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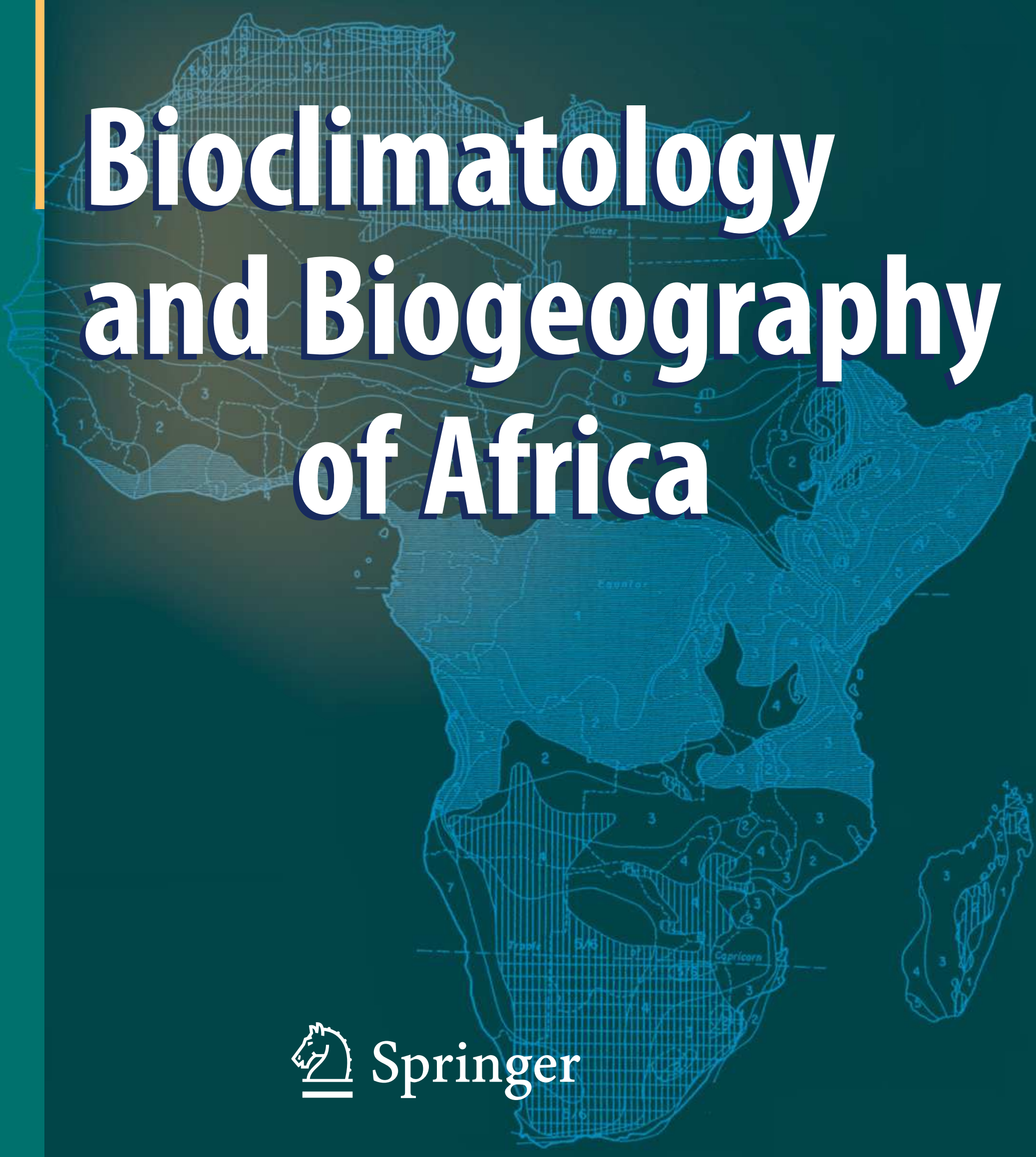
Bioclimatology and Biogeography of Africa



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Introduction

Abstract Chapter 1 deals with general problems and methodology: Scope of the study, Basic concepts, Classification criteria: Energy flow, Water stress, Dry seasons and drought, Cold stress and its relationship to latitude and altitude, Frost hazard occurrence, Rainfall distribution and amount, Potential evapotranspiration, *P*/PET ratios, Temperature and frost sensitivity/tolerance, Relationship between annual temperature and ETo, Ratios between *P* and ETo as aridity indices, Effect of wind on PET or ETo, Other significant climatic parameters: Vapour pressure, Relative humidity, Saturation deficit, Soil distribution, Impact of agro-hydraulic works, Land-use patterns and agricultural production systems, Flora, Vegetation, Fauna, Wildlife and livestock populations, Human and animal diseases as related to climate, Human comfort.

The methodology is based on a series of criteria at distinct levels of classification:

- Seasonality of rainfall resulting in Mediterranean (winter precipitation, summer drought), Tropical (summer monomodal precipitation, winter drought) and Equatorial (bimodal, spring and fall precipitation, winter and summer drought) families of bioclimates, based on the annual patterns of rain and temperature, as expressed in the climatic diagrams of Bagnouls and Gaussen, popularized by Walter and Lieth in their Klimadiagramm Weltatlas.
- Amount of precipitation and *P*/PET ratios within each family (hyper-humid, humid, sub-humid, semi-arid, arid to hyper-arid), based on decreasing *P*/ETo ratios.
- Mean minimum daily temperature of the coldest month as an index of winter cold stress in each family, and its relationship to elevation (lowlands, midlands, highlands and Afro-alpine zones).

A large table (17 pp.) shows the annual values for ten key climatic parameters for the 962 weather stations of the database.

H.N. Le Houérou, *Bioclimatology and Biogeography of Africa.*

1.1 Scope

The aim of the present bioclimatic and biogeographic classification is to provide a basis of comparison between various regions and zones within the African continent, and with comparable areas from other continents such as Latin America (Le Houérou 1990c) or the Indian subcontinent (Le Houérou 1992f). The present classification shows, for instance, the main differences and similarities between agro-bioclimatic conditions in West Africa and in East Africa on the one hand and, on the other hand, between the Sudanian ecological zone beyond 10°N and the Miombo Woodland zone south of 10°S, and also between the extra-tropical and Mediterranean zones of northern and southern Africa.

Moreover, the present classification also shows the remarkable latitudinal climatic homogeneity of the Sahelian and Sudanian ecological zones, as opposed to the striking and contrasting climatic heterogeneity of the comparable zones of eastern and southern Africa (Le Houérou 2006c). It should also constitute a rational basis for national, regional and sub-regional rural development planning and for agricultural research organization such as plant and animal introduction, the extrapolation or interpolation of experimental or developmental findings, and systems research.

It should be kept in mind, however, that the continental scale of this study does not allow, in principle, for country-level direct application. Nevertheless, it does provide a methodology and a framework for such national or provincial applications. The problem of possible applications will be examined in the concluding chapter.

1.2 Basic Concepts

1.2.1 General

The core of the present classification was first published in a study of afforestation in the Sahel (Le Houérou 1976), then in a study of the grasslands of Africa, a plenary lecture at the XIIIth International Grassland Congress (Le Houérou 1977), and in an Ecological Study of Ethiopia (Le Houérou 1980a, 1984a). It was further developed in an Ecoclimatic Classification of Inter-Tropical Africa (Le Houérou and Popov 1981), the agro-bioclimatic classification of Africa (Le Houérou et al. 1993), the classification of the Arid Zones of Northern Africa (Le Houérou 1989a), of the bioclimatology and biogeography of northern Africa (Le Houérou 1995a), of the Red Sea Basin of East Africa and Arabia (Le Houérou 2003), and of Marmarica (Egypt-Libya; Le Houérou 2004a). It therefore results from a stepwise approach as my field experience progressed. This classification is based on both aridity and frost tolerance, unlike many others based only on a sole aridity index.

A similar classification, based on the same principles, was proposed for Kenya in a seemingly independent approach (Braun 1982; Jätzold and Schmidt 1982).

The originality of the present classification is the combination of a rather large number of criteria of various climatic and biological nature, following the concepts of the early phytogeographers (Köppen 1900; Flahault 1904; De Martonne 1926; Emberger 1930; Köppen and Geiger 1930; Gaussen 1938; Bagnouls and Gaussen 1953a, b), as shown below.

A. Climatic criteria
- Seasonal patterns of rainfall distribution:
  winter vs. summer rainfall;
  monomodal vs. bimodal patterns.
- Amount of annual rainfall.
- Variability of annual rainfall.
- Dependability of annual rainfall.
- Length of the rainy season.
- Dry seasons and drought (water stress), severity and length of the annual dry season.
- Temperatures and thermal limiting conditions to plant growth (cold stress and heat stress).

B. Biological criteria
- Distribution of community types of vegetation.
- Distribution of individual native plant species, phytogeography and centres of endemism.
- Distribution of wildlife and game species.
- Distribution of livestock species and breeds.
- Occurrence of major pests and diseases (sleeping sickness, malaria, schistosomiasis, river blindness, piroplasmosis, rinderpest, contagious pleuro-pneumonia, etc.).
- Human comfort and tolerance to heat.

C. Agronomic criteria
- Land use as controlled by climatic criteria.
- Soil distribution.
- Crop distribution patterns.
- Distribution of agricultural production systems.
- Distribution of livestock species and breeds and of livestock production systems.

D. Geographic criteria
- Relationship between altitude, latitude and temperature: lowlands, midlands and highlands.
- Relationship between continentality, rainfall and temperature.
- Relationship between ocean currents and coastal deserts.
- Relationship between ocean and land masses: the monsoons and trade winds.

The basis of the classification is the relationship between various biological criteria (including agronomic) and climatic factors, as the latter are much easier to apprehend, discriminate and quantify, since they are represented on cartographic documents.

1.2.2 Energy Flow and Budget

Global radiation is shown in Tables T1–3 and Fig. 11. Radiation is, for a large part, controlled by latitude (Fig. 11); the highest values in Africa are found in the central and southern Sahara (R_g = 200–220 kcal cm^{-2} $year^{-1}$), the lowest in the Gulf of Guinea (R_g = 140 kcal cm^{-2} $year^{-1}$), due to cloudiness. Africa is objectively the warmest continent of the planet (Le Houérou 1990a, 1992a, 1996a). At higher latitudes, radiation is reduced due to the smaller incident energy flow.

An approximate relationship exists between global radiation and potential evapotranspiration whereby ETo ≈ 0.0085 R_g (global radiation), where ETo is expressed in mm of mean annual reference potential evapotranspiration, computed via the Penman-Monteith equation, and R_g in cal cm^{-2} $year^{-1}$ (Le Houérou 1972, 1984a). Since this relationship accounts for neither advective lateral energy (oasis effect) nor wind speed, it provides a low estimate in windy areas such as the Sahara and the Sahel (NE continental trade winds = "Harmattan") but is approximately correct in other African zones such as northern, central, eastern and southern Africa. In Fig. 11, the isolines of R_g can be equated with the values of global radiative evapotranspiration potential (GREP) shown in Table T1 (Le Houérou and Norwine 1985).

Net radiation (R_n) is about 45% of global radiation R_g (Uchijima and Seino 1987). The *P*/GREP ratio, similar to Budyko's dryness index, is a reasonable approximation of the *P*/ETo ratio; it may be used as such for depicting broad ecological zones—e.g. the value of 0.06 corresponds with the upper limit of hyper-arid zones (i.e. true deserts); the 0.30 value may be equated with the limit between arid and semi-arid zones, etc.

Photosynthetically active radiation (PAR) is approximately 40% of R_g and 80% of R_n (Le Houérou 1980b, 1982a, 1989b; Le Houérou and Norwine 1985). Figure 11 gives a reasonable approximation of GREP, R_n and PAR, in addition to R_g.

Variations in the quotient between ETo and *T* appear directly related to the magnitude of the aerodynamic parameter in the final expression of the Penman equation: ETo/*T* averages 96.9 in the Sahara, dropping progressively to 45–55 towards the equator, to the zone of so-called equatorial stillness (Table T2; see Table A1 for details). One exception to this rule is the Red Sea shores area and N. Somalia where the values of this ratio are comparable with those of the Sahara and of the Kalahari.

Table T1 Relationship between global radiation and global radiative evapotranspiration potential (GREP), disregarding the aerodynamic term of the theoretical equation (Le Houérou et al. 1993)

Global radiation (kcal cm^{-2} $year^{-1}$)	GREP (mm)
120	≈1,000
140	1,200
160	1,400
180	1,550
200	1,700
220	1,900

Similar trends have been observed in other zones of strong persistent winds—in Patagonia, for instance (Le Houérou 1999b).

Table T3 shows the relationship between rain-use efficiency (RUE) and the equivalent water-use efficiency (WUE). This aspect is developed in more detail below.

1.2.3 Drought

In nature, as well as for crops, there are large differences between plant species (and cultivars) in terms of tolerance to water stress and drought. In most ecological classifications, water stress tolerance is given as the first discriminating criterion, commonly followed by tolerance to low temperatures, i.e. frost. Physiological drought usually occurs in plants when soil water matric potential drops to −1.5 MPa (−15 bars) or below, which corresponds to the permanent wilting point of

Table T2 Regional relationship between mean annual temperature (*T*, °C) and mean annual reference potential evapotranspiration (ETo; see also Tables T13, T14 and A1 for details; *SD* standard deviation, *CV* coefficient of variation, *SE* standard error)

Ecological zones	No. stations	ETo/*T*	SD	CV	SE
Arid, semi-arid & sub-humid					
The Sahara	109	96.9	8.1	0.08	2.5
Northern Africa	98	79.4	11.2	0.14	2.7
The Sahel	141	79.2	9.5	0.12	2.2
Eastern Africa	198	74.1	11.0	0.15	1.8
Southern Africa	75	86.5	10.9	0.13	2.2
Sub-total/mean					
Arid, semi-arid & sub-humid	621	79.8	10.7	0.14	2.2
Humid, hyper-humid & Central Africa	221	51.2	12.5	0.24	0.84
Global total/mean	842	65.5	11.6	0.19	1.5

Table T3 Rain-use efficiency (RUE, kg DM ha^{-1} $year^{-1}$ mm^{-1}; *DM* dry matter) and equivalent water-use efficiency (WUE, kg H_2O kg^{-1} DM; Le Houérou 1984b)

RUE	WUE	RUE	WUE	RUE	WUE
20	200	15	500	10	1,000
9	1,111	8	1,250	7	1,326
6	1,666	5	2,000	4	2,500
3	3,300	2	5,000	1	10,000
g DM kg^{-1} H_2O					
20	2.0	15	1.5	10	1.0
9	0.9	8	0.8	7	0.7
6	0.6	5	0.5	4	0.4
3	0.3	2	0.2	1	0.1

mesophytes. Some xerophytes and halophytes, however, are able to extract water from the soil under water potentials of −5 MPa or less. Nevertheless, the amount of soil water content beyond a Ψ value of −5.0 MPa is very small indeed in absolute terms, as shown in the curves in Fig. 54 (Le Houérou 1962b, 2005a).

Climatic drought occurs when precipitation falls below unsaturated soil surface evaporation over a time span of a few days (1 week to 10 days). It has been empirically demonstrated for decades that climatic drought occurs when rainfall, expressed in mm, is below twice the mean temperature in °C (de Gasparin 1848, 1854; De Martonne 1926; Bagnouls and Gaussen 1953a, b; Walter and Lieth 1960; Walter et al. 1975; Le Houérou 2005a, b). I have shown that this empirical value corresponds fairly well with evaporation from bare soil (0.4 $E^{0.75}$, according to Prescott and Thomas 1949). I have also shown that this same value of $2t$, in mm, corresponds rather closely with 0.35 ETo, as computed via the Penman-Monteith equation, or "reference potential evapotranspiration" referred to as ETo in the present publication (Le Houérou and Popov 1981; Le Houérou et al. 1993; Allen et al. 1998). However, the equivalence of 0.35 ETo with bare soil surface evaporation is an average experimental value (rather than empirical), resulting from a broad database established from crop experiments using lysimeters with various soil types under various climatic conditions (Doorenbos and Pruitt 1975). In other words, the amount of water that is present in the soil in excess of soil surface potential evaporation, i.e. in excess of 0.35 ETo, is available to plant roots and, therefore, this threshold corresponds with a rational limit between rainy and dry periods (Le Houérou and Popov 1981). On a monthly timescale, the length of the dry season is identical when considering the threshold either of $P = 2t$ or of $P = 0.35$ ETo in 92% of the cases of our database of 962 weather stations of Africa (Table A1; Le Houérou and Popov 1981; Le Houérou et al. 1993).

This correspondence between $P = 2t$ and 0.35 ETo leads to another approximate equation (Figs. 37–40) in which, since 0.35 ETo $\approx 2t$, it follows that ETo $\approx 0.19t$ on a daily timescale, $1.33t$ on a weekly timescale, $5.7t$ on a monthly time scale and $68.64t$ ($\approx 70t$) on an annual timescale (Le Houérou 1989a, 1990c). A similar equation was put forward by Riou (1980) based on mean maximum monthly temperature. I have shown that using the mean maximum does not bring any better correlation, compared to when using the mean (Le Houérou 1995a). The relationships between the MAT and ETo are shown for each of the 53 countries of the database in Table A1.

The similarity between $2t$ and 0.35 ETo, in terms of depicting the limit between rainy and dry seasons, is shown in Figs. 23–26 in the climatic diagrams of 32 weather stations from N., W., E. and S. Africa, and their relationships in Figs. 37–40. The annual number of days when $P > 0.35$ ETo thus corresponds with the length of the rainy season(s) per annum, as expressed in number of days. This time span is shown in Table A1 for the 962 African weather stations of the database utilized herein.

The intensity of the dry season can be rather accurately assessed via the P/ETo ratio (Le Houérou et al. 1975; UNESCO 1977/1979; Le Houérou and Popov 1981; UNEP 1992; Le Houérou et al. 1993; Le Houérou 1995a, 2005a, b). The length and intensity of the dry season, or the length of drought, is thus estimated by means of two indices:

(a) duration: the annual number of dry days when $P < 0.35$ ETo,
(b) severity/intensity: the annual *P*/ETo ratio, in percent.

The latter is shown in Table A1. These two criteria are actually correlated in a highly significant manner, as shown in Figs. 23–26 and 37–40 (Le Houérou 1989a, 1995e). Most of the previous classifications have been based on empirical indices combining rainfall with one or several other climatic variables such as temperature, vapour pressure, saturation deficit, energy flow, pan evaporation and Piche evaporation (e.g. Merriam 1898; Köppen 1900; Transeau 1905; Lang 1920; Szyemkiewicz 1925; Mayer 1926; Emberger 1930, 1955; Andrews and Mazé 1933 (quoted but not referenced by Aubréville 1949 and by Emberger 1955); Scaetta 1935; Swain 1938; Curé 1943; Penman 1948; Thornthwaite 1948; Wissman 1948; Aubréville 1949; Giacobbe 1949; Prescott and Thomas 1949; Dubief 1950; Capot-Rey 1951; Mangenot 1951; Turc 1951, 1961; Bagnouls and Gaussen 1953a, b; Gaussen 1954; Budyko 1958, 1974; Walter and Lieth 1960; Holdridge and Tosi 1967; Papadakis 1975). These are more or less successful in depicting climatic drought and climatic water stress hazard. PET refers to the values obtained from Penman's standard equation ETPp, or its Penman-Montieth corrective variant, ETo. It is shown below that in Africa ETo is, on average, ca. 9% higher than ETPp (Tables T12–T14). The Penman-Monteith equation in herein preferred because the values it yields are the closest to lysimeter-measured ETP. Moreover, among the ca. 100 published formulae for evaluating PET, the Penman-Monteith equation is the most appropriate from the purely physics viewpoint because, unlike most of the other equations, it accounts for both the energetic-radiative and the aerodynamic parameters governing evaporation (Allen et al. 1998). The latter is considered through the albedo, oasis effect and wind speed, while most of the other equations rely only on the energetic terms either directly through the radiative budget or indirectly through temperature.

An approximate equivalence between the present classification and the widely used classifications of Köppen and Geiger (1930) and of Bagnouls and Gaussen (1957)—the latter popularized by Walter and Lieth's Klimadiagram Weltatlas (1960)—is given below. The equivalence with Braun's (1982) and Jätzold and Schmidt's (1982) classifications for Kenya is given in Tables A17 and A18, and Fig. 49.

Köppen and Geiger's Bioclimatic Classification (1930)

A. *Megathermal climates*. Inter-tropical rainy climates ($18°C < T$)

- A_f Tropical wet all months having a mean rainfall above *60 mm*
- A_m Tropical humid climate with a short dry season: at least 1 month having *27* to *60 mm* of average rainfall
- A_w Tropical wet-and-dry climate with at least 1 month having less than *27 mm* of average rainfall
- w' Maximum rainfall in autumn
- w'' Two rainy and two dry seasons
- *s* Summer dry season (rare)

- *i* Range of temperature between warmest and coolest month < 5°C
- *T* Mean annual temperature, while *t* is the mean monthly temperature.

B. *Xerothermal climates*

BW Arid and desert climates (Wüste = desert)

- BW_w Winter drought = tropical
- BW_s Summer drought = Mediterranean
- BW_n Frequent fog, littoral deserts (Nebel)
- *h* Annual temperature above *18°C* (heiss) = low latitude/altitude
- *k* Annual temperature below *18°C* (kalt) = mid-latitude/altitude
- *k′* Temperature of warmest month below *18°C* = high latitude/altitude

BS Semi-arid climates (steppe)

- BS_w Winter drought = tropical
- BS_s Summer drought = Mediterranean
- BS_n Frequent fog (nebulous, littoral)
- *h* Annual temperature above *18°C* = low latitude/altitude
- *k* Annual temperature below *18°C* = mid-latitude/altitude
- *k′* Temperature of warmest month below *18°C* = high latitude/altitude.

Limits between A_w, BS and BW climates

Evenly distributed rainfall: BW $< r = 2T + 14 <$ BS $r = 2T + 14 < A_w$
Summer rains (BW_w, BS_w): BW $< r = (2T)/2 <$ BS $r = 2T < A_w$
Winter rains (BW_s, BS_s): BW $< r = (2T + 28)/2 <$ BS $r = 2T + 28 < C_w$.

C. *Mesothermal climates* ($-3 < T < 18$°C)

- C_f No dry season; driest month having above *30 mm* mean rainfall
- C_w Winter drought; rainiest month having over 10 times the rainfall of the driest month, or 70% or more of annual rain in the warm season
- C_s Summer drought; at least 3 times as much rain in the wettest winter month as in the driest summer month, or 70% or more of the average annual rainfall in the 6 cool months.

D. *Microthermal climates*

In Africa, microthermal climates pertain only to the Afro-alpine and Mediterraneo-alpine climates.

- Average temperature of the coldest month is below *−3°C*, average temperature of the warmest month below *10°C* = Afro-alpine (treeless)
- When the average temperature of the warmest month is above *10°C*: Afro-subalpine; the isotherm of *10°C* for the warmest month roughly corresponds with the tree line.

Note: *The data shown in italics* in Köppen's formulae above are considered as arbitrary and empirical (*−3, 10, 14, 18, 27, 28°C; 27, 30, 60 mm*), with no experimental basis. The approximate equivalence is given only because Köppen and Geiger's classification is still being utilized in some countries, and not only in Africa.

Bagnouls and Gaussen's Classification (1957)

Bagnouls and Gaussen's classification is based on:

(a) Seasonal and monthly rainfall distribution patterns.
(b) Seasonal and monthly temperature distribution patterns.
(c) Mean annual temperature.
(d) Intensity of dry season(s).
(e) Length of dry season(s).

Criteria (d) and (e) are based on an empiric indicator, the xerothermic index, i.e. the annual number of dry days when precipitation in mm is below twice the temperature in °C, after a number of corrections in terms of air humidity, fog, etc. The various weather stations are illustrated in the form of "ombrothermal diagrams" (see Figs. 23–26; see also Sect. 2.4).

