there was sometimes not enough light. He used an east-facing office in the morning and moved to a west-facing one after lunch. He was invited to take his lunch in the cafeteria at the Meteorological Office, in the separate room for higher civil servants, irreverently known to junior staff as "the Golden Trough". That suited him: it meant he could do some shopping, and visit the bank and Post Office, en route between the two buildings at lunchtime.

At the beginning, he wrote his own letters and documents, until he employed a secretary, Jane Khoury, who, he recollected, “must have been one of the best typists in the world”. The financial regulations were still to be adopted. Initially, no funds were available for capital expenditure, only for consumables. He couldn’t for example buy typewriters; the financial constraints were such that he had to hire them. Following long discussions in the Finance Committee, this was done, but with the option to buy during the first two years.

He stayed at the Royal Ascot Hotel, but soon rented a small terraced house on the south side of Ascot. His wife Bente arrived in the spring. They started looking for a family house immediately, and found a suitable one in Finchampstead. It would be June before his finances were sorted out; as a foreign national he could not use the standard UK mortgage arrangements. Finally, Barclays Bank arranged a suitable loan. They had moved into the house by the time their children came from Ann Arbor, one by one over the course of the summer. The two eldest had arranged summer vacation jobs there.

Wiin-Nielsen was determined that the Centre would not become dedicated solely to meteorological research. He agreed with the objective that the Centre would instead move as quickly as possible to become an operational source of real-time weather forecast information for the benefit of the National Meteorological Services of the Member States. He believed that there was no point in re-inventing the wheel, so to speak. Instead of planning to spend the first decade developing its own model, he set a target date of August 1979 for the first operational forecasts, using whatever means were available.

His first difficult task was to assemble a well-qualified group for the development work ahead. He took the view that he wanted people who could in principle join the permanent staff once the Convention came into force. Talent is rare, and he knew that he needed to attract the best in their fields from among the scientific and technical staff of the future Member States. As the Centre was to be both a scientific and an operational institution, Wiin-Nielsen decided there should be three Departments: Research, Operations and Administration.

It was time for the COST secretariat to be relieved of responsibility for the Centre. An early priority was given to getting administrative assistance. James Clark of the UK Meteorological Office was appointed temporarily to help deal with administrative issues.

It was clear that Lennart Bengtsson was very interested in coming to work at the Centre. Wiin-Nielsen had known him very well over the years.

A graduate of the Universities of Uppsala and Stockholm, he had been interested in meteorology from his teens. For his military service, he had taken advantage of a new arrangement set up by Prof Carl-Gustaf Rossby, under which two months of basic military service was followed by academic studies under “excellent and inspiring teachers” including Bert Bolin, Bo Döös and Aksel Wiin-Nielsen. Bengtsson remembered Wiin-Nielsen teaching him the Fjørtoft Graphical Technique, a manual method of numerical weather prediction. After a spell as assistant to Tor Bergeron at the University of Uppsala, Bengtsson joined Bo Döös in setting up a numerical weather prediction unit at the Swedish Meteorological and Hydrological Institute (SMHI).

In the 1960s Bengtsson became involved with planning for the First GARP Global Experiment (FGGE), visiting the United States several times. He explored the need for global data assimilation and collection of the global data for FGGE. Another of his activities was being Chairman of the World Meteorological Organization (WMO) Working Group on Numerical Weather Prediction. In addition he had published a number of papers on numerical forecasting, and had been involved in the Global Atmospheric Research Programme (GARP). Bengtsson was an ideal candidate for the post of Head of Research at the Centre. While Wiin-Nielsen and Bengtsson rapidly agreed on terms, his appointment formally had to await Council approval.

Meanwhile, Jean Labrousse of France had been highly recommended to head the Operations Department. Like Bengtsson, Labrousse had been an active member of the Interim Planning Staff for ECMWF. When Wiin-Nielsen approached him, however, he was non-committal on the telephone; Labrousse appeared to be somewhat reluctant to take a post at the Centre. During a visit to Paris, Wiin-Nielsen and Labrousse got down to serious negotiations. Labrousse explained that while he wanted to come to the Centre, there were two problems. One was that his immediate superior Mr Mittner was unwilling to grant the leave of absence required. The other was Madame Labrousse, Janine, who perhaps understandably couldn’t imagine living isolated in the British countryside! Wiin-Nielsen made an appointment with Mr Mittner and Mr Gosset, who was deputy to the Director-General. Mittner argued that he couldn’t do without Labrousse, because they were on the brink of moving the department to Toulouse. Gosset explained that the transfer wouldn’t happen for at least some two years, and Labrousse was given leave of absence for that period. He agreed with his wife that they would live in an apartment in west London. Labrousse would “reverse-commute” against the flow of traffic, leaving London in the early morning and returning in the evening.

Wiin-Nielsen was highly satisfied with the appointments. The three worked together outstandingly well on building up the Centre in the next few years. They complemented each other excellently. It was clear that Bengtsson was not happy at the beginning about the idea of living in Britain, as there were major differences between general attitudes in Britain and Sweden. He frequently referred to an article in the Swedish press, which said that any Swede who had lived in Britain for two years or more could never go back to Sweden, because he would have lost all his efficiency! Wiin-Nielsen was amused to note that Bengtsson eventually retired to live in England, continuing his research at the University of Reading, in an office just a couple of miles from the Centre.

Labrousse always envisaged going back to France after a short time, but in fact he stayed at the Centre for close to eight years, before returning to become Director-General of Météorologie Nationale, the French Meteorological Service. Perhaps we can look ahead to a party in December 1981, when the Council bade farewell to Labrousse. The Council President Dr E. Linglebach from Germany, having recognised Jean Labrousse's "great skill and ability" in recognising the important problems, noted: "you have always found workable solutions", and further: "j'ai admiré votre logique française et votre humeur gallic!"

Bengtsson and Wiin-Nielsen were working on getting the experimental forecasting up and running. In line with his objective to start operational forecasting soon, Wiin-Nielsen contacted two groups in the USA, who were well advanced in terms of model building. One was at the University of California, Los Angeles (UCLA), led by Professor Yale Harvard Mintz, "the only person I know" said Wiin-Nielsen "who was named after two universities!" The other was at the Geophysical Fluid Dynamics Laboratory (GFDL), under Dr Joseph Smagorinsky. Both of them agreed to make their modelling and other software available, on condition that the Centre sent a scientist to work with their groups for a few months, to gain a full understanding of the complex software. This was agreed, and Robert Sadourny, at the Centre on leave from the Centre National de la Recherche Scientifique (CNRS), went to Los Angeles. Also Tony Hollingsworth, who was a newly recruited scientist and later became Head of Research, went to Princeton.

In the meantime, Labrousse was working on getting temporary use of a computer for installation at Bracknell. A Service Agreement with Control Data Limited came into effect on 26 August 1975. The hired CDC 6600 was slow, and although far from satisfactory for the requirements, it had enough capacity to allow trial forecasts. It was installed in John Scott House, a building close to Fitzwilliam House. In December the Service

Agreement was changed to a Lease Agreement, giving unlimited access to the computer. In addition, time was purchased on the IBM 360/195 at the Meteorological Office.

Recruitment of staff from Member States for the Research and Operations Departments continued. All were conscious that the spin-up time allowed for the entire complex system to get to fully operational forecasting was very short — too short, in the opinion of some.

When it came to appointing the Head of Administration, Germany strongly supported Dr Wolfgang Dieter von Noorden for the post. He replaced Mr Clark, who if given the choice would have liked to continue. It is fair to say that the working styles of von Noorden and Wiin-Nielsen were very different. Wiin-Nielsen needed to make a myriad of decisions large and small in a rather short period and while under pressure to produce results quickly. Von Noorden's background in the larger and more bureaucratic administration of the Federal Republic of Germany did not match well with Wiin-Nielsen's requirements at the time. Discussions on administrative and legal matters were at times difficult, even heated. After a relatively short time, von Noorden left the Centre, to take up an appointment with INMARSAT in London.

Committee meetings moved from Belgium to Britain. Conference rooms of sufficient size and with the required facilities for simultaneous interpretation were unavailable in Bracknell. Suitable premises were found at the Headquarters of the International Coffee and Cocoa Organisation in London. Those who attended the meetings remembered them for the four different kinds of excellent coffee, always provided for free! Centre staff gradually gained more experience with meetings. The underlying papers got shorter and better, thanks largely to the precision and brevity of the original English documents, whose preparation was handled by Ernest Knighting (normally referred to simply as "K"), a consultant who had recently retired from the Meteorological Office. K did a "marvellous job" of introducing Wiin-Nielsen, Bengtsson and Labrousse to the sometimes subtle nuances of the British system. Labrousse later referred to him as "une figure, très intelligent, très fin, avec un esprit critique très acerbe et au final très constructif."

At an early stage, an estimate was needed of how many members of staff would finally be required. A surprisingly small number — just over 30 — was allowed for the Administration Department. An international organisation has heavy requirements for administrative personnel including recruitment of international staff, and for translation, as well as general services, building maintenance and liaison with the authorities of the host country. The Operations Department became the largest; it was clear that the Centre would work round the clock. Many technical staff would be required to supervise and maintain the computer and telecommunications installation, the software and other technical equipment. These were estimated to total about 65. Around 35 scientists would be required for the Research Department. The total was thus taken to be around 130. The architect assigned to the building project, Mr Kidby, needed these numbers, even though they were a shot in the dark at that early stage.

Kidby also needed an estimate of how many square metres would be needed for computing equipment and other technical installations. That was more difficult, as the planning staff still had no idea what computers might be acquired in the years to come. The most pessimistic assumption had to be made that the largest machines then available would be installed. This proved to be wrong, as the Centre's choice, a CRAY computer, was highly compact. On the other hand, the more usual problem of the building being too small was avoided; later there was adequate space for replacement mainframe computers, which would run in parallel with those already installed. Furthermore, space was available for a large archive and for the many magnetic tapes used by the computer system in the 1970s. It was not until more than 30 years later that the Computer Hall would need to be extended; a contract for this extension was signed in July 2004.

The architect also needed to know how many of the staff would be men, and how many women; this would affect the number of toilets required. Wiin-Nielsen looked him in the eye and told him that there would be equal numbers of each. Kidby proceeded accordingly.

Working with Kidby went well on the whole. Kidby said that it was good working with precise people, but there was one point of serious disagreement. There was an energy crisis at the time in the UK. As the electricity supply might fail, it was important for the Centre to have two large diesel generators, which could provide the Centre with the backup supply required, and some large batteries to ensure that computing would continue uninterrupted if the power supply failed. This was absolutely essential, as it would take up to 30 minutes to get the diesel generators up and running. Data could therefore be lost, and the programs running adversely affected. Kidby agreed to all this, but when Wiin-Nielsen said the batteries should be in the basement below the computer room, Kidby disagreed: “We don't do basements in Britain”. The reason for this was that they were always damp and hence unusable. Wiin-Nielsen explained there were basements in the Netherlands and Denmark in areas below sea level. But the answer was the same: “We do not do basements”. There was a deadlock. One weekend

Wiin-Nielsen, Bengtsson and Labrousse visited the site and visualised the finished building in drawing form. They realised that if the whole complex was rotated through a few degrees, the computer room would be on a sloping section of the site, so there would be room for two floors on the low side and one on the high side. Wiin-Nielsen suggested this at the next meeting. Agreement was reached, and the batteries were installed on the ground floor under the computer room, which was strictly speaking no longer a basement.

A separate wing held an excellent lecture theatre seating 126, and a large conference room for the Council, its Committees and other groups, containing an oval table large enough to accommodate the Chairman, 42 delegates and 40 advisers. Five interpreters' booths allowed for simultaneous interpretation to and from the five official languages of the Centre. There were also smaller meeting rooms. The final wing contained the offices, with the library on the top floor.

It was necessary to have discussions with the UK government on matters concerning the Centre, such as negotiating the Headquarters Agreement between the Centre and the UK, which laid down the rights and obligations of the Centre; Wiin-Nielsen was given a contact at the UK Foreign Office, Miss Phyllis Smith. She helped greatly with many issues raised, and wrote the first draft of the Headquarters Agreement. This was based on similar agreements with other organisations, but contained one perhaps rather unusual provision. The Centre was granted a 999-year lease on the land free of charge, with the condition that, when the land and buildings reverted to the UK, the buildings had to be in the same condition as received. Wiin-Nielsen was intrigued; he asked Kidby how long he thought the building would last. The answer was that they "didn't build for centuries any more, only perhaps for 60-70 years". After a little discussion, he and Wiin-Nielsen agreed that this would be a problem for others to worry about! Wiin-Nielsen signed the Agreement for the Centre.

In the two weeks 1–12 September 1975, the first of what was to become an annual series of ECMWF Seminars was held at the Met Office College in Shinfield Park. Prof Pierre Morel from Laboratoire de Météorologie Dynamique (LMD) France dealt with data and its assimilation in numerical models, Dr Kiku Miyakoda from GFDL reviewed how physical processes were modelled, as well as numerical methods. Dr Cecil Leith from NCAR described progress in understanding uncertainties in the initial state and in the representation of physical processes. More than forty participants attended from the Member States. This was the beginning of the Centre's major programme of advanced training. Each year since, the Centre has organised well-attended Training Courses in meteorology and computing, as well as Seminars and Workshops.

At the first Council session on 4–6 November 1975, Wiin-Nielsen presented his first report to Council. (The role of the Council and its Committees is outlined in Annex 2.) Contracts with the Centre staff had expired the preceding Saturday, but had been extended to cover the period of the Council session! However, he noted that with the Convention coming into force, and the adoption of staff regulations and financial regulations, the days of improvisation were over; the Centre was now on a sound footing. He noted the importance of the forthcoming major First GARP Global Experiment (FGGE) exercise, planned for about the time that the Centre would be ready to begin operational forecasting.

The Centre's headquarters building was opened on 15 June 1979 with speeches from His Royal Highness Prince Charles, Prof Lauri Vuorela of Finland, who was Council President at the time, and Wiin-Nielsen. Dr E. Süssenberger, first Council President, and as we shall see later a key figure in planning the Centre from the beginning, was among the guests invited to attend the opening ceremony.

While the contract for the Centre's computer was put out to tender, in reality there was no credible competitor; this was a one-horse race. The contract was negotiated and signed with Cray Inc. Such a major purchase had to be approved by the Council, taking into account the opinions and recommendations of the Finance Committee. Labrousse was outstanding in presenting the issue to the Committee and Council. He had considered all the possible clauses of the long and complicated contract and answered questions clearly. The representative in Europe of Cray Inc, Mr Peter Appleton Jones, was also of great help. The Centre had the first prototype CRAY-1, later replaced by a completely new machine. It — and the same was true for its successors — was surprisingly reliable for such complicated hardware and software. Before the start of operations, foreseeing the absence of a backup mainframe computer, Member States were advised to plan for the loss of perhaps one forecast per week, or two or three a month, to allow for unexpected hardware or software problems. In the event, only a handful of forecasts were partially or completely lost in the first operational year from 1 August 1979. These were later re-run to maintain a full archive. Operational forecasting seven days per week began on 1 August 1980; none of the forecasts were lost after that date and delays were few.

Wiin-Nielsen left the development of the science to Bengtsson and his staff in the Research Department. They made rapid and substantial progress in creating the Centre's own forecasting model. Studies of the model software obtained from the USA, and the experience gathered from other institutions, as well as their own substantial stock of experience, all contributed. The task, quite simply, was to put together a model consisting of the best components from the scientific literature or created in-house. Bengtsson was a driver; he demanded, and demanded again, more and more of his staff. He was impatient with doubters. He never accepted “luck” as an explanation for success, or “bad luck” as an explanation for failure. He peppered his staff with questions, constantly raising the level of expectation. He had “the vision thing”. Perhaps more important, he had the staff who were able and willing to carry out the necessary research. It was common to find Centre staff working late into the evening, and at weekends and holidays. Years later, when Bengtsson was Director, the prospect was raised by the Administration Department of keeping account of staff hours worked. Bengtsson vetoed this rapidly. He knew that if staff realised just how much time they were putting in, this would likely have resulted in a reduction of the hours worked!

In spite of his administrative and management responsibilities, Wiin-Nielsen maintained a close personal interest in the scientific work. Sakari Uppala, a Finnish scientist working on the FGGE data at the Centre, remembered Wiin-Nielsen regularly coming into the FGGE office, pulling up a chair, lighting one of his famous low-tar cigarettes, and asking: “OK now, what’s new today?”

There was one major subject on which Wiin-Nielsen felt very strongly, and which led to some intense, even difficult, discussions between him and the staff of the Research Department. That was the use of the mathematical “semi-implicit scheme” in a global forecast model. This — to allow longer time steps in the model — was a major gamble taken on Bengtsson’s insistence. He needed to use this numerical formulation to allow the use of a high-resolution global model. Semi-implicit time differencing is relatively more stable and allows larger time steps than the explicit time differencing then used. A model with a time step of 20 minutes would need only one-quarter of the computing resources required by a model with a five-minute time step. He planned to use David Burridge’s experience of the semi-implicit scheme already in use at the UK Meteorological Office.

Burridge had been one of the first recruits to the Centre in May 1975 as a member of the Interim Planning Staff. He had been at Florida State University for a year from September 1979, when he had been awarded his PhD in mathematics by Bristol University. He had come to the Centre following five years’ experience as a scientist involved in forecasting research at the UK Meteorological Office, working as part of a strong team headed by the legendary Fred Bushby. They had developed a 10-level model with 100 km horizontal resolution extending over the Northern Hemisphere, which was designed to predict frontal development and rainfall. Burridge went on to become the Centre's Head of Research, and later its longest-serving Director, holding that post from January 1991 until his retirement in June 2004. In 1995, Queen Elizabeth II awarded Burridge the prestigious title of Commander of the British Empire (CBE) for his services to meteorology.

Burridge was given overall responsibility for the numerical aspects of the first model. Bengtsson was convinced that successful medium-range prediction would require a resolution of at least 2° in latitude and longitude. This could not sensibly be achieved without replacing the explicit scheme with a semi-implicit scheme. Wiin-Nielsen was concerned that the scheme would in fact lead to a running time of the forecast that would be longer than operationally feasible, and that errors would be introduced into the forecasts. Bengtsson and his staff stuck to their guns. Experiments showed that only insignificant differences were introduced in the forecasts when the more efficient semi-implicit scheme was used. Eventually Wiin-Nielsen, after being shown the experimental evidence of the benefits, reluctantly agreed. The scheme was used in the model. The first version of the model was tested in 1977, when the CRAY-1 was installed. Testing continued throughout 1978. The Centre was ready to start operational forecasting in 1979, as planned.

The results were promising. Compared with forecasts produced in the USA, Britain, France, Sweden and Japan, the Centre's trial forecasts were clearly best. By 1979/80 the Centre was already providing forecasts useful on the average for up to 5 or 6 days ahead — a wholly remarkable achievement.

One of the keys to Wiin-Nielsen's effectiveness as Director and Chief Executive Officer of the Centre was his admired natural ability to forge creative working relationships: first between the Centre staff in its three Departments of Administration, Research and Operations, and then between the secretariat of the Centre, the Council, its Committees and various Working Groups. His ability to manage Council and Committee sessions became the stuff of legends. It was said that he would allow discussions to proceed, listen to the national delegates state their positions, and when discussion reached an impasse, would produce his own well-prepared proposal, to the relief of those sitting around the table, who were happy to approve it.

Wiin-Nielsen was proud to be able to say that the Centre and its staff, with their efforts, had delivered the forecast products on time, and with high quality. Wiin-Nielsen later noted that for him, this was the greatest experience of his life: to be allowed to head this major project, which required scientific insight, technical ability, practical action and a good working relationship with Council and its Committees. He recognised that this could never result from the work of one man. It called for collaboration, respect for other people's opinions and abilities, and above all constant, unyielding hard work with a definite aim kept clearly in focus. Wiin-Nielsen noted that the feeling of satisfaction that comes with such good results after five years' work is quite different from the euphoria felt on achieving a scientific result in a limited investigation. Taking small steps never feels entirely satisfactory. Nor does taking action without complete scientific knowledge. But certainty and perfection have never figured prominently in the story of human progress. The Centre's staff had to use all the collected knowledge that they and others had of the atmosphere's behaviour on a grand scale of time and space to develop a model which would run on the Centre's computer. The work of 40 or 50 people "wrestling with all the details, day in, day out, evenings and weekends too", was brought to a successful conclusion. Wiin-Nielsen stressed that it is they collectively who should be honoured for the good results.

It has been said that "things are as they are because they were as they were". There is no doubt that a large part of the credit for the success of the Centre as a world-renowned scientific research and operational institution is due to the initial leadership of one man — Prof Aksel Wiin-Nielsen, its first Director.

By early 1979, another change was in the air for Wiin-Nielsen. Arthur Davies from the United Kingdom had been Secretary-General of the World Meteorological Organization (WMO) since 1955, and would be retiring at the end of the year. The representatives to WMO from the European States sought a suitable candidate to replace him. With his well-recognised and admired success in establishing the Centre as a world leader, Wiin-Nielsen's name was soon being considered. He was not enthusiastic at the prospect. Taking on the management of a long established secretariat, without a well-defined operational or research task, was, as we have seen, not a pleasant prospect for him. He was however subject to strong persuasion by some important delegates to the Centre's Council. They were themselves the Permanent Representatives of their States to WMO, and knew of the importance of the task of the WMO Secretary-General. With reluctance he allowed his name to be put forward. Wiin-Nielsen was elected in summer 1979, and with considerable regret left the Centre at the end of the year.

In the event, Wiin-Nielsen remained in his post at WMO for only one term of four years. In 1984 he became Director of the Danish Meteorological Institute, and in that function attended sessions of the ECMWF Council. He was in fact elected as Vice-President of Council in 1985 and President in 1986. In 1987 he became Professor of Physics at the University of Copenhagen, and in 1995, Professor Emeritus of the University. In his retirement he had use of an office in the headquarters of the Royal Society in Denmark, close to his home, where he continued actively to pursue his research interests.

Chapter 2

The beginnings — the political background

Meteorology is international. The rain washing the dust from the vine leaves in France this morning is from the same frontal system that will be starting the windscreen wipers on the German autobahns this evening, and irritating the cyclists in Leiden tomorrow as they pedal their way to work.

Closer European co-operation in the field of meteorological research, and the practical application of the results of that research for forecasting the weather, has been of interest for a very long time. In July 1951, Prof Carl-Gustaf Rossby published a "Note on Co-operative Research Projects" in which he stated that:

> *the relations between meteorologists in the south and in the far north of Europe are not nearly as intimate as one might wish.*

Further:

> *Studies are now being conducted . . . to determine the advisability of organising international scientific laboratories . . . the organisation of an International Computing Centre appears to have been accepted in principle.*

He also noted that:

> *the national weather services are likely to profit more from properly staffed and equipped independent research teams organised and operated in academic settings outside the regular government services than from any attempt to conduct the required research within the rigid framework of the official government meteorological bureaus.*

As a result of the initiative taken by Prof Rossby, and with the strong support of the former Minister for Foreign Affairs of Sweden, Richard Sandler, the renowned International Meteorological Institute (IMI) in Stockholm was created in 1955 by a decision of the Swedish Parliament.

Its objective was “to conduct research in meteorology and associated fields and to promote international scientific co-operation within meteorology”.

Indeed, when the IMI was set up, work in using computers to provide weather forecasts had already progressed. By October 1954, Sweden was preparing to make the world’s first “operational” numerical forecasts; “operational” in the sense that the forecasts were available before the actual weather.

In the 10 to 15 years following creation of the IMI, a great deal happened in the world of politics and science. Meteorological science and technology advanced on multiple fronts. Some form of rather undefined European political integration was under way.

The idea of setting up a “European Meteorological Computer Centre for Research and Operations” had an unusual starting point. The initiative came not from scientific or technical sources but rather from the political arena. Previously it had been customary for meteorologists to develop plans for the improvement of their services. These plans were submitted to their Governments, who were asked to provide the financial resources required.

In this case, however, the stimulus came from the Governments. The meteorologists were requested to develop plans following a political initiative.

In 1963, in a recommendation to its Council, the Commission of the European Communities called attention to the importance of scientific and technical research. A Working Group on Policy in the Field of Scientific and Technical Research was set up within the EC Committee for Medium-Term Economic Policy. This Working Group, first chaired by Prof Maréchal, later by Prof Aigrain, made a decisive contribution to the establishment of the Centre. The most important tasks of the Group were to:

> *define those areas in which the efforts in the field of applied research, especially in comparison with the efforts of other countries, had evidently been insufficient, and those developed areas in which the dynamic forces closely and directly depended upon the development of scientific and technical research.*

We note in passing that bad, or at least tortured, English was apparently already established as the lingua franca for Europe!

In 1967 the Council of Ministers of the European Communities dealt with all aspects of general research policy. The European Community of Coal and Steel created in 1951, and the European Economic Community (EEC) and the European Atomic Energy Community (EURATOM), both established in 1957, had jointly prepared a document: “Memorandum on problems raised by the scientific and technical progress in the European Community”. This contained an analysis of the general situation, taking into account the economic state of Europe. The promotion of projects of great economic importance was considered; co-operation was particularly emphasised. The document stated that:

> *The individual European countries can no longer develop and implement their own policies in the field of technology; on the contrary, they must . . . unite their forces, and aim at a common organisation,*

and later:

> *Training of an adequate number of highly qualified researchers and technicians is another basic requirement for the success of every research work. In this field, for which the States are responsible in the first place, increased efforts are required. At the same time, it has to be considered how to prevent a great many European researchers and technicians from emigrating forever to third counties.*

It appears that meteorological projects were suggested for the first time on 29 March 1967. In a document submitted to the Working Group "Policy in the field of scientific research" we find that:

> *According to German belief, the possibility of international co-operation in the following fields could be discussed:*
>
> 1. *Natural Sciences*
> 2. *Engineering Sciences*
> 3. *Medicine*
> 4. *Agricultural and veterinary sciences*
> 5. *Future sociological and political tasks in research and development.*

Among the 11 subjects under "Natural Sciences" we find two relating to meteorology: "longer-range weather forecasts" and "influencing weather". Through today's eyes, the reference to influencing weather may seem a bit strange. In the mid-1960s, however, meteorologists were hopeful that soon rain and snowfall could be encouraged or reduced by artificial means, hail made less harmful, fog dissipated, hurricanes steered away from populated areas and more. Early optimism has since given way to cold realism. It remains true that "you can't fool with mother nature"; but at the time, there was no indication that weather modification would by-and-large wither on the vine, while application of computers would become widespread in almost all areas of meteorological science.

The Working Group on Policy in the Field of Scientific and Technical Research was asked to present a report to the meeting of the Council of Ministers in October 1967. This contained a great many suggestions about areas of science and technology where there could be useful European co-operation. In June 1967, seven areas were emphasised:

- documentation research,
- language translation,
- computer installations for scientific purposes,
- oceanography,
- materials research,
- annoyance caused by noise, and
- refuse disposal.

The Working Group decided to concentrate on the most important areas, and in July it gave its opinion that, for the time being, four areas were worthy of promotion:

- information processing,
- traffic and telecommunications,
- oceanography, and
- metallurgy.

In October 1967, the Council of Ministers recognised that political co-operation of the six Members of the EEC had come to something of a deadlock. They adopted a resolution at a meeting in Luxembourg, which asserted that the Member States of the European Economic Community — Belgium, France, Germany, Italy, Luxembourg and the Netherlands — were willing to extend their co-operation in fields outside economics, and specifically to implement an energetic programme to promote scientific and technical research. The Council was of the opinion:

> *that progress in scientific and technical matters was a fundamental factor affecting the economic growth and general development of the Member States of the Communities and in particular their competitive capability;*

and

> *that the achievements of European countries in the field of scientific and technical matters and their industrial application had not been as rapid during the previous few years as those recorded outside Europe in a certain number of branches essential to the development of modern industrial economies, and that Europe is far behind in this field creates a serious risk to its medium and long term economic and social development.*

At its session on 31 October 1967, the Council of Ministers agreed to the proposal of the Working Group on Policy in the Field of Scientific and Technical Research, with minor modifications. The Council required the Working Group to examine the opportunities for co-operation in six fields:

- information science and telecommunications,
- development of new means of transport,
- oceanography,
- metallurgy,
- nuisances, and
- meteorology.

Expert Groups for each of these areas were set up. The Council requested Reports before 1 March 1968, allowing only four months for their preparation, so that it could submit conclusions before 1 June 1968. It required that the Reports should “take into consideration the co-operation existing at the present time in other international organizations, and should seek means to enable other European States to participate in such projects”. This was particularly relevant for meteorologists, who were already well accustomed to working internationally.

The meteorologists of the Member States of the European Communities were thus presented with a unique opportunity: to study, by official order, the fields in which joint actions were possible.

It was a frustrating fact in the world of European meteorology that meteorologists from Western Europe wishing to work with other European meteorologists found it easiest to do this by going to the United States, and in some cases to the Soviet Union. The USA had a number of university departments in the field with lecturers, researchers and professors from several European countries.

Novosibirsk had a strong school in meteorology, with good expertise in numerical techniques. Guri Marchuk in 1962 had set up a computational centre of the Siberian Department of the USSR Academy of Sciences in Novosibirsk. Extensive research on atmospheric and oceanic physics, along with studies on computing technology and software, were conducted under his guidance. Marchuk later became President of the Academy of Sciences of the USSR, and served as Vice Chairman of the Council of Ministers of the Soviet Union. Lev Gandin, author of more than 200 journal articles and 14 books, was there as well. Several scientists from Météorologie Nationale, France, spent periods in Novosibirsk.

Western Europe lacked co-operative opportunities in other scientific fields as well as in meteorology. Many European scientists of several disciplines had emigrated to take advantage of the better research opportunities elsewhere. It was becoming accepted that individual states would find it difficult to resolve the problem; a common initiative was required.

Work started immediately.

Chapter 3

Meteorological developments 1967 to 1971

A visionary concept in 1967 became ECMWF four years later.

November 1967:	Longer range weather forecasting and research using a very large European computer installation
April 1969:	European Meteorological Computer Centre for Research and Operations
May 1970:	European Meteorological Computing Centre (EMCC)
August 1971:	European Centre for Medium-Term Weather Forecasting (ECMW)
November 1971:	European Centre for Medium-Range Weather Forecasts (ECMWF)

It is worth looking at some of the detail of this evolution.

In November 1967, the important "Expert Group for Meteorology" was established under the Chairmanship of Dr E. Süssenberger, who had been President of the German Weather Service, Deutscher Wetterdienst (DWD), since August 1966. Within a short time, Prof E. Lingelbach, who would become President of DWD in 1977, visited the National Meteorological Services of the six countries in the EEC to elicit opinions on European co-operation in the field of weather forecasting. A physicist Mr van der Kolk from the European Communities accompanied him.

Most countries agreed that co-operation should extend beyond the six nations of the European Communities. Many topics met with general approval:

- meteorological measurements by satellites and by EOLE constant-volume pressurised balloons,
- turbulence,

- convection,
- experts' meetings,
- tropical meteorology,
- general circulation,
- influencing weather on the small scale (for example dissipation of fog),
- synoptic meteorology,
- dynamical climatology in the Mediterranean area,
- agricultural meteorology,
- bio-meteorology,
- infra-red measurements,
- longer range weather forecasting and research using a very large European computer installation,
- atmospheric optics,
- international research programmes,
- radio-sondes,
- visual range measuring instruments,
- instruments for measuring cloud altitude,
- European manufacture of balloons,
- wind shear,
- air pollution,
- three-dimensional wind measurements,
- research stations in the Antarctic,
- exchange of research results, and
- documentation and ozone measurements.

In this rather long list we can find the first mention of what became the European Centre for Medium-Range Weather Forecasts.

The Expert Group for Meteorology first met on 4 January 1968 in Brussels. Of the six countries of the European Communities, only Luxembourg was not represented. Detailed discussions were held on the projects. Three sub-committees were established to define the individual projects more precisely and to assess their merits.

- **Sub-committee I:** Structural problems, secretariat, and integration into the EC, general questions of standards, standardisation and industrial questions, basic questions of common programmes.
- **Sub-committee II:** Development of new instruments, standardisation of existing instruments, new measuring procedures, documentation.
- **Sub-committee III:** Scientific programmes in general, homogenising ozone research, seminars, floating balloons, buoy systems, computer centre, satellites in meteorological research and operations.

The members of Sub-committee III, responsible *inter alia* for the "computer centre", were Prof Rosini (Italy), Prof Schmidt (the Netherlands), Prof Lebeau (France), Dr van Isacker (Belgium), Dr Lingelbach (Germany) and Mr van der Kolk (European Communities).

One important question considered by Sub-committee III was whether it was justified at that time to invest considerable sums of money in a centre for Numerical Weather Prediction (NWP) using a powerful computer — was the science sufficiently developed to consider such a project?

In April 1967, Dr Süssenberger had informed the WMO Congress that in his view:

> *weather prediction for the general public, aviation and shipping, posed a crucial problem. A frontier had been reached which could not be crossed by conventional methods; beyond a relatively short-range prediction period of 36-48 hours, the accuracy of forecasts left much to be desired.*

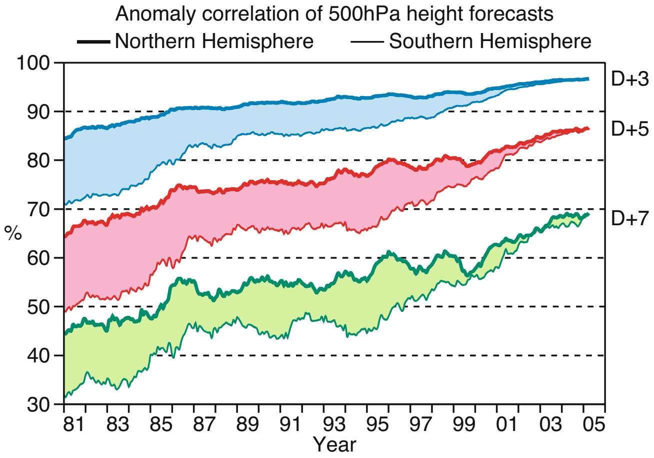
With the benefit of hindsight, one can see that the Centre developed and grew during the 1970s and early 1980s in intimate association with the vast scientific and technical work of the Global Atmospheric Research Programme (GARP).

Following the establishment of the World Weather Watch in 1963, GARP was perhaps the most ambitious scientific undertaking in the history of meteorology, indeed perhaps in the entire field of geophysical science. GARP aimed to reveal nothing less than the details of the dynamics of the atmosphere of the planet. Launched in 1967 by WMO, with the collaboration of the International Council for Science (ICSU), GARP lasted 15 years. Its field experiments led to dramatic progress in weather forecasting. One of these, the GARP Atlantic Tropical Experiment (GATE), which took place from June to September 1974, was unprecedented in its scale and success.

Some 70 countries participated in GATE. A huge observational system, including over 40 ocean research vessels and a number of meteorological aircraft, as well as balloons and meteorological satellites, was deployed. The unique results were fundamental to our understanding of the large-scale weather systems of the tropics. Some thirty years later, the Centre as part of its Re-Analysis Project would use the unique and valuable collection of GATE observations again to prepare analyses of the global atmosphere at that time — we will return to this in Chapter 13.

The crowning achievement of GARP was undoubtedly the First GARP Global Experiment (FGGE), planned first for 1977, then 1978, and brought to fruition in 1979. [Since there was no "SGGE", the alternative official name "Global Weather Experiment" should perhaps be used. However, the expression “Figgy” has been embedded in the hearts of many at the Centre over the years, so we continue with FGGE here.]

The National Meteorological Services of 170 nations, as well as space agencies and research institutes, participated in FGGE. It is due to the work of FGGE that we have the vast observational network of the World Weather Watch that constantly measures and probes the atmosphere, the sea and the land today. FGGE laid the foundation of the global system of geostationary and polar orbiting satellites, which now form the space-based observing system of the World Weather Watch. New methods of analysis in operational weather forecasting were developed — in fact from necessity. Major NWP centres around the world found, somewhat to their dismay, that their systems then in use were quite unable to produce good analyses of the tropical atmosphere! Major improvements were made in the forecasting models.



Forecasts improved steadily during the years from 1980, as a result of improvements in the global observing system, more powerful computers power, and advances in the science: in the Centre’s data assimilation system and forecast model. Seven-day forecasts in the Northern Hemisphere became more accurate than five-day forecasts of 1980, and five-day forecast accuracy reached that of the three-day forecasts made 25 years earlier.

In the Southern Hemisphere, the improvement was even more marked. In the early 1980s Southern Hemisphere three and five day predictions were not much better than those of the Northern Hemisphere for five and seven days respectively. Two decades later, forecasts for both Hemispheres were of similar accuracy - a gain of about four days in the accuracy of Southern Hemisphere predictions.

The shaded area shows the differences in forecast accuracy between the Hemispheres. Score: Anomaly correlation, 500 hPa height. See Simmons AJ and Hollingsworth A (2002) Some aspects of the improvement in skill of numerical weather prediction. Quart J Roy Meteor Soc 128: 647–678.

Other GARP field experiments included the Alpine Experiment (ALPEX) in 1982, which led to greater understanding of cyclogenesis and the mechanisms driving local mountain winds, and the Monsoon Experiments of 1978–1979, which improved forecasting of regional monsoon circulation. Such historic experiments have contributed to the remarkable headway that has been made in moving the time-scale of skilful weather forecasts in mid-latitudes using NWP from two or three days ahead, the best achievable in the 1960s, to seven to ten days ahead today.

GARP led to the establishment in 1979 of the World Climate Programme, which included the World Climate Research Programme (WCRP), under which many important experiments and programmes were developed. As a result of GARP, the performance of NWP models improved significantly. Invaluable services could be provided to a wide range of socio-economic activities such as aviation, shipping, agricultural production and water management, and early warnings given of weather and climate-related natural disasters.

In 1968 however, this was all in the future. GARP had been launched only the year before. Although meteorologists were optimistic, even excited, at the prospects promised by GARP, concrete evidence was needed and sought to justify establishing the “computer centre”.

Pioneering work in NWP in the previous years, some in Europe but more especially in the United States, showed that the time was right for Europe to combine its scientific and technical resources in meteorology to make best use of the powerful computers that could be foreseen.

While L. F. Richardson had laid down the scientific basis of NWP around 1920, exploitation had to await the development of fast computers. In 1950 John von Neumann assembled a group of theoretical meteorologists at Princeton’s Institute for Advanced Study (IAS). The “Meteorology Project” ran its first computerised weather forecast on the Electronic Numerical Integrator and Calculator (ENIAC) computer in 1950. The group’s model, like Richardson’s, divided the atmosphere into a set of grid cells and employed finite difference methods to solve differential equations numerically. The 1950 forecasts, covering North America, used a two-dimensional grid with 270 points about 700 km apart. The time step was three hours. Results, while far from perfect, justified further work. The pioneers of NWP activity at that time include Prof Joseph (Joe) Smagorinsky, Jule Charney and Norman Phillips.

About 1952, von Neumann, Charney, and others convinced the Weather Bureau and several research and forecasting agencies of the Air Force and Navy to establish a Joint Numerical Weather Prediction (JNWP) Unit. The

JNWP Unit opened in Suitland, Maryland in 1954, under George Cressman. It began routine real-time weather forecasting in May 1955. However, it was well over a decade before numerical methods began to outstrip the accuracy of the "subjective method" employed by human forecasters.

Europe developed a great deal of expertise in NWP during the 1950s and 1960s. Meteorological research was part of the mission of the National Meteorological Services, and was funded at a relatively high level. In Europe, there was no divide between theoreticians and applied meteorologists — that is, the "bench forecasters" — as was generally the case in the United States. Europeans were in a position to develop meteorological theories and to try out the results in practice. Visiting European scientists played a significant role in the developments taking place in the United States. Theoretical advances such as air-mass analysis and the polar front theory of the Bjerknes's Bergen School were used daily in operational forecasting offices. Meteorology as a science was able to advance at a steady pace.

Indeed the same philosophy of applying the results of research rapidly to the operational forecasts, accepted without question as being the natural way to do it, was surely an important factor in the later success of ECMWF. Research scientists at the Centre were justly proud when operational implementation of a change to the assimilation system, the model physics or the numerical scheme, gave an upward slant to the graphs quantifying the forecast skill.

Europeans also viewed meteorology as a science on a par with astronomy and other physical sciences. The concept of geophysics — the methods of the physical sciences being applied to the phenomena of the earth's atmosphere and ocean — was already well established in Europe. Meteorologists such as Bert Bolin, Fred Bushby, John Sawyer, Arnt Eliassen, Ragnar Fjörtoft, Rainer Hollmann and Heinz Reiser were making important contributions to the advance of NWP both in research and operations. Often they had help and encouragement from their American colleagues, though for some their technical facilities were not generally as advanced as those in the American institutes. And as we have seen, another scientist working in the field at that time was Aksel Wiin-Nielsen.

The Royal Swedish Air Force Weather Service in Stockholm was the first in the world to begin routine real-time numerical weather forecasting, with the broadcast of forecasts in advance of weather. The Institute of Meteorology at the University of Stockholm, associated with Carl-Gustaf Rossby, developed the model. Forecasts for the area covering Europe and the North Atlantic were made three times a week on the Swedish BESK computer using a barotropic model, starting in December 1954. In the years following, work on NWP was actively underway in Finland, Germany, France, Belgium and the UK.

We return now to the Expert Groups established by the Council of Ministers of the European Communities. Their work came to a stop at the end of February 1968, when the Communities reached a political crisis. The hiatus lasted for several months. Work started again at the end of 1968 when the Council of Ministers requested the Groups to continue their work and to submit their reports by early 1969. In the Reports, the possibilities of co-operation with European States not in the EEC were to be taken into consideration.

The proposals submitted by the Expert Group for Meteorology in April 1969 centred around six main points. The inclusion of non-Member States was considered desirable. Two of the proposals met with the approval of the governmental representatives:

- major operations in modern meteorology, and
- meteorological equipment projects.

Taking into account the international nature of meteorology and the considerable financial effort involved in such major operations, it was suggested that Europe’s future major contribution to the World Weather Watch should be made jointly by the European states. The Group also considered the development and operation of meteorological satellites.

At this stage, it had become generally accepted that one of the “major operations in modern meteorology”, the establishment of a meteorological computer centre in Europe, was scientifically justified and was likely to be successful. As Dr Süssenberger later noted: “all agreed on a project for a medium-range weather forecasting centre — an issue close to the heart of all National Meteorological Services, but one they could not realise alone because of the lack of scientific ability and computer capacity”. In its Report the Expert Group on Meteorology gave pride of place to its proposal to establish a joint meteorological computing and research centre. It would be equipped with sophisticated information processing hardware and would mainly be engaged in medium-range weather forecasting, with the name “European Meteorological Computing Centre for Research and Operations”.

The second proposal concerned the joint development, standardization and purchase of meteorological equipment, for example automatic meteorological stations, radiosondes and balloons.

At around this time, a new institution was being established for the promotion of European research beyond the framework of the European Communities: “European Cooperation in Scientific and Technical Research” or COST. Nineteen States formally established COST in 1971. Mr C. L. Silver, President of the COST Senior Officials, noted at the first session of the ECMWF Council in November 1975 that his predecessor as President, Dr Rolf Berger of the Research and Technology Ministry of Germany, "was the man who above all drove this project through the political difficulties that assailed it in those days". He spoke of Dr Berger's "persistence, which for some of us was rather tough".

The Report from the Working Group on Policy in the Field of Scientific and Technical Research mentioned in Chapter 2 was finally published in 1969. The Report gave another impetus to the development of the Centre, although it mainly considered projects in six non-meteorological areas.

The Expert Group stressed that while the projects being considered were of great potential use to the Member countries, participation of other European countries was also very desirable. European states not belonging to the European Communities should be invited to participate. Meteorological problems needed to be tackled over large geographical areas. This was particularly important as well because the United Kingdom, which did not belong to the European Communities at that time, had good meteorologists with significant expertise in the field. The UK Meteorological Office had been producing and disseminating numerical forecasts of pressure, winds and temperature at 1000, 500 and 200 hPa to 48 hours ahead since November 1965. Its Director-General, John Mason, had outlined to the WMO Congress and Executive Committee in 1967 his impressive plans for modernising and re-equipping the Meteorological Office.

In October 1969, the Council agreed to extend the scope of the projects beyond the European Communities. Its President addressed a letter to nine European non-Member States: Austria, Denmark, Ireland, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom, in which he informed them that the Member States of the Communities would welcome their participation in the planned operations in the field of scientific and technical research. In their replies all the non-Member countries agreed in principle to participate. Thus the way was open for the work to extend to 15 countries. Later, at their request, Finland, Greece, Turkey and Yugoslavia participated. In 1970, representatives of all the participating countries examined the project. A new co-ordinating body called the "Committee of Senior Civil Servants" was set up.

The existing outline plans had to be formulated as detailed proposals before consideration for final approval by the Ministers of the participating countries. In particular, cost/benefit analyses had to be carried out. The different meteorological Projects were dealt with as separate COST Projects.

The various Projects were now considered in a new framework. The joint development, standardization and purchase of meteorological equipment was awarded to a new group on “Oceanography-Meteorology”. The Project for a European meteorological satellite was postponed pending developments at the European Space Research Organization (ESRO), which had been created in the early 1960s.

The remaining Project, the establishment of a “European Meteorological Computing Centre for Research and Operations” was allocated for exclusive handling to a special Expert Group. The object was to prepare a Project Study, with the clear objective of allowing the Conference of Ministers to decide whether the Project should be realised or not. The Project Study, chaired by Dr Süssenberger, and with Vice-Chairman Mr R. Schneider of Switzerland, started its work in April 1970 and completed it in August 1971. Amongst the more than 50 experts who took part in various sessions of the work of the Group were two future Directors of ECMWF, Jean Labrousse and Lennart Bengtsson. Daniel Söderman, a future Head of Operations and Deputy Director, was also a member, as were future Presidents of, and national delegates to, the ECMWF Council.

Years later Süssenberger stressed the excellent co-operation in the Expert Group. The team spirit of the Group allowed the work to be carried out in a very harmonious atmosphere from the outset: “a positive outcome was almost guaranteed”. The group was determined to achieve results. Discussions were extremely focussed. According to Süssenberger, “the results were highly appreciated by the high-ranking European authorities”.

The starting point of the study was the fact that while scientifically European meteorology was far advanced, it no longer played a significant political role on the world stage. In modern language, it was punching well below its weight. For example, the two World Meteorological Centres of the World Weather Watch in the Northern Hemisphere were situated in Washington and Moscow; the highly developed countries of Western Europe did not have similar institutions in spite of their progressive National Meteorological Services and research institutes.

At their meeting on 23 April 1970, all of the delegations to the Expert Group expressed their interest in principle in the proposed European Meteorological Computer Centre for Research and Operations. They recognised the need for international co-operation, but stressed that the technical requirements must be detailed, and account taken of the work of other organisations. Reservations were expressed by the delegation of Norway: the work of the Centre must not duplicate the work of other meteorological centres of similar character, must be within the framework of the World Weather Watch, and not become an obstacle to the development of National Meteorological Services. The United Kingdom also expressed a reservation: because of the comparatively advanced state of its work in this domain, the best contribution of the UK would be to facilitate the exchange of personnel and scientific information between British organisations and the envisaged European Centre. By May 1970, the Centre had been renamed the "European Meteorological Computing Centre" or EMCC.

A Working Party suggested to Ministers on 10 June 1970 *inter alia* that they:

> *confirm the interest shown by all delegations in the setting up of the EMCC (Project 70) whose purpose will be to provide public services, to carry out research directed towards improving these services, principally in the field of medium- and long-range weather forecasting, and to train the scientific staff of the national meteorological centres and to state their agreement to take part in a detailed study of the project;*

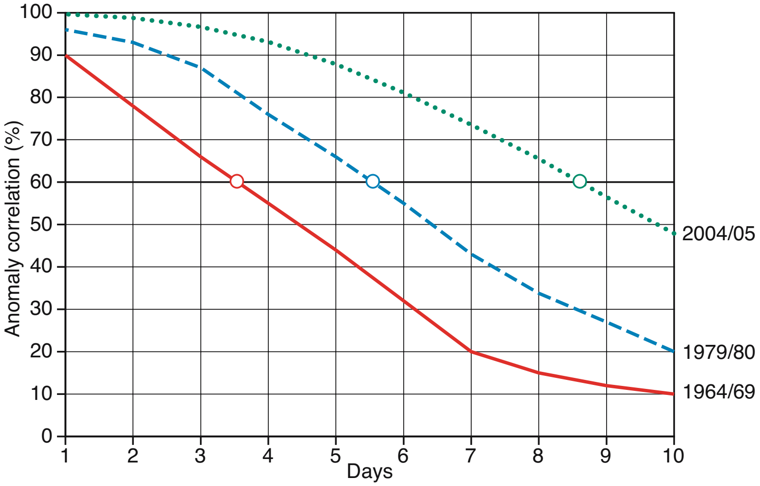
The first reactions of the political bodies of the European Communities indicated that this project was considered to be of particular interest. Physicists, for example, had already created a number of international and highly regarded institutions in which problems exceeding the capacity of individual countries were tackled. Meteorology with its long tradition of successful co-operation was seen as being particularly appropriate for such a joint European venture. On 19 October 1970 the Working Party on the EMCC was instructed by a Committee of COST Senior Officials to continue its work, and to state its views on whether the Centre should:

- have scientific and/or public service roles, and how these roles might be combined, and
- be a centralized body, or a network between national centres, or a combination of the two.

The Working Party was also asked to specify the cost and arrangements envisaged for each alternative.

The International Meteorological Institute in Stockholm was seen as a model. By 1970 there had been enormous progress in data handling, atmospheric modelling and computer technology. This had made feasible, in principle, the production in reasonable time of useful weather forecasts beyond the period of up to three days or so, which was at the time the absolute limit in operational NWP. Indeed in operational forecast offices of the time, while 24- to 48-hour numerical predictions were routinely used operationally, forecasts to 72 hours or more were at best treated with caution. Experimental prediction with an advanced general circulation model in the United States had shown considerable promise for forecasts up to 4 to 10 days ahead; see the figure.

There was agreement among scientists that no fundamentally new principles would be encountered in developing dynamically derived medium-range forecasts, and that these forecasts would prove to be superior to those produced by then-current methods.



Scores showing the average accuracy of a series of predictions to 10 days ahead:

- for 12 experimental forecasts made during the period 1964 to 1969,
- for ECMWF forecasts for the winter of 1979–80, the first year of operations, and
- for the winter forecasts of 2004–05.

A score above 0.6 is generally accepted as indicating that the forecasts are still on the average useful. The score remained above that level until about 3½ days in the experimental medium-range forecasts during the late 1960s.

For comparison, the score remained above 0.6 until 5½ days in the December to February forecasts made during the Centre's first year of operations, and until 8½ days in the forecasts made 25 years later.

The experiment made at GFDL at Princeton New Jersey in the late 1960s was the first indication that medium-range numerical forecasts would be feasible.

Score: Anomaly correlation, 500 hPa, Northern Hemisphere. The 1964/69 score is adapted from Miyakoda et al. (1972) Cumulative results of extended forecast experiments. Monthly Weather Review 100: 836–855.

However, at that time, it was clear from experience both with operational short-range prediction and with general circulation models that the future application of dynamic methods to medium-range forecasting would involve more than a simple extension of short-range models. While the latter's success depended mainly on their ability merely to redistribute the kinetic and available potential energy within the atmosphere, medium-range models would have to be able to describe energy production and dissipation. They would have to include the hydrological cycle. The models would have to allow extra-tropical cyclones to form, develop and decay. Also, interactions with tropical phenomena implied that the circulation of the Southern Hemisphere had to be taken into account to make Northern Hemisphere forecasts for periods longer than about a week. Further it was anticipated that treatment of the interactions between atmospheric and oceanic circulations would be required for good-quality medium-range predictions.

In contrast to the situation in medium-range forecasting, there was at the time no promising approach to long-range prediction for a period of a month or a season by dynamical methods. Therefore, the logical decision was made to concentrate research and development capacities on the construction of atmospheric models suitable for dynamic medium-range predictions of increasing quality, thereby extending the range of useful deterministic forecasts as far as possible. Monthly and seasonal predictions were assigned lower priority for the initial work of the Centre.

In addition, numerical experiments had shown that further progress in short-range forecasting was likely to be achieved by studying the dynamics of small-scale phenomena and developing appropriate fine-mesh models. This research would be undertaken in parallel with that done in atmospheric modelling for medium-range predictions. It was foreseen that continuous interaction would benefit both.

It was clear that the development and routine application of atmospheric models for medium-range forecasting required tremendous computing power. Even the fastest computers operational at the time would not suffice. Establishing a meteorological computing centre devoted largely to the development of routine medium-range forecasting, therefore, was foreseen to be a costly and challenging project. It was likely to be beyond the financial resources and the research capabilities of most European National Meteorological Services. A combined effort was called for.

This conclusion was supported by the anticipation that the future development in short-range weather forecasting, including the need for finer resolution and quantitative precipitation forecasts, would considerably increase the computer requirements of national centres and would take up much of the computing capacity available to them.

Although the preparation of routine medium-range forecasts together with the associated research activities provided the main arguments for the projected European Meteorological Computing Centre, it was clearly reasonable to expect that this Centre would provide advanced training to post-graduate scientists in NWP and related disciplines.

It was foreseen that the Centre would make available its advanced computing facilities to National Meteorological Services for activities beyond their computing resources, for example research into the dynamics of small-scale systems. The computing facilities of the Centre could be accessed by national institutions via Remote Job Entry, using the same telecommunication network as would be required for rapid dissemination of the medium-range predictions to the computer systems of the services.

Furthermore, the Centre could support related national research activities, for example numerical studies of local phenomena, by offering suitable working facilities to visiting scientists from national centres. The Centre should also serve as a European meteorological data bank.

The Working Party on the EMCC met on 9 November 1970 and 15 January 1971 under its Chairman Dr Süssenberger and Vice-Chairman Mr Schneider. At a meeting of an Expert Group on 19–20 November 1970, Study Groups were set up to prepare a Report to Dr Süssenberger's Working Party.

- Project programme, especially the cost of the work (Reiser, Hipp).
- Forecasting model and its effect on the computing power required (Bengtsson, Lavalle).
- Requirements and production of the data of the Centre (Palmieri, van Isaker).
- Time schedule for the achievement of the Centre.

At its meeting on 15 February 1971, the Expert Group set up another Study Group "EMCC — Telecommunication aspects" with Chairman Jean Labrousse, which produced a detailed Report on 3 April 1971.

Lennart Bengtsson and Lodovico La Valle, head of the Meteorological Computer Centre of the Italian Meteorological Service in Rome, visited laboratories and factories in the USA between 8 and 21 March 1971: NCAR, GFDL, NMC in Suitland, IBM in Poughkeepsie, Burroughs and UNIVAC in Pennsylvania and Washington, Control Data in Minneapolis, and Texas Instruments in Austin. On 29 April 1971, they prepared a report on "Present activities, organisation and plans for the future of some advanced laboratories for dynamical meteorology and numerical forecasting". The other Study Groups also prepared input for the Project Study.

Chapter 4

The Project Study

The Study Group chaired by Dr Heinz Reiser had the task of preparing the Report: “Project Study on European Centre for medium-range weather forecasts”. The Group had representatives from a wide range of nationalities, all experts in their fields:

H. Reiser	Germany	Chairman
J. Van Isacker	Belgium	
J. Labrousse	France	
R. Pone	France	
L. La Valle	Italy	
S. Palmieri	Italy	
D. J. Bouman	Netherlands	
K. Cehak	Austria	
D. Söderman	Finland	
L. Bengtsson	Sweden	
E. Knighting	United Kingdom	

The impressive and important 76-page Report, with Annexes totalling 130 pages, was presented to Dr Süssenberger, Chairman of the Working Party on the European Meteorological Computing Centre, on 5 August 1971. The Report incorporated the results of all the Study Groups mentioned at the end of the last Chapter.

With hindsight, the work of Reiser’s Group is remarkable. The basic ideas on the organisation, implementation and performance of the Centre as prepared by the Group in 1971 and summarised below bear a striking resemblance to the Centre 35 years later. All the important aspects, organisational, administrative, scientific and technical, were covered. These are now described.

The operations of the Centre should effectively supplement the present activities of the national centres; duplication should be avoided as far as possible.

Numerical Weather Prediction (NWP) requires the use of the most powerful available computers; the expected development in medium-range forecasting would call for even more computing power. Accordingly, the Centre should be in a position to take advantage of new developments in computer systems.

The development and continuous improvement of operational medium- and long-range predictions at the Centre would be the main responsibility of the research section. In order to extend this research capacity, to promote co-operation and contacts with national institutions and to facilitate the exchange of views and knowledge, working facilities should be provided for temporary groups working on associated research problems. These groups would consist of visiting scientists from national groups and members of the permanent research staff.

The problems of routine forecasting and associated research in atmospheric modelling are closely related. Experience at National Meteorological Services, however, suggested the need for a separate “research group” which was to be independent of the routine operations. The latter would be the responsibility of an “operational group”; there would be continuous interactions between these groups. The results obtained from operational forecasts would influence the development of more advanced atmospheric models; new developments by the research group would be included in updated versions of the routine model.

The main responsibilities of the research group were to be the development and intensive testing of dynamic models for medium-range predictions of increasing quality. The operational group would be responsible for all applications outside the research sector, including operating the computing system. Their tasks would include the preparation, dissemination and verification of dynamic medium-range forecasts as well as special services to national centres, telecommunications problems and the creation and maintenance of a European data bank.

A clear organisational separation between the research staff and the staff needed for the operation of the Centre was desirable, to protect research and development activities from the increasing operational requirements.

For the implementation of the Centre three main phases were considered: initial phase, transition phase and fully operational phase. The initial phase would start well before the installation of the computing system and involve construction and testing of a first model. The transition phase would be characterized by a tentative routine application of this model with initial analyses obtained from other centres and a steady approach towards the fully operational phase. For this final phase a fixed ratio of the computing time available for (a) routine operations, (b) model-orientated research and (c) the requirements of National Meteorological Services was recommended: "at a first guess, nearly equal parts should be assigned" to each of these. It was calculated that the daily routine forecast would normally take about one hour per forecast day, so about 10-12 hours for the ten-day prediction. It was suggested that about one-third of the computing resources would be available for Member State use — not leaving much time for research when operations got under way!

If better but more time-consuming models became operational their computational requirements should be satisfied by extension of the computing capacity rather than by reduction of the computing times allotted to research and other services.

High-speed data links between the Centre and associated National Meteorological Services were indispensable for the dissemination of the medium-range predictions. Some of these data links were also necessary for rapid input of digital data in the form of grid-point values or pre-processed data originating from European and other centres. The satisfactory incorporation of all these data requirements into existing and projected WMO telecommunication channels appeared unlikely; a separate data net for the envisaged computing centre was needed. All these high-speed data links should be capable of operation in full or half duplex mode and hence would provide an ideal basis for teleprocessing of data.

For routine medium-range forecasts, analyses of the current global atmosphere from which the predictions would begin would of course be needed. The supply of analyses was to be the responsibility of the operational group. According to WMO plans, routine global analyses were to be prepared at the World Meteorological Centres (WMCs) of Washington, Moscow and Melbourne. There were additional plans to establish a Global Analysis Centre, in connection with the Global Atmospheric Research Programme (GARP), which might be situated at one of the WMCs.

It was therefore assumed that after 1975 the Centre would in principle be able to obtain suitable global analyses from one of the WMO Centres for its forecasting activities, and not have to devote scientific efforts and its valuable computing resources to making its own. Some, especially in Germany and the UK, felt rather strongly that the Centre should not develop its own analysis system.

It was however also envisaged that the Centre might at some stage perform its own analyses in real time. This would become a necessity if the Centre were to receive and process observations from European satellites. Such an extension of its responsibilities would influence the planning for telecommunications and the composition of the scientific personnel. However, the study did not consider these problems further.

In any event, if suitable, good quality, analyses could not be obtained from the WMO Centres, it was foreseen that a major effort would be required to prepare global analyses at the Centre. These analyses would involve extensive use of satellite data with the development of appropriate techniques for assimilating the new data into the models.

We have noted that the medium-range had been characterized as a forecast period of 4 to 10 days. It was assumed (wrongly, as it turned out!) that models with rather crude estimates of energy production and dissipation and using hemispheric integration areas could successfully cover the short-range period of up to four days.

Though the models were expected to produce full sets of forecast charts from analysis to the end of the medium-range, it was evident that the geographic scale of predictable phenomena would increase with the forecast period. Short-range forecasts should be able to predict the location and intensity of rather small-scale, well-developed pressure centres, and major temperature changes and precipitation amounts over small areas. Medium-range predictions were expected to indicate the significant changes of the weather over fairly large areas. It would be the Centre’s responsibility to investigate possible long-range prediction methods following a satisfactory solution of the medium-range forecast problems.

With the state of knowledge in 1970, a detailed description of an atmospheric model for medium-range forecasting was not possible without some rather arbitrary assumptions. To make a reasonable estimate of the computer requirements, it was necessary to consider the structure of an unfiltered dynamic model, without implying a recommendation for the characteristics of the actual model to be developed by the Centre. The model corresponded roughly to the models used in the USA for weather and climate simulation: at the National Center for Atmospheric Research, the Geophysical Fluid Dynamics Laboratory, and the University of California.