Approximate and simplified equivalence between the bioclimatic classifications of Bagnouls and Gaussen (1957) and of Le Houérou and Popov (1981)

	LH & P		B & G	
No. of months dry season	A. *Mediterranean climates* (winter, i.e. short days, rainy season)		*Xerotheric climates* (summer, i.e. long days, dry season)	
12*	Hyper-arid**	($Q < 6$)	Desertic or eremic	($300 < X$)***
9–11	Arid	($6 < Q < 28$)	Subdesertic	($200 < X < 300$)
7–8	Semi-arid	($28 < Q < 45$)	Xerothermo-mediterranean	($150 < X < 200$)
5–6	Sub-humid	($45 < Q < 75$)	Thermomediterranean	($100 < X < 150$)
3–4	Humid	($75 < Q < 100$)	Mesomediterranean	($40 < X < 100$)
1–2	Hyper-humid	($100 < Q$)	Submediterranean	($0 < X < 40$)
	B. *Tropical climates* (unimodal, summer rainy season)		*Xerochimenic climates* (winter dry season)	
12	Hyper-arid	($Q < 5$)	Desertic	($300 < X$)
9–11	Arid	($5 < Q < 30$)	Subdesertic	($200 < X < 300$)
7–8	Semi-arid	($30 < Q < 50$)	Markedly thermoxerochimenic	($150 < X < 200$)
5–6	Sub-humid	($50 < Q < 75$)	Weakly thermoxerochimenic	($100 < X < 150$)
3–4	Humid	($75 < Q < 100$)	Mesoxerochimenic	($40 < X < 100$)
1–2	Hyper-humid	($100 < Q$)	Subaxeric	($0 < X < 40$)

	C. *Equatorial climates* (bimodal rainy season, winter & summer drought)		*Bixeric climates* (two dry seasons)	
12	Hyper-arid	($Q < 5$)	Desertic	($300 < X$)
9–11	Arid	($5 < Q < 30$)	Subdesertic	($200 < X < 300$)
7–8	Semi-arid	($30 < Q < 50$)	Markedly bixeric	($150 < X < 200$)
5–6	Sub-humid	($50 < Q < 75$)	Moderately bixeric	($100 < X < 150$)
3–4	Humid	($75 < Q < 100$)	Weakly bixeric	($40 < X < 100$)
1–2	Hyper-humid	($100 < Q$)	Subaxeric	($0 < X < 40$)
	D. *Tropical and equatorial wet climates*		*Thermaxeric climates* ($X \neq 0$)	
$20 < t$****	(yearlong rainy season, no dry season)		(no dry season)	$15 < t$
$15 < t < 20$	E. *Midland inter-tropical climates*		*Mesaxeric climates*	$10 < t < 15$
$8 < t < 15$	F. *Highland inter-tropical climates*		*Cool xerochimenic climates*	($t < 10$)
$0 < t < 8$	G. *Afro-alpine & subalpine inter-tropical climates*		*Cold xerochimenic climates*	($t \neq 0$)
$0 < t < 8$	H. *Mediterraneo-alpine and subalpine climates*		*Cold xerotheric climates*	($t \neq 0$)

* A dry month in the present classification is understood as a 30-day period when P (mean annual precipitation, = MAP = MAR) is equal or inferior to 0.35 ETo. In the Bagnouls and Gaussen (1957) classification, a dry month is characterized by a rainfall in mm equal to or lower than twice the mean monthly temperature t in °C. The two approaches yield quite comparable results, as shown in Figs. 23–26. The correlation between 0.35 ETo and $2t$ is shown in Figs. 37–40 (Le Houérou 1992e).

** $Q = 100\ P/\text{ETo}$, ETo being assessed via the Penman-Monteith equation.

*** X is the xerothermic index of Bagnouls and Gaussen, i.e. the annual number of days when $P < 2t$, after corrections using air moisture, days of mist, fog, etc. T is the mean annual temperature, in °C. Days with RH > 70%: days with fog, mist and dew are arbitrarily counted as 1/2 dry day when they occur during the dry season.

**** m is the mean daily minimum temperature of the coolest month in °C, usually January in the northern hemisphere and July in the southern hemisphere.

1.2.4 Cold Stress: Relation to Latitude and Elevation

Cold stress has always been recognized as one of the major factors controlling plant growth and distribution (Merriam 1898; Köppen 1900; Emberger 1930; Bagnouls and Gaussen 1953a, b; Walter and Lieth 1960; Holdridge and Tosi 1967, etc.).

There are large differences between species in terms of tolerance to cold and frost, and to heat as well. The coldest area on the planet, apart from Antarctica, is N.E. Siberia (minimum minimorum temperature registered at Verkhoyansk (67°35′N) is −70°C vs. −80°C in Antarctica). Some eastern Siberia fir, spruce, pine and larch species, as well as many species of the tundra (e.g. dwarf birch, grass-like willow, various Ericaceae) are known to still have some photosynthetic activity when temperature drops to −5°C or slightly below (Birot 1965). On the other hand, some inter-tropical species require minimum temperatures above 18–20°C, such as the palm-oil tree, cocoa, cashew, raphia, coconut, hevea and clove (see section below on C_3, C_4 and CAM species; Tables A1, A10, A11, A16, A19, and Figs. 12, 15, 16, 23–26, 28, 31–33, 41–43, 49–51, 55, 56).

Most of the tropical species start physiological activity when temperature rises above 12 to l5°C (e.g. maize, sorghum, cotton, sugarcane). These are usually killed in their above ground parts by freezing temperatures. Other subtropical species may tolerate short light freezing, such as olive, carob, avocado, most cacti, acacia spp., citruses (orange, lemon); these are usually killed when temperature drops to between −5 and −10°C. On the other hand, some desert and arid zone species such as saltbushes (*Atriplex* spp.) are extremely tolerant to heat and may still present some physiological activity (e.g. photosynthesis) at leaf surface temperatures of 50°C and above (Caldwell 1975; Osmond et al. 1980; Le Houérou 1992h).

From the physiological viewpoint, when temperature requirements are concerned, one may consider three main groups according to carboxylation pathways: the C_3 species, i.e. most of the temperate and Mediterranean species and most trees and shrubs, in which the first products of photosynthesis are made up of C_3 compounds. These have an optimum functioning temperature of around l5–20°C. The C_4 species, in turn, present a "Kranz" structure in their leaf vascular bundles; these essentially include tropical species, particularly grasses, such as maize, millet, sorghum, sugarcane, and most of the genera and species in tropical tribes of grasses: Andropogonoideae, Aristidioideae, Chloridioideae, Eragrostoideae, Maydioideae, Panicoideae, Pappophoroideae, Sporoboloideae, Zoysioideae, and a few shrub spp., e.g. *Atriplex* spp. However, it is noteworthy that, contrary to expectations, rice species are all C_3, including the African native and floating types.

The optimum functional temperature of C_4 species is about 10°C above that of C_3 species, i.e. around 25–30°C. The proportion of C_3 and C_4 species in flora and among crops depends on latitude and elevation; it reaches some 80–90% of grass species in inter-tropical lowlands (Ziegler et al. 1981; Hattersley 1983; Batanouny et al. 1988).

The CAM (Crassulacean acid metabolism) photosynthetic pathway occurs in fleshy (succulent) species such as Crassulaceae, cacti, pineapple, bromeliads, *Euphorbia, Kleinia, Caralluma, Agave, Dracaena, Aloe, Sansevieria, Kalanchoe* and dozens of others among the 3,000 spp. of succulents in the world. Species belonging to this carboxylation pathway type are found mostly under mild to warm climates with relatively high air moisture; CO_2 uptake occurs at night, since stomata are usually closed during the daytime. These are common in the higher midlands and lower highlands, particularly the cactoid and coralloid tree spurges such as

Euphorbia abyssinica, E. candelabmm, E. tirucalli, E. thi, E. neglecta, E. cussonioides, E. obovalifolia and many others such as N. African and insulo-Atlantic *Euphorbia resinifera, E. balsamifera, E. echinus, E. nubica, E. beaumierana, E. officinamm, E. mauritanica* and *E. antiquorum*. These are all more or less frost sensitive; they hardly tolerate any freezing. Their presence in any environment is thus an indication of mild thermal winter conditions and of fairly high air humidity (Le Houérou 2003, 2004c).

Optimum CO_2 uptake occurs at night temperatures around 15°C, in CAM species; uptake then steadily decreases when ambient temperature drops below 5°C or rises above 25°C (Nobel 1989). CAM species are also characterized by a very high water-use efficiency (50–300 kg H_2O consumed for each kg of dry matter (DM) produced, vs. 500–1,500 for most C_3 and C_4 species; Le Houérou 1984b; Table A19).

The climatic criterion utilized to represent winter-cold hazard varies according to authors: mean annual temperature, mean temperature of the coldest month, mean monthly minimum temperature of the coldest month, and mean daily minimum temperature of the coldest month (*m*). I have shown, with accurate real-life examples (Le Houérou 1975, 1989a), that the latter criterion is, by far, the most accurate and reliable among those mentioned, as identified by Emberger as early as 1930.

I have shown that this criterion (*m*) is closely correlated with the annual number of freezing days, i.e. with the length of the cold season and with frost hazard (Le Houérou 1959a, 1969, 1984a, b, 1989a, 1992e, 2005a, b; Le Houérou et al. 1975, 1979). The reader is referred to Figs. 23–26, 33, 41, 43, 51 for the correlation between *m* and the average annual number of freezing days in Algeria.

The relationship between *m* and the number of freezing days is shown in Tables T4 and T5. The frost-free period corresponds with a mean daily minima of the coldest month above 8°C. The occurrence of frost hazard (number of days with minimum temperature below 8°C) is shown in Table A10 for some 310 African weather stations included in the Frère and Popov (1984) database.

Naturally, the cold-stress hazard depends on latitude and elevation. The altitudinal gradient is similar in Africa to that of other parts of the world, i.e. an average decrease of 5.5°C per km increase in elevation. This, however, is subject to significant local deviations, for various reasons such as thermal inversion, aspect and slope. Generally, frost may occur above 2,000 m elevation at the equator, and 1,000 m at the tropics. Since the distance between the equator and the tropics is 2,560 km, we have a poleward decrease of 1,000 m in elevation for a latitudinal shift of 2,560 km, or 0.391 m per km or 43 m per degree of latitude in the altitudinal limit of frost hazard. The approximate relationship between latitude, altitude and frost occurrence hazard is shown in Tables T4 and T5. Frost occurrence hazard does not mean it actually freezes every night but that it may freeze during the period considered. The difference between temperatures under shelter and at an open ground surface is about 4±1°C under a clear sky; in other words, a minimum daily temperature of 4°C may correspond to actual light ground surface freezing. The frost-free period is shown in

Table T4 Approximate relationship between latitude, elevation and frost occurrence in Africa

X = Latitude (°, ′) = 40–0.02Y	Y = Elevation (m a.s.l.) = 2,000–50X
0.0, Equator	2,000
5	1,750
10	1,500
15	1,250
20	1,000
23.27, Tropics	837
25	750
30	500
35	250
40	0.0

the ombrothermal diagrams of Figs. 23–26 as the period when $t > 15$°C; $15 > t > 10$°C: frost possible; $10 > t > 5$°C: frost probable; $5 > t > 0$°C: frost assured.

The average values shown in Table T4 are liable to significant deviations depending on local conditions such as aspect, slope, topographic and geomorphic conditions (e.g. thermal inversion), degree of continentality, and distance from large bodies of free water (inland seas, lakes, swamps, etc.). The same lapse rate was found in the Mediterranean Basin (Le Houérou 2005a, b).

Generally, frost occurrence corresponds with the following conditions:

- Mean annual temperature below 25°C.*
- Mean daily temperature of the coldest month below 13°C.**
- Mean daily minimum temperature of the coldest month below 8°C under shelter.

The occurrence of frost in Africa is shown in Tables T4, T5, T23, T29 and T33, and Figs. 23–26, 28, 31, 33, 41, 43 and 48.

* It should be noted that, although often used for this purpose, the mean annual temperature is a poor indicator of frost occurrence at the continental scale; mean annual temperatures between 15 and 20°C may be associated with non-freezing winter temperatures, such as on the Mediterranean shores of northern Africa, and the Atlantic shores of Morocco and of south-western Africa, subject to the cooling influence of the Canary and Benguela currents respectively. The non-freezing mean diurnal temperature is regarded to be 15°C (Gaussen 1954), 17°C (Holdridge and Tosi 1967; UNESCO 1977/1979) or 18°C (Köppen and Geiger 1930).

** The coldest month is January in the northern hemisphere, and July in the southern hemisphere. Conversely, some light winter freezing may occur in areas having a mean annual temperature up to 25°C; this, however, is extremely rare, reported only for a very small number of continental stations in the central Sahara, such as Adrar, In Salah and Djanet, as shown in Tables T4 and T21.

Table T5 Surface coverage of frost occurrence in Africa (cf. Tables A10, A16, Figs. 12, 23, 28, 31, 33, 43, 48, 49, 51)

Region	Area (km^2)
Inter-tropical Africa	1,267,051
Madagascar	116,800
Northern Africa	1,423,090
Southern Africa	1,359,794
Total	4,196,735
	= 13.8% of the continent

1.2.5 Frost Hazard Occurrence in Africa (Explanatory Notes)

Below are given explanatory notes to Tables T5 and A10.

A. Frost occurrence is herein defined as the annual period, expressed in days, when the mean daily minimum temperature of the coldest month, under standard meteorological shelter, is equal to or below 8°C. In previous publications, I had chosen 7.0 or 7.5°C but, as there are a few exceptions, I here prefer a "safer" 8°C. This means that, when the average daily minimum temperature of a given month is above 8°C, there is virtually no risk of freezing under standard shelter. It by no means signifies that it would necessarily freeze when *m* drops below 8°C but, rather, that there is a slight risk it might (Le Houérou 1975, 1989a). In other words, when *m* rises above 8°C, there is actually no freezing risk and many tropical crops can be grown, as long as water is available. A mean daily minimum temperature of 8°C in any month corresponds to an average monthly temperature of 15 ± 2°C (Bagnouls and Gaussen 1957). Actual freezing at ground surface level under a clear sky usually occurs when the minimum shelter temperature drops to 4.0 ± 1.0°C or below; under cloudy skies the difference may decrease to 0.5 ± 2.0°C between standard shelter and ground surface (Le Houérou 1977).

B. A light frost hazard (LFH) period is understood as the annual number of days when the daily mean minimum temperature lies between 4 and 8°C, i.e. when the mean minimum of the coolest month lies between 4 and 8°C; some cold-sensitive crops such as citruses may still be commercially grown under certain situations, or when $10 < t < 15$°C.

C. Hard frost hazard (HFH) corresponds with a daily minimum temperatures between 1 and 4°C, i.e. when $10 > t > 5$°C; detailed surveys have shown that the threshold of tolerance to severe frost is 1°C, and not 0°C as some authors have stated (Le Houérou 1969; Bortoli et al. 1969; Floret et al. 1973, 1978).

D. Severe frost hazard (SFH) is admittedly the annual number of days when the average daily minimum temperature drops to +1°C or below, or when 5°C > *t*.

E. Total frost occurrence hazard (TFOH) is the sum of the days of LFH, HFH and SFH, i.e. the annual period when $t < 15$°C.

F. *T* is the average annual temperature ($t_M + t_m/2$; Fig. 12).

G. t_M is the mean annual maximum temperature (Fig. 50), and t_m the mean annual minimum.

H. *m* is the mean daily minimum temperature of the coolest month (Fig. 51).
I. *t* is the mean temperature of a given month.
J. The weather stations and the data examined below are those included in the Tables of Agrometeorological Data, by M. Frère and G. Popov, published by FAO in 1984. They include some 962 weather stations from 54 countries. Some 240 of these weather stations deal with frost hazard (26%) and, of course, many others that are not listed in this database. These are complemented by the WMO (1996) Climatic Normals Database (Clino). They belong to the extra-tropical zone and to the inter-tropical highlands (usually above 1,000–1,500 m elevation, depending on latitude). The overall relationship between temperature, elevation and latitude is shown in Section 1.2.4 above.
K. The latitude, longitude and elevation of the weather stations listed in Table A10 are shown in Table A1.
L. Table A10 lists the frost occurrence hazard by country and weather station in alphabetical order. All the stations in the database are shown for the extra-tropical countries, whereas only those concerned with frost hazard (t < 15°C in any month) are given for inter-tropical countries.

1.3 Classification Criteria

1.3.1 Latitude

Latitude plays an overriding role in energy flow and its distribution at ground surface, temperature and potential evapotranspiration. One may thus distinguish in a first approximation extra-tropical zones and inter-tropical zones. In the former, slope and aspect play a major role in the energy budget of every piece of land surface—hence, the notions of sunny slope (Adret in French, Sonnenseite in German, Soleiado in Spanish) and of shady slope (Ubac in French, Schattenseite in German, Sombrado in Spanish; see Sect. 1.3.7).

In the inter-tropical zone, on the contrary, aspect and slope play little, if any, role in energy budgets, given the incidence angle of incoming sunrays.

The distribution of global radiation is shown in Fig. 11. Radiation is highest on the tropics, and globally higher in the northern hemisphere than in the southern. Figure 11 also shows that the thermal equator is at 16°N in Africa, i.e. in the Sahel, the ecological zone adjacent to the southern border of the Sahara. Here, the mean annual temperature may locally reach 30°C, making this the hottest broad ecological region on earth in terms of mean annual temperature (Le Houérou 1982b, 1984a, 2003).

Correspondingly, potential evapotranspiration is highest at the thermal equator in the northern Sahel where it may locally reach 3,000 mm year^{-1} in Mauritania, Mali and Niger (Riou 1975; Frère and Popov 1984; Sivakumar et al. 1984, 1993; Morel 1992; Table A1 and Fig. 13). Evaporation in Lake Chad (13°N) is estimated to average 2,350 mm year^{-1} (Tetzlaff and Adams 1983) and 2,500 mm in Lake

Nasser (Aswan Dam; Gishler 1976). These values are consistent with Riou's measurements of ETP (Riou 1975).

Latitude also plays a major role in the distribution of seasonal rainfall, as the rainy seasons follow the apparent march of the sun at the zenith (Figs. 46–48). Between 10°N and 10°S, the rains exhibit a bimodal pattern, whereas between 10°N and 10°S and the tropics (23°27′N and S), the seasonal distribution follows a monomodal pattern, occurring during the monsoon of the Gulf of Guinea (Figs. 17–22)—hence, the major criterion of discrimination based on monomodal (i.e. tropical) and bimodal (i.e. equatorial) with double monsoon-season (NE and SW) rainfall regimes. In the extra-tropical zones, the distribution is more complex; it may be either weakly monomodal or bimodal. The impact of latitude on the temperature and rainfall regimes is shown in Figs. 46–48, taken from Aubréville (1949) and De Martonne (1927a, b).

1.3.2 Rainfall

1.3.2.1 Annual Amount

Africa has both the absolute lowest and third highest record of mean annual rainfall recorded on the planet. The Sahara is circumscribed by the isohyet of 100 mm of annual rainfall (Tables T6, T23, Figs. 1–3; Le Houérou 1959a). In the eastern Sahara, an area of 2.8×10^6 km² receives 10 mm year^{-1} or less, while some 1.5×10^6 km² receive an average 5 mm year^{-1} or less (Fig. 1). The lowest record is virtually zero over a large area of some 1×10^6 km² in the eastern Sahara, and the so-called Libyan and Nubian deserts of Libya, Egypt and Sudan (Tazerbo, Kufra, Dahla, Kharga, Farafra, Luksor, Aswan, Abu Simbel, Wadi Halfa), where the long-term mean approximates 0.5 mm year^{-1}. When I visited Kufra in 1964, the weather station had no rain recorded over the preceding 12 years. This low record is shared with the Atacama desert of Chile and Peru (Iquique, Arica, Ica), where it essentially never rains. Nevertheless, the eremitic zone is much smaller there, and high air moisture does occur at least for part of the annual cycle, in contrast to the eastern Sahara.

Table T6 Rainfall belts in Africa: surface area and percent of the continent

Zones	Rainfall belts (mm year^{-1})	Area (10^3 km²)	%
Hyper-humid	>1,500	7,851	25.0
Humid	1,000–1,500	3,636	12.0
Sub-humid	600–1,000	2,892	9.5
Semi-arid	400–600	2,951	10.0
Arid	100–400	3,570	12.0
Hyper-arid	50–100	3,017	10.0
Eremitic (true desert)	0–50	6,932	20.5

The highest record in Africa comes from the western foot of mount Cameroon, at Victoria next to the town of Debundscha where rainfall reaches an annual mean of 10,383 mm; in Debundscha itself, the mean value is 9,895 mm over a 40-year period, with an absolute annual record of 14,694 mm in 1919 (Suchel 1972; Dubief and Bücher 2001). This almost challenges the record of Cherrapunji, in Assam, with 11,477 mm as an average between 1851 and 1960, and an absolute annual of 26,461 mm in 1860/1861, and also the record of Tutunendo in Colombia, with 11,770 mm $year^{-1}$.

Again, one should first differentiate between winter and summer rains. North of the Tropic of Cancer, almost all rains fall in the winter season between (September) October and April (May). The short days half-year period represents 80 to over 90% of the average annual total, although in some years late rains may occur in May–June and early rains in September, but these amount to little in the overall mean and still less in terms of rain-use efficiency. Naturally, cool-season rains are in principle more efficient in terms of plant production potential, as they correspond with a period of relatively low potential evapotranspiration, and as C_3 native plants and crops are adapted to grow under moderate temperatures. A tropicality index—summer trimester precipitation/winter trimester precipitation (STP/WTP)—indicates the rate of "tropicality", symmetrically to the "Mediterraneity index", which is WTP/STP (Le Houérou 1999b, 2005a, b).

South of the Tropic of Capricorn, the situation is much more complex since there are, in South Africa, both summer and winter rains. The proportion of these vary from N to S and W to E, as shown in Fig. 30. The proportion of summer rains varies from 85% at the tropic to less than 20% at the SW tip of the continent between the Cape of Good Hope and the mouth of the Orange River. As a consequence, Mediterranean-type vegetation and crops are restricted to the areas having less than 40% of summer rains, corresponding to a large proportion of the South African arid zone (Le Houérou 1994b).

Table T6 shows the various rainfall belts covering specific areas on the African continent and in Madagascar (also see Figs. 1–5, 32, 49, and Tables A16–A18). For a more accurate evaluation of aridity belts, see Tables A16–A18, although the latter is based on a somewhat different criterion, i.e. the *P*/ETo ratio, and therefore does not strictly correspond with rainfall belts.

1.3.2.2 Seasonal Patterns

The seasonal distribution pattern is a major criterion in the present classification. Seasonality strongly affects annual variability and rain-use efficiency, particularly in arid, semi-arid and sub-humid zones, which represent some 31.5% of the continent, another 30.5% being desert, as shown in Fig. 32, and in Tables A16 and T1.

A few examples of these efficiencies are given below. Western African semi-arid and arid zones are under a monomodal rainfall distribution pattern, rangelands are largely made up of annual grasses, whereas in East Africa under a bimodal regime, rangelands in fair condition are dominated by perennial grasses. This bears overriding

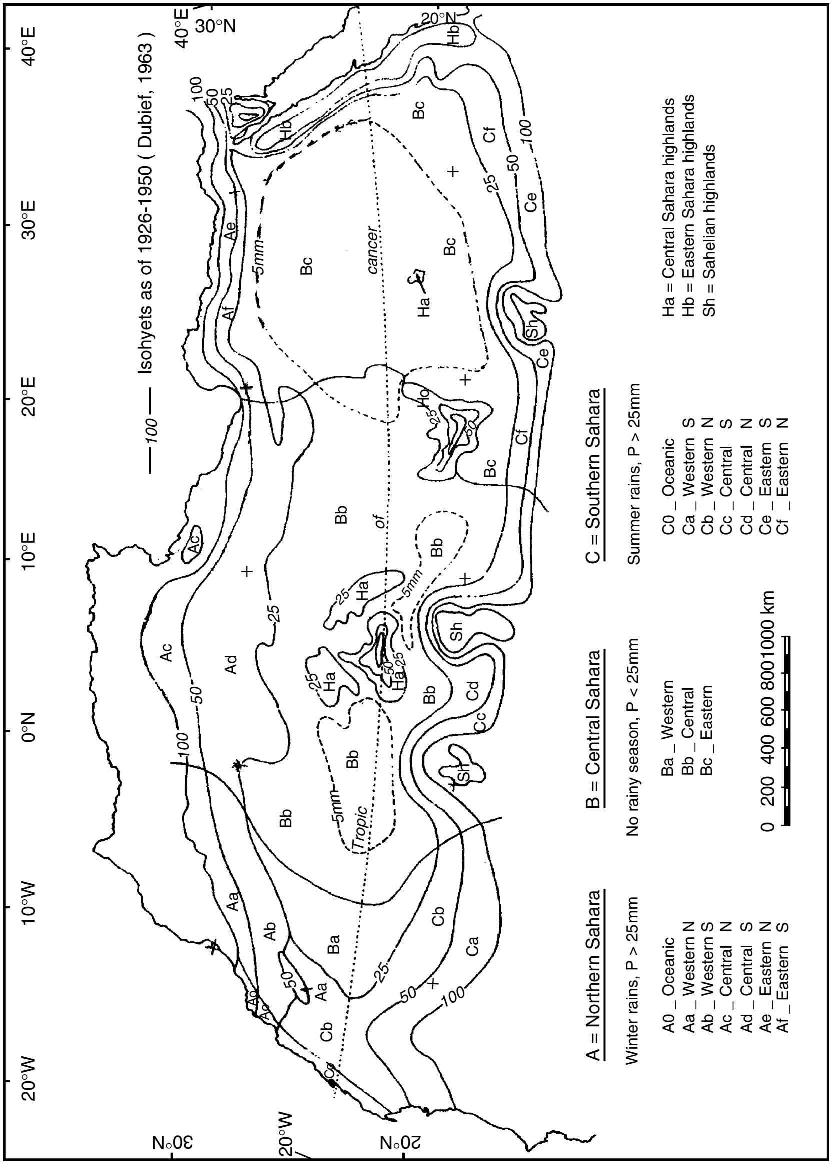

Fig. 1 Mean annual precipitation and bioclimatic limits of the Sahara (Le Houérou 1995a)

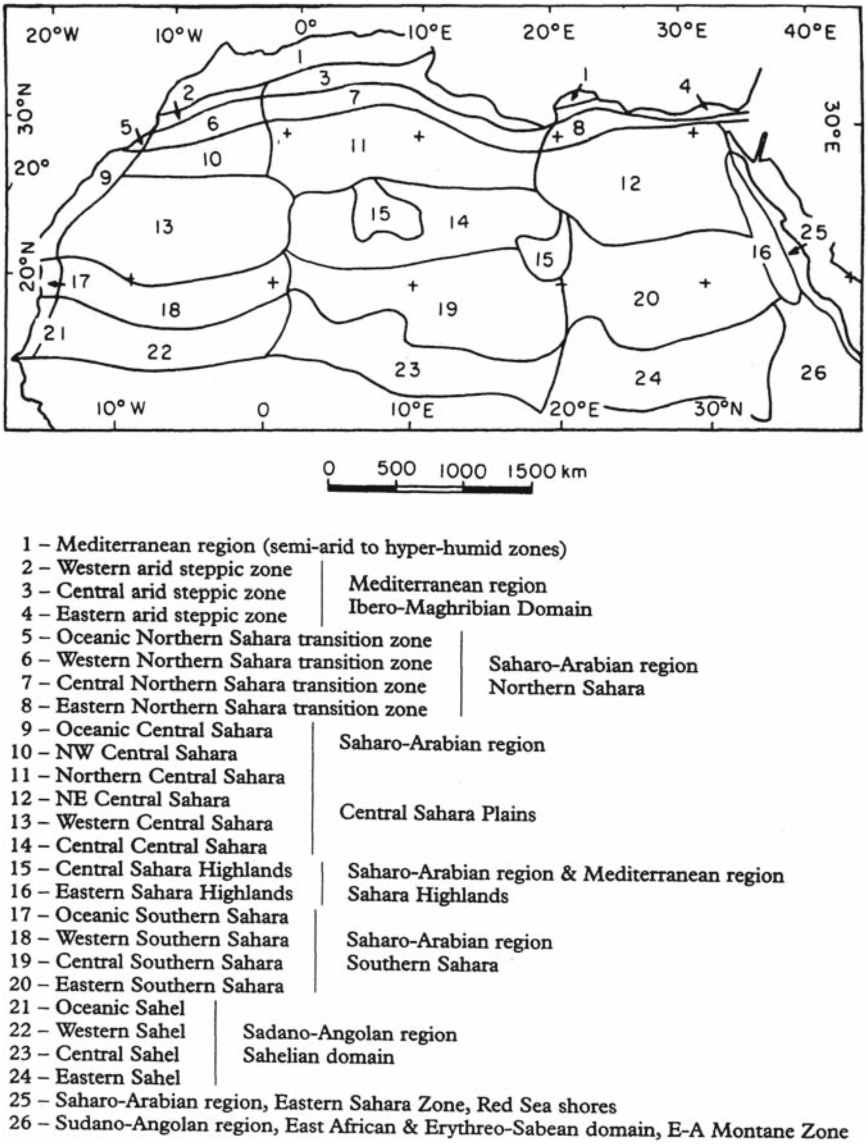

Fig. 2 Sketch of the phytogeographic subdivisions of the Sahara and neighbouring territories (Quézel 1978; Le Houérou 1995a)

consequences. In West Africa, successful cereal cultivation (i.e. pearl millet) requires some 400 mm of mean annual rainfall for a 80% harvest probability. The same probability requires an average of 600 mm under the bimodal regime of East Africa (Cochemé and Franquin 1967; Brown and Cochemé 1969; Davy et al. 1976; Dancette 1979; Le Houérou and Popov 1981; see Sect. 1.3.2.3).

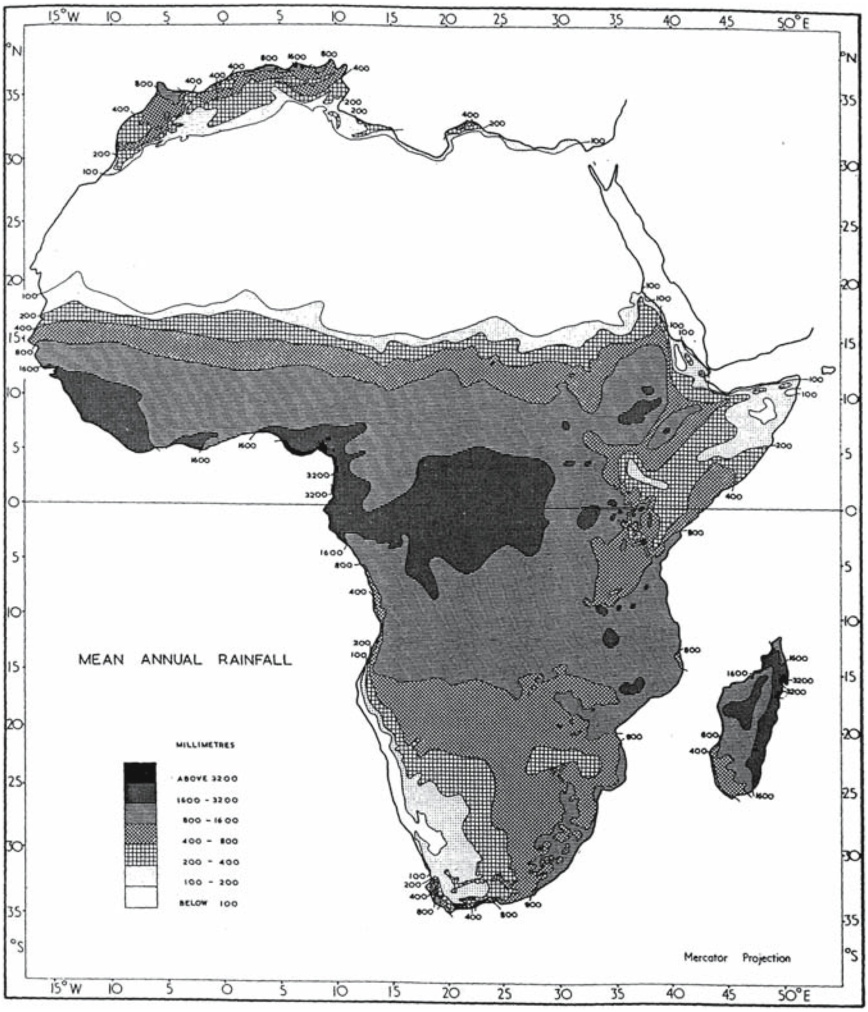

Fig. 3 Geographic distribution of mean annual precipitation (mm) in Africa (Thompson 1965)

Similar examples may be cited under Mediterranean climates: in northern Africa with a prevailing bimodal regime, reliable and commercial cultivation of cereals (barley, wheat) requires 400 mm of annual mean, whereas in the Near East under a monomodal regime, commercial cultivation requires no more than 300 mm as a minimum (Wallen and Brichambaut 1962; Le Houérou 1982b, 1988a, 1995a, 2005a, b). This is due partly to the fact that annual variability is greater under bimodal than under unimodal regimes, as shown in Figs. 4–9. Variability is thus higher in East Africa and North Africa (bimodal) than in western Africa and the Near East (monomodal). I have therefore distinguished the following:

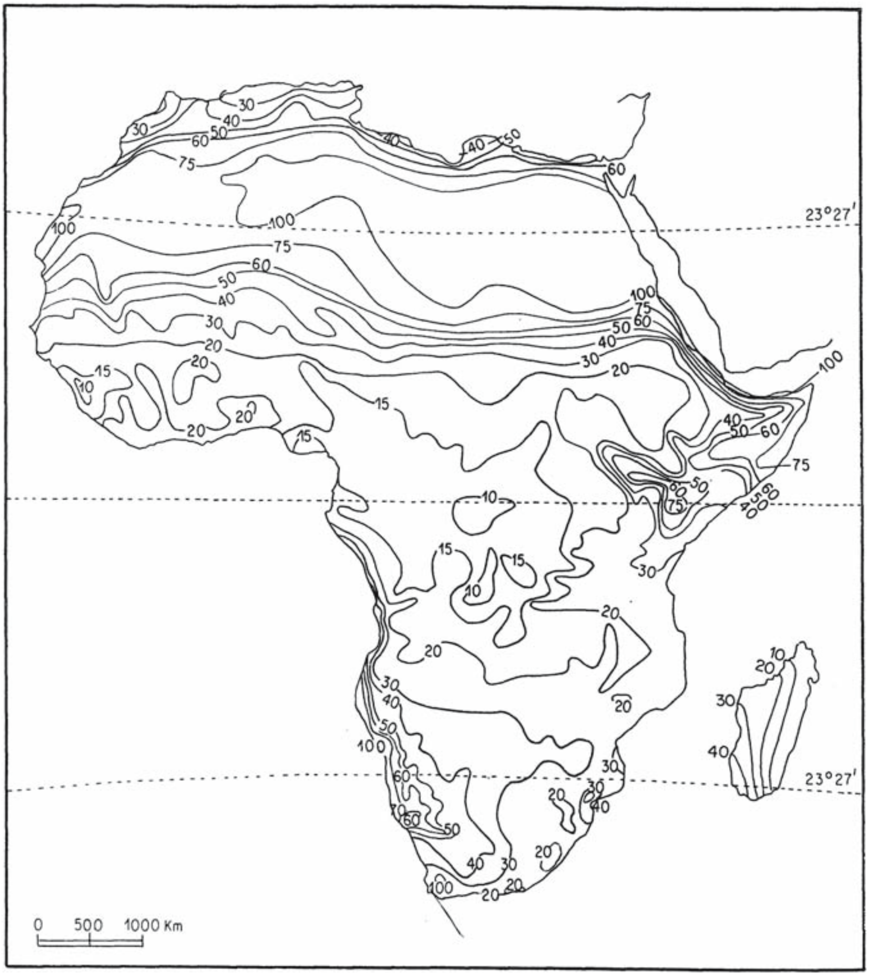

Fig. 4 Geographic distribution of the coefficient of variation of the mean annual precipitation (×100) in Africa (Griffiths and Hemming 1963; Nicholson et al. 1988)

A. Extra-tropical climates (latitudes > 23°27′)
- A.1 Over 60% of annual rains fall during the winter season, i.e. Mediterranean climates: northern Africa and the SW tip of the continent.
- A.2 Over 60% are summer rains: subtropical climates (southern Africa).

B. Intermediate
- B.1 The Sahara (Mediterranean to the north, and tropical to the south).

C. Inter-tropical climates (latitudes $10° < L < 23°27′$)
- C.1 Monomodal rainfall pattern, i.e. one single rainy peak: tropical climates (i.e. between 10 and 23°27′N and S).
- C.2 Bimodal rainfall pattern, i.e. two (or more) rainy peaks: equatorial climates (i.e. between 10°N and 10°S).

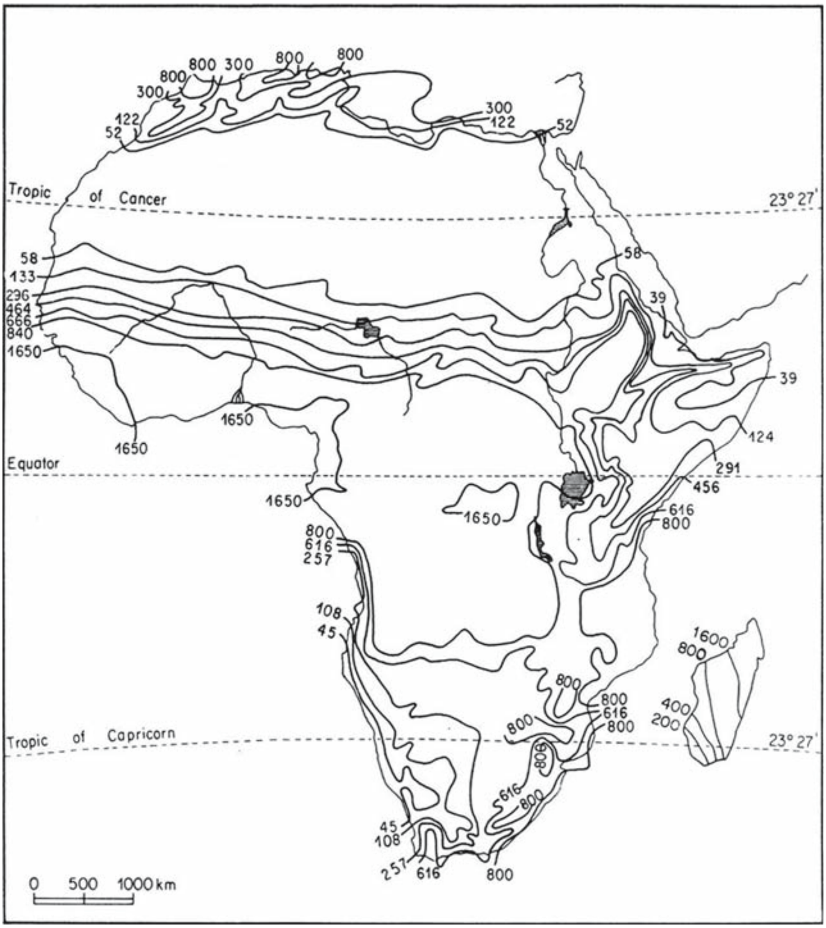

Fig. 5 Geographic distribution of the isohyets of reliable annual rainfall (p = 0.8; Le Houérou 1962a)

It is of utmost importance to note, however, that under equatorial climates the two rainfall peaks may or may not be separated by a dry season, i.e. by a period when P falls below 1/3 of ETo. Whenever there are two dry and two rainy seasons, the regime is labelled “2” in Table A1; otherwise, it is labelled “1”, even if there are two rainy peaks. The labels “1” and “2” in Table A1 thus do not necessarily correspond with monomodal and bimodal regimes. My meaning of monomodal and bimodal is therefore identical to that of other authors such as Nicholson et al. (1988) and De Martonne (1926, 1927a, b).

It should also be emphasised that tropical (monomodal) patterns are usually associated with contrasting thermal regimes, whereas equatorial (bimodal) patterns are associated with homogeneous thermal regimes (seasonal amplitude ≈ 5°C) with yearlong high temperatures, as shown in Figs. 25 and 26.

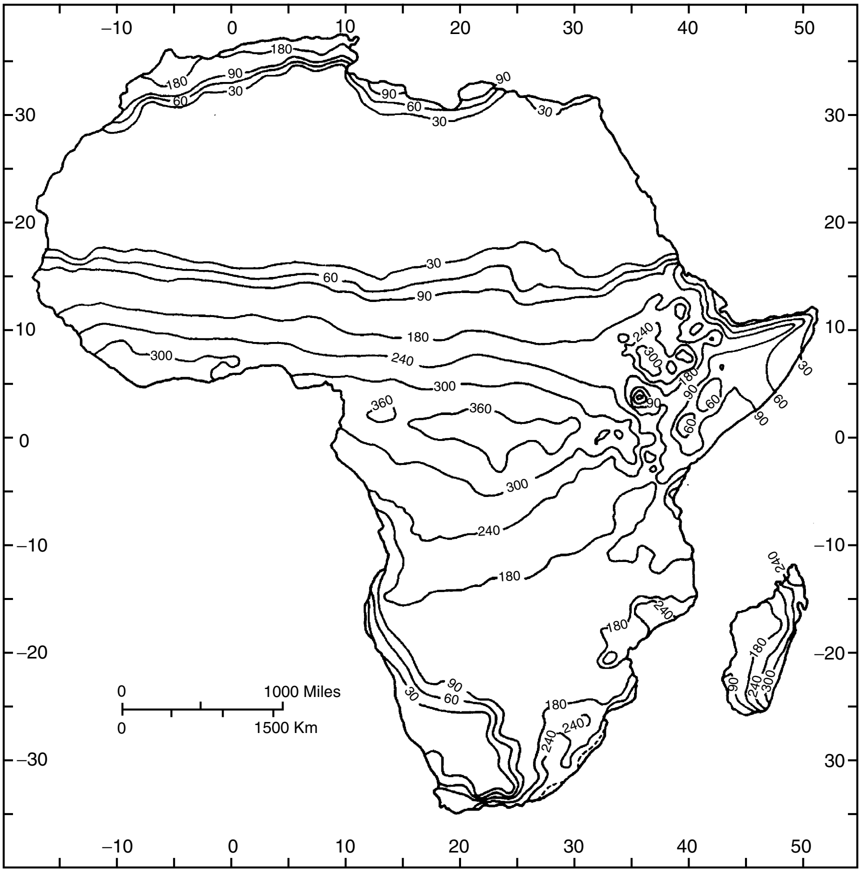

Fig. 6 Length of the rainy season (no. of days when *P* > 0.35 Eto; Le Houérou et al. 1993)

In a Mediterranean type of climate, rains are centred between the equinoxes of September and March—hence, the traditional label of "equinoxial rains". They start with the autumn season and end in springtime, i.e. (September) October to April (May) in the northern hemisphere, and (April) May to September (October) in the southern hemisphere.

In tropical climates, rainfall is centred on the solstices—hence, the traditional label of "solsticial rains" (June in the northern hemisphere, and December in the southern hemisphere). In equatorial climates, rains are thus centred on the equinoxial periods when the apparent march of the sun passes at the zenith (hence, the traditional names of zenithal rains or equinoxial rains).

Initiation and end of the rainy seasons are shown in Figs. 23–26 and 42–44.

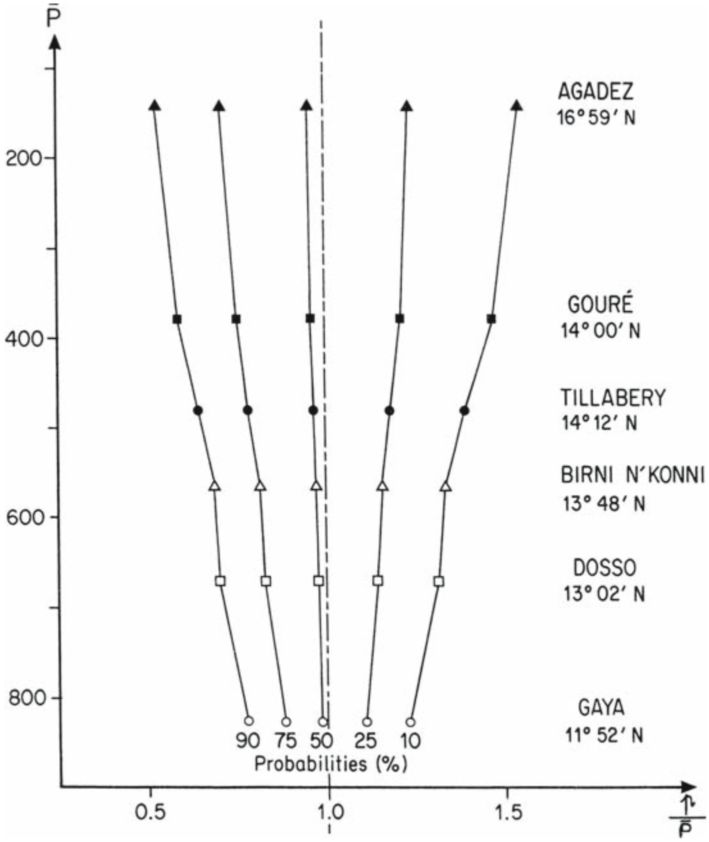

Fig. 7 Annual rainfall probability in the Sahel as a function of the mean and of latitude: example of the Rep. of Niger (*p* annual rainfall probability, *P* normal rainfall; Le Houérou and Popov 1981)

1.3.2.3 Length of Rainy Season

General, Crop Requirements

The length of the rainy season is correlated with the annual rainfall amount within each climatic family, as shown in Figs. 6, 17–26, 40 and 44. The length of the rainy season is classically assessed as the period when rainfall in mm is above twice the temperature in degrees Celsius (de Gasparin 1848, 1854; De Martonne 1926; Bagnouls and Gaussen 1953a, b; Walter and Lieth 1960; Le Houérou and Popov 1981). Popov and I have modified this empirical criterion for the period when *P* rises above 0.35 ETo (Le Houérou 1977; Le Houérou and Popov 1981; Le Houérou et al. 1993). The rationale behind the selection of the latter criterion is that many lysimeter experiments with various crops on various soils in various parts of the world have shown that water consumption between sowing and emergence, i.e. soil

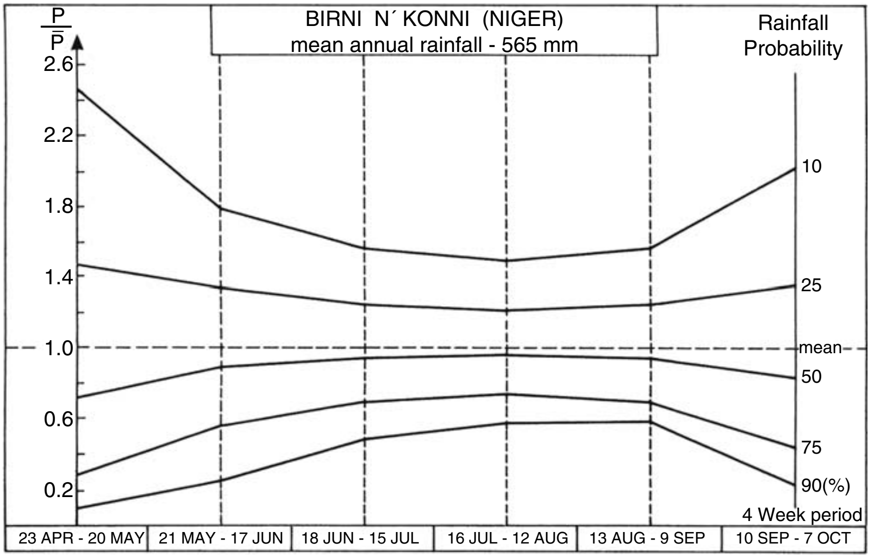

Fig. 8 Relationship between various seasonal rainfall probabilities and the norm (*p/P*) in the Sahel zone of the Rep. of Niger, for a 4-week period during the rainy season (Le Houérou and Popov 1981)

surface evaporation, is most often between 0.3 and 0.4 ETo (Penman/Monteith; Doorenbos and Pruitt 1975; Doorenbos and Kassam 1979; Allen et al. 1998). This is shown in Table T7 for a number of crops. This is the initial "K_c" coefficient of irrigation agronomists. It follows that the amount of water in the soil beyond 0.35 ETo is available to plants. This criterion therefore seemed to constitute a rational choice to distinguish the rainy from the dry season. In most cases, the two criteria ($P < 2t$ and $P < 0.35$ ETo) yield quite similar results, as shown in Figs. 23–26. On a monthly basis, the results are identical in 92% of the cases (Le Houérou and Popov 1981) from our 962 weather stations database (Frère and Popov 1984).

Other authors have selected a value of 0.5 ETo, i.e. the rainy season corresponds with the period when $P > 0.5$ ETo (Cochemé and Franquin 1967, 1968), but the criterion of 0.5 ETo is an arbitrary one without any experimental basis, established with caution at a time when the relationship between ETo and soil surface evaporation had not yet been elucidated. Hargreaves (1975a, b, 1977, 1988) and Hargreaves and Samani (1985) used the value of $P > 1/3$ MAI (moisture availability index), which is equivalent to DP/ETo, DP being dependable precipitation, i.e. the amount of precipitation occurring 3 years out of 4 in this system.

This criterion of $P > 0.33$ MAI roughly corresponds with $0.25 > P$/ETo in high-rainfall areas where DP~0.75P (DP/ETo) = (0.33)0.75(P/ETo). Since rainfall distribution is markedly skewed in low-rainfall areas, DP may represent only 40 to 60% of the mean (see Figs. 3–5). I have used a similar but more demanding criterion, RR, reliable rainfall, defined as rain occurring with 80% probability, i.e. in 4 of 5 years, and not 3 of 4 years as advocated by Hargreaves. In such cases, 0.33 MAI represents

Table T7 Evaporation from bare unsaturated soil. Crop coefficient (K_c) for the initial crop stage between sowing and emergence (from Doorenbos and Pruitt 1975; Doorenbos and Kassam 1979; Allen et al. 1998)

Crop	K_c (% ETo)[a]	Crop	K_c (% ETo)
Banana		Bean	
tropical	40–50	green	30–40
subtropical	50–65	dry	30–40
Cabbage	40–50	Cotton	40–50
Grape	35–55	Groundnut	40–50
Maize/corn		Onion	
green/sweet	30–50	dry	40–60
grain	30–50	green	40–60
Pea, fresh	40–50	Pepper, fresh	30–40
Potato	40–50	Rice	110–150
Safflower	30–40	Sorghum	30–40
Soybean	30–40	Sugar beet	40–50
Sugarcane	40–50	Sunflower	30–40
Tobacco	30–40	Tomato	40–50
Watermelon	40–50	Alfalfa/lucerne	30–40
Olive	40–60	Citrus, clean weeding	65–75
		no weed control	85–90

[a] Average of first column for initial stage = 35.5% ETo (Penman/Monteith); average of second column = 58%. Note: first column = under high humidity (RH > 70%) and/or low wind speed ($U < 5\,m\,s^{-1}$). Second column = under low humidity (RH < 20%) and/or strong wind ($U > 5\,m\,s^{-1}$). In all cases, in medium-textured soils (silt or sandy loam); values should be decreased for sandy soils and increased for clay soils (cf. Tables T6, T17, T19 and Fig. 54)

Table T8 Length of the annual rainy season in various ecozones

Ecozone	Length of annual rainy season (days)
Hyper-arid	0–5
Arid	5–120
Semi-arid	120–170
Sub-humid	170–240
Humid	240–270
Hyper-humid	270–365

only 13 to 20% of P ($0.33 \times 0.40P = 0.13$ and up to $0.33 \times 0.60P = 0.20$). Thus, I consider Hargreaves' criterion to be rather low, although I agree with the rationale on which it is based, which is particularly sound.