It was agreed that the Centre initially should not develop a very advanced and complicated model, but rather try to set up a first version on the basis of general circulation models already available and proven, and later to produce more advanced versions.

Since it was planned to perform operational forecasts for 4 to 10 days, a fairly complete description of the non-adiabatic processes, including the complete hydrological cycle, and also of the dissipative forces in the atmosphere, was deemed necessary.

The computer requirements of the forecasting model had to be thoroughly considered in the Project Study. The estimates made were based on a representation of grid-points for the medium-range model with a grid distance of 150 km from the North Pole to about 20°S, increasing to about 300 km south of 20°S.

Such a grid would consist of somewhat more than 15,000 grid-points horizontally. The corresponding vertical resolution would be about 100 hPa to 150 hPa in the troposphere. If some additional levels in the surface boundary layer and in the stratosphere were added, the model would have at least ten levels. There would thus be about 200,000 grid-points in the computer model. Sub-grid scale phenomena, such as cumulus convection, would be taken into account by describing their effects statistically on the parameters of the large-scale flow, that is to say, they would be "parameterized". Since only very limited knowledge was available on the effects of the oceans, the sea surface would be represented rather crudely in the first version of the operational model.

Over the continents, the coupling between the atmosphere and the underlying earth depends mainly on the available ground moisture and the snow cover. These time-dependent properties had also to be included in a model for medium-range forecasting.

Both the routine computation of medium-range dynamic forecasts and the corresponding research in atmospheric modelling would determine the main computer requirements for the Centre. All other operational activities, including possible preparation of global analyses and processing of satellite measurements for these purposes, were considered to be smaller by an order of magnitude and did not affect the main requirements for computing speed and capacity of fast internal memory. [With the benefit of hindsight, we can see that this severely underestimated the benefit of a good analysis for a medium-range forecast. We will see later just how important the Centre's analysis system, and its research into use of satellite data, would become.]

For operational weather prediction, a practical ratio of computing time to real time was taken to be about 1 to 20, which corresponds to about one hour computing time for a one-day forecast or half a day for a forecast to ten days. When these model characteristics:

- 200,000 grid-points,
- 3,000 operations per grid-point per time step,

- 5 minute time-step, and
- 1 to 20 ratio of computing time to real time

were combined, a total of 600×10^6 operations per time step would be executed within 15 seconds. This meant a required computing speed of 40×10^6 instructions per second or a 40 Million Instructions Per Second (MIPS) main-frame computer.

The model assumptions represented a rather conservative estimate based on limited experimental experience. Hence a speed of about 50 MIPS was considered appropriate; further substantial improvements in the model were foreseen to call for speeds of 100 MIPS or even higher. If there was a computer that could be upgraded to at least 50 MIPS without major reprogramming, it was deemed to be economic to equip the Centre in the beginning with a computer system of 10 to 20 MIPS. The fully operational phase, however, could not start before a computing speed of about 50 MIPS became available.

The Working Group on the required telecommunication links made an extensive study under the guidance of its Chairman Jean Labrousse of France. The data volume would be considerable, so that a speed of 2400 bits/sec for the telecommunication lines was considered necessary.

With respect to personnel it was foreseen that the Centre would need a Director, and a Research Department with six senior scientists. These would have experience in NWP and atmospheric modelling and special qualifications in one of the following fields.

- Atmospheric physics
- Boundary layer physics
- Small-scale phenomena
- Initialization procedures
- Numerical methods
- Statistical diagnoses

Two junior scientists — capable of original research — would assist each of these six senior scientists, programming model codes and carrying out related research and development activities under supervision of the senior scientists. Eight assistants for auxiliary work, for example lower-level programming, were considered to be necessary within the research staff. Research work was to be co-ordinated and inspired by its Deputy Director.

Besides this permanent research staff, financial provision was planned for at least five additional posts reserved for visiting scientists from other research groups. These facilities would not only reinforce the potential of the Centre but also offer excellent opportunities for European scientists to work on special problems in NWP and associated fields.

The Operations Department under a Deputy Director would be subdivided into two sections. One would be responsible for the technical operations of the computing system, with its size dependent on the requirements of the eventual computing installation. The other section would be more scientifically orientated. It would be responsible for the meteorological aspects of routine applications and for the contacts with the National Meteorological Services and WMO. Under a computer manager there would be five scientists and five system analysts. In addition there would be five programmers and seven assistants as well as thirty-two operators and eight additional auxiliary personnel. This would mean a staff of 64 persons in the Operations Department. Together with a second Deputy Director and 26 staff in the Research Department, and a further 21 in the Administration Department under a third Deputy Director, a total staff of about 110 persons was expected to be required. About 40 would have a university education or equivalent qualifications.

The study recommended that the Centre should be used also for training. With the rapid development of NWP and its growing influence on the daily routine work of National Meteorological Services, there was an increasing need for adequate training facilities in NWP for postgraduate meteorologists. Since the successful application of dynamic methods in NWP required a broad operational basis, universities were normally not in a position to provide the training required.

Some of the National Meteorological Services with experience in NWP had already organised regular training courses, some in co-operation with universities. These courses were normally intended as an introduction to NWP, and were designed for meteorologists without specific experience in this field and thus emphasized the basics. High-level training facilities for scientists actively engaged in research and development work on advanced NWP were provided at the time either in a fairly unsystematic way by their temporary assignment to an established research group, or by special seminars, symposia and similar arranged by interested organisations or societies.

In particular, it was noted that more ambitious seminars or training courses in applied dynamic meteorology for postgraduate participants were best organised on a basis of international co-operation. Thus the establishment of the Centre offered an excellent opportunity to create central training facilities for NWP and related disciplines in Europe. Such an extension of the Centre's activities would not only serve directly the National Meteorological Services involved but would also help to build up the Centre's scientific image.

It was noted that the Centre's operations should effectively supplement the activities of National Meteorological Services with a minimum of duplication. Furthermore the Centre should co-operate with the existing international organisations, and in particular with WMO. For this reason a representative of the Secretary-General of WMO was invited to attend the more important sessions of the Expert Group for Meteorology.

We have seen that at this time WMO had well-developed plans for the advance of meteorology, especially the World Weather Watch Plan and the joint WMO-ICSU Global Atmospheric Research Programme (GARP). This Programme was aimed at improving understanding of the physical basis of the general circulation of the atmosphere and at increasing forecast accuracy for extended periods. As well as large observational experiments, GARP planning called for tremendous efforts in atmospheric modelling and numerical experimentation.

The World Weather Watch (WWW) is an impressive worldwide weather observing system. Its origin lies in the 1961 UN General Assembly Resolution on the Peaceful Uses of Outer Space, which owed much to the address made by American President J. F. Kennedy to the General Assembly. It is designed to make up-to-the-minute meteorological and related information available to all countries. The WWW is a truly remarkable example of international co-operation. It is composed of the Global Observing System (GOS), the Global Telecommunication System (GTS), and the Global Data-Processing System (GDPS). The WWW has supplementary programmes dealing with Satellite Activities, Instruments and Methods of Observation, Tropical Cyclones, and Emergency Response Activities.

One of the very important purposes of the WWW is to stimulate and facilitate the research work necessary to improve the accuracy and extend the useful range of weather forecasts. The Centre would be developing methods of medium-range forecasting as its primary task, and subsequently providing routine operational forecasts. Its proposed objectives were thus closely related to those of WMO. Indeed the work of the Centre would have a considerable impact on the development planned by WMO.

The creation of the Centre, with its aim of developing advanced models for extended forecasts and with a considerable potential for numerical experimentation, coincided very well with the plans of GARP and would contribute to its implementation. In turn, the Centre would profit considerably from the scientific progress expected from GARP.

The Centre would contribute to the Global Data-Processing System by storing data and making them available.

The economic benefits of meteorological activities were well known.

However a project of the magnitude needed to create the Centre, based as it was on the initiative of the European Common Market, had to be scrutinized carefully with a view to its own economic benefits. A panel under the chairmanship of Dr Schneider from Switzerland dealt with this problem.

As a general principle for the benefit analysis it was assumed that the quality of a six-day forecast would be about the same as the quality of the best of the two-day forecasts then available in Western Europe. Since existing literature on benefits of medium-range forecasting offered little quantitative information, and since an approach using models was not feasible within the time limits given, the group decided to seek the views of people involved in weather sensitive activities.

In all, 156 interviews were held in 15 countries. The interviews covered meteorological requirements for a variety of sectors: agriculture, construction, electricity and gas production and distribution, transport, food merchandizing, water supply and protection against natural disasters. As a first result, it revealed that there was a general interest in medium-range forecasts of 4 to 10 days. The annual gain, mainly to agriculture, construction and transport, from better medium-range forecasts would be 200 million Units of Account (UA). On 1 January 1972, 1 UA = £0.437. The cost of the Centre during the first five years of establishment was estimated to be nearly 20 million UA. During the operational phase the annual cost would reach 7.5 million UA, so that the cost/benefit ratio was about 1 to 25.

The computing cost estimates were based on the assumption that the purchase price would be equivalent to 48 monthly leases. This simplification eliminated the question of purchase or leasing, and allowed specification of an approximate annual cost.

For comparison, the National Meteorological Services of the six countries of the EEC spent 57 million UA in the year 1967/68, and between them employed about 7,900 staff, 1,200 with a university education. In 1970, the 17 potential Member States spent more than 110 million UA on meteorological activities. These figures refer to National Services only; the many university departments and research institutes were in addition to that.

Thus, the analysis confirmed that establishment of the Centre would bring great economic benefits at comparatively little cost.

A decision on the future location of the Centre meant consideration of some economic, technical and social aspects. There were however some technical arguments that favoured it having a central location. The cost of telecommunications would be lower. As the Centre would require an enormous amount of data, it should be located near to the European telecommunication centres of the Main Trunk Circuit of the WMO Global Telecommunications System; i.e. within, or near to, the triangle London–Frankfurt–Paris. Another desirable prerequisite for the site of the Centre would be the proximity of a national meteorological centre with operational experience in NWP and a recognized university with interests in the related disciplines of natural science. The opportunity for personal contacts and direct exchange of views would improve the scientific performance of the Centre and result in closer linkage to meteorological practice.

Thus, the Centre should be near a large town with a meteorological centre, a university and good traffic connections.

The study on the European Meteorological Computing Centre came to the following conclusions.

- There was need on practical and scientific grounds for developing operational medium-range forecasting techniques. These techniques would be based on numerical integrations of the meteorological equations demanding computing power far beyond that available at national institutes for short-range numerical predictions.
- The most efficient way of developing and applying these techniques was to create a Centre, devoted primarily to this task.
- The best way to realise such a Centre was the creation of a centralized institute with a staff of about 110 and equipped with outstanding computing facilities. It would be connected to national centres by high-speed data links.
- In addition to its primary task, the Centre would provide an excellent stimulus to research in dynamical meteorology, especially NWP methods for Europe.
- Additional support to the National Meteorological Services would be available through the creation at the Centre of advanced training facilities and a data bank.
- The Centre and its corresponding telecommunication network were expected to become fully operational in its own headquarters five years after a positive ministerial decision had been taken.
- The cost during the first five years would be nearly 20 million UA. During the operational phase the annual cost would reach 7.5 million UA.
- There would be technical and financial advantages in locating the Centre in an area roughly designated by the triangle London–Frankfurt–Paris.
- The Benefit Analysis study estimated the annual gain, mainly to agriculture, construction and transport, from better medium-range forecasts to be 200 million UA, giving a cost/benefit ratio of better than 1:20.

In his memorandum of 26 August 1971 to Dr R. Berger, the Chairman of the Committee of Senior Officials for Scientific and Technical Research, Dr Süssenberger stated:

> *I enclose herewith the report by the Study Group on a 'European Centre for Medium-Term Weather Forecasting' (ECMW) (COST/138/71), with a request that it be considered and be made the subject of a resolution.*

In an address in October 1971 in Lisbon, Dr Süssenberger noted:

> *Whether it will be possible to create the first joint European meteorological institution depends on the decisions of the competent political bodies. The meteorological experts have recommended such an institution in a very cooperative European spirit. Most of our meetings took place in a building named 'Charlemagne' located near to Place Schumann, in Brussels.*
>
> *It is to be hoped that the mentality and the spirit of these two great historic European men stand sponsor when the politicians will take their decision.*
>
> *Of course also for us meteorologists, the European future will call for certain national renunciations. Without such national renunciations we cannot implement common projects of the order of magnitude described. But only such projects will put the European meteorological community in a position to take over again in the world the place, which corresponds to its historical achievements.*

The conference of Ministers convened by the Council of the European Communities in November 1971 considered the Report of the Study Group. It formally confirmed their intention to establish the European Centre for Medium-Range Weather Forecasts. This was the first use of what became the Centre's name.

This is the official name: "Medium-Range" not "Medium-range" and "Forecasts" not "Forecasting". And it is abbreviated ECMWF not ECMRWF — although a web search for the latter gives a dismayingly large number of responses!

Dr Süssenberger became interim President of the Council pending the coming into force of the Convention, and later served as Council President from November 1975 until December 1976. After he retired, he recollected: "my participation in this project was one of the most satisfying tasks in my professional career".

He was pleased that the far-sighted ideas of Prof Rossby, who in 1951 stated "the organisation of an International Computing Centre appears to have been accepted in principle", had eventually got the recognition they deserved. The government of Germany considered the establishment of the Centre as the best outcome of the studies carried out by the various groups who planned meteorological co-operation at a European level. Only very few of the intended projects could be realised. This one was realised, according to Süssenberger, “thanks to the excellent co-operation between meteorologists, who have for 150 years been used to working together internationally and to solving their problems together”.

Chapter 5

The Convention

Norway decided not to sign the Convention. Iceland was left out by mistake. The states of 'Eastern Europe', as we used to call that part of the world, were purposely excluded from membership of the Centre. A single ambiguous word in the Convention seemed to indicate that Italy was a Member State without it having to go to the trouble of, well, becoming a Member State. Drafting, and then finally agreeing on, the necessary legal document to establish an international organisation, even one as small as the Centre, and one restricted to scientific and technical objectives, can be an interesting process.

In November 1971 the Council of Ministers of the EEC decided to establish the Centre. A Convention was required to bring this international organisation into existence.

A first draft of the Convention was considered at a meeting of an ad hoc group on 9-10 December 1971. Thirty-two senior representatives from 14 of the participating states attended. Many further drafts of the Convention and its associated Protocol of privileges and immunities were prepared throughout 1972 and 1973. Credit must be given here to Marie-Annik Martin-Sané, the head of the French delegation to the meetings. She had been heavily involved in drafting the Convention of WMO, and was well known to and respected by the meteorologists for her detailed drafting and negotiating skills. She was instrumental in briefing Bob White, chief of the US Weather Bureau — predecessor of the National Weather Service — and the first Administrator of NOAA, on the status of planning for the Centre.

The Convention set up the Centre as an independent international organisation. Although conceived as a COST action initiated by the EEC, the Centre has only one tenuous formal link with the European Union. "Instruments of accession" to the Convention, that is the documents confirming that States have become Member States of the Centre, are "deposited in the archives of the General Secretariat of the Council of the European Communities" [now the European Union, EU].

Fifteen States signed the Convention on 11 October 1973: Belgium, Denmark, Federal Republic of Germany, Spain, France, Greece, Ireland, Italy, Yugoslavia, the Netherlands, Portugal, Switzerland, Finland, Sweden and the United Kingdom. It was then open for signature until 11 April 1974. Austria signed on 22 January 1974. Luxembourg and Turkey did not get around to signing. Norway, however, was in a special category of its own making; a firm decision was made in Norway not to sign the Convention.

Actually there was no obligation on a State to sign. For example, during the debate in Dáil Eireann, the Irish parliament, leading to Ireland's approval of the Convention, the Minister for Science and Technology Mr Ryan noted that the Convention "was signed, so signifying formally Ireland's participation in the project". By Article 23 and the Annex, it was enough for a State to have taken part in drafting the Convention to become a Member State.

The Convention, available on www.ecmwf.int, is not written to be an easy read. It is after all a legal document with international ramifications. However let's take a little time to look at some interesting or just curious bits; we shall leave the important legal and technical aspects to the important legal and technical experts.

The preamble has a list of eight "Considerings", outlining the justifications for establishing the Centre:

> *CONSIDERING the importance for the European economy of a considerable improvement in medium-range weather forecasts;*
>
> *CONSIDERING that the scientific and technical research carried out for this purpose will provide a valuable stimulus to the development of meteorology in Europe;*
>
> *CONSIDERING that the improvement of medium-range weather forecasts will contribute to the protection and safety of the population;*
>
> *CONSIDERING that, to achieve these objectives, resources on a scale exceeding those normally practicable at national level are needed;*
>
> *CONSIDERING that it appears from the report submitted by the Working Party responsible for preparing a project on the subject that the establishment of an autonomous European centre with international status is the appropriate means to attain these objectives;*
>
> *CONSIDERING that such a centre could also assist in the post university training of scientists;*

> *CONSIDERING that the activities of such a centre will, moreover, make a necessary contribution to certain programmes of the World Meteorological Organisation (WMO), in particular the world system of the World Weather Watch (WWW) and the Global Atmospheric Research Programme (GARP), undertaken by the World Meteorological Organisation in conjunction with the International Council of Scientific Unions (ICSU);*
>
> *CONSIDERING the importance that the establishment of such a centre can have for the development of European industry in the field of data-processing,*

The last of these expressed a hope that was not fulfilled. Europe was never able to develop "data processing", that is computing systems, of sufficient power to meet the requirements of the Centre. The Centre's mainframe computers have all come from the United States or Japan.

Article 1(5) is specific: "The headquarters of the Centre shall be at Shinfield Park near Reading (Berkshire), in the territory of the United Kingdom of Great Britain and Northern Ireland." This has left the Centre in an odd position. While the Headquarters Agreement with the UK, in its Article 24(3), rather sensibly makes provision for the Centre to leave the UK, the Convention does not. The obvious solution of amending the Convention is, as we shall see later, an extraordinarily difficult and time-consuming task — don't think months, think years, perhaps a decade or more. So if the UK had decided it no longer wanted to be a Member State - however unlikely this may have been — it is not at all clear what the Centre would have done.

The language issue was discussed often and at length. At the important meeting of COST Senior Officials on 5–6 March 1973 when the location of the Headquarters was decided, the Italian delegation opened a lengthy discussion on languages by stating that the Italian government maintained its reservation on the wording of Article 1(6). The inclusion of Italian as an official language was a matter of principle and the Italian government attached great importance to it. The Belgian delegation had a reservation on the use of Dutch (Belgium has French and Dutch as official languages). The Netherlands delegation stated that if Italian were included, the Dutch government would associate itself with the Belgian reservation. The German delegate could not accept five official languages of equal value in the Convention. The Spanish delegation pointed out that organisations like ELDO, ESRIN and CERN used only French and English. It added: "If the Centre had to have additional languages, why not Spanish?" The Yugoslav delegate stated that if Italian and Dutch were to be official languages, then he would have to enter a reservation in favour of the use of Serbo Croat. The final wording in the Convention was agreed at a later meeting. According to Article 1(6) the Centre has five official languages: Dutch, English, French, German and Italian, and three working languages: English, French and German.

There is simultaneous translation to and from the five official languages at sessions of the Council. Some documents are translated into the five languages. The three working languages English, French and German are used at meetings of some Committees of the Council, and many documents are provided in these three languages. For other Committees "one language only" is used. This diplomatic phrase avoids specifying English, the language in fact used.

Article 2 lays down the objectives of the Centre. While "medium-range weather forecasts" are referred to, "medium-range" is not defined in the Convention, in spite of talk in the planning phase of "forecast periods of 4 to 10 days". Agreeing on the definition proved to be surprisingly difficult, not only on scientific grounds, but also for practical or quasi-political reasons. A rigid definition of the overlap between short- and medium-range prediction, which could perhaps be considered to vary with geographic location or season, and which different services with different computing and scientific resources might wish to define differently, would have been considered unacceptable.

It was not until 1986 that Council was able to agree on a definition, in the context of its adoption of a long-term strategy for the Centre. It then agreed with a proposal from its Scientific Advisory Committee that "the separation between short range prediction to be performed at the National Meteorological Services and medium range prediction to be performed at ECMWF is both logical and practical" and went on:

> *The medium range should be considered the time scale beyond a few days in which the initial conditions are still crucially important.*

This excluded for example climate prediction — another potentially awkward quasi-political problem! However, the text continued: "there appears to be no justification for separating the scientific problems associated with medium and so-called extended range prediction".

The lack of definition proved useful to the Council in implementing the Convention. We shall see that the Centre was able to extend its activities to monthly and seasonal prediction as the science and technology developed.

In Article 3 we find that the Centre may conclude co-operation agreements with States. Looking ahead to the interesting wording of Article 23, we find that membership of the Centre was open *only* to the 19 States that took part in drafting the Convention. Early drafts of the Convention stated that "any European State which is not a Signatory to the Convention may accede thereto". It was not until the eighth preliminary draft dated 17 July 1972 that we find the much more restrictive text appearing: "any European State which is not a Signatory and which took part in the ministerial conference held in Brussels on 22 and 23 November 1971 may accede thereto". By October 1972, the restrictive wording of the final version of Article 23 had appeared:

> *After the entry into force of this Convention, any State which is not a Signatory and is mentioned in the Annex may accede to this Convention, subject to the consent of the Council . . .*

The States "mentioned in the Annex" are those "which took part in the drafting of the Convention".

This closing, or restriction, of membership appears to be unique for such an international organisation. Documentary evidence does not show the reason for this restrictive criterion — at least the writer has not been able to find any. However, it would be reasonable to assume that this is not unrelated to the fact that the work leading to establishment of the Centre and the drafting of the Convention was under way during a particularly difficult period of the cold war. For example, in 1968, the Communist Party leader in Czechoslovakia, Alexander Dubcek, decided to bring about a Socialist democratic revolution. The efforts of the Warsaw Pact countries and the Soviet Union failed to stop Dubcek from carrying out his reform plans. Troops from the Soviet Union, Poland, Hungary, Bulgaria and the German Democratic Republic invaded Czechoslovakia on 20 August 1968. In this context, it is perhaps understandable that the States that established the Centre were mindful of their desire to ensure that the States of what was then "Eastern Europe" were to be excluded from membership. For the Federal Republic of Germany, the German Democratic Republic was perhaps a particular consideration.

At a meeting in WMO, the delegation from the USSR asked that Russia as a European country could become a member of this planned "European" organisation. The representative of France, Mr Bessemoulin, responded that he would not object to this, if he could become a member of all organisations of the communist block dealing with Europe! Laughter effectively closed this line of questioning.

The wording of Article 23 was to prove to be a really awkward problem for the Centre in later years, when the cold war ended and states such as Poland, Hungary, the Czech Republic, the Baltic States and others from the region applied for membership of the Centre. The co-operation agreements allowed by Article 3 went some way to helping the Centre meet their requirements. The Council later decided to amend the Convention to allow other States to become Member States — see below.

In Article 4, the Member States give to Council the powers and the duty to implement the Convention. We find in Article 4(2) that one of the Member State representatives should be a representative of his "national meteorological service", while Article 2(1)(e) has an objective to make available the results of the Centre's work in the most appropriate form to the "meteorological offices of the Member States". This is an interesting distinction, since the latter term can perhaps be taken to include more than the National Meteorological Services. The Council makes the output of the Centre available to all in the Member States, and indeed to the entire world, in various forms, and especially via the Internet. However, "making available the results of the Centre's work in the most appropriate form" has not been easy or straightforward. We shall consider this in Chapter 18.

Article 9 defines the Director as the Centre's chief executive officer, responsible to the Council. Article 10 refers to the staff. Note that the "recruitment of staff shall be based on personal qualifications, account being taken of the international character of the Centre". We shall deal with staff matters in more detail in Chapter 19.

Article 13 refers to the payment of Member States' contributions. The States fund the Centre pro rata their wealth, measured until 1999 by their Gross National Product (GNP), and thereafter by Gross National Income (GNI), which had replaced GNP in economic usage. The scale of contributions is revised every three years to reflect the changing wealth of the States. From the beginning the four biggest contributors to the Centre's budget have been Germany 21% in 1973 becoming 23% in 2005, France 20% becoming 16%, UK 17% becoming 16% and Italy 12% becoming 13%. Between them these four have been contributing about 70% of the total budget through the years. Ireland was the smallest contributor: 0.5% in 1973, 0.9% in 2005 (evidence of the Celtic tiger!) — until Luxembourg joined in July 2002: 0.2%. By Article 13(3) a late joiner has to pay a sum towards the costs already met by the existing States.

Article 18 allows the Council by two-thirds majority vote to propose amending the Convention. An amendment will not enter into force until it has been accepted by all Member States.

Article 19 allows a Member State to denounce the Convention. However, the Convention makes no provision for a Member State simply to cease to exist, and that is what happened to the Socialist Federal Republic of

Yugoslavia (SFRY), one of the signatory states of the Convention. In June 1992, in accordance with a UN Resolution, the Council instructed the Director to suspend the telecommunications connection with Belgrade. This technical move did nothing to remove the SFRY from the list of Member States.

ECMWF is an independent international organisation. Any decision taken by the Council on, for example, the succession to the SFRY, would have set a precedent with far-reaching implications. So on the revenue side of the budget for the years 1993 to 2001 there was listed a contribution due from that State, which the Centre knew it would never receive. The EU had the duty to notify all Member States when Luxembourg joined; how could it inform the SFRY? This wholly unsatisfactory situation continued year after year. In June 2001, the Council was considering amending the Convention. This would require the approval of all Member States. Council finally decided that the SFRY "has ceased to be a party to this Convention" and passed a resolution to that effect.

And for the record: there is only one minor typographical error in the English version of the Convention. Article 17(1) has the phrase "interpretation of application". It should read: "interpretation or application". Praise is due to the skill of the typists in the years before word-processing!

Norway took part in drafting the Convention, and so was entitled to become a Member State from the date the Convention came into force. However, in a letter of 12 October 1979 from Wiin-Nielsen to the Ministry of Foreign Affairs of Norway, he notes that "the Norwegian Government decided in 1973 that it was unable to sign the Convention". Why was this?

Both Prof Ragnar Fjørtoft, Director of the Norwegian Meteorological Institute at that time, and Prof Arnt Eliassen from the University of Oslo, advised the Ministry in charge of the Institute, then the Ministry of Church, Education and Science, not to join ECMWF. Eliassen had spent some time in the USA — he visited the Institute of Advanced Studies, Princeton as part of a research team for the academic year 1948–49. He also visited the University of California at Los Angeles and MIT. Both Fjørtoft and Eliassen played important roles in 1948–50 in the work leading to the first integration of the barotropic equation, a significant milestone in the development of Numerical Weather Prediction.

Their advice was based on their interpretation of Lorenz' now well-known theory on the predictability of non-linear systems, the "butterfly effect". They were of the opinion that the weather simply could not be predicted ten days ahead. Although their interpretation was at least arguable, they were very reputable scientists and their advice carried great weight in the Ministry. Later Directors of the Meteorological Institute, Prof A. Langlo and Prof A. Grammeltvedt, were unable to change the opinion of this Ministry. In his later years, Eliassen was somewhat reluctant to discuss the matter, suggesting that he realized that his advice had not been the best. Sometimes, perhaps, deep insight can lead to an unwise decision!

On a scientific level, good relations were maintained between Norway and the Centre. In fact, Eliassen was one of the main lecturers at the third ECMWF Seminar in September 1977.

Through the years the ECMWF Director and Council made many formal and informal efforts to convince Norway to join. When Norway finally became a Member State in 1989 it was due to an intervention by the Environment Minister in the Cabinet, to which the Norwegian Meteorological Institute does not report. Norway had been refused permission to participate in a research project on the Antarctic ozone hole. The reason given was that this project made substantial use of ECMWF data, and Norway was not a Member State. The refusal was perhaps very much associated with the desire of the international community, and many meteorologists in Norway, to change Norway's non-membership status; the staff of the Institute had by now given up trying to convince its own Ministry.

Anton Eliassen, the son of Arnt Eliassen, was at that time Deputy Director of the Meteorological Institute. With his connections to the scientific community of atmospheric chemistry, he was kept informed of developments. Prof Henning Rodhe of Stockholm University, the ozone project leader, and Prof Ivar Isaksen at Oslo University, were keen for Norway to join the Centre, and, with others in this complex political situation, played key roles.

The Environment Minister was Sissel Rønbeck. She was made aware of this rather serious rebuff to Norway in 1987 while she was in Montreal signing the Protocol on Substances that Deplete the Ozone Layer — the "Montreal Protocol". As soon as she arrived home she took the matter up in the Cabinet. The higher officials in the Ministry of Church, Education and Science, who were still against joining, found themselves circumvented, and Norway was welcomed as a Member State on 1 January 1989.

Luxembourg also could have been a Member State from the start. There were several tentative approaches at high level over the years, with a visit to the Centre from the responsible government minister of Luxembourg in 1986. In September 1987 "the Luxembourg government decided to ask for full membership beginning on 1 January 1989". The Director of ECMWF and the President of the ECMWF Council visited Luxembourg in April 1989. It became clear that there would be technical difficulties in establishing a unit within Luxembourg that would be able to take proper advantage of the Centre's output. There were many informal discussions between

Centre staff and representatives of Luxembourg in the following years. Membership was delayed until July 2002, when Luxembourg finally became a Member State.

The meteorologists of Iceland have over the years been somewhat cross with their Foreign Ministry, blaming some unknown and therefore unnamed low-level functionary in that Ministry for having decided that this COST action was an affair that would be of no interest to Iceland. It has even been rumoured that the letter of invitation was put aside and forgotten, or cast into the waste paper basket. However, the records of the COST archives suggest a simpler explanation for the omission of Iceland from the list of Member States. As mentioned in Chapter 3, the President of the Council of the EEC addressed a letter to nine European States that were not Members of the EEC, in which he informed them that the Member States of the Community would welcome their participation in the planned operations in the field of the scientific and technical research. Iceland, for unknown reasons but we can safely assume in a forgetful moment, was simply not sent a letter of invitation. The fault, if we wish to call it such, appears to lie mainly with the EEC, not with an official of the government of Iceland.

However Finland, Greece, Turkey and Yugoslavia participated “at their own request” — they also had not been sent a letter of invitation. It could perhaps be legitimately argued that Iceland was partly at fault, in that it missed the opportunity to participate in a similar way to these four States.

On 9 October 1975 the Secretary-General of COST was able to write to the States that had ratified, accepted or approved the Convention informing them that:

> *since the conditions required . . . have been fulfilled, this Convention will enter into force on 1 November 1975 for the Kingdom of Belgium, Denmark, the Federal Republic of Germany, Spain, the French Republic, Ireland, the Socialist Federal Republic of Yugoslavia, the Netherlands, the Swiss Confederation, the Republic of Finland, Sweden and the United Kingdom of Great Britain and Northern Ireland.*

But let us make our way to sunny Rome, sit at a table at an outdoor café, order a cappuccino, smile at the world, and start idly reading the Convention — the Italian version of course. The Convention was “drawn up in a single original in the Dutch, English, French, German and Italian languages, all five texts being equally authentic”.

You will hardly have started reading before you will find yourself sitting up in your chair and forgetting the cappuccino. You have found something interesting!

Now let us try a little multi-lingual exercise. Article 1(3) of the Convention is given below in all five languages. Take a pencil and underline the important words ‘States parties’ in all five versions. Please excuse the legalistic language. A State becomes a “State party” to the Convention by ratifying, accepting, approving, or acceding to, the Convention.

In Dutch:	De leden van het Centrum, hierna noemen ‘Lid-Staten’, zijn de Staten die partij zijn bij deze Overeenkomst.
In English:	The members of the Centre, hereinafter referred to as ‘Member States’, shall be the States parties to this Convention.
In French:	Les membres du Centre, ci-après dénommes ‘Etats membres’, sont les Etats parties a la présente convention.
In German:	Die Mitglieder des Zentrums, im folgenden als ‘Mitgliedstaaten’ bezeichnet, sind die Staaten, die Vertragsparteien dieses Übereinkommens sind.
In Italian:	I membri del Centro, qui apresso denominati ‘Stati Membri’, sono gli Stati firmatari della presente Convenzione.

That was not too difficult, was it? Except perhaps for Italian? You are probably reaching for your Italian-English dictionary at this stage, except of course if you are Italian! The Italian version appears to suggest that perhaps it is not necessary to be a contracting party, but only a signatory State, “Stati firmatari”, in order to be considered a Member State.

The Italian delegation to the first session of the Council held in November 1975 was understandably of the opinion that Italy had therefore to be considered a Member State of the Centre, and said so, even though it had not yet gone through the procedure followed by the existing Member States.

What a nightmare this would have opened up! Since the Italian version was valid for all, then all signatory States — including Italy — would have become subject to all obligations of membership, including financial obligations, even before they had ratified, accepted, approved, or acceded to, the Convention. Other Articles and wording of the carefully crafted Convention would have become absurd, meaningless or at variance with others. Not having signed, could Norway join the Centre? By the Italian version of Article 1(3) it could not, but by Article 23 in all language versions it could, since it had taken part in drafting the Convention!

Other delegations, while too polite to express their undoubted horror, did not share the opinion of the Italian delegation, and referred to the wording in the other language versions. Legal clarification was sought from the COST secretariat, and obtained in time for the second Council session in May 1976. The legal opinion noted that "the discrepancy may be regarded as a simple linguistic error". However all versions had been signed by the plenipotentiaries of the States, and "it would be scarcely practicable to consider a correction, since an international instrument would be required which would involve an exceedingly cumbersome procedure". In the Italian text, the term "Stati firmatari" should be interpreted as "contracting parties". Finally, the opinion stated that signing the Convention does not in itself entail membership of the Centre. Italy then went through the formal procedure, and became a Member State in September 1977.

Thus, the issue was solved. In any event it cannot arise again, since all the signatory States became Member States.

Portugal became a Member State on 1 January 1976, Turkey on 1 May 1976, Greece on 1 September 1976, Italy on 1 September 1977, Norway on 1 January 1989 and Luxembourg on 1 July 2002.

Co-operation agreements have been concluded with several States: Iceland (December 1980), Hungary (July 1994), Croatia (December 1995), Slovenia (June 1997), Czech Republic (August 2001), Serbia and Montenegro (January 2003), Romania (December 2003) and Lithuania (March 2005). Other countries of the former Eastern Europe have approached the Centre with a view to membership.

International organisations and ECMWF have also established co-operation agreements: World Meteorological Organization (WMO, November 1975), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT, May 1988), African Centre of Meteorological Applications for Development (ACMAD, May 1995), Joint Research Centre (JRC, May 2003), Preparatory Commission for the Comprehensive Nuclear Test-Ban Treaty Organisation (CTBTO, June 2003), and the Executive Body of the Convention on Long-range Transboundary Air Pollution (CLRTAP, January 2005).

By March 1972, the scale of financial contributions of the Member States was first being considered. The other basic documents for the Centre — the Staff Regulations, the Financial Regulations and the Headquarters Agreement to be concluded between the Centre and its host state — all were painstakingly drafted in the course of the next two years.

The first session of the Council held on 4–6 November 1975 was addressed by Dr Davies of WMO, Dr Mason, representing the government of the host country, Dr Shregardus of KNMI, speaking as Vice-Chairman of the Interim Committee, and Mr Silver, Chairman of the COST Committee of Senior Officials of the EEC Council. It was at this Council that Aksel Wiin-Nielsen was formally appointed Director.

By letter of 25 February 1991, the President of the Meteorological Service of the Republic of Hungary, Dr Iván Mersich, sent “an application of Hungarian Meteorological Service to join ECMWF as a member”. This was one of Dr Mersich’s first acts in his post — he had been appointed on 19 February. At the Council session the following June, the German delegation noted that “the Convention was very clear; at the time it had been concluded, the Centre had been made very exclusive, and the Convention was tailored to the requirements of the Member States. The Convention could be changed only with great difficulty and over a long period of time.” This was true.

Council cannot itself amend the Convention; it can only recommend an amendment to the Member States. These will then one by one consider accepting the amendment. Amendments “shall enter into force thirty days after receipt by the Secretary-General of the Council of the European Communities of the last written notification of acceptance”. Since 18 States will have to follow their own legal procedures to decide on acceptance, and since government legal teams understandably proceed not always with haste, it can be expected that some time, perhaps years, will elapse before the last written notification of acceptance will have been received.

While no Member State was in favour of considering full membership for eastern European countries at that time, all were in favour of some assistance being given to these countries. We have noted above the conclusion of co-operation agreements with several of these States.

In December 1999, the Council requested the Director to clarify the legal situation concerning the possibility of Co-operating States becoming Member States. At first, an attempt was made simply to add States to the Annex; in June 2000 Council asked the Policy Advisory Committee (PAC) “to examine the framework for adding States to the Annex of the Convention”. Legal opinion at the end of 2001 indicated that a relatively simple procedure could be adopted: Council adopting a “Resolution affirming the consent of all the Member States to the accession of new States . . .” and allowing the necessary revisions to the Annex in a similar way. However, some Member States found themselves unable to agree with this opinion because of their own legal advice. It became clear that a change to the Convention would be required, even though this was foreseen to be a lengthy process.

This opened the possibility of a wider examination of the Convention. Since the process of amending the Convention was known to be lengthy and difficult — according to Italy: "it is not feasible to repeat the procedure of amendment often" — some felt that the entire Convention should be examined. Council therefore asked the Director to contact all Member States: "Member States could also raise other issues if they so wish." Some did raise other issues.

Germany wished the Centre "to play an independent, reliable and durable role in operational monitoring of the environment", and to restrict the maximum financial contribution of any Member State to 22% of the total budget. Belgium believed that a new Convention should be drafted to reflect the current situation [the Centre was carrying out activities such as wave forecasting and seasonal prediction not explicitly mentioned in the Convention for example]; the review of the Convention should evolve from a new vision of the Centre. Italy wished to examine other important issues, such as monitoring the environment, long-range forecasting and relations with the EU and WMO; in addition, some of the work of the Centre was of relevance for climate prediction. Spain wished Spanish to be incorporated as an official language, and for an amendment to allow the Centre's headquarters to be located outside the UK. The UK wished the voting procedure to be modified. Others had additional issues that they wished Council to consider. At the end of 2002, Council set in motion the procedure of consultation with Member States. It convened an extraordinary session of the PAC, and asked delegates "to analyse the proposals and views of the Member States in a creative and flexible atmosphere, to arrive at a consensus view as far as possible". Thus began a process leading eventually to a recommendation of Council to the Member States in April 2005 that the Convention be amended.

By December 2003, the Council had reached consensus on the text of amendments, with the exception of an amendment relating to languages: "the highest authorities in Spain had stressed the requirement that Spanish be an official language". It would take more than a year before agreement was finally reached in December 2004. The language issue was solved by a proposal from the PAC, which had as Chairman Massimo Capaldo from Italy, a former research scientist at the Centre and also a former Head of Operations:

> *The official languages of the Centre shall be the official languages of the Member States.*
>
> *Its working languages shall be English, French and German.*

> *The Council shall determine the extent to which the official and working languages shall respectively be used [by a double two-thirds majority vote, i.e. at least two-thirds of the States voting in favour, and these representing at least two-thirds of the budget].*

As well, and most importantly, the Convention now would allow “any State which is not a Signatory” to the Convention to become a Member State, subject only to the consent of Council.

Further, an important modification was made to an objective of the Centre:

> *to develop, and operate on a regular basis, global models and data-assimilation systems for the dynamics, thermodynamics and composition of the earth’s fluid envelope and interacting parts of the Earth-system, with a view to:*
>
> *i) preparing forecasts by means of numerical methods;*
>
> *ii) providing initial conditions for the forecasts; and*
>
> *iii) contributing to monitoring the relevant parts of the Earth-system.*

Many other, mostly minor or editorial, changes were included in the recommendation to the Member States. The amendment was recommended unanimously. At the time of writing the amendment was being considered by the Member States for acceptance.

After it comes into force, it can be expected that many, perhaps most, Co-operating States will wish to accede to the Convention, thus becoming Member States. It can be expected also that other States from Eastern Europe will wish to do the same.

Chapter 6

In the United Kingdom

The location of the Centre was considered first in November 1970. A sub-Committee of the Expert Group decided to begin an action programme *inter alia* to carry out a preliminary analysis of the local factors that would be taken into account when determining the site. On 26 January 1971, the sub-Committee was already able to state that a prerequisite condition was proximity to a large university, to ensure an exchange of views on scientific developments, and to a National Meteorological Service (NMS), to keep the Centre informed on the practical work of the NMSs. In his covering Memorandum to the "ECMW Project Study" of 5 August 1971, Dr E. Süssenberger, Chairman of the Working Party on a European Centre for Medium-Term Weather Forecasting (ECMW), stated:

> *There are practical reasons for siting the new ECMW within or near the London–Frankfurt–Paris triangle. It has become clear that the only viable solution is for the ECMW to be organized as a central institution with its own large computer.*

Senior representatives from 14 of the participating states attended a meeting of an ad-hoc group on 9–10 December 1971. They considered a first draft of the Convention. As well, there was considerable discussion on the criteria that should be applied when deciding on the location of the Centre. By January 1972, the list of criteria was (almost) finally agreed. In March 1972, the candidate states were invited to let the secretariat know by 15 April of their intention to apply for the Centre to be sited on their territory.

Belgium, Germany and the UK responded, and Italy and the Netherlands asked for more time to consider the matter. On 3 May, the Commission of the European Communities responded with a detailed proposal to have the Centre on the territory of the European Joint Research Centre (JRC) at Ispra, in Lombardy, Italy. On 4 May, Denmark indicated that its government wished to host the Centre.

The Meteorological Office of the UK had been carrying out operational numerical weather prediction since late 1965. The newly appointed Director-General Dr John Mason had insisted, against the wishes of some of his cautious senior staff, that the results of more than ten years active and productive research in the field be brought into operational use, especially since other European countries had been producing operational numerical forecasts for some years.

In June 1972, Patrick J. Meade, Director of Services of the Meteorological Office, stated in an internal UK document:

> *We should go firmly for ECMWF on scientific and technical considerations alone, making it clear in discussion with our European colleagues that the project stands a good chance of failure if Bracknell is not chosen. Looking at the subject nationally, I consider that among all the projects arising — ECMWF, Satellite Ground Station, Centres for GATE, GARP and so on — ECMWF is the prize really worth winning. In the medium and long term the national Centre associated with ECMWF will inevitably develop into a WMC; other national centres will have their scope and research effort restricted as to area of interest and time scale for forecasting. We should firmly relegate the side issues to a trivial level: the Department of Trade and Industry for example want us to include in our paper a note on the benefits to local trade if ECMWF is to be located at or near Bracknell.*

A draft paper for Ministers of the UK Government stated:

> *If the bid fails . . . the participation of the UK should be small but not discouraging. The Bracknell effort in the field of interest to ECMWF is so extensive and the objectives are of such great potential from the economic standpoint that it would be absurd to transfer any of this effort from Bracknell where adequate support facilities are at hand to a site where no comparable facilities would be available for several years. Since the value to the UK of forecasts for a week ahead has been estimated at £10 million per annum it would be most unwise to suspend the Bracknell effort or transfer it to unfavourable surroundings for five years or more. If the Bracknell effort is maintained it is possible that the Meteorological Office will be issuing medium-term forecasts before ECMWF could reach an operational stage in another country.*
>
> *In the event that the bid fails, the UK should be ready to offer facilities at Bracknell for the training of staff, to arrange exchanges of personnel and to make data and techniques freely available . . . The extent of any direct UK financial contribution should be limited to a token amount.*

Accordingly the Meteorological Office recommended to its Government that:

> *It is sound in principle to establish ECMWF.*
>
> *In this project the scientific and technical considerations are of overriding importance and point clearly to the Bracknell area as the only sensible location for the Centre.*
>
> *Appropriate assurances should be given as to the provision of adequate working accommodation at the proposed site in the grounds of the Meteorological Office College at Shinfield Park.*
>
> *If the UK bid for the Centre fails, the Bracknell effort in the field to be covered by the ECMWF should be maintained and UK participation in ECMWF should be limited accordingly.*

On 2 August 1972, the Working Party on the "Questionnaire on the site for the European Centre for Medium-Range Weather Forecasts" sent a Report to the Committee of COST Senior Officials. The Report contained an analysis and interpretation of the very detailed and comprehensive information in the proposals for the Centre to be sited in:

- Belgium — in the centre of Brussels;
- Denmark — at Hørsholm, 23 km from Copenhagen;
- Germany — 2 km from Wiesbaden;
- the Netherlands — near Maastricht-Heerlan;
- UK — a site at Reading, 60 km from London;
- land of the Joint Research Centre at Ispra, Italy — this was a proposal of the Commission of the European Communities.

Housing for the staff, education facilities for foreigners, religious worship, climate, communications facilities and other factors were evaluated. Further representations were made by the various candidate states in the following months.

At the request of the Committee, a Working Group consisting of Jean Labrousse, Daniel Söderman and Mr M. Ulrich of Switzerland visited the various sites in the period 2 to 13 October 1972. They assessed the general and technical criteria that had been adopted for determining the site of the Centre, taking care to stress the subjective nature of their judgements!

- Although the site proposed by Belgium was judged favourably in most respects, the offer was withdrawn later in October.
- The Research Centre at Hørsholm north of Copenhagen was one of the group's favourite sites. It was close to the Danish Meteorological Institute, which was not one of the biggest NMSs. This was considered

an advantage as proximity to a large NMS could result in it having too much influence on the new organisation.

- The UK site was situated at Shinfield Park west of the Meteorological Office headquarters at Bracknell, sharing a boundary with the Met Office College; in fact, it formed part of the College grounds. One of the questions the group had asked in advance concerned educational possibilities for the multi-national children of Centre staff. All except the UK emphasised the existence of good multi-national foreign schools. Not having received a fully satisfactory reply from the UK, the question was put again during the visit. The reply from Patrick Meade, along the lines of “how could you envisage not sending your children to the best [British] educational system in the world?” was well remembered even many years later as a somewhat incomplete response.
- A site southwest of Wiesbaden in Germany was, with the Danish site, given a high priority by the group. There was a castle on the site “which could possibly also be used” as well as a “two-storey building, which is presently used as a club by US troops”.
- The Netherlands had a range of possible buildings on the proposed site. Only one of these was big enough for the permanent needs of the Centre. This building would have to be bought, at high cost, and it would be suitable only if it was split into two units, since its size was greater than that required.
- The territory of JRC at Ispra in Italy was, like the Netherlands site, “far from any team of research workers in the field of numerical forecasting”. Also, it was on land of the EEC. Membership of the Centre was not the same as that of the EEC, so political difficulties could have arisen.

Edward Heath, who had been Prime Minister of the UK since 1970, was committed to increasing Britain’s influence in Europe. Dr Mason visited Downing Street and persuaded Mr Heath of the benefits of having the Centre in the UK. It seems that Mr Heath, a keen amateur sailor with an interest in meteorology, was rather easy to convince! A strong memorandum was sent from the Government of the UK to COST detailing the technical advantages of having the Centre at Shinfield Park. It went on:

> *There are also political considerations. Her Majesty’s Government considers that at the time of our entry into the EEC it is particularly important that we should be in a position to be able to announce publicly that an important European scientific institution is being set up in the United Kingdom.*

A preliminary poll among the States at the end of November 1972 indicated that support for the UK proposal was strong, with six “first preference” votes and two “second preference” votes. Hørsholm and Wiesbaden had four “first preference” votes and two “second preference” votes each, Ispra had two and one, and Maastricht one and two.

At this stage, Germany decided not to press its bid, preferring to leave the field open for Germany to obtain the European Patent Office (EPO), which was established by a Convention signed, like that of the Centre, in 1973. The EPO was in fact set up in Munich, Germany.

Germany now believed that “the decision is likely to fall between Bracknell and Copenhagen and at the decisive vote . . . there will probably be only these two alternatives”. After informal discussions with some of the representatives of France, Sweden and Switzerland, Germany contacted Spain and Turkey, who had voted for Germany in the preliminary poll. It informed them that they “were all of the same opinion that it would be best if a smaller country took the seat thus guaranteeing that the Centre maintains its international character . . . it is better in view of the independence of the Centre if it is established at a place without any large national centre existing”. It asked that they “consider Copenhagen as the most suitable place”.

The 18th meeting of the Senior Officials of the COST Group took place in Brussels on 5–6 March 1973. On a proposal from the Chairman Dr R. Berger of Germany, which the UK had informally inspired, it was agreed that item 3b “Site for the European Meteorological Centre” should be taken first. The Chairman asked if those candidates whose bids had attracted the least support were in a position to withdraw their bids, as he had suggested at the previous meeting. This was not agreed, and a discussion followed on the voting procedure.

The Chairman asked each candidate to declare first whether or not it would continue to participate in the Centre in the event of its bid being unsuccessful. Germany, the Netherlands and Denmark confirmed continued participation. The UK delegation, however, gave an ambiguous response by stating that this was a hypothetical question; Her Majesty’s Government would make its views known when the draft Convention was complete, including the paragraph stating the location of the Centre. It emphasised that the decision on location was essentially to be based on technical merit. The Danish delegate suggested that if the UK was not prepared to participate in the project in all circumstances, it was perhaps improper for it to participate in the vote. During these exchanges the Italian delegate noted that his government could not commit Italy to participate either, but Italy was prepared to accept the procedure. The Chairman declared a 15-minute break, during which he and other delegates appealed to the UK representatives to change their position. However the UK delegation made it clear that it was acting on firm instructions; this was a matter of principle.

Voting then took place by secret ballot. In the first round, there were eight votes for the UK, six for Denmark, and two each for the Netherlands and Ispra. The two bids that got the lowest number of votes were withdrawn. In the second round, there were 12 votes for the UK and six for Denmark. The UK bid was declared successful. In response to a question from the delegation of France, the head of the UK delegation noted again that its stand on the declaration issue had been one of principle. The UK bid had been submitted in good faith; they believed it to be technically the best and were grateful for the support now shown. He expressed his strong conviction that the UK government would in fact sign. It would be a privilege and an honour to have this Centre located in the United Kingdom. The Danish delegate offered his congratulations.

We have already seen Patrick Meade's view in 1972 that the UK "should firmly relegate the side issues to a trivial level: the Department of Trade and Industry for example wants us to include in our paper a note on the benefits to local trade if ECMWF is to be located at or near Bracknell". As with most internationally financed organisations, the UK has over the years gained substantial economic benefit from the Centre.

A Dutch company General Technology Systems (Netherlands) BV had made "a detailed assessment of the economic and other benefits which are created by the fact that the European Space and Technology Centre ESTEC is located in the Netherlands". Director David Burridge commissioned the company to make a similar assessment for the Centre. The Study: "The Economic benefits to the United Kingdom as host of the International organisation ECMWF" was completed in February 1995. It used 1994 as the reference year. The economic benefit to the UK for that year was assessed to be £10,936,000 with the UK contribution to the budget being £2,564,000. This gave a benefit/cost ratio of 4.26. Taking into account economic multipliers, the increase in economic activity in the UK was £25,371,000. Also the increase in employment in the UK was the equivalent of 485 full-time jobs.

We noted in Chapter 1 that the Director Aksel Wiin-Nielsen signed a Headquarters Agreement that laid down the rights and obligations of the Centre vis-à-vis the UK as host State. There was a necessarily legalistic "Schedule of terms of occupation" attached, with an important provision.

> *The Owner hereby covenants with the Occupier as follows: (1) Until the expiration of twenty years from the date of occupation to repair, redecorate and otherwise maintain all the external parts of any Buildings . . .*

The UK has arranged and paid for many costly repairs, including replacement of the large roof of the Computer Hall and strengthening its floor, and replacing all the windows in the office block. This twenty-year period expired on 12 June 1999. After negotiation, the Second Permanent Under Secretary of State of the Ministry of Defence, Roger Jackling, authorised the extension of the period for a further twenty years, until 2019. In April 1999, the responsibility of the host country for maintenance of the Centre's buildings was taken over by the Met Office.

We have seen that the site of the Centre shared a boundary with the Met Office College. Relations between the Centre's Director and staff, and the staff of the College, were excellent from the beginning. The College was a pleasant facility, with open grassland covering much of the site. While the area of the Centre's grounds was sufficient for its original buildings, car parks and ancillary equipment, there was limited room for expansion on its own land. With permission, which was always forthcoming, the Centre used the College grounds for sports and social purposes. It provided overflow car parking during Seminars and on other occasions when large numbers of visitors came. Large marquees were erected there when the Centre was celebrating some important event, including the official opening of the building at Shinfield Park on 15 June 1979, and the 25th anniversary of the Centre on 1 December 2000. Staff from France, Germany and Italy were introduced to the pleasures of the English game of cricket on the College grounds.

In November 2000, the Under Secretary of State for Defence, Dr Lewis Moonie, announced that the Met Office had chosen to move its headquarters from Bracknell to Exeter in the southwest of England. This meant that the Met College would move from Shinfield Park. The Centre's Director David Burridge was taken somewhat by surprise at the announcement. He had not previously been aware of the planned move.

Since the grounds of the College were directly beside those of the Centre, and were to be sold for house building, this was a matter of serious concern for the Centre's Council and Director. In addition to losing the long-standing use of the valuable College facilities, the Centre would face a future without the possibility to extend. And this unwelcome development coincided with an expansion of the Centre's activities.

The Centre's responsibilities were growing, and with them its requirement for more office accommodation and extra space for its technical equipment. There were additional activities associated with seasonal prediction and wave forecasting, involvement in processing satellite data, and increasing work involving EU-funded projects. All this meant that the original space, which foresaw office accommodation for 145 permanent staff and up to 10 visiting scientists, was already insufficient for its needs. In 1998, the Centre had leased, and had erected on the grounds, a second-hand temporary modular accommodation block. This provided 18 offices. The building was initially leased for a five-year period. In the Financial Statement of Accounts for 1998, the auditors commented:

> *While not questioning the Centre's present difficulties to provide accommodation for its staff, we wish to emphasize that the chosen solution is only a temporary one and may not be the most economical in the long run. We hold the view that thought should soon be given to the future office accommodation needs of the Centre to be able to make a qualified decision on the actions necessary to prepare for the time after the end of the five year renting period of the temporary building.*

In December 2001 the Council requested the Director to bring forward detailed proposals for consideration in spring 2002 about the Centre's requirements for office accommodation.

Plans, including those for the Centre to become more involved in the EU/ESA Project Global Monitoring for the Environment and Security (GMES), meant that there would soon be an urgent need for additional offices. We will see below that additional space for computer equipment would also be required. Burridge asked that two acres — less than a hectare — of the College land be made available for possible future expansion.

In the view of Peter Ewins, Chief Executive of the Met Office, "the Headquarters Agreement . . . makes it clear that the acquisition of accommodation for future expansion is at the Centre's own cost . . .The Met Office is obliged to dispose of its assets at full market value . . . the land . . . has a market value in the region of £1.5 million per acre". Thus the land under discussion had a market value of about £3 million. Burridge did not agree with Ewins' interpretation of the Agreement, which referred to additional buildings, not additional land. It was established practice that international organisations were provided with land free of charge by the host Country. At the Council in December 2001, Ewins suggested that the Director write to the Foreign and Commonwealth Office of the government with a justification for his request.

In June 2002 the Council expressed its concern that imminent action by or on behalf of the UK government, the host of the Centre, "may constrain development of the Centre", and passed a Resolution requesting that "the additional land could be made available to the Centre . . . free of charge as is the practice for international organizations".

In December 2002 Ewins informed the Council that "the situation had moved substantially and to the benefit of the Centre . . . allowing a sufficient quantity of land to be provided to the Centre for its use without cost". However the additional plot of land made available was considerably smaller than that requested by the Centre, and far from sufficient for future needs.

Following discussions on the contract with IBM for the High Speed Computing Facility in December 2001, the Council requested the Director to review the Centre's infrastructure requirements to ensure that the Centre was well prepared for the next Invitation to Tender or any extension of the Service contract with IBM.

At the end of 2004, the floor area available for the installation of computer equipment in the Centre's Computer Hall was full, following completion of the installation of the IBM computer. This meant that a parallel run of a future replacement machine, of unknown architecture, would be impossible. The Council approved the Director's proposal to extend the Computer Hall, increasing its size by 50%. Also it decided to construct an additional office block, with the extra land provided by the Met Office being used to re-site the parking area.

Throughout 2003–04 the Centre had lengthy, detailed and sometimes difficult discussions with Wokingham District Council (WDC), the local authority, in attempting to obtain permission to build an extension to the Computer Hall, together with an additional office block. WDC objected to the plans. However, permission for the Computer Hall extension was granted in November 2003, and construction began in summer 2004.

The application to build a new office block ran into major difficulties. A building in the grounds of the Met Office College, close to the Centre's boundary, was a "Listed Building"; it thus merited special consideration, although it was in a semi-derelict state. Permission was finally given in September 2004 for construction of a re-sited block. Completion was planned for 2006.

Autumn 2004 saw an interesting development. A plot of land of 5,000 m^2 beside the entrance gates to the Centre, with a building known as "Keeper's Cottage", was offered for sale, but with little public advertising. Several house builders, potential purchasers of the site, lost interest when they discovered that access to the site from the main road was very limited. One of these approached the Centre to enquire if he could have permission to share the Centre's entrance as an access road to the site. Permission was refused, but Dominique Marbouty, ECMWF Director since June 2004, realized for the first time that the land was for sale. He approached the vendor as a potential purchaser. A price was agreed, subject to contract, to purchase the site prior to auction, which had been planned for 20 October.

Speedy action was required if the purchase was to proceed. Marbouty approached the Chief Executive of the Met Office, the President of Council and other Member State representatives. At its meeting in December 2004, the Council approved the acquisition of the Keeper's Cottage site, with the expectation that the UK, as the host country, would eventually finance the acquisition, thus becoming owner of the site, but making it available to the Centre.

Chapter 7

1974 to 1980: the Formative Years

The period 1974 to 1980 was clearly a busy and exciting time with lots happening, starting so to speak with a clean sheet of paper.

- ✓ Recruiting staff.
- ✓ Completing the building at Shinfield Park, with its computer hall, offices and conference facilities.
- ✓ Dealing with the complex legal and administrative issues that arise when setting up an international organisation.
- ✓ Acquiring, installing and keeping in reliable operational state the CRAY-1 mainframe computer and the Cyber 175 front-end computer.
- ✓ Implementing the telecommunications system based on the Regnecentralen 8000 computer.
- ✓ Setting up courses and seminars for advanced training in numerical weather prediction for the scientists of the Member States.
- ✓ Designing and implementing the complex data acquisition and quality control software and archives.
- ✓ Acquiring, modifying and bringing to operational state the even more complex data assimilation & modelling software.
- ✓ Designing and programming the software to run the operational suite.
- ✓ Completing — on time — the first operational medium-range forecasts.

The goal was clear: to turn the dreams and hopes of the early planning groups into reality.

It is impossible to do justice to such diversity of effort at the level of synthesis required by a book such as this. To combine these separate elements to form a coherent complete story is a challenge. Each deserves a chapter of its own, perhaps even a book to describe some adequately.

Within the Centre in these years, there was a great deal of hard work, anxiety and worry, but also increasing optimism, and in general a growing sense of achievement and accomplishment. Adrian Simmons and David Burridge independently remembered it as a “very exciting time”. Massimo Capaldo, a scientist newly arrived from Italy, who would years later become the Head of Operations, described the atmosphere of the Centre simply as “amazing”. Capaldo remembered the codes being typed by secretaries and the punch cards being used, until new Video Display Units arrived. In this, his first experience of work in an international environment, he recalled the different nationalities easily working and socialising together, with progress being made in many areas of research. Jean Labrousse remembered the quality of Wiin-Nielsen’s management: defining objectives clearly and then letting the staff work in their own way to achieve these. Thanks to this, they “were never under pressure”.

In retrospect, it is worthwhile recognising that the Centre was able to avoid becoming either another international bureaucracy, or an ivory tower research institute. Above all, it was planned as an operational scientific and technical institute. Under Wiin-Nielsen’s admirable leadership, it developed into just that. Simmons remembered that “in working atmosphere it was more like a university research department than a national weather service”. Partly this was because all the staff were newcomers. Everyone was learning to work with others in a complex mixture of nationalities. The Centre was fortunate to be able to recruit many good young scientists, the best in Europe in their fields: meteorology, numerical methods, modelling and data assimilation, computer science and technology, telecommunications, international administration, and related disciplines. This provided all the virtues of vigour, passion and pluralism that such a blend of nationalities and skills can bring. In the first years, there was a great deal of social intermingling between nationalities, both informally and — after the restaurant in the new building became available in late 1978 — semi-formally. For example, there were the “International Social” evenings, when staff of different nationalities brought national food dishes to be shared, with sometimes music and dancing to follow. One scientist arriving from France noted the “beautiful melting-pot effect, the first in European science”.

Undoubtedly the size of an organisation matters. An organisation is made up of individuals, all with different kinds of responsibility. For an organisation of up to perhaps 150 or so, everyone in principle can quickly recognise everyone else, and have an idea of what they do and their role. This was especially important in the early days, when all were learning and experimenting in one way or another. Many were for the first time working with people from other countries, with different work and social habits and expectations. Friendly and productive lateral discussions between staff in the three departments of Administration, Operations and Research were normal, often informally over coffee or lunch in the Centre’s restaurant after the move from Bracknell to the new building at Shinfield Park.