Thus defined, the length of the rainy season is as shown in Table T8, and Figs. 6–9, 23–26, 37–40, 43, 44, 46 and 47.

The data in Table T8 are approximate mean values, since the length of the rainy season with respect to the P/ETo ratio depends to some extent on affinity with the major climatic families extra-tropical, tropical and equatorial (for details, see

Tables A1, A5, A9 and Figs. 17–22). In Figs. 23–26, the rainfall curve remains above the 0.35 ETo and $2t$ curves throughout the rainy season. Conversely, the 0.35 ETo and $2t$ curves remain above the rainfall curve yearlong in hyper-arid zones. There are, however, some exceptions to this rule in areas that are not hyper-arid. In such rare cases, the 0.35 ETo curve remains yearlong above the P curve in spite of the fact that these areas are not really hyper-arid, according to other criteria (vegetation, crops, soils). In various arid zones ($300 > P > 100$ mm year^{-1}), I actually found 75 arid land stations (of 4,000, i.e. 1.9%) where the precipitation curve remains below the 0.35 ETo and $2t$ curves throughout the year. Among those, 22 (29%) are in Africa (Table A1)—e.g. in Djibouti City (Fig. 25b). So far, I can not propose any rational explanation for these findings.

The relationship between the length of the rainy season (i.e. the annual number of days when $P > 0.35$ ETo) and the dry season severity ($P < 0.35$ ETo) is shown in Figs. 19 and 23–26 for extra-tropical, tropical and equatorial climates. The length of the rainy season is a very important bioclimatic criterion, often more so than the absolute total amount of rainfall, both for crops and native vegetation, in particular under semi-arid, sub-humid and humid agro-bioclimates (Cochemé and Franquin 1967; Brown and Cochemé 1969; Hargreaves 1975a, b, 1977, 1988; Boudet 1975; Doorenbos and Pruitt 1975; Kassam 1976; Davy et al. 1976; Lomas 1978; Dancette 1979; Doorenbos and Kassam 1979; Frère and Popov 1979; Higgins et al. 1979; Braun 1982; Jätzold and Schmidt 1982; Hargreaves and Samani 1985; Oldeman 1990). It is, in particular, an essential factor to consider in selecting crop species and cultivars as well as in evaluating range and forest potentialities and planning livestock development and breed selection (e.g. zebu vs. taurine cattle in connection with trypanosomiasis hazard or tick-borne diseases; see sections 1.3.16 & 1.3.17 below).

Further refinement could be added by subdividing the rainy season into various sequences such as shown in Tables T9–T11.

Other authors have selected different discriminating thresholds: Cochemé and Franquin (1967):

Intermediate season: $1.0 > P > 0.5$ ETo

Humid season: $P >$ ETo.

Hargreaves (1975a, b) proposed the sequences shown in Table T10.

The sequences proposed herein are, therefore, in practical terms very close to Hargreaves' and also to the sequences used in the UNESCO and UNEP maps

Table T9 Subdivisions of the rainy season

P and ETo values	Subdivision type
$0.35 > P > 0.20$ ETo	Pre- or post-rainy season
$0.50 > P > 0.35$ ETo	Intermediate rainy season
$0.75 > P > 0.50$ ETo	Sub-rainy season
$1.0 > P > 0.75$ ETo	Full rainy season
$P > 1.00$ ETo	Heavy rainy season

Table T10 Hargreaves' system of moisture availability index (MAI)

MAI	Category	*P*/ETo
0.33 > MAI > 0.0	Very deficient	≈0.0–0.25
0.67 > MAI > 0.34	Moderately deficient	≈0.26–0.50
1.0 > MAI > 0.68	Somewhat deficient	≈0.51–0.75
1.33 > MAI > 1.01	Adequate	≈0.76–1.0
MAI > 1.34	Excessive	≈1.05

distinguishing various aridity zones on an annual basis: arid, semi-arid, sub-humid, humid and hyper-humid zones. As mentioned above, MAI (moisture availability index) is the rainfall occurring under a 75% probability.

Yet other authors, using the temperature criterion, have selected the following definitions:

- $2t > P > t$ intermediate season
- $3t > P > 2t$ sub-rainy season
- $P > 3t$ full rainy season.

Some plant species, either natural or crops, are able to grow under some moisture stress during the pre-rainy season (xerophytes), such as *Atriplex* spp., or to escape drought due to a very short biological cycle, such as some perennial forage species including *Cenchrus ciliaris, Chrysopogon plumulosus, Digitaria nodosa, Sporobolus ioclados* and *Lasiurus sindicus*. This is valid also for annual crops such as barley (75–90 days), pearl millet, finger millet, cowpea, safflower, sesame, pigeon pea, Guinea sorrel, and the "fonio" semi-crop of the Sahel (*Digitaria exilis*; see Table A19).

Most crops, however, do not tolerate any moisture stress. These are labelled mesophytes and, therefore, would grow only under sub-rainy and full rainy season conditions—e.g. sorghum, cotton, peanut, sweet potato, 120-days millet, cowpea, cashew nut, cassava, pawpaw and mango, for those tolerating some drought. Drought-intolerant crops can grow only in a full rainy season (maize, beans, tobacco, sunflower, sugarcane, banana, tea, coffee, rice, soybean, yam, etc.). Other crops require permanently humid conditions (hygrophytes)—e.g. oil palm, pineapple, cocoa, raphia, hevea, coconut, vanilla—and therefore need a heavy rainy season throughout their biological cycle. The same reasoning applies to forage species as well as to forest and afforestation species, as shown below and, for crops, in Table A19.

Selection of forage species in function of rainy season length

A. Common, more or less drought-tolerant fodder species and crops in the hot tropics (90 < RS < 180 days)

a. Annual legumes

Canavalia ensiformis, Jack bean
Clitoria ternatea, butterfly pea, Kordofan pea
Lablab purpureus, Lablab bean
Macroptilium atropurpureum, Siratro
Macrotyloma axillaris, horse gram
Macrotyloma uniflornm, horse gram
Stylosanthes hamata, Hamata stylo
Vigna unguiculata, cowpea, Niébé (W. Africa)

b. Perennial legumes

Cajanus cajan, pigeon pea
Desmanthus virgatus, Desmanthus
Rhynchosia memnonia, Rhynchosia
Rhynchosia minima, Rhynchosia
Stylosanthes fruticosa, shrubby stylo
Stylosanthes scabra, shrubby stylo
Stylosanthes subsericea, silky stylo
Stylosanthes viscosa, sticky stylo

c. Annual grasses

Cenchrus biflorus "cram-cram" (W. Africa)
Cenchrus prieurii
Chloris virgata
Eleusine coracana, finger millet
Eleusine indica, crowsfoot grass
Eragrostis tef (= E. abyssinica), tef
Hordeum vulgare, barley
Panicum miliaceum, proso millet
Pennisetum glaucum, pearl millet (= *P. typhoides* = *P. americanum*)
Pennisetum pedicellatum
Setaria italica, foxtail millet
Sorghum sudanense, sudan grass
Sorghum vulgare, forage sorghum
Sorghum bicolor, grain sorghum

d. Perennial grasses

Andropogon gayanus {gamba (Haoussa) or {ouaga (Bambara)
Botriochloa ischaemum, yellow blue stem
Botriochloa pertusa, seymour grass
Cenchrus ciliaris, buffel grass
Cenchrus setigerus, birdwood grass
Chrysopogon plumulosus (≈C. aucheri)
Cynodon dactylon, bermuda grass
Cynodon plectostachyus, Naivasha star grass
Dichanthium annulatum
Digitaria nodosa, nodose finger grass
Digitaria smutsii, Smuts' finger grass
Ehrharla calycina, perennial veld grass
Eragrostis curvula, weeping love grass (incl. *E. chloromelas* & *E. lehmanniana*)
Eragrostis superba, hatjes grass
Heteropogon contortus, spear grass
Lasiurns sindicus (=L. hirsutus)
Panicum antidotale, blue panic
Panicum coloratum, Makarikari grass
Urochloa mosambicensis, Sabi grass

B. Fodder crops moderately or non-tolerant to drought (180 < RS < 365 days)

a. Annual legumes

Stylosanthes humilis, Townsville lucerne

b. Perennial legumes

Calopogonium mucunoides, calopo
Centrosema pubescens, centro
Desmodium intorlum, greenleaf desmodium
Desmodium uncinatum, silverleaf desmodium
Pueraria thumbergiana, kudzu
Glycine wightii, fodder soya
Lotononis bainesii, Lotononis
Mucuna pruriens, velvet bean (= *Stilozobium aterrimum*)
Pueraria phaseoloides, tropical kudzu
Stylosanthes guianensis, Oxley stylo
Vigna luteola, Dalrymple cowpea

c. Annual grasses	
Coix lacryma-jobi, Job's tears grass	*Zea mays*, maize, Indian corn
d. Perennial grasses (see also Tables A14 & A19)	
Axonopus compressus, carpet grass	*Paspalum dilatatum*, Dallis grass
Axonopus scoparius	*Paspalum notatum*, Bahia grass
Bekeropsis uniseta	*Pennisetum clandestinum*, Kikuyu grass
Brachiaria brizantha, signal grass	
Brachiaria decumbens	*Pennisetum purpureum*, elephant grass
Brachiaria mutica, Para grass	*Setaria anceps*, golden timothy (incl. *S. Sphacelatha* & *S. Splendida*), foxtail grass
Brachiaria ruziziensis, Ruzizi grass	
Digitaria decumbens, Pangola grass (incl. *D. pentzii* & *D. "umfolozi"*)	*Sorghum almum*, Columbus grass
Echinochloa pyramidalis, greater bourgou	*Stenotaphron secundatum*, St Augustine grass (incl. *S. dimidiatum* & *S. americanum*), Pemba grass
Echinochloa stagnina, lesser bourgou	
Panicum maximum, Guinea grass	
	Tripsacum laxum, Guatemala grass

Selection of afforestation species for the hot tropics in function of rainy season length

A. Common species more or less tolerant to drought. i.e. to short rainy seasons (90–180 days in an approximate decreasing order of tolerance to drought; N = native, E = exotic; see also Table A14)

N	*Leptadenia pyrotechnica*	N	*Hyphaene thebaica* (phreatophyte)
N	*Capparis decidua*	N	*Salvadora persica* (phreatophyte)
N	*Acacia ehrenbergiana*	N	*Faidherbia albida* (phreatophyte)
N	*Grewia tenax*	E	*Prosopis juliflora* (phreatophyte)
N	*Acacia tortilis* subsp. *raddiana*	N	*Acacia nilotica*
N	*Balanites aegyptiaca*		var. *adansoni*
N	*Acacia senegal*		var. *tomentosa*
E	*Jatropha curcas*		var. *kraussiana*
N	*Acacia laeta*		var. *indica*
N	*Commiphora africana*	N	*Pterocarpus lucens*
E	*Parkinsonia aculeata*	E	*Dalbergia sissoo*
N	*Acacia tortilis* subsp. *tortilis*	N	*Acacia seyal*
E	*Acacia holosericea*	E	*Anacardium occidentale*
N	*Acacia tortilis* subsp. *spirocarpa*	E	*Eucalyptus microtheca*
N	*Maerua crassifolia*	E	*Eucalyptus camaldulensis*
N	*Moringa oleifera*	N	*Ficus ingens, F. gnaphalocarpa, F. capensis*
N	*Euphorbia balsamifera*	N	*Phoenix dactylifera* (phreatophyte)
N	*Bauhinia rufescens*	E	*Prosopis cineraria* (phreatophyte)
N	*Combretum aculeatum*	N	*Ziziphus spina-christi* (phreatophyte)
N	*Adenium obesum*	N	*Conocarpus lancifolius* (phreatophyte)
N	*Commiphora quadricincta*	E	*Casuarina equisetifolia* (coastal belts, phreatophyte)
N	*Feretia apodanthera*	N	*Ziziphus mauritiana*
N	*Borassus aethiopum* (phreatophyte)	N	*Crataeva adansoni*

N	*Sclerocarya birrea*	N	*Stereospennum kunthianum*
E	*Cassia siamea*	N	*Tamarindus indica*
E	*Albizzia lebbek*		

B. Common afforestation species moderately tolerant to drought, i.e. to intermediate length of rainy seasons (180–240 days)

E	*Acacia melanoxylon*	N	*Acacia seyal*
E	*Acacia mearsnii*	N	*Adansonia digitata*
N	*Acacia mellifera*	N	*Annona senegalensis*
N	*Acacia sieberiana*	N	*Bombax costatum*
N	*Afzelia africana*	N	*Anogeissus leiocarpus*
N	*Cassia sieberiana*	E	*Tectona grandis*
N	*Borassus aethiopum* (phreatophyte)	N	*Ceiba pentandra*
N	*Butyrospermum paradoxa*	N	*Cordyla pinnata*
E	*Casuarina equisetifolia*	N	*Celtis australis*
E	*Casuarina cunninghamiana*	N	*Crataeva adansoni*
N	*Combretum glutinosum*	N	*Diospyros mespiliformis*
N	*Combretum nigricans*	E	*Eucalyptus citriodora*
N	*Dalbergia melanoxylon*	E	*Eucalyptus tereticornis*
N	*Entada africana*	N	*Erythrina* spp.
N	*Euphorbia tirucalli*	E	*Gmelina arborea*
N	*Euphorbia abyssinica*	N	*Grewia bicolor*
N	*Euphorbia candelabum*	N	*Grewia mollis*
E	*Grevillea robusta*	N	*Lannea acida*
N	*Juniperus procera* (=*J. excelsa*)	N	*Lannea microcarpa*
N	*Khaya senegalensis*	N	*Maytenus senegalensis*
E	*Leucaena leucocephala*	N	*Parinari curatellifolia*
E	*Mangifera indica*	N	*Parinari excelsa*
N	*Mitragyna inennis*	N	*Parinari macrophylla*
N	*Parkia biglobosa*	N	*Peltophornm frugineum*
E/N	*Poinciana reggia* (=*Delonix reggia*)	E	*Pithecellobium dulcis*
N	*Prosopis africana*	E	*Pithecellobium saman*
N	*Sclerocarya birrea*	N	*Pterocarpus erinaceus*
N	*Stereospermum kunthianum*	N	*Sterculia setigera*
N	*Tenninalia avicennoides*	N	*Strychnos spinosa*
N	*Tenninalia brownii*	N	*Tenninalia sericea*

C. Common afforestation species little tolerant to drought (240 < RS < 365 days)

E	*Acrocarpus* spp.	N	*Danniellia klainei*
N	*Antiaris africana*	N	*Distemonanthus benthamianus*
N	*Aucoumea klaineana*	N	*Entandrophragma angolense*
N	*Canarium madagascariensis*	N	*Entandrophraglna candollei*
N	*Canarium schweinfurthii*	N	*Entandrophragma cylindricum*
N	*Chrysobalanus orbicularis*	N	*Entandrophragma utile*
N	*Cola cordifolia*	N	*Fragara heitzii*
N	*Dalbergia* spp.	N	*Gilbel1iodendron dewevrii*
N	*Danniellia oliveri*	N	*Guiboul1ia ehie*
N	*Guiboul1ia demeusii*	E	*Eucalyptus saligna*
N	*Gowrilerodendron balsamiferum*	E	*Eucalyptus pilularis*
N	*Guarea cedrata*	E	*Eucalyptus robusta*
N	*Juniperus procera*	E	*Eucalyptus urophylla*
N	*Khaya anthoteca*	N	*Lophira alata*
N	*Khaya ivorensis*	N	*Lovoa trichiloides*

N	*Landolphia heudelotii*	N	*Morus mesozygia*
N	*Mammea africana*	N	*Mitragyna ciliata*
N	*Monsonia alata*	N	*Nesogordonia papaverifolia*
N	*Microberlinia brazzavilliensis*	N	*Ochroma lagopus*
N	*Nauclea diderrichii*	N	*Ongokea gare*
N	*Ocotea usambarensis*	E	*Pinus carribea*
N	*Oxystigma oxyphyllum*	E	*Pinus hundurensis*
E	*Pinus patula*	E	*Pinus elliottii*
E	*Pinus radiata*	E	*Pinus kesiya*
E	*Pinus pseudostrobus*	E	*Pinus merkusiana*
N	*Alstonia congensis*	E	*Pinus oocarpa*
E	*Araucaria* spp.	N	*Piptadeniastrnm africanum*
N	*Afzelia bipindensis*	N	*Pterocarpus soyauxii*
N	*Brachystegia cynometroides*	N	*Pterygota macrocarpa*
E	*Callitris* spp.	N	*Podocarpus gracilior*
N	*Cedrela odorata*	N	*Podocarpus milanjianus*
N	*Chlorophora excelsa*	N	*Staudtia stipitata*
N	*Coelocaryon preussii*	N	*Swetenia macrophylla*
N	*Cordyla pinnata*	N	*Tighemella heckelii*
N	*Dacroydes buettneri*	N	*Terminalia ivorensis*
N	*Detarium microcarpum*	N	*Terminalia macroptera*
N	*Diospyros crassiflora*	N	*Terminalia superba*
N	*Elaeis guineensis*	N	*Paraberlinia bifoliata*
N	*Erythrophleum ivorense*	N	*Pericopsis elata*
N	*Erybroma oblongatum*	N	*Pycnanthus angolensis*
E	*Eucalyptus deglupta*	N	*Ravensara crassifolia*
E	*Eucalyptus grandis*	N	*Sclerocarya sylvatica*
E	*Eucalyptus grandis X saligna*	N	*Sygygium guineense*
E	*Eucalyptus maculata*	N	*Terretia utilis*
E	*Eucalyptus maideni*	E	*Tectona grandis*
E	*Eucalyptus microcarys*		

1.3.2.4 Variability and Dependability of Annual Rainfall

As in most parts of the world, rainfall variability in Africa is inversely related to the mean. The coefficient of variation changes from over 100% in the heart of the Sahara to some 15% in the rainforest. This is shown in Tables A2–A9 and in Figs. 4, 5 and 7–10.

From this it is clear that the variability, for a given mean, depends on the rainfall regime. It is usually greater in bimodal than in monomodal regimes. These datasets show, for instance, that contrary to a commonly held opinion, for a given long-term mean, rainfall variability in the Sahel is lower than in northern, eastern and southern Africa; it is actually one of the lowest on earth for an arid region (Le Houérou 1988b, 1989b, c, 1992g). Variability has been assessed via two different criteria: the coefficient of variation (CV), which is the quotient of the standard deviation by the mean ($CV = 100\sigma/x$), and the variability index (VI), utilized in Australia, which is

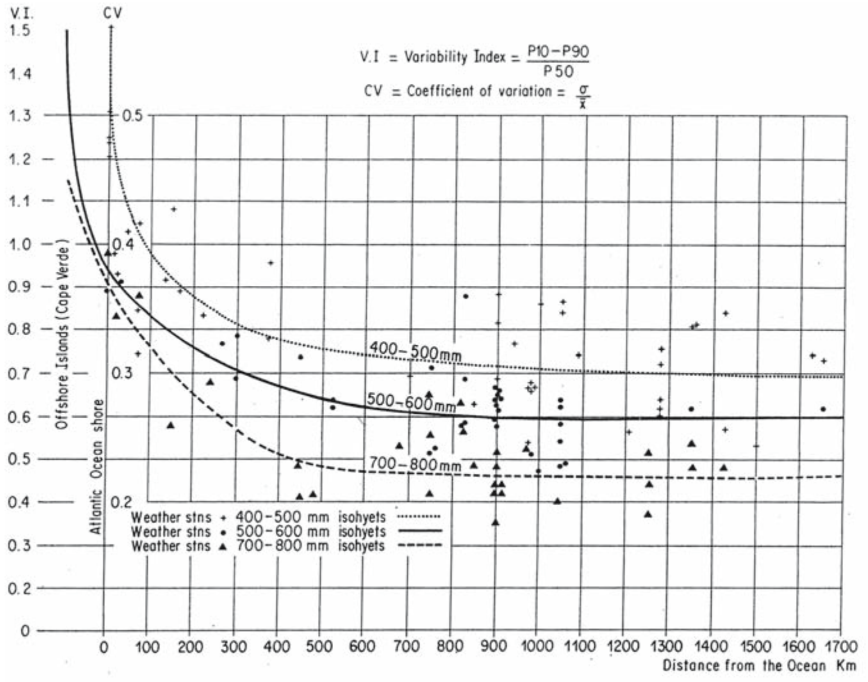

Fig. 9 Variability of annual rainfall in western Africa as a function of the distance from the Atlantic Ocean (Le Houérou et al. 1993)

the quotient of the difference between decile 9 and decile 1 to the median (decile 5): (D9–D1)/D5. The relationship between the two criteria is quite good, as shown in Tables A2 and A3, and in Figs. 7–9, with a correlation coefficient of 0.96 (Le Houérou 1999a). In theory, the variability index is more accurate in low-rainfall areas, as it does not depend on the shape of the distribution and its skewness, in contrast to the coefficient of variation. In practical terms, however, the difference is negligible for our purpose.

Rainfall variability is a significant parameter but most often overlooked. It becomes more important as the mean annual rainfall decreases. As a matter of fact, what is of practical significance is not the average rainfall but the reliable rains (RR), i.e. those occurring 4 years in 5, on which agricultural development planning should be based (Hargreaves 1975a, b; Dancette 1979; Virmany et al. 1980). However, the RR are not related to the mean in a simple and straightforward way (Le Houérou 1988b, 1989b, c). At the border of the Sahara, the RR is only 40–50% of the mean, while above an annual average of 600–800 mm, it represents around 80% (Figs. 4–9). This is due to the skewness of the distribution in arid zones. If one is to establish any sound and reliable development planning, it is therefore necessary to know the annual and monthly variability in order to determine the amount of RR. This may be

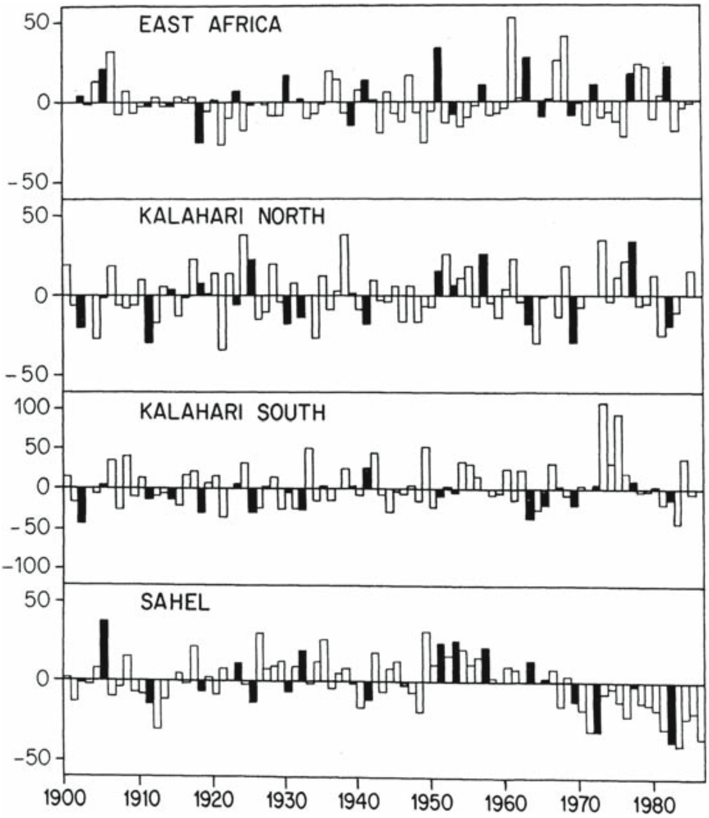

Fig. 10 Long-term trends of annual rainfall in four regions of Africa during the period 1901 to 1986, and deviation from the norm. ENSO years are *shaded* (Nicholson et al. 1988)

achieved by using the Gamma distribution law (Hargreaves 1975a, b onwards; Mosiño and Garcia 1981; Le Houérou 1985a, b).

1.3.2.5 Rainfall Gradients

Mean annual rainfall is subject to altitudinal and latitudinal gradients, which in turn are strongly affected by local situations.

Altitudinal lapse rate: as a general rule, one may expect a positive altitudinal gradient of 10 ± 5% for each increase of 100 m in elevation; in other words, rainfall doubles for an increase of elevation from 500 to 1,500 m up to a maximum, which again varies with local conditions, from 2,500 to 3,500 m and then decreases on higher mountains, in the Afro-alpine and Mediterranean-alpine zones (Le Houérou 1959a, 1969, 1984a, 1989a, 1995a, 2005a, b). The lapse rates vary strongly with

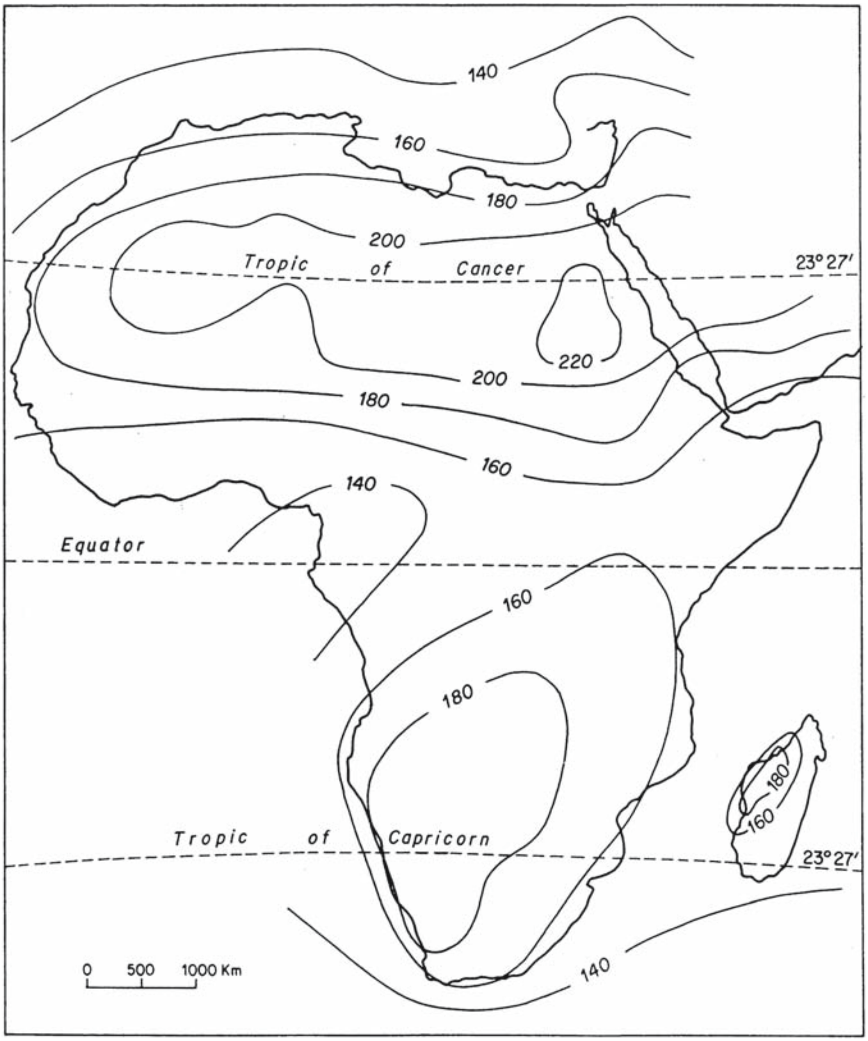

Fig. 11 Global radiation (kcal cm^{-2} year^{-1}; Landsberg et al. 1965). Note that 1 kcal cm^{-2} year^{-1} = 41.9 MJ m^{-2} year^{-1} = 1.33 W

slope and aspect, i.e. rain shadows or rain-exposed slopes, the presence or absence of a foehn effect, etc.

The latitudinal gradient is also strongly influenced by local geographic situations but, by and large, there is a decrease from a maximum rainfall under the equator (around 1,500–2,000 mm) to an absolute minimum of 0–200 mm under the tropics. Striking departures from this behaviour include the Somali-Ethiopian desert along the Red Sea shores, where rainfall is far less than the overall latitudinal lapse rate would imply. Along the Indian Ocean shores south of the equator, there is no

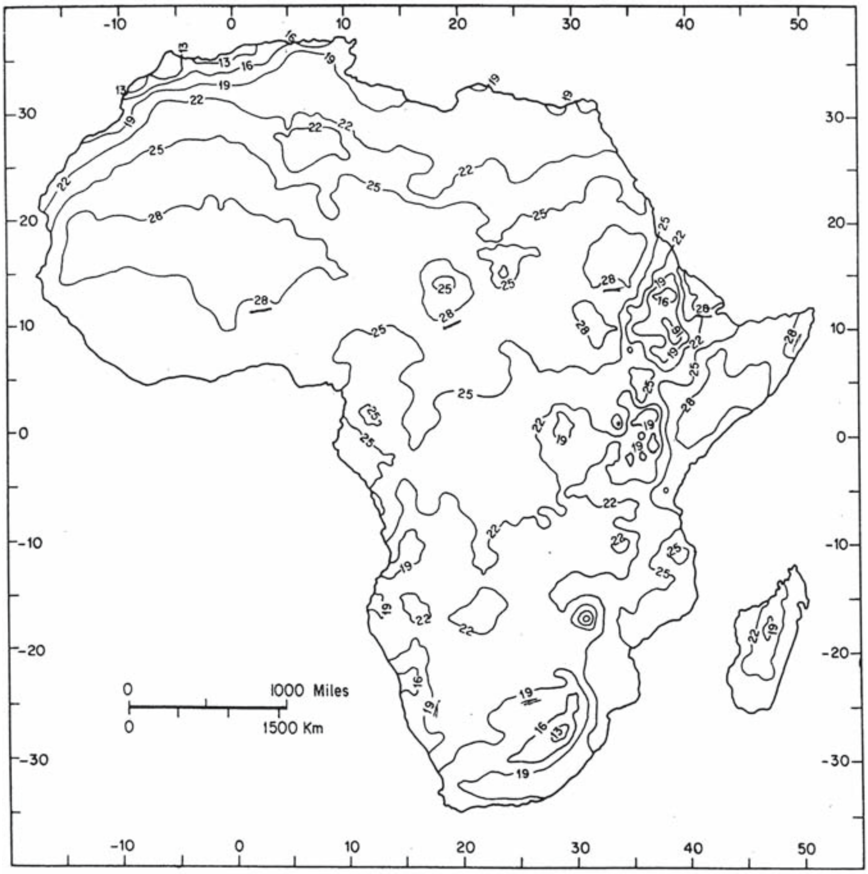

Fig. 12 Geographic distribution of mean annual temperature (°C) in Africa (Le Houérou et al. 1993)

latitudinal gradient; rainfall varies little (1,000 ± 200 mm from Mombasa, Kenya at 4°S, to Port Elisabeth, South Africa at 34°S.

In the Sahel, conversely, the gradient is quite obvious and the lapse rate quite uniform: *an increase of one mm per km southwards off the Sahara border* (Le Houérou 1976). In the Sudanian and Guinean ecological zones, the gradient is similar but with strong deviations along the Atlantic Ocean shores of the Gulf of Guinea, associated with the SW monsoon trajectory and depending on the shoreline angle with this trajectory. The consequences of the geographic distribution of land and ocean masses for the spatial distribution of rainfall is examined in the next section.

1.3.2.6 Evolution of Annual Rainfall, Causes of the Sahel Drought

The analysis of rainfall data since the beginning of instrumental records, in the mid-19th century, does not show any unambiguous trend in any part of the continent, with

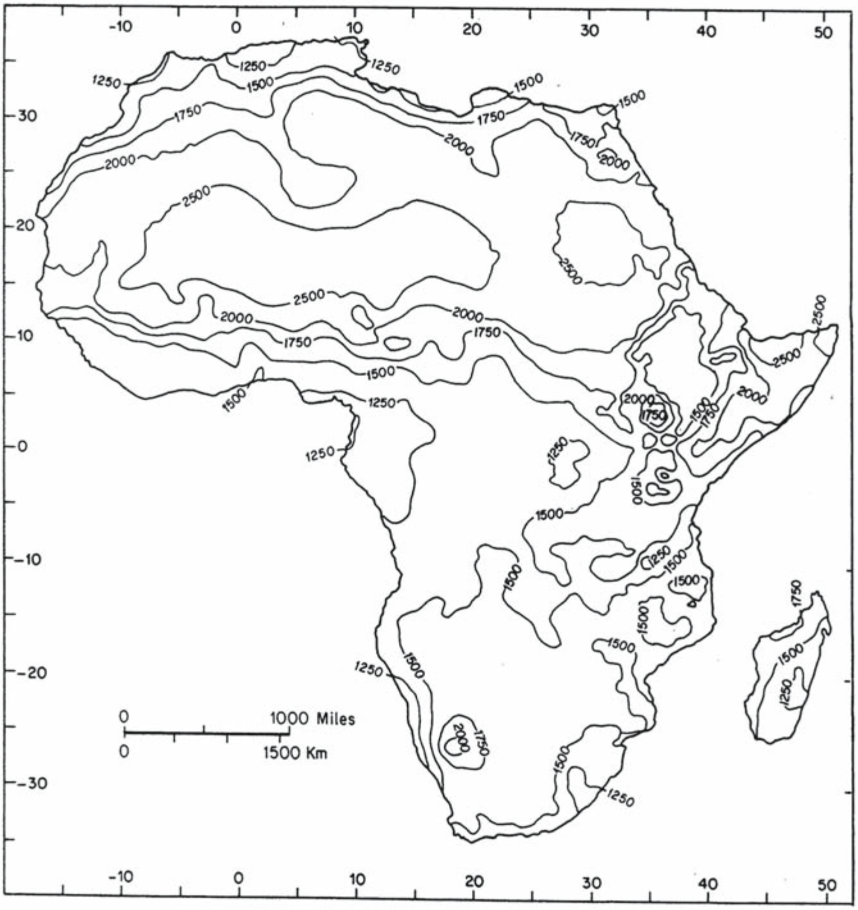

Fig. 13 Geographic distribution of mean annual ETo in Africa (Le Houérou et al. 1993)

the exception of a medium-term trend in the Sahel between 1970 and 1990 (Griffiths and Hemming 1963; Le Houérou 1969; Griffiths 1972; Tyson 1978, 1986, 1990; Nicholson 1978, 1979, 1981; Nicholson et al. 1988). The data for the Sahel, the Kalahari and East Africa are shown in Fig. 10 for the period 1900–1986 (Nicholson et al. 1988). This figure shows that annual rainfall declined in the Sahel from the late 1960s to 1986, without any of these 17 years reaching the 1900–1968 mean. The rainfall decline in the Sahel is analyzed in Tables A4–A9. These data tend to show that the decline is less than often stated. It also shows that the decline decreases from N to S as the long-term mean increases but, surprisingly, also from W to E.

Figure 10 clearly suggests that the Sahel great drought does not seem tied to the ENSO (El Niño Southern Oscillation), contrary to other arid zones such as in Latin America, China, India and Australia (Nicholls 1987). The great Sahel drought (1970–1990) seems to have corresponded with a relatively high sea surface

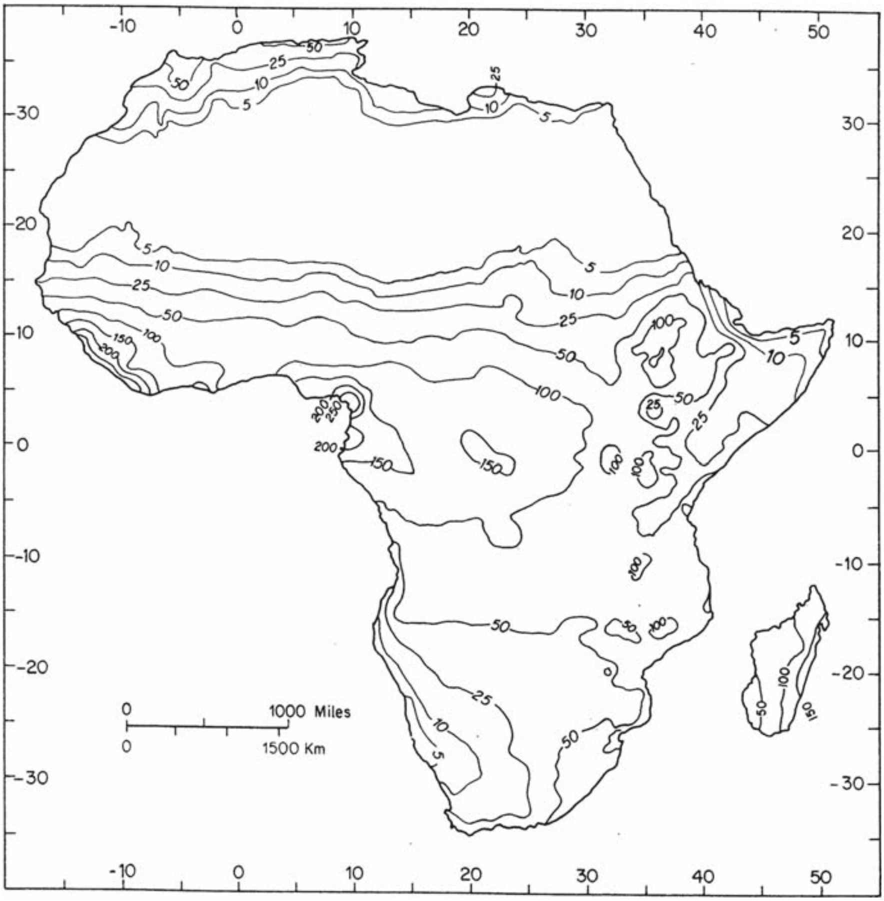

Fig. 14 Geographic distribution of mean annual aridity index (*P*/ETo × 100; Le Houérou et al. 1993)

temperature (SST) in the southern Atlantic, whereas the Sahelian rainy period of 1948 to 1968 coincided with relatively low SSTs (Mahé 1993).

In the Gulf of Guinea, the strength or the weakness of the upwellings in the Guinea equatorial current may reach 0.5–1.0°C deviation from normal over periods of several weeks. SST seems to control the strength of the St Helena anticyclone—hence, the more or less northward progression of the Inter-tropical Convergence Zone (ITCZ; normally between 0 and 10°N) during the boreal summer, and hence the progression of the Inter-Tropical Front (ITF) and the amount of rain that falls over the Sahel and Sudan ecological zones. Any reduction in the upwellings of the Guinea tropical current offshore of the Ivory Coast, Ghana, Togo and Benin, and therefore relatively high SSTs in that area, coincides with high rains on the northern shores of the Gulf of Guinea and with lower than normal rains in the Sudan and the Sahel belts. Conversely, relatively strong upwellings, i.e. low SSTs, cause relatively

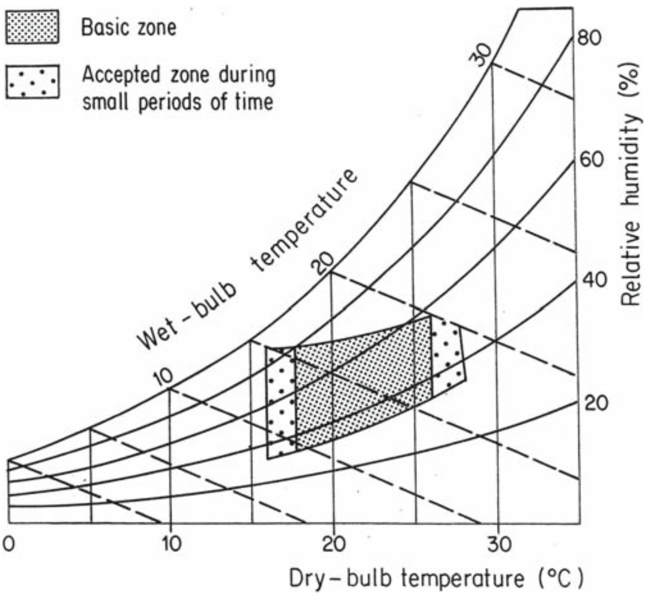

Fig. 15 Thermal neutrality and human comfort as a function of temperature and air humidity (Canha da Piedade 1986)

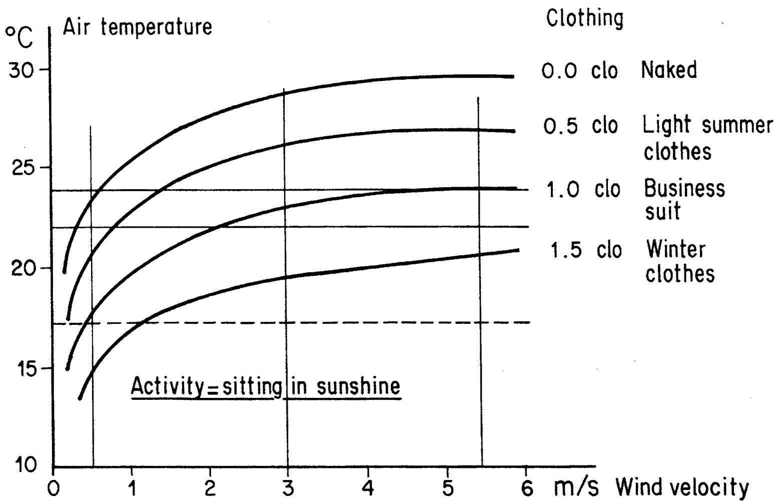

Fig. 16 Comfort diagram combining wind velocity, temperature and clothing, for a person sitting in the sunshine (Kristensen and Esben 1986)

low rains in the Gulf and higher than normal rains in the Sudan and the Sahel ecozones. The annual SST amplitude was around 6°C, whereas the interannual range of anomalies was 2–3°C between 1854 and 1990 (Lamb 1978; Hastenrath and Lamb

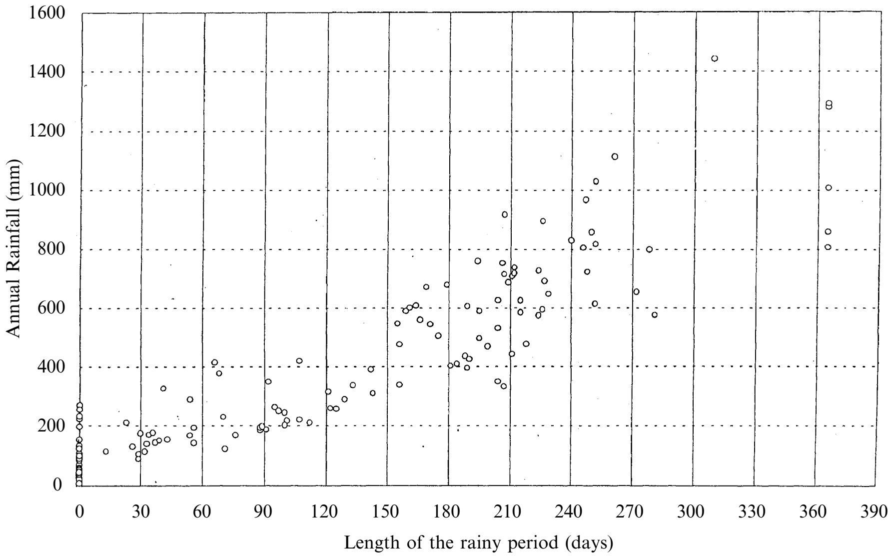

Fig. 17 Relationship between mean annual rainfall and the length of the rainy season ($P > 0.35$ ETo) in extra-tropical Africa (Le Houérou et al. 1993)

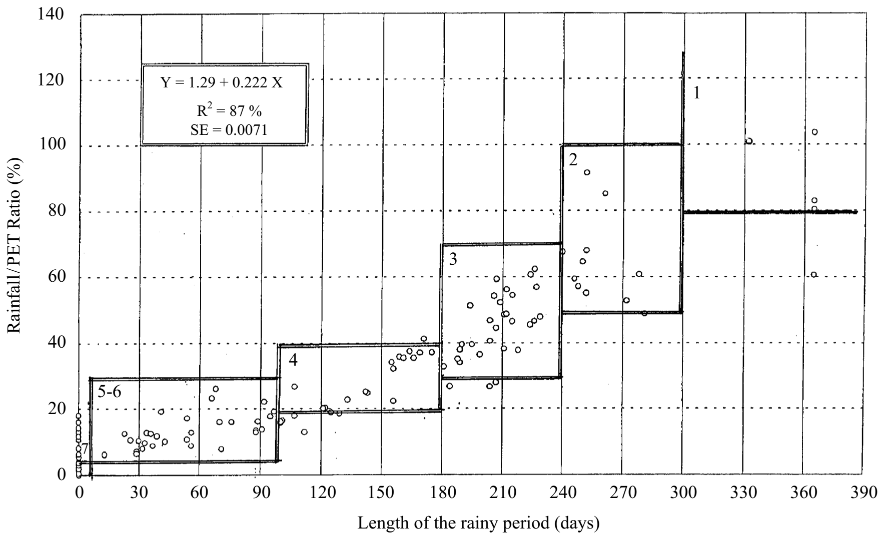

Fig. 18 Relationship between the aridity index (P/ETo × 100) and the length of the rainy season ($P > 0.35$ ETo) in extra-tropical Africa (Le Houérou et al. 1993)

1977; Hirst and Hastenrath 1983; Folland et al. 1986; Demarcq et al. 1988; Janicot 1990; Fontaine 1991; Fontaine and Bigot 1991; Mahé 1993; Janicot and Fontaine 1993; Mahé et al. 1993). There seems to be a Southern Atlantic Oscillation (SAO) comparable to the Pacific ENSO.