It is worth trying to cover the story of these years with a broad brush, and to exemplify the intellectual effort and dedicated hard work with some details. In the chapter "The first Director", we covered some of these matters from Wiin-Nielsen's point of view. We will avoid unnecessary repetition.

Staff were recruited. The Convention came into force in November 1975, and staff then in post were given new contracts from January 1976.

Year	Number
1976	53
1977	81
1978	115
1979	139

Number of staff in post on 31 December of the years 1976 to 1979.

The table of staff requirements for 1980 showed 145 posts; however, of these, four were suppressed following a review of the Administration Department in that year. The number of staff stabilised at about 140 for many years to come.

The Centre was set up with a clear focused objective: to produce the best medium-range weather forecasts in the world. The timing was fortunate: there was a massive storehouse of research and development from the 1960s from the United States as well as Europe that could be tapped — sources of data, analysis techniques, different numerical schemes, and more.

A forecast begins from an analysis of the current state of the atmosphere, which has assimilated many different kinds of observational data, from ships, land stations, balloons, satellites and other sources.

Selection of a good data assimilation system was crucial. Lennart Bengtsson, the Head of Research, was well connected to the best sources of scientific advice. He had highly relevant experience from his work preparing for the First GARP Global Experiment (FGGE), which we have considered in Chapter 3. We have noted the explicit reference to the Global Atmospheric Research Programme (GARP) in the introduction to the Convention. By the time of the first session of the Council in November 1975, GARP was underway. Wiin-Nielsen noted in his Report to the Council that "FGGE as part of GARP is essential for the Centre. FGGE happens to take place at the time the Centre will be ready to start operational forecasting. We hope to have an opportunity to participate in FGGE — it will give the best initial state to start operational forecasting."

Looking back, we can see that Bengtsson, with his GARP experience, exercised good judgement in making important strategic decisions that put the Centre on the right path immediately. He decided to use a global model, not a hemispheric or regional system. The analysis would be based on "three-dimensional Optimum Interpolation". This used the statistics of past observations of temperature, wind, humidity and so on to ensure best use the current observations, and to ensure that neighbouring observations were in conformity with one another; we consider this further in Chapter 8. In addition, he was able to recruit the right people to do the work.

An early suggestion was made that the Centre, being a medium-range forecasting centre, should use global analyses already being produced at other major European short-range forecast centres. The Centre could then devote its research and development efforts, and computing resources, to developing the numerical scheme and physics of its forecasting model. This approach was firmly rejected. Although with some appeal at first glance, it was argued that the Centre would need to do its own analyses if it was to make best use of the data expected to be available from satellites. This turned out to be a vitally important decision. It meant that the Centre had from the beginning complete control over its entire system. In the event, a significant proportion of the improvement that the Centre achieved in its medium-range forecasts has been due to its sophisticated analysis system. Over the years, of the computing resources used for the operational forecasts, about 40% has been devoted to producing the most accurate starting point for the forecasts, and 60% to producing the medium-range and ensemble forecasts. In 2005, about 30% of the computing resources used in daily operations were for assimilating the data, 20% for two high-resolution "deterministic" forecasts, and 50% for two runs of the Ensemble Prediction System.

A computer model was required. We have seen in the first Chapter that Wiin-Nielsen contacted two groups in the USA, who were well advanced in terms of model building: Dr Joseph Smagorinsky, the Director of the Geophysical Fluid Dynamic Laboratory (GFDL), and Professors Yale Mintz and Akio Arakawa of University of California at Los Angeles (UCLA). Smagorinsky was a visionary who played an important leadership role during FGGE. His paper at the joint American Meteorological Society/Royal Meteorological Society meeting in London in 1969 set out GFDL's agenda for 20 years. He was also chairman of the Joint Steering Committee, which was leading GARP and planning FGGE. Smagorinsky knew Wiin-Nielsen well, and had worked with Bengtsson on the Working Group for Numerical Experimentation. Smagorinsky and Arakawa agreed to provide the Centre with copies of their model codes.

Tony Hollingsworth had joined the Centre on 1 March 1975, as the second member of the new Research Department, under Lennart Bengtsson, its Head of Research. There were just eight names in the telephone list at that time — Aksel Wiin-Nielsen, Jean Labrousse, Lennart Bengtsson, Ernest Knighting, and Jim Clarke, with secretarial staff, Jane Khoury, Martine Russell and Jill Llewellyn. Hollingsworth had had a long interview with Wiin-Nielsen in December 1974. For the first hour or more, he felt that the interview was going badly. Hollingsworth then realised that they had been discussing his work at MIT for the three years to 1970, followed by his year at Oregon State University, and then his period as a founding fellow of the UK Universities Atmospheric Modelling Group at the University of Reading. This was all good stuff, but was not in line with Wiin-Nielsen's determination that the Centre would not become an ivory-tower research centre. At last reading Wiin-Nielsen's body language, Hollingsworth stressed his three-year stint as a bench forecaster at Shannon Airport in his native Ireland, making operational forecasts for the public as well as the special forecasts needed for aviation. Suddenly the tone of the interview lightened. Wiin-Nielsen offered him a post.

Further scientific staff joined on 1 May including David Burridge, Roger Newson, Robert Sadourny — on six month's leave from CNRS in France — and Zavisa Janjic. The Centre at this time was housed on the top two floors of the Social Security Office at Fitzwilliam House in Bracknell.

Robert Sadourny had spent two periods at UCLA, at the department led by Prof Mintz, first as a student in 1965-66, later as a visitor in 1969. Mintz was making major contributions to the science, combining theory, diagnostic analysis, and modelling across a broad range of interests. Mintz's career lasted more than four decades, and included work on analysis and modelling of the planet's general circulation, planetary atmospheres, stratospheric ozone transport and ocean circulation. Much of his scientific work involved collaborations with an unusually talented array of younger scientists.

As we saw in Chapter 1, Sadourny spent four weeks at UCLA in 1975 investigating the UCLA model code for its suitability for the Centre's work.

Hollingsworth was sent to GFDL to pick up Dr Kikuro Miyakoda's forecasting version of the GFDL code. Miyakoda supplied Hollingsworth with an informal documentation of his model in April, which Hollingsworth studied, together with all available information about the GFDL model. He visited GFDL for six weeks from early June. The weather in Princeton was sweltering. Some consolation came from a telephone call from Burridge back in Bracknell where he mentioned that it was snowing. A few weeks earlier, temperatures of 30°C in Bracknell had melted the insulation on the card-reader that provided access to a CDC 6600 at a computer centre in Rijswijk, Netherlands!

On arrival at GFDL, Smagorinsky handed Hollingsworth over to the care of Miyakoda, whose successful experimental medium-range forecasts published a few years earlier — and shown on page 33 — were influential in the decision to set up the Centre. In his first conversation, Miyakoda noted that the ECMWF initiative was extremely important for the future of numerical weather prediction. In his opinion, if ECMWF succeeded, that success would open many doors for the future development of meteorology. On the other hand, if ECMWF failed, those doors would be closed for meteorology for decades to come. Hollingsworth's mission was vitally important to GFDL.

In September 1975, Miyakoda would be one of the principal lecturers at the Centre's seminar on "Scientific Foundations of Medium-Range Weather Forecasts". He would review the existing methods of modelling physical processes of the atmosphere in mathematical terms, and the numerical procedures for making the forecasts.

Miyakoda and his associates showed Hollingsworth several cabinets full of listings of their codes — model code, GATE data assimilation code, field interpolation codes, diagnostic and verification codes, graphics codes and more. This rich library of meteorological knowledge, the result of some tens of skilled man-years of intellectual effort by some of the masters of the science, was offered to Hollingsworth. He was overwhelmed.

This openness was characteristic of most US federally funded science then and since. Software and data developed or collected with federal funds were essentially in the public domain. The Centre received the software free and essentially without conditions. Over a cup of coffee, Smagorinsky explained why there were no conditions on the software, and why he was so free with the model: his policy was to distribute the model to any scientific institute that would have available the computer power required to run it at sufficiently high resolution. Smagorinsky's only requirement was that the Centre should acknowledge GFDL in any work done with their software, and should not pass it on to third parties without GFDL's consent.

Hollingsworth gratefully accepted copies of the model, interpolation, diagnostic, and verification codes, but decided to concentrate most of his effort on the model. Miyakoda, together with his associates Lou Umscheid and Joe Sirutis, helped Hollingsworth formulate a work-plan for his visit. His objective was to bring back the GFDL model source code, and modify it so that it could run on the CDC 6600 being installed at John Scott House, Bracknell. At the time GFDL was using the Texas Instruments Advanced

Scientific Computer (ASC). Hollingsworth wanted an initial dataset which, although at low resolution, would be sufficient for test purposes, and two ten-day forecast runs, at differing resolutions. Jim Walsh was GFDL's main computer expert. Hollingsworth needed his help to get the forecasts with all their special write-ups through the ASC. Walsh's disposition was sunny and positive, but when Hollingsworth outlined his work-plan, he shook his head. There was no way he or Hollingsworth could get through the work in less than six months, much less in six weeks.

Hollingsworth got started, relying heavily on Sirutis, Umscheid and Walsh to get the computing done. He was living in an ancient army base close to downtown Princeton, sharing a wooden apartment with Carlos Mechoso. There was no air-conditioning in his room, so he was happy to work 14-hour days in the luxury of the air-conditioned GFDL offices. His work proceeded apace.

Smagorinsky, Miyakoda, and others at GFDL thus provided a major impetus to getting the Centre operational. Their practical help and generosity in providing their model in 1975 was of great importance to the Centre in its planning, software design, and scientific development.

The reasons for GFDL's institutional generosity became evident in the succeeding weeks. Dr Frederick G. Shuman had been Director of the National Meteorological Center (NMC), Washington, since 1963. He had had the difficult task of keeping an operational NWP system running, producing forecasts on schedule every day whilst introducing necessary improvements. His was not primarily a research institute. Burridge noted that Schuman's job was to say the least a challenge, since "it took a mixture of science and art to run an operational NWP system at that time".

Since the late 1960s Smagorinsky had been trying to persuade Schuman that NMC should follow up Miyakoda's forecast results by initiating a vigorous programme in medium-range forecasting. Smagorinsky had failed in this effort. Perhaps this was partly because of Shuman's conservatism and lack of will to introduce methods not originating at NMC, possibly based on a desire to avoid the difficulties inherent in introducing new software into operations. Another factor may have been institutional rivalry. However, Hollingsworth suspected that most of the problems were because of the sometimes abrasive relationship between these two formidable personalities. After failing for eight years to persuade NMC to get involved in medium-range forecasting, by 1975 Smagorinsky was eager to help the infant European institute, which was led by respected friends and which was charged with the operational implementation of one of GFDL's most important initiatives.

Hollingsworth returned to the Centre towards the end of July with copies of the model software and with initial data sets. At the same time Sadourny returned from the UCLA, where Mintz had provided him with copies of their model code.

Sadourny, who had expertise in designing finite difference schemes for atmospheric models, co-operated with Burridge in developing the Centre's barotropic model. In fact, Sadourny's finite difference scheme was used in the operational model until the spectral model came into use some years later. For personal reasons — getting married! — Sadourny returned to France after only six months. He recalled the difference between his pure research work at CNRS and his work at the Centre. At the Centre, "he had felt under some pressure to produce results which were oriented to the Centre's forecasting goal", although he later recalled the "pleasant atmosphere and good working relationships" with his colleagues.

Hollingsworth got the GFDL model running on the 6600 within a few days, and completed and validated a low-resolution forecast to ten days by mid-August. By mid-September he had adapted the cunningly-contrived GFDL I/O scheme to enable him to make a forecast with a higher-resolution model on the CDC 6600, which had only about 24K memory. At the first Council session on Tuesday 4 November 1975, Wiin-Nielsen was able to report that "the scientific staff by working very hard in the last weeks have on Friday night last finished the first experimental forecast to 10 days. The forecast was made from real data from 1965." The model had a grid of 4° in latitude and longitude. Even with this large grid size it took more than four hours computer time for a one-day forecast. Graphical output was produced as "zebra-charts" plotted on line-printer paper, which Bengtsson and Hollingsworth enjoyed highlighting with coloured pens.

In parallel with this work, David Dent got the GFDL model running on the IBM 360/195 computer at the Met Office in Bracknell. The resulting verification, and comparison with the UCLA model was the subject of the Centre's first internal scientific publication, ECMWF Technical Report 1.

In 1976 and 1977 David Burridge, Jan Haseler and Rex Gibson wrote the adiabatic code for the ECMWF grid-point model, which a consortium of European countries was still using 25 years later as the basis of the High-Resolution Limited Area Model (HIRLAM). The software design of this model benefited a great deal from the detailed study of GFDL's software design.

We have mentioned in Chapter 1 the heated discussions with Wiin-Nielsen on Bengtsson's decision, which some thought to be a high-risk gamble, to use the semi-implicit scheme for the forecast model. At that time use of such a scheme, which correctly conserved important statistical properties of the atmosphere, such as energy, had been restricted to models for limited areas. However Burridge had worked on this sort of scheme in the Met Office. Bengtsson recruited Dr Ian Rutherford, a research scientist at the "Division de Recherche en Prévision Numérique" (RPN) in Montreal, who served as Head of the Data Assimilation Section. Andrew Lorenc, recruited from the Met Office, also played a key part in the development of the data assimilation system.

In one sense, the Centre had an advantage over National Meteorological Services; its model was global. Models covering limited areas had problems at the edges or boundaries of the areas covered; these models made use of stable numerical techniques difficult.

The Centre's reputation was growing in the world meteorological community. In autumn 1977, Prof M. A. Petrossiants, the Director of the Hydrological Research Centre Moscow, accompanied by Dr V. Sadokov, visited the Centre. Wiin-Nielsen, Bengtsson and Labrousse made a return visit to Moscow in January 1978. Soon after, two visitors from Academgorodok in Siberia came to the Centre: Dr Gennadi Kontarev, who stayed from 1979 to 1980 and Dr Vassily Lykossov, 1979 to 1981. Both were students and graduates of the renowned Prof Guri Marchuk.

During his visit, Kontarev gave several seminars on the adjoint method. He wrote a report "The adjoint equation technique applied to meteorological problems", published internally at the Centre in September 1980. The method had been developed by Prof Marchuk in 1974 to calculate the sensitivity of seasonal forecasts of Atlantic sea surface temperatures at three-month or six-month ranges to the initial sea surface temperatures in other areas of the world. We will see in Chapter 8 that the adjoint technique was to become important in development of the Centre's forecasting system.

In these years, the Centre's educational programme became well established. Distinguished invited lecturers, as well as the Centre's scientists, gave presentations to annual autumn Seminars. Meteorological and computer training courses extending over several weeks were given for the benefit of advanced students from the National Meteorological Services.

In 1978 the computer hall and office block at Shinfield Park were ready for occupation, while work continued on the conference block. During the last days of October the staff moved from Bracknell to Shinfield Park. The CRAY-1 Serial Number 9 installed in the computer hall replaced the Centre's prototype CRAY-1 Serial Number 1, which had been installed at the Rutherford Laboratory. The CDC Cyber 175 was transferred from the Rutherford Laboratory to the new computer hall. Member State scientists began using the system immediately; Council had decided that 25% of the

Centre's computer time should be allocated for National Meteorological Service use.

There were two alternatives for the model physics. The GFDL physics code was implemented in the ECMWF model as one option. The second was the first physics package developed by the research staff at the Centre. This package in effect put together the results of 15 years of intellectual capital, based on worldwide research into modelling atmospheric physics, which to date had been relatively unexploited. Bengtsson's plan was to hope for success with the ECMWF physics package, which had many modern ideas, and to use the well-known and proven GFDL physics package as the fallback. Hollingsworth recalled Bengtsson expressing his nervousness about the development of the physics: "For God's sake Tony, don't let them put too much dynamite in the model!" — "them" being the scientists of Hollingsworth's section: Michael Tiedtke, Jean Francois Geleyn and Jean Francois Louis.

Hollingsworth led the team with the long and technically difficult job of making a set of ten-day forecasts on the Centre's first CRAY-1 at the Rutherford Laboratory. There was a slow response time, and it was difficult to get the data to and from the computer. Assessing the performance of the two sets of physics was the principal objective. The GFDL physics package used a rather simplified representation of rain, snow, convection, internal turbulence in the "free" atmosphere aloft, turbulence at and close to the surface, and the effects of radiation and its interaction with the model clouds. It had been in use at GFDL for 15 years, and so was robust and well tested, with well-known properties. In contrast the ECMWF physics package was more complex with more feedback loops; it was a state-of-the-art system, but with unknown characteristics. The model used was chosen to be close to the planned first operational model: a horizontal resolution of about 300 km, 15 levels in the vertical, an enstrophy-conserving finite difference scheme, and a semi-implicit time-stepping scheme. Good-quality global analyses from February 1976 provided by NMC Washington were used as the initial data from which the forecast experiments were run.

The main result of this work, completed in 1978/79, was something of a shock. Each of the two sets of forecasts with the Centre's numerical scheme, using ECMWF or GFDL physics, had large amplitude, and similarly distributed large systematic errors in the large-scale flow. However the differences between the GFDL and ECMWF physics packages were surprisingly small. There was no obvious way of choosing between the two with respect to forecast quality. Objective scores were no help, they were on the whole similar for both versions. Bengtsson decided to use the Centre's own physics package for the operational model. It had the best science, and the best prospect for later improvements — and as it happens the most dynamite! This work, called the "Spring Experiments", provided vital clues for later diagnostic work on orography and surface exchange processes, and set the research agenda for developments of the model physics for the next decade, leading to major model improvements in the period 1980–83.

The Centre's first model was based on a grid-point approach, in which the forecast variables are specified on a set of evenly spaced grid points. The model resolution is defined by the space between the grid points; the closer they are, the higher the resolution. For a model covering a limited area this is fine. But the Centre had a model covering the globe. As we have noted above, this has a significant advantage over the models used by the National Meteorological Services, in that it had no horizontal boundaries. These boundaries give rise to computational problems, which can quickly spread towards the centre of the model area. However, as we approach the North and South Poles, there is a different problem: the grid points get closer and closer, leading eventually to computational problems when we reach the Poles.

There is an alternative — the spectral model, which uses continuous waves to solve forecast equations; this was designed specifically for global domains. In fact, Lennart Bengtsson first met David Burridge and Adrian Simmons at a meeting on spectral models held in August 1974 in Copenhagen. Work had begun at the Centre already in 1976 on designing a spectral version of the Centre's model. In May 1976, Bengtsson noted that "great attention is being paid to semi-implicit integration schemes and also to spectral representations", and that an "experiment will replace the computation of finite difference horizontal derivatives in the GFDL model by spectral derivatives". In fact, the Centre had a spectral model formulated even before the start of operations using the grid-point model.

As the highest priority was to get operational prediction started, the grid-point model was used; it was a good model, with efficient and stable numerical techniques, and as we have seen good physics package. The horizontal grid was 1.875° in latitude and longitude, equivalent to about 200 km near the equator, and with 15 levels between the surface of the earth and the top of the model atmosphere at about 25 km.

To run the forecast operationally, software was required to manage the entire operational suite. The observational data were received on magnetic tapes delivered by car or motorbike several times a day from the Met Office in Bracknell, until high-speed telecommunications links were installed. These data had to be checked and quality-controlled on the front-end computer, and put in a database. At analysis time the data required were extracted. Then the analysis and forecast were run. The forecast fields required for the Member States and the Centre's monitoring of the data, analyses and forecasts, and for the archives, had to be extracted as the forecast was running.

Many more operations of a technical or operational nature were required in real time. Roger Newson from the UK, as head of the Meteorological Division in the Operations Department, had overall responsibility for the initial pre-processing programs, graphic software and telecommunications. The ECMWF Meteorological Operational System, or EMOS, developed in the Operations Department by Joël Martellet and his team, managed this complex operation. Martellet was able to save time by taking advantage of the fact that Météorologie National in France had the same CDC front-end processor; he based the Centre's system on the data pre-processing program suite of France. There were some lively discussions within the Operations Department on the relative merits of adaptation or re-writing the programs.

A Meteorological Operations Room was established and suitably equipped. Here the operational forecasts were monitored, rejected observations examined, and the consistency and accuracy of the daily forecast runs discussed between scientists of the Meteorological Operations Section and the Research Department staff. This careful systematic monitoring of the observational data flowing to the Centre from all over the globe was unique in meteorology, an on-going and increasing effort that would in a few years prove its worth to the world meteorological community.

Whether over-optimistic, or perhaps suffering from an attack of hubris, coming maybe from relief that progress to date had been so good, Wiin-Nielsen reported to Council in May 1979 that: "reliable forecasts can be provided to the Member States up to about one week. The forecasts are, from time to time, remarkably good up to 10 days, but this is not the general result."

The Centre's first real-time medium-range forecast was made in time for the official opening of the building at Shinfield Park on 15 June 1979. The staff then took a well-earned breather. Looking back to May 1976, Wiin-Nielsen gave the Council a detailed plan for the Centre's programme of activities, beginning with a "request for proposals for computer system", through "completion of HQ building" and "acceptance of computer", and with the date of 1 August 1979 as the date on which operational forecasting would begin, with "forecasts prepared 2–5 days per week".

Operational forecasting did in fact begin on 1 August, with forecasts to ten days ahead five days per week. The first day of August 1979 was tense. The day started smoothly with delivery of the data tapes on time. Decoding and quality control of the data, and data assimilation cycles, analyses and initialisations all proceeded to schedule. However, computer problems arose during the evening. By 02 UTC, only day one of the forecast was completed, when by this time seven days should have been produced. There was a bug in one of the programs processing the output. After some work, it was fixed. Much to the relief of the tired staff, the forecast ran straight through without further problems. Thus, the first operational forecast was completed as planned, but about four hours behind schedule. In the weeks following, the forecasts were all produced successfully, with only minor delays and problems. For Member States without telecommunications links — many of them — forecast charts were despatched by mail on the morning after the forecast had been produced!

It was clear from the successful implementation of the operational system that the Centre had talented and motivated staff, and not only in research. The computers were at the leading edge of the technology, and as Burridge later remembered were “not the easiest to get working, or to keep working reliably”.

Forecasts were made seven days per week from 1 August 1980. Initially dissemination of the forecasts to Member States was restricted to the first seven days, in view of the uncertainty of the quality of the forecasts after day seven. However it transpired that some Member States were able to enter the Centre’s system via their telecommunications links — which they were fully entitled to do — and were downloading the forecasts for days eight to ten. This was clearly unfair to the others. The forecasts to day seven were then termed “operational”, the later forecasts “experimental”, and all products were made available to all Member States.

Chapter 8

The Analysis System — from OI to 4D-Var

Previous Chapters have outlined the origins, establishment and beginning years of ECMWF. We are now starting to consider the development of the Centre's activities in discrete areas. The first paragraphs of this Chapter are general; they apply to all of the Centre's activities.

Many hundreds of man-years of the work of advanced, capable and talented scientists, and many thousands of hours of the most powerful computing resources, have been devoted to development and regular operation of one of the world's most sophisticated computer models of the dynamics, thermodynamics and composition of the fluid envelope of our planet.

At the time of writing about 70 experienced scientists work directly on the ECMWF forecasting systems. When Lennart Bengtsson became Director in January 1982, Dr Lingelbach of Germany, having noted that "it would mean bringing coals to Newcastle explaining your abilities to the audience," went on:

> *And you are not alone. You have the helping force here of men and women, I think it is no exaggeration to call it a potential unique in the world. And you also have 17 nations behind you. The Member States will ask you from time to time to be as economical as possible. However, you can be sure that all these European nations wish to see the best results possible from the institute they have founded, having in mind the tremendous economic value of medium-range weather forecasts. All the members know very well that this has its price.*

We won't try to be comprehensive. A good way to be boring is to be sure to leave nothing out. Detailed documentation on the analysis system and model is available elsewhere: on the web, and in ECMWF publications and the open literature. We'll try to give the reader an impression of the nature and extent of the research activity over the years. You will note the extent of collaboration with the scientists at Météo France. This exemplifies the benefits of the close co-operation with scientists throughout Europe. Many scientists from the ECMWF Member States and other States, including researchers from the USA, Australia and China, shared in the work. They brought their expertise to the Centre, and went home with the benefit of their experiences — and enough personal contacts to last a lifetime!

Right at the start, Bengtsson made an important decision: the Centre's research analysis and forecast models would be developed from the current version of the operational models. Each time the operational model was changed, this new model became the basis of the research model. Bits of it, for example surface effects, clouds and heating, would be examined intensively, off-line as it were, by a group of scientists. Successful research would lead to a change in the research model. Running this in parallel with the operational forecast for days or weeks tested research as it was coming to fruition. On an agreed date, the research model became the operational model, and the "old" operational model was switched off. This wasn't only practical — it was a smart move. It concentrated the minds of the researchers, as their work had a clear objective and would be considered fruitful if there was an immediate impact on ECMWF products. Fundamental groundbreaking research was going to be carried out, but this wasn't a place that would appeal to ivory tower researchers.

The observation network that evolved in the 1970s was very different to that of a decade or two earlier. With the major initiatives of the Global Atmospheric Research Program (GARP) and First GARP Global Experiment (FGGE), it was clear that the pace of change would accelerate. Much more data would come from satellites. In addition data would be sent from buoys scattered over the oceans of the world, and commercial aircraft traversing the major air routes of the world would increasingly send wind and temperature data. More importantly, all these data would be very different to those collected at regular "synoptic" hours from thermometers and other instruments on the ground or carried aloft by balloons. In the future, data from various observing systems, with an irregular distribution in space and time, and with varying and incompletely known error properties, would need to be assimilated. In the words of Aaron Fleisher to the Sixth Weather Radar Conference of 1957:

More data, more data,
Right now and not later,
Our storms are distressing,
Our problems are pressing,
We can brook no delay
For theorists to play,

Let us repair to the principle sublime,
Measure everything, everywhere, all of the time.

Bengtsson was fully aware that the highest-quality depiction of today's atmosphere, with regular distribution of "field variables" such as wind, temperature and humidity, and with good estimates of their errors, would have somehow to be produced to provide the starting point for the Centre's medium-range forecasts. And the work would have to be completed by 1979; a reliable and fully functioning analysis system had to be in operation by then.

The analysis system was of highest priority. In 1975, Bengtsson went to Paris to attend a Study Conference on Four-Dimensional Data Assimilation. There he met Andrew Lorenc, who was working on an analysis system at the UK Met Office. Outside the conference one evening, Bengtsson had a beer with Lorenc, and after a chat invited him to apply for a post at the Centre. Lorenc started at the Centre, at that time still located in Bracknell, in April 1976.

When Lorenc joined the staff, Gorm Larsen from Denmark, already at the Centre, had written a two-dimensional "Optimum Interpolation" or OI analysis scheme. A six-hour forecast "background" carried information forward from the observations received earlier. New information was contained in the many thousands of observations arriving through high-speed telecommunications lines in the last six hours. The OI system was designed to combine these; the error characteristics of both sources of information were taken into account. The analysis system would also provide the basis for the Centre's work with FGGE data, discussed further in Chapter 14. It was "multivariate", coupling the height of the pressure surfaces with the wind. The initiative for using the OI system was Bengtsson's. It turned out, in Tony Hollingsworth's words, to be "a big gamble of Lennart's that was hugely successful", but a well-founded gamble coming from Bengtsson's GARP experience. He was aware that other major analysis centres had achieved only limited success in analysing the data from tropical regions made available from the GARP Atlantic Tropical Experiment (GATE) in 1974.

We have noted that it is of the highest importance to reduce the errors in the initial analysis. Errors at the start — and no matter how hard we try, these can never be completely eliminated — will grow as the forecast proceeds. A small error in the analysis will give rise to a bigger error in the one-day forecast that, after a week, can have become large enough even to dominate the forecast.

Operational implementation of the OI approach required resolution of a number of practical issues. It was not easy to invert a matrix corresponding to a global data set. A series of local calculations requiring differing compromises on data selection, continuity between adjacent analysis volumes, multivariate relationships, and so on had been required. Lorenc, whose previous work had involved “Observing System Simulation Experiments” or OSSEs for FGGE, took on the job of thinking how the Centre could build a three-dimensional OI system, incorporating the satellite measurements of thick slices of the atmosphere that were expected to be a key component of the future global observing system. Shortly afterwards, Ian Rutherford from Canada was recruited as visiting scientist and acting Head of Data Assimilation Section. Rutherford was influential in the overall approach and in the design of the system to be used at the Centre. He was perhaps the first to apply statistical interpolation in a data assimilation cycle with a forecast background — he had published a paper on this in 1972 in the *Journal of the Atmospheric Sciences*.

Data were *analysed* on pressure levels, 850 hPa, 500 hPa etc. However, the lowest *model* level followed the terrain, and the levels above were related to the lowest level; this greatly simplified the model equations. Thus, the model levels were so-called “sigma” levels — the pressure normalised by the surface value. Transformation from analysis levels to model levels was required before and after each analysis. Rutherford advocated an “incremental” approach; only the analysis increments would be interpolated to model levels, that is, the differences between the first guess and the analysis, and not the analysed fields. The boundary-layer structure provided by the first guess would be retained. A scientist from France Olivier Talagrand did the work leading to the implementation, and the change was made to the operational system in December 1980, some time after Rutherford’s departure. We will see later that Talagrand was influential in making a major improvement to the Centre’s data assimilation scheme.

Rutherford was also influential in the terminology used by the team at the Centre. He didn’t like the term “first guess” which was generally applied to the six-hour forecast that was used as the starting point for the analysis. In Rutherford’s opinion, that implied the analysis was a “second guess.” He didn’t like “Optimum Interpolation” either; he believed that in practice it was not optimum. Hence, he would have liked the team at the Centre to use the terms “background” for “first guess”, and “Statistical Interpolation” instead of “OI”, but in fact the term “OI” stuck! Lorenc remembered Rutherford as “a great mentor and friend”. In that early stage, his experience of operational schemes was invaluable to Lorenc, and to the work at the Centre.

Lorenc wrote most of the code of the three-dimensional OI system developed at the Centre. Rutherford and Larsen used early versions of the new OI system to make analysis error variance calculations for the FGGE observing systems. Results were fed into the design of the FGGE system. Tests of the OI system in 1977 were made using Data Systems Test (DST) data collected by the National Space Administration, USA, for two two-month periods, August–September 1975 and February–March 1976. The DST data were similar in quality and coverage to the data the Centre anticipated receiving in 1979–80, at the beginning of its operations. They included satellite temperature soundings of the atmosphere, winds estimated from satellite cloud observations, and aircraft weather reports. The early tests were already able to show the large impact of satellite data on Southern Hemisphere analyses, and some beneficial effect on analyses over data-sparse oceanic areas of the Northern Hemisphere.

In the OI system, to analyse for example the wind at a single grid point, all observations containing relevant information — and this may be measurements of other "variables" such as pressure or temperature as well as wind — within a three-dimensional "radius of influence" were selected. Thus, the system was multivariate — measurements of several variable quantities were used to analyse a single variable. The "first guess" or "background value" at the grid point was interpolated to all the observation points, and a "correction" to the background value found by subtracting it from the observed value. The analysed value was found by adding the background value to the weighted average of the corrections. The analysis was made statistically "optimal" by ensuring as far as possible that the weights took into account the relationships between the wind, temperature, pressure and so on. Further, the accuracy of the different types of observations was assessed, to ensure that they were each given their proper weight.

Analyses based on OI are not completely "balanced"; the mass and wind fields are not fully consistent. Consequently, if forecasts are run directly from the analyses, adjustments of the mass, temperature and wind fields are required, and these generate large amplitude gravity wave oscillations in the first few hours of the forecast. A process called "initialization" removes these oscillations, without destroying the meteorologically significant structures. Different techniques can be used in the initialization. At the Centre, Dave Williamson, a visitor from the US National Center from Atmospheric Research, and staff member Clive Temperton implemented the so-called "Non-linear Normal Mode Initialization" or NNMI. The model's "normal modes" — mathematical idealizations that can describe the evolution of perturbations — were used to adjust the initial conditions of the model so that the unwanted high-frequency oscillations were removed from the subsequent forecast. Temperton and Williamson had the benefit of help from the visiting Danish scientist Bennart Machenhauer, the inventor of NNMI.

Work progressed well in 1978 with a nine-level version of the model. The horizontal grid spacing, or resolution, used for the analysis was 3.75°. A continuous data assimilation test was run over six days of observations from the DST set. The results compared favourably with analyses from other major centres. The following year the analysis system was improved, to analyse the data at the horizontal resolution of the model, 1.875°, and at 15 levels. The analysis system was ready in time for operational prediction to begin in mid-1979.

Another significant milestone was reached soon afterwards: production of the FGGE analyses began in December 1979 using the system; see Chapter 14.

Ensembles of grid points within "boxes" were used in the analysis system. It was found that there could be substantial gains in computational efficiency, with very small changes in the resulting forecasts, by (a) reducing the number of data selected for the analysis levels, and for the variables such as wind and temperature, and (b) reducing the area covered by the boxes.

The "incremental" approach to the analysis mentioned above was introduced late in 1980, with significant changes for the better in the modelling of global convection and in the heat transferred to the surface.

Not only the atmosphere was analysed. The earth's surface — soil moisture, soil temperature and snow cover — also influenced the forecast, and had to be analysed. A method of analysis developed by DWD, the German Weather Service, was used as the basis for this.

Much research was now under way on ensuring that the observations were as well checked as possible, and that erroneous data were identified and corrected if possible, and otherwise rejected. One particularly interesting piece of scientific detective work was finding a systematic error in data from an isolated radiosonde station: Marion Island.

Marion Island, Republic of South Africa, located in the southern Indian Ocean, 2,300 km southeast of Cape Town, is one of the most isolated places in the world. A volcanic island, it has an area of 290 km^2. The discovery of the island is accredited to the French explorer Nicolas Marion-Dufresne in 1772. Neither he, nor later, Cook in 1776, Ross in 1840, or the *Gauss* expedition of 1901 were able to land because of adverse weather conditions! South Africa established a radiosonde station there that started sending its valuable reports of the wind, temperature and humidity from above the island twice each day from January 1961. Weather reports from such an isolated region, previously a data-void for meteorology, were of course extremely valuable.

As we have seen, the Centre's data assimilation system uses a short-range forecast to give the background for the analysis. This background is modified to take into account the observational data. The daily reports from Marion Island were unremarkable, and were routinely assimilated to give the analysis. However looking at the monthly mean data during 1981, something odd was noticed: there were systematic differences averaging about 10° to 12° between the background winds and the reported winds. There were of course no nearby stations that could be compared. This was worrying. Was there a fault in the ECMWF analysis scheme or forecast model that was unrealistically and systematically backing the wind? Thorough testing showed nothing obvious that could explain the discrepancy.

A polite query was sent to the South African Meteorological Service. An investigation showed that when the software to calculate the wind direction had been installed many years earlier, magnetic north, instead of geographic north, had been assigned as the reference for wind direction! The local operators took the necessary corrective action.

An intensive joint project between scientists in the Meteorological Operations Section and those in the Research Departments in 1982 showed that other data were having a detrimental effect on the analyses. Some observing platforms were sending persistently incorrect reports, some had large random or systematic errors, and some simply did not code their data properly according to the agreed standards! In 1985, the Centre was designated by WMO as Lead Centre for monitoring global upper-air data. In mid-1985, the Centre provided WMO with the results of monitoring surface ship and radiosonde data for the three months March to May 1985, beginning a regular reporting that led to improvements in the Global Observing System of the World Weather Watch. Since then the Centre has regularly produced consolidated Reports or "suspect" lists of observations that consistently are of low quality. Action by local operators usually follows.

Earlier, in November 1979, the Council had set up a Working Group on a future observing system. The Group, chaired by Andrew Gilchrist of the UK Meteorological Office, was asked to "assess the requirements to be met by a future observing system". The group met during 1980, and considered "Observing System Experiments". These are carried out with numerical models and analysis systems to investigate a variety of issues:

- Assessing how observations affect analyses.
- Planning an observing network to give sufficiently accurate analyses — what kind of observations? — how far apart? — what accuracy is required?
- Testing alternative observing systems to determine their cost-effectiveness, thus guiding how resources should be best allocated.

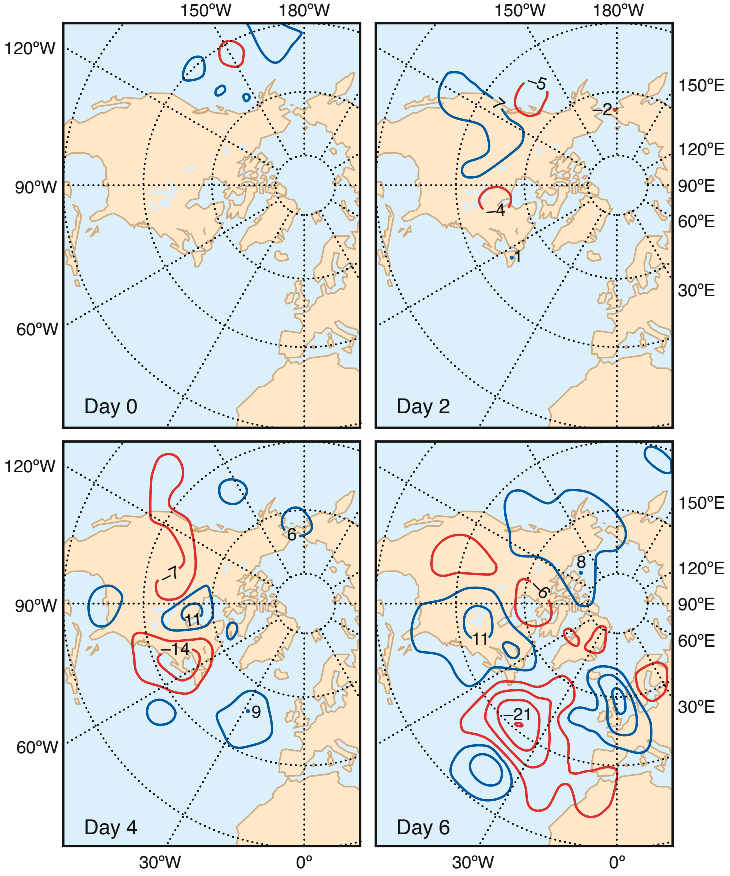
The last of these was emphasised. For the European Meteorological Services, decisions had to be made on the future observing system for the North Atlantic region as well as over Europe. Conventional systems were becoming more and more costly. New observing systems (e.g. automatic stations, buoys and satellites) would become increasingly available. The science of forecasting was advancing rapidly; it should not be hampered by deficiencies in the observations. Up to then the European Services had acted independently. It was now time for co-operative action, taking into account the commonality of interests of the services. A series of Observing System Experiments, involving scientists from four Member States, was under way by 1984.

Frédéric Delsol joined the Operations Department from Météo France at the beginning of 1982 for a four-year stint at the Centre. After studying modelling of precipitation schemes and boundary layer processes under Daniel Rousseau, he had been in charge of the avalanche-forecasting centre at Grenoble, and then had become Director of the Bordeaux regional centre. On his arrival at the Centre, he was quickly impressed by how the Centre had managed to harness the complex analysis and forecasting system to apply research ideas and results in a practical way. In Delsol's mind, he compared it to an astronomical telescope; without the telescope, astronomers' theories would have remained unproven. For the first time, the entire global observing system could be actively monitored in real time and erroneous data quickly and efficiently identified.

An interesting joint study between the Centre, the UK Met Office and NMC Washington in 1983 used identical sets of observational data to produce analyses and forecasts from the three systems. In some cases, the analyses were quite different. The differences were amplified in the forecasts. The research allowed identification of the best features of the different analysis systems, and indicated how the systems could be improved.

The study showed that what is happening to the weather in mid-Pacific today can affect the weather over Europe less than a week from now. The figure shows one case of a relatively small difference between the ECMWF analysis and that of NMC in mid-Pacific. The difference resulted from slightly different ways of handling satellite and weather ship data. We can see that small differences in the two-day forecasts over North America grew to larger differences over east Canada and stretching into the Atlantic by day four, and by day six, gave substantial differences in the forecasts over the North Sea and Europe, extending to Italy.

A comprehensive evaluation by David Shaw, Peter Lönnberg, Tony Hollingsworth and Per Undén identified many deficiencies in the optimum interpolation statistics, data selection, and quality control applied in the analysis. In 1984–85, major changes to the assimilation system were made to correct these deficiencies. Further research addressed the question of spreading information from the observations horizontally and vertically in the analysis, and how the information in one variable, for example wind, can be applied to another variable, for example pressure, in the multivariate analysis.



Differences between two forecasts made with the ECMWF model. One forecast was made starting with the ECMWF analysis, the other starting with the analysis made by NMC Washington. "Day 0" shows the difference between the analyses. The differences increase as they move from west to east in the wind flow, from the Pacific over North America and on towards Europe. By Day 6, there are significant differences between the forecasts over the European area. Level: 300 hPa, contour interval 1 decametre, starting from 00 UTC on 18 February 1979. See Hollingsworth et al. (1985) The response of numerical weather prediction systems to FGGE level IIb data. Part I. Analyses. Quart J Roy Meteor Soc 111: 1–66.

The suite of analysis programmes, more then 90,000 lines of code, was rewritten in 1985–86 to give a new, more efficient and more flexible analysis system. We have seen above that interpolation was required from the pressure levels of the analysis to the models "sigma" levels. While the "incremental" approach to this interpolation had improved the situation, the new system eliminated this pressure-to-sigma interpolation entirely. Data were now interpolated directly using a new three-dimensional multivariate analysis scheme at the levels at which the measurement was taken, without having to interpolate to "standard" levels. The entire troposphere was now analysed at once, no longer divided into "slabs" of atmosphere. Humidity analysis was significantly improved.

Throughout the years, the real or effective horizontal resolution of the analysis was significantly below that of the forecast model. In fact, weather systems with length scales below about 500 km could not be properly analysed. The resolution of the analysis was strongly controlled by the horizontal forecast error correlations; work began leading to an improvement in the resolution to about 300 km by July 1988.

After a period of steady improvement in the forecasts, Burridge recalled how from the mid-1980s the scores levelled out. It seemed that a plateau had been reached in the Centre's forecast accuracy. Even some on the Scientific Advisory Committee believed that the Centre had reached its limit; one said that it had in a sense "used up its intellectual capital" by that time. Burridge had the growing feeling that in fact the Centre's Optimum Interpolation data assimilation system had been pushed to its limits. The many different kinds of data coming from the satellite instruments were just not being used optimally. Something needed to be done here, but it was not yet clear just what.

We will see in the next Chapter how collaborative work between the Centre and Météo France, starting in 1987 with the development of an "in-core" model, led to development of what was to become known in 1992 as the "Integrated Forecast System" or IFS. Philippe Courtier, seconded to ECMWF from Météo France in Toulouse, had been investigating both "variational data assimilation" — a new technique, that was to become a key part of the Centre's system — and the potential for a "stretched" computational grid, which would allow enhanced resolution of the spectral model in places of particular interest. The former was of direct interest to both the Centre and Météo France, the latter appealed to Jean-François Geleyn for use in a model for Météo France. Toulouse was running a global model as well as a model covering a limited area. A model with variable resolution, one with an "elastic" or "stretched" grid allowing lower resolution for example over the Pacific, and higher resolution over France, could replace both of these.

In variational data assimilation one begins, as in OI, with the differences between the analysed values on the one hand, and the observed and background values on the other. Determining the adjustments to the background forecast that will minimize the sum of the weighted measures of these differences gives the analysis. The weights applied depend on estimates of the typical errors of the observations and background forecasts. They take dynamical imbalances, for example between wind and pressure fields, into account. In three-dimensional variational (3D-Var) assimilation, the differences from the observed values are somewhat artificially assumed to be valid at specific analysis times (usually the "synoptic hours" of 00, 06, 12 or 18UTC). In four-dimensional (4D-Var) assimilation, the differences are processed at the time of each observation. The minimization therefore involves repeated model runs for the period over which observations are being assimilated, typically six or twelve hours. This clearly requires very large computing resources.

Development of 4D-Var was seen at the outset as especially promising because of its optimal use of the so-called "asynoptic" data measured continuously by satellite, and because variational assimilation in general opened the door to the direct use of radiance data from satellites that we will consider in Chapter 13.

Where did the concept of variational assimilation originate? We saw in Chapter 7 that in 1980 a scientist visiting from Russia, Dr Kontarev, gave several seminars on the adjoint method that had been developed by Prof Marchuk in 1974. This method allows computation of the sensitivity of any output parameter to any input parameter for any dynamical system at a reasonable cost. Olivier Talagrand, who as we have seen developed the incremental approach to OI, followed the lectures. He returned to his institute in Paris, the Laboratoire de Météorologie Dynamique (LMD), and started working on the adjoint method in collaboration with a mathematician Xavier Le Dimet. Initial experiments with a shallow-water model were unsuccessful; gravity waves generated too much noise. However he proposed further research to his students. One of them, Philippe Courtier, newly-arrived at LMD from Météo France, started to work with a filtered model, that is one that filtered out the unwanted effects of the gravity waves. By 1985, Courtier and Talagrand had obtained results showing that they had tamed the gravity-wave noise. Now the possibility was opened to apply the variational technique to an operational NWP system.

Talagrand returned to the Centre in early 1987. With Courtier, now a staff member on secondment from Météo France, he started a feasibility study on use of variational analysis in the Centre's system. Their conclusion, that it would be more efficient to re-code the entire model than to write the adjoint of an old code, was not universally welcomed. However they persisted, with encouragement from Burridge. Their pioneering work resulted eventually in an award from the Academie des Sciences.

There was much work to be done before the benefits of the investment in variational data assimilation could be reaped. In October 1988, Lennart Bengtsson noted that "major efforts are required before this technique can be developed into a practical system". This was true; 3D-Var did not become operational at ECMWF until January 1996 and almost ten years had elapsed before Florence Rabier put the finishing touches to the world's first operational 4D-Var system, implemented at the Centre in November 1997.

Throughout this long period, Burridge, first as Head of Research, then as Director, "kept the faith". He defended his research programme from those who queried the computing cost, and the overall feasibility, of 4D-Var. He was disappointed that the UK Met Office did not become involved, and share the workload. For him, this was "a very tough time". He remembered the Council as being generous in its approach; it was not overly critical when quick results were not forthcoming from the long research programme. The benefits indeed took some time to become apparent; some claimed that years of research work seemed not to be producing anything useful. Eventually however Burridge was pleased that his conviction had been vindicated; it was not until the mid-to-late 1990s that it became clear that the decisions of the late 1980s to work towards 4D-Var were justified. He noted later with satisfaction that at last "it became generally recognised that the substantial forecast improvements over the following years came largely from 4D-Var". In the next Chapter, we will see just how much forecast accuracy improved from the late 1990s.

Burridge believes that still, at the time of writing, the potential of 4D-Var has not been fully realised. He is confident that there are "one or two more days of predictability to be gained from the Centre's forecasting system". The challenge remains: to exploit fully the new data types.

The Centre was at the forefront in using these kinds of data. Operational introduction of 4D-Var has followed at other Centres. Jean-Noël Thépaut, one of the pioneers of pre-operational development of 4D-Var at the Centre, played a key role in the work leading to implementation at Météo France in June 2000, and Andrew Lorenc himself, who had returned to the UK Met Office in 1980, led work there that brought 4D-Var implementation in October 2004.

The ECMWF data assimilation system will play an important role in studies of observing system impact and observation network design, aiming at optimisation of the global observing system. The international work is coordinated through WMO, and a programme called EUMETNET Composite Observing System (EUCOS) which is run under the auspices of the Network of European Meteorological Services (EUMETNET).

Chapter 9

The Medium-Range Model

The comprehensive atmosphere-ocean-land model developed at the Centre over the years forms the basis for the Centre's data assimilation and forecasting activities. In other Chapters, we review the Centre's activities in analysis, wave modelling, seasonal prediction and ensemble forecasting. Here we will review briefly the development of the main high-resolution medium-range model.

We see in Article 2 of the Convention that *inter alia* the objectives of the Centre shall be:

- to develop dynamic models of the atmosphere with a view to preparing medium-range weather forecasts by means of numerical methods;
- to carry out scientific and technical research directed towards improving the quality of these forecasts.

A model covering the globe would be required. As we have seen, the weather in mid-Pacific today can influence the weather over Europe five or six days later. Today's weather south of the equator will influence the weather next week in the Northern Hemisphere. Besides, States in Europe have an interest in global weather: for ship-routeing, for offshore oil exploration in the southern Pacific and elsewhere, for expeditions to the Antarctic, and for many other activities.

In Chapter 7 we saw how the Centre prepared its first operational medium-range forecasts beginning in August 1979. For its time, the Centre's model of the world's atmosphere was sophisticated. It delivered five-day forecasts to the National Meteorological Services with average accuracy similar to that of the best of the two-day forecasts that had been available to them ten years earlier.

We saw that a grid-point model was used, in which the temperature, wind and humidity were predicted on a network of points, separated by about 200 km around the equator, but closer together in the east-west direction nearer the poles. The network was repeated at 15 levels between the surface, on which pressure, as well as rain- and snowfall were predicted, and the top of the model atmosphere, which was at a height of 25 km. The lower levels were separated vertically by a few hundred metres, those aloft by a couple of kilometres. Each level had 28,800 points; the model had 432,000 grid points in total.

At the beginning, the definition of cloud in the model was perhaps by today's standards somewhat primitive, but was nonetheless impressive. When the humidity at a grid point exceeded 100%, stratus clouds formed. Rain or snow would fall if the temperature was low enough or if there was enough liquid water. Convective or cumulus clouds were formed depending on the instability of the grid column and convergence of water vapour. Rain falling through the model atmosphere would evaporate in dry air.

Short-wave radiation incoming from the sun, long-wave infrared radiation from the earth to space, and multiple scattering of radiation between cloud layers, were all calculated. Absorption of heat by water vapour, ozone and carbon dioxide was taken into account as well. Computing the effects of radiation took lots of computer power, and so was done only twice each forecast day at the start.

The laws of physics tell us what moves the air around, what makes it warmer or cooler, and what makes clouds give rain or snow. The model was based on the gas law for a mixture of dry air and water vapour, the laws of conservation of mass and water, the equation for momentum and the first law of thermodynamics. Heating and cooling of the atmosphere by radiation, the turbulent transfer of heat, moisture and momentum, the thermodynamic effects of evaporation, sublimation and condensation and the formulation of rain and snow were all described.

Starting from the analysis at noon, a forecast was made of the tiny changes in wind speed and direction, temperature, and humidity at each of the 432,000 grid points for 15 minutes later at 12.15. This gave a new starting point. A new forecast was made now for 12.30, and so on until after 960 15-minute time steps the forecast to ten days was completed. For each step, seven numbers — the temperature, wind and so on — were required at two time steps at each grid point — a total of six million numbers. The fields were stored on four disks of the CRAY-1. All the data for a vertical slice of atmosphere above a line of latitude were moved from the disks to the CRAY-1 memory. The CRAY-1 would perform the calculations for this slice, return the results to disk, and then move on to the next. About 50 million calculations were made each second, and the forecast to ten days took a little less than four hours. Although the analysis cycles were run over weekends, forecasts were run only from Monday to Friday. Weekend running of the forecast began in August 1980.

Development of the model from scratch to operational implementation was an achievement that was a source of pride to Wiin-Nielsen, and indeed to all the staff of the Centre. David Burridge had been given the task of designing the numerical scheme for the model. Burridge, Jan Haseler from the UK, Zavisa Janic from Yugoslavia and others, made their first experiments, making forecasts from low-resolution "Data Systems Test" analyses, which had been compiled for FGGE. It was soon evident that the model had the benefit of a robust and stable numerical scheme. Tony Hollingsworth, Head of the Physical Aspects section, with Jean-Francois Geleyn from France, Michael Tiedtke from Germany and Jean-Francois Louis from Belgium were largely responsible for the model physics.

A research team including David Burridge, Jan Haseler, David Dent, Michael Tiedtke and Rex Gibson went to Chippewa Falls, the Cray factory, in mid-1977 on a memorable trip. In between sometimes heated discussions between Tiedtke and Gibson, who did not always find it easy to see eye-to-eye, with Burridge trying to keep the peace, Dent calmly typing away at the console, and Haseler getting some sleep under the table, the team managed to complete a one-day global "forecast" on a CRAY-1 at a speed about ten times faster than that of the CDC 6600.

By the end of the year, more predictions to ten days were being run. The scientists of the Research Department would run many thousands of numerical experiments in the years to come. Work was easier when the staff moved to Shinfield Park in late 1978, where the Centre's CRAY-1 and CDC Cyber 175 had been installed in the Computer Hall.

Broadly, the work on modelling the atmosphere numerically to give a forecast can be separated into:

- the analysis (or assimilation of the observations to give the initial fields from which the prediction starts); this is dealt with in the previous Chapter;
- the "physical aspects" of the model, such as modelling the processes that cause condensation of water to form clouds, rain, and snow; the consequent generation or absorption of heat, friction as the wind blows close to the surface and so on; and
- the "numerical aspects", including modelling the movement of parcels of air, heating of air by compression and cooling by expansion, what sort of grid is best, or even if the calculations should be made not on a grid, but instead using continuous waves in a "spectral" version of the model.

Within this broad-brush description, other essential work was required. Systems were developed to diagnose the model behaviour, and its accuracy and performance. Basic questions had to be answered. Given the power of the CRAY-1, what was best: to increase the model resolution, i.e. bring the grid points closer together, or make the physics more sophisticated? What was the best way to eliminate from the calculations those things not required for the forecast? For example, the atmosphere is suffused with gravity waves, most of which have little influence on what tomorrow's weather will be like. A numerical model will use up lots of resources modelling these unless they are somehow eliminated.

In September 1977, Michel Jarraud, then a young scientist from Météorologie Nationale, France, attended a weeklong Seminar prepared by Centre staff on Physical Processes in Models. By the end of the week, he thought that "this must be the best laboratory [for meteorology] on the planet!" Lennart Bengtsson was on the lookout for capable scientists. He visited Paris in early 1978. Jarraud, who like Frédéric Delsol had studied under Daniel Rousseau, was working on spectral techniques in the group led by Michel Rochas, a scientist who played a significant but perhaps sometimes unrecognised role over the years in propagating the advantages of spectral techniques for numerical modelling. There were not many in Europe, or indeed elsewhere, working in this area of research. The model resolution at the time in Météorologie Nationale was very low, constrained as it was by the computing power available. Although Jarraud had published nothing at that time in the open literature, Bengtsson recognised Jarraud's talent and ability, and he wanted to have the best in spectral expertise at the Centre. He opened Jarraud's eyes to the vision of the computing power planned at the Centre, and otherwise enthusiastically presented a prospect of the future in medium-range prediction. He encouraged Jarraud to apply for a post.

Jarraud remembered trying without success to find Bracknell, then the temporary site of the Centre, on his large-scale map of England; he had "no idea" where in the UK it was! He telephoned his colleague Jean-Francois Geleyn, who was already at the Centre working with Michael Tiedtke and others on physical aspects of the model. Geleyn, who was also keen for Jarraud to join the team at the Centre, picked him up at Heathrow for his interview. Jarraud joined the Centre in June 1978, and stayed until the end of 1985 as a scientist working on spectral methods in the Research Department. Although the Centre has its three "Working Languages" of English, French and German, Jarraud soon recognised the need to improve his English. It was frustrating for him not to be able to express himself fluently in what was the common language for most day-to-day communication with his colleagues. He went on to play a major role in the development of the Centre's model, together with Adrian Simmons, who brought to the Centre his experience of working on spectral modelling with Brian Hoskins at Reading University. After four years back in Paris as Director of the national forecasting division in France, Jarraud returned to the Centre in 1990 as Head of the Operations Department, and became Deputy Director in 1991.

In Chapter 1 we saw that Aksel Wiin-Nielsen became Secretary-General of WMO in 1980. Twenty-four years later, in 2004, Jarraud was appointed to the same post. In early 1994, he was approached to allow his name to be put forward as Deputy Secretary-General of WMO. He would have liked to have stayed longer at the Centre, but noted that "you cannot always choose the ideal time". The post would become vacant in January 1995. While it was "a big gamble" it would give him the opportunity to "do more for many more countries". The Centre had 18 Member States, WMO more than 190 Members. The challenge was attractive. After serving as Deputy Director of WMO from 1995, he was elected Secretary-General from 2004. Thus, two of the five Secretaries-General of this important specialised agency of the United Nations had significant ECMWF background.

On arriving at the Centre in 1978, Jarraud worked with Fons Baede; his first task was to make the spectral code work on the Centre's CRAY-1. Later he worked on the model resolution, and on comparisons between the performance of the spectral and grid-point models.

By the end of 1977, work on the spectral numerical technique had progressed: preliminary ten-day forecasts were being run with the spectral model, and compared with the operational grid-point model. "It seems to me", wrote Fons Baede of the Research Department, "that the spectral model is mathematically and numerically more elegant than the grid point model". However, he noted that the spectral model "still requires a network of grid points on the globe".

Other improvements to the numerical scheme were in hand. Clive Temperton wrote a highly efficient Fast Fourier Transform, substantially reducing the number of computations needed to make the forecast. The "semi-implicit" version of the model further reduced the computational time to 25% of that required for the explicit version, with almost identical results — a 15-minute time step, instead of a 2½-minute step of the explicit model. In early 1979, the decision was made to use the semi-implicit scheme for all forecast experiments. A limited-area version of the model was tested over a region of the Northern Hemisphere.

Improving the modelling of clouds and other physical aspects was a priority task for the Research Department. In Chapter 7 we mentioned the

1978–79 “Spring Experiments”, which tested two different versions of the model. By the end of 1978, 14 global experimental forecasts had been run to ten days to compare the physics of two models, one with the physics developed at the Centre, the other with the GFDL physics. As we saw in Chapter 7, the results showed that “the performance of the two schemes is very similar, and the calculation time is also approximately the same”. Bengtsson decided that since “the possibilities of improving the ECMWF scheme are much larger and it is very likely, when a more realistic treatment of topography and of clouds and of albedo will be introduced, the higher degree of physical realism with the scheme developed at the Centre will prove to be better”, the Centre’s scheme would be used.

Already studies of “systematic” model errors, errors that would normally be undetectable in a single forecast but were identified by diagnosing model behaviour over long periods, were actively pursued. The systematic errors of the two “Spring Experiment” models were similar.

Proper representation of mountains in the model — the orography — was clearly needed. As well as reducing errors from inadequate representation of steep slopes, the distribution of the orography as it affects the large-scale model flow somehow has to be taken into account. Aspects to be investigated included the barrier effect of mountain ranges, the low-level drag slowing the air as it flows over the rough ground and the influence of gravity waves as they propagate up from the mountain ranges to affect the flow in the stratosphere.

By 1980, the physical parametrization had been improved. Convective heating was more realistically modelled, leading to reduction in an erroneous drift of the jet stream. The model’s boundary layer — the lower level that feels the effects of the surface below — had been improved. Better exchange coefficients for heat, moisture and momentum reduced erroneous creation of intense low-pressure systems. Investigation of the creation and dissipation of kinetic and available potential energy, energy conversions and transfers of heat, moisture and momentum globally and in defined geographical areas were important for identifying model errors.

The systematic errors in the forecasts became well organised and persistent after day five, with two maxima, one over northwest Europe, the other over Alaska. Substantial research went into understanding the causes of these, and minimising them. It became evident that tropical systems were not active enough in the model. Too much energy was transferred from equatorial regions into the cyclone belt, leading to a westerly circulation more intense than the observed.

Tests in 1980 showed that model orography strongly influenced prediction of blocking weather patterns over Europe, when a depression to the south and an anticyclone to the north block the westerly flow. The Alps in particular played a significant role in development of low-pressure systems in the Mediterranean. In April 1981, a more realistic representation of orography was introduced in the model.

In the year to September 1980, the spectral version of the model was run weekly, to give 53 model integrations that could be compared with the operational grid-point forecasts. The year-long trial ensured that the seasonal variability was taken into account. Claude Girard and Michel Jarraud summarised the results in a paper "Short and medium range forecast differences between a spectral and grid point model":

- The spectral model gave better forecasts.
- The differences, although small numerically, were synoptically significant.
- The systematic errors of the two were similar.

Overall, the spectral model gave an impressive six-hour improvement in forecast performance.

Jarraud later recalled the methodological approach at the Centre, unique in the meteorological world, to careful and exhaustive testing of research results. The Centre had the talented staff and the necessary tools to do its job of improving medium-range forecasting.

In co-operation with scientists at Météo France, Jarraud and Ulrich Cubasch, who later went on to the Max Planck Institute in Germany, ran the spectral model for a single six-year "forecast" starting from 15 November 1979. The purpose was not to attempt a forecast, and not even to see how the model "climatology" would compare to that of the real atmosphere. Rather the experiment was designed to study the time variability of the model atmosphere in its most important aspects. In the event, it did pretty well; the annual cycle was a major feature, and even though the sea surface temperature was the same from year to year, the model proved its ability to simulate anomalous years.

There was a certain amount of "creative tension" at this time, leading to some heated discussions in the Research Department between the grid point and spectral teams. Jarraud remembered the friendly competition between the grid point supporters Burridge and Gibson on the one hand, and the spectral team on the other including himself and Simmons. Finally, in November 1980, "the only rational choice was made", in the words of one of the spectral modellers. It was decided in principle to develop a new operational code based on the spectral method.

The independent scientists of the Scientific Advisory Committee (SAC) expressed concerns about how the spectral model would deal with steep mountains. Testing of higher horizontal and vertical resolution began in 1981. It was this work that lead to development of the envelope orography outlined below.

On 21 April 1983, the "new operational model" was introduced, the first operational forecast of the Centre based on the spectral code. As Secretary-General of WMO, Jarraud displayed prominently in his office the charts of this first spectral forecast. More than 20 years later, he was still using the punch cards from the model as notepaper and bookmarks! It was a "T63 resolution" spectral model, that is, with "triangular truncation" at total wave number 63, meaning that it could resolve 63 waves in the atmosphere around a great circle on the globe. Thus, weather systems with wavelengths down to about 700 km were computed. Sub-grid-scale processes were computed at the grid points of what was now referred to as the "Gaussian" grid. The Gaussian grid was a latitude/longitude grid in which the spacing of the latitudes was (almost!) regular. It had a "hybrid" vertical coordinate with 16 levels and a revised time-stepping scheme.

Simmons later recalled how this was "an exciting period of really productive research" when he, an Italian scientist Stefano Tibaldi, visiting scientists Ed Lorenz from MIT and Mike Wallace from the University of Washington, Michel Jarraud and others, were running an intensive programme of experiments on many aspects of research such as predictability, model performance, and representation of orography.

By 1985, atmospheric models based on spectral techniques had taken over from their finite difference predecessors in many operational and research institutes.

The mean orography of the earth was used at the beginning. Studies showed that effects of mountain barriers were being systematically underestimated. More generally, a marked sensitivity to the orography was found in experiments. For example, formation of cyclones in the lee of the Alps was improved if the model orography was artificially raised. An "envelope orography" was developed, and used operationally from April 1983. The mean orography was raised by adding $\sqrt{2}$ times the standard deviation of the very small-scale orography as measured by satellites to the grid-square mean orography. Objective comparisons of forecasts made with and without envelope orography of important winter situations had shown that the model had been improved and systematic errors reduced.

The end of 1984 saw completion of a major programme of experiments, developing a model that would take full advantage of the multi-tasking capability of the CRAY X-MP computer. At the same time, modelling of the boundary layer, radiation and convection were all being intensively investigated. The high-resolution, now T106, model, with improved modelling of shallow convection and of radiation, including better representation of the effects of clouds and aerosols, was ready. Waves down to 400 km were modelled at this resolution. The comprehensive physical parametrization schemes included shallow and deep convection, a radiation scheme that allowed interaction with model-generated clouds, and the diurnal radiative cycle.

At last, Lennart Bengtsson was ready to propose introducing the new model as the operational model. The SAC was shown the results of experiments comparing the new model with that currently operational. The results were not very spectacular. The SAC Chairman, Fred Bushby of the UK, noted informally that "the real secret when you bring in a new scheme or model is not to make the forecasts worse! The main benefit of the new system is its potential for further development." The new T106 model became operational in May 1985.

Concerns with the envelope orography were being felt. Short-range forecast errors had increased, if only slightly. The envelope behaved differently in differing weather regimes, especially in summer. There were differences between the levels at which the weather observations were reported, and the model heights. Masao Kanamitsu, a scientist visiting from Japan, joined Jarraud and Simmons in reassessing the impact of the envelope orography at various resolutions, in preparation for implementation of a higher-resolution model in May 1985. While concluding that the envelope was, on the whole, satisfactory, it was becoming clear that a more sophisticated approach to modelling the effects of mountains was required.

In May 1986, three additional levels were introduced in the model stratosphere, giving 19 levels in total, with the top level now at 30 km.

Research by Martin Miller, Tim Palmer and others, in parallel with work in other major forecasting centres, was showing the importance of considering "gravity wave drag". Waves are generated as the air flows across large mountain ranges like the Rockies. The high-level wind was slowed by the waves breaking at high levels, thus extracting momentum from the flow. Incorporating the effect in the model in 1986 reduced the systematic overprediction of the speed of the westerlies, and improved modelling of the ultra-long waves around the Hemisphere.

Prediction of surface temperatures and other weather elements when snow was lying on the model surface was being investigated. A canopy of vegetation can mask snow on the ground. Research was under way into a scheme to describe the interaction between snow and canopy.

For the first decade or so, the development of the analysis was to a large extent independent of model development; this followed common practice at all major forecasting centres. For example, the spectral model code was separate to that of the analysis, leading to some duplication of work and the risk of inconsistency between the codes. A researcher in the analysis section, Jan van Maanen, was devoting virtually all his time to analysis-related aspects of keeping the spectral model going in operations.

We have referred elsewhere to the substantial co-operation between scientists at the Centre and those in the Member States. We will see now that a fortuitous accident of timing and personal contact led to many years of collobaration in model development between the Centre and France, with a level of co-operation almost unique in meteorology. The development of a new forecasting system began in 1987. It lead to integration in a single consistent Fortran code of the world's biggest set of forecasting models, analysis code and other numerical tools, the so-called "Integrated Forecast System" or IFS.

Development began from the advances in computer hardware. Computer memories were becoming bigger. Simmons recalled how the prospect of keeping the model in the computer's central memory, as an "in-core" model, was an attractive possibility that could soon be realised. Coding for the repeated in-out transfers and the associated problems could be avoided. A re-coding of the ECMWF model was required.

We saw in the previous Chapter that Philippe Courtier of Météo France in Toulouse had been investigating variational data assimilation. Courtier, now an ECMWF staff member, and Simmons were discussing recent research, in Courtier's case the need to code the "adjoint" of the Centre's operational model, which would be required for this kind of assimilation technique, over coffee in the Centre's restaurant. They agreed that the paths of their research were very close. They decided jointly that a new global spectral model should be coded, together with its "tangent linear" version. This was a necessary step to coding the adjoint. The model and its equations are at the core of the data assimilation algorithm in variational assimilation; the assimilation is in fact built around the model. The model code had to be integrated into the assimilation code if the Centre was to be able to use the promising very powerful technique of variational assimilation.

Discussions between Simmons, Courtier and Geleyn referred to in the previous Chapter evolved naturally into an informal and fruitful collaboration. Formally, there was no "management" agreement or decision, either on the part of Lennart Bengtsson or of the management of Météo France. The collaboration evolved naturally over the years, with communication scientist-to-scientist, programmer-to-programmer, group-to-group. It was a stunningly successful example of co-operation between scientists of many nationalities and backgrounds, male and female, some experienced, some recent graduates, working (most of the time!) in harmony to improve the two different but complementary systems. The exchange of scientists between France and the Centre was a key factor.

In the following years, Météo France in Toulouse developed its “Action de Recherche Petite Echelle Grande Echelle” or ARPEGE system in parallel with the Centre’s development of the IFS. In the literature, the terms IFS/ARPEGE or ARPEGE/IFS are used. Scientists at the Centre in Reading and those in Toulouse developed and maintained in common a single major code. Both the scientific and technical aspects needed for research experiments and operational forecasts were kept consistent. Mats Hamrud had with Courtier written the first lines of the IFS code. The new system integrated most of the applications, from analysis to initialisation to modelling, into this single code. At the time of writing, Hamrud continued to manage the truly vast code of the entire IFS system; both Simmons and Miller remarked on his invaluable knowledge and expertise.

Model development began quickly in Paris until 1991, thereafter in Toulouse, and at the Centre. The Centre adapted its existing model physics; Toulouse developed a new physics package. The first operational ARPEGE model was operating in Toulouse by September 1992, two years ahead of the Centre’s operational IFS. The stretched grid became operational in Toulouse in October 1995. The code was robust; it survived several changes of computer systems in Toulouse and Reading.

Soon after his arrival back at the Centre in 1990 as Head of the Operations Department, Michel Jarraud noted that there was a need for more systematic, perhaps even formal, interaction between the scientists working in the Research Department and those in the Meteorological Division of the Operations Department, to communicate better the monitoring results from the Meteorological Operations Room.

He instituted regular so-called “OD/RD meetings”, held four times a year, at which useful scientific and technical information was exchanged and actions followed up. Meteorological Operations staff presented results of operational monitoring of data and verification scores of the forecasts, and research staff presented their diagnoses of the assimilation and model. Questions and issues arising from these presentations were then aired. The meetings were restricted to Centre staff, allowing opinions to be freely expressed and discussed. Some “Special Topics” were included, for example performance of tropical cyclone predictions, or the behaviour on the model in polar regions. Over the years these meetings proved themselves to be surprisingly useful. Major issues were identified and addressed, some not even having been recognised by the scientist whose presentation had raised the issues!

September 1991 saw the next major change in model resolution at the Centre. Following a programme of research that had stretched over five years, a T213L31 model, able to define 213 waves around the globe, and with 31 levels, was introduced.

This new higher-resolution system depended crucially on a major improvement to the numerical scheme of the model: the "semi-Lagrangian" scheme. With this, the time step can be made relatively long, without falling foul of the mathematical criterion leading to computational instability: the numerical collapse of the forecast. Hal Ritchie, a visiting scientist from the Meteorological Research Branch of Environment Canada worked on this scheme. Ritchie, with Mariano Hortal, Clive Temperton and Adrian Simmons, implemented a significant new dynamical core for the model, providing the basis for model development in the future. Tests on the original version of the new model showed that a three-minute time-step was required; increasing this to four minutes led to computational instability. Use of the "semi-Lagrangian" scheme allowed a 20-minute step, which together with the reduced Gaussian grid enabled completion of a ten-day forecast in four hours rather than 24!

At this resolution, waves in the atmosphere with a wavelength of 190 km and above could be followed. There were now 4,154,868 points in the model at which wind, temperature and humidity were predicted, almost ten times as many as in the 1979 model. The grid became a "reduced" Gaussian grid. The number of grid points along a latitude circle decreased towards the poles, so the grid point spacing was about 60 km on the whole globe. In addition:

- Three surface and sub-surface levels took into account vegetation cover, gravitational drainage, capillarity exchange, surface and subsurface runoff, deep-layer soil temperature and moisture.
- High, medium, low and convective clouds were all modelled, as were stratiform and convective precipitation.
- Carbon dioxide was fixed at 345 parts per million by volume.
- Aerosols, ozone, solar angle, diffusion, ground & sea roughness, ground and sea-surface temperature, ground humidity, snow-fall, snow-cover & snow melt, radiation (incoming short-wave and out-going long-wave), friction (at surface and in free atmosphere), gravity wave drag, evaporation, sensible and latent heat flux were all included.

In 1992, model low-level cloud was changed to reduce errors in prediction of near-surface temperatures near the Baltic and North Sea coasts, and reduce over-prediction of low-level clouds over the Mediterranean in summer, and over snowfields in winter.

Improvements to the cloud and radiation parametrization were made in 1993. Experiments on soil surface, including hydrology, and very low level (boundary layer) processes lead to many improvements to the operational model in August 1993. However, further experiments on envelope orography gave an unexpected result - its continued use improved the forecasts significantly. This was despite the fact that the mismatch between model level and the height of observations over hills and mountains meant a significant loss of low-level data, there was over-prediction of convective rain and snow, and heavy rain related to orographic lifting was incorrectly widened and intensified. It appeared that the benefits of envelope orography could still be realised by further work on planetary boundary layer.

The benefits of gravity wave drag in the model were confirmed by the same set of experiments. Advantage was taken of field experiments over the Pyrenees to compare the model drag with that in the real world. The model was found to underestimate the mountain torque; flow separation in the lee of the Pyrenees had been underestimated. Development of a new representation of orography began - but the envelope orography had served the Centre well for more than 10 years, even though most of the staff of the Research Department had never been completely comfortable with its use in the model.

In March 1994, after the major rewrite of the forecast model, the Integrated Forecast System became the operational system. The research team, in collaboration with the GMD National Research Center for Information Technology in Bonn and Météo France, also developed a portable version of the IFS code to be used as a “benchmark” code for testing and comparing parallel distributed-memory or Massively Parallel Processing computers.

In April 1995 the envelope orography was — at last — replaced by a smoothed mean orography together with a scheme to parameterise the effects of sub-grid-scale orography. Model mountains were now correctly blocking low-level wind flow, and drag on the wind due to flow separation caused by this sub-grid-scale orography was better modelled - these were novel features. In addition, a new and unique scheme developed by Michael Tiedtke to model the main processes associated with clouds consistently was introduced into the model. Both cloud fraction, and the ice and water content of clouds, were being predicted as model variables.

In the years following, research continued at an accelerating rate on improving the numerical and physical aspects of the model, including much more efficient use of the two-time-level version of the semi-Lagrangian scheme. In September 1996, the operational suite was implemented on the new Fujitsu VPP700.

Research started in the mid-1990s to improve the stratospheric resolution and to raise the top level of the model. The higher levels were needed to assimilate new kinds of data collected by satellite from the mesosphere, 50 to 80 km above the surface, well above the existing model top of about 30 km. Agathe Untch, newly-arrived at the Centre, quickly found herself fully occupied with the task.

In April 1998, the model resolution was increased from T213 to T319 on a linear grid; now waves down to 125 km were predicted. By March 1999, Untch had succeeded in the difficult task of raising the model ceiling; according to Hortal, this was "a remarkable achievement". There were now 50 levels, with the highest close to 65 km. Stratospheric ozone data could now be assimilated and modelled, and - another triumph for 4D-Var - wind information could now be gleaned from the ozone measurements in the stratosphere.

In October 1999, ten more levels were added close to the ground. The grid-point total had now reached 8,300,760, with in addition 553,384 in surface and sub-surface layers.

In June 2000, a new scheme for parameterizing surface fluxes and processes was implemented. A grid-box was separated into fractions, called "tiles", with six over land: bare soil or ground, high or low vegetation, high vegetation with snow under, snow on low vegetation, and two over oceans, one for water, the other for ice. Separate calculations were made for each tile.

November 2000 saw the next major upgrade, with a T511L60 model, modelling waves with wavelength as small as 80 km. There were now 20,911,680 grid points in the upper air and 1,394,112 in surface and sub-surface layers, 39 km apart on average.

In 2002 new versions of the IFS cloud and radiation schemes were being developed to benefit data assimilation. Operational model changes in 2002 included:

- A revised short-wave radiation scheme with variable effective radius of liquid cloud water.
- Retuning of the land surface parametrization to reduce winter and spring warm biases in low-level temperatures.
- Improved physics for the wave model.
- Improved wind-gust post-processing.

A significant achievement in 2002 was the implementation of a "finite element" method of mapping the continuous variables of the atmosphere onto the set of discrete values that are needed on the model levels. Untch and Hortal managed to develop a method that reduced the errors to eight times smaller than those of other finite element schemes.

Increasingly, the details of the model formulation were being addressed. Although systematic model biases had been much reduced, those that remained were especially important for forecasting beyond the medium range. Seasonal forecasts in 2003 were predicting too much rain over sub-Saharan Africa. The sub-tropical North Atlantic had low-level wind errors of about 5 m/s. These biases were building up in the first ten days; suspicions were arising that the development of extra-tropical depressions was being affected. Model aerosol concentrations were improved. Reduced aerosols in the Sahara region reduced the rainfall there by improving the radiative heating budget. The resulting knock-on reduction in release of latent heat improved the winds over the sub-tropical North Atlantic.

In early 2005, Deborah Salmond, together with Hortal, made an experimental one-day forecast with a 10 km resolution — T2047 — version of the Centre's spectral model. The "forecast" — needing over $2x10^{15}$, or 2,000 billion billion, floating point operations — took about one hour to run, using 768 processors on the IBM P690+ computer. While impossible to implement operationally with today's computers, the experiment demonstrated that the spectral technique could still be used successfully at very high resolution.

Looking back over the 25 years or so of operational activities, the Centre has had four significant horizontal resolution changes with a similar number of changes in the vertical resolution. Each change to higher resolution has been based on realistic expectations of improved accuracy in

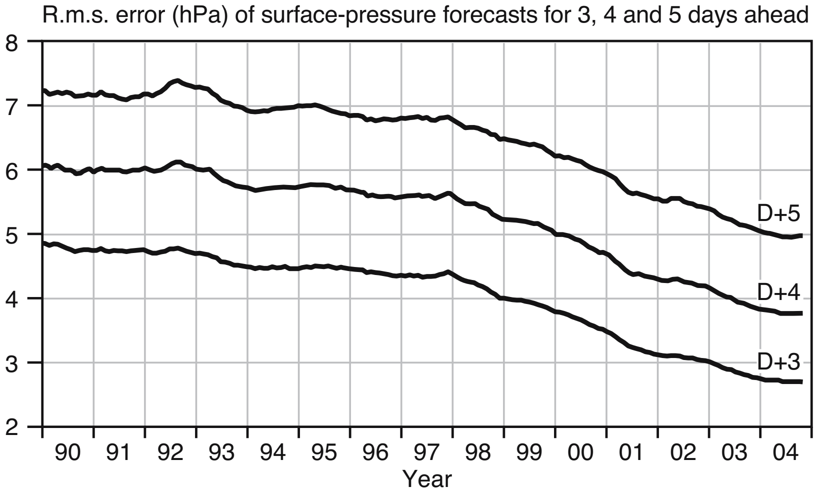
- the representation of basic model components such as orography and land/sea definition,
- synoptic and sub-synoptic systems,
- weather features and parameters such as fronts, cloud and rain bands, jets, and
- assimilating observations both space-based and surface-based.

These refinements in resolution have brought systematic improvements to the ocean wave forecasts, especially near coastlines and in the confined waters typical of the European region, which particularly benefit from the more accurate surface winds. Each change has also contributed significantly to the long-term positive trends in objective forecast skill measures. Precipitation forecasts and tropical cyclone tracking improved as well.

Operational forecasts have improved a lot since the late 1990s. Forecasts of severe weather including tropical cyclones, the more general forecasts of weather elements such as near-surface temperature, cloud and precipitation, and prediction of ocean waves, have all improved.

In 2005, Simmons investigated the quality of the three– to five-day forecasts from 1990 onwards. He showed that there was a general trend towards lower forecast errors; see the figure. Encouragingly, improvement since 1997 was shown to have been rather faster for ECMWF than for other major global forecast centres. In comparison with the best of the others, the Centre's forecasts were at least twelve hours better in the Northern Hemisphere and close to one day better in the Southern Hemisphere.

Determining just which part of the system has given the biggest improvements in the forecasts raises complex issues. Evidence indicates that improvements have stemmed from improved data assimilation — which itself benefits from a better model — the availability of new or improved types of observation, refinements in modelling the physical processes, and from resolution increases across the entire forecast system. Higher resolution gave a distinct recent improvement in handling smaller scales of motion.



Decreasing errors show that forecasts are getting better. The scores show that the five-day forecasts (D+5) made in 2004 were as good as the four-day forecasts (D+4) of 2000, and the three-day forecasts (D+3) made in 1990. The four-day forecasts of 2004 were as good as the three-day forecasts made in 1999. An improvement of one day in the accuracy of the medium-range prediction in a period of four or five years is a notable achievement. Score: root-mean-square error of surface pressure, both Hemispheres, tropics excluded.

The progressive refinements in the resolution of the assimilation and of the deterministic forecasts transfer their benefits to the Ensemble Prediction System (EPS). The higher quality of the initial conditions, and the fact that the EPS uses resolutions that have been previously well tested and efficiently configured, both play a role.

At the time of writing, experiments show that increasing the resolution of the 4D-Var assimilation system would give more accurate initial conditions for the forecasts. We saw that a very clear benefit accrued from the resolution changes made in November 2000. Experiments at even higher resolution confirm that there is still much to be gained from further resolution improvements.

Chapter 10

Ensemble prediction — forecasting the error

Some weather forecasts are wrong. Some always will be. Probably every weather forecaster will remember to his dying day the forecast that was his worst experience, whether he presented it on television to an audience of millions, or gave it to his future in-laws for a wedding. Perhaps both! The same is probably true for the meteorologist who works in the relative safety of research, but who has perhaps unwisely advised his golf club in anticipation of an important match day.

Why? What determines the accuracy of a forecast? Is not the accuracy of numerical forecasts steadily improving?

Errors in the forecast, starting from errors in the initial state from which the forecast is run, will increase inexorably as the forecast period lengthens. They will eventually grow until the forecast is no longer useful. We know that there are these errors. No matter how carefully the measurements are made, we do not have the initial state exactly right. Indeed, we would not wish to. The temperature of the air just above the surface of a black road in full sunshine is not useful information for a large-scale numerical model. Neither is the wind direction just in the lee of woodland. Even on the larger scale, there are known errors in the wind, temperature, humidity and other fields. Instruments are not completely accurate. Satellites typically measure averages over fairly large areas and depths of atmosphere. This is actually closer to what a global numerical model requires: a representative value for an area covering perhaps 25x25 km^2.

In addition, the forecast of a numerical model varies in accuracy from day to day and from place to place. Some weather situations are just easier to predict. Further, the predictability of the weather varies between geographical regions. Compare the difficulty of making a forecast for Iceland in winter with making one for Bahrain in summer. And in addition, the errors that are there at the beginning will grow at different rates, depending on the flow on that day and at that place.

In October 1986 the Centre's Scientific Advisory Committee (SAC) considered a "new and challenging area of research": forecast skill and predictability. It noted that "there was a general feeling that the prediction of skill, if it turns out to be possible with an acceptable degree of accuracy, would provide important additional information which could contribute further to more sophisticated applications of the forecast products".

The predictability of weather, and indeed climate, is determined by more than just the uncertainties in the initial conditions. The model formulation is only an approximation to the atmosphere. A good estimate of the impact of such uncertainties on forecast accuracy is essential if we wish to quantify the risk of bad weather. Hence, no weather or climate prediction can be considered complete without a forecast of the associated predictability.

Can one determine in advance when a forecast will be more skilful than average? Or — equally valuable information — when the forecast can be expected to be useful only for say the first two or three days? The Centre has approached the problem using "ensembles" of up to 100 forecasts from the same starting time, but with perturbations, or changes, made to both initial conditions and model formulation for each "member of the ensemble", that is, for each individual forecast. The resulting "ensemble" of forecasts can be interpreted as a probabilistic prediction of the future weather.

ensemble (ahñsah'ñbl)

n **1**: a team of musicians playing or singing together; 'a string ensemble' **2**: a cast other than the principles [syn: supporting players] **3**: the chorus of a ballet company [syn: corps de ballet] **4**: an assemblage of parts or details (as in a work of art) considered as forming a whole [syn: tout ensemble] **5**: (*Math.*) a group of systems with the same constitution but possibly in different states

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[French, from Old French, *together*, from Late Latin insimul, *at the same time*]

Determining in advance the error of a forecast turned out to be an interesting scientific challenge. It began from studies already under way examining the model's so-called "systematic" errors; these give important clues to determine how the model can be improved.

Stefano Tibaldi from Italy joined the Centre's Research Department in October 1977. After initially coding the humidity analysis and researching use of previously unused measurements in radiosonde observations, he later worked with Adrian Simmons, a visiting US scientist Mike Wallace, Klaus Arpe and Ernst Klinker, and others, documenting the systematic wind and temperature errors in the Centre's models and on research into their origins. For example, study of patterns of wind errors had suggested that some mid-latitude forecast errors originated in the tropics. However, experiments showed that errors in the tropical Pacific and Atlantic were in fact only small contributors to the errors in the mid-latitude forecasts. Instead, the errors in the jet stream over the Atlantic were traced back to the treatment of the Rocky Mountains over North America, while in contrast the Pacific jet turned out to be unaffected by the Himalayas upstream. Its errors were locally generated.

Over the years, growth of systematic errors with forecast length was reduced, although even ten years later, in 1987, the SAC noted that "their signature remained mainly the same".

In 1984, a new "Diagnostics and Predictability Section" was formed, with Tibaldi as Section Head. The study of making a "forecast of the forecast error" or perhaps better: a "forecast of the forecast skill" began, with Ulrich Cubasch from Germany and Franco Molteni from Italy as well as Tibaldi.

Lennart Bengtsson recruited Tim Palmer from the UK Met Office in February 1986. Soon after, Palmer took over leadership of the section from Tibaldi, who for personal reasons decided to return to the sunnier climes of Italy. Palmer had previously been part of the Met Office group working on extending the forecast range to a month, using ensembles of forecasts. At the time of recruitment, he had just returned from the University of Seattle, Washington, USA.

At the Centre, Palmer extended his studies of predictability. In particular, he started looking for predictors of forecast skill. The error of yesterday's 24-hour forecast, the statistical "spread" of the errors of successive forecasts, patterns of the flow — "empirical orthogonal functions" — and the error growth of the forecast itself in its earliest stages, all showed promise. A statistical scheme to predict skill based on these predictors was run in quasi-operational mode in the winter of 1987-88. The output was a prediction of the probability that the skill or error of a forecast would fall into one of five *a priori* equally likely fields. However, a *caveat* was attached to the output. While some degree of skill in the method was expected, it was recognised that a better, more dynamical, basis was required if significant progress was to be made.

Based on work in the early 1970s by C. E. Leith, Palmer and his colleagues Robert Mureau from the Netherlands and Molteni were now planning what was called at the time “Monte-Carlo” forecasting, in which a number of forecasts — an ensemble — was made. The name “Monte-Carlo” was misleading, implying randomness to the selection of the members of the ensemble. The members were in fact selected on a sound scientific basis. Hence, the name “Ensemble Prediction System” or EPS, was soon adopted. Roberto Buizza from Italy joined the team in 1991.

After making the first forecast, small changes were made to the analysis, changes that were within the range of the known errors of the analysis. Thus, the second analysis was in principle almost as accurate as the first, but it was different, and a forecast run from this would differ from the first. This would be repeated several times, so that an ensemble of different forecasts, all for the same time, would be made. Since each forecast had in principle similar accuracy, the ensemble could be examined statistically for the likelihood — or the statistical probability — of precipitation, cold or hot spells, strong winds and more.

A substantial research effort devoted to the assessment of predictability on the monthly and seasonal timescales was now starting. It was based on chaos theory, one of the major scientific developments of the twentieth century. Chaotic systems are governed by precise equations that determine their evolution, but they are characterised by behaviour that is unpredictable and seemingly random. The equations are said to be “non-linear” and are unstable to small perturbations. The EPS provided a practical tool for estimating how small differences in the analysis could affect the subsequent forecast.

Thus, Prof Ed Lorenz’s concept of chaos theory was to be applied with a practical goal. Lorenz developed his theory to study the range of predictability of the atmosphere, an inherently chaotic system. At the Centre, many numerical “butterflies’ wings” were to be flapped in the model’s atmosphere; the resulting different forecasts would be examined statistically to determine the predictability of the real atmosphere.

There were preconditions for a successful outcome. The model used should have no large systematic errors; the results would be only as good as the model. The size of the ensemble should be large; small samples would produce unreliable statistics and probabilities. Theory suggested that an ensemble of about 50 members would be required to account for the different structures possible. Very powerful computers would be required.

Starting with 24 members in initial experiments, the sizes of the ensembles had reached 32 by 1992. Since running the ECMWF operational model to ten days took about two hours, the ensemble had to be run at a lower resolution, such that an individual ten-day prediction would be completed in about two minutes. Clearly, more computer power would allow the resolution of the model, and the size of the ensemble, to be increased in the future.

The EPS approach could in principle be applied to the model as well as to the analysis; for example, the parameterisation of the small-scale properties in the model could be perturbed. Thus, to take into account the effect of uncertainties in the model formulation, each forecast can be made using slightly different model equations. Work continued over the following years, and by winter 1992–93, a real-time EPS experiment was under way.

From December 1992, the ECMWF operational medium-range numerical prediction system was made up of two elements. One was the operational forecast produced using a model with 31 levels capable of resolving atmospheric waves with a resolution down to 190 km. After almost nine years of experimentation in the field, and at first only three times a week, the other element was an EPS using a model at the lower resolution of 700 km and 19 levels. In this first system, only the analyses were changed. The uncertainties arising from model errors were not taken into account. At this time NCEP too started to produce operational EPS forecasts.

The Centre's pioneering Ensemble Prediction System started to provide a growing range of new products to help forecasters deal scientifically and quantitatively with the day-to-day variations in the predictability of the atmosphere. The EPS allows forecasters to predict the skill of the operational forecast objectively — to forecast the forecast skill.

In July 1993, participants from ten Member States attended a two-day Expert Meeting on the EPS at the Centre. They reviewed the status of the still experimental system. How large should the dispersion of the forecasts in the EPS be? Too small, and the different forecasts lie closer to each other than to the verifying analysis; too wide, and the statistics would not be useful. It was clear that the most important EPS products would be probabilities of temperatures being significantly above or below normal, the so-called "anomaly", and precipitation.

Making realistic initial perturbations turned out to be a key factor, and an interesting scientific challenge. Early attempts essentially added random noise at each grid point. This did not work. The model by and large simply dissipated the resulting perturbations into the flow. Instead, it was necessary to change or perturb the analyses in unstable regions, and to perturb them in the right way.

Information on the inherent dynamical instabilities of the flow was used. The perturbations had to be designed to represent the uncertainties of the operational analysis. The "spread" of the forecasts in an ensemble could be increased or decreased simply by increasing or decreasing the amplitude of the perturbations applied to the analysis. However, in practise it soon became clear that increasing the amplitude resulted in an increasing number of poor forecasts. A correlation was found between the skill of the forecasts and the amount that the ensemble spread, a necessary precondition for the viability of the EPS.

From May 1994, the EPS was run daily, instead of three days a week. The value of the EPS for predicting occurrences of severe weather, strong winds or heavy rain for example, as well as its use for prediction of forecast skill, was recognised by the SAC in early 1994. For example even if say only 5 to 10 forecasts in an ensemble of 50 were to predict an unusually severe storm a week from now, this would be taken as a first warning of an event to be monitored with care in later forecasts.

An evaluation of the EPS in mid-1996 showed that the system provided "non-trivial" information about the forecasts out to the limit of the Centre's operational prediction, to ten days ahead. Probabilities of temperature anomalies showed a significant degree of skill. Two problems were recognised. Although reduced, systematic model errors can never be eliminated, especially with the rather low resolution required to run a large number of forecasts. In addition, there was insufficient spread in the EPS. More powerful computing could alleviate these, allowing increased resolution and more forecast runs, i.e. a larger sample size.

A major upgrade to the EPS was introduced in December 1996: now there were 50 members instead of 32, and the resolution of the model was increased to 31 levels with the grid spacing reduced to 120 km. We note that the Centre was now running 50 forecasts each day at the resolution of the operational medium-range model five years earlier!

In late 1996, a study using a high-resolution T213 31-level EPS system showed how the system could be used to give a measure of confidence in forecasts of extreme rainfall during intense Mediterranean storms. Three cases were studied: in all three, the high-resolution prediction indicated extreme precipitation. In two cases, one over Italy and the other over Greece, the EPS suggested a high probability of such precipitation, and heavy rain did occur. In the Italian case, which occurred in November 1994, catastrophic flooding and land slides over northern Italy and southern France led to the loss of more than 60 lives. Over Greece in October 1994, heavy rainfall in the region around Athens caused the loss of 12 lives and much property damage. In the third case, the EPS gave a low probability, thus not supporting the high-resolution forecast of intense precipitation over northern Italy. This was correctly identified by the EPS as a false alarm.

The Centre's operational prediction of the severe floods over Europe in January 1995 was consistently successful. This was due in large part to the good performance of the EPS, which gave consistently high probabilities of heavy precipitation.

An investigation into the possibility of using models or analyses from other forecast systems, e.g. that of the UK Met Office, was made; however available evidence indicated that it was the analysis differences that were important, rather than model differences, in producing the required divergence in the forecasts making up the ensemble. In 1995, EPS results were being exchanged between the Centre, the UK Met Office and NMC Washington, and performances of the differing systems were being compared.

The EPS produced huge amounts of data: 50 different forecasts to ten days ahead of all weather parameters for the entire globe. How can such veritable avalanches of data, produced daily, be best presented to a potential user? First, of course, the probability distribution of any weather parameter anywhere can be determined. We have seen that probabilities of temperature anomalies and rainfall can usefully be derived. Beyond this, "clustering" and "tubing" of forecasts were investigated. "Clusters" of several forecasts in the ensemble brought together those forecasts that were on the whole similar. For example, 10 of the 50 forecasts with a predominantly northerly flow over Europe might form one cluster, 7 or 8 with mainly anticyclonic flow another and so on. For a "bench forecaster" who has to make up his mind how to present the weather for the week ahead on TV, such clusters, stressing similar forecasts in the ensemble, were useful tools.

"Tubing" of the forecasts took a different approach. It could be assumed that the ensemble mean is more likely to be the best indicator of the future weather. "Tubes" of the different forecast elements were derived, leading from the central group of forecasts to the different extremes. Thus, forecasts in the different tubes all differed in a similar way from the mean.

Both clustering and tubing were designed to facilitate an interpretation by the human forecaster of the large volume of EPS information, and complemented well the probability information.

In 1998, the EPS model was again enhanced. Uncertainties that the analysis system had detected were added to the uncertainties growing rapidly at the beginning of the forecast. Now also, the system was taking into account model uncertainties caused by known errors in the model's treatment of physical processes in the atmosphere. The scheme to do this, known as "stochastic physics", had been developed and implemented by Miller, Palmer and Buizza; it introduced a random noise into the equations. Many advantages resulted from the changes of 1996 and 1998: the ensemble mean was more skilful, the spread of the predictions was improved, and the probabilities became more reliable.

In 1998, David Richardson carried out some work at the Centre to address the question: what is the economic value of the EPS? Is it in fact worth the cost? If on being given a forecast, a user decides to take action that he would not otherwise have taken, and benefits economically from this, the forecast will have been of value to the user. Indeed before an offshore oil rig costing hundreds of millions of Euros to build can be towed from its port of manufacture to its eventual site, the operator must be able to convince his insurer that he has obtained the best weather forecast for the route and for the duration of the tow, a period of perhaps several days. A full analysis of the benefits of a forecast system requires detailed knowledge of the weather-sensitivity of the application, and the decision-making process of the user.

Richardson examined the case of a decision-maker who can choose to take action or do nothing, and the resulting cost and/or loss. For example, the cost could be to "grit the roads", and the loss would be that arising if frost occurred and the roads remained without grit. The advantage of EPS probabilities became evident; the user can select a probability threshold appropriate to his needs. Richardson showed that a six-day EPS forecast at the then level of accuracy would provide about 60% of the savings that would be gained with a perfect knowledge of the future weather.

In November 2000, with more powerful computers, the EPS was again enhanced: the resolution was now increased to 80 km. The vertical resolution had been increased to 40 levels the previous October. The pace of change was accelerating. Now each of the 50 forecasts run daily had a higher resolution than that of the main medium-range model in use at the beginning of 1998. The performance of new system was compared to that of the old. As would be expected, there was a significant gain in predictability, of about 12 hours in fact. The higher resolution EPS was generally better able to predict the intensity of severe storms, even to about six or seven days ahead. In particular, experiments showed the EPS to be better capable of predicting the intensity and the position of the severe storms that affected Europe in December 1999.

It was now evident that the EPS had reached a mature stage. Its output products were suitable for use in weather risk management. The storm in France in December 1999 caused about €10 billion damage. Weather-related damage increased in frequency during the 1990s. Demand for relevant information increased from commercial interests as well as from the public. It was increasingly recognised that a single forecast can fail to indicate the intensity, location or timing of a severe weather event. A study by Roberto Buizza in 2001 showed how the EPS could be used to update and refine *a-priori* estimates of possible losses, and to quantify the probability that a “maximum acceptable loss” will occur. The work was extended to reduce errors in predicted energy demand using EPS predictions of wind, cloud cover and temperature.

Frederico Grazzini and Francois Lalaurette developed two new tools to help condense the massive flow of information from the EPS system. The “EPS-gram” summarises the time sequence of weather at a single point. The “Extreme Forecast Index” identifies the likely occurrence of significant but rare weather events.

The increased accuracy of the EPS predictions was quantified in 2001. The skill of the three-day forecasts at the end 2001 was better than that of the two-day forecasts made at the end of 1996. The skill of the seven-day predictions was similar to that of the five-day predictions five years earlier.

Studies in early 2001 showed the benefit of having large numbers of EPS forecasts for events that are difficult to predict. In 2002, a second EPS 50-member forecast was run each day, starting from 00 UTC — the normal EPS was from 12 UTC. While this doubled the number of members of the daily ensemble, it did mean that it was made up of two different sets. The obvious alternative of running a single EPS with 100 members from the same time was explored. The 100-member system gave gains in predictability of six to 12 hours. However, the second EPS was run from data that were 12 hours later, with an immediate gain of 12 hours predictability for these 50 members. An EPS allowing users to update their decisions more than once a day as new information became available appeared best for dealing with the prediction of extreme events.

The Centre became involved through its EPS work with many partners in developing a European Flood Forecasting System (EFFS) for four to ten days in advance. The system was designed to provide daily information on potential floods for large rivers such as the rivers Rhine and Oder as well as flash floods in small basins. It was designed as a pre-warning system to water authorities that already have locally-produced forecasting systems up to perhaps three days ahead from national services. The system could also provide flood warnings for catchments that at present did not have a forecasting system — the case for some eastern European countries. The system would include detailed models for specific basins as well as a broad-scale model for entire Europe. The main objectives of the project were to:

- take advantage of currently available Medium-Range Weather Forecasts (4-10 days) to produce reliable flood warnings beyond the current flood-warning period of approximately three days,

- design a Medium-Range Flood Forecasting System for Europe that will produce flood warnings based on the Medium Range Weather Forecasts, and
- produce flood forecasts in regions where at present no flood forecasts are made based on the newly developed system.

An experiment aimed at “accelerating improvements in the accuracy of high-impact 1-14 day weather forecasts for the benefit of society and economy” started in the new years of the millennium under WMO auspices. If the number or density of observations in a region — for example over the North Atlantic — where an active weather system was expected to form can be increased, the errors in the analysis will be reduced, and the resulting forecast, in an important part of the atmosphere, will be improved. THORPEX, a loose acronym for “The Observing System Research and Predictability Experiment”, sometimes thought of as “a 21st century FGGE”, but with wider goals, is an international research programme to accelerate improvements in the accuracy of one-day to two-week high-impact weather forecasts. These improvements will lead to substantial benefits for humanity, as we respond to the weather related challenges of the 21st century.

THORPEX research topics include: global-to-regional influences on the evolution and predictability of weather systems; global observing-system design and demonstration; targeting and assimilation of observations; societal, economic, and environmental benefits of improved forecasts. THORPEX establishes an organisational framework that addresses problems in weather research and operational forecasting whose solutions will be accelerated through international collaboration among academic institutions, operational forecast centres, and users of forecast products.

The planned establishment of TIGGE (THORPEX Interactive Grand Global Ensemble) would be a major advance. TIGGE will be a vast multi-model global ensemble system, bringing together ensemble forecasts from many centres, including perhaps NCEP (USA), CMC (Canada), ECMWF, Met Office (UK), CMA (China), JMA (Japan), KMA (Korea) and BoM (Australia).

The feasibility of targeted observations had been demonstrated in the major “Fronts and Atlantic Storm Track Experiment” (FASTEX) in 1997. The Centre was a participant. The “Atlantic THORPEX Regional Campaign” (A-TReC) of October and November 2003 attempted for the first time to control a complex set of observing platforms in a real-time, adaptive manner.

During A-TReC:

- uncertain forecast events were identified,
- information on the location of sensitive areas for each case was provided, and
- mechanisms were in place to deliver extra observations from these areas at short notice.

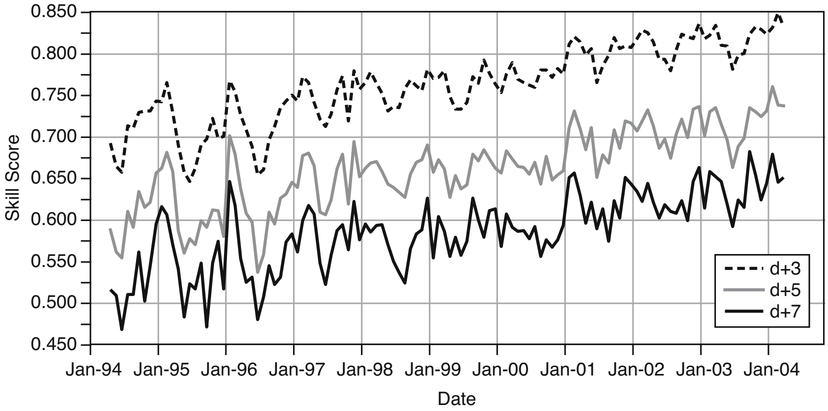
During the campaign, additional observations were triggered over the North Atlantic, Europe and northeast Canada. In total 32 cases were identified, 22 of which were targeted with additional observations.

The successful operational running of A-TReC justified further work in developing more efficient methods and techniques to control the observing system. The Centre generated data sets of the A-TReC observations, which were made available to download for research purposes from the ECMWF web site. Much more work in this area was planned for the coming years.

The figure shows the ten-year improvement in skill of the EPS system to early 2004.

What about the practical applications of all this? Weather forecasts are used in energy trading, as weather is a dominant driver in energy prices, feeding into the expected supply/demand balance. Changes in forecasts affect trader expectations: significant shifts in weather patterns between model runs often lead to increased volatility in market pricing. Opportunities are there to make, or lose, significant sums of money. “While accurate forecasts are valuable, even more important is knowledge of the uncertainty in the forecasts”, according to Dr Isla Gilmour of Merrill Lynch Commodities Europe. “Market traders use EPS forecasts to determine the accuracy and uncertainty of the forecasts. Those of the Centre have the highest reputation.” Gilmour, who worked on predictability research at NCAR after being awarded her doctorate by Oxford University, now works full-time within the commodities market. Weather forecasts are of interest to commodities traders. For example:

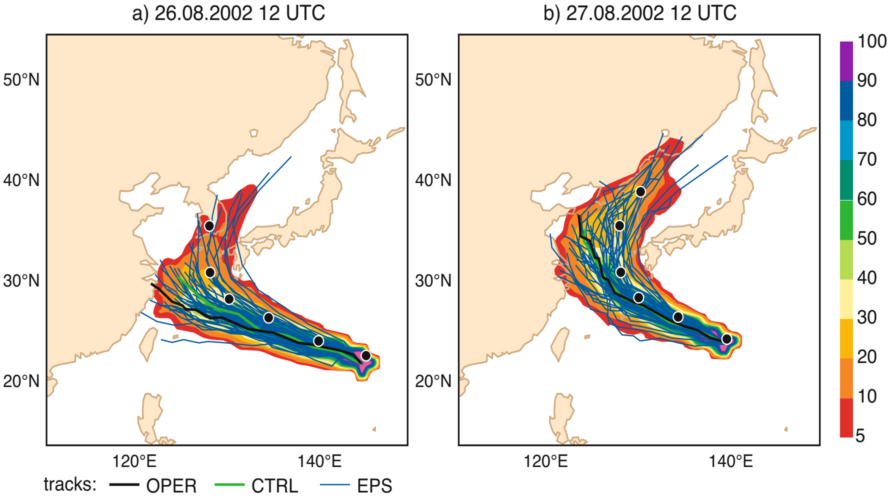
- temperature changes affect gas and electricity demand,
- precipitation affects hydro generation of electricity,
- clouds affect demand for power — late afternoon cloud over London can increase consumption by 1 Gigawatt, and
- winds are important for estimating wind power.



The skill of EPS forecasts has been increasing. The seven-day (D+7) forecasts of 2004 are as accurate as the five-day (D+5) forecasts of 2000, the D+5 forecasts of 2004 as accurate as the three-day (D+3) forecasts of 1996. Note the improvements in skill at the end of 1996, and again at the end of 2000, when improvements to the model resolution were made. Score: Ranked probability skill score, Northern Hemisphere, 500 hPa height.

The prospect of running the EPS to 14 days is of great interest. The volatility of the markets may be reduced if 14-day forecasts became available, since the ECMWF EPS forecasts have a high credibility. In some ways, the requirements are surprising: forecast consistency can be of greater importance than accuracy. Requirements vary with area; the Scandinavian market, where hydroelectricity is of high importance, is very different to that of central Europe, where temperature, precipitation and wind are all of interest.

Tracking tropical cyclones — hurricanes and typhoons — can and does provide several days warning of the likely landfall. While property losses from these destructive systems have increased substantially in the last century, as more buildings are erected in effected areas, loss of life has been almost eliminated in regions where the population can be evacuated. The EPS was upgraded in 2002 to include perturbations that would grow in the area of tropical depressions. The uncertainty in tracking hurricanes could now be estimated in advance. The figure shows the EPS probability that a cyclone will pass within a 65 nm radius from a given location at any time during the next five days, the so-called “strike probability”.



The probability based on the EPS forecasts that a tropical cyclone will pass within 65 nautical miles during the next five days starting at 12 UTC on a) 26 August 2002 and b) 27 August 2002. The blue lines show the 51 forecast tracks of the cyclone. The colour shading, see key, shows the probabilities. The operational high-resolution forecast track is black, with black circles showing the five daily positions of the centre of the cyclone. The green line is the EPS forecast made using the lower resolution of the EPS, but without any perturbations.

For severe events like this, the system is designed to minimise the number of "forecast misses", at the expense of increasing the number of false alarms. For successful use of the EPS for severe weather prediction, action has to be taken on the basis of small probabilities given well in advance; the users have to able to understand and deal with a relatively high false alarm rate.

In 2003, in recognition of his work at ECMWF, Tim Palmer was made Fellow of the Royal Society. According to the Society:

> *Palmer's research will impact everyone that makes weather sensitive decisions, for personal, economic or humanitarian reasons. By giving precise quantitative information on the day-to-day variability in the predictability of the weather or climate, quantitative cost/benefit analysis can be made of possible decision strategies. This could vary from a supermarket trying to decide how much ice cream to stock in the coming week, to authorities trying to decide whether to evacuate a region ahead of a possible hurricane strike.*

Tim is also very enthusiastic about some of the interdisciplinary research he is engaged in, working with groups trying to forecast possible malaria epidemics, river flooding, and crop failure. The humanitarian impact of a reliable weather and climate prediction system is enormous. As Tim says: 'Malaria kills millions every year. With a reliable seasonal ensemble forecast system, resources to help prevent an epidemic can be targeted on those specific regions forecast to be most at risk'

Chapter 11

Seasonal prediction

Lennart Bengtsson, at the beginning of his term as Director in 1982, decided to address a major issue: the strategy for the Centre's development in the years to come.

Bengtsson made a first, unsuccessful, attempt to persuade Council that the Centre should become involved in prediction beyond the medium-range in his "Ten-year Plan 1985-94", which he presented to Council in November 1984. This Plan had been prepared over a period of some months during spring to autumn 1984. Four eminent scientists helped to draw up the Plan: Prof Bo R. Döös from Sweden, Prof Klaus Hasselmann from the Max Planck Institute in Germany, Prof Aksel Wiin-Nielsen — the first ECMWF Director who had recently retired from his post as Secretary-General of WMO — and Dr David Johnson from NCAR in the United States.

With such experienced and eminent scientists working on it, it was — not surprisingly — a remarkable document. It foresaw *inter alia* the involvement of the Centre in "Extended-range forecasting — monthly prediction", as well as in wave prediction. The Plan stated:

> *There is a considerable body of information including observational studies, theory and forecast experiments, which suggests that the slowly-varying forcing due to anomalies of, for example, sea-surface temperature, sea ice and snow influences the atmospheric circulation on monthly time-scales.*

A strategy was envisaged:

> *to extend the forecast range [by] development of methods for extended-range forecasting based on stochastic-dynamic or similar techniques.*

The "limit of predictability" of weather is something around two weeks. This is related to the inevitable growth of errors as we move further from our starting-point — today's weather. We make our forecast knowing that we have modelled only imprecisely the forces that move the air, make water vapour condense to make rain, and so on. However, prediction on seasonal time-scales is possible if we assume that:

- the atmosphere can be affected by sea surface temperatures that change slowly, on time-scales of say a season or more,
- we can predict these changes in sea surface temperatures, and
- we can model their effects on the atmosphere.

In November 1984, the Centre had already made pilot evaluations of the usefulness of "lagged-average forecasting" for extending the range of useful forecasts as part of its programme of numerical experimentation. With this technique, a low-resolution version of a spectral model was run to more than a month ahead from nine different initial conditions separated by six hours, and the results averaged.

A beginning to long-range weather prediction can be attributed to Sir Joseph Norman Lockyer, a talented British astronomer. It was he who discovered helium in the sun's atmosphere in 1868, 27 years before that element was found on the Earth. A prolific writer, he founded the science periodical *Nature* in 1869 and edited it for more than 50 years. Lockyer was convinced that solar activity had an effect on the world's weather and climatic changes. The pages of *Nature* carried many articles concerning the influence of the sun on tropical agriculture. Much of his work from 1868 lay in obtaining weather and climatic data from across the world to be collated with his observations of the sun. He thought that the number and size of sunspots was related to the amount of rainfall on Earth. His son James published a paper jointly with Sir Norman in 1900 "On solar changes of temperature and variations of rainfall in the region surrounding the Indian Ocean". Work on the solar influence on the worlds weather systems continued to be a major theme of his research.

Serious scientifically-based efforts at seasonal prediction continued in the early 20th century with attempts to predict the onset and intensity of the Indian monsoon. At that time, the monsoon was believed to occur independently of other weather patterns such as El Niño, the recurrent warming of the Pacific Ocean, which we now know produces catastrophic and disparate effects worldwide: torrential rains, river flooding, landslides, severe droughts, and wildfires. While scientists in South America were busy documenting the local effects of El Niño, Sir Gilbert Walker was on assignment in India, studying monsoons. A British scientist, Walker, who was the head of the Indian Meteorological Service, had been asked in 1904 to try to predict the vagaries of India's monsoons after an 1899 famine caused by monsoon failure. If the rain between June and September is significantly below normal, there can be drought, crops can fail and widespread famine and starvation can follow. This was the case in 1899-1900. Walker has been credited with being the first to note that weather is a phenomenon with global-scale influences.

Walker was convinced that the monsoon changes were in some way tied to global weather. He associated some patterns of rainfall in South America with changes in ocean temperatures. A connection between pressures at stations on the eastern and western sides of the Pacific, between Tahiti in French Polynesia and Darwin, Australia was found. He noticed that pressure rises in the east were associated with falls in the west, and vice versa — he called this the "Southern Oscillation". In addition he realized that the Asian monsoons were often linked to drought in Australia, Indonesia, India, and parts of Africa. He claimed a connection between the Indian monsoons and mild winters in western Canada. Walker was convinced that all these events were part of the same phenomenon.

Walker noted that the random failure of the monsoons in India often coincided with low pressure over Tahiti, high pressure over Darwin, and relaxed trade winds over the Pacific. He was publicly criticized for suggesting that climatic conditions over such widely separated regions of the globe could be linked. His colleagues were skeptical of theories that gave a simple, single explanation for worldwide weather patterns, and in fact he was unable to translate his ideas into a scheme to predict the nature of the monsoons. However Walker did predict that whatever was causing the connection in weather patterns would become clear once wind patterns above ground level, which were not routinely being observed at that time, were included. He was right.

Walker's results fell into oblivion until Jacob Bjerknes, in 1960, started to study the causes behind El Niño. In the 1970s and 1980s, the groundwork was laid for significant advances in the science. A system of measurement of the oceans started to be established. This included tidal gauges on islands in the tropical Pacific, instruments deployed by merchant ships to measure temperatures to 500 m below the surface, and — later — satellites measuring sea level using altimeters. It became clear that the oceans could and did force the atmosphere into systematic weather patterns — and vice versa. In the late 1960s to early 1970s wind-driven "Kelvin" waves in the oceans were predicted theoretically. These are waves trapped in the equatorial belt. They have a scale north to south of 300 km or so, but an east to west wavelength of thousands of kilometres. Observations in the mid-to-late 1970s verified the theory. Numerical modelling soon advanced to the stage where these waves were being successfully modelled.

In 1982/83, the most intense El Niño in the instrument record to that time occurred — the strongest in 300 years. The resulting collapse of fishing off the shores of Ecuador and Peru, widespread flooding, disease, famine and more resulted in a combined worldwide bill estimated at US$ 20-30 billion. And this El Niño had been raging for months before it was finally and convincingly recognized as an El Niño! In 1982, the eruption of Mexico's El Chichón volcano pumped at least ten times as much ash into the stratosphere as had Mount St. Helens in 1980. The volcanic dirt in the atmosphere confused instruments on the satellites, and incorrect sea-surface temperatures were being reported. While meteorologists had their suspicions that something serious was indeed happening in the Pacific, many oceanographers were not convinced.

Oceanographers and meteorologists were determined not to be caught out again. Under the leadership of Adrian Gill, eminent scientist and author, they developed a scientific programme "Tropical Ocean–Global Atmosphere" (TOGA), implemented as part of the World Climate Research Programme of WMO. TOGA started in 1985 and was completed in 1995. This highly successful ten-year international research effort produced fundamental new knowledge of the processes that couple the tropical Pacific Ocean to the global atmosphere. It ultimately led to the successful prediction capability for the El Niño phenomenon. The programme developed and implemented a tropical Pacific Observing System to monitor the state of the tropical Pacific Ocean, providing real-time records of the evolution of El Niño events.

The centrepiece of this observing system was the Tropical Atmosphere Ocean (TAO) array, with 68 moored buoys spanning the tropical Pacific, measuring sea surface temperature, surface winds and the thermal structure of the upper ocean. TOGA also conducted an unprecedented international field campaign TOGA Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) in 1992–93 to quantify air-sea interaction processes in the tropical western Pacific Ocean.

Back now to the Centre's role in seasonal prediction. In retrospect probably unwisely, Bengtsson's strategic "Ten-year Plan 1985–94" had been prepared entirely without the involvement of Council, and was presented to Council in November 1984 in the form of a glossy full-colour 58-page brochure. While Bengtsson's intention in presenting the Plan in this way was to convince the Council of the merits of the various proposals, perhaps the impression was given that Council should adopt the Director's Plan in its entirety, or not at all. And, to be fair, the Member States represented on Council would have to provide the resources required to bring any such plan to fruition. The Council discussion on the Plan was mixed. While some delegates welcomed it, Council as a body was clearly not inclined to adopt the Plan as presented.

Bengtsson agreed to develop a document, with practical proposals, for the following Council session, with input especially from the Council's Scientific Advisory Committee. He noted that there was support for the proposed research into long-range forecasting.

The "Ten-year Plan 1985–94" evolved into the "ECMWF Long-term Strategy 1987–1996", a — shall we say — more cautious, or less ambitious document. Reading the two side by side, the Strategy makes a slightly depressing read. Council adopted it in May 1986. Reference to forecasting beyond the medium range was restricted to two somewhat repetitious sentences in Section 4 "The Programme of Research":

> *It will be necessary to carry out extended integrations to study systematic model error and as an aid in predictability research*

and:

> *Extended range integrations will be required to assess not only systematic model errors but as an aid to research into atmospheric predictability*

and one sentence under "Operational Aspects":

> *The forecasting scheme and the range of dissemination products will be enhanced to include . . . should Council so decide, forecasts in the extended range.*

Clearly the Council was not at the time in favour of the Centre becoming involved in seasonal prediction.

The definition of "medium-range" just adopted by Council: "the time scale beyond a few days in which the initial conditions are still crucially important" would appear to have allowed seasonal prediction; the initial conditions of the ocean are of crucial importance. However the "politics" of seasonal prediction highlights a continuing dichotomy. While for most Member States the ECMWF products are essential for their work, there is a continuing risk that the work of the Centre can overlap the activities of the National Meteorological Services. The Directors — and staff — of these services can understandably feel uncomfortable if they see the Centre encroaching so to speak on their territory. A division of responsibility between the Centre and its Member States needs to be maintained.

Finland voiced disappointment that the text relating to extended-range forecasting had now been removed almost totally. This was work that was clearly beyond the individual capability of the smaller Member States; it hoped that by the end of the ten-year period, the Centre would be able to provide its Member States with extended-range forecasts.

It would be fair to say that privately Bengtsson was extremely unhappy with the Council's de facto rejection of his plan for the future work of the Centre. Not only seasonal prediction but also other aspects such as wave prediction — see later — were weakened or entirely removed before the strategy document was adopted. He noted later that "this made me begin to realise the inertia of established institutions such as the National Meteorological Services, and the fragility of international organisations".

Bengtsson knew that the observation system, the computers, and most of all the science, had advanced sufficiently in the recent years. It was time for a serious scientifically-based programme to begin at the Centre.

In any event, once the possibility of long-term prediction by the Centre had been raised, Bengtsson was not going to let it go away. He was convinced of the merit of such prediction. In spite of Council's reaction to his proposal, Bengtsson informed Council that in the future "extended-range prediction would form an inherent part of the Centre's research programme". In his Four-year Programmes presented to Council after this, extended-range prediction was consistently mentioned.

Already in the early 1980s, Aksel Wiin-Nielsen and Ulrich Cubasch had made extended-range experimental model "predictions" looking at the impact of the Sea Surface Temperature (SST) on the tropical circulation. An intense El Niño in 1982–83 provided a test case for further work in 1984. Two forecasts were run to 50 days. One had the normal SST, the second the El Niño anomalous SST. For the first ten days, there was little difference between the forecasts. In the later stages, after 15 days or so, the second forecast was measurably better. Thus use of the correct SST had correctly modified the forecast. However compared to other models, for example that being run at the UK Met Office by Tim Palmer and his colleagues, this early ECMWF effort was relatively — even "spectacularly!" — unsuccessful.

As we saw in Chapter 10, Bengtsson recruited Palmer from the Met Office; he had a strong research interest in extending forecasts to the seasonal scale. Later, Palmer and his colleague Cedo Brankovic did much work quantifying the impact of the ocean on atmospheric seasonal predictability using an improved version of the model.

Work done elsewhere was now showing the advantage of coupling the atmospheric model to a model of the world's oceans. For example, in 1986/87 a coupled model had predicted an "El Niño Southern Oscillation" (ENSO) — a climate oscillation with a worldwide impact. Palmer was feeling frustrated; he believed that the Centre should be in the forefront of these exciting developments. He recalled later that "the politics of the situation in the mid-1980s meant that the Centre became fully involved in seasonal forecasting with coupled general circulation models relatively late. However we caught up, and became one of the leaders in the field."

Also in the 1980s, Stefano Tibaldi and his colleagues, with an uncontroversial and straightforward extension of medium-range work, carried out a programme of 30-day integrations. The programme used some ensemble ideas. It was not until about 20 years later, in 2004, that 30-day forecasts became part of the Centre's operational work.

In 1990, the Köberstiftung in Germany awarded Lennart Bengtsson, Bert Bolin and Klaus Hasselman the prestigious Förderpreis for their work relating to short-term climatic changes. Using his and Hasselman's funds, Bengtsson hired a young, active scientist, Tim Stockdale, from Oxford University.

Bengtsson left the Centre at the end of 1990, but on becoming Director, David Burridge gave his full support to the Centre's involvement in the field. This was in spite of the opinions of some senior staff that the Centre had been successful in large part because it had focussed strongly on its main task of medium-range prediction.

Tim Stockdale, now with Burridge as Director, worked as a consultant on a joint seasonal prediction project between ECMWF, the Max-Planck-Institut für Meteorologie (MPI) in Hamburg — where Bengtsson now was — and KNMI in the Netherlands. Stockdale spent some months in Hamburg in 1992. The joint project was able to complete the development of the Hamburg Ocean Primitive Equation (HOPE) model and couple it to the ECMWF atmospheric model, thus giving the Centre its first coupled ocean-atmosphere model, albeit a model strictly for research.

In May 1992, Burridge reported to Council that ongoing research at the Centre showed that "in the tropics, interannual variations in the sea surface temperature impart a high degree of predictability to the atmospheric fields". Further "an ocean model developed at MPI over a number of years has been coupled to a T21 version of the Centre's model".

A meeting held at the Centre in December 1992 considered a "scientific assessment of the scientific prospects for monthly and seasonal forecasting". The document, prepared by Tim Palmer, by now Head of the Section, and Prof David Anderson from Oxford University, was published in the *Quarterly Journal of the Royal Meteorological Society* in 1994. Evidence presented included the theoretical basis for seasonal prediction, a review of the results of experiments of various kinds that had been carried out by groups in Europe and the USA, and the modelling needs including those for assimilation of data. A careful distinction was made between the potential for such prediction in the tropics — where it was expected that useful skill could be achieved — and areas such as Europe, where the potential for seasonal forecasts was limited. The effects of coupling between the tropical oceans and the atmosphere were greatest in the tropics. North and south of the tropics, including over the Atlantic and Europe, there are large-scale energy transformations, for example at frontal zones, which are much less affected by the tropical ocean temperatures — though even here, a strong El Niño can extend its influence.

At the request of the Council, a Workshop on seasonal forecasting chaired by Jean-Claude André of Météo France was held at the Centre in February 1994. Its aim was to prepare a feasibility study, including costing, of an experimental programme of seasonal forecasting, and to analyse the economic benefit of seasonal forecasting with the help of potential users of the forecasts. Council discussed the Report of the Workshop in June, including a proposal for a Plan of Action. There was wide support among delegates for the Centre to have an experimental programme of seasonal prediction, although the UK delegate expressed a preference for operational prediction to be done by a network of National Meteorological Services.