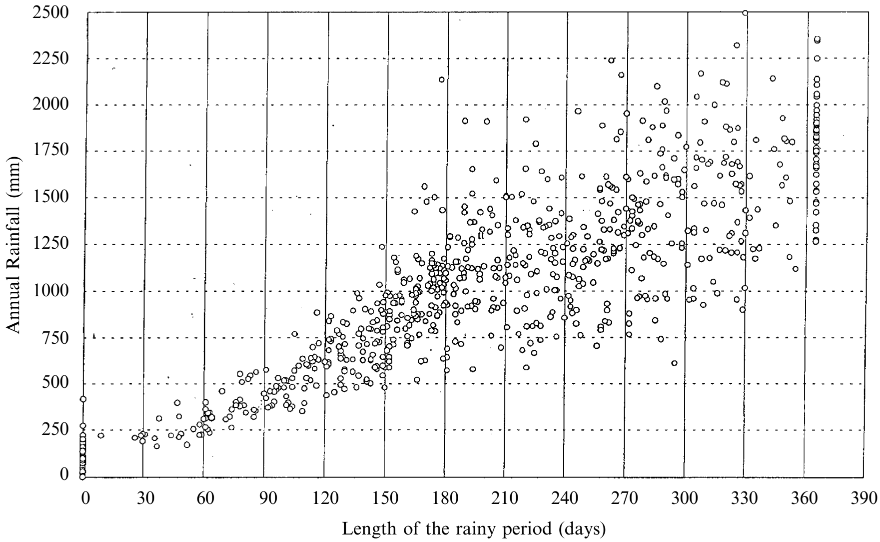

Fig. 19 Relationship between mean annual rainfall and the length of the rainy season (*P* > 0.35 ETo) in African tropical agro-bioclimates (Le Houérou et al. 1993)

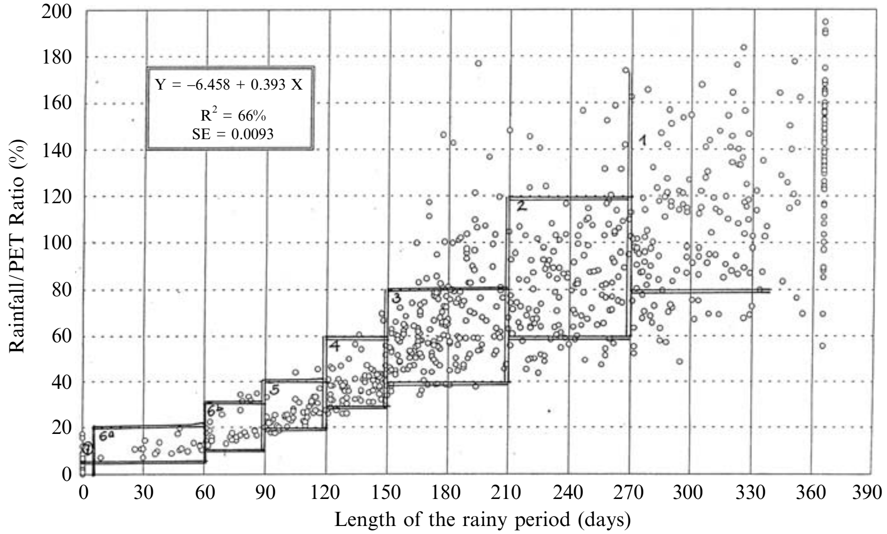

Fig. 20 Relationship between the aridity index (*P*/ETo) and the length of the rainy season (days when *P* > 0.35 ETo) in the tropical agro-bioclimates of Africa (Le Houérou et al. 1993)

This situation is highly reminiscent of the ENSO of the S. Pacific, which results in reduced upwellings offshore of Chile and Peru—hence, high rainfall on the western Andes and drought in N.E. Brazil. Conversely, strong upwellings in the

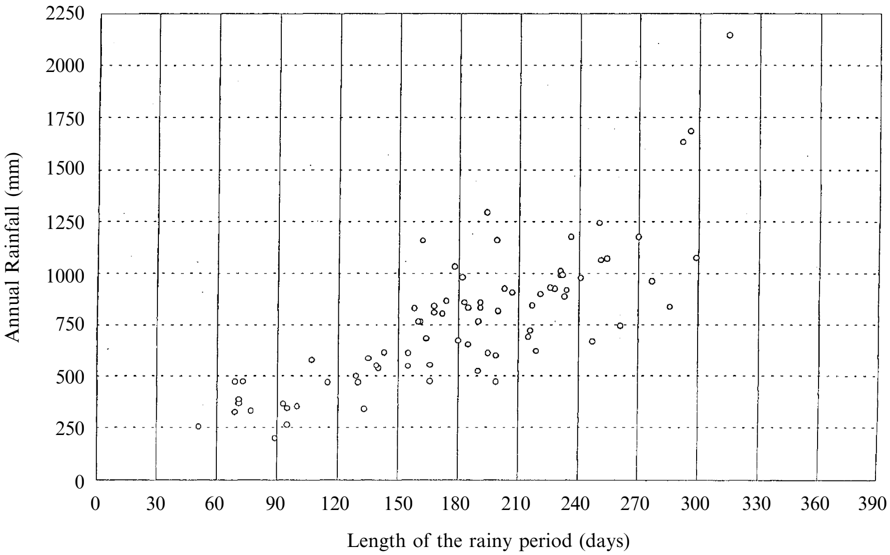

Fig. 21 Relationship between mean annual rainfall and the length of the rainy season(s) ($P > 0.35$ ETo) in the equatorial agro-bioclimates of East Africa (Le Houérou et al. 1993)

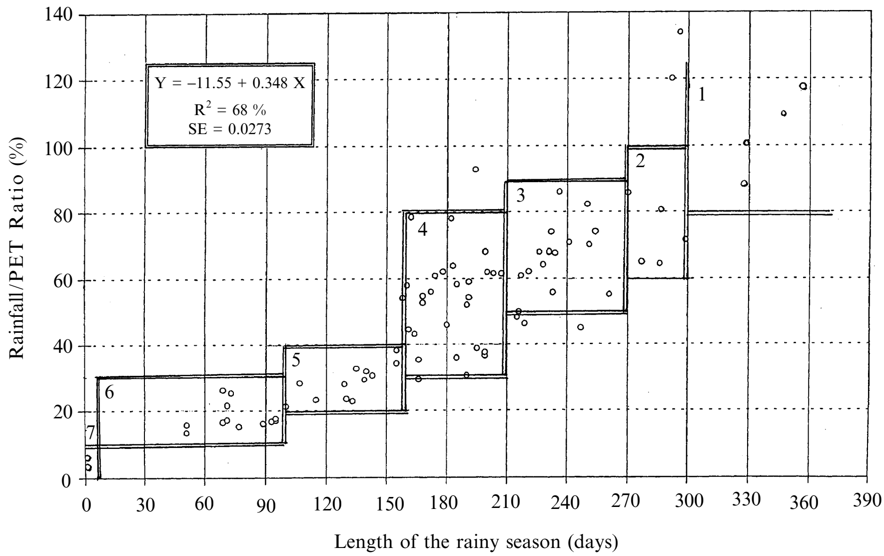

Fig. 22 Relationship between the aridity index (P/ETo) and the length of the rainy season(s) in the equatorial agro-bioclimates of East Africa (La Houérou et al. 1993)

Humboldt current are correlated with drought in Chile and Peru and high rainfall in N.E. Brazil. It would thus seem that the Sahel rains depend indirectly on the strength of the Benguela current, in a similar way to the N.E. Brazil rainfall being connected with the Humboldt current variations with a ca. 2-month time lag (Gasques and Magalhaes 1987).

In the various Mediterranean climate areas of the planet, there is no significant change in annual rainfall over the period of instrumental record, i.e. over the past 150 years (Le Houérou 1959a, b, 1969, 1994a, c, d, 2005a, b; Le Houérou and Aïdoud, unpublished data). In fact, there has most likely been none since ca. 2,500 years B.P.

Dendrochronological studies on cedar trees (*Cedrus atlantica*) from the Middle Atlas mountains of Morocco record tree rings dating back some 1,000 years ago, show that the recent Sahel drought is not unprecedented in terms of length and severity. Several lengthy droughts occurred in the Middle Atlas of Morocco over the past 7 centuries, in particular during the periods 1240–1365, 1395–1420, 1490–1550 and 1610–1640, and also some long high-rainfall periods during 1010–1120, 1430–1480 and 1750–1780 (Stockton 1985). These studies are of particular significance because the study site lies very close to a typically arid zone in terms of horizontal distance (10 km). One may thus consider the Sahel drought as a probable oscillation, rather than a definite long-term trend.

Pollen analysis studies show that the present climatic conditions prevailed throughout Africa over the past 3,000 to 4,000 years. Various geological and palaeontological studies, however, show dramatic climatic changes during the Holocene and the Pleistocene, with alternating dry and wet periods, and with concurring shrinkages and expansions of the rainforest, and simultaneous and opposite expansions and shrinkages of the Sahara. A general humid phase prevailed from 4,000 to 10,000 years B.P. and a very dry period from 10,000 to 20,000 B.P., and so forth. The Sahara, for instance, was some 500–600 km south of its present limit during the period of establishment of the Ogolian dune system (Kanemian) between 10,000 and 20,000 years B.P. This has been proven by pollen analysis, former lake levels, and various sedimentary deposits such as diatomites, aeolian sand and loess deposits (Maley 1981), as well as large present-day vegetated dune fields down to the northern border of the Central African Republic (10°N).

As a consequence of increasing atmospheric pollution by CO_2, N_2O, CH_4 and chlorofluorocarbons, a warming of the atmosphere may take place. Presently available global circulation models (GCMs) predict an increase of 1–2°C in the African inter-tropical zone, and 2–3°C in the extra-tropical zones between 25° and 45°. As a consequence, annual PET would increase by 70–140 mm (Le Houérou 1993a) in the extra-tropical zone. If, as expected, rainfall does not increase substantially, the *P*/PET ratio will decrease. In sub-humid, humid and hyper-humid zones, this would be compensated for by "carbon fertilization", i.e. enhanced photosynthesis due to increased CO_2 concentration, and the resulting improvement of water and rain-use efficiencies. In arid and semi-arid zones where water availability is a strong limiting factor, however, the situation may deteriorate due to water stress, and even carbon fertilization would not compensate for a worsened *P*/ETo ratio (Le Houérou 1991a–c, 1992c, 1993a).

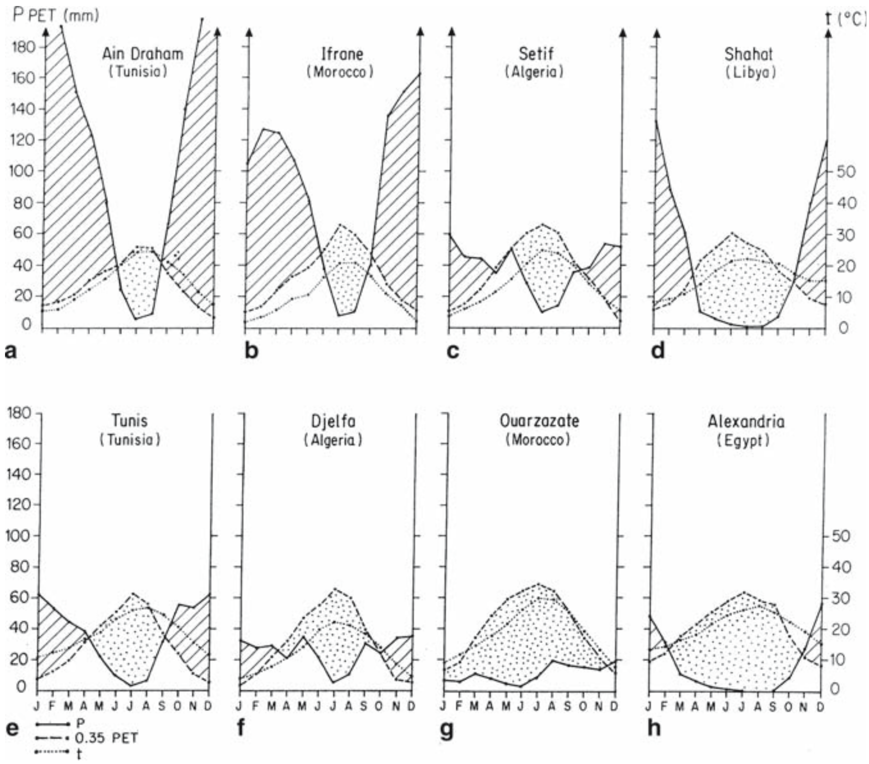

Fig. 23 Climatic diagrams for eight weather stations from northern Africa (Le Houérou 1995e).

a Ain Draham (Tunisia)
Hyper-humid Mediterranean agro-bioclimate with temperate winters

Lat. 36°46′N	P = 1,534 mm	2t = 360 mm	Rainy season = 265 days
Long. 08°42′E	T = 15 °C	0.35 ETo = 328 mm	P/ETo = 142%
Elev. 739 m	m = 3.9 °C	ETo = 1,080	

b Ifrane (Morocco)
Humid Mediterranean agro-bioclimate with very cold winters

Lat. 33°30′N	P = 1,112 mm	2t = 259 mm	Rainy season = 240 days
Long. 5°10′W	T = 10.8 °C	0.35 ETo = 400 mm	P/ETo = 97.2%
Elev. 1,665 m	m = −5.0 °C	ETo = 1,143	

c Setif (Algeria)
Semi-arid Mediterranean agro-bioclimate with cold winters

Lat. 36°11′N	P = 469 mm	2t = 334 mm	Rainy seasons = 199 days
Long. 5°25′E	T = 13.9 °C	0.35 ETo = 402 mm	P/ETo = 36%
Elev. 1,081 m	m = 0.3 °C	ETo = 1,287 mm	

d Shahat (=Cyrene) (Libya)
Sub-humid Mediterranean agro-bioclimate with temperate winters

Lat. 32°49′N	P = 539 mm	2t = 382 mm	Rainy season = 135 days
Long. 21°52′E	T = 15.9 °C	0.35 ETo = 419 mm	P/ETo = 45.1%
Elev. 625 m	m = 4.3 °C	ETo = 1,196 mm	

1.3.2.7 Other Geographic Factors Affecting Rainfall: the Role of Oceanic Currents

Apart from elevation and latitude, other geographical factors may strongly influence rainfall, such as the orientation of coastlines with respect to rain-bearing winds. The case is particularly clear on the northern shores of the Gulf of Guinea. Annual rainfall reaches 2,000–4,000 mm in areas where the shoreline is perpendicular to the trajectory direction of the SW monsoon, such as in Guinea, Sierra Leone, Liberia, the Ivory Coast and Nigeria. The values decrease to 700–1,200 mm in those areas where the shorelines tend to be parallel or at an acute angle to the main direction of the monsoon, such as in Ghana, Togo and Benin (Accra, 765, Lomé, 924 and Cotonou, 1,241 mm; see Table A4 and Figs. 3, 6, 9).

However, cold upwellings off the shores of Ghana, Togo and Benin may be partly responsible for the lower rainfall in this area (Maley 1989, 1990; Mahé 1993; Mahé et al. 1993). Sea currents are major initiators of geographic rainfall distribution, cold currents being a factor of aridity in neighbouring lands and warm currents a cause of high precipitation on the shores.

The cold Canary current, running in a NE–SW direction offshore Morocco and Mauritania to N. Senegal, is a factor of aridity in S.W. Morocco, Mauritania, the Eastern Canary Islands (Lanzarote, Fuerte Ventura) and the Eastern Cape Verde Islands (Sall, Boa Vista, Mayo, Santiago). The colder Benguela current along the coasts of South Africa, Namibia and S. Angola is a cause of very low precipitation (Alexander Bay, 44, Luderitz, 17, Swakopmund, 8 and Moçamedes, 50 mm). In both cases, the upwellings also produce mist and fog and high air moisture in a coastal

Fig. 23 (continued)

e Tunis (Tunisia)
Semi-arid Mediterranean agro-bioclimate with mild/warm winters

Lat. 36°50′N	P = 443 mm	2t = 444 mm	Rainy season = 174 days
Long. 10°14′E	T = 18.5 °C	0.35 ETo = 363 mm	P/ETo = 42.7%
Elev. 4 m	m = 7.0 °C	ETo = 1,037 mm	

f Djelfa (Algeria)
Arid Mediterranean agro-bioclimate with cold winters

Lat. 34°41′N	P = 308 mm	2t = 319 mm	Rainy season = 135 days
Long. 3°15′E	T = 13.3 °C	0.35 ETo = 383 mm	P/ETo = 28.2%
Elev. 1,144 m	m = 0.5 °C	ETo = 1,093 mm	

g Ouarzazate (Morocco)
Arid Mediterranean agro-bioclimate with cool/cold winters

Lat. 30°56′N	P = 126 mm	2t = 456 mm	Rainy season = 15 days
Long. 6°54′W	T = 19 °C	0.35 ETo = 496 mm	P/ETo = 8.7%
Elev. 1,140 m	m = 1.0 °C	ETo = 1,417 mm	

h Alexandria (Egypt)
Arid Mediterranean agro-bioclimate with very warm winters

Lat. 31°22′N	P = 191 mm	2t = 485 mm	Rainy season = 75 days
Long. 29°57′E	T = 20.2 °C	0.35 ETo = 475 mm	P/ETo = 14.0%
Elev. 32 m	m = 9.2 °C	ETo = 1,358 mm	

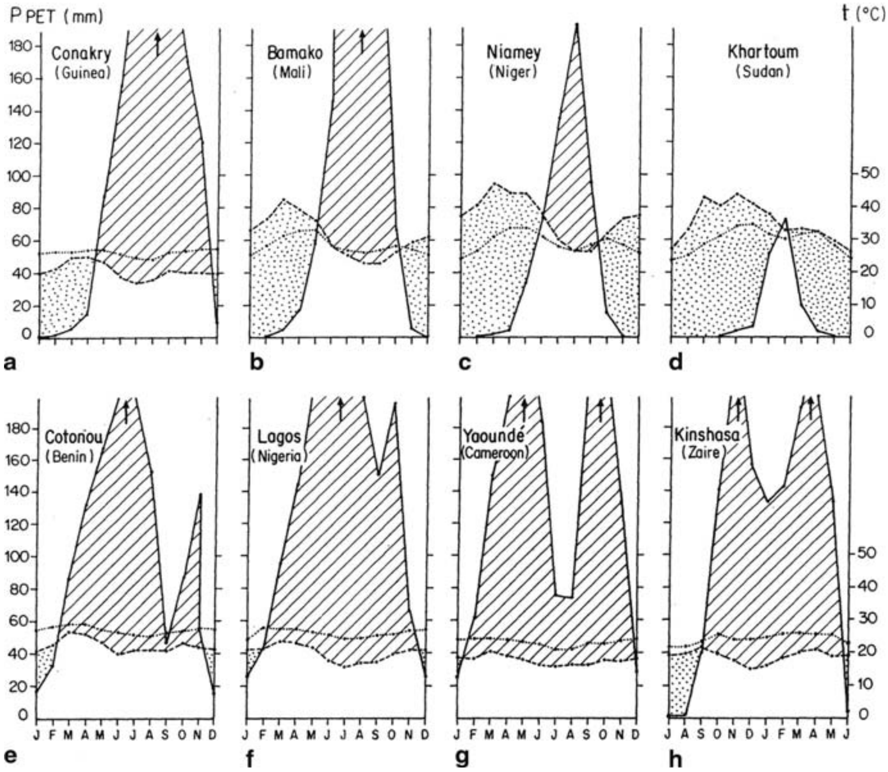

Fig. 24 Climatic diagrams for eight weather stations from western Africa (Le Houérou 1995e).

a Conakry (Guinea)

Hyper-humid tropical agro-bioclimate in the Guinean ecological zone, with very warm winters

Lat. 9°64′N	*P* = 4,296 mm	2*t* = 636 mm	Rainy season = 210 days
Long. 13°37′W	*T* = 26.5 °C	0.35 ETo = 507 mm	*P*/ETo = 296%
Elev. 49 m	*m* = 22.0 °C	ETo = 1,449 mm	

b Bamako(Mali)

Sub-humid tropical agro-bioclimate Sudanian ecological zone, with very warm winters

Lat. 12°38′N	*P* = 1,075 mm	2*t* = 674 mm	Rainy season = 155 days
Long. 08°02′W	*T* = 28.1 °C	0.35 ETo = 748 mm	*P*/ETo = 50%
Elev. 332 m	*m* = 16.0 °C	ETo = 2,136 mm	

c Niamey (Niger)

Semi-arid tropical agro-bioclimate Sudano-Sahelian ecological zone, with very warm winters

Lat. 13°29′N	*P* = 573 mm	2*t* = 694 mm	Rainy season = 120 days
Long. 02°10′E	*T* = 28.9 °C	0.35 ETo = 870 mm	*P*/ETo = 23%
Elev. 224 m	*m* = 15.6 °C	ETo = 2,485 mm	

d Khartoum (Sudan)

Very arid tropical agro-bioclimate Saharo-Sahelian ecological zone, with very warm winters

Lat. 15°36′N	*P* = 158 mm	2*t* = 713 mm	Rainy season = 20 days
Long. 32°33′N	*T* = 29.7 °C	0.35 ETo = 849 mm	*P*/ETo = 6.5%
Elev. 380 m	*m* = 16 °C	ETo = 2,427 mm	

belt some 50 km wide. These considerably reduce PET, compared to inland data in the same region; this reduction is of the order of 20–40%, as evident in Table T11.

Fog and drizzle occur 100–150 days per year in the coastal Namib desert, bringing a rainfall equivalent of 50–150 mm (130 mm in Swakopmund, Nagel 1962).

The cold currents are thus a source of very low rainfall; however, aridity is somewhat mitigated by occult precipitations and relatively low ETo, so that these littoral deserts may be regarded as "attenuated deserts", relative to their inland counterparts (Table T11). Warm currents such as the Guinea, the Mozambique and the Somali bring high rainfall in the Gulf of Guinea, Strait of Mozambique, S. Somalia, Kenya and Tanzania coastal zones.

These currents have their counterparts on other continents that result in similar climatic consequences: the subtropical west sides of continents are thus arid while the east sides are rainy. The counterpart of the Benguela current is the Humboldt current of Chile/Peru, while the Canary current is the equivalent of the California current, etc.

Other consequences of cold currents and their upwellings are the presence of abundant plankton and prosperous industrial fisheries, such as in S. Morocco, Mauritania, Namibia, Chile, Peru and Baja California (Le Houérou 1998a).

1.3.2.8 Occult Precipitation

Occult precipitation from fog, mist, low clouds or dew may locally constitute quite a significant contribution to the water budget of the environment. These are fairly poorly known, partly due to the difficulty of accurate evaluation and the lack of

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Fig. 24 (continued)

e Cotonou (Benin)
Humid equatorial agro-bioclimate sub-Guinean ecological zone, with very warm winters

Lat. 6°21′N	P = 1,329 mm	$2t$ = 650 mm	Rainy seasons = 230 days
Long. 2°23′E	T = 27.1 °C	0.35 ETo = 540 mm	P/ETo = 86%
Elev. 9 m	m = 24.0 °C	ETo = 1,543 mm	

f Lagos (Nigeria)
Hyper-humid equatorial agro-bioclimate Guinean ecological zone, with very warm winters

Lat. 6°27′N	P = 1,732 mm	$2t$ = 626 mm	Rainy seasons = 315 days
Long. 3°24′E	T = 26.0 °C	0.35 ETo = 478 mm	P/ETo = 127%
Elev. 38 m	m = 22.0 °C	ETo = 1,367 mm	

g Yaoundé (Cameroon)
Hyper-humid equatorial agro-bioclimate Guinean ecological zone, with very warm winters

Lat. 3°50′N	P = 1,684 mm	$2t$ = 562 mm	Rainy seasons = 335 days
Long. 11°31′E	T = 23.4 °C	0.35 ETo = 434 mm	P/ETo = 135%
Elev. 760 m	m = 19.0 °C	ETo = 1,240 mm	

h Kinshasa (Zaire)
Humid equatorial agro-bioclimate Guinean ecological zone, with very warm winters

Lat. 4°19′S	P = 1,420 mm	$2t$ = 590 mm	Rainy seasons = 290 days
Long. 15°22′E	T = 24.60 °C	0.35 ETo = 457 mm	P/ETo = 109%
Elev. 310 m	m = 20.7 °C	ETo = 1,305 mm	

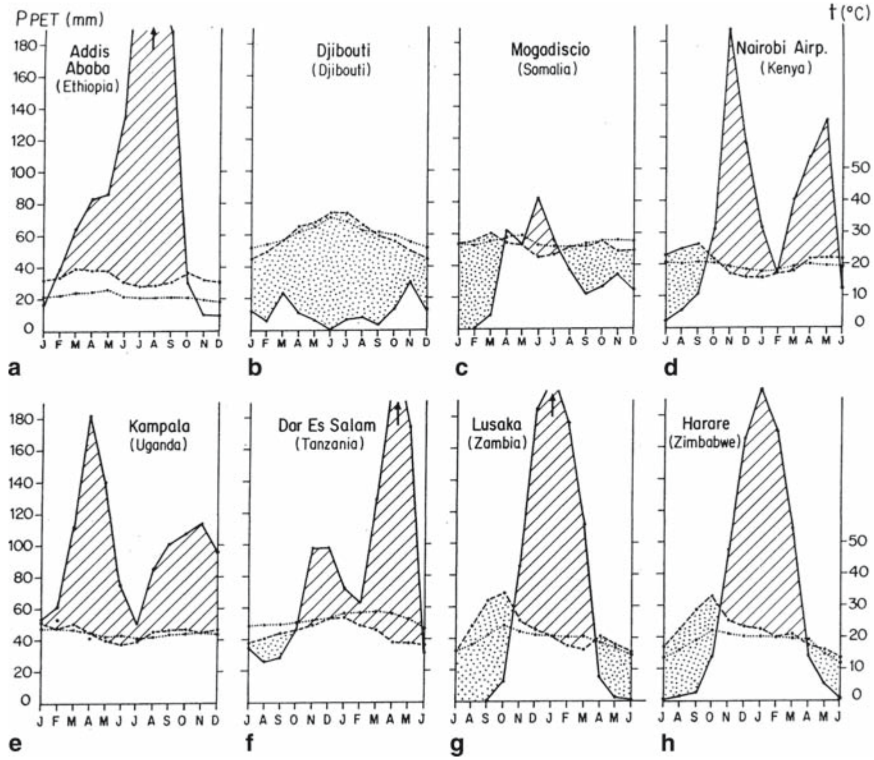

Fig. 25 Climatic diagrams for eight weather stations from eastern Africa (Le Houérou 1995e).

a Addis Ababa (Ethiopia)

Humid highland equatorial agro-bioclimate with mild/warm winters

Lat. 09°02′N	*P* = 1,235 mm	2*t* = 384 mm	Rainy seasons = 244 days
Long. 38°45′E	*T* = 16 °C	0.35 ETo = 403 mm	*P*/ETo = 99%
Elev. 2,408 m	*m* = 7.7 °C	ETo = 1,150 mm	

b Djibouti (Djibouti)

Arid lowland equatorial agro-bioclimate, with very warm winters

Lat. 11°36′N	*P* = 135 mm	2*t* = 720 mm	Rainy seasons = 0 days
Long. 43°09′E	*T* = 30 °C	0.35 ETo = 692 mm	*P*/ETo = 6.8%
Elev. 7 m	*m* = 22.8 °C	ETo = 1,978 mm	

c Mogadiscio (Somalia)

Semi-arid equatorial lowland agro-bioclimate, hot winters, East African *Acacia-Commiphora* ecological zone

Lat. 02°02′N	*P* = 394 mm	2*t* = 648 mm	Rainy seasons = 105 days
Long. 45°21′E	*T* = 27 °C	0.35 ETo = 636 mm	*P*/ETo = 22%
Elev. 9 m	*m* = 23.0 °C	ETo = 1,818 mm	

d Nairobi Airport (Kenya)

Equatorial sub-humid highland agro-bioclimate, with warm winters

Lat. 01°19′S	*P* = 844 mm	2*t* = 463 mm	Rainy seasons = 275 days
Long. 36°55′E	*T* = 19.3 °C	0.35 ETo = 485 mm	*P*/ETo = 61%
Elev. 1,624 m	*m* = 11.2 °C	ETo = 1,385 mm	

standard, broadly accepted measuring methods, as no device can condensate fog the same way as tree leaves do. Moreover, there are substantial differences between species depending on leaf shape and structure, e.g. sclerophyll, malacophyll, broad leaf, acicular (Schemenauer and Bridgman 1998; Le Houérou 1998a).