Meanwhile, in Australia, the Bureau of Meteorology had developed a comprehensive, robust ocean data assimilation system based on the ECMWF Optimum Interpolation system used for the atmosphere. The system had been running since 1988. In late 1994, Stockdale visited the Bureau for some months, where he installed the Centre's coupled system on the Bureau's computers. He experimented with the ocean data assimilation system. Stockdale took back to the Centre the software for this system, giving the Centre now all the necessary ingredients to carry out coupled seasonal forecasts.

In December 1994, the Council finally approved "an experimental programme of seasonal prediction with a view to improving medium-range forecasts" — exactly ten years after Bengtsson had first raised the issue. The reference to "improving medium-range forecasts" gave the assurance that the programme would lie legitimately within the ECMWF core programme. David Anderson was recruited from Oxford University in early 1995 to head the four scientists of the Seasonal Forecasting Group at the Centre.

Steady advances were made in the following years with help of funding from the EU. One of the early projects was PROVOST, a European Project on "Prediction of Climate Variations on Seasonal to Interannual Timescales", run in 1995–98, and coordinated by the Centre. This quantified potential predictability using several atmospheric General Circulation

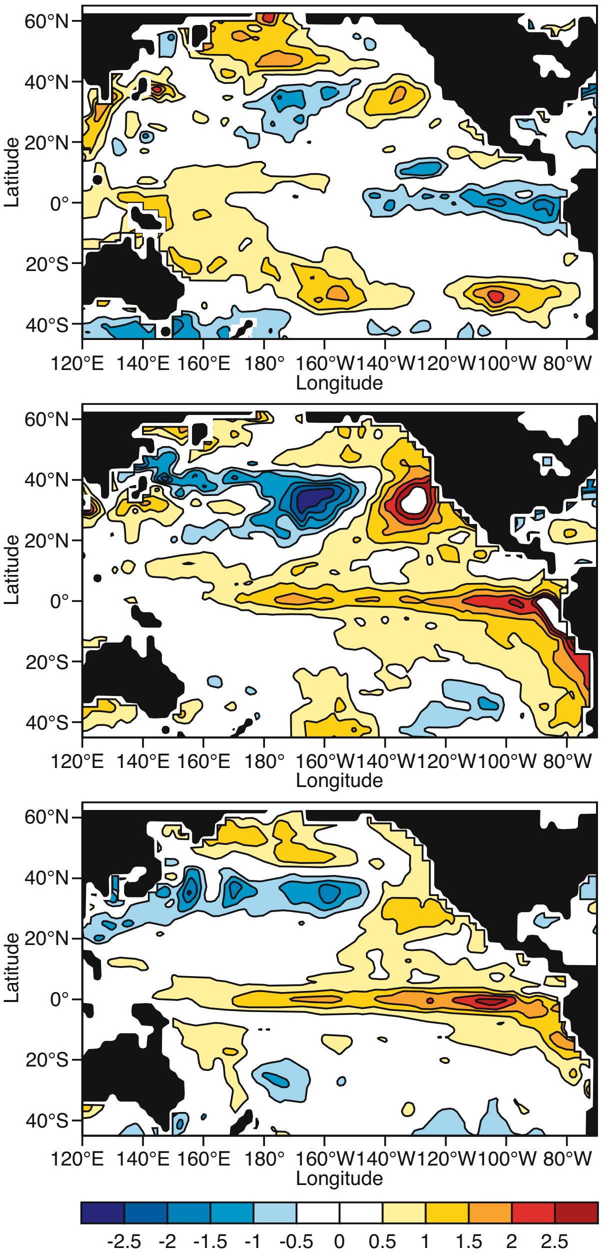
Models (GCMs) to represent the response of the atmosphere to anomalies of the Sea Surface Temperatures (SSTs). Observed SSTs were used in the experiments, not those predicted by the coupled ocean-atmosphere model developed by the Seasonal Forecasting Group at the Centre.

Research continued at a rapid pace. The coupled system was assembled using the "Ocean Atmosphere Sea Ice Soil" (OASIS) coupler from the Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, CERFACS, in France. Using the coupler facilitated modelling the exchanges of momentum, heat and freshwater fluxes — precipitation minus evaporation — between atmosphere and ocean. It is these exchanges that drive the ocean circulation. The model ocean passed the changed SSTs back to the atmosphere; thus the model was now predicting the SSTs.

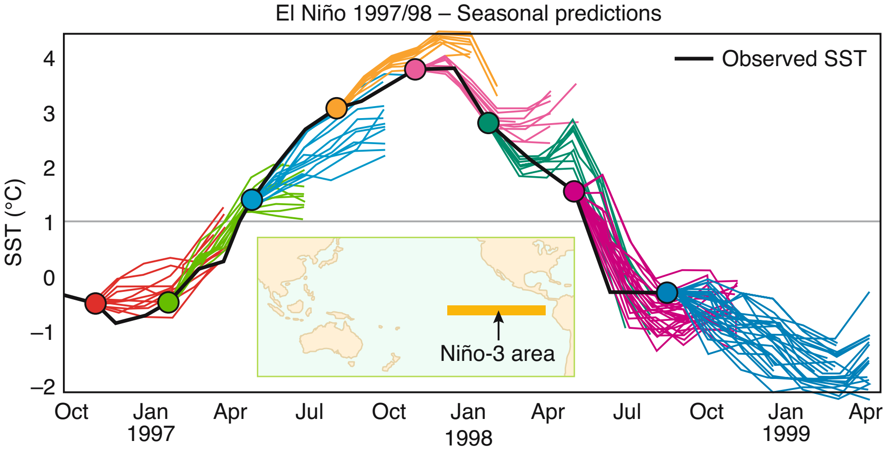
The seasonal forecasts were run to 200 days ahead three days per week, in delayed mode until early 1997, in real time thereafter. By early 1997 a significant El Niño was being predicted by the ECMWF system. The forecast was for a strong El Niño in mid-year — see the figures. The Centre's team felt nervous; other models were not showing this. In the coming weeks, observations were showing signs of significant warming of the oceans. Was this indeed the beginnings of a major El Niño? — some still had doubts.

In fact the ECMWF model was making an accurate prediction of a major El Niño — that of 1997/98. These were still clearly research forecasts. However Council for humanitarian reasons agreed to make them available to the world meteorological community through the World Wide Web. National Meteorological Services in Africa, Asia and South America were being called on to provide their best information on the likely effects of the El Niño in their countries. The Council decision was made in early December 1997. The Centre's team was proud to have been able to complete the difficult technical steps required, so that the forecast products were on the ECMWF website before Christmas.

By 1998, the team was confident that the model was now in overall good shape. It had systematic model errors, but these were generally known. The team was able to hand over the now (almost) robust seasonal prediction system to the Operations Department. The first quasi-operational experiences were good. The model gave a good prediction of significantly above-average rainfall for the 1998 winter and spring in Australia. The termination of the 1998/99 La Niña event by a rapid warming of the Pacific ocean surface was predicted better by the ECMWF system than by others.



Sea surface temperature anomalies in the Pacific. Top: Observed, December 1996, a weak cold anomaly. Middle: Observed, May 1997, a strong El Niño. Bottom: Forecast for May 1997 made in December 1996. The strong warming of the equatorial Pacific was well predicted.



The black line shows the observed evolution of the sea surface temperature anomaly in the Niño-3 area starting in October 1997. The coloured lines show the ensemble forecast to six-months ahead, starting at three-month intervals, made with the Centre's first real-time seasonal forecast system. The plot was produced by CLIVAR based on data from ECMWF.

Another Workshop on seasonal forecasting was held in early 1999. Agrometeorology, insurance, medicine and weather-derivatives financial sector were all represented, reflecting the increasing worldwide interest in (and marketing of!) seasonal forecasts. There was an increasing demand that ECMWF forecasts be made more widely available, not only for research, but for humanitarian and commercial interests as well. In June 1999, the Council agreed to continue to make a selection of the seasonal forecasts freely available on the ECMWF website, and asked its Policy Advisory Committee to look into commercialisation issues. In November 2000, the Council agreed to make these forecasts available commercially.

By early 2000, prediction of the number of hurricanes in the Atlantic and tropical cyclones in the Pacific, and forecasts of the year-to-year displacement of the cyclone genesis region in the Pacific, were showing promise. Further, work began on making predictions to a month ahead, intermediate between the medium-range and seasonal time-scales.

European interest in the scientific and technical challenge of seasonal prediction and coupled ocean-atmosphere modelling and analysis was not confined to the Centre. Such models were being developed at the UK Met Office and Météo France. Other groups involved in research in the field included those at Electricité de France, at KNMI in the Netherlands and at

CERFACS. As usual there was excellent collaboration between the research staff at the Centre and those in the national services and the institutes.

By end 2001, a European multi-model "ensemble" of seven coupled models of the EU-funded Project entitled "Development of a European Multi-model Ensemble System for Seasonal to Interannual Prediction", the DEMETER Project, was entering the production phase, with six of the models installed at the Centre. Named after Demeter, the goddess of fertility in ancient Greece, the object of the Project was to develop a well-validated European coupled multi-model ensemble forecast system for reliable seasonal to interannual prediction, including establishing its practical utility, particularly to the agriculture and health sectors. The Centre coordinated the project. Research was advancing satisfactorily, making good use of the 40-year Reanalysis data — see Chapter 14.

Another project, "Enhanced Ocean Data Assimilation and Climate Prediction" (ENACT), funded by the European Union in 2002–04, aimed to enhance European capabilities in the fields of global ocean data assimilation and analysis systems associated with climate modelling and prediction. ENACT emerged from another project for "Developing Use of Altimetry for Climate Studies" (DUACS) — the name is self-explanatory.

The possibility was developing to take advantage of the different models in DEMETER to make real-time operational forecasts, by a so-called "multi-model" approach. The Centre worked with the UK Met Office to install their coupled model on the ECMWF computer system, integrating it with the ECMWF model, with the intention to produce a common set of forecast products — rainfall, temperature and so on.

In May 2002, the Director exchanged letters with Peter Ewins, Chief Executive of the Met Office, formalising the joint research and operational activity of the Centre and the Met Office in this area. All Member States of the Centre were to have full visibility of and full rights of use of the work and its results.

Soon after, the Director exchanged letters with Jean-Pierre Beysson, Director of Météo France, by which Météo France would join in multi-model seasonal forecasting. By late 2004 all three models were running at the Centre. The data were being archived in the ECMWF MARS archival system.

In 2003 planning for two more EU projects was developing. Both were funded in 2004:

- ENSEMBLES continued the work of DEMETER to develop multi-model ensemble forecasts and to link climate forecasts to applications in agronomy, health, hydrology, energy and more. In addition, ENSEMBLES would test the skill of multi-model ensembles against other techniques for representing model uncertainty, such as stochastic physics and perturbed parameters. Unlike DEMETER, ENSEMBLES integrations would assess the decadal as well as seasonal predictability of climate. The overall aim of ENSEMBLES was to develop a unified European ensemble system for prediction of climate across a range of timescales, from seasons to decades and beyond.

- The "Marine Environment and Security for the European Area" (MERSEA) project aimed to develop a European system for operational monitoring and forecasting on global and regional scales of the ocean physics, biogeochemistry and ecosystems. The prediction timescales of interest extended from days to months. The integrated system would form the ocean component of the future Global Monitoring for Environment and Security (GMES) system.

We have seen that development of the model and data assimilation system for medium-range forecasting complemented the valuable work on short-range prediction in the Member States, with much two-way exchange of ideas, methods and research. In the same way, there was synergy from the joint efforts in seasonal prediction work at the Centre, and the work on climate and climate change, global warming and similar in institutions throughout Europe. Further, there was synergy between the research projects funded by the EU, and the Centre's requirements for useful operational seasonal prediction. Accelerating research in Europe and indeed throughout the world in these important and related areas was the consequence.

Chapter 12

Wave prediction

In February 1953 the dikes protecting the Netherlands were breached by the onslaught of hurricane-force northwesterly winds on top of exceptionally high spring tides. The Dutch Surge Warning Service, which had been established after a destructive surge in January 1916, issued forecasts of dangerously high water levels several hours before they occurred. However the floodwaters came in the night, and the warning came too late to allow evacuation by the limited emergency services. The lives of 1,835 people were lost, almost 200,000 hectares of land flooded, 3,000 homes and 300 farms destroyed, and 47,000 heads of cattle drowned; it was the Netherlands' worst disaster for 300 years. In eastern England, almost 100,000 hectares were flooded and 307 people died in this storm on that terrible night. Flooding caused by storm surges was nothing new to the Netherlands, but this time, the nation and the world were stunned by the extent of the disaster.

The tapestry hanging in the ECMWF Conference Room was a gift from the Netherlands. It shows the 500 hPa circulation on 1 February 1953. The storm over the North Sea was responsible for widespread devastation.The tapestry serves perhaps to remind delegates of the importance of timely and accurate medium-range forecasts.

Accurate prediction of ocean wave and swell is required, not only for commercial applications, such as avoiding damage to ships, cargo and crew by routeing vessels away from strong head winds and high waves, but also for the protection of lives and property on land.

In Chapter 11 "Seasonal prediction" we noted Lennart Bengtsson's far-seeing "Ten-year Plan 1985–94", which he presented to Council in November 1984, but which was not adopted. As we saw in that Chapter, the problem was not in the science, but in the presentation of a glossy brochure, without prior consultation with the Council. In Bengtsson's Plan was a two-page section on "Wave Prediction". It is worth quoting this in full.

> ***5.2.5 Wave prediction***
>
> *An important application of the Centre's medium range forecast is that associated with marine activities. Shipping, fisheries and offshore operations, for example, are all strongly dependent on weather and typically require marine weather forecasts extending to the full limit of the medium range deterministic forecasting period.*
>
> *Surface or near-surface parameters, available directly from the model or derived from model parameters, are routinely made available to the Member States, including for example, wind at the 10-metre level or temperatures at 2 metres. An integral part of marine weather, however, is the sea state, which is not included in the present operational forecast system of the Centre. Wave forecasts are needed both globally and for the medium range (for example for ship routeing) and with a spatial and temporal resolution of the same scale as is required for the prediction of the synoptic scale weather disturbances which generate the waves. The integrations of the numerical wave model such as that which has been developed at the Max Planck Institute for Meteorology at Hamburg are best carried out on the same spatial grid and with the same time step as the atmospheric model used to predict the surface winds driving the model. In practice this can be achieved effectively only by integrating the wave and atmospheric models in tandem.*
>
> *There have been significant developments in recent years in ocean wave modelling. Our understanding of the dynamics of surface waves has increased significantly as a result of a series of field programmes and experience with a sequence of first- and second-generation wave models. The European wave modelling community is currently in the process of developing a new, third-generation wave model, which may be expected to yield a further significant improvement in wave forecasting skill. However, the full potential of these advances can be realised only with*

access to powerful computing facilities and the use of a sophisticated global atmospheric model to drive the wave field.

Present wave prediction models are based on the integration of the radiative transfer equation for the two-dimensional wave spectrum. Simple empirical wave prediction tables relating wind or sea parameters such as the significant wave height and period to the wind speed, fetch and duration are still sometimes used in engineering applications; these have long been superseded in routine forecasting operations. The transfer equation describes the propagation of the different wave components of the spectrum, with different frequencies and propagation directions, at their appropriate group velocities, and the changes in the energies of the components produced by wind forcing, dissipation and higher order nonlinear wave-wave interaction. The models predict the full two-dimensional spectrum (typically several hundred components) at each time step and grid point. The number of degrees of freedom carried by a wave model is therefore normally higher than that carried by an atmospheric model. However, the physical processes are simpler to compute (after parameterization of the highly complex multi-dimensional Boltzmann integral representing the nonlinear interactions) and it is therefore estimated that the integration time needed for a third generation spectral wave model is of the order of 10% of the integration time of an atmospheric model of the same spatial resolution.[1]

The operation of a global wave model by the Centre would also be timely in view of the advent of the first European remote sensing Earth Resource Satellite ERS-1. The high rate of surface wind and wave data to be produced by ERS-1 can be effectively exploited in an operational or quasi-operational model only at a large forecasting centre such as ECMWF. However, the Centre will need to cooperate with universities, research centres and weather services in order to develop the necessary models and data assimilation techniques. An active participation in the development of good wave forecasts is also in the interest of the Centre and of the World Meteorological Community for winning the cooperation of ship operators to obtain an improved data coverage over the oceans.

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[1] Twenty years later, the integration time needed for the third generation spectral wave model running operationally at the Centre was in fact 9% of the integration time of the operational atmospheric model, which had similar spatial resolution. Klaus Hasslemann wrote this part of the text — what excellent forecasting skill was being demonstrated!

> *It is therefore proposed that the operations of the Centre be extended to include global, medium range forecasts of the two-dimensional surface wave spectrum as an additional ocean component of the global weather forecast products of the Centre.*
>
> *In addition to a global wave model, there will also be a need for limited area, high-resolution wave models for the Eastern Atlantic, North Sea, Mediterranean and Baltic, which may require input from the global wave model to provide boundary condition. These can be developed and operated by the national weather services in a similar way to that in which limited area high-resolution atmospheric models are run by the Member States.*

The Council discussion in November 1984 on Bengtsson's Plan showed that some were in favour of wave prediction: Italy "expressed great pleasure that wave prediction was included; this should be done also for the Mediterranean and the North Sea". Denmark noted that "wave prediction is of interest to the Member States engaged in ship routeing". For the UK, "testing of wave models as part of the Centre's research" could be carried out. Some were neutral: for Ireland and France, wave prediction should be considered a special application, and "wave prediction is not important for Austria, but it is not opposed". The question of resources was raised. None spoke against wave prediction being carried out at the Centre.

At its next session in May 1985, Council considered a document on the "ECMWF Long-term Strategy". This document still contained a significant section on "Operational medium-range forecasting of ocean waves". There was now some unease being expressed: Germany "was not ready to agree to operational wave forecasting, it did not believe that this corresponded to the provisions of the Convention". Council asked its Scientific and Technical Advisory Committees to examine the strategy.

In reporting to Council in November 1985, the Scientific Advisory Committee "considered that, in terms of European science and the European remote sensing programme in particular, it would be very desirable for the Centre to become involved with the data to come from Earth Resource Satellite ERS-1 and to provide a central focus for the Ocean Wave Modelling Programme". [The ERS-1 satellite, launched in July 1991, produced a large volume of surface wind and wave data, which required powerful computing resources with sophisticated software for its exploitation.] Neither Germany nor France could agree with this opinion of the Committee.

In the "ECMWF Long-term Strategy 1987–1996" adopted unanimously by Council in May 1986, the only mention of wave prediction was under "Operational Aspects": "The forecasting scheme and the range of dissemination products will be enhanced to include . . . should Council so decide, forecasts . . . of ocean waves". As with seasonal prediction, however, Bengtsson was determined that the Centre would not stand aside from developments in this important area, in spite of the less than warm reception of the proposal by Council. And at the least, the ice had been broken, and some Member States had expressed support for the Centre's involvement in prediction of ocean waves.

It is of course the wind that makes the waves — the so-called wind-driven sea. The transfer of momentum downwards from the rapidly moving air forces the formation of waves, which are the visible manifestation of this downward transfer of horizontal momentum from the air to the water. Swell is different — this is the result of distant storms. Swell from the North Atlantic beating against the west coast of Ireland may very well have been caused by hurricanes some days ago in the Caribbean.

Beginning in the late 1950s, numerical wave models were being formulated in terms of the so-called energy balance equation for the two-dimensional wave spectrum. These "first-generation" models developed through the 1960s assumed that the waves suddenly stopped growing when they reached some prescribed empirical saturation level. They greatly underestimated the effect of interactions between waves. In mathematical terms, these interactions are non-linear, and not easy to treat or to model.

Klaus Hasselmann, who was Director of the Max-Planck-Institut für Meteorologie (MPI), Hamburg from February 1975 until November 1999, had developed the theory of the general structure of the source function of the deep-water transport equation in 1960. However none of the wave models developed to the mid-1980s were able to compute the wave spectrum from first principles. Klaus Hasselmann and his wife Susanne had begun significant research at the Institute to parameterize better these non-linear interactions. They developed the theory of non-linear transfers of energy and momentum between waves in the 1960s — a theory that could be introduced into the numerical models only in the 1980s.

Through the 1970s measurements of wind effects on waves led to the development of second-generation models, which attempted to model better the wave-wave interactions. Although an improvement, the models were still unable to handle the complex seas generated for example by hurricanes or intense small cyclones — the very situations for which wave forecasts were most required. Also they had difficulty in treating the transition from the sea waves, which are locally generated, to the swell.

A study in 1984 compared the success of first- and second-generation models. Severe weaknesses were identified in the models.

Knowing that computing power would continue to increase quickly, and knowing from contacts with the European Space Agency (ESA) the nature of the global sets of observational data of wind and waves that would become available in the coming years, Klaus and Susanne Hasselmann decided to speed up the pace of research by increasing collaboration with other groups. They contacted the Royal Netherlands Meteorological Institute (KNMI).

Peter Janssen, who was later to become Head of Ocean Waves Section at the Centre, had joined KNMI in 1979 from the University of Eindhoven, where he had completed his doctorate on plasma physics. At KNMI, a simple numerical wave prediction model had already been introduced to complement the manual techniques for wave and swell prediction, based on wind forecasts, which had been developed at KNMI during the 1950s and 1960s. The second-generation model was based on sound if simple physical principles.

While there was some representation of wind, sea state and swell in the models of the time, there was full awareness that much work was required to improve the parameterisation. Janssen's work in plasma physics allowed him quickly to involve himself in wave modelling. At the beginning of October 1979, he started working on the theory of ocean waves, including the interaction of wind and waves. By 15 December 1979, Janssen had developed the theory of the two-way interaction between the wind and waves. This was far ahead of model development at the time — in fact it was not until June 1998 that the theory was satisfactorily introduced into operational wave prediction.

The establishment of the international WAM — acronym for "Wave Modelling" — Group in 1984 stimulated European research into numerical wave prediction, in particular by collaborating on the development of a third-generation model. The Group included Klaus and Susanne Hasselmann — whose work laid the foundations for the model — Gerbrand Komen, Luigi Cavaleri from Italy, and Peter Janssen. The WAM Group had grown by 1990 to include about 40 scientists, mainly but not exclusively European.

The necessary good, efficient algorithm for computing non-linear transfers, and a reliable parameterization of the dissipation of energy, had been developed. The third-generation model would predict not merely wave height at a point but the full spectrum of waves, without a separation between wind-driven sea and swell.

Bengtsson had known Klaus Hasselmann for some time, and was familiar with his work — he had in fact done some of his work at the Centre as a scientist working on a special project. Bengtsson invited a group to meet at the Centre on 12 December 1985, six months before Council would adopt the Strategy, to discuss the elements that would be required for an operational system of wave prediction. The group consisted of Klaus and Susanne Hasselmann, Janssen, Komen, Cavaleri, and Dorethea von Berg from MPI.

There was a little understandable resistance from some — but not all — senior staff in the Centre's Research Department. Some were not in favour of the Centre being diverted from its main task of medium-range prediction of the atmosphere. Bengtsson was convinced that he was making a correct and important decision, and he pressed ahead.

Following the recommendation of the group, Bengtsson decided to invite three scientists to the Centre for the two months of January and February 1986: Peter Janssen, Anne Guillaume from France and Luciana Bertotti from Italy. The work was done as a "special project" under the auspices of KNMI — actually a COST Project headed by Gerbrand Komen. Large computing resources were made available, but there were no free offices at the time — the group worked from tables in the Centre's Classroom and a small meeting room!

By the end of the two months, a working analysis and forecasting system had been set up. The wave analysis was derived from the analysed winds, and the predicted waves were generated from the forecast winds using a third-generation model. In March, the researchers returned to their home institutes; while the group as such disbanded, work continued and the team met again from time to time as part of the COST Project.

At the same time, three other research scientists working at the Centre, two from the USA, V. J. Cardone and J. A. Greenwood, and Magnar Reistad from the Norwegian Meteorological Institute, implemented a high-resolution (25 km grid spacing) model for simulation of the sea state during hurricanes in the Gulf of Mexico. The results were encouraging, in that the predicted sea state agreed well with the data observed from buoys in the Gulf.

ESA concluded a 12-month contract with the Centre to run from March 1986 to study the use of information from the ERS-1 satellite. This satellite had scatterometer instruments designed to measure the sea state all over the globe. Wind speed and direction, wave height, height of the sea by an altimeter, and sea temperature by a radiometer were all measured.

In September 1986, Janssen returned to work at the Centre under a one-year contract with ESA. During the course of the work, it became increasingly clear that the Centre would benefit from a global wave model for its work in assimilating data, and in particular in processing the data from the ERS-1 satellite. Further, for accurate near-surface wind prediction, the parameterization of the momentum transfer from the air to the ocean, which results in a slowing of the wind, required knowledge of the wave spectrum, such as was produced by the wave model.

In December 1986, a new flexible version of the model and the required pre-processing software was implemented on the ECMWF computing system, from generation of the required initial spectral fields to archiving of the output and plotting of the output forecast fields.

There were important developments elsewhere too. In 1987, a major international field experiment in the Labrador Sea was begun, to increase understanding of wind-generated ocean waves, and to assess the relative superiority of the recently developed third-generation wave models. Dutch and Canadian research ships, Canadian and American research aircraft and the American Geodetic Satellite (GEOSAT) spacecraft all took part. GEOSAT was a US Navy satellite designed to measure sea surface heights to within 5 cm.

Janssen decided that the ECMWF model should be in at least a quasi-operational state as soon as possible. At 15.00 on Saturday 7 March 1987 a button was pushed to start the Centre’s first quasi-operational global wave forecast. From then on a 24-hour analysis and a five-day forecast were run daily. Verification of the forecast quality by comparison with any available buoy data and with the measurements from the Labrador field experiment was begun. Results were promising.

After spending some months working with Piero Lionello from Italy developing the first data assimilation scheme for waves, Janssen returned to KNMI on 1 October 1987. Work continued at the Centre by a series of visiting scientists: Lionello who developed the data assimilation system further, Liana Zambreski from the USA who stayed until October 1989 and collaborated with MPI in the work, Heinz Günter who worked on the numerical scheme and the efficiency of the wave model, Bjorn Hansen, working for ESA on ERS-1 altimeter and scatterometer data, and others.

Up to now the work was formally to further the Centre’s research. In June 1987, the Council discussed the Director’s report on the experiments in wave modelling. Comments now were generally favourable. For example: “The Netherlands was fully in favour”, “Sweden strongly supported”, Germany “welcomed progress”, Finland “supported the proposal that wave forecasts be carried out operationally” and the UK “welcomed the research in wave modelling”. There was some caution: Germany, France and the UK suggested that operational implementation should be clarified with respect to the Convention.

Council asked the Director to prepare a paper on global wave modelling. An assessment on the quality of the wave forecasts, the resources required and the formal aspects of the Centre running an operational wave model, were all to be considered. The Director's document noted that a wealth of sea state data would become available from several satellites to be launched in the following two to three years. Use of these data would require a data assimilation system such as that at the Centre to provide analyses of the global wave and low-level wind fields. There was a strong coupling between the winds over the oceans and the waves generated by those winds. Successful assimilation of wave data required a good wave prediction model, such as the WAM model.

Operational wave prediction at the Centre would require only three scientific staff. At this stage it was estimated that less than 10% of the "number crunching" computing power needed for the atmospheric model would be needed, and 10% or less of the Centre's archive and telecommunications resources.

The Scientific and Technical Advisory Committees (SAC and TAC) considered the Director's paper that autumn. The SAC noted that the wave model "appeared to be well based", and because of the "possible impact on both the representation of the oceanic boundary layer and the optimal use of future satellite data it was scientifically important for the Centre to be involved with global wave modelling". The TAC recommended that research into wave modelling continue at the Centre.

At the Council discussion in December 1987, Germany "noted that improved medium-range forecasts could be expected as an outcome of global wave modelling", and "it was important that the European countries be in a position to take advantage of [European remote-sensing satellites] when they were launched". The UK agreed, "otherwise the very large investment in this satellite would be partly wasted". France "was in favour of a continuation of the research programme at approximately the same level of resources as before". This was what Council agreed.

Why was Council somewhat reluctant to allow the Centre to become more deeply involved in wave prediction at the Centre? Partly this was because the formal position was not entirely clear. ECMWF is an independent international organisation established by nations to carry out specific objectives that are specified in Article 2 of the Convention. In a sense, the Convention can be compared to the constitution of a State. Wave prediction was not mentioned, so it was necessary that Council could convince itself that wave prediction was somehow an integral part of the objectives. Partly, there was a strong commercial interest in wave prediction; this was a profitable and increasing source of revenue for some Member States. It has always been desirable that the work of the Centre and that of its Member States should not overlap. The United Kingdom in particular had a well-established programme of wave prediction of its own, with which it was commercially successful.

Research advanced at an increasing pace through 1988 and 1989. Italian teams visited the Centre for weeks at a time, developing a high-resolution wave prediction model for the Mediterranean and Adriatic Sea, and carrying out research into the effects of severe storms. Verification of the Centre's WAM global model against data from buoys in the Atlantic near the east coast of the USA showed generally low prediction errors but some biases, and in two cases the model failed to increase waves in response to increasing wind speeds. At KNMI, the third generation WAM model with 75 km resolution was implemented on the Convex computer. Optimisation of this KNMI version of the model continued. Janssen developed a theory for wind and wave coupling. He spent three months May to July 1990 at the Centre. Research at MPI progressed on modelling and data assimilation. The WAM model was implemented at IBM's Bergen Scientific Centre in Norway for research by staff of the Norwegian Meteorological Institute. Data of the sea state under Hurricane Josephine obtained by the crew of the Challenger space shuttle were compared to the waves predicted by different models. By early 1990, the WAM model had been implemented for operational testing at the US Navy's Fleet Numerical Oceanography Center in Monterey California. It was implemented also at Tsinghua University in China.

It was now time to place the activities at the Centre under a more formal umbrella. The Council in May 1989 had adopted a procedure for "Optional Projects". These were to be Projects from which individual Member States could opt out, so to speak, by declaring that they were not interested in participating. A year later, in May 1990, the Council considered a proposal for a Project for "prediction of ocean waves (associated with the validation of ERS-1 data)". A proposal for the Project had to come from a Member State, and the document was presented by the Netherlands. In fact David Burridge helped significantly in its preparation.

Council discussion was generally in favour; considerable support was expressed. However an ad-hoc working group was formed to clarify difficulties which were identified during the discussion: for example the UK "would have to be convinced of the value of the third generation wave forecasting model in relation to the resources required before it would be prepared to join". Italy, France and Germany also expressed the need for clarification relating to commercial interests, funding of the project and more.

At its following session in December 1990, the Netherlands presented an enhanced proposal. The UK noted that "great difficulties could be foreseen for funding meteorology in Europe in the coming years. . . . It was concerned that all possible alternative sources for the prediction of ocean waves had not been addressed. . . . the UK had offered to make available to other national services the wave forecast which it produced". However other delegations supported the proposal including Germany: "this would be a potentially useful application of resources of the Centre", Italy: "at a time when funding was difficult nationally, funds for Optional Projects should be encouraged", and France, which: "saw a link to the medium-range atmospheric model". The position of the UK was softening, partly perhaps because of the strong interest its Director-General John Houghton had in satellite meteorology and in the ERS satellites in particular. Dr Houghton later became renowned also for his work as Co-chairman of Working Group 1 (Science) of the Intergovernmental Panel on Climate Change.

Council approved in principle operational wave forecasting as an ECMWF Optional Project, with all except the UK (which abstained) voting in favour. Council gave a two-year deadline for the provision of the necessary computing, manpower and financial resources; otherwise its approval would lapse. In fact the Member States involved were able to get their act together quickly, and at its session in June 1991, the Council approved the implementation of the Project. A "Reduced Council" was set up to oversee the Project, consisting of representatives of the 14 participating States. Greece, Austria, Switzerland, Turkey and the UK opted out, but Iceland, a Co-operating State, participated from the beginning.

The scientists working on the Project were not ECMWF staff. They were employed as consultants, and normally there had been a two-year limit on consultants' contracts. Council therefore had to waive this limit for the staff to be employed on the Project. Janssen returned to the Centre in early 1992, working on a project funded by the Dutch Remote Sensing Board (BCRS).

On 1 July 1992, operational wave forecasting formally began with a 3° global model forecasting to ten days, and a 0.5° model covering the Mediterranean forecasting to five days. Forecasts were made once per day. Operational verification of the forecast quality was given high priority, and implemented within a year. Research continued with the implementation of ERS-1 altimeter data in the model, and installation of software from MPI to allow regular comparison of the model waves with the ERS-1 data. In August 1993, the sea-ice boundary in the model was improved.

Spain had been active in wave modelling for some time, and there was by now growing collaboration between the scientists at the Centre and those in Spain and Italy to compare the Mediterranean model with buoy data, and also with researchers in France.

In 1993, the UK was invited to join the Project. The UK delegation noted that Europe benefited from the additional work done by the UK on wave forecasting, but suggested that the UK should be entitled to the Project's software. Greece and Germany suggested that wave forecasting be done not as an Optional Project with the existing 14 States participating, but as a "core activity" to be covered by the Centre's normal budget. In June 1994, Council agreed that the Project's software would be available to non-participating States on an exchange basis.

In early 1994, the main technical work to increase the resolution to 1.5° was completed. This model was run in parallel with the operational 3° model for some months to validate it scientifically before stopping the run of the 3° model.

The value of the Centre's work to ESA was quickly demonstrated: partly in response to feedback from the Centre's monitoring of the ERS-1 data, ESA changed the software used to calculate significant wave height.

In December 1994 Council considered at length having wave prediction as a core activity. The cost of wave prediction was about £200,000 per year. There was one Member State that continued to have strong reservations on scientific and technical as well as formal grounds: the UK. In line with its preference to achieve where possible consensus on issues relating to the Convention, Council decided that wave forecasting would continue as an Optional Project.

In February 1995, Janssen returned to the Centre, now as Head of the Ocean Wave Project. By this time, advantage was being taken of the fact that the wave model predictions depended strongly on the quality of wind forecasts; the wave model was used to validate planned changes to the atmospheric model. Changes to the atmospheric model in April 1995 led to a marked reduction in the errors of the wave forecasts, and therefore in the wind forecasts, in the Southern Hemisphere winter.

In June the resolution of the Mediterranean model was increased to 0.25°. Software was developed to extract monthly mean wave forecasts, and using data collected by the Portuguese Meteorological Service a study of the interannual variations of the wave field in the North Atlantic began.

On 21 April 1995, ESA launched the ERS-2 satellite. Now work was begun to cross-compare the data from the two Earth Resource Satellites: wind, wave, altimeter and more. Software was developed in collaboration with MPI in Hamburg.

Larger computers, scientific advances including improved numerical schemes that used a grid similar to that of the atmospheric model's "reduced Gaussian grid", and improved satellite data were now pointing to the desirability of another increase in model resolution. Consequently a feasibility study was made in late 1995 of having a 0.5° global model. The study laid the groundwork for such a model to be introduced in 1996.

Also in 1995, Janssen, with Pedro Viterbo from ECMWF, and in collaboration with the scientists at KNMI, began work on a major development: the “coupling” of the wave model with the atmospheric model. Ocean waves play an important role in transferring momentum and heat between air and sea, and vice versa, at the ocean surface. The steeper waves created by locally strong winds increase the drag on the wind by some 50%, thus slowing it.

In essence, in a coupled model, the atmospheric model runs for one time step. The ocean wave model is then run for one time step, using the winds predicted by the atmospheric model. The slowing of the wind from the wave-induced stress is now determined. Thus, this two-way interaction gives quantitative information on the slowing of the airflow. A study of the impact of the modelled rough ocean surface on the predicted development of Atlantic storms showed significant differences between the experimental coupled model and the original uncoupled model; the central pressures of the storms were not so deep in the coupled model.

The performance of the model continued to improve. An assessment of the performance of the wave model during 1995 compared the wave heights and periods with buoy data. Wave heights were underestimated by about 10%; this was associated with the assimilation of ERS-1 data, which were known to underestimate wave height. However the results showed a reduction of 25% in the errors of predicted wave height since 1988 — a real improvement in the quality of wind and wave forecasts. In fact now wave forecasts were being used for quality control of buoys. Prompted by large differences between the observed and predicted waves in the northeast Atlantic, the buoy operator replaced the wave sensors on the buoys. The differences were much reduced. All in all, the scores suggested that Northern Hemisphere wave forecasts were now useful to about five days ahead.

In April 1996, ERS-2 wave height data replaced those from ERS-1. Analysis and forecast data were being routinely exchanged between the Centre and the UK Met Office, Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey California, Atmospheric Environment Centre Canada and the National Centers for Environmental Prediction (NCEP) Washington, to compare model performance. Operational runs of a 0.5° global model began in parallel with the operational 1.5° model. In areas of intense storms, the higher resolution could give a better representation of the more intense wave systems. Also, close to the coastline, a dramatic improvement in the quality of wave prediction was noted. The 0.5° global model became the operational model in December 1996. The model achieved the best scores ever achieved to that time in February 1997, with a one-day forecast error close to the known accuracy of the buoy data.

Nevertheless the ERS-2 under-estimation of the wave height in "young wind seas" with steep waves continued to be a problem.

Development of the coupled model was almost completed by end 1997. A systematic study into the benefits of coupling using 12 forecast cases showed that the hoped-for reduction in model errors was achieved. In the coupled forecasts, near-surface winds were slowed considerably by the rough water surfaces. Even the 500 hPa height scores for the atmospheric model were improved. At the December Council session the UK delegation stated that the UK wished to join the Project if it was added to the core programme of the Centre. All delegations welcomed this.

In June 1998, meeting in Tromsø, Norway, the Council agreed to incorporate the Project in the 1999 budget of the Centre, thus making it a core programme. The Director was now able to give staff contracts to the three scientists working on the Project from 1 January 1999. As a "late joiner" the UK paid £45,000 to contribute to the costs already incurred in setting up the Project.

The coupled version of the model became the operational model, with a resolution of 55 km, in June 1998, after being extensively tested. In the following years, its performance was closely monitored. A large reduction in the errors of the predicted waves was recorded, especially in the tropics and Southern Hemisphere. Forecasts of surface wind forecasts also showed improvements. Comparisons of the forecast errors with those of other centres showed the consistently superior performance of the ECMWF system.

The Mediterranean model had already been extended to cover the Baltic Sea and the Black Sea. It was now extended further, to cover the North Sea, the Norwegian Sea and the North Atlantic north of 10°N. Its resolution was now 28 km. Its forecasts were run to five days, as compared to the ten-day forecasts of the global model.

In 1999, research was under way on use of the ensemble prediction technique, as discussed in Chapter 10, for wave forecasting. In particular an experimental Ensemble Prediction System for ship routeing was developed and tested. Initial results were promising; in half the cases, the lowest cost route was found, compared to one-fifth of the time using the operational system.

One worrying problem remained. There was concern at a systematic under-prediction of wave height when large waves were observed; under-prediction of about 1 m was found when waves of about 10–15 m were observed. An extensive study showed that under-estimation of wind speed in the analysis was the cause. This was related to the 5 m height of the anemometers on buoys; the analysis assumed that they were at the standard

10 m level. Since the wind is slower at 5 m than at 10 m, the completed analysis ended up with slow winds. A fix was introduced in November 2000, at the same time as a further increase in model resolution to 40 km. Forecast error was immediately reduced; compared to buoy data, both wind and wave forecasts were improved. Nevertheless, persistent low model wind speeds continue to be a problem. However increasing the horizontal resolution helps alleviate this.

In recent years a dedicated effort has lead to an increase in the number and type of observations in the wave analysis scheme. In January 2003 assimilation of low-frequency spectra from the satellite-borne Synthetic Aperture Radar (SAR) started. Following the successful ERS missions launched in 2002 the Environment Satellite (ENVISAT) with ten remote sensors, including a dual frequency radar altimeter, built according to new design specifications, was launched. The altimeter gave significantly better measurements of the wave height. Use of the ENVISAT altimeter data in the analysis scheme from October 2003 improved the quality of the wave forecasts.

Following the considerable progress in wave forecasting made during the past 20 years, what need is there for further development? Let us consider some of the applications in which the wave spectrum plays an important role.

Recently there has been rapid progress in the understanding of the generation of extreme sea states such as freak waves. Prediction of the likelihood of events like these would be of clear benefit to the marine world. To achieve this, accurate predictions of the detailed “low-frequency” part of the wave spectrum, that is to say the long waves, are required. The wind-wave forecasting systems developed up to now cannot provide such predictions. More work is needed to investigate the relationship between spectral shape and the occurrence of these extreme states.

Remote sensing applications require knowledge of how the sea surface reflects and emits radiation. This includes instruments like the Advanced TIROS Operational Vertical Sounder (ATOVS), altimeters, scatterometers and Special Sensor Microwave Imager (SSM/I) that are carried on satellites. The reflection and emmision of radiation from the ocean surface depends in a straightforward manner on the range and distribution of wave slopes — the “slope spectrum”. We need to know about the “high-frequency” part of the wave spectrum, the small choppy waves, for this.

We have seen that knowledge of the high-frequency spectrum is important if we want to determine the air-sea momentum exchange. This is the case also for the exchange of carbon dioxide between atmosphere and oceans. In the Centre's current wave model the parametrization of the high-frequency spectrum is a good first guess. The actual spectral shape is not well understood. Much experimental and theoretical work is needed to obtain a convincing and working model for these high frequencies.

And work is just beginning on the impact of the ocean waves on the large-scale ocean circulation.

Exciting times in the field of ocean waves lie ahead.

Chapter 13

Data from on high

Satellites are very expensive — but vitally important — sources of data for weather prediction. At the time of writing, the Centre is using data from about 30 instruments on 17 satellites, instruments that are probing and measuring the earth's atmosphere, and its oceans and land. A single instrument on a weather satellite can provide many thousands of bits of data each second.

Proper exploitation of the vast flow of global data streaming from satellites requires the most powerful computers and the most sophisticated data-handling and analysis software. The Centre has a long history of fruitful relations with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), as well as with the European Space Agency (ESA). There has also been good co-operation with the National Oceanographic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) in the USA. The Centre has had quick access to many new kinds of satellite data, and has often been the first operational user.

The first European operational geostationary satellite Meteosat was launched in 1977. Initially, ESA was responsible for the satellite, and for its observation processing and so on. Mr R. Mittner, Director of Météorologie Nationale of France, was appointed Chairman of a Meteosat Operational Programme Working Group at an international meeting in Paris in 1981. Plans were in hand to establish an organisation, later called EUMETSAT, that was to be given the task of carrying responsibility for Meteosat. Serious consideration was given to attaching EUMETSAT to the Centre. There were good practical reasons for this. The Centre's system would be using the satellite data heavily, and the Centre's requirements could be expected to be influential in the design of future satellites. The proposal would depend on the willingness of the 17 Member States of ECMWF to modify the Convention establishing the Centre. However, it would have been awkward to bring this proposal to fruition. Amending the Convention would take a great deal of time, and the groups of States supporting the two organisations would not necessarily be identical.

Later, an alternative solution, with a co-operation agreement between the Centre and EUMETSAT, was considered, with EUMETSAT having its own legal personality, operating so to speak under the wing of the Centre. The Centre would administer EUMETSAT staff and make its equipment available to EUMETSAT.

In the end, after much discussion, EUMETSAT was established in June 1986 as an independent organisation with headquarters in Darmstadt, Germany.

EUMETSAT inherited the Meteosat satellite programme from ESA in January 1987. Today, EUMETSAT establishes, maintains and exploits European systems of operational meteorological satellites. As well as being responsible for the launch and operation of the satellites, EUMETSAT delivers satellite data for monitoring the climate and for detecting global climate change as well as for operational weather prediction.

In May 1988, the Centre and EUMETSAT concluded a co-operation agreement, formally agreeing to keep each other informed of activities “in which there may be mutual interest”. By this time, the Centre was already using a vast quantity of information from satellites.

Geostationary satellites, at an altitude of about 36,000 km, provide a continuous view of the earth from an apparently stationary position above the equator. Instruments on polar-orbiting satellites, flying at much lower altitude, typically around 800 to 1,200 km, provide more precise details about the atmosphere, including its temperature and moisture profiles, from the surface to the highest levels. A polar satellite’s orbit is fixed relative to a line from the middle of the earth to the sun; the earth is rotating within the orbit. They cover polar regions that cannot be viewed from a geostationary orbit. The lack of in-situ observational coverage in parts of the globe, particularly the Pacific Ocean and the Southern Hemisphere, has led to an increasing role for satellite data. An important programme initiated in the 1990s was the EUMETSAT Polar System, a joint venture with the US agency NOAA. EUMETSAT will assume responsibility for the “morning” — at local time — polar orbit, while the USA will continue with the “afternoon” coverage. EUMETSAT and NOAA instruments will be carried on its Metop satellites, a series of satellites providing service well into the second decade of the 21st century.

EUMETSAT has thus become one of the major partners providing satellite systems for observing our planet, and Europe has taken a leading place in monitoring global weather and climate. Its success ensures the availability of key satellite data for Europe and for many developing countries. We will see in Chapter 14 the approval in February 2005 of a ten-year strategic plan for the Global Earth Observation System of Systems (GEOSS). At first, GEOSS will build on existing satellites and sensors. These will include not only the operational EUMETSAT and NOAA satellites, but also ESA's Envisat, launched in March 2002, and NASA's Earth Observing System satellites. Later launches will be coordinated.

Tony Hollingsworth's visionary understanding of the importance of investing in the assimilation of satellite data lead to the Centre developing a strong research programme that has exploited a wide variety of satellite data. The data were used not only to improve the analyses and forecasts, but also to verify forecasts. Systematic errors and model biases that otherwise could have gone unnoticed were revealed. Increasingly, work had to be planned well in advance, so that data from a new satellite instrument could be used as soon as possible after launch. Hollingsworth worked hard to ensure good working relations and strong interaction with satellite agencies during his years as the Centre's Head of Data Division and later as Head of Research.

The Centre used satellite-measured winds generated at the European Space Operations Centre (ESOC) as soon as they became available in the late 1970s. Infrared radiation emitted by the cloud tops to the geostationary satellite could be used to estimate the cloud top temperature. The height of the clouds could then be found by comparing the cloud top temperature with the analysed temperature at different levels of the model atmosphere. Visible clouds were tracked to provide estimates of the wind speed at the height of the clouds, provided of course that clouds anchored in the lee of high ground were ignored! Feedback from monitoring at the Centre helped to improve the estimates. Use of these data improved the small-scale flow in the tropical analyses and close to frontal systems.

In later years, separate estimates of the wind were made from the movement of features detected in high-resolution measurements of the water vapour. Careful quality control was required to produce usable wind fields; the technique was refined during the years.

The Centre was improving its use of TIROS Operational Vertical Sounder (TOVS) data from the polar-orbiting satellites. Research in 1987–88 concentrated on determining the information content of the temperature and humidity data, and evaluating the techniques used to retrieve temperature and humidity from the radiances measured by the satellite instruments.

The impact of data on the Centre's forecasts was of course carefully monitored. By 1989, the quality and resolution of the analysis had improved to the extent that the Director, Lennart Bengtsson, reported to Council that while the impact of satellite data was positive and large in the Southern Hemisphere, where there were comparatively few other data sources, there was one startling conclusion: "it has been found that the overall impact of satellite temperature soundings has had a minor *negative* effect on the forecast quality . . . over the Northern Hemisphere!" Following the significant improvements to the Centre's system in the preceding two years, the errors in the "background" fields, that is, in the short-range forecasts, were smaller than the errors in the temperatures retrieved from the satellite measurements. Use in the Centre's system of temperature data calculated from satellite measurements actually degraded the quality of the analyses; the short-range forecasts had become more accurate than the data! And these were from measurements that had been made at very great expense.

With hindsight, part of the problem lay with the data assimilation system itself. In a well-tuned system, inaccurate observations can be used in such a way that they will do no harm; they will be given a "weighting" corresponding to their accuracy and the usefulness of their data content. For example at the time of writing, the Centre's background forecasts are often more accurate than the (actually quite accurate) radiosonde data, but these radiosonde data are still used to advantage in the system.

However, in those years, use of satellite data was far from optimum. The instruments measure the radiation upwelling to space from gases in the atmosphere. A complicated retrieval procedure was required to provide estimates of the temperature. Processing the raw radiance data, the actual instrument measurements, was needed in the early years, because the data assimilation systems then in use could not properly handle unprocessed data. When early satellites were launched, the numerical models needed not what the satellites measured (i.e. infrared, microwave and other radiation coming from gases and clouds in the air, and from the sea, ice and earth below), but the temperature and wind. These were the quantities that had been available from balloons and aircraft, so the assimilation systems had been designed for these kinds of data. However, the act of processing the radiance data to retrieve these numbers introduced errors. As well, even with the most careful processing, spurious signals could be introduced into the data.

One of the benefits of the Centre's variational assimilation system being developed in co-operation with Météo France was that it could use the raw, unprocessed, radiance data directly. In a sense, instead of taking the satellite measurements, and trying artificially to extract or retrieve quantities that the models required, such as temperature, the variational system was able to tune the model atmosphere so that the radiation that would be emitted from the top of the model atmosphere towards space would correspond to the satellite readings.

There is another advantage to using raw data. It can be a year or more after the launch of a satellite before processed data can be made available; the raw data are available typically within a month after launch.

Bengtsson highlighted “the necessity to undertake major efforts to develop better methods for the determination and use of satellite observations”. In May 1989, a Workshop was held jointly with EUMETSAT on “the use of satellite data in operational weather prediction”. Urgent work was identified, and close contact was soon forged between the scientists at the Centre and those at EUMETSAT.

At the end of 1989, Council unanimously approved a proposal to set up a Satellite Data Research Unit at the Centre, with Switzerland noting “the very great cost associated with technical operational satellites”. The Unit was established in February 1990 with responsibility “for developing systems to use operationally available satellite data and to assess the performance of future observing systems”. A first task of the new Unit was “to improve the use of satellite temperature soundings . . . by direct assimilation of clear radiances . . . ”.

An initial staff of two under John Eyre soon expanded. Many skilled and experienced scientists and consultants, several funded by EUMETSAT, worked on satellite data at the Centre in the following years. In early 2005 there were 19 scientists working in the Satellite Data Section under Section Head Jean-Noël Thépaut. These included Graeme Kelly from Australia, who had been at the Unit from its inception.

Soon after its establishment, the Unit was comparing the cloud-clearing schemes used by the Laboratoire de Météorologie Dynamique (LMD) France, the UK Met Office, NESDIS in the USA and the University of Naples to produce “clear-column radiances”, that is data from regions not affected by clouds. By 1992, rapid and substantial progress was being made in research into the use of satellite data. Use of one-dimensional variational analysis (1D-Var) for retrievals of temperature data over the Northern Hemisphere was showing improvements in forecast skill; this was employed from June 1992 in the operational system. An improvement in the analysis of the humidity was soon seen. A great deal of work was required and many problems had to be overcome before extension to the rest of the globe could be implemented in December 1994.

Arrangements were made to ensure that the Centre would receive wind and ocean wave data in near real time from the scatterometer and altimeter on board the new Earth Resource Satellite (ERS-1) launched in July 1991, to allow calibration and validation of the data. The ERS-1 included three major radar systems among its many instruments.

- A scatterometer sent a beam from two antennae. The returned signal bouncing back from ocean waves about 5 cm high provided wind information; the waves are generated directly by the wind.
- The Synthetic Aperture Radar (SAR) was a quite different instrument with much higher power consumption. Elaborate signal processing and the motion of the instrument meant that the instrument could be turned into the equivalent of a radar with a very long antenna, a "synthetic aperture". Ocean waves and swell were measured.
- The third radar was an altimeter; it sent a radar chirp 50 times each second. The return signal gave a very accurate estimate of the height of the instrument above the variable ocean surface, actually about 780 km, allowing ocean currents to be measured, since the dynamic height of the ocean surface determines the currents. Wave height was also measured, and used in the analysis of the Centre's ocean wave model.

Feedback to ESA continued to contribute to trouble-shooting the ERS-1 data. For example, ESA software could not discriminate between "upwind" and "downwind" signals from the scatterometer; the ambiguity led to the possibility of incorrect surface winds being retrieved from the satellite data. With feedback from the Centre's team, ESA was soon able to develop corrections to the satellite bias problems in (a) the scatterometer calibration and (b) the statistical model that ESA had been using to relate radar backscatter from the ocean waves to estimate the wind. Methods being used to estimate wave heights were also improved.

The ERS-2 satellite, launched in April 1995, provided much useful data in the following years. Data from the scatterometer instrument gave estimates of the surface wind speed and direction. A comparison of background wave height and altimeter wave height data soon showed that use of these data had a beneficial impact on the surface wind field analysis. These data were used operationally from 1996, and improved the model significantly in the tropics, with smaller effects elsewhere over the globe. The Centre monitored the winds and radar backscatter data; quality control procedures were steadily improved. ERS-2 also carried a new instrument GOME that measured ozone. Ozone data were analysed by the Centre from 2002.

"Future system studies" were underway to specify instruments for planned satellites, including some that would not be launched for a decade or more. Experiments were made on the impact of satellite winds and aircraft reports on the Centre's forecasts. The team at the Centre was involved in studies to draw up specifications for the advanced instruments required on the Meteosat Second Generation and for the planned Third Generation, as well as for the ground segment for the planned EUMETSAT Polar System.

The team developed a system to simulate global data sets to investigate different scenarios for a satellite Doppler wind lidar instrument; this was needed for an "observing system simulation experiment". Liaison with ESA continued: at the time of writing the Centre was actively involved in preparing to process data from the ADM-Aeolus mission scheduled for launch in October 2007. This, ESA's second Earth Explorer Core Mission within its Living Planet Programme, was designed to make direct measurements of global three-dimensional wind-fields. Named after Aeolus, who in mythology was appointed "keeper of the winds" by the Greek Gods, the Aeolus satellite will be the first mission to observe the Earth's wind patterns from space directly.

The Centre's assimilation system was modified in the late 1990s to allow use of the raw radiance data from operational NOAA polar-orbiting satellites.

- Information from each of the five TOVS and Advanced TOVS (ATOVS) instruments were treated as independent sources of radiance data that was assimilated in their natural scan geometry, thus avoiding the attempt to combine or map the different readings to a single location.
- The data were assimilated where they were measured, avoiding artificial adjustment of the variation of the radiance when an instrument took measurements away from the vertical.
- Since clouds and precipitation interact with atmospheric radiation, it was much easier to use data from areas with clear skies. A battery of tests searched for the characteristic signals of cloud and precipitation. While this processing was generally quite effective, at times some data included significant radiances from clouds and precipitation. The Centre's analysis screening used short-range forecasts to compute clear sky values of the "window channel" radiances, giving better results than the previous processing.

Numerical experiments of these first steps in use of raw satellite data in real time confirmed that useful improvements in the analyses and forecasts had been achieved. Observing system experiments in 1998 confirmed that satellite data had a significant positive impact on both analyses and medium-range forecasts in both Hemispheres.

In 1999, major changes were made to the operational assimilation of the radiance data. In May, after an extensive trial over a four-month period, direct operational assimilation of raw TOVS and ATOVS data began. Additional levels were introduced in the high atmosphere of the model, and ozone was introduced as another variable in the data assimilation system. An immediate improvement in forecast scores throughout the troposphere and stratosphere was achieved.

The total amount of water vapour in a column of the atmosphere could for the first time be measured, in almost all weather conditions, over the oceans with the launch of the first Special Sensor Microwave Imager (SSM/I) instrument, as long ago as June 1987; it was carried on a spacecraft forming part of the US Defence Meteorological Satellite Program. The instrument measured the microwave radiation emitted by water vapour in the atmosphere below. This was useful in principle, for example to diagnose the model's hydrological cycle. First, the satellite data had to be verified against "ground truth": the measurements made by radiosonde instruments that happened to coincide with the passage of the satellite. The "ground truth" itself is not always truthful; radiosonde humidity sensors for example are notorious for their errors! Years of research into use of SSM/I data came to fruition in February 1998, when a 1D-Var retrieval of SSM/I data was run as part of the operational suite, giving regular plots of total column water vapour, surface wind speed and cloud liquid water. Also the SSM/I provided wind speed data from over the oceans, but unlike the scatterometer, not wind direction.

The edges of sea-ice fields derived from SSM/I brightness data were up to 300 km better than those used operationally. Tropical precipitation was also estimated from radiance data from the SSM/I instrument. The radiance data being emitted was strongly affected by rain. Using this to modify the initialisation of diabatic heating in the model was first investigated at the end of 1990. It took until 2005 — 15 years later — before research had progressed sufficiently to allow the data from places where it was raining to be assimilated.

In December 1998, the Centre concluded an agreement with the Met Office, under which the Centre participated in a Satellite Applications Facility (SAF) for Numerical Weather Prediction (NWP). The objectives of the SAF were to accelerate the development of techniques for more effective use of satellite data in NWP, and to prepare for effective exploitation of the data coming from satellites planned for launch in the future.

In April 2000, the model-based correction of biases in the TOVS and ATOVS radiance data was applied to the SSM/I radiances. Now there was almost global coverage of wind speed over oceans, and of total column water vapour. The Centre's development of bias-correction and the improved understanding of the error characteristics of the raw radiances led to a considerable increase in the volume of satellite data assimilated.

The ongoing co-operation between ECMWF staff and those at EUMETSAT and ESA was producing a range of benefits. Operational changes were made in 2000 to the calibration and quality control of Meteosat data by EUMETSAT. In fact, many other users of satellite data were now using the Centre's statistics as early warnings, or as confirmation of problems.

It's not easy to use radiance data from the channels that measure emissions from the low atmosphere over land, or from cloudy skies. Emissions from the earth's surface, or from clouds, have to be separated from the radiances from the air. In 2000, an experimental system was developed to analyse the contributions from the surface, and to separate them from the atmospheric data. Adjusting the surface temperature and emissivity within the 4D-Var assimilation system accomplished this. Work continued to optimise the technique, so allowing use of these valuable data over land.

The NASA AQUA spacecraft was launched in May 2002, carrying the high-resolution Atmospheric InfraRed Sounder (AIRS) instrument. AIRS was the first 'hyperspectral' sounder, making measurements in 2,378 spectral channels. Information on profiles of temperature and humidity was provided, at enhanced vertical resolution compared to the previous generation of operational satellite sounders. AIRS was a research forerunner for instruments with similar performance on operational satellites later in the decade.

A subset of radiance data from AIRS was made available to ECMWF in near real time from the end of October. Before this date, significant technical development was made using simulated AIRS data sets provided by NOAA/NESDIS. With this intensive preparation, experiments in cloud-screening, monitoring and assimilation impact could begin almost immediately following the arrival of the real AIRS data. Tony McNally and his colleagues carried out a 100-day trial of the use of AIRS data. They showed that the assimilation of AIRS data had reduced errors in both short-range and medium-range forecasts, and concluded "that we now have a safe 'conservative' assimilation system for AIRS which should be considered for operational implementation". AIRS data started to be used operationally from October 2003, with small but positive changes to the forecasts. This, the first operational use of advanced infrared sounder data, paved the way for use of data from planned future operational satellites such as Metop, to be launched in 2006, which will carry the Infrared Atmospheric Sounding Interferometer (IASI).

A co-operation agreement was concluded with ESA in May 2005.

As in other areas of its work, we find the Centre starting from small beginnings in its research into, and operational use of, satellite data, and growing as the years passed to provide an impressive body of scientific expertise. Again, we have a flavour of the extensive collaboration between the research teams at the Centre and those outside, at EUMETSAT, in institutions in the Member States, and elsewhere. And again, we see that the groundwork is laid to ensure so far as possible that use of the future global observing system is optimised.

Chapter 14

Re-analysis — towards a new ERA

The World Weather Watch is an astonishing technological achievement. Nations of the world spend billions of Euros each year to measure and probe the atmosphere and oceans of our planet. Many different types of observing systems are used:

- Satellites passively measure the radiation emitted by the surface of the earth and the sea; from this the temperatures can be deduced. The atmospheric greenhouse gases too are radiating to space; satellites measure this radiation to provide information about the temperature of the air aloft.
- Instruments on satellites emit bursts of high-energy radiation to the sea surface; the reflected radiation measures the waves, and in addition the surface wind speeds can be estimated.
- More than one thousand instrumented balloons drift through the air each day, measuring pressure, temperature and humidity as they rise to 20 km or more. The balloons are tracked by radar, so telling us the wind speed and direction.
- About two thousand buoys have been lowered into the ocean from ships, to sink to a depth of two km, recording salinity and temperature. They drift at this depth for ten days, continuously measuring, before rising to the surface and sending the collected measurements to satellites.
- Hundreds of floating buoys drift on the surface, sending to satellites the wind, and the sea and air temperatures.
- Fleets of commercial aircraft measure wind and temperature every ten minutes high over the earth's surface.