On the offshore islands of the Canary and Cape Verde at specific elevations and in windward exposure, trade winds may bring mist, fog and drizzle that amount to various proportions of the conventional rains, and sometimes more. These are fully used only by vegetation that is capable of condensing fog on its foliage. As low vegetation cannot make full use of the condensation potential, the elimination of trees results in a significant aridization of the environment (Kassas 1956; Nagel 1956, 1961, 1962; Hassan 1974; Schulze and McGee 1978; Edwards et al. 1979; Le Houérou 1984b; Blot 1991; Acosta Baladon and Gioda 1991; Rioux et al. 1997; Canto 1998; Calamini et al. 1998; Jimenez et al. 1998; Puig et al. 1998).

In forested areas, atmospheric water condensation zones are characterized by the presence of epiphytes, in particular hanging lichens of the genera *Usnea (U. articulata)* and *Telechistes* spp., but also ferns and orchids, and American bromeliads such as the "Spanish moss" *Tillandsia usneoides* and *T. recurvata*.

As it is difficult to extrapolate and generalize in this matter, I shall give below a few case studies from Africa and its offshore islands. Southern Africa has a number of fairly well-known case studies (Nagel 1956, 1959, 1961, 1962; Kerfoot 1968; Schulze and McGee 1978; Le Houérou 1998a; Mtuleni et al. 1998; Seely et al. 1998). Winter fogs tend to predominate in winter-rain regions and summer fogs in summer-rain regions.

Fig. 25 (continued)

e Kampala (Uganda)
Humid equatorial midland agro-bioclimate, with warm/very warm winters

Lat. 00°19′N	*P* = 1,180 mm	2*t* = 526 mm	Rainy seasons = 365 days
Long. 32°37′E	*T* = 21.9 °C	0.35 ETo = 533 mm	*P*/ETo = 77%
Elev. 1,140 m	*m* = 18.0 °C	ETo = 1,523 mm	

f Dar-es-Salaam (Tanzania)
Sub-humid equatorial lowland agro-bioclimate, with warm/very warm winters

Lat. 06°50′S	*P* = 1,083 mm	2*t* = 619 mm	Rainy seasons = 240 days
Long. 39°18′E	*T* = 25.8 °C	0.35 ETo = 535 mm	*P*/ETo = 71%
Elev. 14 m	*m* = 18.8 °C	ETo = 1,528 mm	

g Lusaka (Zambia)
Sub-humid tropical midland agro-bioclimate, with warm winters

Lat. 15°25′S	*P* = 804 mm	2*t* = 470 mm	Rainy season = 180 days
Long. 28°19′E	*T* = 19.8 °C	0.35 ETo = 539 mm	*P*/ETo = 52%
Elev. 1,280 m	*m* = 9.5 °C	ETo = 1,541 mm	

h Harare (Zimbabwe)
Sub-humid tropical midland agro-bioclimate, with mild winters

Lat. 17°50′S	*P* = 814 mm	2*t* = 437 mm	Rainy season = 180 days
Long. 31°01′E	*T* = 18.0 °C	0.35 ETo = 527 mm	*P*/ETo = 54%
Elev. 1,472 m	*m* = 6.5 °C	ETo = 1,507 mm	

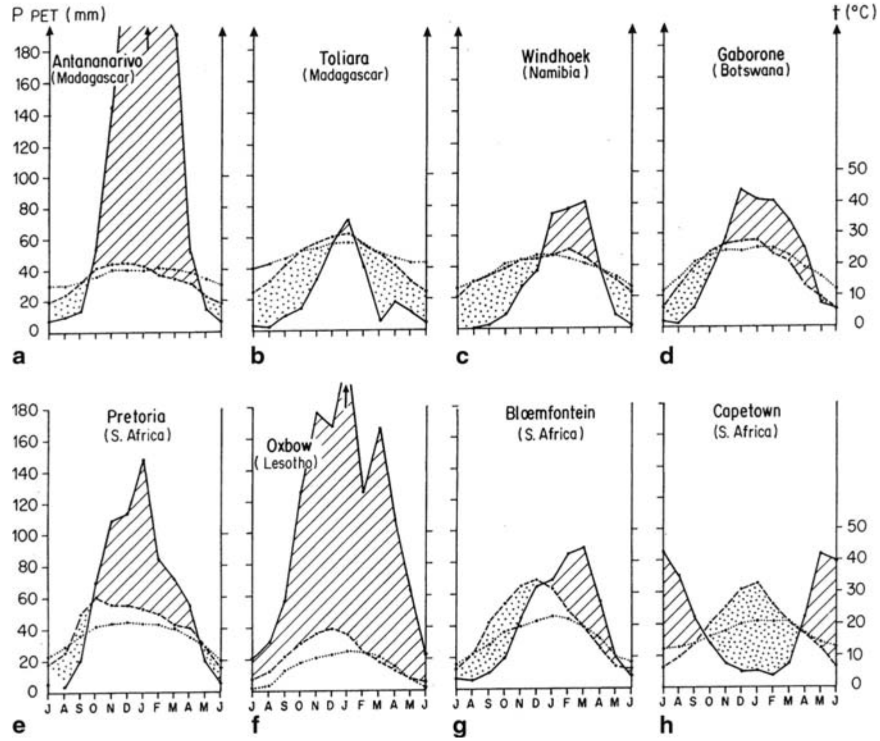

Fig. 26 Climatic diagrams for eight weather stations for southern Africa and Madagascar (Le Houérou 1995e).

a Antananarivo (Madagascar)

Hyper-humid tropical midland agro-bioclimate, with warm winters

Lat. 18°54′S	P = 1,329 mm	$2t$ = 439 mm	Rainy season = 210 days
Long. 47°32′E	T = 18.30 °C	0.35 ETo = 400 mm	P/ETo = 116%
Elev. 1,310 m	m = 10.0 °C	ETo = 1,143 mm	

b Toliara (Madagascar)

Arid tropical lowland agro-bioclimate, with very warm winters

Lat. 23°23′S	P = 275 mm	$2t$ = 578 mm	Rainy season = 45 days
Long. 43°44′E	T = 24.2 °C	0.35 ETo = 540 mm	P/ETo = 18%
Elev. 8 m	m = 14.0 °C	ETo = 1,544 mm	

c Windhoek (Namibia)

Arid tropical midland agro-bioclimate with mild/warm winters

Lat. 22°34′S	P = 361 mm	$2t$ = 456 mm	Rainy season = 110 days
Long. 17°06′E	T = 19.8 °C	0.35 ETo = 459 mm	P/ETo = 28%
Elev. 1,728 m	m = 6.0 °C	ETo = 1,311 mm	

d Gaborone (Botswana)

Semi-arid tropical highland agro-bioclimate with temperate winters

Lat. 24°40′S	P = 520 mm	$2t$ = 480 mm	Rainy season = 155 days
Long. 25°55′E	T = 20 °C	0.35 ETo = 461 mm	P/ETo = 39%
Elev. 980 m	m = 3.6 °C	ETo = 1,318 mm	

At the highest point of Table Mountain (1,100 m) above Cape Town to the south, 5,664 mm were measured as a 5-year average, i.e. as much as 3 times the rain-gauge precipitation, with no month recording less than 311 mm. Along the west coast of southern Africa, radiation and advection fog is formed when warm inshore surface water mixes with the upwelled cold water of the Benguela current. Nagel (1962) cites an average of 121 days of fog per annum for Swakopmund, with a recording of some 130 mm of water.

The same author estimates that along a 3-km-wide coastal strip in the central Namib desert, some 150 mm may be caught by plants. A well-known case is that of *Welwitschia mirabilis* of S.W. Angola and N.W. Namibia, which seems to almost entirely survive on this water resource. In South Africa between the sea, latitudes 32–33° and longitude 20°, centred on the Olifants River Basin in an area of some 50,000 km^2, fog precipitation has been reported to be equivalent to 300 mm per annum (Schulze and McGee 1978), i.e. equal to or greater than rain-gauge values.

Summer fog in South Africa is common in the Transvaal and Natal provinces: 18 "fog catcher" gauges yielded precipitations 105 to 280% in excess of those recorded with standard rain gauges (Nagel 1962). In Natal's mist belt, fog occurs 1–4 days per month from November to February, while in the Drakensberg mountains, fog contribution adds some 400 mm per year, i.e. 33% more to rainfall at 1,800 m elevation on SW-facing slopes from October to March.

At Chisenga (10°S, 33.30°E, alt.≈1,200 m, MAR≈1,000 mm) in N.W. Malawi at the border of Zambia, 146 fog days have been recorded per annum but the contribution in

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Fig. 26 (continued)

e Pretoria (South Africa)
Sub-humid subtropical agro-bioclimate with cool winters

Lat. 25°44′S	*P* = 715 mm	2*t* = 430 mm	Rainy season = 210 days
Long. 28°11′E	*T* = 17.9 °C	0.35 ETo = 461 mm	*P*/ETo = 52%
Elev. 1,326 m	*m* = 2.5 °C	ETo = 1,386 mm	

f Oxbow (Lesotho)
Hyper-humid subtropical montane agro-bioclimate, with very cold winters

Lat. 28°43′S	*P* = 1,281 mm	2*t* = 175 mm	Rainy season = 365 days
Long. 28°37′E	*T* = 7.3 °C	0.35 ETo = 266 mm	*P*/ETo = 169%
Elev. 2,650 m	*m* = −5.9 °C	ETo = 759 mm	

g Bloemfontein (South Africa)
Semi-arid subtropical highland agro-bioc1imate with cold winters

Lat. 29°07′S	*P* = 552 mm	2*t* = 384 mm	Rainy season = 180 days
Long. 26°11′E	*T* = 16.8 °C	0.35 ETo = 481 mm	*P*/ETo = 40%
Elev. 1,422 m	*m* = 0.2 °C	ETo = 1,374 mm	

h Cape Town (South Africa)
Semi-arid agro-bioclimate with mild/warm winters

Lat. 33°54′S	*P* = 506 mm	2*t* = 398 mm	Rainy season = 150 days
Long. 18°32′E	*T* = 16.8 °C	0.35 ETo = 428 mm	*P*/ETo = 41%
Elev. 17 m	*m* = 7.0 °C	ETo = 1,225 mm	

Table T11 Coastal Atlantic vs. inland ETo (database: Frère and Popov 1984; Le Houérou 1997a, b, 1998a; see also Tables T14 and T15)

	Coastal zone ETo (mm)	Same latitude, inland zone ETo (mm)
Namibia		
Luderitz	1,000	
Keetmanshoop		2,176
Swakopmund	1,042	
Windhoek		1,595
S. Africa		
Alexander Bay	1,236	
Pofadder		1,636
Upington		1,725
Angola		
Moçamedes	1,200	
Mauritania		
Nouadhibou	1,914	
Atar		2,352
Morocco		
Agadir	1,236	
Marrakech		1,469
Sidi Ifni	1,065	
Tan-Tan		1,454
Tarfaya	1,121	
Ouarzazate		1,591
Essaouira	1,091	
Kasba-Tadla		1,500
Overall average	*1,212 = −42%*	*1,722 = +30%*

terms of amount of rain equivalence has seemingly not been measured (Schulze and McGee 1978).

In the mountains that run parallel to the SW shores of the Red Sea from S.E. Egypt to the "Horn" of Africa, Cape Gardafui (i.e. over a distance of some 2,650 km), there is a more or less continuous mist belt between 600 and 1,800 m elevation, depending on local conditions. This belt bears particular types of vegetation including a number of CAM (Crassulacean acid metabolism) species such as *Aloe* spp., *Kalanchoe* spp., *Sanseviera* spp. and, above all, the tall cactoid spurges (*E. grandis, E. abyssinica, E. candelabrum, E. tirucalli, E. robecchii, E. balsamifera* subsp. *adenensis), Dracaena schizantha* (dragon tree), and a number of evergreens—*Juniperus procera, Pistacia emarginata, Ceratonia aureothauma, Olea africana, Barbeya oleides, Buxus hildebrandtii, Sideroxylon buxifolium, S. gillettii, Celtis africana, Dodonaea viscosa, Rhus* spp., *Euclea schimperi, Acokanthera schimperi, Cadia purpurea*—and other evergreen Mediterranean-like sclerophyllous shrubs (Kassas 1956; Hemming 1966; Hassan 1974; Le Houérou 1984a, 1998a, 2003; Blot 1991). In Somalia, S. Yemen and Hadramaout, this mist belt is the exclusive habitat of Frankincense trees: *Boswellia sacra = B. carteri* and *B. freereana* in the highlands at the border of Ethiopia and Somalia. The Frankincense trees seem to depend, to a large extent, on fog condensation for their water budget, as the cushion-like sucker roots at the base of the stem are likely not fully functional in terms of soil water absorption, growing directly on bare, unweathered, massive solid blocs of rock material in cliffs and on large fallen boulders.

In the Day mountain's juniper (*J. procera*) forest of Djibouti (1,500 m a.s.l., $P = 300 \pm 200$ mm), Blot (1991) found the following values for "contact cloud" condensation and dripping, i.e. occult precipitation over a 2-year record (1982–1984) under *Juniperus procera* (12 m high, 25% canopy cover): an average annual of 49% of the open ground rain-gauge record; in *Acacia etbaica* open savanna (6 m high, 15% canopy cover), 18%; in nearby short grass swards of *Cynodon dactylon* and *Aizoon canariense*, 4%. These observations clearly show the paramount importance of vegetation structure in the condensation and occult precipitation processes, and the overriding influence of trees on local microclimate and bioclimatic conditions.

Similar weather conditions and vegetation types also prevail in the opposite mountains on the N.W. shores of the Red Sea and of the Gulf of Aden (Hijjaz, Assir, Yemen, Hadramout) and on Socotra Island, offshore Cape Gardafui (Le Houérou 2003).

On Mount Kulal, a small isolated mountain between Lake Turkana (former Lake Rudolf) and the Chalbi desert (2°80′N, 37°E, 60 km N–S, 30 km E–W, elevation 2,381 m) in northern Kenya, a very steep rainfall gradient occurs, viz. about 150–200 mm in the desert at 500 m elevation, and some 1,800 mm at the top at 2,381 m a.s.l. Vegetation varies from *Acacia-Commiphora* desert scrub at the foot of the mountain, to evergreen rainforest at the top over a horizontal distance of some 15 km. Above 1,300 m, low orographic clouds and fog occur 25 to 75% of the time, depending on the season, the wetter periods being the months of April and November, the heart of the two rainy seasons. At the Gatab station (1,450 m a.s.l.), the mean annual rainfall recorded was 1,400 mm, i.e. a mean lapse rate of +115 mm for each 100 m upwards. The dripping from condensed fog and drizzle under juniper (*J. procera*) trees measured over 2 years amounted to 24% of open land precipitation recorded in a glade 200 m away, after due consideration of stem flow (≈10%) and interception (≈20%; Edwards et al. 1979).

Situations similar to that of Mt Kulal are not unusual in E. Africa, as suggested by the distribution of native vegetation and visual observation (hanging *Usnea*, etc.).

On the Canary Islands, the zone of fog and clouds facing the NE trade winds is situated between 750 and 1,500 m elevation. On NE slopes, the *Laurisilva* of broad-leaved evergreen forest and Canary Pine forests occur at these elevations but, on slopes with other orientations, they occur some 500 m higher up (Huetz de Lemps 1959; Kunkel 1976; Bramwell and Bramwell 2001; Le Houérou 2004a).

On the Cape Verde Islands, the maximum precipitation, clouds and fogs from the NE trade winds occur between 500 and 1,000 m. At Curalinho (950 m a.s.l.) on the island of Sao Tiago, fog condensation is estimated to yield about 1,200 mm per year, versus a mean annual rainfall of 1,077 mm (Le Houérou 1980c). Measurements made with the Grünow fog captor yielded 7 times as much water as did a conventional rain gauge in the Serra de Malagueta (900 m a.s.l.) in Sao Tiago in 1979–1980, i.e. 4,975 vs. 699 mm (Acosta Baladon and Gioda 1991).

On the SW slopes, by contrast, clouds dissipate as far as the southern side of the mountain crest, and there is a very strong foehn effect. Weather stations on SW slopes yield 50% less rain than those situated on the NE slopes at the same elevations (Le Houérou 1980c).

The foehn effect may locally play a most significant role in agro-bioclimatology but there is a general dearth of data on this subject in the literature.

1.3.3 Potential Evapotranspiration (PET)

The concept of potential evapotranspiration, coined and introduced by C.W. Thornthwaite in 1948, has been accompanied by a revolution in bioclimatology and agro-meteorology, replacing empirical indices by a rational scientific parameter. However clear the concept is in its principles, the facts have been far from generally accepted. I am aware of over 100 different main predictive equations and many more derived thereof, allowing for the computation of PET from various basic climatic parameters. These may yield annual values varying by over 50%—e.g. Thornthwaite's vs. Blaney and Criddle's (1962) computing procedures. The equation usually considered as the most accurate, Penman's (1948), has been modified more than a dozen times by various authors. These equations yield values that may differ by more than 25% from those arrived at using Penman's standard equation. This particular issue is developed in more detail below. The latest modified form is that proposed by Monteith (1973) and, according to the international agreement orchestrated by FAO, this new equation is labelled ETo or reference potential evapotranspiration, now considered as the world standard (Allen et al. 1998).

The ETo values given in Tables T1, T11–T14 and Figs. 13, 23–29 are based on Penman's equation as modified by Monteith (1973), and are about 9% higher than those derived from the standard equation of 1948, as shown in Tables T12–T14.

The data used in Figs. 23–27, 29 and 37 are computations based on the standard equation and the database published by Frère and Popov (1984), those in Fig. 44 on Le Houérou's equation (1972, 1984a, b). The former dataset was extracted from the FAO's Agrometeorological Data Systems (Amdass). This includes about 17,000 meteorological/rainfall stations worldwide, compiled from both published and unpublished sources. The Africa Amdass database includes 1,200 weather stations having over 20 years of records, 962 of which are used in Table A1. In Table A1, PET was computed via the Penman-Monteith equation (ETo) shown below, following the recommendation of an Expert Consultation on the "Revision of FAO Methodologies for Crop Water Requirements" resulting from a meeting held in Rome in May 1990 (Allen et al. 1998). The meeting recommended a combination formula for the computation of reference evapotranspiration (ETo), as shown below.

Defining reference evapotranspiration (ETo) as the rate of evapotranspiration from a hypothetical crop with an assumed crop height of 12 cm, a fixed canopy resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground, and not short of water, the estimation of ETo can be determined with the combination formula based on the Penman-Monteith approach. When combining the derivations for the aerodynamic and radiation terms, the combination formula can be called the *Penman-Monteith predictive equation of ETo*:

$$\text{ETo} = \frac{0.408\Delta(R_n - G) + \gamma[(900)/(T + 273)]U_n(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)}$$

where ETo is the reference crop evapotranspiration (mm day^{-1})
R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1})
G is the soil heat flux (MJ m^{-2} day^{-1})
T is the average temperature (°C)
U_2 is the wind speed measured at 2 m height (m s^{-1})
$(e_a - e_d)$ is the vapour pressure deficit (kPa)
Δ is the slope of the vapour pressure curve (kPa $°C^{-1}$)
γ is the psychrometric constant (kPa $°C^{-1}$).

When no measured radiation data are available, then net radiation can be estimated as follows:

$$R_{na} = R_{ns} - R_{nl}$$

$$R_{ns} = 0.77(0.19 + 0.38^{n}/N)R_a$$

$$R_{nl} = 2.45 * 10^{-9}(0.9_{n}/N + 0.1)0.34 - 0.14\sqrt{e_d})(T_{l\alpha}{}^{4} + T_{kn}{}^{4})$$

$$G = 0$$

where R_{na} is the net radiation (MJ m^{-2} day^{-1})
R_{ns} is the net shortwave radiation (MJ m^{-2} day^{-1})
R_{nl} is the net longwave radiation (MJ m^{-2} day^{-1})
R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1})
n/N is the relative sunshine fraction
$T_{l\alpha}$ is the maximum temperature (K)
T_{kn} is the minimum temperature (K)
e_d is the actual vapour pressure (kPa).

A few PET measurements have been carried out over several years, in particular in Tunisia (Damagnez and De Villèle 1961; Damagnez et al. 1963; De Villèle 1965), Senegal (Dancette 1976), Chad, the Central African Republic and the Congo (Riou 1975). Measurements with evapotranspirometers (lysimeters) are not free from criticism; the choice of the test turf grass, in particular, bears overriding consequences. In Tunisia, for instance, the reference sward was composed of *Pennisetum clandestinum* (Kikuyu grass), mainly for reasons of ease of handling, maintenance and management,

Table T12 Comparison of the results from various methods of evaluation of ETP/ETo

	Measured, Kikuyu grass (5 years), Damagnez et al. (1963)	Dancette (1976), *Cynodon dactylon* & *Digitaria decumbens*	Penman (1948) standard predictive equation	Penman/Monteith = ETo	Thornthwaite (1948)	Damagnez, 0.72*t*	Turc (1961)	Le Houérou (1972), 0.0085 R_g	Papadakis (1975)
Tunisia									
Gabes	1,431		1,292		996	1,570	1,417	1,325	1,140
Gafsa	1,552		1,290		1,042	1,552	1,408	1,441	1,680
Kairouan	1,338		1,450		1,008	1,407	1,324	1,448	1,600
Kebili	1,649		1,539		1,171	1,459	1,459	1,558	2,170
Sfax	1,090		1,070		962	1,450	1,382	1,290	950
Sousse	1,200		1,125		933	1,350	1,343	1,318	980
Thala	1,190		1,000		818	1,200	1,190	1,242	1,280
Tunis	1,390		1,037		932	1,391	1,390	1,338	1,909
Average	1,355		1,225		983	1,422	1,364	1,370	1,361
	1.00		0.90		0.72	1.04	1.00	1.01	1.00
Senegal/Mauritania									
Rosso/Podor & Richard									
Toll		2,404	2,151	1,910		–	–	1,907	2,035
Bambey		2,011	2,095	2,113		–	–	1,935	2,625
Sefa		1,679	1,506	1,830		–	–	1,853	2,435
Average		2,031	1,917	1,951		–	–	1,898	2,635
		1.00	0.94	0.96				0.93	1.06

Table T13 Compared data for Chad, Central African Republic and Congo (Brazzaville)

Methods, stations	Riou (1975), measured (*Cynodon, Paspalum*)	Penman ETo	Penman ETPp	Le Houérou (1972), 0.0085 R_g	Papadakis (1975)	Riou (1975), class A pan	Riou (1975), Colorado pan	Lake Chad
Faya/Largeau	–	(2,803)	(2,654)	(*1,963*)	(3,410)	(4,423)	–	–
Bol Matafo	2,146	2,100	2,079	*1,853*	2,700	3,492	3,037	2,350
Bol Dune	(2,267)	–	–	–	–	3,716	(3,231)	
Ndjamena	1,882	1,900	1,788	*1,915*	2,670	2,814	2,535	
Bousso	1,610	1,750	1,711	*1,915*	2,550	2,320	2,053	
Moundou	1,590	1,598	1,612	*1,874*	2,420	2,259	1,999	
Bangui	1,227	1,358	1,383	*1,778*	1,450	1,559	1,380	
Brazzaville	1,071	1,300	1,420	*1,709*	1,360	1,292	1,154	
n	6	6	6	*6*	6	6	6	
Average	1,588	1,668	1,666	*1,846*	2,192	2,289	2,026	
	1.00	1.05	1.05	*1.16*	1.38	1.44	1.28	

but this species is cold-sensitive in the extra-tropical zone, entering a state of vegetative rest during the winter months from November to February in the mild-winter zone, and from October to March in the cold-winter zone. This species therefore does not grow during this period and, thus, cannot meaningfully serve to measure PET (Le Houérou 1969). PET measured on *Medicago sativa* (c.v. "Provence") was 10% higher than on Kikuyu grass (De Villèle 1965).

Such problems do not occur in the lowland inter-tropical zone where low temperatures are usually not a limiting factor for plant growth. The plant used was millet in Senegal—cultivars Sanio (120 days life cycle), Souna (90 days) and dwarf GAM (75 days)—and the experiments were carried out during the rainy season only (Dancette 1976). Water-use efficiency varied in the range 334–434 kg H_2O per kg DM above ground (Dancette 1978). In Chad, the Central African Republic and the Congo, two perennial grass swards were utilized in twin experiments: *Cynodon dactylon* and *Paspalum notatum*. The two species differed by less than 1% in their respective PET over a 3-year experimental period (Riou 1975). *Cynodon dactylon* and *Digitaria decumbens* were used in Senegal, yielding essentially identical values (see Tables T12, T13; Dancette 1976).