The expensive part of meteorology is collecting the data; "more data, more data, right now and not later" isn't cheap. The World Weather Watch costs the nations of the world some billions of Euros each year; the annual budget of the European meteorological satellite organisation EUMETSAT alone is close to 300 million Euros. The ECMWF data assimilation system is probably the most advanced system for analysing the data; the Centre's annual budget is around 40 million Euros. Cartridges worth a few hundred Euros in the Centre's archive easily holds a year's worth of these valuable data.

A ten-year strategic plan for the Global Earth Observation System of Systems (GEOSS) was approved at an Earth Observation Summit in February 2005 in Brussels. Initiated by the United States, and with the Centre participating from the start, GEOSS will evolve slowly from national systems to become a coordinated comprehensive set of observations. The aim is to integrate observational systems around the world to avoid existing massive duplication of efforts and ensure that gaps in coverage are filled. More than 60 nations and 30 international organisations, including EUMETSAT, the European Commission and the European Space Agency, are working to establish the network of Earth observation systems. WMO will host the secretariat. GEOSS will focus on benefiting society. Weather prediction, our understanding of climate variability, agriculture, and human health and well-being will all be beneficiaries.

Truly vast amounts of information for the Global Observation System are stored in the ECMWF archives: observations of weather from all over the globe — temperature, wind, humidity, pressure and more — from the 1950s to the present time. While useful for many applications in its raw form, there are important questions that cannot be answered by the observations without further processing: Has the June temperature at 5,000 m above the North Atlantic changed on the average between the 1960s and the present decade? Have the wind speeds around the roaring 40s in the Southern Hemisphere increased, decreased or remained unchanged?

Analyses of the global atmosphere have been made from the beginning of the Centre's work and, like the data, stored in the archives. In principle the analyses can answer questions like these. However the analysis system itself has been steadily developing as the computers became more powerful, as the data sources — especially satellite data — have advanced and as the science progressed. Thus comparison of a temperature analysis made in June 1980 with one made in June 2000 would be misleading.

An analysis, strictly speaking a "re-analysis", of all the observational data of past years in the database using a single, frozen, modern analysis system has a clear appeal. This difficult and complex project has been accomplished by the "ECMWF Re-Analysis" (ERA) project. We will see that this project exemplifies the truly global co-operative nature of meteorology. As well, it has exposed the Centre to a much wider user community of research scientists worldwide, a critical group who are constantly providing the Centre with feedback on the quality of its output.

The start of ERA goes back to the data collected and analysed in real time from the beginning of operational forecasting at the Centre, during the FGGE (First GARP Global Experiment) period of December 1978 to November 1979. In the early years Bengtsson kept in mind the possibility of using the FGGE assimilation system as the Centre's back-up system in case of delay in implementing the operational system. Sakari Uppala from Finland joined the Centre in June 1978 to work with Per Kållberg from Sweden, who was already at the Centre. Kållberg was appointed as Project Manager in July 1978.

Kållberg and Uppala formed the basis of the Centre's "FGGE Section". Scientists from other interested institutes were seconded to work at the Centre in this effort in the following years: from Norway — Knut Bjorheim, the USA — Paul Julian and Steve Tracton, Japan — Masao Kanamitsu, and from Australia — Peter Price. And of course Bengtsson had a very keen interest in the everyday progress and decisions in the project. Wiin-Nielsen too kept himself informed.

Some of the raw instrument readings, called "Level I" data, for example radiance data from satellite sensors, had to be converted by the institutes receiving them to provide "Level II" weather parameters such as temperature and wind. Some of these were available within 10 hours of observation time. These formed "Dataset IIa" and were available for operational analyses. Others were delayed for up to several months to build the best possible observational dataset. This, called "Dataset IIb", included all the special observations deployed during FGGE such as drifting buoys, special aircraft data and balloon soundings, some radar data, constant level balloons, and cloud track winds from geostationary satellites. Lots of surface data were received. Archiving capacity was being stretched beyond its limits, and much of these data were not included, with surface data thus making up a small fraction of the total volume. The Level IIa data were collected and managed by a complex WMO data processing and management system before reaching the Centre. The final IIb Datasets were merged at the Space Based and Special Observing System Data Centre in Sweden, but — as noted above — with a delay of several months; this was a complex operation.

Level IIIa analyses were those produced operationally at the National Meteorological Center (NMC) Washington and other institutes from the Level IIa data. Much later the IIIb analyses were produced by the ECMWF FGGE system using the non-real time Level IIb data. Parallel to the work at ECMWF, the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton in the USA produced its own version of the Level IIIb analyses. The Centre worked closely with GFDL in planning and carrying out the re-analyses.

The Level IIIb analyses were to be archived in the two World Data Centres for Meteorology in Moscow and Ashville, North Carolina for worldwide distribution. They were also of course archived by the Centre.

Many diagnostic tools for monitoring the analysis production had to be developed. Weaknesses in the analysis system were identified and corrected. In February 1979, and again in April and May, a series of near-real-time tests of the entire FGGE data processing organisation, from the primary data producers to the final analyses, were completed — so-called "End-to-End Tests". During one of these, a visitor from ESA/ESOC, John Morgan, later EUMETSAT Director, was impressed to see for the first time "cloud drift" winds — winds estimated from cloud movement measured by satellite — being used in a numerical analysis.

Sea surface temperature analyses based on non-satellite data were produced for every ten-day period.

We saw in Chapter 8 the influence of Andrew Lorenc's work on the ECMWF assimilation system. His results were vitally important for the success of the Centre's FGGE efforts. Already he had developed the "Data Quality" files, predecessors of what today are called "feedback files", which recorded events during the complex quality control and analysis operations. These were crucial in the Centre being later declared a Lead Centre for monitoring global upper-air data in the WMO system, noted in Chapter 8.

The Centre could not begin production of the IIIb Dataset until December 1979. Production initially was slow with many teething problems both with the Level IIb data as received, and also with the ECMWF operational analysis scheme, which was used to produce the IIIb Dataset. Boxes of 1,600 bits per inch or bpi tapes were collected from Sweden. A major effort was made to produce a complete successful assimilation for 00 UTC on 16 January 1979, and a ten-day forecast was run. This analysis and forecast were used as a test version; any new development was first verified against this. The quality of this forecast was — somewhat fortuitously — excellent. Bengtsson plagued the Research Department, and Andrew Lorenc in particular, for months afterwards to find out why changes being introduced into the fledgling forecasting system made this one case worse!

Three months of analyses were completed by mid-May 1980, and six months by early October. By April 1981, production had reached into September 1979 and analysis tapes up to June had been delivered to the World Data Centres. Already significant changes had been made to the ECMWF operational assimilation system, but the FGGE system was kept unchanged; the goal was to produce a consistent set of analyses for use in general circulation and climate studies.

The assimilation of the FGGE data, at the time the most complete set of global observations ever assembled, to produce set of global analyses every six hours throughout the FGGE year — the IIIb Dataset — was completed in summer 1981. This Dataset allowed for the first time detailed examination of phenomena in areas of the globe normally almost devoid of observations such as the Indian Ocean. Paul Julian and Masao Kanamitsu, experts in tropical circulation, paid particular attention to these areas. Significant cross-equatorial flows could be followed clearly in the analyses.

A series of "Observing System Experiments" (OSEs) was begun in association with FGGE, and carried out by groups of scientists coordinated by the European Working Group on Future Observing Systems discussed in Chapter 8. These important experiments were designed to assess the impact of different types of observations on the resulting analyses and forecasts. How important were temperature data, as measured by satellite, for forecasting over the South Atlantic? Or cloud drift winds for predicting the tropical weather? Series of forecasts to ten days were run, with differing data types removed before carrying out the analyses. For example, over the Northern Hemisphere, forecasts to seven days ahead starting from analyses using all data had the same accuracy as five and a half day forecasts made without satellite or aircraft data — a gain of 36 hours in medium-range forecast skill. From the OSE results, some of which were surprisingly significant, planning replaced informed guesswork in deciding on the future observing systems for the World Weather Watch.

Kållberg had returned to Sweden in 1982, but work continued on the FGGE data in the new Numerical Experimentation Group with Sakari Uppala and Stefano Tibaldi. Visiting scientists from the USA and from China, as well as from the Member States, took part in the work. The US National Science Foundation funded some of the visitors.

A new set of the observational data was delivered to the Centre in 1984–85, including additional observations and corrections to errors in the earlier Level IIb Dataset. By this time also many improvements had been made to the ECMWF analysis system. As reinforcement for the section Kållberg returned to the Centre for nine months in 1985. FGGE data including the Special Observing Periods 5 January to 5 March and 1 May to 20 June 1979, when intensive measurement campaigns were carried out, were re-analysed using the upgraded Final Level IIb data. Final IIIb analyses were delivered to the World Data Centres by the end 1986. The new analyses proved to be measurably superior to those made earlier. Subsequently the Final Level IIb data was used extensively for new and "comprehensive" OSEs over two separate two-week periods. During these Experiments clear positive impact on the forecast quality was proven from the main observing system components. On the completion of these Experiments the FGGE work was essentially finished, and Uppala left the Centre in 1987.

From the important and valuable experience of the FGGE re-analyses, Bengtsson consulted many scientists worldwide on the possibilities of re-analysing the operational archive of the Centre — all the observations that had been received since 1979. Born in India, Prof Jagadish Shukla was a member of the US TOGA panel and the scientific steering group of the international TOGA. Shukla invited Bengtsson to the Center for Ocean-Land-Atmosphere Studies (COLA), Calverton, Maryland, USA. He discussed with Bengtsson proposing wider re-analysis projects — his proposal having been turned down by NMC Washington. Bengtsson and Shukla published a paper in 1988 advancing the concept of re-analysis.

- A comprehensive analysis of global observations based on a four-dimensional data assimilation system with a realistic physical model should be undertaken to integrate space and in situ observations to produce internally consistent, homogeneous, multivariate data sets for the earth's climate system.
- Current and future observing systems are very expensive and dominate the expenditure budgets of the meteorological Services.
- There is no doubt that a reanalysis of global data over, say, a period of ten years is a considerable effort, both in manpower and computer resources.

Kevin Trenbreth and Jerry Olson in the USA had independently suggested that major global re-analyses be carried out. These suggestions about extensive re-analyses to produce climate data sets, which included detailed comment on the difficulties and how they might be overcome, were not well received in the beginning. Gradually, however, the meteorological community came to accept the concept. Several groups around the world are today carrying out re-analyses to produce data for climate research. Typical research applications which make good use of re-analyses include research on general circulation diagnostics, atmospheric low-frequency variability, the global hydrological and energy cycles, studies of predictability, coupled ocean-atmosphere modelling and observing system performance.

Slowly the concept of an ECMWF Re-Analysis (ERA) was developed. It was planned to use the 15 years of data in the archives from 1979 to 1993 inclusive: "ERA-15". Bengtsson left the Centre at end 1990. The new Director David Burridge gave his full support to the project, and became the Project Chairman. The project team was Rex Gibson as Project Manager together with Kållberg and Uppala who both returned to the Centre.

In the planning and development phase a Steering Group advised on matters of scientific and policy importance. Additional advice was obtained by setting up an External Advisory Group, comprised of eminent scientists from Europe and the USA.

Before beginning the ERA production, the assimilation system had to be defined. Proven, modern data assimilation, not necessarily identical to that of the operational suite, was required. The project began in February 1993 with a comprehensive set of experiments in the form of parallel data assimilations and forecasts, usually over three week periods and with extensive diagnostics. The first phase of the work included also the acquisition and preparation of the observations, and forcing fields such as sea surface temperatures, experimentation to determine the composition of the production system, and the development of both the production system and the internal validation tools.

A reliable production system capable of performing data assimilation was developed. The system was separate from both the operational and research systems. Using the combined experience of the Centre's Operations and Research Departments, the systems in use were studied carefully, slimmed down where necessary, modified to use the data in an archive as opposed to real-time data, and optimised for performance. This resulted in a prototype system capable of performing at the required rate, which was further refined and completed while being used as the principle vehicle for the initial ERA experimentation.

It was decided early on that to optimise the use of resources the re-analyses should be carried out with a horizontal resolution of T106. For the vertical resolution 31 levels were used, rather than the 19 that corresponded more closely to the horizontal resolution, since the higher vertical resolution produced clearly superior analyses particularly around the tropopause.

At the time, "envelope orography" was being used in operations to parametrize the effects of sub-gridscale mountains. A new parametrization of the effects of sub-gridscale orography based on mean orography, and including a revised formulation of the gravity wave drag, developed by Francois Lott and Martin Miller, was also available; this was discussed in Chapter 9 when we considered the model. Test assimilations using this scheme showed no negative effects, while up to 10–15% more observations were accepted at 1000 hPa and 925 hPa. This scheme was chosen.

Using a prescribed soil climatology, which is based on very sparse information and may suffer from inconsistencies, as had been used in the pre-1995 operational system, had the risk of "forcing" a re-analysis towards its climate. Hence a new four-level self-contained soil parametrization scheme developed at the Centre by Anton Beljaars and Pedro Viterbo for operational implementation was selected for ERA.

Ongoing work in the Research Department on the new variational assimilation scheme (3D-Var), and a new cloud parametrization with cloud water and cloud fraction as predictive parameters, were not sufficiently mature at the time of decision and were not selected for the re-analysis. The final production system was adopted in 1994. There followed a period of sustained production, monitoring and validation throughout 1995 and the first nine months of 1996.

The observations used by ERA came mainly from the ECMWF Meteorological Archive and Retrieval System (MARS). Additional sources included:

- 250 km cloud-cleared satellite radiance data.
- Ship and buoy observations from the "Comprehensive Ocean Atmosphere Data Set" (COADS), the most extensive collection of global surface marine data over the period.
- FGGE and Alpine Experiment (ALPEX) II-b data.
- Satellite cloud winds made available by Japan.
- The "pseudo-observations" (PAOBs) made available by NMC Melbourne: sea-level pressures, estimated from satellite imagery and forecast fields, over data-sparse parts of the Southern Hemisphere.
- Supplementary radiosonde and aircraft data, also provided by Japan.
- TOGA buoy and other oceanic data.

By 1979, winds and temperatures were being received from commercial aircraft all over the globe, although most of the flights, and therefore most of the data, were in the Northern Hemisphere. The reports improved significantly over time both in coverage and quality, with aircraft in flight reporting automatically every ten minutes replacing infrequent manual reporting. During the 1990s the frequency of reports increased automatically during takeoff and landing, thus giving a "profile" through the atmosphere of wind and temperature.

Once production began late in 1994, the scientific emphasis gradually moved from experimentation to monitoring and validation. The external forcing fields were validated before the production started by means of maps, averages and time series. Every effort was made to detect potential problems that would require further investigation as early as possible. When appropriate, production was halted and re-started from an earlier date. In some cases production was allowed to continue, but the month or months concerned re-run later. The monitoring made use of a set of quality control tools, whose output, usually in the form of graphical information, was continuously assessed. All graphical and tabular monitoring results were kept both as hard copies and as files. Diaries were kept of all special events and problems encountered.

Production and monitoring continue throughout 1995 and into 1996. During the second quarter of 1996 the first pass through the full 15 years was completed. Monitoring enabled many errors arising during production to be located and rectified. Nevertheless two lengthy periods needed to be re-run. A bug, present also in the operational system, was undetected until the re-analysis had completed up to August 1980. The bug significantly affected humidity at upper levels. Secondly, much cloud track wind data were accidentally excluded from June 1990 to October 1992, due to a change in their format affecting the data in the archive. A re-run of the first period was particularly desirable, as it presented an opportunity to run the FGGE year with the same observations and forcing fields as the National Centers for Environmental Prediction (NCEP). Both re-runs were completed in September 1996.

By November 1996, Burridge was able to report to Council that “the ERA project has completed its production phase with the creation of a new, validated 15-year data set of assimilated data for the period 1979 to 1993”. A Re-analysis Workshop held in July 1996 had almost 100 participants, an indication of the now high level of research interest in the project.

The ERA-15 data set contained global analyses and short-range forecasts of all relevant meteorological parameters, beginning with 1979, the year of the FGGE, and running to 1993. All analyses and forecasts were generated by a modern, consistent data assimilation system. The system included better “first guess” preliminary fields and a more efficient dynamical balancing for the assimilation of observed data. The new FGGE analyses were compared with those of other institutions such as NCEP, and the original GFDL analyses.

“Madden-Julian” oscillations are events that are associated with enhanced deep thunderstorm activity moving eastward from the Indian Ocean into Indonesia, and then into the Western Tropical Pacific. These oscillations give rise to “Oceanic Kelvin Waves” below the ocean surface, which propagate eastward along the equator carrying abnormally warm sub-surface water toward, and eventually to, the South American Coast. An Oceanic Kelvin Wave reaching the coast of South America is a signal that El Niño is coming. The capability of representing “Madden-Julian” oscillations in the re-analysis and in the ECMWF and old GFDL analysis was investigated by comparing with satellite observations. The oscillations were successfully reproduced by the new analysis. However agreement with the satellite data was not quite satisfactory. It was found that the use of satellite-observed wind and aircraft data in the data assimilation needed particular care.

The ERA-15 project was a global effort. It received funding and assistance from many quarters, including:

- ECMWF Council,
- European Union,
- University of California Program for Climate Model Diagnosis and Intercomparison (PCMDI),
- Japan Meteorological Agency (JMA),
- World Climate Research Programme (WCRP) of the World Meteorological Organization (WMO),
- Center for Ocean-Land-Atmosphere Studies (COLA),
- National Center for Atmospheric Research (NCAR),
- National Centers for Environmental Prediction (NCEP), and
- Cray Research Incorporated.

ERA-15 data were made available to ECMWF Member States through the MARS archive, to university users within the UK through the British Atmospheric Data Centre (BADC), to University users in Germany through the Max-Planck-Institut für Meteorologie (MPI), and to the UCAR community in the United States through NCAR.

Close co-operation was also established between the ERA team and the teams responsible both for the NCEP re-analysis, and for the re-analysis performed by the NASA Data Assimilation Office.

Production continued until September 1996. The team was desperately running ERA-15 up to the minute the last of the CRAY systems was powered down on 1 October 1996.

The world moves on! In May 1997, Burridge reported to Council that "an initial assessment has begun into the feasibility of a 40-year re-analysis, making use of the additional observation archives being obtained from NCAR". This would quickly become another global effort.

Euroclivar was the European component, funded under the Fourth Framework Work Programme, of an international research programme on "Climate Variability and Predictability" (Clivar) addressing many issues of natural climate variability and anthropogenic climate change. The need for a project with the objectives of ERA-40 was recognised by Euroclivar. It "strongly recommended that a new 40-year re-analysis be made in Europe in the next five years".

ERA-40 was expected to make a significant contribution to those objectives of the Fifth European Community "Framework V" Programme covering "Research, Technological Development and Demonstration" that related to the World Climate Research Programme. It would, for example, provide data in support of projects such as DEMETER, which would explore the potential for seasonal prediction, and PROMISE, a programme on the "Predictability and Variability of Monsoons, and the Agricultural and Hydrological Impacts of Climate Change". This would make extensive use of ERA-40 analyses for validating climate and seasonal prediction models and for driving crop models for impact studies. Studies of ozone depletion and other aspects of atmospheric chemistry could also benefit from ERA-40.

Within a year, substantial progress had been made in reception and initial processing of data from NCAR. The complete NCAR archive of TOVS satellite data, beginning as early as 1978, had been received. These data had to be processed to a form suitable for the ECMWF variational data assimilation system. An External Advisory Group for ERA-40 had been formed. Scientists were being seconded from China, Japan and the USA to work on the project. EUMETSAT had agreed to re-process cloud track winds from the 1980s. A bid for EU funding under the Framework V activities was made.

The Centre's validation programme was augmented by a variety of external validation projects:

- Koninklijk Nederlands Meteorologisch Instituut — Ocean waves
- Max-Planck-Institut für Meteorologie — Hydrological cycle
- Météo France — Ozone, stratospheric analyses, ocean surface fluxes and Alpine snow
- Met Office — Clear sky radiation simulation
- National Center for Atmospheric Research — Observations and mass, heat, energy and moisture diagnostics
- University of Reading — General circulation, climate variability

The Centre, in practise Adrian Simmons, would coordinate the project. The Centre would produce the analyses.

In the planning phase the partners were represented by Klaus Arpe of MPI, Tony Slingo of the Met Office, Pascal Simon of Météo France, Gerbrand Komen of KNMI, Roy Jenne and Kevin Trenberth of NCAR, and Brian Hoskins and Julia Slingo of the University of Reading. ECMWF contributors included Adrian Simmons, Sakari Uppala, Per Kållberg and Keith Edwards. Rex Gibson was Project Manager for the preparatory phase of ERA-40. Simmons and Gibson wrote the proposal for ERA-40. Ongoing management of the complex project was largely shared between Simmons and Uppala, who became project manager on Gibson's retirement from ECMWF at the end of August 1999.

A variational data assimilation system was planned, to make a new synthesis of the in-situ and remotely sensed measurements made over the period beginning in mid-1957. A major improvement had been made to the atmospheric observing system in preparation for the International Geophysical Year of 1958 which had as its goal: "...to observe geophysical phenomena and to secure data from all parts of the world; to conduct this effort on a coordinated basis by fields, and in a space and time, so that results could be collated in a meaningful manner".

Thus, starting in 1957, ERA-40 would produce analyses every six hours throughout the 40-year period, extended to 45 years as we shall see, supplemented by intermediate three-hour forecasts. The products would be of high temporal and spatial resolution, with grid spacing close to 125 km in the horizontal and with sixty levels in the vertical, extending from the surface to a height of about 65 km.

The basic analysed variables would include not only the conventional wind, temperature and humidity fields, but also stratospheric ozone and ocean wave and soil conditions. Model snow would fall on the model surface and accumulate; the snow depth was adjusted according to observations when available, otherwise, it was allowed to change slowly to the climatological values. The production of a three-dimensional ozone field consistent both with available ozone observations made by satellite, and with the dynamical state of the atmosphere, was needed for investigations of the composition of the atmosphere. Ozone measurements were preferred over climatology for RTTOV, a radiative transfer model for very rapid computation of radiances at the top of the atmosphere and transmittance profiles for a range of operational space borne radiometers. RRTOV was the result of collaboration between the Centre, the Met Office and Météo France.

A coupled ocean-wave model was introduced. Ocean wave height was based on the use of satellite data from the altimeter onboard the ERS satellite, available from 1991. Before then, the waves were driven by the analysed surface winds. ERS also carried a scatterometer to measure microwaves reflected from the ocean surface.

Additional information would be stored on the quality of the observations used and of the analyses generated.

A sophisticated archival/retrieval system would be used to store the results and make them widely available. Compact sub-sets of the data would be generated for worldwide user on the public data server. Customers and users of the results would gain maximum benefit from the information by being provided with extensive documentation.

ERA-40 built on experience gained with ERA-15. It adopted the innovative variational analysis techniques, especially for assimilating satellite data. New types of observation and improved specifications of sea-surface temperatures and sea-ice distributions were used.

The partners in this project — and indeed many others — supported the acquisition and preparation of the necessary observations, the trial production and validation of analyses, the assessment of user requirements and the general planning of the project. Per Kållberg, Sami Saarinen from Finland and Angeles Hernandez from Spain were scientists in the Group. Graeme Kelly and many other Research Department scientists contributed to the work, often in their spare time. Institutions in China, Japan and the USA funded the secondment of staff to work on the project. Scientists from the Member States contributed as well. Several other institutions provided copies of their archives of past observational data.

Fujitsu Ltd provided substantial computing support for the project: they donated the VPP300 system that had been installed at the Centre before the VPP700. EUMETSAT re-derived winds from Meteosat-2 images for the period 1982–1988. In addition the World Climate Research Programme and the Global Climate Observing System provided funds in support of an External Advisory Group for the project.

Re-analysis projects must proceed at sufficient speed for them not to be continually overtaken by developments in data-assimilation technique and large-scale computing. Funding from the EU enabled the basic production of the re-analyses to be completed within the planned period of about two years, and enabled the necessary validation and demonstration studies to be undertaken.

By the end of 1998, work was underway, preparing the assimilation systems for experiments to ensure that the systems to be used would meet the scientific and technical requirements for the project. The External Advisory Group met in March 1999; help was forthcoming to get missing satellite data, and advice given on what should be archived. Work was under way in the Met Office in the UK, NCEP in the USA, and in the Arctic Climate System Study project of WMO, to specify consistent sea temperature and ice fields for the ERA-40 period.

A vast range of satellite data was used: cloud track winds, total column water vapour content, radiances (which indicate temperatures), ozone measurements and more. The need for a smooth transition from satellite to satellite was given special attention, particularly in the stratosphere where little other data were available.

Preparatory work was required on many kinds of data. Measurements made by radiosondes from different manufacturers had to be made compatible and biases removed, especially for the earlier data. However, by the end of 1999, problems were being systematically identified and corrected, and 25 years of preliminary test assimilations had been completed.

Even though not all the satellite data were ready, it was felt that the remaining problems were manageable, and production began in 2000 with the period from 1989. To have a spin-up, assimilation started from September 1986. The period 1957 to 1988 was delayed pending further studies of the data. By mid-2001, the re-analysis reached to the end of 1990, and the first year, 1957, had been analysed. Data coverage varied a lot during the period; it was notable that — while of course satellite data increased — the coverage of the valuable data from instrumented balloons over the oceans, and from the land area of the former Soviet Union, in the 1950s was far superior to that available in recent years.

Verification showed that the overall analysis quality was higher than expected. However, the value of external validation was soon evident. MPI identified serious deficiencies in the water cycle, which were traced to a coding error in surface-level data as received. Also NCEP reported that incorrect times had been assigned to radiosonde reports. Monitoring at KNMI revealed assimilation of erroneous ERS-1 altimeter ocean-wave-height data. Unrealistic rainfall in the 1990s over tropical oceans was detected by several validation partners' monitoring, as well by the Centre. Assimilation was at times suspended while the problems were addressed.

By mid-2002, production was progressing in three streams:

- 1957 had reached September 1962,
- 1972 had reached September 1976, and
- 1989 had reached April 1997.

Forecasts run from the ERA-40 analyses were superior in many ways to the operational forecasts that had been run before 1999. Detection of tropical cyclones was good.

As planned, production of the ERA-40 analyses from 1 September 1957 to 31 December 2001 was completed shortly before the Fujitsu service ceased on 31 March 2003. Fujitsu in fact allowed the VPP700E computer to remain on site for a further month, and ERA-40 was extended to August 2002.

ERA-40 was the first re-analysis dataset in which an ocean wind-wave model was coupled to the atmospheric model. It provides the longest and most complete existing wave dataset. The ERA-40 ocean wave analyses became the natural choice for studies of the climatology and variability of ocean waves, and for predicting extreme values of wave parameters over the whole globe.

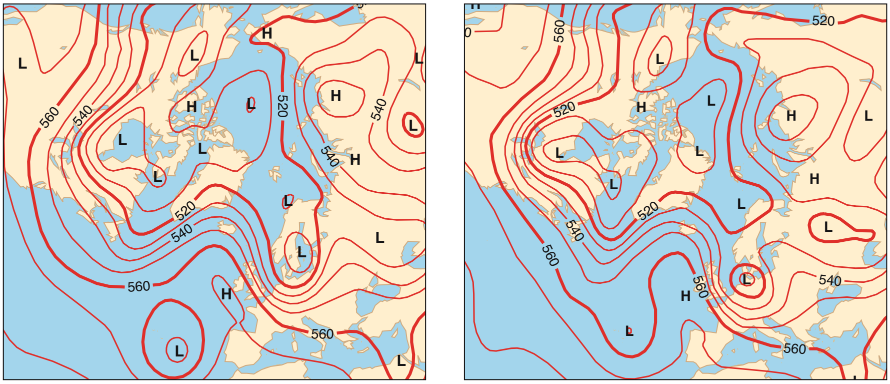
The existence of the ERA-40 dataset allowed detailed studies including "re-forecasts" of major European weather events. To study the Dutch storm of 1 February 1953 mentioned in Chapter 12, the period 1 January to 10 February 1953 was analysed, see figure.

The study shows not only that today's analysis techniques can be used for periods up to 50 years ago, but also that today's numerical prediction models, if available, could have given warning of the weather leading to the floods.

Before finishing this story, we can quantify the rapid advances in technology.

- In a two-year period starting in 1980, a global re-analysis for just one year, the FGGE Level IIIb Dataset, was produced. It added 10 GB — ten thousand million bytes — of data and fields to the Centre's archive.
- In 1994–96, a 15-year period was analysed to give ERA-15, adding 2000 GB of data and fields — about 130 GB per year.
- A 45-year period (ERA-40) was analysed in 2000-03. The archives increased by 70,000 GB, more than 1,500 GB per year.

Finer resolution, together with requirements for a greater range of information from the analyses and forecasts, account for the increases.



The upper-air (500 hPa) three-day forecast for 1 February 1953 is on the left, the ERA numerical analysis for that date to the right. Compare these with the tapestry on page 142, for which a hand analysis of the storm made in 1953 was used in the design. Note the good analysis and "forecast" of the storm made with ERA data. Thus, today's analysis technique can be extended back, to analyse significant historical weather events.

The ease of access to these datasets has improved. The FGGE analyses were available only by mounting up to 50 tape reels. All the ERA-15 and ERA-40 products — about 33 TB, or 33 million million bytes — are available effectively on-line for users from the Member States and Co-operating States. About 400 GB of the most useful ERA-40 products are also accessible freely on-line to researchers worldwide through the ECMWF public data server.

The ERA-40 re-analyses have been used for a wide range of applications: studies on bird migration, to detect climatic temperature trends, on seasonal variations of climate and their better prediction, and much more. Re-analyses in general and ERA-40 in particular has contributed greatly to different aspect of climate research.

The success of the ERA re-analyses and of the first-generation US re-analyses led the Japan Meteorological Agency, in association with the Japanese Central Research Institute of Electric Power Industry, to undertake JRA-25, a re-analysis from 1979 to 2004. A re-analysis from 1948, which is being continued in close to real time, has been produced in the USA by NCEP in collaboration with NCAR. As well, the Data Assimilation Office of the National Aeronautics and Space Administration, USA, has produced a sixteen-year re-analysis from March 1980. NCAR has set up a comprehensive ERA-40 data service for UCAR and other US members of the research community. At the time of writing, around 4,000 users worldwide have downloaded data from the subset made freely available online by ECMWF.

Chapter 15

Archives and Graphics: towards MARS, MAGICS and Metview

The long-term goal was clear: to support the large and growing scientific community by providing a service from the ECMWF databases. Observational data, analyses and forecasts would all be easily retrieved and supplied to support scientific field experiments, climate studies and more. However, it was all a bit chaotic at first. Different ad-hoc solutions were being applied to individual requirements.

Newly recruited research staff started their work in 1975. Research progressed quickly in modelling, data assimilation and other areas. Model software had been acquired and was being modified and tested. The results of experiments had to be stored. They were copied onto tapes. The tapes were stored in John Scott House in Bracknell, at the Rutherford Laboratory after installation of the CRAY-1 there, and later in the computer hall at Shinfield Park. In actuality, they were easily accessible only to those who had written the data to the tapes. So long, that is, as they could remember the formats used to write them, where they were stored and so on.

However, although formats were generally documented, the data were not easily accessible to anyone else. It was not even clear how long they should be kept. Some scientists left the Centre after a short period, effectively abandoning their files. There was no functioning operational archival and retrieval system at the Centre until 1979, when operational forecasting started.

By dint of necessity, the Research Department set up its own system for storing and retrieving their data, interpolating data to give meaningful fields, and plotting and displaying the results. This system, advanced by the standards of the time, was used for the “Spring Experiments”, mentioned in Chapter 7, FGGE work and other Research Department activities. On the whole, it worked fairly well. However, the system was still based on private files. Researchers had to spend more and more of their valuable time in housekeeping their private archives. It was not a satisfactory permanent solution.

Besides the practical danger that the archives of the Centre would eventually become a black hole, into which data would be placed, never to be seen again, there was a strong legal and political need for a proper archive. As early as 1970, the Project Study Plan for the Centre specified, after "better medium and long term forecasts for Europe and training facilities for post-graduate scientists", the requirements for a functioning archive.

Data bank

1. *Aims*
2. *Nature and quantity of information to be stored*
3. *Means:*
    - *material requirements*
    - *personnel*

It was planned the Centre would have an efficient data bank for the use by meteorologists in the Member States. The Convention as adopted in 1973 specified among the objectives of the Centre: "to collect and store appropriate meteorological data", and to make these data "available to the meteorological offices of the Member States". They would no longer have to depend on the service provided by the World Meteorological Data Centre in Obninsk, Russia. With the technology of the time, for example, Obninsk could not read 200 bpi tapes sent from Regional Meteorological Centre (RMC) Bracknell — although they could read those from ECMWF.

A group of experts met in July 1975 to consider requirements for graphical systems, both for the interim period leading up to the completion of the Centre's building, and later when the Centre's own computing facilities had been installed. Requirements for chart production, volume of output and coding for graphics were discussed. Recommendations were made on hardware and software, leading eventually to the acquisition of Versatec 8122 online electrostatic plotters being installed in Shinfield Park, superseding the Varian Statos offline plotters at Rutherford Laboratory.

Design of the ECMWF Meteorological Operational System (EMOS) began in early 1977, when the newly recruited staff of the Meteorological Applications Section of the Operations Department were in Fitzwilliam House in Bracknell, working under the direction of Joël Martellet, recruited from Météorologie Nationale, France. By October of 1978, even before the move to Shinfield Park, the plan for EMOS had been finalised. EMOS had the same logical structure required for any large operational numerical forecasting centre:

- System for acquiring weather reports
- System for pre-processing and quality-controlling the reports
- Reports Data Base (RDB) into which the reports were streamed

- Analysis and Forecast system
- Post-processing system, to prepare forecasts for despatch to the Member States and for archiving
- System for disseminating the analyses and forecasts
- Archiving system
- Scheduling system, called the “Supervisor-Monitor-Scheduler”
- Operational Watch

The “Supervisor-Monitor-Scheduler” (SMS) was the software that ensured proper synchronisation and scheduling of the operational programs. In autumn 1979 the entire complex system was ready for implementation. The Operational Watch provided information to the meteorologist on duty in the Meteorological Operations Room: “information on request typed on a keyboard from an alphanumeric VDU or a graphical VDU terminal”.

One important component of EMOS was the archiving system. It was planned that “8 to 10 6250 bpi (bits per inch) tapes will be mounted every day” to archive the weather reports from three days earlier, together with the current day’s analysis and forecasts. For security, the tapes would be duplicated. Weekly or monthly, a third copy would be made and stored outside the computer hall. Punch cards with various directives would be used to extract observations, analyses or forecasts.

A system “GETDATA” was designed and implemented by analyst John Chambers in the early 1980s, to give easy access to the archived data. It located the data that had been produced recently and was still held on disk, and the archived data that had been stored on tapes. Which tape held which data was recorded in a “master index”, providing a primitive database. The tape reels were kept on racks in the computer hall. Following a request for data, an operator received a printed tape ID number. The operator retrieved the tape and loaded it on a tape reader. When a faulty tape was discovered it was discarded, the backup immediately copied, and the copy used to meet the request. GETDATA worked well for a time. Its users were on the whole happy with the system, and soon became familiar with the directives used to retrieve data. The user no longer had to be aware of the operational timetable, of the methods and formats used to store the different kinds of data, or of technical changes to the archives.

However, it had its problems. Data from experimental forecasts were being stored in different formats, and some formats were dependent on the hardware and software of a specific computer system. Special routines were required to access the data. An additional irritant for Member State scientists was that they were charged units from their allocation of computer resources, not only for the data retrieved, but also for the computing resources used to carry out the retrieval. These were unknown in advance, and could be large. A consultant from the University of Reading developed a utility called "FINDATA" that got around this. A short FINDATA job was submitted, costing only a few units, that launched a GETDATA request, and the user got his data without paying the unfair overheads.

By the standards of the time, enormous amounts of information were being stored. By mid-1983, it was foreseen that "the rate of growth of archived data is such that the tape library will be completely full within two years".

Visualisation tools were required for research and for monitoring the operational forecast. No acceptable package was available. In-house development started. This led over the years to advanced packages that were tailored to the developing demands from the research and operational users at the Centre and in the various institutes in the Member States.

In early 1982, a "GETPLOT" system for plotting fields was introduced. Now analyses and forecasts retrieved from the archives could be easily plotted. Later, overlaying of fields, plotting observations onto plotted fields, data coverage maps and cross-sections showing vertical slices through the model atmosphere were added. By 1985, GETPLOT had been replaced by the Meteorological Applications Graphics Integrated Colour System (MAGICS), a powerful software system for plotting map contours, satellite images, wind fields, observations, symbols, streamlines, isotachs, axes, graphs, text and legends.

As the scientists in the Research Department completed enhancements to the analysis and forecasting systems, the improvements had to be introduced into the operational forecast running under EMOS. There was of course a wonderful system in place to make introduction of the changes foolproof. But of course, any system can be defeated! And it was, an embarrassing number of times. We will draw a veil over most of these, but one was memorable.

In principle, changes were made once weekly, on Tuesdays, thus avoiding weekends; the rest of the working week was available to sort out unforeseen consequences. One analyst needed to make just "one tiny change" to adjust a single archive model level on a Friday afternoon before going on vacation to an isolated telephone-free farmhouse in France for a week. This was before mobile telephones were available. It took him several weeks' work, including re-running a number of complete forecasts, to regenerate the missing fields from the archives that resulted from his "one tiny change".

GETDATA was beginning to show its weaknesses as the volume of the ECMWF archives, and demand for access to them, grew. Use of magnetic tapes meant that data were organised sequentially; this was far from ideal. The limit to the number of tapes that could be mounted for reading was being reached. A more comprehensive system was clearly required. It was "planned to make it a major objective of the Centre over the next few years to increase its on-line storage capacity and its data handling capability". Work began in 1982, with Peter Gray and Dick Dixon of the Computer Division starting to make plans.

After some consultation with the Director Lennart Bengtsson, Daniel Söderman decided to set up a project team, with John Hennessy as project leader, to design and implement the application software for the data-handling project. Hennessy later became Section Head of the group in charge of the archives. The team started work in November 1982. Appropriate meteorological scientists at the Centre and Computer Division staff were nominated to liase with the project team.

During its 17th session, the Council, following the recommendations of its Technical Advisory Committee, authorized the Director to conclude the contract for a Data-Handling Subsystem "after completion of a detailed study to be made jointly with IBM UK Ltd. to confirm that the performance of the system will meet the Centre's requirement". The study was performed by Dick Dixon and David Dent from ECMWF and Mr N Bartlett and Mr P Goody from IBM UK Ltd. during the period 23 March to 3 June 1983. The 24-page report of this study concluded: the Common File System (CFS) "can be implemented and maintained on the proposed hardware configuration using a general-purpose network. The CFS package (including its user interfaces on the computers connected to the Data Handling Processor) when suitably modified will meet ECMWF's functional requirements. The manpower required to make these modifications is estimated at approximately 76 man-months." The projected requirements had been estimated at about 5,000 MB stored and 10,000 MB retrieved daily.

Choosing CFS, the Common File System, was a groundbreaking decision on the Centre's part. As far as is known, no other meteorological centre was using, or even contemplating, any comparable data management software at that time. The Centre had a unique opportunity to shape the way this product would develop. It grasped the opportunity by providing input on the specification of such new features as magnetic tape support, tape "families" and multiple partial data access. ECMWF staff members were able to collaborate on developing the code for these features: the CFS code was well-structured, it was written in the PL/1 high-level programming language and it had a reasonably comprehensive set of internal documentation, produced by staff at the Kirtland Air Force Weapons Laboratory and at Los Alamos Scientific Laboratory (LASL), the originator of CFS. Several LASL staff members visited the Centre for weeks at a time to help in this joint venture. One in particular, Emily Willbanks, had a long association with the Centre that continued even after CFS was finally retired from service.

The Meteorological Archival and Retrieval System (MARS) introduced in June 1985 ran on an IBM/MVS mainframe: an IBM 4341, and used CFS as the underlying data storage management software.

Originally, MARS was designed to handle field data only. It was extended in the following years to become a complete archive, which would store, and retrieve, vast quantities of data. The meteorological observations that had been used as model input, as well as all analysis and forecast fields, results of research experiments, Member State results from work on the Centre's computers, data from the Re-analysis Project, and more were eventually all in MARS.

The IBM 4341 system had 8 MB of memory, an online capacity of 12.5 GB of disk space, six IBM 3420 tape drives and an IBM 3851-A01 mass storage system with sufficient cartridges to hold 35 GB; soon extended to 105 GB. This machine was the first robotic tape device that the Centre installed. A key element in the implementation of MARS was the development of the "data highway" to provide the necessary high-speed links between the Centre's different computers; this would be the Centre's first Local Area Network (LAN).

In 1985, the Commission for Basic Systems (CBS) of WMO recognised the need for new codes for efficient transfer and storage of meteorological data between and within data processing centres. Different codes would be required for observational data on the one hand, and for forecast and analysis products on the other. The Centre decided that where possible, its archives would store data in internationally agreed forms. Daniel Söderman was the originator of a new efficient code for forecast and analysis products "Grid In Binary" or GRIB. ECMWF staff participated in the earliest stages in the development of GRIB. With Söderman's strong backing, this code was approved by CBS in October 1985, and the related Binary Universal Form for Representation (BUFR) of meteorological data, was approved in early 1988.

At the beginning of MARS development, neither GRIB nor BUFR had yet been developed, although an experimental version of the GRIB code was available, and this format was used. Partly because of the Centre's experiences with the code, some changes were made before the code was adopted by WMO. In the absence of GRIB and BUFR, MARS formats were to be machine-independent ECMWF binary format.

In MARS, the underlying data organisation was hidden from the user. A MARS retrieval was expressed in meteorological terms (date, parameter, level) and not in terms of "files". The data were stored using standard meteorological formats, which are machine independent.

Data storage design was logical. Frequently-used files were held on-line on disks. Less frequently used files were kept on cartridges in the mass storage device, together with large files that would use up too much valuable disk space. Files that were used only infrequently were stored on magnetic tapes. Since no manual intervention was needed to mount the cartridges, data on these were effectively on-line, but took longer to access than the data on disk. The CFS software maintained this hierarchical file system. The remaining data were kept on tapes in racks in the computer hall, requiring an operator to retrieve and mount the tape in response to a request for little-used data or very large files.

Related to MAGICS was Metview, the ECMWF visualization software, developed under a co-operative project between the Centre and the Brazilian Centre for Weather Prediction and Climate Studies (INPE/CPTEC), with assistance from Météo France. Metview was designed to retrieve data from MARS, and tranform it in a form that MAGICS could handle. It matured to become a highly adaptable modular package, with the aim of providing "desktop publishing" capacities to the operational and research meteorologist. The computational capacity of Metview rested on an easy to learn, high-level macro language particularly adapted to weather data. Metview, MARS and MAGICS are used at the time of writing to produce the plots for the ECMWF websites. Metview is the user interface, used to request for example some forecasts. The Metview request goes to MARS to retrieve the fields from the archives. It then uses MAGICS to create the contours, titles, map background and so on. Finally it puts the forecasts on the user's screen or plotter.

Beginning in 1989, all field data previously retrieved by GETDATA, with the exception of forecasts from the years before 1985, were gradually converted to GRIB format and re-archived under MARS, thus extending the MARS archive back to the beginning of the Centre's operations. Observation archiving in MARS started in 1990. Observations from earlier years were systematically converted to BUFR and archived. Not only were the observations stored. The observations went through many quality control checks for accuracy before being used in the analysis; the results of all these checks, including substituted values, flags indicating the accuracy of the data, and bias information were also stored in the archives, never to be discarded.

MARS retrievals were interfaced to MAGICS, providing an impressive plotting and display service with a simple common interface between the two. By 1987, MARS retrievals were being used freely and often by Member State users.

To meet requests for data quickly and efficiently, work began in 1985 to create a series of special compact data sets that were to be provided by the ECMWF Data Services, together with software tools allowing direct extraction, or simple tape copying, of reasonable subsets of data in internationally accepted formats. These included high-resolution global analyses from the FGGE year, data sets from the Tropical Ocean–Global Atmosphere (TOGA) experiment, a large set of data from over Europe collected during the Alpine Experiment (ALPEX), and analyses and forecasts from other global forecasting centres such as Bracknell and Washington.

By now, the volume of tapes was beginning to present a storage problem in the computer hall. Further, in the mid-1980s it was felt that the CFS system would need replacement within a few years time. The Centre embarked on a study of available systems. Few of the systems on the market could meet the end-of-decade requirements, and those that could were inferior to the existing CFS system. The study showed just how good the existing system was! The initial assumption that the market would provide, and clearly indicate, an appropriate successor, was quickly proved over-optimistic. Plans were made to extend the life of CFS. ECMWF staff visited Los Alamos National Laboratory, and vice versa, working on joint development projects to enhance, and extend the usability of CFS.

In June 1987 an IBM 3090-150E was installed; this replaced the IBM 4341 in October. Difficult technical work followed throughout 1988, implementing a new operating system, required to speed up access to the archives. A new utility "ECFILE" for storing and retrieving data not suitable for saving as MARS data started to be used from October 1988; by then 11 GB of data were being transferred daily between the CRAY X-MP/48 and the data archiving system.

In December 1990, Council approved the purchase of an automated cartridge library system from Storage Technology Ltd, to improve the Centre's archival storage. Four of these very large modules or silos had been installed by September 1992. On 4 January 1992, an IBM ES/9000-580 was implemented, and immediately improved the performance of the data handling system. The IBM ES/9000-580 was upgraded to an IBM ES/9000-720 on 29 January 1994. In 1998, an IBM SP2 system replaced the ES 9000 data-handling computer.

MAGICS was being used by thirteen Member States as well as the National Meteorological Services of Australia and India by 1989. MicroMAGICS, a version of MAGICS to be run on IBM PCs, was developed by the Brazil's INPE/CPTEC in that year. In 1989, GETDATA was finally brought to an end.

The Centre was now dispatching several hundred tapes of archive data to users worldwide each year. The Cyber tapes were copied, over a period of months, to the high-density data handling tape cartridges. About 25,000 ½-inch 9-track tapes were disposed of in 1989.

In 1994, MARS software was enhanced to allow ECMWF staff to access the archives from their newly installed workstations. The beginning of serious work on the Re-analysis Project meant many internal changes to the MARS system. Further, the MARS client software had to be ported to a new computer, a Fujitsu VPP300/16 that was installed to port codes and enable the Centre to become familiar with the Fujitsu UXP/V operating system that would be installed on the VPP700 mainframe computer later that year.

CFS was becoming increasingly difficult to support. Los Alamos was moving to a new product, the High Performance Storage System (HPSS), and no new development was being done on CFS. It was becoming obvious that the Centre would have to move to a new system for its data management requirements. In 1995, the Centre concluded a contract with IBM to supply a new Data Handling System (DHS), which would eventually replace the CFS-based system. The new DHS would use the Adstar Data Storage Manager (ADSM) instead of CFS as the underlying management system used by MARS. A new utility was developed called ECFS, the ECMWF File Management System, which was to become the replacement for ECFILE. ADSM ran on AIX, IBM's Unix operating system and could be distributed over a set of servers, rather than having to rely on a single mainframe as did CFS. This meant that the system could grow incrementally, purchasing server hardware year by year as necessary, rather than having to buy a large mainframe from time to time.

In 1995, Baudouin Raoult and Manuel Fuentes began design of a new MARS system. The system was completely rewritten using Object Oriented design in the C++ programming language running under Unix. By 1997, the new version was ready for trial, and the "back-archiving" — copying to new media — from CFS to ADSM started. At the end of 1998, the CFS-based MARS system was switched off, ending 15 years of exceptional service. A total of 32 TB (32 million million bytes) of data was back-archived in 18 months. The Object Oriented approach allowed rapid development of MARS. A web interface was created, giving users the ability to navigate through the vast archive, and retrieve and plot sample fields. A new system to index fields by parameter, data source or time was quickly being used by many scientists to find data in the archive.

Moving to the new data archiving system was not without its problems. The Centre was pushing the capabilities of the hardware and software to the limit. To keep the number of magnetic tapes manageable, new magnetic tape technology with increasingly dense tape media was used. At first 10 GB of uncompressed data could be held on a cartridge, then 20 then 40, until at the time of writing 300 GB of uncompressed data are written onto a single IBM 3592 cartridge. As an early adopter of this technology, the Centre saw more problems than it would have had it waited for the technology to become mature. At times, three copies of the data were stored, to guard against loss due to tape failure or unrecoverable parity errors. Back-archiving had an additional advantage: it ensured the integrity of the data. The more dense media reduced the physical size of the tape archive.

The ECMWF Data Services, set up to deal with requests for archive data from research scientists worldwide, extended its work to include supply of software developed at the Centre, including MAGICS, to meteorological institutes. Further it found itself becoming more involved in assisting the Member States in their provision of real-time data and forecasts to their clients, simplifying the ECMWF Catalogue of Real-time Products and setting up an on-line system for costing items from the Catalogue.

By the year 2000, the MARS archive held 185 TB of data. In answering requests to save and retrieve data, the system typically handled up to 18,000 operations each day with up to 200 GB of data being transferred. The hourly rate peaked at over 1,000 save/retrieve operations, transferring 20 GB of data. The ECFS archive held 50 TB of data in 4.5 million files, transferring 150 GB of data daily in about 10,000 files.

However, ADSM was not designed for use in the way that the Centre was using it. Developments planned by IBM that would have helped considerably were shelved. The system struggled whenever a file-system grew to more than a million files; the support staff spent too much time in problem-solving. The Centre issued an Invitation to Tender for the "Acquisition of a Replacement Data Handling System" at the beginning of 2001. Before that, use of the existing DHS was painstakingly investigated. Logs were analysed and statistics were produced. From these, the likely trends out to 2007 were deduced.

In late 2002, following a competitive tender, a new IBM Data Handling System was installed, the cornerstone of which was the HPSS, the High Performance Storage System.

Once again all the archive data had to be transferred to the new system. The back-archiving and migration from ADSM to HPSS was accomplished smoothly and transparently, a task that taxed the skill of the analysts of the Computer and Meteorological Divisions. The users of MARS and ECFS were entirely unaffected by the work. MARS data were the first to be migrated; this was accomplished in 2003. However, there was a delay in the migration of ECFS data until a new version of HPSS was installed, better suited to how ECFS stored and accessed data. The Centre had been the "beta-test" site for this new version throughout most of 2003. Other HPSS sites were pleased with the Centre's role in helping to ensure that the product finally produced was stable and secure.

The ECFS migration took about ten months to accomplish throughout 2004. Both MARS and ECFS were designed so that the underlying data structures could be re-arranged while allowing the end user to use the same data request and without preventing access to the data, even temporarily. Because MARS and ECFS are so flexible in this respect, the same data could exist in both the old ADSM-based system and in the new HPSS-based system concurrently. Once the analysts were confident that the two copies were identical, the MARS or ECFS server could be instructed to start serving the data from the new HPSS system.

The Centre's service to the research community was improved by developing a data server to supply immediate, free and direct access to data sets on-line.

At the time of writing, MARS holds observations from five decades. On 17 October 2004, MARS passed the symbolic milestone of 1 PB of primary data — not counting backups — where 1 PB is 1024 TB or 2^{50} bytes. MARS had at that time around 8.6 billion (8,600,000,000) fields of common weather variables — wind, temperature, rain — and others not so common — altimeter corrected wave height, depth of ocean salinity maximum, ozone mass mixing ratio etc. ECFS had about one quarter that amount of data, held in over 12 million files.

This mountain of valuable information can be mined for many kinds of research into our atmosphere and oceans. It is easily accessed through a standard web browser. A client can follow how his or her request is being processed by the MARS servers, and can reformulate later requests to get the most out of the system.

MARS has proved itself to be a flexible, reliable, user-friendly system. It has been able to accommodate many new kinds of data: observations from many satellite instruments, two-dimensional wave spectra, reanalysis data, ensemble forecasts, monthly and seasonal forecasts, output from special projects such as DEMETER, PROVOST, HIRETYCS (High Resolution Ten Year Climate Simulations), and much more. One of its great strengths is the backward compatible interface: a retrieval request that was submitted in 1985, if submitted in the same form today, would still work. MARS software has become an integral part of many Member States' systems, and is also used in the Bureau of Meteorology in Australia. It stands the core of the Centre's manipulation of its data; development will continue in the future.

Chapter 16

The computer system: CDC, Cray, Fujitsu, IBM

There are three basic components of the Centre's work:

- Observational data from the atmosphere, land and oceans.
- Advanced scientific software.
- Powerful computer system.

In this Chapter we review the development of the computer system.

As we have seen, the first version of the ECMWF model was developed in the period 1975 to 1978 on a Control Data Corporation 6600 computer, one of the most powerful systems available at that time. A Service Agreement with Control Data Limited, in force from August 1975, provided access to the machine. The Agreement, which initially allowed 40 hours use per week, increasing to 70 hours per week from August 1976, was changed to a Lease Agreement in December 1976; this gave the Centre unlimited access to the machine. With the early version of the forecast model, 12 days of elapsed time was required to produce a ten-day forecast! In addition, the Centre negotiated limited time on the IBM 360/195 – 370/158 systems at the Met Office in Bracknell.

In May 1975 the Centre issued preliminary notification to manufacturers of its requirements for a computer system to be installed in 1978. Exploratory talks with interested manufacturers followed. Tor Bloch, of CERN, and David Burridge visited the United States in November 1975. There they surveyed the state of development of the most powerful computers. Burridge noted that "the software team at Cray Research are under considerable pressure and are in a state of high tension!" Their Report was followed by six months' intensive effort by staff of the Operations and Research Departments, assisted by experts from the Member States: Dr D. Henze (Germany), Mr A. Monod-Broca (France), Mr R. Longbottom (UK) and Mr N. Spoonley (UK), as well as Tor Bloch. Their work led to the issue in July 1976 of an Invitation to Tender for the computer system, which was sent to all Member States.

The minimum specifications for the main computer were:

- speed 50 MIPS (million instructions per second),
- central memory one million words,
- mass storage 200 million words,
- card reader capable of reading 1,000 cards per minute, and
- a line printer capable of printing 1,000 lines per minute.

A front-end computer system was required to control the work of the main machine, with:

- speed 3 MIPS,
- central memory two million bytes,
- mass storage 3,000 million bytes,
- three card readers, each capable of reading 1,000 cards per minute,
- a card punch,
- nine 6,250 bpi (bite per inch) 9-track magnetic tape units,
- four line printers, each capable of printing 1,000 lines per minute,
- 12 visual display units (VDUs), a microfilm recorder, four plotters, and
- a 20-line telecommunications system operating at 9,600 bits per second bps.

A nominal data transfer rate of 10 to 20 million bits per second (bps) between the main and front-end computers would be required.

There were three contenders for the main computer.

- CDC Star100C from Control Data Corporation
- CRAY-1 from Cray Research
- TI-ASC from Texas Instruments — the "Advanced Scientific Computer"

No more than half a dozen CDC Star100 machines, designed by Jim Thornton, were sold. The Star100C later evolved into the CYBER 205 and eventually into the ill-fated ETA line of computers.

The CRAY-1 was the brainchild of Seymour Cray, the designer of the CDC6600 and CDC 7600 during his time at Control Data. He set up his own company (perhaps surprisingly, with a small amount of backing from Control Data - then a competitor) to build this revolutionary vector computer.

Just over half a dozen TI-ASC computers were built. Most were used for oil reservoir simulation and exploration data processing. None were sold after the arrival of the CRAY-1, and Texas Instruments then withdrew from the supercomputer market.

Staff of the Operations Department made a second visit to the USA in September 1976. As well as the main computer manufacturers, they visited Los Alamos Scientific Laboratory, NCAR, the Naval Research Laboratory and NASA Langley Research Center. On 11 October the tenders had been received, and a Tender Evaluation Board had prepared its recommendation on the choice of computer.

The signing of the contract for the CRAY-1 on 22 June 1977 by Prof Aksel Wiin-Nielsen and Mr Seymour Cray.

In November 1976 the Council created its first Advisory Committee, in addition to the two mentioned in the convention: the Scientific Advisory Committee and the Finance Committee. This new Committee was the "Advisory Committee to assist in assessing the financial aspects of the acquisition of the Centre's computer system". The Committee, in co-operation with the other two Committees, worked swiftly and efficiently under its chairman Mr M. Deloz from Belgium, and with Mr J. C. Hirel from France as chief technical advisor. By March 1977, the Council was able to authorize the Director to send a Letter of Intent to Cray Research Incorporated, informing the company of its decision in principle to acquire a CRAY-1 computer. The company was called "Cray"; the computers were called "CRAY".

The choice of a front-end computer was not as clear-cut. The recommendation to Council was for a CDC CYBER 175. There was some debate in Council on the possibility of the Centre acquiring a European machine, in accordance with the hope expressed in the Convention relating to "the development of European industry in the field of data-processing". In particular the UK delegation supported a computer manufactured by ICL. The Advisory Committee, with the exception of the UK representative, concluded that either a CYBER 175 or a CYBER 174 should be selected as the front-end system. The UK representative stated that "the ICL proposal could be regarded as fully acceptable". Council agreed that further tests of the ICL 2976 and 2980 computers be made before reaching a decision. At its meeting in May 1977, after some debate on the outcome of the tests, and taking into account the extra work and an anticipated delay of more than a year in linking the ICL and CRAY-1 computers, Council voted in favour of the CDC CYBER 175. At this meeting, Council also approved the contract with Cray Research.

David Dent from the Centre worked at Chippewa Falls from April to October 1977, learning the CRAY software, and assisting his colleagues who were visiting Cray to carry out numerical experiments. The software was rather primitive at the time with new versions of the CFT compiler being installed almost daily. A tri-partite agreement was signed between ECMWF, Cray Research Inc. and Control Data to develop the "station software" that would enable the CDC computer to act as a front-end for the CRAY-1. From November 1977, the Centre's scientists had access to Cray's Serial Number 1, the first production model of the CRAY-1 series to leave the factory in Minnesota. It was installed in the Rutherford Laboratory. The CYBER 175 was installed there in January 1978. The CDC 6600 service then ceased. These machines were used to test the programs required to produce an operational forecast, allowing progress to be made in the work required for implementing the operational suite.

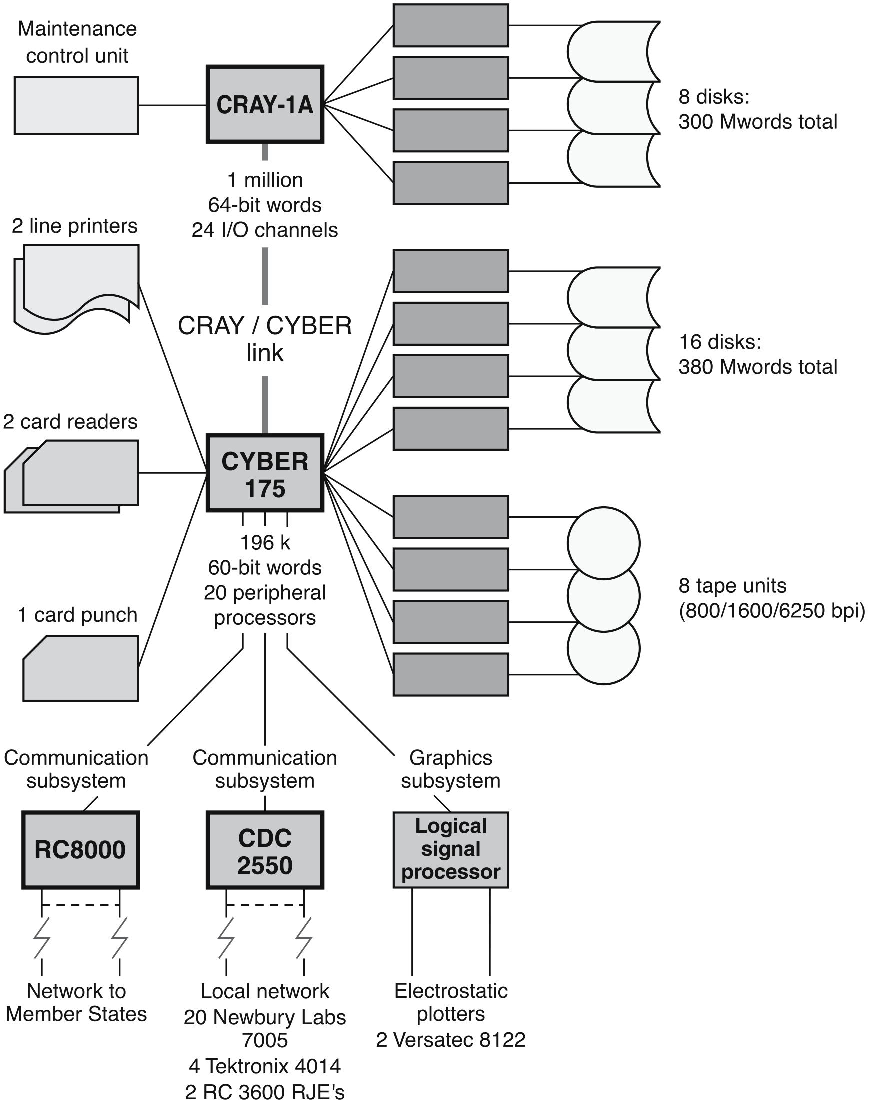
Wiin-Nielsen signed the contract with Control Data Limited on 28 November 1977. The following morning the Control Data account manager telephoned Wiin-Nielsen and asked if he could agree to a second signing of the contract. He sheepishly admitted that after celebrating the historic deed he had managed to mislay the original document somewhere on the London Underground system!

The staff, apart from the computer operators working at Rutherford, was still in the temporary offices at Bracknell. Remote job entry terminals and VDUs were connected to the Rutherford facilities. Data were interchanged via magnetic tape, with a courier service between Bracknell and Rutherford. The prototype CRAY-1 gave an impressive average overall availability of over 95%. The availability of the CYBER — a tried and tested machine — was more than 99%.

Wiin-Nielsen, with the advice of Jean Labrousse and Lennart Bengtsson, decided at an early stage that portability was of paramount importance for the Centre's software. For this, good documentation of the software would be vital. FORTRAN, a symbolic programming language, was chosen, against the advice of some colleagues in the Met Office that the Centre should use assembly language instead, in order to squeeze the last ounce of processing power from the machine.

The Centre's own CRAY-1A, serial number 9, was installed in Shinfield Park on 24 October 1978. This was the first export order for a Cray computer.

Provisional acceptance was completed on 10 November. A full computer service started on a trial basis in December, despite the limited staff then employed. The Rutherford service ceased. Serial Number 1 had some hardware modifications made to it to make it more suitable for crypto-analysis work. It was then shipped to a site belonging to the UK Ministry of Defence, prior to their installation of a CRAY-1 in March 1979.



The computer system in 1978.

The CRAY-1A was a single processor computer with a memory of 8 Mbytes and a disk subsystem totaling 2.4 Gbytes. With a clock cycle time of 12.5 nanoseconds (equivalent to 80 MHz) and the ability to produce two results per cycle, the system therefore had a theoretical peak performance of 160 Megaflops. Running the operational forecast model, the machine was capable of a sustained performance of 50 Megaflops (50 million floating-point arithmetic calculations per second). Its reliability was over 99% at the time of its final acceptance on 6 February 1979. The mean time between hardware faults was 94 hours during its first year.

At a meeting with ECMWF in 1976, Seymour Cray was asked why his machine used only parity error detection on its memory subsystem rather than SECDED: Single Error Correction Double Error Detection. His response was "Speed!" — SECDED would add an extra clock cycle to every memory reference. His questioner commented that parity errors were the single most common cause of system crashes on the CDC 7600 at the University of London Computer Centre, a computer system that Cray himself had designed while at Control Data Corporation. Cray made no response, but he obviously took note of the comment; all Cray machines apart from Serial Number 1 of the Cray-1A used SECDED.

When the Centre delivered the first operational medium-range forecast to its Member States on 1 August 1979, a ten-day forecast required about five hours of CPU time, a reduction by a factor of 50 in the time required on the CDC 6600.

Compared to today's systems, the Cray Operating System (COS) was fairly rudimentary. New versions were released regularly, in the very early days weekly, even daily. These were tested as thoroughly as possible, given the need to take dedicated "system sessions" lasting up to three hours. Although some critical problems were indeed isolated during the testing phase, it could and did happen that the new system would be put into production only to be withdrawn the same day due to bugs being discovered. Peter Gray, then the Head of Computer Operations Section, was well remembered for asking "Why wasn't this found in testing?" He knew of course that no matter how much testing was done in the limited time available, this did not compare to running a full and varied production workload on the machine. Reverting to an earlier level of the system was in general fairly easy: loading a different removable disk pack on the disk drive of the Data General Eclipse control workstation and re-booting the CRAY machine from that software.

Member State use of the system was limited in the beginning due to the lack of high-speed telecommunications links. Council had a lengthy discussion in May 1978 on the Report of its "Advisory Committee on the Use of the Centre's Computer System by the Member States", presented by its Chairman, Fred Bushby of the UK. The Committee had recommended that not less than 25% of the time should be available for the Member States. In December 1978, Council agreed with this proposal, with an allocation of 10% for "Special Projects" to be approved by the Council, the remainder to be split: 35% equally among the States and 65% allocated according to the financial contributions.

Although the UK telecommunications link was installed in March 1979, delays in establishing it meant that data were still being transferred by magnetic tape in November. The link became fully operational only at the end of April 1980. The link with Sweden was installed and working in October 1979, followed by Germany in November 1979. Member State visitors to the Centre also used the system. In all they used only 6% in 1979. The operational suite used 34% while the remaining 60% was taken by the Research Department, including the FGGE project.

In October 1979 the Centre hosted the fourth Cray User Group (CUG) meeting. Most of the sites that had installed CRAY-1 systems were represented; Cray Research sent a large proportion of their development team to the meeting. Los Alamos Scientific Laboratory, NCAR and the National Magnetic Fusion Energy Computer Centre had hosted the three previous CUG meetings. As was already customary, a social evening was arranged, in this case at a country pub in the Chilterns to the northwest of Reading. A coach was arranged to take the delegates and Cray employees to the pub, at the top of a steep hill. It was a lively evening. The locals taught anyone willing to learn how to play the pub games of darts, dominoes, shove-ha'penny and cribbage. Peter Gray, who had organised the evening, was horrified when the coach driver quietly took him aside after they had arrived at the pub, and informed him that the brakes on the coach had failed as they were climbing the hill. If the pub had been at the bottom of that very steep hill instead of at the top, Cray could have ended up without a software development team, and the future of the company could have been very different!

Geerd-R. Hoffmann from Germany succeeded Rob Brinkhausen as Head of Computer Division in 1980, and held the post until 1997. Hoffmann was renowned as a skilled negotiator in the many complex discussions with manufacturers over the years. The continuing success of the Centre in acquiring the best computer equipment available at the time is in no small way attributable to him and to his successor Walter Zwieflhofer.

In the following years, use of the system steadily increased. Hardware and software were upgraded to meet requirements. In 1981, the CRAY online disk capacity was increased by 75% and that of the CYBER doubled.

By 1981 there was a terminal in the office of each scientist and programmer. At the end of that year, a CYBER 730E — later renamed the 835 — was installed to ease the interactive workload on the 175.

In 1982, the Centre issued an Invitation to Tender for a data handling sub-system and a local computer interconnection sub-system. At the end of that year, a VAX 11/750 mini-computer was installed for graphical applications.

In spring 1983, it was decided that a Loosely Coupled Network (LCN) would be acquired from Control Data Ltd to provide high-speed file transfer between the different parts of the system. At the end of the year, a high-speed coaxial trunk was delivered as the first phase of the LCN. Installation of more components continued in the following year.

During 1983, time was rented on the CRAY-1S computer at the Atomic Energy Research Establishment at Harwell, 50 km from the Centre. A smooth-running and efficient procedure was developed to enable this remote machine to be used. Data were transferred on magnetic tape. In all 285 research forecasts to ten days were run on this machine.

Cray was an impressively successful company; it had grown from 50 employees in 1976 to more than 1,300 in 1983. From its contacts with Cray, the Centre was made aware of the development of a new kind of machine, the dual processor CRAY X-MP, MP standing for "Multi-Processor". Benchmarking exercises during the second half of 1982 confirmed that this machine was fully compatible with the CRAY-1A, and contract negotiations with Cray were begun. One very advantageous aspect of the contract was the lower maintenance charges that the Centre negotiated. Ambitious plans were made for development of the ECMWF computer system, in effect, the replacement of all of the Centre's first-generation system. The replacement was completed by mid-1984.

In November 1983, a dual processor CRAY X-MP/22 was installed, which entered service on 13 March 1984. This had two CPUs and two million (8-byte) words of main memory, thus "22" — 2 CPUs, 2 million words (16 Megabytes). It had 128 Megabytes of secondary memory supplied as a Solid-state Storage Device (SSD). Its clock cycle was 9.5 nanoseconds (105 MHz), with a theoretical peak performance of 400 Megaflops. Its reliability was better than that of the already reliable CRAY-1A, with a mean time between hardware failures double that of the 1A. Its throughput was 3.3 times that of the CRAY-1A, exceeding the criterion laid down at the time of acquisition. Although the CRAY-1A was retained for three months as a back up, it was never required to fill this role.

Financing of the purchase of the CRAY-XMP was rather interesting. In November 1983, Council authorized the Director to purchase the dollars in stages in advance by means of forward purchase contracts. About US$9 million was due in May 1984, the remaining US$1 million in August. Although it was planned to purchase the May requirement in five equal amounts in each of the months January to May, the Director decided to wait until March, after the acceptance tests had been passed, before starting the purchase. As it happened the delay was to the Centre's advantage, because the exchange rate pound to dollar went from US$1.40 to US$1.48 from January to March. However, rapid and significant exchange rate fluctuations at this time made the experience nerve-wracking for those involved; they were more used to dealing with scientific and technical rather than currency problems!

The Centre used the system to pioneer the operational use of multitasking, by having two separate tasks running, one on each processor. One task handled the Northern Hemisphere, the other the Southern Hemisphere, giving a speed-up of almost a factor of two over the single-tasked code. The approach was generalized so that any even number of processors could be used, processing several rows simultaneously. Small inefficiencies arose, since the concurrent tasks required slightly different amounts of computation time — mainly because convective activity differed over the globe — but overall, a high average Central Processing Unit (CPU) utilization was achieved.

Additional improvements introduced with the X-MP system included an I/O (Input-Output) Subsystem, which allowed the disks and network devices to be handled more efficiently, and the SSD, which provided facilities for I/O at speeds substantially faster than those achieved using disk. While greatly improving program performance, the SSD complicated the scheduling of jobs on the system. The Centre's analysts had to develop code that was incorporated into the Cray Operating System (COS), used to checkpoint the SSD memory, to ensure that it was available for use when the operational suite of jobs needed to run. This code was then handed over to Cray for inclusion in the next official release of COS.

Graphical applications were vitally important. Internal and external workshops were held to consider the need for a unified graphical system for the Centre. The basic graphical software would be proprietary, while contouring, observation plotting and so on would be developed within the Centre. The first graphics hardware and software at the Centre was developed in the earliest years, and proved itself an excellent tool. A Graphics Project Group was established in 1984 to design and implement a second-generation system. This led to development of the Meteorological Application Graphics Integrated Colour System or MAGICS, which provided the basis for the Centre's future graphics developments for the coming decades.

Although in 1982 only 40% of computer resources allocated to Member States was actually used by them, their use of the system continued to increase rapidly. In 1984, usage was doubled compared to the previous year. The telecommunications links were now coming under strain; they were unable to handle the requirements for remote use of the system. This, together with the increasing demand for more of the ECMWF forecast products, led to Council approval of an earlier than planned replacement of the telecommunications system the following year. The Technical Advisory Committee (TAC) set up an ad-hoc sub-group to follow the work leading to the replacement.

In 1985, Council began discussions on the next mainframe computer. Budgetary considerations dominated the discussion. The ECMWF budget was moving towards one of "zero growth in real terms", a principle adopted by Council in May 1986. Council decided to finance the acquisition by a combination of bank loan of £5 million, the remainder to be financed by overdraft. Favourable interest rates were negotiated, and the loan was repaid in installments of £1 million in each of the following five years. The Head of Research, David Burridge, developed a cash flow model to project the monthly cash positions in each month up to 1992. The model was based on continually updated bank base rates, exchange rates, budget projections and other factors.

The Centre continued its interesting and perhaps even adventurous financial activities by acquiring the US dollars required for the next computer on the forward currency market. During 1985, almost US$3 million was acquired in several installments at an average rate ofUS$1.3286 to the £1. In December, the Council authorised the Director to purchase the remaining US$1.4 million at once if the spot rate reached US$1.40 to the £1.

In December 1985, a four processor CRAY X-MP/48 was installed. It replaced the CRAY X-MP/22 after passing its final acceptance test on 11 February 1986. This system had 4 CPUs with a cycle time of 9.5 nanoseconds (102 MHz), 64 Megabytes of memory, 256 Megabytes of SSD and 13 Gigabytes of disk space, with a theoretical peak performance of 800 Megaflops.

The technical work required for the installation was impressive. All the extra power and cooling equipment had to be installed in advance — new condensing units, power cables and motor generators. On 4 December 1985 the boxes containing the new computer were wheeled in the back door of the Computer Hall. Within 48 hours the installation was completed, the machine powered up and testing was begun. The final configuration of the system was ready for testing on 21 December 1985.

In the following years, the system continued to give a stable and on the whole satisfactory service. In early 1988 the CRAY was upgraded to allow implementation of two high-speed data transfer channels connecting it to the archive system, based now on the IBM 3090-150E, which had replaced the IBM 4341 in October 1987, and a direct link to the LCN.

Leaks in the roof of the Computer Hall led to the roof being replaced at some considerable expense by the UK government, the building's owners, during 1988.

In May 1988, the Council began considering again the Centre's future computer requirements. It was now planned that in the future the Centre would no longer buy its computers, but would instead buy a "computer service", which would include the possibility of upgrading the system. A predictable cash flow year-on-year is more manageable than one with large annual fluctuations that would result from buying large computers every few years. The concept has advantages for the computer manufacturers as well. It was intended by this to ensure that the Centre would continue to have computer equipment of a standard suitable for its requirements, and with financing that the Member States could manage. This "service agreement" concept has continued to work well over the years and was still in use some 17 years later.

The work of a sub-group of the TAC was reported to Council in May 1989. The Council made funds available for preparation of the Computer Hall for installation of the next mainframe.

A CRAY Y-MP 8/864 replaced the last X-MP system in 1990. This system had 8 CPUs with a cycle time of 6 nanoseconds (166 MHz), 512 Megabytes of main memory, 1 Gigabyte of SSD memory and 62 Gigabytes of disk space, with a theoretical peak performance of 2.75 Gigaflops. This was the first supercomputer at the Centre with a Unix operating system. The previous three CRAY systems had used Cray's proprietary operating system COS. The Y-MP used Cray's implementation of Unix called UNICOS, based on ATT System V Unix with Berkeley extensions, and with further enhancements developed by Cray Research. This heralded the gradual introduction of Unix systems at the Centre. In the future all the systems used from desktops PCs to supercomputers would run some form of Unix. The operational model was transferred to the Y-MP on 7 November 1990.

The replacement of the two Cyber 855s front-end computers that had been installed in early 1989 with a Cyber 962-11 configuration was also agreed in 1990.

In 1992 a Cray C90/16-256 replaced the Y-MP. This system had 16 CPUs with a cycle time of 4.167 nanoseconds (240 MHz), 2 Gigabytes of main memory, 4 Gigabytes of SSD memory and 120 Gigabytes of disk space.

Each CPU of the C90 produced 4 results per clock cycle giving a theoretical peak performance of 960 Megaflops per CPU or just over 15 Gigaflops for the whole system. Its installation was not without problems. A chip design problem meant that programs that contained memory-addressing errors could corrupt other independent, programs running on the machine. This led to a delay in accepting the system, as processors were shipped back a few at a time to the manufacturing plant at Chippewa Falls to be re-engineered. The C90 eventually passed its final acceptance test on 2 January 1993. To compensate for the delay, Cray provided the Centre with a CRAY Y-MP4E system for five months from June.

Up to this time, all the Cray supercomputers at the Centre, apart from the single processor CRAY-1, were Shared Memory Processor (SMP) systems. Each of the processors in the system could access any part of the memory. In 1994 the Centre entered the new world of distributed memory parallel processing. The Service Agreement with Cray was extended on 7 June 1994, leading to a CRAY-T3D being installed in July-August, as additional equipment to the C90. Final acceptance was passed on 5 October.

This system comprised 128 Alpha microprocessors, each with 128 Mbytes of memory. The processors were connected by a fast interconnect in the form of a 3D-torus. This system was a distributed memory system with each processor "owning" 128 Mbytes of memory. The "PARMACS" message-passing programming paradigm was used to enable processors to access the memory that was attached to the other processors. Substantial changes were made to the forecasting system so that it would operate efficiently on this type of architecture. The T3D itself did not have any disks or network connections — these were provided by a small YMP-2E system connected to it by a 200 Mbytes/sec high-speed channel. The system was well suited to running the operational Ensemble Prediction System.

On 30 November 1993, the NOS/VE service, which had provided access to the computer system for many years, was terminated. From then on, access was via workstations.

Throughout these years, computer security was becoming more and more important at the Centre as well as in the rest of the world. Trials of access via smart cards began in 1994. These were still used to provide secure access more than ten years later.

On 19 July 1994 an improved version of UNICOS, UNICOS 8, was installed on the CRAY. This was a major improvement over version 7, effectively halving the CPU time used by the operating system. Users' jobs had 10% more computing time available.

In December 1994, Council approved the cash flow for the period 1996 to 2000 to fund the replacement of the C90. This led to an invitation to manufacturers to tender against a money stream. The responses to the tender were excellent. After considerable debate and deliberation by the tender evaluation board the Director advised Council to accept the offer from Fujitsu Limited.

Massimo Capaldo returned to the Centre after an absence of some 15 years, now as Head of the Operations Department. Immediately he was faced with the challenge of the move from the familiar CRAY systems to the Fujitsu computers. This was a "quantum change, something of a leap in the dark", but justified by the clearly superior offer from Fujitsu. The Cray team was understandably very disappointed by the decision.

In 1996 a small VPP300/16 system was installed for familiarization and testing, followed by the first of three large Fujitsu VPP systems, the VPP700/46. This initially had 39 Processing Elements (PEs) for computation, another six for I/O and one acting as a "primary-PE" running the batch subsystem and interactive work. This was also a distributed memory system, with each PE having direct access to its own 2 Gigabytes of main memory. But whereas the T3D had scalar processors, each VPP700 PE consisted of a single vector processor, similar to that of the Cray-C90, with a theoretical peak performance of 2.2 Gigaflops, giving a total peak performance of around 90 Gigaflops for the "compute nodes". This Fujitsu system incorporated a very high speed non-blocking crossbar interconnect, which had low latency and very high bandwidth, enabling messages to be passed from any PE to any other PE at speeds of up to 1 Gigabyte per second. On 14 July, it had passed all its acceptance tests. The number of processors was increased to 116 in September 1997, to provide a total peak performance for the whole system of over 250 Gigaflops. The VPP ran the operational suite and dissemination from 18 September. The last of the CRAY systems was powered down on 1 October 1996, ending 20 years of contractual relations with Cray Research.

In 1998 a VPP700E with 48 processors was installed. The VPP700E was similar to the VPP700, but with slightly faster processors (2.4 Gigaflops). It was planned to install a VPP5000 system in early 1999, but in a situation reminiscent of the C90 design problem, it was found at a very late stage that there was a design fault in one of the VPP5000 CPU chips, so delivery had be delayed for several months while this was rectified. At last, in October 1999 the VPP5000, initially with 38 processors, later with 100, was installed. It passed its acceptance tests on 16 February 2000. The VPP5000 Processing Elements were almost a factor four faster than those of the

VPP700 that it replaced, with a theoretical peak performance of 9.6 Gigaflops. The processor had a chip to speed up indirect memory accesses. Fujitsu dubbed this chip the “LASCAW” chip, after the name of a subroutine in the model code; the chip was designed specifically to improve the performance of this subroutine.

Before the VPP5000 could be fully accepted, the operating system had to be brought into line with that on the other VPPs to make it “Y2K compliant”. At that time other Y2K issues were already being addressed at the Centre. Members of staff were requested to correct year 2000 faults in the software for which they were responsible by October 1998. The first Y2K problem at the Centre actually occurred on the data handling system on 26 September 1997. The CFS data management system used the value 999 to indicate an infinite retention period. Unfortunately 999 days from the first day of the new millennium was 26 September 1997 and on that date CFS started complaining about invalid retention dates!

Capaldo returned to Italy in February 1999 after four years as Head of Operations. He would have liked to stay, and Director Burridge wanted to keep him. However for administrative reasons, Italy insisted that he return. He was “proud to have been involved in the huge amount of work during that time: changing from CRAY to Fujitsu, implementation of variational analyses, seasonal prediction, wave forecasting, ECMWF Re-analysis, ensemble prediction and more. We were pioneering lots of new things.” The discussions in WMO concerning commercialization issues lead to the Centre’s Operations Department publishing its first Catalogue of Products during his time; his work in Italy before coming to the Centre had well prepared him for dealing with these difficult issues.

Early in 1999 a stand-alone test system was set up to test all the major components of the Centre’s software. Horst Böttger, as Head of the Meteorological Division, had the worrying responsibility to ensure that so far as possible harm to ECMWF operations would be minimised. He, and other Centre staff, contributed to the work of a WMO Working Group on the Y2K problem. At a WMO meeting hosted by the Centre in 1999, it was decided that the Centre would monitor data around the turn of the year, and the provision of information to WMO Members was agreed. The Centre was responsible for informing the nations of the world in real time of problems, or lack of them, with incoming data. It set up an area on its web site, which was able to report the trouble-free arrival, first of Australian and Pacific data, immediately after the hour (and millennium) changed at sequential time zones. An alcohol-free party was organised at the Centre for the night of 31 December, to ensure that relevant staff would be available throughout the night in anticipation of problems. In the event the change to 1 January 2000 passed without major incident, although the date was wrong on some of the plotted charts.

In May 2000, operations were transferred to the VPP5000 system. It was upgraded to its final configuration with 100 processors in July 2000, at which point its sustained performance on the operational model was about 288 Gigaflops, compared to its theoretical peak of 960 Gigaflops.

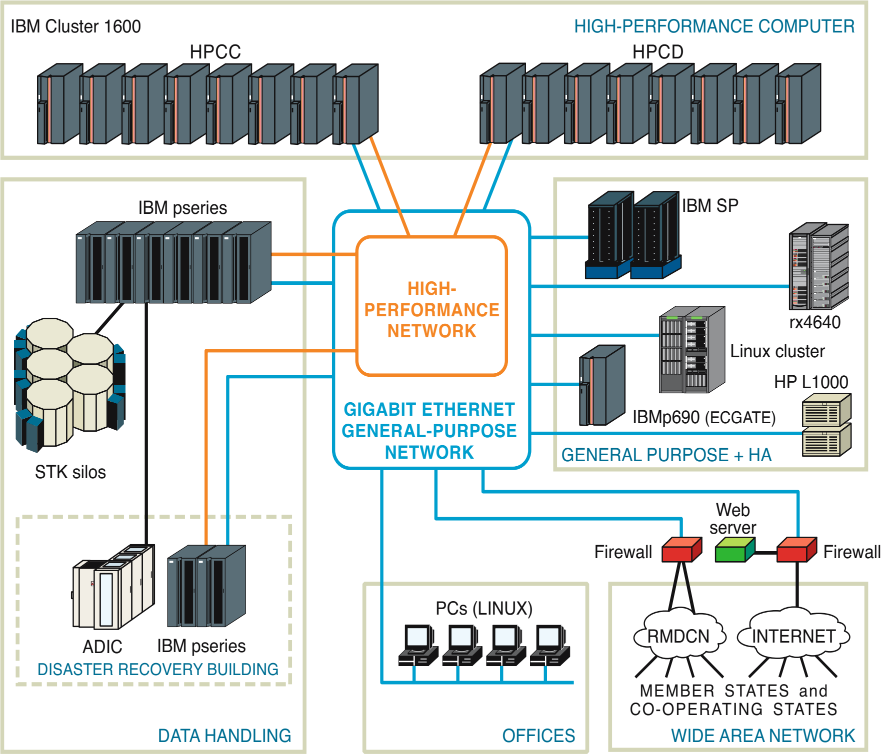
A disaster recovery system was installed in 1999 outside the Computer Hall in a separate building, to hold back-up copies of important data sets.

Planning began in 2000 for the replacement of the Fujitsu. An Invitation to Tender was issued on 23 March 2001. IBM's offer was judged the best value for money. Early in 2002 a single 32-processor p690 server was delivered as a familiarization and test system and in the second half of the year of Phase 1, two IBM Cluster 1600 systems, were installed and commissioned. Each cluster comprised 30 IBM pSeries p690 servers, each with 32 CPUs with a clock cycle time of 1.3 GHz (5.4 Gigaflops peak) logically partitioned into four 8-CPU nodes each with 8 Gigabytes of memory. A "colony" switch, which was an IBM-proprietary interconnect, connected these nodes. Each cluster contained a set of four "nighthawk" nodes connected to the switch to provide the I/O capabilities to the network and to a set of fibrechannel RAID disk subsystems. There were initial firmware problems with memory and the colony switch adapters. It took a long time to convince IBM of the seriousness of the problem, but it was sorted out just in time to start the acceptance tests. This led Dominique Marbouty, then Head of the Operations Department, to remark "It is frustrating that IBM waits until the last minute to sort out these problems, but it's amazing what they can do in that last minute!" The first operational forecasts from this system were produced on 4 March 2003.

The Fujitsu VPP systems were decommissioned at the end of March 2003. However, we saw in Chapter 14 where we discuss Re-Analysis, that Fujitsu allowed the VPP700E computer to remain on site for a further month, and ERA-40 was extended to August 2002, hitting the 45-year mark. The VPP5000 was shipped to Toulouse, where Météo France used it to upgrade its computer system.

At the end of 2001, IBM informed the Centre that a user group named SP-XXL, made up of sites that had installed very large IBM systems, met twice a year. The next meeting would be in February 2002. IBM suggested that the Centre contact one of the sites and ask them to sponsor the Centre to join the user group. This would allow ECMWF representatives to attend, and thus have access to confidential information that was disclosed by IBM at that meeting. Further, the Centre could exchange information with other sites with similar systems. The National Energy Research Scientific Computing Center (NERSC) at the Berkeley Laboratory in California, kindly agreed to sponsor the Centre. The meeting gave IBM a platform to inform the sites about their future plans and products. Further, it collectively added weight to the views, opinions and arguments of these major customers to help shape the future direction and development of IBM's high performance computing strategy.

In 2004 Phase 3 replaced the Phase 1 system. Phase 2 was skipped in favour of an increase over the committed performance of the Phase 3 system. Phase 3 consisted of two clusters each of 70 IBM pSeries p690++ servers, each with 32 CPUs with a clock cycle time of 1.9 GHz (7.6 Gigaflops peak) and 32 Gigabytes of memory. These nodes were connected by a "federation" switch (pSeries High Performance Switch), an IBM-proprietary interconnect.



The computer system in 2005.

We have seen the computing facilities at ECMWF evolving from a single-CPU CRAY-1 to a large dual cluster of shared-memory processor systems. The sustained performance has grown 70,000-fold and the complexity of the system has increased by at least an order of magnitude. There has been some simplification, for example in the adoption of Unix in one form or another as the operating system on the main computers, rather than the mixture of different proprietary operating systems of the early years.

One of the analysts at ECMWF remembered reading an article in the late 1970s that predicted that one day wristwatches would have more processing power than the CRAY-1. Mobile phones and personal digital assistants of 20 years later were approaching that. In the coming decades, mainframe computers will continue to increase in power. If the Centre is to keep its position in the forefront of NWP, it is clear that continuing access to some of the most powerful systems available at any particular time will be required.

Specification	**CRAY-1A**	**IBM Cluster 1600**	**Approximate Ratio**
Architecture	Vector CPU	Dual Cluster of scalar CPUs	
Number of CPUs	1	~4,500	4,500:1
Clock Speed	12.5 nsec (80 MHz)	0.525 nsec (1.9 GHz)	24:1
Peak performance per CPU	160 MFLOPS	7.6 GFLOPS	48:1
Peak performance per system	160 MFLOPS	~34.2 TFLOPS	220,000:1
Sustained performance	~50 MFLOPS	~3.5 TFLOPS	70,000:1
Memory	8 MBytes	~4.5 TBytes	550,000:1
Disk Space	2.5 GBytes	~50 TBytes	20,000:1

Comparison of the 1977 CRAY-1A with the 2005 IBM supercomputer

Chapter 17

Communicating the forecasts: mail and 50 baud to RMDCN

In Chapter 3 we saw the far-sighted plans made in 1971.

> *High-speed data links (2400 bits/sec) between the Centre and associated national centres were indispensable for the dissemination of the computed medium-range predictions. Some of these data links were also necessary for rapid input of digital data in the form of grid-point values or pre-processed data originating from European and other centres. The satisfactory incorporation of all these data requirements into existing and projected WMO telecommunication channels appeared unlikely; a separate data net for the envisaged computing centre was needed. All these high-speed data links should be capable of operation in full or half duplex mode and hence would provide an ideal basis for teleprocessing of data.*

In June 1975 the "First Meeting on Data and Telecommunications Needs", convened by the Centre, was held in London with the approval of the Interim Council following a recommendation of the Scientific Sub-Committee. Eleven of the Signatory States were represented, with an observer from WMO. Jean Labrousse was elected Chairman. In his welcoming address, Director Wiin-Nielsen noted that:

> *The Centre is not located in the geographical centre of the participating countries, but rather in the corner to the north and west. I am also told, although these decisions were made before I had even heard of the Centre, that the site evaluation teams were told that they should not give preference to a central location because the communication network and its cost would be part of the budget of the Centre and thus shared on a proportional basis between the Member States. It goes without saying that if such a policy is not used in the future, but instead that each country has to pay for its lines to the Centre, it will be very inexpensive for*

> *the host country and very expensive for the far-away countries, say Finland and Greece, and Turkey when she joins our family. The difficulty is of course that the statements made above are not discussed in the convention or protocol, but are only part of a general understanding, or you might say a gentlemen's agreement. However it goes without saying that we are all gentlemen, and it will be expected that we live up to such general understandings.*

The meeting was an informal planning meeting primarily concerned with technical considerations. It was considered important that, to minimise technical problems, the Centre would be fully responsible for implementation, operation and maintenance of the network. Requirements for the operational products of the Centre were discussed; around 40 million characters per day were foreseen as the total amount of information to be disseminated. The WMO representative stressed that no spare capacity would be available on the Global Telecommunications System (GTS), the network used for global exchange of weather data between all countries of the world, in particular during the FGGE period 1978–79.

Lennart Bengtsson considered the envisaged structure of the operational forecast routine, and presented preliminary views on the volume of analyses and forecasts to be produced and on principles of dissemination. Since it could be expected that the internal model parameters would be frequently modified, as a first principle it would be assumed that the form of the disseminated products would be independent of the internally-used parameters of the model. Resulting interpolation errors would be small. Only basic quantities would be disseminated; it was expected that the Member States would compute derivatives (e.g. vorticity and divergence, mean and extreme values, and quantities such as thickness, dew-point depression and potential temperature). It was proposed that the Centre would restrict sending of products that had not been properly tested and verified.

The meeting agreed that as a minimum, 10 million characters would be disseminated each day. Procedures and protocols to be used on the lines were considered; it was clear that WMO GTS procedures would not be suitable in view of the special requirements of the Centre such as access to databases and remote use of the system. Thus sharing GTS networks would not be feasible; a dedicated ECMWF network would be required. [We will see that improvements in technology and software did allow just such sharing of the lines 25 years later.]

In July 1975 the report of the meeting was considered by the "Consultative Sub-Committee on Scientific and Technical Matters of the Interim Committee of the European Centre for Medium-Range Weather

Forecasts". The Sub-Committee endorsed the intention to confine dissemination to the basic variables, "with the understanding that such a restriction should not be applied too strictly". Furthermore the Centre "should not be expected to provide operationally a variety of services normally associated with short-range predictions".

The telecommunications links to the Member States, envisaged in this early planning of the Centre, were "to be postponed until 1981 or later" according to the 1976 programme presented to Council in May 1976. Not surprisingly some Member States did not welcome this delay. Finland tabled a Note on the subject, inviting Council "to express its view on the necessity of a dedicated telecommunications system and to instruct the Centre to find the cheapest possible solution to the problem". Council set up an "Advisory Committee on matters relating to communications between the Centre and the Member States", with Daniel Söderman of Finland as Chairman. The terms of reference of the Committee included evaluating Member State requirements for forecast products of the Centre, the means of distribution, how the Member States could use the computer system, and the technical and financial aspects.

In November 1976 the Council decided that a medium-speed network should be used, though for technical reasons it would start with a mixed network including some low-speed lines. In the Annual Report for 1976, a system of 20 lines of 9,600 bps was specified as the least required. In November 1977 the Council adopted the recommendations of the Committee, after amending the text so that it would be clear that the cost would be shared according to Wiin-Nielsen's "gentlemen's agreement":

> *[Council] approved that the cost for the telecommunications network proposed by the Advisory Committee be incorporated in the Centre's programme of activities.*

The Committee's work led to a speedier implementation of the telecommunications system with the issue of an Invitation to Tender in July 1977, specifying a turnkey system for hardware and software. Protocols were agreed and accepted by Council in December 1977 that would become standard for communications between the Centre and the Member States.

The Committee continued its work until November 1978 when the Council established the Technical Advisory Committee (TAC), which elected Jean Lepas of France as its first Chairman. The work of the "Advisory Committee on the Use of the Computer System" (ACUCS) was also transferred to the TAC. Daniel Söderman became Head of the Operations Department in 1980.

By end 1977, a decision had been reached; the contract was signed on 14 March 1978. The chosen contractor was Service in Informatics and Analysis (UK) Ltd (or SIA) who supplied the software, with A/S Regnecentralen of Denmark as subcontractor for the hardware, centred on an RC8000 computer. The software design, including development of the international protocols, was largely completed by end 1978, using hardware temporarily installed in SIA's London office. The Centre acted as agent for Germany, Denmark and Sweden to develop a link package to be used with Regnecentralen equipment; this was operating in the three States by March 1980. The first Network Front End Processor was installed in June 1979. The communications system passed final acceptance at the end August 1980. By December 1980, medium-speed (2400 or 4800 bits per second) lines had been established to Denmark, Germany, Sweden, and the UK; lines to France and Ireland were in test. Most other States had 50 or 100 Baud lines operational.

The operational forecast suite was ready from the start to disseminate ECMWF forecast products through the network. Dissemination could be started at the end of each post-processing time-step as well as according to a pre-defined time schedule, collecting the products required by a Member State from a Dissemination Data Base.

The forecast model predicted changes in wind, temperature etc. on pressure surfaces normalised with respect to surface pressure (so-called sigma surfaces) and with a horizontal resolution of 1.875°. These model surfaces and resolution would change relatively frequently. Hence the fields coming from the CRAY were transformed to standard pressure levels and a resolution of 1.5°; these standard levels and resolution would be maintained, thus insulating the user from the model changes.

It was envisaged that several thousand fields would be disseminated daily, having been transformed and restructured from the files coming from the CRAY into a format usable by the forecast offices on the Member States — either an "ECBIT binary code" or an internationally-recognised WMO GRID code. Only the link to Greece was established in August 1979 when the first operational forecast was run; 27 products were disseminated in total from this forecast.

A facsimile transmission to the UK Met Office at Bracknell, with onward transmission to Offenbach and Paris, was arranged. Otherwise analysis and forecast charts for the Atlantic and European area were despatched by mail the following morning. The mail service continued for many months to some States. In contrast, by November 1982, the UK delegation to Council was expressing "surprise at the high number of products (8,000) distributed daily by the Centre to the Member States". It was explained that this included all times, levels and sub-areas despatched to all Member States.

Multi-streaming software was developed to allow simultaneous transmission of forecast products and output from remote batch jobs. A second RC8000 computer was purchased to provide backup. Backup for the acquisition of observational data was provided by a second link to the GTS via Offenbach, as a complement to that via the UK Met Office. At the end of 1981 only five Member States were depending on low-speed links: Spain, Italy, Greece, Yugoslavia and Turkey.

From 1 August 1981, the Centre disseminated a range of its most important products on the GTS, making them available free of charge to all countries of the world. This was in line with the admirable tradition of the world of meteorology, whereby data and products were exchanged freely. Fields of surface pressure and 500 hPa height for the Northern Hemisphere to five days, and for the Southern Hemisphere to four days (at the time, the accuracy of the Southern Hemisphere forecasts was lower), and analyses for the wind fields for the tropics at 850 and 200 hPa, were made available, and were quickly being used in forecast offices world-wide. Although the model resolution was 1.875°, GTS dissemination was at lower 5° resolution. By 1983, Australia, New Zealand and South Africa were using Southern Hemisphere forecasts, while China, Japan, USA, Hong Kong and India were using those for the Northern Hemisphere. Valuable reports on the quality of the forecasts and their usefulness in operational prediction were received regularly.

Dissemination on the GTS increased steadily in the following years, additional products and levels added, the resolution increased, and the forecast period extended, as the forecast quality improved.

In December 1983, the Council endorsed the establishment of a subgroup of the TAC "to follow the work leading to a replacement of the telecommunications sub-system". The sub-group met in January 1984. In July 1984, an Invitation to Tender for a new telecommunications system was issued.

In May 1985 Council approved a contract with Software Sciences Ltd (SSL) for a new telecommunications system. During 1986 the Regnecentralen telecommunications system was replaced by a system based on a cluster of four Digital Equipment Corporation VAX 11-750 computers. This, then called the New Telecommunications Computer (NTC), was providing a reliable service by the end of the year, and delays, which had proved a problem with the previous system, had been eliminated. The Regnecentralen was powered off on 20 September 1986, after 7 years and

50 days service. By December 1986, all Member States were connected with lines of 2,400 to 9,600 bps, except for the remaining low-speed lines to Italy (100 baud), Yugoslavia and Turkey (50 baud each). In July 1988, all links had become medium-speed, ranging from 2.4 to 14.4 kbps.

In 1986, five Member States co-operated in implementing a National Telecommunications System (NTS), similar to the joint project carried out in 1978-80. The NTS was also based on VAX computers, but now with a modular approach to the software design. DECnet protocols were used as the final "transport layer". Costs of £50,000 for developing the software for the system were shared between the participating States.

A new dissemination scheme was implemented in June 1986 offering model level data, important for those running their own models, as well as pressure level data, any geographical area, any grid point system or spherical harmonic coefficients and some ad hoc services. From now on Member States could maintain their own product lists using a menu-based interactive system.

From January 1988, ECMWF data on the GTS were in GRIB format at the higher resolution of 2.5° — although the GRID dissemination at 5° resolution was maintained. Line speeds were steadily upgraded. By 1989, sixteen lines were at 9.6 kbps or higher, the remaining two at 4.8 kbps. Five Member States had established NTS connections, five more were in test. The increased speeds and volumes of transmission led to an acute overload of the system; a VAX 8250, soon upgraded to an 8350, was purchased to alleviate the situation.

In 1992 Météo France started to use the TCP/IP protocol as the "transport layer" for its connection with the Centre. This proved to be an important milestone; since then, TCP/IP has become a standard in computer networking.

In the same year, products to be used as boundary values for limited area models were disseminated for the first time. Links were now increasing to 64 kbps to several Member States, and a link of this speed was set up with the University of London Computer Centre to connect the Centre to JANET, the new "Joint Academic Research and Education Network" in the UK, and through this to the international Internet. Early Internet experience was mixed with some reports of delays and loss of service.

The internal network was expanded by the installation of a fully duplicated network based on fibre optics.

In December 1992, the Council approved the use of the network for electronic traffic routeing, thus enabling Member States to use the connections with the Centre for data exchange between each other.

By early 1993, more than 55,000 products were sent to the Member States each day. Internet use was increasing for acquiring research data.

In December 1993 Council approved 64 kbps as the base speed of the network to be phased in from April 1994. Prior to this, individual States had to pay for the additional cost of lines above 9.8 kbps. France at its own expense upgraded its link to 128 kbps from December 1994. The first link to one of the new Co-operating States from Eastern Europe, Hungary, was ordered in late 1994. As a Co-operating State, Hungary paid the cost of this link. Direct dissemination to Hungary (9.6 kbps) and Iceland (64 kbps) started in 1995. In April 1994 the last country (Austria) using the NTC protocol suite had started using TCP/IP. Now that all Member States were either using TCP/IP or DECnet as the transport protocol, the VAX 8350 was removed and the VAX 6210/6310 cluster was replaced by two VAX 4100 systems.

In 1995, dissemination of individual EPS forecasts started. The data volume increased to 90,000 products, totaling 675 Megabytes. A major achievement in 1996 was the design and implementation of a new distributed Fields Data Base.

Close scientific co-operation with NOAA in the USA continued to be a notable feature of the Centre's work. EPS products, forecasts to ten days, and rainfall forecasts in support of an intercomparison project were among the products sent to National Centers for Environmental Prediction (NCEP) of NOAA in Washington. The Centre received increasing amounts of satellite data from NOAA.

In May 1994, Regional Association VI of WMO, covering the region of Europe, decided to establish a new telecommunications network, to be called the Regional Meteorological Data Communication Network (RMDCN). This was required to meet the any new GTS requirements for the 49 members of RA VI, about half of whom were ECMWF Member States or Co-operating States. A Steering Group considered the legal and administrative framework, as well as technical and cost/benefit aspects. Not surprisingly, discussions with ECMWF staff showed that the use of a common network for GTS and ECMWF products could be beneficial; a saving of 20% to 40% could be achieved in the overall annual cost of about US$4 million.

The delegate from France to the Council session of July 1996 — who happened to be Dominique Marbouty, later to become Head of the Operations Department and then in 2004 ECMWF Director — submitted a proposal for the integration of the GTS and the ECMWF network. Council requested its Policy Advisory Committee to consider political consequences and its Technical Advisory Committee to consider technical aspects. The Director would liaise with a RA VI Working Group on the matter.

In 1996, the range of ECMWF products on the GTS was extended to seven days in the Northern and Southern Hemispheres, and to five days in the tropics.

By mid-1997 145,000 products — a data volume of 1.4 Gbytes - were being disseminated each day. New products and parameters continued to be added, for example temperatures and wetness of the soil at levels below the surface of the earth, and high-resolution wave products. Council agreed that the Centre could be accessed via the Internet, and a secure system protected by a Firewall was soon installed and functioning well. The link to JANET was upgraded to 8 Mbits per second.

A TAC sub-group on the RMDCN met in February and June 1997, and a Workshop was held in March on Managed Network Services. Almost all RA VI Members were now expressing an interest in participating in the project. A network with speeds of 128 kbps was anticipated. A detailed plan was presented to Council in July 1997. In December 1997 Council approved an exchange of letters with WMO detailing the responsibilities of the Centre and of RA VI Members. By mid-1998, the Invitation to Tender for the RMDCN had been completed, and in December 1998 a contract was signed with EQUANT NV for the provision of a Frame Relay network service using TCP/IP as the transport protocol for the RMDCN countries. Work on the new network was soon under way, with a pilot phase involving France and Portugal in early 1999, initial deployment of the network with 31 States participating, in summer 1999, and site acceptance tests running from mid-October. This was not one of the easier projects for the Centre. A multitude of connectivity and throughput problems were experienced during implementation. The initial deployment was complete and the network accepted in March 2000. Soon, most Member States were using the network for most of their meteorological communications.

ECMWF products were being provided increasingly to international scientific activities:

- “Labrador Sea Ocean Convection Experiment”;
- “Fronts and Atlantic Storm-Track Experiment” (FASTEX) which used the products to take decisions on intensive observing periods;
- “North Pacific Experiment” (NORPEX);
- Support operations on the Very Large Telescope at the European Southern Observatory in Chile;
- “Tropospheric Ozone Production about the Spring Equinox” (TOPSE) — this requiring research flights from Denver Colorado to the North Pole;
- “Middle Atmospheric Nitrogen Trend Assessment” (MANTRA) programme run by the University of Toronto, Canada;
- “Aerosol Characterization Experiment — Asia” (ACE-Asia) under the International Global Atmospheric Chemistry Programme;

- "Trace and Chemical Evolution over the Pacific" (TRACE-P) experiment organised by NASA;
- "Dynamics and Chemistry of Marine Stratocumulus" (DYCOMS) project run by UCAR in the USA;
- Mesoscale Alpine Programme.

Forecasts were provided to many non-Member States for limited periods in support of environmental emergencies, for example to the States of North Africa to help with a locust plague, to Glavgidromet in Tashkent for selected locations in Uzbekistan around the Aral Sea, to the Czech Republic prior to the Co-operation Agreement coming into force at a time of major flooding, and to Pakistan for monitoring heavy monsoon rains. In early 2000, new dissemination streams were introduced in support of scientific field experiments.

As its name suggests, the National Centers for Environmental Prediction (NCEP) is the civilian weather forecast centre for the United States. A fire in the power supply of the CRAY C-90 computer at NCEP in Suitland, Maryland, USA on 27 September 1999 was fought by over-enthusiastic firefighters, who sprayed the insides of the US$30 million machine with an ordinary fire extinguisher. Computer rooms have special carbon dioxide-based fire extinguishers, but firefighters picked up an all-purpose carbonate extinguisher outside the data center. They were very thorough in applying the chemical dry carbonate; the residue of the fire extinguisher left the computer beyond repair. NCEP was now left without a functioning supercomputer. On request, the Centre gave permission to NCEP to use ECMWF ensemble forecasts for real-time medium-range (6–10 day, and "week two") weather prediction. In addition they were used for a new "Threats Assessment" outlook developed in the USA to give warning of weather and climate events that posed a potential threat to life, property or economic interests.

During 1999, with the turn of the millennium and the Y2K problem approaching, the dissemination software was completely redesigned and rewritten to run on a Hewlett Packard High Availability System HP9000. This brought to an end the Centre's use of the system based on VAX computers and DECnet, begun in 1986. All States were now using TCP/IP as the transport protocol for dissemination, communications with the Centre for use of the computer system, and all related use of the network.

The ECMWF web site was being increasingly used. Extensive revisions to the structure, content and style of the site were implemented in December 1999 and again in early 2002, when the public and Member State sites were merged, with controlled access to the parts of the site restricted to authorized users. Researchers were allowed immediate and free access to very extensive ECMWF data bases.

The RMDCN network was being connected to more and more States. The Russian Federation signed its Accession Agreement in 2001. EUMETSAT connected in the same year. At the end of the year, experts from China, Kenya, Russia and France, under a WMO umbrella, were analyzing the possibility of connecting the RMDCN to Nairobi, Dakar, Algiers, Cairo, Jeddah, New Delhi and Beijing. Tokyo was interested also. The system was seen as a significant opportunity to improve the global meteorological telecommunications network. The Centre acted as focal point for technical, financial and administrative matters. WMO regarded the system as “an outstanding success in its functionality and reliability, and also in its cost structure and cost development . . . it is exemplary”. China became a member of the RMDCN in 2002. Also South America started work on an RMDCN for that region; the Centre was represented at a meeting in November 2001, and helped in the preparation of the Specifications of Requirements and the contract.

By 2002, more than one million products were being disseminated each day, with a volume of 12 Gbytes, almost doubling the number and volume of the previous year.

By 2004, with the exception of the connection with the UK Met Office all connections to the Member States and Co-operating States were via the RMDCN, with speeds ranged from 64 kbps to 1.5 Mbps. The Centre had a highly resilient connection to the RMDCN via two 34 Mbps links. A 2 Mbps private leased circuit was used for the connection to the UK Met Office. The network base speed became 768 kbps for communication between the Centre and the Member States in early 2005.

As of early 2005, 40 countries were connected to the RMDCN, as well as EUMETSAT, and 2,650,000 products were being disseminated daily. The Centre’s Internet connection was a 60 Mbps link to JANET. Its connections to the rest of the Internet now included a link to the Geant network, which provided a high-speed backbone between most research networks within Europe and to the USA

Chapter 18

Commercial issues

Weather forecasting is a valuable business. One Euro invested in meteorology is generally recognised as yielding ten to twenty Euro or more in terms of profits made, casualties avoided, harvests saved and so on. The more accurate the forecasts, the more they are worth. With a good four-day forecast, retailers can send their ice-cream orders to their sunniest outlets and adjust their window displays for rain or sun. Cinema audiences, medicine consumption, routes taken by ships and aircraft, and electricity consumption all vary according to the weather. Weather is the single most important factor in influencing price volatility, volume fluctuations and revenues in the energy industry. In winter, power companies can save perhaps €100,000 a day if they know in advance how high users will turn up their heating. In response to the deregulation of the power industry the weather derivatives market was developed. The companies involved needed a financial vehicle to help manage their exposures to weather risk. Re-Insurers and financial institutions soon entered the market, and the market expanded to include "end user industries" that are affected by the weather, such as beverage sales and agriculture. The more valuable the forecasts become, the more the commercial companies want to get into the business.

In the decades after the Second World War, funding from aviation supported in large part the development of many of the European National Meteorological Services (NMSs). For example, aviation required, and to an extent paid for, the expensive network of weather ships providing essential observational data over the Atlantic.

We need to look at the Centre's involvement in commercial issues in the wider context. In Europe, commercial meteorological activity by non-governmental organisations, having been generally at a low level, started to pick up in the 1970s. There was a growing, and potentially profitable, demand for applied weather services. As it happened, this coincided more or less with the years of the Centre's establishment. Indeed, we have seen in Chapter 4 the study on the potential significant economic benefits of good-quality medium-range forecasts; this was one of the justifications for the establishment of the Centre.

The commercial meteorological sector in the USA was becoming increasingly active in the late 1960s. The private companies, both in Europe and the USA, were keenly interested in using ECMWF forecasts as soon as they became available. Some European NMSs also began commercial activities, so that governmental agencies found themselves competing with the private sector. The Centre therefore developed its data policy in the framework of some difficult discussions affecting the NMSs. The Centre and its Council were not in the forefront of these discussions, but were concerned by them. The Centre watched with interest the meetings in WMO on the subject.

The commercial interests of Europe's state-owned NMSs were, and continue to be, widely different. Some had a duty to increase revenue from selling their own and ECMWF forecasts, in part as a response to reduced government support. Others had no such duties. Their abilities to exploit commercial opportunities varied.

Some complained that the commercial companies had unfair advantages. The US National Weather Service (NWS), according to the rules that govern it, is not allowed to sell information. In fact, under pressure from commercial agencies, the NWS had been obliged to stop producing "commercial value added services" for delivery to those interested in purchasing specialised forecasts. This had to be the role solely of the private sector in the USA. The NWS gave private companies the data it received from the WMO, and its own computer forecasts, without charge. NWS products, including predictions for the European area, were even distributed free of charge by the Freie Universität, Berlin. European private meteorological companies used them. They sold forecasts based on the data, without having to invest in costly satellites and other observing infrastructure, or supercomputers.

On the other hand, the private companies complained that the NMSs had the advantage of easy access to ECMWF forecasts. They asked that these forecasts be made available to them without charge, following the American example. Some Member States funded the Centre from NMS budgets, and their income came partly from revenue raised by their commercial activities. If ECMWF products were to be made available to all without payment, why should they not simply denounce the Convention, ending their obligation to contribute to the Centre's budget, knowing that they would continue to get the valuable forecasts anyway? Or, should not private companies contribute directly to the Member State contribution to the ECMWF budget? Furthermore, we have seen in Chapter 14 that the cost of collecting suitable observational data on which the forecasts are based greatly exceeds the cost of processing the data and making the forecasts, by a factor of perhaps 100 or even more. Commercial issues indeed introduced complications into an already complicated world!

The United States government view on commercial meteorological matters was, to say the least, not widely shared by the European NMSs. There was much more private meteorological activity in the USA than in Europe. The American companies were becoming active in Europe, competing not only with the European private sector but also with the European NMSs. Discussions became strained. Some in the USA, with the best will in the world, found it difficult to comprehend the European point of view; the position of the USA was similarly beyond the comprehension of some in Europe. The Congress of WMO, its supreme body, noted in 1991 that "commercial meteorological activities (have) the potential to undermine the free exchange of meteorological data and products between National Meteorological Services". A frightening abyss was facing the international world of meteorology. The consequences would have been serious for the entire world, not only for ECMWF.

Eventually WMO in 1995 passed "Resolution 40: WMO policy and practice for the exchange of meteorological and related data and products including guidelines on relationships in commercial meteorological activities". The Resolution was wide-ranging, taking into account not only commercial matters, but data and products to be provided freely and without restriction to research, education and other users. The interests of developing countries whose NMSs could be affected by commercial sector's commercial use of the data originating in their territory were considered. So were relations between the NMSs and the commercial sector. Resolution 40 was not perfect, but it did provide a framework for commercial activities.

Earlier, in May 1990, the ECMWF Council had set up the "Advisory Committee to consider, and make recommendations regarding, the establishment of a Meteorological Licensing Agency". The immediate trigger for this was a meeting of the Western European Directors in April 1990, at which there had been a long discussion on the implications of commercialisation of weather information and competition in Europe. The Meteorological Licensing Agency would as one of its first steps concern itself with the sale and control of ECMWF products.

However there was a somewhat longer history of Council wrestling with the interesting, difficult and at times very complicated issue of commercialisation of ECMWF forecasts. The Centre itself is an international organisation established by a Convention that does not include selling its forecasts as an objective. It is an organisation “owned” by its members and its role is to enhance their powers, rather than appropriating them. The Centre provides its forecasts to the NMSs of its Member States, and it is for the NMSs to decide what to do with them, commercially and otherwise.

As early as 1980 the Council had adopted “Rules governing the distribution of results from the Centre’s work”. For commercial organisations in non-Member States: “No data will be provided on any terms”; for those in Member States: “the request is to be submitted to the National Meteorological Service”.

In 1983, a distinction was made between distribution by the Centre, and by the NMSs of the Member States. Council “adopted, on a provisional basis, the draft guidelines governing the dissemination of ECMWF operational products”. ECMWF should pass on any request from commercial organisations to the NMS of the Member State concerned. If it was not clear which was the appropriate one, the request should be passed to all the NMSs. In turn the NMSs “should not distribute ECMWF products to bodies in a non-Member State” — this was in fact a complete ban on such distribution.

However the legal and political situation was not at all clear. In the international arena, there can be something of an ambiguity concerning the sovereignty of a State, and its rights and duties as a member of an international organisation. There was lack of agreement among the Member States on how commercialisation could be approached. Every year from 1981 to 1985 the Council found itself discussing dissemination of ECMWF products. It was not even clear whether this was an issue for the Council. In 1985, the position of Sweden was that the NMSs could not be bound by guidelines adopted by the Council. Each Member State had the freedom to do as it wished. France agreed that the Convention did not bind the Member States with respect to their national sovereignty. The problem of selling or not selling ECMWF products was not a problem for the Centre and should not be discussed by Council.

Such fundamental lack of clarity in a potentially important and divisive area was highly unsatisfactory, especially taking into account the growing activities of the private weather companies in Europe. In addition, the European Commission was taking a growing interest in commercial activity in the Common Market. The Single European Act, re-launching the single market by reducing trade barriers, was signed in 1986.

On 23 June 1987, a press release from Accu-weather Inc of State College, Pennsylvania announced “a major agreement with a consortium of

European Governments giving Accu-weather exclusive rights to market the European Model in North America". Nordmet, a consortium of the NMSs of Denmark, Finland and Sweden, had negotiated the contract with Accu-weather. The contract, to extend over a 15-month period, committed Nordmet to providing Accu-weather with information based on ECMWF forecasts. Neither Richard Hallgren, Director of the US National Weather Service, nor Lennart Bengtsson, the Director of the Centre, nor the ECMWF Council, had been informed in advance of this contract.

On 11–12 June 1987, less than two weeks before the Accu-weather press release, the Council had had a lengthy discussion on distribution and charging policy. EUMETSAT, the European meteorological satellite organisation supported by many of the ECMWF Member States, was considering adopting a policy on this subject. ECMWF Director Bengtsson had noted that it was essential to have a consistent policy between the two organisations, and "If revenue is generated from outside the Member States from sale of the Centre's products, this should be shared pro rata among the Member States". In the discussion, many of the complications arising from commercial issues in the framework of long-standing international meteorological co-operation were raised. The Council asked Dr Heinz Reiser, president of DWD, the NMS of Germany, to convene a sub-group of NMS Directors to draw up a Report on the matter, to be considered in the autumn.

The press release from Accu-weather came as a bombshell into these delicate discussions. Hallgren sent a copy to Bengtsson, who immediately queried the Nordmet Directors. On 29 June, the Directors of the NMSs of the Centre's other Member States were informed of the contract, and of its duration and scope, in a telex signed by the Directors of the NMSs of Denmark, Finland and Sweden. At the same time, Hallgren was formally informed of the contract. On 3 July, Bengtsson noted in a letter to the NMS Directors "the damaging repercussions this may have for international co-operation in meteorology". Dr (later Sir) John T. Houghton, Director-General of the Met Office, noted that "from my conversations with Mr Hallgren it is clear that he and his service in the USA are seriously embarrassed: 'how can I continue to defend free dissemination of US satellite data?' was his reaction". The Nordmet weather services, on the other hand, restated their belief that this "was not a matter for the ECMWF Council".

The President of Council was requested by many Member States to convene an extraordinary session of the Council. The session was held on 4 September 1987. The Chairman Prof S. Palmieri of Italy noted that "the links of mutual trust, loyalty and co-operation among meteorologists within Europe and outside were very firmly established, enabling projects of great value to humanity, to be established. Increasing interest in commercialisation was not a negative sign". The Council after a wide-ranging discussion, asked that Dr Reiser's Working Group meet on the following day and prepare Guidelines governing the dissemination of ECMWF real-time (as opposed to archive) products, to replace the existing Guidelines. The new Guidelines were adopted in November 1987, stating that "Member States should distribute . . . products . . . to all other bodies in non-Member States only with the approval of the Council". The contract with Accuweather, which was not at all as wide-ranging as the press release had implied, ran its course but was not renewed.

The commercialisation of ECMWF products continued to be a matter for Council discussion in the following years. As we noted, some Member States had a real interest in generating revenue from sale of the forecasts of their own NMSs as well as those of the Centre; others especially in the 1980s had little or no interest, and to an extent were observers rather than active participants in the discussions.

The problem was a difficult one to pose properly. It had many facets, and all had to be taken somehow into account

- How would ECMWF forecast products be distributed:
  - within the NMS's own State.
  - to another Member State.
  - within the EU, or more widely throughout the EEA.
  - for research: a very wide range of valuable information is available free of charge to the worldwide research community.
  - to commercial entities within the Member State, in another Member State, or in another country.
  - to other NMSs.
  - to international organisations.
- If the forecast supplied by an NMS was based only on Centre data, or if it was partly based on the NMS's own data, and if "partly", by how much.
- Whether real-time forecasts and archive data should be treated differently.
- How prices or tariffs could properly be decided for atmospheric forecasts, wave forecasts, seasonal forecasts and EPS products.
- How a "level playing field" could be assured, so the NMSs in their commercial activity would not have an unfair advantage over private companies and vice versa.
- How the benefits of membership of the Centre could be maintained;
- How the revenue should be allocated.

- How the differing individual Member State legislations could properly be taken into account.
- How the provisions of the ECMWF Convention, which is an internationally agreed legal document, could properly be taken into account.
- How relevant EU legislation could properly be considered.

As we saw, different Member States had different views and interests, sometimes radically different, on the matter. A wide range of the Centre's most valuable forecasts are available free of charge to all on the ECMWF web site. Many more of its forecast products are sent free of charge to the NMSs of all countries of the world for use in their national forecast offices, transmitted on the same telecommunications links used for exchanging observational data. And all involved had a desire to ensure that ECMWF forecasts would be widely used to the benefit especially of the citizens of its Member States.

Meanwhile in the early 1990s and independent of the Centre, development of legislation by the European Commission led to a review of the traditional practices of the NMSs. Competition between NMSs, if perceived to be unfair, could threaten their very infrastructure, including maintenance of the vital observation networks. A "gentleman's agreement", as it was widely called, had been in existence for many years, under which NMSs operated commercially only within the borders of their own individual States. This could not continue within the European Union. The practices of the NMSs needed to be harmonized with European law relating to competition and the open market concept. The NMSs, being governmental organisations, had of course to ensure they did not infringe the competition rules defined by European legislation.

In 1995, the NMSs established an "Economic Interest Grouping" under Belgian law located in Brussels, called ECOMET. Its primary objectives were to:

> *preserve the free and unrestricted exchange of meteorological information between the NMSs for their operational functions within the framework of WMO regulations and to ensure the widest availability of basic meteorological data and products for commercial applications.*

This added yet another facet to be taken into account by the Council. A further objective of ECOMET was to recover part of the infrastructure expenses of the European NMSs by a contribution from all commercial users. The NMSs had developed in ECOMET a legal framework to establish equal competition conditions for the public as well as for the private sector. The data policy of the Centre had now to be considered in the light of the policies not only of EUMETSAT but also of ECOMET.

In November 1996 Council asked the Director to consult with the Director of EUMETSAT and the Chief Executive of ECOMET with a view to establishing a Working Group "to propose harmonized Rules relating to commercialization of meteorological products, to examine proposals for development of the Rules". The "Joint Harmonization Group" (JHG) Chaired by Fritz Neuwirth of Austria considered the measures required to ensure that NMSs in their commercial activities treated ECMWF, EUMETSAT and their own NWP forecasts under equivalent conditions. It considered tariffs including discounts, maximum and minimum fees, costs of delivery and transmission and more. It reported to each session of Council until June 1998 when Council noted that it had accomplished its mandate, and dissolved it.

Again in the year 2000, it was queried whether the Council can decide if ECMWF products can be used commercially within the Member States. It asked its Policy Advisory Committee to consider the matter. In December 2000, the Centre decided to extend the range of products made available to NMSs throughout the world. Forecasts to seven days of wind, temperature, pressure, humidity, and the probabilities of heavy rain, snow and strong winds, would henceforth be made available without charge.

Products from the Centre's work in seasonal prediction were becoming commercially valuable. The Centre decided in 2001 to make these products, forecasts to six months ahead of temperature, rain, snow, wind and more for the entire globe, available to private forecasting companies.

By now matters concerning commercial issues and distribution of ECMWF data were being considered by the Technical Advisory Committee, Finance Committee, Policy Advisory Committee, a Working Group of the Council, and Working Groups of some Committees, all of whom were drawing up opinions and recommendations for the Council to consider!

In 2001, Council set up a new Committee, the Advisory Committee for Data Policy (ACDP), which would be able to draw together all the strands that were being dealt with piece-meal. Since its establishment, the ACDP has been busy. It has extensively reviewed the Centre's data policy, with a view to encouraging and developing use of ECMWF forecasts for both commercial and non-commercial applications. It has worked to ensure a level playing field within Europe for all commercial users, those in the private sector and those in the NMSs. It has reviewed the charging levels, rationalisation of costing, widening the range of products made available to the private sector, and maximum tariffs; these were reduced substantially. The Policy Advisory Committee also has continued to devote considerable attention to important policy issues concerning ECMWF data.

Chapter 19

The Staff

The Centre was established to combine the scientific and technical resources of its Member States to use the most powerful computers with the objective of improving to the quality of medium-range weather forecasts. The staff were expected to do groundbreaking research. They would have to be of the highest calibre, and recruited from all over Europe.

In Chapter 2 we noted the July 1951 opinion of Prof Carl-Gustaf Rossby that:

> *the relations between meteorologists in the south and in the far north of Europe are not nearly as intimate as one might wish.*

This opinion was undoubtedly widely shared. However, on the face of it, there are major problems in bringing together staff from countries with wide economic and cultural differences. For a start, meteorologists' national salaries across the States supporting the Centre vary by a factor of ten or more. How could an equitable salary for the staff of the Centre be established?

The ground was of course well prepared. The level of salaries for professional staff of the United Nations is determined on the basis of the "Noblemaire Principle", named after the Chairman of a Committee of the League of Nations. The Committee noted that "it would be most unfortunate if the scale of salaries were fixed at a rate which made it impossible to obtain first-class talent from those countries where the ordinary rate of remuneration is above the general average". The Principle, formulated in 1921, states that: "the international civil service should be able to recruit staff from all its Member States, including the highest-paid". By this Principle, the salaries of professional staff are set by reference to the highest-paying national civil service. For the United Nations the federal civil service of the USA was for a long time taken as the highest paid national civil service. In 1995, as part of a periodic study, Germany was found to be better paid in the application of the Principle. And of course a large proportion of any international staff "incurs additional expenses and makes certain sacrifices by living away from their own countries".

The Headquarters Agreement of 1977 foresaw accommodation for 145 permanent staff and up to 10 visiting scientists. For an organisation of this size, with staff coming from about 20 States, it would be an administrative nightmare to try to determine salaries, allowances and pensions internally. Within Europe however, as early as 1956, a team of independent experts was employed by four independent international organisations based in France to "examine all aspects of the problems relating to the emoluments of the staff of OEED (now OECD), NATO, WEU and the Council of Europe". These four organisations had at the time a total staff of 1,900. The resulting "Serre's Report", published in 1958, was a comprehensive review of the structures and staffing of the organisations, and had a proposal for future co-operation. A "Coordinating Committee of Government Budget Experts", soon known as the CCG, made up of representatives from the Member States and the Secretariats of the four organisations, met for the first time in June 1958. The views of the Secretaries-General or equivalent of the organisations on remuneration, and later on pensions, could be coordinated with those of the Member States. In 1960 a permanent Committee with a chairman replaced the often-changing group of representatives. In 1963 the Heads of Administration established their own Committee (CHA). In 1965, ELDO and ESRA, who together became the European Space Agency (ESA), joined the Coordinated Organisations.

Before recruitment of ECMWF staff could begin, a decision clearly had to be made on the salaries to be offered. At the first meeting of the Centre's Finance Sub-Committee in Brussels in July 1974 it was "decided that the salaries of ECMWF should follow the principles, but not the actual scales, of the Coordinated Organisations. The aim must be to devise scales, which will attract recruits from all the Member States and yet be acceptable to the host country. It is proposed that salaries should be fixed at 92% of the Coordinated Organisations salaries for UK based staff."

"UK salaries would be in line with the other Member States if salaries for staff in the UK were reduced to 92% of their present levels . . . There are however possible drawbacks . . . the most serious being that at A6 level they would be lower than at least two national services, Germany and Denmark." Based on the 92% rate, the proposed monthly salary for the ECMWF Deputy Director was £520–£720, for a senior scientist £390–£530 and for a secretary £180–£240.

At its first session in November 1975 Council, with Germany and the UK voting against, "adopted the scale of staff salaries and allowances applicable for the staff of the Coordinated Organisations serving in the United Kingdom" — the full scale, not 92%. This decision opened the door to attracting the best European scientists to the Centre. The level of remuneration offered by the Centre helped partially to compensate for the upheaval to family life caused by a move to a country with a different currency, housing market, language and system of education, and being away from friends and relatives. Still, and in common with most other international organisations, the percentage of staff from the host country, in this case the UK, was in general consistently higher than from the other States, partially because most of the supporting staff — those not scientists or computer experts — were locally recruited.

Council also authorised the Director to apply for membership of the coordinated system. In May 1976, the Council adopted the Pension Scheme Rules of the Coordinated Organisations. Two years later, the Director had to inform Council that "the Centre was not yet a full member of the Coordinated Organisations". The Centre was, however, granted observer status and thus had the opportunity to contribute indirectly to the work of coordination. Throughout the time as an observer, the Centre had been following the recommendations of the CCG in respect of salaries, allowances and the Pension Scheme.

The problem with the Centre joining the coordinated system was in part political. NATO is one of the Coordinated Organisations. The Socialist Federal Republic of Yugoslavia was a Member State of the Centre, thus giving it access to the ECMWF High Performance Computing Facility, including the CRAY supercomputer. NATO was unwilling to support the ECMWF application. The UK delegation informed Council that its delegation to NATO had been asked to urge that the Centre's application for membership of the Coordinated Organisations be placed on the NATO Council agenda. Others also encouraged their NATO representatives to help the Centre's application.

It was not until late 1987, after a meeting of the Secretaries-General of the organisations, that the then Secretary-General of NATO Lord Carrington informed the ECMWF Director Lennart Bengtsson that NATO had agreed to the Centre becoming a full member of the Coordinated Organisations with effect from 1 January 1988. This was some 13 years after it first applied for membership. From then on the Centre participated actively in discussions of the Coordinating Committee of Government Budget Experts (CCG), the Committee of Representatives of the Secretaries-General (CRSG), and the Committee of Representatives of Personnel (CRP).

As well as the Convention, a “Protocol on the privileges and immunities” of the Centre came into force on 1 November 1975. The privileges and immunities are those normally granted to staff of international organisations and include immunity from jurisdiction in respect of acts performed by them in their official capacity, inviolability for their official papers and documents, and the right to import free of duty furniture and personal effects at the time of taking up a post.

In 1978 the Council opened discussion on the length of contracts given to staff of the Centre, and “in particular to the ‘A’ grade (i.e. professional) staff seconded from the National Meteorological Services”. The discussions continued off and on both in Council and between Director and staff until Council approved a Staff Contract policy in November 1985.

The sensible proposals for “a limited number of long-term appointments at the Centre, and a steady flow of scientific staff into the Centre, since the Centre needed a constant supply of new talent, and the National Meteorological Services needed some feedback from the Centre,” have set the contract policy of the Centre ever since. Initial appointment is usually for four years, with second and subsequent appointments for five years. All vacancies are widely advertised, including on the web. Proposals to fill a post are submitted to a Selection Board, which gives advice to the Director. Similarly, recommendations to renew a contract, with the exception of the Head of Department posts, are submitted to a Contracts Board. A representative of the Staff Committee participates as observer at the meetings of the Selection and Contracts Boards. Council approves the appointment of the three Heads of Department and of the Financial Controller on proposal by the Director. For all other posts, Council has left the implementation of the policy to the discretion of the Director. Over the years, there has been a regular turnover of about eight to ten scientific staff each year, enough to ensure a continuing inflow of fresh ideas, while at the same time ensuring continuity.

In June 1979, noting that the Centre had come to the end of its “build-up” phase, the Director suggested to Council that the “continuing responsibilities of the Administration Department should now be reviewed”. A Board of Review composed of delegates from Belgium, France and Switzerland carried out the review, and submitted its report on 1 October. The Report aimed to rationalise the work of the Department. It analysed the working of the Department, and proposed regrouping functions, in effect reducing the number of sections from five to three. In all, four posts would be eliminated.

After brief consideration, the Council in December decided to invite the Staff Committee and the Finance Committee to comment, and to consider the Report at its session in April 1980. At this session, the Chairman of the Board of Review noted *inter alia* that the "problems of the Administration Department had been increased by the tension existing between the previous Director and the Head of Administration". Council decided that the Chairman of the Staff Association, Dr Jean-Francois Louis, would be invited to make a statement on the Report and answer questions. He would then be requested to withdraw prior to the Council discussion. This procedure was not found acceptable; the Staff Association had repeatedly asked to be present during Council debate on staff matters. After a statement explaining his objection to the "secrecy", the Chairman of the Staff Association informed Council that the Staff Committee had decided to resign.

Council then had a lengthy discussion on the Report and in response to a proposal from Director Jean Labrousse, decided to suppress four posts in the Administration Department, and to advertise the post of Head of Administration.

It is fair to say that with this single exception, the contract policy has been applied over the years with little friction between staff, Director and Council. Relations between staff and management have been co-operative rather than confrontational. The Staff Regulations provide for an Appeals Board, to allow staff to appeal against a decision of the Director. In the early years there were nine appeals. However since 1990 there has been only one appeal, and that was to settle a technical point, requiring a correcting decision by Council to a Rule in the Pension Scheme.

In recruiting staff, the Director is bound by the Convention:

> *The recruitment of staff shall be based on personal qualifications, account being taken of the international character of the Centre. No post may be reserved for nationals of a particular Member State.*

Throughout the Centre's history, the Member States have on the whole respected the independent authority of the Director in appointing staff, although it is perhaps inevitable that the London embassies of one or two Member States have at times sent letters supporting applications from their nationals. It has been recognised that, given the scientific and technical nature of the Centre, appropriate staff have been appointed based on their scientific and technical qualifications and experience, and that the international character of the Centre has been taken into account in appointing staff. Perhaps unusually for an international organisation, an a-political approach has been taken to recruitment. The success of the Centre, as well as the level of remuneration, has attracted many talented scientists to work there.

Participation of staff in the Centre's medical and pension schemes is compulsory. In 1975, the Council continued payment into a Provident Fund that had been established during the interim period leading up to the Centre's establishment. The Fund was financed by staff (7% of their salaries) and the Centre (14%). The following year the Council decided, in accordance with the practise of the Coordinated Organisations, to liquidate the Fund and transfer the funds to the ECMWF budget. Thereafter all contributions to the Pension Scheme were considered simply as revenue to the budget, and payments would be made "pay-as-you-go" from the budget. The Member States guaranteed to pay the pensions, as they would become due. In 2002, the Council decided that the Pension Scheme adopted in 1976 should be progressively phased out, and a fully funded Pension Scheme be introduced for staff recruited from January 2003.

The British school system is quite different to those in the other Member States. Fortunately for ECMWF staff coming from other Member States, a European school opened in Culham in Oxfordshire, about 35 km from the Centre, in 1978. It was required for the children of the 1,000 or so staff of the Joint European Torus project. It had five language sections: English, French, German, Dutch and Italian, which happened to coincide with the five official languages of the Centre. The final examination was the European Baccalaureate, which gave entry to European universities. The Centre concluded an agreement with the School in 1989, allowing the children of ECMWF staff to enrol in the school at favourable fees. As the staff were mostly on temporary contracts, enrolment of their children in the European School facilitated re-integration into their national curricula more easily when they returned home. Children of many UK staff also attended the school. They welcomed the opportunity to have their children educated with the children of their expatriate colleagues.

Contributions to the budget of the Centre are based on a scale fixed every three years on a Gross National Income formula approved by Council based on statistical data received from OECD. We have seen in Chapter 5 that the biggest contributor to the budget has always been Germany, which in recent years has contributed about one-quarter of the total budget. It is then within the spirit of the convention that the Director has appointed successive Heads of Administration from that State. This is not a requirement, and may change in the future.

From the beginning, Council recognised the need for short-term employment of scientists with specialised skills, for example in some particular aspect of modelling. While staff recruited to positions in the approved Table of Posts come from the Member States, and in recent years from Co-operating States, scientists employed as "Consultants" can and do come from the USA, Australia or other countries as well as from the Member States. Council initially decided that their appointment should be limited to two years, and that the Staff Regulations should not apply but that they should be employed under guidelines laid down by the Director.

Over the years, there has been an increase of activities in such fields as satellite data research, seasonal forecasting, re-analysis of atmospheric data, Regional Meteorological Data Communications Network (RMDCN) and the introduction of two Optional Programmes: "Prediction of Ocean Waves" and "Boundary Conditions for Limited Area Modelling". Increasingly consultants have been developing and maintaining "core" activities, such as Computer User Support, Archives and Graphics. Some have been funded from the ECMWF budget, with some other funded from participation in external "special projects". Council recognised the important contribution of consultants to the success of the Centre. Consequently it approved over the years the conversion of some consultancy positions into staff posts, thus increasing the number of posts in the Table of Posts to 163 in 2005. With the steady increase in the number of externally funded special projects in particular, the number of consultants had increased to over 50 by 2005.

It is perhaps a sign of good planning, or maybe simply due to the rather small size of the Centre, that the structure of the organisation has remained virtually unchanged over the years. The Operations Department has had a Computer Division and Meteorological Division from the beginning. The Administration Department has made no major changes since 1980. With effect from 1 January 2002, the Research Department added a "Probabilistic Forecasting and Diagnostics Division" to the two existing divisions: Model Division and Data Division.

Chapter 20

And the outlook is . . .

At the beginning, some said that the abbreviation "ECMWF" was unmemorable. If the Centre was to achieve recognition, they said, a recognisable and pronounceable acronym should be chosen. It perhaps is a measure of the Centre's success that "ECMWF" is instantly and widely recognised today worldwide in the field of meteorology.

The Centre was created with specific objectives: to make good medium-range weather forecasts, and to keep making the forecasts better. Success was not inevitable. We have seen the many decisions made by the Directors and Council, and the interconnections between the staff at the Centre and scientists throughout Europe and indeed the world, which led to this success. There have been no overnight wonders. Results have come from incremental improvements. Planning and long-term commitment have paid off. The environment of the Centre has encouraged the change and evolution required to make progress. Innovation has been promoted. New ideas have evolved.

Michel Jarraud had been at the Centre as research scientist from 1978 until 1985. On his return in 1990 as Head of the Operations Department he noticed "a big difference: before, the Centre had been in its development phase, it was now in a mature operational phase — equally exciting, but different". Later, as Secretary-General of WMO, he often used the Centre as an example of the benefit of combining different scientific cultures. The different theoretical and practical approaches throughout Europe to physics and mathematics were a contribution to the "creative tension" of the Centre in its early days. The Research Department was not only tolerant to different ideas, it positively welcomed them. New approaches: spectral modelling, the adjoint technique, variational assimilation, better ways to use satellite data, development of new convection schemes, and more, all resulted. No single approach was regarded as automatically superior to others.

Unlike a usual research institution, there was little or no pressure to publish articles. The goal was not to achieve recognition by having one's work being referenced or quoted. The goal rather was to improve the operational forecasts. Results of research programmes were at times, especially in the early years, simply in the form of hand-written notes. Over the years, of course, the Centre's scientists contributed a substantial body of work to the scientific journals. Jarraud noted the continuing importance of the Centre's restaurant in exchanging ideas and solving problems! Most staff used the lunch and coffee facilities. A researcher who was becoming bogged down in a problem, becoming frustrated or discouraged, could air it informally, and often get new ideas or new approaches to his problem.

The Centre has developed the largest and most comprehensive NWP archive in the world. This major asset for research in seasonal prediction, climates, observing systems and other areas is made freely available to the world's research community. The Centre has led the way in prediction of ocean waves, and in seasonal forecasting, ensemble prediction, data assimilation, data monitoring and more.

The Centre has recognised its responsibility to the wider meteorological community. On 1 July 1988, the Centre became a Regional Specialised Meteorological Centre (RSMC) of WMO, specialising in medium-range forecasting. The Centre gives global medium-range warnings of severe weather — winds, rain, severe extra-tropical storms, floods, drought and hurricanes — to National Meteorological Services worldwide. Although not of highest priority for Europe, the Centre has developed prediction products for tropical cyclones and made them available to the RSMCs with responsibility for such predictions.

Relations between the Council and the Director have been good. The Council has been patient when the going was tough, especially when results were slow in coming from the research programme. It has been clear that Council delegates have been proud of the Centre's achievements. The Centre is generally seen as an indispensable part of the meteorological scene in Europe. By now, some thousands of European meteorologists have worked at the Centre, or attended training courses or seminars, or visited. Many more have used the Centre's data in their research, or have used its computing facilities.

It has been remarked that public awareness of the Centre is greater outside Europe than at home, even though it was first set up under COST, an institution of the EEC, now the European Union (EU). In spite of its origins, the Centre has at the time of writing little regular contact with the EU, apart of course from its research programmes. It would be mutually advantageous to develop such contact. Both Director and Council now agree that the profile of the Centre should be raised. The funds for the Centre come from the taxpayers of Europe; there should be awareness of how these funds are being expended and the results that are achieved.

The Centre will continue to be active in developing European and worldwide collaboration in the atmospheric and related sciences. Some funding for many important aspects of the Centre's work comes from space agencies and the European Union research funds, as well as from national sources. The Centre has supported many field experiments. It has met space agency requirements for engineering, calibration and validation of data coming from new satellite instruments.

The research community worldwide has been using the Centre's output freely, easily and extensively. However, the extent of operational use of the Centre's output in the Member States has not been as great as hoped by some. Some think that the Centre's data policy in this respect has been somewhat too restrictive, although understandable perhaps when seen in the context of guaranteeing the benefits of membership to those who fund the Centre. The Advisory Committee on Data Policy will continue its efforts to encourage more use of the forecasts.

The Centre is now, in 2005, at a turning point in its history. Although there has been a continuous exchange of personnel between the Centre and its Member States, a small team of scientists and managers stayed on from the 1970s. These include David Burridge, Tony Hollingsworth, Adrian Simmons and Horst Böttger, who played significant roles in the build-up phase and during its first three decades. These have left or will leave soon.

Turnover of staff has nevertheless been one of the Centre's strengths. With the amended Convention, noted in Chapter 5, the Centre's activities will expand. The amended Convention will play a part in ensuring the continued success of the Centre. New States will join, contributing additional fresh scientific talent to the Centre's team, as well as easing the financial burden on the existing States. New Member States also will have an influence on the direction the Centre will take in the future. The basics however remain. Undoubtedly the focus of the Centre will remain on improving the quality of the medium-range forecasts.

While it is easier to maintain a feeling of enthusiasm in creation than in consolidation, the Centre's atmosphere and working environment has remained exciting and challenging. New complexities continue to emerge for the development of medium-range prediction. In addition, new demands for environmental monitoring and longer-range atmospheric and oceanic prediction will continue to arise.

However, the financial outlook is cause for concern. The price of the ever more powerful computers needed to address these important issues is anticipated to rise, and maybe rather steeply. Even ten years ago, the expenditure on pensions was nominal. Now, as more staff retire, pension costs are becoming significant. Council decided on a new, and in the short term more expensive, pension system in 2002. Also, buildings are getting older and need refurbishment, and a new building programme began in 2004. Council in the coming years will have to be able to find significant amounts of new funding just to maintain the present level of the Centre.

The demand for weather information will increase and the need to reduce the risk of weather-related damages will grow. Probabilistic information from Ensemble Prediction Systems has already been used to extract quantitative early warning signals of high-impact weather. Also dynamical and statistical techniques have been applied to obtain weather and weather risk information at the smaller scale and for single locations.

Europe currently lacks operational capabilities to provide adequate warnings of widespread severe weather in the coming season. Fifteen thousand excess deaths were recorded in the heat wave of summer 2003. Although forecasts of this heat wave in the days leading up to it were good, medium-range warnings for such natural disasters three to seven days in advance and short-range forecasts up to three days ahead need to be further improved. In the coming years, new developments are expected to increase the synergy between the ECMWF global deterministic and probabilistic forecasting systems and the regional, higher-resolution forecasting and application systems run operationally at national and regional levels. New applications will be developed to increase further the use of ECMWF forecasts in different sectors, including health management, agriculture, energy, hydrology and water management.

As the Centre begins to consider its strategy for the coming decade, severe weather prediction is already stressed. Development work resulted in new forecast products for severe weather prediction based on post-processing forecasts from the Ensemble Prediction System (EPS), including:

- an Extreme Forecast Index,
- tropical cyclone tracks and strike probabilities,
- tropical cyclone frequency in seasons,
- wind gusts and heavy precipitation probabilities, and
- maximum wave and freak wave forecasts.

National Meteorological Services of the Member States, Co-operating States and WMO use the Centre’s products widely for their official duties, including issuing early warnings and alerts for civil protection, such as:

- storm surge prediction,
- flood forecasting,
- wave forecasting, and
- air trajectory computation, for predicting transport of pollution.

Most severe weather events are limited to geographically small areas, or are caused by small-scale features embedded in larger-scale weather systems. It is clear that resolution is important in predicting their occurrence and intensity. Our ability to forecast severe weather is partly limited by the inherent unpredictability of the phenomena in question, and partly by the skill in predicting the large-scale patterns with which they are associated.

The scales of atmospheric weather systems that can reasonably be described by a numerical model are in fact many times larger than the nominal grid separation. A 100 km grid is capable of describing accurately the dynamical circulation of a weather system whose scale is about 800 to 1,000 km or larger. Smaller-scale phenomena fall, so to speak, between and through the grid-points. Thus, typical climate models with 300 to 400 km grids cannot represent many sub-synoptic scale systems at all, and only poorly represent many features such as storm tracks. Resolutions of 15 to 30 km will improve the description of important structures within active synoptic weather systems. In particular, they will capture better the true intensity of the highly energetic systems associated with severe weather events.

At the time of writing, the global analysis and prediction system at ECMWF has the highest resolution of any such system in operational use. However, other major forecasting centres plan to run similar or higher resolution models in the next few years: the Met Office in the UK and the Canadian Meteorological Center with 40 km, Japan Meteorological Agency with 20 km, and the German Weather Service (DWD) with 20 km. ECMWF resolution will reach 25 km in 2005. If the Centre is to conserve its leading position, major efforts will be required.

There is international interest in the possibility of designing global climate models with resolutions of the order of 1 to 3 km. Very limited experimentation has been performed. There are many research issues to be addressed. The aim would be to reduce the number of sub-grid physical processes that need to be parametrized, so decreasing the uncertainties and errors in the models. The computational costs are truly vast. At the time of writing, a global version of the Integrated Forecast System (IFS) with a 2.5 km grid would require a full day of computation on the current IBM mainframe to provide a one-day forecast! It will probably be decades before operational global NWP can consider such an approach. The experiences of both climate research into high-resolution modelling, and regional NWP, which will soon be using such resolutions over small areas, will influence grid refinement in global NWP.

Substantial improvement in the quality of analyses and short-range forecasts has been achieved by improved modelling and data assimilation techniques, and from the improved observations, especially the space-based component of the global observing system. It is now generally acknowledged that the long-term effort to develop, build and refine the 4D-Var system has been a good investment. The system is built on a firm theoretical basis. Extensions will be implemented to meet future requirements. The 4D-Var technique gives the flexibility required to deal with a wide variety of observations. It can extract information from data that are only indirectly linked with the model or analysis variables. Data assimilation system of the future will need to take full advantage of the information obtained from diversifying space-based observing system technologies, in terms of meteorological quantities, greenhouse gases, aerosols and airborne chemicals.

We have noted that the ECMWF variational data assimilation system is an ideal tool for determining the uncertainty in the atmospheric analysis. It is ideal also for directing the deployment of “targeted observations”, for example sending unmanned aircraft to collect data form areas crucial for the future development of a storm. Operational targeting has been implemented for several years in winter over the Pacific, and even longer over the Caribbean basin during the hurricane season. Over the Atlantic, the potential to target storm tracks was assessed in 1997 during the FASTEX field experiment, and in 2003 during the north Atlantic THORPEX Regional Campaign. The European Composite Observing System Programme of EUMETNET was at the time of writing developing a concept of operational targeting for the Atlantic Basin. ECMWF is well placed to contribute to these activities.

While the analyses produced through data assimilation serve their primary function as initial conditions for deterministic forecasts, they also provide a long-term record of the atmosphere and climate. Furthermore, environmental monitoring for the global Earth system is becoming increasingly important. Thus, different requirements are imposed on the design of the future data assimilation system, partly overlapping and partly conflicting: higher resolution, reliable estimation of analysis uncertainty, longer assimilation windows, increased number of analysed fields, and coupling to ocean and land-surface analyses.

Parametrized physics will remain an important aspect of the Centre’s IFS for the foreseeable future. With increased resolution, orography will be better represented. While some mesoscale convective systems will be resolved, parametrization will still be necessary. In fact, the requirements for parametrization will be even more demanding as there is a gradual transition from "parametrized" to "resolved" processes. The behaviour of parametrization at a variety of resolutions is of particular importance to the ECMWF environment. The model is applied with a wide range of resolutions, from seasonal forecasting at low resolution to the deterministic forecast and "outer loop" data assimilation at the highest resolution.

New research elsewhere will be followed closely; promising developments worldwide will be evaluated in the context of the Centre's requirements. Experience has shown that the link between research and implementation in large-scale models is by no means trivial. For example, studies of entrainment in shallow convection, and of diffusion in stable boundary layers, have suggested rather different parameter settings to those used in large-scale models. Often some aspects of model performance deteriorate, due to compensating errors, after making an improvement to a part of the model.

There is an increased demand for good quality precipitation forecasts, for example for predicting severe weather, and for hydroelectricity generation. Further development of the cloud and convection schemes and optimisation of these schemes in their interaction with the model dynamics will be needed to meet this demand. The use of sub-grid variability of moisture as a new model variable is central in this line of research. Work on the moist physics will go hand in hand with work on assimilation of precipitation and clouds.

Over the years, the number of applications of the ECMWF system has increased: ensemble forecasting, ocean wave modelling, seasonal forecasting and ozone chemistry. Although these applications put emphasis on different aspects of the model, they also provide a multi-dimensional constraint on the system and give information on model problems from a different perspective. With GEMS — see below — even more information will become available, for example on convective and turbulent transport, through modelling and verification of aerosols, trace gases and other chemical components.

Increased horizontal and vertical resolution will help to improve parametrization, for example by resolving more of the sub-grid orography and by better resolving the vertical structure of clouds. On the other hand, increased resolution may bring new problems of partially resolved mesoscale systems. Improvements in the parametrized physics will also increase the computational burden. Increased computing resources will allow more detailed modelling of the land surface scheme, new variables such as aerosols, improved physics codes of increased complexity, improved radiation, enhanced evaluation of model changes and better testing of new model versions.

Member States and Co-operating States are using ECMWF probabilistic Ensemble Prediction Systems (EPS) for medium- and extended-range forecasts in health management, agriculture, energy, hydrology, water management and more. The use of extended-range forecasts for severe weather prediction was rather limited initially, but following the success of the DEMETER project, research into application areas such as health and agriculture has been growing. It can be expected that the planned evolution of the forecasting system and the resolution increases to be implemented throughout the forecast range, together with research into the use of multi-model systems, will give a further boost to the development of new applications of these probabilistic forecasts.

Ensemble Prediction Systems are now recognised as essential to realise the economic value of numerical weather and climate forecasts. The key areas of development in EPS concern first the initial and model perturbation strategy, then determination of the resolution of the model versus the ensemble size. With the same computing resources, doubling the model resolution would mean decreasing the size of the ensemble by a factor of about ten. However the balance between ensemble size and model resolution is not only scientifically complex, it may also depend on the users' requirements and risk perception.

Intensive research will continue in many aspects of data assimilation. It will be increasingly important to produce reliable estimates of analysis uncertainty, as required for flow-dependent characterization of the short-range forecast error within the data assimilation itself, and for improved specification of the initial uncertainty in the EPS. This will involve near real time running of a data assimilation ensemble, necessarily at lower resolution than that of the main data assimilation cycle for the deterministic forecast.

Many different configurations for the future operational suite and substantial increases in analysis resolution can be envisaged. Continued improvement of the physics and better representation of background errors at small scales provide further prospects for benefit from higher-resolution analysis. Increased resolution of the forecast model allows for a more accurate comparison between observations as well as the use of high-resolution satellite observations.

It is certain that a vast amount of new data will become available in the next ten years or so. The current Envisat and EOS era provides a wealth of observational data from space. Beyond 2010, the operational Metop series will measure upper troposphere greenhouse gas, for continuation of the Global Ozone Monitoring Experiment (GOME) capability for ozone. More greenhouse gas measurements for the upper troposphere will become available.

Exploitation of the new data including sea-ice, land, clouds and rain, and wind and temperature profiles through the depth of the atmosphere, will improve the observation of the hydrological cycle and monitoring of our global environment. Satellite data will be complemented by more data from "conventional" sources: more dropsondes from aircraft, more automated observations from commercial aircraft, and ground-based radar profilers measuring the atmosphere overhead to a height of 30 km. In the next five years, an increase in the volume of data by a factor of 10 or more can be anticipated, with further increases later when geostationary satellites provide high-resolution soundings.

The Centre will lead the EU-funded project on "Global and Regional Earth-system (Atmosphere) Monitoring using Satellite and In-situ Data" (GEMS), an Integrated Project of the joint ESA-EU Global Monitoring for Environment and Security (GMES) initiative. The Centre will create a new European operational system to monitor atmospheric composition, dynamics and thermodynamics, and to produce medium-range and short-range air-chemistry forecasts, through improved exploitation of satellite data.

Sophisticated operational models and global and regional data assimilation systems exploiting satellite and in-situ data will be needed to provide initial data for the GEMS forecasts. The project will develop state-of-the-art estimates of the sources, sinks and inter-continental transports of many trace gases and aerosols. These estimates, based initially on the retrospective analyses, and later on operational analyses, will be designed to meet policy makers' key information requirements relevant not only to the Kyoto and Montreal Protocols but to the UN Convention on Long-Range Trans-boundary Air Pollution as well.

These operational "status assessments", which are accurate syntheses of all data, will allow sources, sinks and transports of atmospheric trace constituents to be documented, a requirement for the Kyoto Protocol, in which the developed nations agreed to limit their greenhouse gas emissions relative to the levels emitted in 1990.

GEMS will develop, and implement at ECMWF, a validated, comprehensive, and operational global data assimilation and forecast system for atmospheric composition and dynamics. The composition and dynamics of the atmosphere from global to regional scales, and covering the troposphere and stratosphere, will be monitored using all available remotely sensed and in-situ data. Operational deliverables will include current and forecast three-dimensional global distributions four times daily, with a horizontal resolution of 50 km, and with 60 levels between the surface and 65 km, of key atmospheric trace constituents including:

- greenhouse gases, initially including carbon dioxide, and progressively adding methane, nitrous oxide, and the potent greenhouse gas sulphur hexafluoride, together with radon to check advection accuracy,
- reactive gases, initially including ozone, nitrogen dioxide, sulphur dioxide, carbon monoxide and formaldehyde, and gradually widening to include more, and
- aerosols with initially 10 parameters represented, extending later to perhaps 30 parameters.

The global assimilation and forecast system will provide initial and boundary conditions for operational regional air-quality and "chemical weather forecast" systems across Europe. This will allow the impact of global climate changes on regional air quality to be assessed. It will also provide improved operational real-time air-quality forecasts. GEMS will mobilise European expertise to create such operational services and capabilities. It is hoped that GEMS systems will become operational by early 2009.

Access to substantial High-Performance Computing (HPC) resources has been a major factor contributing to the success of the Centre. It has provided a very good user service with a high level of use of the resources. ECMWF's research community, both in-house and in the Member States, has been able to rely on a good turnaround for numerical experiments. Visiting scientists have commented on the high productivity achieved. The development of tools such as "PrepIFS", software that made submission of analysis, forecast, seasonal prediction and EPS experiments easy, was an important contributor to this. Another welcome effect is that of enabling changes to the forecasting system to be carefully tested before being put into production.

Data handling and archiving services will continue to be key components of the Centre's research and operational framework. The Centre's archive will evolve to cater for the ever-increasing volume of observations. Throughout the life of the archive, user access patterns have changed as technology advanced. The archive will support very large research experiments, such as re-analyses, or very long integrations extending over decades and centuries. To make full use of the wealth of information, data mining techniques will be investigated.

The Centre's popular Seminars, Training Courses and Workshops in meteorology and computing will continue to serve the meteorological community of the Member States and elsewhere.

GARP was launched in 1967. The GARP objectives were to study the physical processes in the atmosphere that are essential for an understanding of:

- The transient behaviour of the atmosphere as manifested in large-scale fluctuations which control changes in weather, to increase the accuracy of forecasting over periods from one day to several weeks; and
- The factors that determine the statistical properties of general circulation in the atmosphere, which would lead to better understanding of the physical basis of climate.

In 1973, there was not a single global NWP centre. Today, almost 40 years after the launch of GARP, there are several. In 1975, there was possibly one published paper on numerical prediction of a tropical cyclone. Today there is an extensive literature on the subject. Television viewers expect to be kept informed on the most recent computer predictions of hurricanes approaching land. The Centre's plans are for a challenging future that surely will see advances comparable to those achieved in its first 30 years.

The Centre's team of world-class technicians and scientists produces the best medium-range and seasonal forecasts of the global atmosphere and oceans. The delegations at Council, representing their States, are facing the challenge of ensuring that the Centre's environment continues to attract these talented people.

In the final analysis, the users of the Centre's forecasts are the people, not only in Europe but also throughout the world, who rely on the best possible weather information to plan and carry out their daily activities. They have a right to expect value for the money they spend, through their taxes, on meteorology. The Centre has its duty to continue to do its best to provide the most accurate information.

The meteorological world will watch with great interest as the Centre, its Council, Director and staff, tackle the scientific, technical, financial and administrative challenges facing it.

Annex 1

The Directors

The Council appoints the Director. He is the Chief Executive Officer of the Centre. Consequently he:

- Represents the Centre in dealings with third parties.
- Is responsible to the Council for the execution of the tasks assigned to the Centre.
- Attends all meetings of the Council.

The Director ensures the proper functioning of the Centre. In carrying out this responsibility he:

- Appoints staff, except the Heads of the three Departments, who are appointed by Council on the Director's recommendation.
- Submits each year the draft programme of the activities of the Centre for the following four years, together with the opinions and recommendations of the Committees on the programme.
- Prepares and implements the budget of the Centre.
- Keeps a record of revenue and expenditure, submits annually for the approval of the Council the accounts relating to the budget, and the balance sheet of assets and liabilities.
- Reports on the activities of the Centre.
- Concludes co-operation agreements.

Prof Dr Aksel Wiin-Nielsen

ECMWF Director
1 January 1974 to 31 December 1979

See Chapter 1 'The First Director'

Born: 17 December 1924

Nationality: Danish

Education: Fil. dr. in Meteorology from University of Stockholm, 1960

M. Sc. in Mathematics from University of Copenhagen, 1950

Fil. lic. in Meteorology from University of Stockholm, 1957

Employment:

1995: Professor Emeritus, University of Copenhagen

1987-1994: Professor of Physics, University of Copenhagen

1984-1987: Director, Danish Meteorological Institute

1980-1984: Secretary-General, World Meteorological Organization (WMO)

1974-1979: Director, ECMWF

1963-1974: Professor and Chairman, University of Michigan, USA

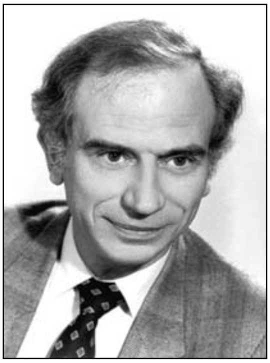
1961-1963: Scientist, Center for Atmospheric Research (NCAR), USA

1959-1961: Staff Member, Joint Numerical Weather Prediction (JNWP), Suitland, USA

1955-1958: Staff Member, International Meteorological Institute (IMI), Stockholm

1952-1955: Staff Member, Danish Meteorological Institute

Jean Labrousse



ECMWF Director
1 January 1980 to 31 December 1981

Aksel Wiin-Nielsen left to take on the post of Secretary-General of WMO in 1979. At its session in June 1979, the Council set up a Selection Committee to consider the appointment of a Director, and by postal ballot, Jean Labrousse was appointed the Director of the Centre. He had been Head of the Operations Department since June 1974, and served as Director for just two years.

M. Roger Mittner, Director of Météorologie Nationale, retired on 31 December 1981. Labrousse was appointed as Director of Météorologie Nationale from 1 January 1982 by the Conseil des Ministres.

Born: 12 November 1932

Nationality: French — Officier de la Légion d'Honneur

Education: Mathematics, Physics, Informatics, Meteorology at Toulouse University and Paris-Sorbonne University

Meteorological Engineer at Ecole Nationale de la Météorologie

Employment: Retired since November 1997.
Honorary Director of Météo France (formerly Météorologie Nationale)
Honorary President of the Association of Former Meteorologists (AAM)

1997: Head of the French Secretariat for Joint Implementation (United Nations Framework Convention on Climate Change), Paris

1994-1997: Scientific Secretary for Meteorology EEC/COST, Brussels

1991-1993: Director of the Earth-Ocean-Space-Environment Department, Ministry of Research, Technology and Space, Paris

1987-1991: Director of the Research and Development Programme WMO

1986-1987: Appointed as Permanent Member ‘Conseil Général des Ponts et Chaussées’, Section 3 (Research) and 4 (Environment)

1982-1986: Director, Météorologie Nationale, Paris

1980-1981: Director, ECMWF

1974-1979: Head of Operation Department, ECMWF

1952-1974: Positions in Météorologie Nationale: Data Processing Manager; Head of the Meteorological Station in Lome-Togo; Teacher at the Ecole Nationale de la Meteorologie

Prof Dr Lennart Bengtsson

ECMWF Director
1 January 1982 to 31 December 1990

Dr Lennart Bengtsson had been Head of Research at the Centre since July 1974. In November 1981, Council appointed him as Director from 1 January 1982. His appointment was renewed in 1985.

In May 1990, Bengtsson notified Council that he had been offered a post as Director within the Max-Planck-Gesellschaft in Germany and that it was his intention to accept the offer.

Born: 5 July 1935

Nationality: Swedish

Education: Ph. D. (fil. lic.) in Meteorology from University of Stockholm, 1964

M. Sc. from University of Uppsala, 1959

B. Sc. from University of Uppsala, 1957

Employment:

2001: Professor, Environmental Systems Science Centre, University of Reading

1991-2000: Director, Max Planck Institute for Meteorology, Hamburg

1982-1990: Director, ECMWF

1976-1981: Deputy Director and Head of Research, ECMWF

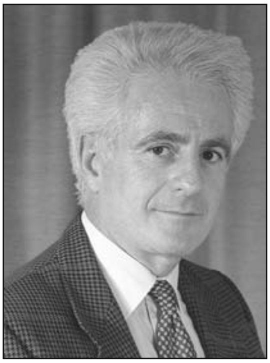
1974-1975: Member of interim planning staff for establishing ECMWF

1965-1974: Head of Division, Swedish Meteorological and Hydrological Institute

1961-1965: Research Meteorologist, Swedish Meteorological and Hydrological Institute

1979: Associate Professor in Meteorology (Docent), University of Stockholm

Dr David Martin Burridge CBE



ECMWF Director
1 January 1991 to 17 June 2004

An unwritten rule or tradition that the Director of an international organisation should not come from the State in which the organisation has its headquarters, perhaps with the intention of avoiding undue influence from the host country, remained in force until 1990. However, in December 1990, the Council broke with this tradition and appointed Dr David Martin Burridge, a native of Wales, as Director from 1 January 1991. He had been at the Centre since 1974, and had been Head of Research since 1982.

In November 1989, Council had considered the appointment of senior staff, and decided that 'in general two terms should be the maximum' for their term of employment. Council broke this rule also when, having renewed Burridge's appointment in 1993, it reappointed him again in 1998 to serve until he retired on 18 June 2004.

Born:	17 June 1944
Nationality:	United Kingdom — Commander of the Order of the British Empire (CBE)
Education:	Ph. D. in Applied Mathematics from Bristol University, 1970
	B. Sc. in Mathematics (First Class Honours) from Bristol University, 1966

Employment:

Retired since June 2004.

1991-2004:	Director, ECMWF
1989-1990:	Deputy Director, ECMWF
1982-1990:	Head of Research, ECMWF
1979-1982:	Head of Model Division, ECMWF
1976-1978:	Head of Numerical Aspects Section, ECMWF
1975-1976:	Member of Interim Planning Staff for establishing ECMWF
1970-1975:	Scientist, Forecasting Research Branch, Meteorological Office, Bracknell
1969-1970:	Assistant Professor, Florida State University, USA

Dominique Marbouty

ECMWF Director from 18 June 2004

In its session in December 2003, Council appointed Dominique Marbouty from France as Director. Marbouty had been at the Centre as Head of Operations since February 1999.

Born: 9 June 1951

Nationality: French

Education: Ecole Polytechnique, Paris, 1970-73
Ecole Nationale de la Météorologie, Paris, 1973-75

Employment:

2004: Director, ECMWF
2003-2004: Deputy Director, ECMWF
1999-2004: Head of Operations, ECMWF
1994-1999: Deputy Director General, Météo France, Paris
1992-1994: Deputy Director, Météorologie Nationale, Paris
1989-1991: Head, Bureau for Operation and Defence, Météorologie Nationale, Paris
1985-1989: Director, Region South-West, Météorologie Nationale, Bordeaux
1984-1985: Deputy Director, Region South-West, Météorologie Nationale, Bordeaux
1978-1984: Head, Snow Research Centre, Météorologie Nationale, Grenoble
1975-1977: Scientist, Météorologie Nationale, Paris and Grenoble

Annex 2

The Council and its Committees

In the words of the Convention:

"The organs of the Centre shall be the Council and the Director. The Council shall be assisted by a Scientific Advisory Committee and a Finance Committee."

The Council

The Convention says that the Council "shall have the powers and shall adopt the measures necessary to implement this Convention". The Council, which meets usually twice per year, is composed of not more than two representatives from each Member State, "one of whom should be a representative of his national meteorological service". Advisers may assist these representatives at Council meetings. A representative of the World Meteorological Organization is invited to take part in the work of the Council as an observer. The responsibilities of Council include:

- deciding on the admission of new Member States to the Centre, and making conditions for such admissions, for example payment of a "joining fee" by late joiners Norway and Luxembourg as a contribution to the expenditure of the other States that have built up the Centre's infrastructure,
- withdrawing membership from a State that fails to fulfil its obligations,
- dissolving the Centre if one or more Member States decide to denounce the Convention so that the financial contributions of the remaining States increase by more than 20%,
- authorising the Director to negotiate and conclude co-operation agreements with States and with international scientific and technical organisations, and
- deciding on the acquisition of computer systems, adopting the staff and financial regulations, and deciding on the myriad other matters required to keep an international organisation functioning.

And of course by approving the annual budget Council arranges for the funding to be provided by the Member States to run the Centre.

Council Presidents

Name	State	Term as President
Dr E. Süssenberger	Germany	1974–1976
Prof L. A. Vuorela	Finland	1977–1979
Mr P. K. Rohan	Ireland	1980
Prof E. Lingelbach	Germany	1981–1983
Prof L. A. Mendes Victor	Portugal	1984–1986
Prof A. C. Wiin-Nielsen	Denmark	1987
Prof S. Palmieri	Italy	1988
Dr H. M. Fijnaut	Netherlands	1989–1991
Dr H. Malcorps	Belgium	1992–1994
Dr A. Grammeltvedt	Norway	1995–1997
Mr U. Gärtner	Germany	1998–2000
Dr L. Prahm	Denmark	2001–2003
Prof A. Eliassen	Norway	2004–

Council Vice-Presidents

Name	State	Term as Vice-President
Dr M. W. F. Schregardus	Netherlands	1974–1975
Prof L. A. Vourela	Finland	1976
Mr R. Mittner	France	1977–1979
Prof E. Linglebach	Germany	1980
Prof L. A. Mendes Victor	Portugal	1981–1983
Dr J. Van Tiel	Netherlands	1984
Dr A. Zancla	Italy	1985
Prof A. C. Wiin-Nielsen	Denmark	1986
Prof S. Palmieri	Italy	1987
Dr H. M. Fijnaut	Netherlands	1988
Dr H. Reiser	Germany	1989–1991
Dr A. Grammeltvedt	Norway	1992–1994
Mr C. Pastre	France	1995
Dr U. Gärtner	Germany	1996–1997

Prof C. Finizio	Italy	1998–1999
Dr L. P. Prahm	Denmark	2000
Mr J-P. Beysson	France	2001–2003
Mr A. V. Serrão	Portugal	2004–

The Scientific Advisory Committee (SAC) has twelve members selected from among the scientists of the Member States and appointed "in their personal capacity" by the Council for a period of four years. Thus, members of the SAC do not represent the interests of the State from which they come; they are independent scientific experts. They represent a broad range of the disciplines relating to the activities of the Centre, modelling, analysis, use of satellite or other specialised data, and more. The Committee is renewed by one quarter every year. Representatives of the World Meteorological Organisation and EUMETSAT take part in the work of the Committee.

The Committee broadly speaking confines itself to the Centre's scientific programme as the Director proposes it and as it is implemented by the Research Department. Normally meeting once a year in the autumn, it draws up, for submission to the Council, "opinions and recommendations on the draft programme of the activities of the Centre drawn up by the Director and on any matter submitted to it by the Council". The Director keeps the Committee informed on the implementation of the programme. The Committee gives Council its opinions on the results obtained.

The SAC has played a crucial role over the years. The independent scientists on the Committee have monitored the Centre's scientific plans, and the progress of implementation of the plans, with a questioning and sometimes sceptical eye. The Director and Head of Research have not always been completely comfortable facing the Committee's scrutiny. The Committee members continued to question that which they found unconvincing. However they supported what they liked, and the Chairman of the SAC, in reporting to Council, was often able to convince Council of the merits of the Director's proposals contained in the Four-year Programme of Activities. Also, there were times when the Director or Head of Research was able to take some satisfaction in having achieved progress, sticking to their convictions against the opinions of some on the Committee! The enthusiasm of the SAC scientists for the work of the Centre was often evident in the language used in their Reports to Council.

Scientific Advisory Committee Chairmen

Name	State	Term as Chairman
J. S. Sawyer	UK	1975–1977
R. Bates	Ireland	1978–1980
F. Mesinger	Yugoslavia	1981–1982
F. Bushby	UK	1983–1984
B. J. Hoskins	UK	1985–1988
B. Machenhauer	Denmark	1989
A. J. Gadd	UK	1990–1992
O. Talagrand	France	1993–1996
P. Lynch	Ireland	1997–1998
J-F. Louis	USA	1999–2001
C. Schär	Switzerland	2002–2004
E. Källén	Sweden	2005–

The Finance Committee is composed of one representative of each of the four Member States paying the highest contributions, and three representatives of the other Member States, appointed by them for a period of one year. These States are normally represented on the Committee for terms of three years. The Committee has some financial powers delegated to it by the Council, for example approving contracts that do not involve very large sums of money. It examines the Director's proposed budget and Programme of Activities in detail, and then draws up, for submission to the Council, opinions and recommendations on these, and on all financial matters dealt with by Council. The Committee usually meets twice yearly, before Council sessions in the spring and autumn.

Finance Committee Chairmen

Name	State	Term as Chairman
P. P. Wrany	Germany	1979-1981
J. Day	UK	1982-1984
U. Gärtner	Germany	1985-1987
B. Mc Williams	Ireland	1988-1990
R. Watrin	France	1991-1993
F. Neuwirth	Austria	1994-1996

M. Palomares	Spain	1997–1999
M. Klöppel	Germany	2000–2002
C. Monteiro	Portugal	2003–2004
L. Frachon	France	2005–

The SAC and Finance Committee are the only two Committees mentioned in the Convention. However, by the Convention, the Council "may set up advisory committees and shall determine the composition and duties thereof". In 1976 Council established three advisory committees.

- An **Advisory Committee on matters relating to communications between the Centre and the Member States**, chaired by Dr Daniel Söderman of Finland, was established in May 1976. The terms of reference of the Committee included evaluating Member State requirements for forecast products of the Centre, the means of distribution, how the Member States could use the computer system of the Centre, and technical and financial aspects.
- An **Advisory Committee on the acquisition of the computer system of the Centre**, chaired by Mr Deloz from Belgium, was established in November 1976. This drew up recommendations leading to the Centre acquiring the CRAY-1 computer.
- An **Advisory Committee on the Use of the Computer System by the Member States (ACUCS)**, chaired by Mr Fred Bushby of the UK, was established in November 1976. The Committee's work eased greatly the problem faced by Council in ensuring a fair distribution of the available computer resources among the Member States.

In November 1978 Council set up the **Technical Advisory Committee (TAC)**. It would have the tasks of the three somewhat ad-hoc Committees, and would otherwise consider the Centre's operational meteorological activities, proposed changes to the computing and telecommunications systems and such matters. In effect, while the SAC and Finance Committee advised the Council on the work and plans of the Research and Administration Departments, the TAC was set up to do the same for the computing and meteorological activities of the Operations Department. The TAC usually meets after the SAC session in the autumn each year.

Technical Advisory Committee Chairmen

Name	State	Term as Chairman
D. Söderman	Finland	1979
J. Lepas	France	1980–1982
W. H. Wann	Ireland	1982–1986
M. H. Haug	Switzerland	1986–1990
W. Struylaert	Belgium	1990–1994
M. Capaldo	Italy	1994–1995
S. Kruizinga	Netherlands	1995–1999
G. Wihl	Austria	1999–2003
K. Soini	Finland	2003–

In May 1990, the Council set up the **Advisory Committee to consider, and make recommendations regarding, the establishment of a Meteorological Licensing Agency**. Its Chairman was Mr Detlev Frömming from Germany. This Committee met only once.

In December 1992 Council had a lengthy discussion on general matters of policy and principle. The **Policy Advisory Committee (PAC)** was set up in June 1993, to advise Council on policy matters that could not properly be dealt with by the other Committees. It considers matters submitted to it by the Council. Its first Chairman was Prof Erkki Jatila from Finland. The PAC normally meets twice yearly, before Council sessions in the spring and autumn.

Policy Advisory Committee Chairmen

Name	State	Term as Chairman
E. Jatila	Finland	1993-1994
H. Sandebring	Sweden	1995-1999
D. Murphy	Ireland	1999-2003
J. de Jong	Netherlands	2003
M. Capaldo	Italy	2004-

A co-operation agreement had been concluded with Iceland in 1980, under which Iceland could attend Council sessions as observer. In June 1994 Council set up the **Advisory Committee of Co-operating States (ACCS)**. This new Committee was composed of representatives of the States with which the Centre would in future conclude agreements. There was the prospect of an increasing number of such agreements in the future following developments in Eastern Europe. The ACCS would be able to give

Council the collected opinions and recommendations of the Co-operating States, without them individually having to attend Council. Its first chairman was Dr Ivan Mersich from Hungary. The ACCS proved to be a useful Committee for maintaining contact between the Secretariat of the Centre and the States on technical and scientific issues, in addition to carrying out its formal function.

Advisory Committee of Co-operating States Chairmen

Name	**State**	**Term as Chairman**
I. Mersich	Hungary	1994–1997
M. Matvijev	Croatia	1998–2000
D. Hrček	Slovenia	2001–2002
J. Roskar	Slovenia	2003–

The Council in December 2001 set up a new Advisory Committee, the **Advisory Committee for Data Policy (ACDP)**, which would review the Centre's data policy, with a view to encouraging and developing use of the Centre's forecasts for both commercial and non-commercial applications. The ACDP representatives were experts from the Member States. Many of them had considerable experience in dealing with data policy issues relating to EUMETSAT and commercial data. Its Chairman was Mr Detlev Frömming from Germany.

Annex 3

List of abbreviations

ACDP	Advisory Committee on Data Policy
ACE-Asia	Aerosol Characterization Experiment — Asia
ACMAD	African Centre of Meteorological Applications for Development
ACUCS	Advisory Committee on the Use of the Computer System
ADSM	Adstar Data Storage Manager
AIRS	Atmospheric InfraRed Sounder
ALPEX	Alpine Experiment
ARPEGE	*Action de Recherche Petite Echelle Grande Echelle*
A-TReC	Atlantic THORPEX Regional Campaign
ASC	Advanced Scientific Computer from Texas Instruments Inc
ATOVS	Advanced TIROS Operational Vertical Sounder
BADC	British Atmospheric Data Centre
BCRS	Dutch Remote Sensing Board
BoM	Bureau of Meteorology (Australia)
bps	bits per second
BUFR	Binary Universal Form for the Representation of meteorological data
CBS	Commission for Basic Systems (of WMO)
CCG	Co-ordinating Committee of Government Budget Experts

CDC	Control Data Corporation
CERFACS	*Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique*
CERN	*Conseil Européen pour la Recherché Nucléaire*
CFS	Common File System
CHA	Committee of Heads of Administration (part of CCG)
CLRTAP	Convention on Long-range Transboundary Air Pollution
CMA	China Meteorological Administration
CMC	Canadian Meteorological Centre
CNRS	*Centre National de la Recherche Scientifique*
COADS	Comprehensive Ocean Atmosphere Data Set
COARE	Coupled Ocean-Atmosphere Response Experiment
COLA	Centre for Ocean-Land-Atmosphere Studies
COS	Cray Operating System
COST	European Cooperation in Scientific and Technical research
CPU	Central Processing Unit
CRSG	Committee of Representatives of the Secretaries-General
CRP	Committee of Representatives of Personnel
CTBTO	Comprehensive Nuclear Test-Ban Treaty Organisation
CUG	Cray User Group
DEMETER	Development of a European Multi-model Ensemble system for seasonal to inTERannual prediction
DST	Data Systems Test
DUACS	Developing Use of Altimetry for Climate Studies
DYCOMS	Dynamics and Chemistry of Marine Stratocumulus
DWD	*Deutscher Wetterdienst* — the German Weather Service
ECFS	ECMWF File management System
ECMWF	European Centre for Medium-Range Weather Forecasts

ECMW	European Centre for Medium-Term Weather Forecasting *(obsolete)*
EEA	European Economic Area
EEC	European Economic Community
EFFS	European Flood Forecasting System
ELDO	European Launcher Development Organization
EMCC	European Meteorological Computing Centre
EMOS	ECMWF Meteorological Operational System
ENACT	ENhAnced ocean data assimilation and ClimaTe prediction
ENIAC	Electronic Numerical Integrator and Calculator
ENSO	El Niño Southern Oscillation
ENVISAT	ENVIronment SATellite
EOS	Earth Observing System
EPS	Ensemble Prediction System
EPO	European Patent Office
ERA	ECMWF Re-Analysis
ESA	European Space Agency
ERS	Earth Resource Satellite
ESOC	European Space Operations Centre
ESRIN	European Space Research INstitute
ESRO	European Space Research Organization
ESSA	Environmental Science Services Administration
EU	European Union
EUMETNET	Network of European Meteorological Services
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUCOS	EUMETNET Composite Observing System
EURATOM	European Atomic Energy Community
FASTEX	Fronts and Atlantic Storm-Track Experiment

FGGE	First GARP Global Experiment
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GARP	Global Atmospheric Research Programme
GATE	GARP Atlantic Tropical Experiment
GB	Gigabyte: 1024 megabytes (about 10^9 bytes)
GCM	General Circulation Model
GEOSAT	Geodetic Satellite
GEOSS	Global Earth Observation System of Systems
GEMS	Global and regional Earth-system (Atmosphere) Monitoring using Satellite and in-situ data
GDPS	Global Data-Processing System
GFDL	Geophysical Fluid Dynamics Laboratory
GMES	Global Monitoring for Environment and Security
GNI	Gross National Income
GNP	Gross National Product
GOME	Global Ozone Monitoring Experiment
GOS	Global Observing System
GRIB	GRIdded Binary (a code)
GTS	Global Telecommunication System
HIRETYCS	HIgh REsolution Ten Year Climate Simulation
HIRLAM	High-Resolution Limited Area Model
HOPE	Hamburg Ocean Primitive Equation
HPC	High-Performance Computing
HPSS	High Performance Storage System
IAS	Institute for Advanced Study
IBM	International Business Machines
ICL	International Computers Ltd
ICSU	International Council for Science

IASI	Infrared Atmospheric Sounding Interferometer
IFS	Integrated Forecast System
IMI	International Meteorological Institute
INPE/CPTEC	Institute for Space Research Centre for Weather Predictionand Climate Studies (Brazil)
JANET	Joint Academic research and education NETwork (UK)
JHG	Joint Harmonization Group
JMA	Japan Meteorological Agency
JNWP	Joint Numerical Weather Prediction
JRA	Japanese Re-Analysis
JRC	Joint Research Centre
KNMI	Het Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
LAN	Local Area Network
LAS	Laboratory for Atmospheric Science (at NCAR)
LASL	Los Alamos Scientific Laboratory
LCN	Loosely Coupled Network
LMD	*Laboratoire de Météorologie Dynamique*
MAGICS	Meteorological Applications Graphics Integrated Colour System
MANTRA	Middle Atmospheric Nitrogen Trend Assessment
MARS	ECMWF Meteorological Archive and Retrieval System
MB	Megabyte: 2^{10} bytes (about 10^6 bytes)
MERSEA	Marine Environment and Security for the European Area
METEOSAT	Meteorological Satellite
MHz	Megahertz: one million cycles per second
MIPS	Million Instructions Per Second
MIT	Massachusetts Institute of Technology
MP	Multi-Processor

MPI	*Max-Planck-Institut für Meteorologie*
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
NCAR	Mational Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction (Washington)
NERSC	National Energy Research Scientific Computing Center (California)
NMC	National Meteorological Center (often refers to NMC, USA)
NNMI	Non-linear Normal Mode Initialisation
NMS	National Meteorological Service
NOAA	National Oceanic and Atmospheric Administration
NORPEX	North Pacific Experiment
NTC	New Telecommunications Computer
NTS	National Telecommunications System
NWP	Numerical Weather Prediction
OASIS	Ocean Atmosphere Sea Ice Soil
OD	Operations Department (of ECMWF)
OECD	Organisation for Economic Co-operation and Development
OI	Optimum Interpolation
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
PAC	Policy Advisory Committee
PAOB	PAid OBservation: Quasi-observations from the Australian Bureau of Meteorology
PB	Petabyte: 1024 terabytes (approx. 10^{12} bytes)
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PE	Processing Element

PROMISE	PRedictability and variability Of Monsoons, and the agricultural and hydrological ImpactS of climatE change
PROVOST	PRediction Of climate Variations On Seasonal to interannual Timescales
RA	Regional Association (of WMO)
RD	Research Department (of ECMWF)
RDB	Reports Data Base
RMC	Regional Meteorological Centre
RMDCN	Regional Meteorological Data Communication Network
RPN	*Recherche en Prévision Numérique* (Montreal)
RSMC	Regional Specialised Meteorological Centre (of WMO)
RTTOV	Radiative Transfer model for TOVS
SAC	Scientific Advisory Committee
SAF	Satellite Applications Facility
SAI	Service in Informatics and Analysis
SAR	Synthetic Aperture Radar
SECDED	Single Error Correction Double Error Detection
SFRY	Socialist Federal Republic of Yugoslavia
SMHI	Swedish Meteorological and Hydrological Institute
SMS	Supervisor-Monitor-Scheduler
SMP	Shared Memory Processor
SSD	Solid-state Storage Device
SSL	Software Sciences Ltd
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
TAC	Technical Advisory Committee
TAO	Tropical Atmosphere Ocean
TB	Terabyte: 1024 gigabytes (about 10^{12} bytes)
TCP/IP	Transmission Control Protocol/Internet Protocol

THORPEX	THe Observing System Research and Predictability Experiment
TIGGE	THORPEX Interactive Grand Global Ensemble
TOGA	Tropical Ocean-Global Atmosphere
TOPSE	Tropospheric Ozone Production about the Spring Equinox
TOVS	TIROS Operational Vertical Sounder
Tnnn Lmm	Triangular resolution at wave number nnn, with mm levels between the surface and top levels of the model atmosphere (a measure of model resolution)
TRACE-P	TRace And Chemical Evolution over the Pacific
UA	Unit of Account (of EEC — on 1 January 1972, 1 UA = £0.437)
UCAR	University Corporation for Atmospheric Research
UCLA	University of California, Los Angeles
UK	United Kingdom
UN	United Nations
UNICOS	A Unix variant for Cray computers
UNIVAC	UNIVersal Automatic Computer
USSR	Union of Soviet Socialist Republics
UTC	Universal Time Co-ordinated
VDU	Visual Display Unit
WAM	WAve Modelling Group
WCRP	World Climate Research Programme
WEU	Western European Union
WMC	World Meteorological Centre
WMO	World Meteorological Organization
WWW	World Weather Watch