Comparing ETPp for the Sahel calculated using the Penman standard equation with other methods, we reach the following averages for 32 shared weather stations in the same database:

	A	B	
Cochemé and Franquin (1967)	Frère and Popov (1984)	FAO (1993) (Penman/Monteith)	Morel (1992)
1,786 mm	2,138	2,223	2,070
= 100	119.7	124.5	115.9

The difference between the values based on standard computation procedures for ETPp, i.e. Frère and Popov (1984) = A, and the Penman/Monteith procedures, FAO (1993) = B, using the same database, is as follows:

Region	B–A × 100	A, no. of shared weather stations
Northern Africa (1)[a]	+9.7	101
Southern Africa (2)	+15.3	65
Sahel (3)	+5.5	138
Eastern Africa (4)	+8.7	178
Overall Africa	+8.9	482

[a](1) Algeria, Egypt, Libya, Morocco, Tunisia
(2) Botswana, Lesotho, Namibia, South Africa, Swaziland
(3) Burkina Faso, Chad, Mali, Mauritania, Niger, Senegal, Sudan
(4) Ethiopia, Kenya, Somalia, Uganda.

The data above show that the Penman/Monteith ETo values are, on average, 8.9% higher than the Penman-standard values (ETPp), using the same database.

Computing PET from radiation values (Table T1) results in fairly correct evaluations, except for the Sahara and the Sahel. Here, the dry continental NE trade winds (Harmattan) brings a considerable amount of energy throughout the dry season, which cannot be accounted for using the global radiation values (Le Houérou 1972, 1984a, b).

The difference in the weighting expressed in the aerodynamic term of Penman's equation seems responsible for most of the discrepancies in PET evaluation reported by various authors using the same database as shown above (Cochemé and Franquin 1967; Riou 1975; Dancette 1976; Davy et al. 1976; Virmany et al. 1980; Frère and Popov 1984; Sivakumar et al. 1984, 1993; Morel 1992; FAO 1993).

The data given above also show that T-hornthwaite's calculation procedure yields evaluations far below all other commonly used equations, and 25–40% below experimental values for Africa. The same conclusion holds for Holdridge's method of evaluation. Furthermore, the data suggest that PET, either measured or calculated via various Penman-derived equations, is about 65% of class A pan evaporation on an annual basis, and about 80% of gross lake surface evaporation (Le Houérou and Norwine 1985).

As could be expected, annual PET is negatively correlated with annual rainfall; the fact emerges from the comparison of Figs. 1 and 11. By contrast, it is positively correlated with annual temperature, as shown by the comparison of Figs. 12 and 13, and Figs. 37–40. Annual PET is also positively correlated with annual global radiation (Fig. 11–13). The annual *P*/PET ratio is thus inversely correlated with rainfall, and positively correlated with temperature and radiation. Assessment of the empirical relationship between PETp and temperature by Riou (1980) and Le Houérou (1989a, b), using distinct parameters, showed a close correlation between PET and temperature. This was as already suggested by Thornthwaite and other climatologists such as Blaney and Criddle, Papadakis, and Turc. It could have been anticipated, since both items are an outcome of the radiative balance. However, this does not consider the aerodynamic term of Penman's equation, resulting in excessively low values in areas of strong persistent winds, such as the southern Sahara and the Sahel. The discrepancy in such zones may reach 20–40% of the final annual PETp values (Le Houérou 1999a).

The relationships between ETo and temperature are shown in Table A1. The highest ETo in Africa occurs in the S. Sahara and N. Sahel, with annual values reaching 3,000 mm with a mean annual temperatures of about 30°C; these are perhaps the highest values recorded on earth for both annual PET and annual temperature in a large ecological zone. The lowest values are found in the rainforest, and in coastal fog deserts such as the Namib or S.W. Morocco where ETo barely reaches 1,000 mm; on high mountains, the values can be as low as 700–800 mm. The relationship with elevation is shown in Fig. 44 for Ethiopia, as an example. A similar relation was found by Jätzold and Schmidt (1982) for Kenya (Fig. 49).

1.3.4 The P/PETp and P/ETo Ratios

As far as I am aware, the *P*/PET ratio was first proposed as a major bioclimatic classification attribute in a phytoecological study of the Hodna watershed basin in Algeria (25,000 km^2), surveyed from 1968 to 1973 and published in 1975 (Le Houérou et al. 1975). This was then used by UNESCO (1977/1979) in the World Distribution Map of Arid Regions (1:25,000,000), and subsequently by UNEP (1992) in the World Atlas of Desertification. This criterion replaces various empirical indices, such as Bagnouls and Gaussen's (1953b) xerothermic index and Emberger's (1930, 1955) pluviothermic quotient. These are both closely correlated with ETo, since ETo is tied to temperature, and since the *M–m* term of Emberger's index, i.e. the relative annual temperature range and an index of continentality, is correlated with the evaporative demand of the atmosphere (Le Houérou 1972).

The *P*/ETo ratio has the advantage of simplicity and accuracy. Moreover, it is strongly and positively correlated with the objective and concrete attribute of mean annual rainfall. For limited regions where ETo varies little, however, classification can be based on mean annual rainfall (Le Houérou 1969); this is evidently not feasible on a continental scale with large variations in ETo, such as in Africa. The geographic variation in PET is nevertheless much smaller than that of rainfall: the former has a range of 1,000 to 3,000 mm per year, whereas the latter exhibits extreme values of 0.5 to 4,000 mm per year, from absolute desert to deep rainforest—a range of 1–3 in the former and 1–8,000 in the latter.

The relationship between the pluvio-evapotranspiratory quotient (*P*/PET) and the length of the rainy season, i.e. the number of days when $P > 0.35$ PET, is shown in Fig. 18 for extra-tropical climates, Fig. 20 for tropical climates, and Fig. 22 for equatorial climates. This relationship is of the same order and nature as that between annual rainfall and the annual length of the rainy season within each group of climates shown in Figs. 17, 19 and 21.

The length and intensity of the rainy season may thus be conveniently represented by a simple, rational and synthetic single index, *P*/PET, a fact which I regard as a meaningful simplification and a progress towards clarification.

1.3.5 Temperature

Of equal importance as the role of water availability in the control of plant growth is that of temperature. Although some species can still have some physiological activity below a leaf temperature of −5°C (some firs and spruce from Siberia), most plants, particularly temperate species like wheat and barley, require mean temperatures above 10°C. Many tropical species start growing above 12–15°C (such as maize, cotton, soja bean, and sorghum), while some require a minimum of 18–20°C, such as cassava, oil palm, cocoa, clove, and pearl millet (Tables T25, T26, T29, T33).

Some species are more or less tolerant to low temperatures and frost. Others are killed around 0 to −2°C.

Figure 12 shows that, globally, the highest temperatures in Africa occur in the S. Sahara and in the N. Sahel, with annual mean values locally reaching 30°C in the N. Sahel, and on the Red Sea shores and some topographic depressions such as the Dalol and Assalé (−175 and −165 m respectively) in Eritrea and Djibouti (Le Houérou 1984a, 2003, 2004d), and the Qattara and Fayum in N.W. Egypt (−134 and −40 m respectively; Le Houérou 2004e). In Africa, the highest mean annual temperatures are recorded along the thermal equator at 16°N, with mean annual temperatures around 30°C, the highest on the planet for a large ecological region (Le Houérou and Popov 1981; Le Houérou 1984a, 1989a).

Low temperatures may be a limiting factor to plant growth in the extra-tropical zones, as shown in Figs. 28, 31, 33, 41, 43, 48 and 51, but this is also the case in the midland and highlands of the inter-tropical zone, as shown in Tables A10, T18, T25, T29, T33, and Figs. 28, 31, 33, 43, 48, 51. The overall relationship between temperature, latitude and altitude is shown in Section 1.2.4.

Cold-sensitive crop species

Among the most cold-sensitive crops are the following:

Clove, *Eugenia caryophyllus*	Cashew, *Anacardium occidentale*
Hevea, *Hevea brasiliensis*	Cassava, *Manihot utilissima*
Elaeis, *Elaeis guineensis*	Cola nut, *Cola acuminata, C. nitida*
Black pepper, *Piper nigrum*	Rice, *Oryza sativa, O. barthii*
Muscat, *Myristica fragrans*	Pineapple, *Ananas comosus*
Vanilla, *Vanilla* spp. (c.v. *fragrans*)	Robusta coffee, *Coffea canephora*
Jute, *Corchorus capsularis (C. olitorius)*	Maize, *Zea mays*
Raphia, *Raphia* spp.	Cardamom, *Eletteria cardamomum*
Millet, *Pennisetum typhoides*	Mango, *Mangifera indica*
Taro, *Colocasia* spp.	Breadfruit, *Allocarpus incisa*
Yam, *Dioscorea* spp.	Sugarcane, *Saccharum officinarum*
Cocoa, *Theobroma cacao*	Coconut, *Cocos nucifera*
Avocado, *Persea americana*	Banana, *Musa paradisiaca*
Arrow root, *Canna edulis*	Pawpaw, *Carica papaya*
Ginger, *Zingiber officinale*	Shea butter, *Butyrospemum parkii* (≈*Vitellaria paradoxa*)

Crop species somewhat tolerant to cold

Guava, *Psidium guyava*	Sunflower, *Helianthus annuus*
Tea, *Camellia sinensis*	Qat, *Catha edulis*
Patata, *Solanum tuberosum*	Citruses, *Citrus romain* spp.
Arabica coffee, *Coffea arabica*	Castor bean, *Ricinus communis*
Tobacco, *Nicotiana tabacum*	Carob, *Ceratonia siliqua*
Sisal, *Agave sisalana*	Safflower, *Carthamus tinctorius*
Ensete, *Ensete ventricosum*	Olive, *Olea europaea*
Cactus, *Opuntia ficus-indica*	Kaki, *Diospyros kaki*
Wattle, *Acacia melanoxylon*	Nugh, *Guizotia edulis*
Teff, *Eragrostis tef*	Galla potato, *Coleus edulis*
Sesame, *Sesamum indicum*	Date palm, *Phoenix dactylifera*

Frost-tolerant crop species

Buckwheat, *Fagopyrum esculentum, F. tataricum*	
Pyrethrum, *Chrysanthemum cinerariifolium*	Cherry, *Prunus cerasifera*
Rye, *Secale cereale*	Almond, *Prunus agmydalus*
Peach, *Prunus persica*	Walnut, *Juglans regia*
Apricot, *Prunnus armeniaca*	Pistachio, *Pistacia vera*
Apple, *Malus communis*	Loquat, *Eriobotrya japonica*
Pear, *Pirus* spp.	Pomegranate, *Punica granatum*
Plum, *Prunus domestica*	Grape, *Vitis vinifera*
Fig, *Ficus carica*	

1.3.6 Relationship Between Mean Annual Temperature and Mean Annual ETo in 21 Countries in Africa

In Table T14, the relationships between mean annual temperature and mean annual ETo are compared among 21 countries in Africa, based on data from 503 weather stations (source: Table A1).

1.3.7 Other Significant Weather Parameters

1.3.7.1 Vapour Pressure, Relative Humidity, Saturation Deficit

Vapour pressure (VP) increases from the Sahara to the rainforest. Considering the annual number of months that VP is below 10 hPa (10 hectoPascals = millibars), we find the values given in Table T15.

Table T14 Relationship between temperature and ETo in various areas of Africa

Country	No. of weather stations	ETo/*T*	Standard error
Algeria	23	80.2	1.6
Botswana	8	76.6	1.4
Burkina Faso	7	72.3	2.5
Cabo Verde	3	65.8	2.1
Chad	12	71.9	3.3
Egypt	27	81.8	1.8
Ethiopia	94	76.2	0.9
Gabon	9	46.2	0.5
Kenya	40	77.2	1.5
Libya	17	84.8	3.7
Mali	18	88.6	4.2
Mauritania	13	83.4	2.6
Morocco	13	76.5	4.6
Namibia	6	81.0	6.1
Niger	11	95.6	3.1
Senegal	14	69.6	2.1
Somalia	24	75.7	3.3
South Africa	42	86.5	2.2
Sudan	63	79.1	1.3
Tanzania	40	67.3	1.5
Tunisia	19	72.8	1.8
Total/mean	503	1,609/76.6	52.5/2.5

Table T15 Zonal distrbution of the annual number of months when VP > 10 hPa vapour pressure in various ecological zones in W. Africa

Ecological zones	No. of months	*P*/ETo (%)
Southern Sahara	7–10	0–5
Saharo-Sahelian zone	5–8	5–30
Sahelian	4–6	30–50
Sudano-Sahelian	3–5	50–75
N. Sudanian	2–4	75–100
S. Sudanian	0–3	100–120
Guinean	0–2	> 120

Relative humidity (RH) and *saturation deficit* (SD) are, by and large, well correlated with mean annual and mean seasonal rainfall. RH increases from an annual mean of 20–30% in the S. Sahara and N. Sahel to 80–85% in the rainforest, whereas SD exhibits the reverse pattern (24 hPa in the S. Sahara to 4 hPa in the rainforest). The mean annual values of vapour pressure (hPa), relative humidity (%), saturation deficit (hPa), and the number of months per year when VP < 10 hPa are shown in Table T16.

Table T16 warrants some comments. The driest areas in terms of air moisture and saturation deficit (SD) are the S. Sahara and N. Sahel, with mean annual RH of

Table T16 Data on vapour pressure (VP), relative humidity (RH) and saturation deficit (SD) in various parts of Africa (compiled from Frère and Popov's 1984 database; *n* number, *x* mean, *M* maximum, *m* minimum)

Area	W. stations *n*	VP (hPa)			RH (%)			SD (hPa)			Months per year < 10 hPa *n*		
		M	*x*	*m*	*M*	*x*	*m*	*M*	*x*	*m*	*M*	*x*	*m*
Northern Sahara	26	14	10	5	57	39	21	23	16	11	12	7	4
Nile Valley & Delta	6	18	17	15	78	71	62	9	7	5	1	0.1	0
Southern Sahara	23	13	10	8	40	30	22	32	24	14	8	7	5
Oceanic Sahara	8	18	17	15	83	69	52	17	8	4	0	0	0
S. African deserts	5	20	14	9	83	70	41	13	6	4	6	2	0
E. African deserts	4	30	26	22	74	64	21	19	15	11	0	0	0
Sahelian ecol. zone	36	18	15	11	51	38	30	33	24	17	8	5	2
Sudanian ecol. zone	33	28	19	15	69	52	42	23	17	11	5	2	0
Guinean ecol. zone	21	30	26	23	88	78	67	13	7	4	0	0	0
E. African arid & semi-arid zone (Ethiopia, Somalia, Kenya, Tanzania)	37	30	21	11	86	62	36	26	12	5	0	0	0
S.E. African arid & semi-arid zone (Zimbabwe, Mozambique, Zambia)	20	24	19	13	76	63	41	18	10	6	0	0	0
Southern African arid & semi-arid zone (Botswana, Namibia, South Africa)	21	16	11	8	63	51	36	16	11	7	8	5	0
N. African arid & semi-arid zone (Maghrib countries)	48	18	14	9	81	66	37	16	7	4	8	3	0
Total	288												

30 and 38%, and SD of 20 and 24 hPa respectively (cf. Tables A1, A5, A6). This situation is also reflected in the ETo map of Fig. 13, and the temperature maps in Figs. 12, 48, 49. Together, these show two areas of major continental aridity: one centred on the borders of Mali, Mauritania, Algeria and Niger and another centred on the Mid-Nile Valley at the border of Chad, Egypt and the Sudan. Among arid and semi-arid zones, the Sahel is by far the driest in terms of air moisture and atmospheric water demand. As a matter of fact, air humidity is very low; it drops below 20% every afternoon from November to January, and below 15% from February to May; it falls below measurable levels on many afternoons from March to May (Le Houérou 1989b). The zonal annual mean RH is 38% with a high of 51% recorded at one station, and a low of 30% at another two stations. SD reaches an annual zonal mean of 24 hPa, much higher than in the N. Sahara.

These facts bear very important ecological and agronomic consequences. For example, cacti, saltbushes and wattles (*Opuntia* spp., *Atriplex* spp. and *Acacia* spp., sect. Phyllodinae) cannot be grown in the Sahel because of the very high SD and low RH, whatever the mean annual rainfall may be, whereas they can be grown in all other African arid and semi-arid zones (N. Africa, E. Africa, S.E. Africa and S. Africa). In these areas, however, RH is generally above 60% and the SD below 12 hPa, i.e. almost double the Sahel RH value and below half that of the Sahel SD. In the coastal Sahel on a few km-wide strip along the Atlantic shore, this is not the case; this narrow belt (≈30–50 km) has an RH value of ca. 75% and an SD of ca. 8 hPa (St Louis, Dakar, Nouakchott, etc.), and cacti, wattles and saltbushes can be grown, as in E. Africa, S. Africa and N. Africa under similar RHs and SDs. The same trends occur in the Insulo-Atlantic Islands: Canary and Cape Verde, with high RH and low SD. Also, the data for the Sahel biozone reflect those recorded for the Sudanian ecological zone where RH averages only 52%, which is still lower than in most arid zones; SD reaches 17 hPa, which is much higher than in the N. Saharan, S. African and E. African deserts. As a result, neither cacti, saltbushes nor wattles can be grown in the Sudan ecological zone, in contrast to the East, South and North African semi-arid zones (Le Houérou 2004e).

Another fact that emerges from Table T16 is the striking homogeneity of the Sahelian and Sudanian ecological zones, as opposed to the situation in N., S. and E. Africa, where the range of values is much broader for VP, RH, SD, and also for the number of months with VP below 10 hPa. In the Sahelian and Sudanian ecozones, the range of RH and SD is within 100–200% of the mean; it reaches 300% and up to 500% in S., E. and N. Africa.

Table T16 furthermore shows a large difference between the Sudanian ecological zone and its counterpart in East and S.E. Africa, such as the Miombo woodland zone (e.g. SD varying by factors of 1 to 3, up to 1 to 5, vs. only ca. 30% in the Sudanian zone). The comparison between the Kalahari and the Sahel, which bear many similarities in terms of climate, soil and vegetation, shows that the Sahelian climate is much harsher with a mean RH of 38 vs. 51%, and an SD of 24 vs. 11 hPa. There are also some other differences between the Sahel and the Kalahari (which, in no way, is a true desert):

(a) the Kalahari, being at about 1,000 m of elevation, enjoys milder temperatures than does the Sahel at the same latitudes: mean annual temperatures are around 20°C, vs. 28°C in the Sahel (Figs. 12, 29, 31).
(b) although the rainfall distribution pattern is similar (monomodal summer rains of the tropical type), the rainy season is clearly longer in the Kalahari, i.e. about 6 months, vs. 2–4 months in the Sahel (Figs. 24c, d and 26d).

1.3.8 Soil Distribution Climatic Aridity and Edaphic Aridity, Rain-Use Efficiency (RUE)

Soil characteristics and properties exert an overriding influence on the local impact of climate, particularly (but not only) with respect to water budget (Table T17, Fig. 54), by either buffering or exacerbating the effects of weather conditions on plants and animals. Rain water is most unevenly distributed in the various sites of the landscape of a given area, depending on soil permeability and depth, slope, aspect, topographic situation (runoff vs. runin) and vegetation type, so that it is appropriate to differentiate between climatic aridity and edaphic aridity (Floret and Pontanier 1982, 1984). I have thus shown that the amount of soil water available on an annual basis may vary by an inter-site mean factor of more than 1–10, even in a climatically and geologically homogenous region with a smooth topography such as the Sologne natural region of central France, a large late Cainozoic alluvial fan of the mid-Loire River (5,000 km^2, Le Houérou 1962b).

On the other hand, soil taxonomic entities are, by and large, distributed over the African continent in a way highly reminiscent of the distribution of agro-bioclimates and of vegetation (World Soil Map 1:5,000,000: Africa, FAO/UNESCO 1976). This is not surprising, since soil genetics depend, to a large extent, on climatic factors and vegetation types, in addition to geological structure and parent material. A study by Higgins et al. (1984) showed that soil limitations in Africa were as follows (in million ha and percent of the total): no limitations 535 (19); serious fertility limitations 419 (15); heavy clay 99 (3); salinity 64 (2); impeded drainage 153 (5); shallow 376 (13); coarse texture 568 (20); desert 459 (16); various 205 (7).

Soil distribution by agro-meteorological zone in Africa is shown in Table A12. A good example of the paramount importance of soil condition for ecological and agronomic potential productivity is given by the case of the rain-fed commercial olive-tree cultivation in the arid zones of central and southern Tunisia and of western Libya (Tripolitania). Commercial rain-fed farming of olive trees covers about 1×10^6 ha (25 million trees) in the arid zone of Tunisia; there are, in addition, some 0.5×10^6 ha of subsistence runoff farming with another 15 million trees. In western Libya there are, similarly, about 150,000 ha (3.5 million trees) under rain-fed commercial farming. Other fruit trees are cultivated under the same conditions—almond, apricot, peach, fig, grapes and rain-fed date-palm trees—but these do not represent more than 20% of the overall area of arid zone arboriculture in Tunisia and Libya: 80% are olive groves. The climate in these rain-fed olive-farming areas is typically arid: mean annual rainfall varies between 150 and 350 mm, most typically 200–250 mm (Sfax, Kairouan, Sidi Bouzid, Sousse, Enfida, Djerba, Zarzis, Tripoli, Zwara, Azizia, Garian, Tarhuna); annual ETo may vary between 1,200 and 1,500 mm, and the pluvio-evapotranspirational ratio is thus between 12 and 20%. Winter temperatures are mild to temperate, with a mean daily minimum temperature of the coldest month between 3 and 8°C.

To my knowledge, these conditions of rain-fed commercial cultivation of fruit trees in arid lands is unique worldwide. It is therefore of interest to analyse why this type of arid land fruit-tree rain-fed farming is agro-climatically feasible (Le Houérou 1959b, 1970, 1992a; Floret et al. 1987).

In the area concerned, rain-fed arboriculture is not successful in all kinds of soils, however deep and chemically fertile. It invariably fails on shallow soils, and on loam and clay soils (unless there is an additional water resource from runoff).

Dry farming arboriculture is successful only on deep coarse sandy soils and, to some extent, on fine sandy soils with additional runoff. Trees are planted 20–25 m apart (i.e. at a density of 17–25 per ha), and their canopy covers 10–12% of the ground surface. The soil surface is kept soft and permanently free of weeds by 6–8 annual light tillings. About 50% of the annual 200 mm of rain infiltrates into the soil, and another 50% is intercepted by the canopy or directly evaporated by the soil surface. Runoff is virtually nil.

All soil volume down to a 200 cm depth is occupied by olive-tree roots and rootlets, i.e. 25 × 25 × 2 m = 1,250 m^3 per tree (Yankovitch and Berthelot 1947; Le Houérou 1959a, b). Rootlets are particularly abundant in the first 20 cm of top soil but tap roots may go down far beyond a 2 m depth. The soil moisture front, following the main winter rains, reaches 100–120 cm but, in rainy years, it may extend to depths of 150–200 cm (Floret and Pontanier 1982). In such coarse sands, 1 mm of rain moistens 1 cm of soil depth at field capacity ($\Psi = -0.066$ MPa), and the water content at permanent wilting point ($\Psi = -1.6$ MPa) is | 0.25 mm cm^{-1}; the amount of available water is thus 0.75 mm cm^{-1} (vs. 0.85 in fine sand, 1.00 in silt, and 1.70 in loam). The amount of water retained beyond a Ψ value of –1.6 MPa is 0.25 mm cm^{-1} in coarse sand, the corresponding values being 0.60 in silt and 1 in loam (Table T17, Fig. 54).

It follows that in areas characterized by light infrequent rains, as in most arid zones, the amount of soil water available on an annual basis is much higher on coarse sandy soils than on silty and loamy soils. This is shown in Table T17 for the hypothetical case of a shower of 25 mm infiltrated rains, isolated in time by over 7–10 days.

In fact, Floret and Pontanier (1982) calculated that a deep sandy soil, moistened to a depth of 100 cm in S. Tunisia, contains (on an annual basis) 50 to 60 mm more water available than does a silty soil under the same conditions, i.e. some 30% of *actual* mean annual evapotranspiration. Furthermore, soil water remains available 2 months longer in deep sandy soils than in silty soils, i.e. in this specific case, 5–6 months vs. 3–4. The same authors found that deep-rooted perennials would be exposed to an absolute edaphic drought ($\Psi < -1.6$ MPa) for an average 4.5 months per year on deep coarse sandy soils, vs. 7.5 months on silty soils (Floret and Pontanier 1982, pp. 142–145).

There is thus no "mystery" in the existence of such thriving olive groves in central and southern Tunisia and western Libya on deep sandy soil, since the canopy cover is

Table T17 Easily retrievable water from soil

Texture	A: infiltrated and stocked (mm)	B: adsorbed ($\Psi < -1.6$ MPa) (mm)	A–B: retrievable (mm)	Number of days of PET allowed[a]
Coarse sand	25	5	20	5
Silt	25	10	15	3
Loam	25	15	10	2.5
Clay	25	2.0	5	1.25

[a] At 4 mm day^{-1} ETo

10% and transpires 100 mm of infiltrated rain on average. One may thus predict an 80% canopy cover would transpire some 800 mm year $^{-1}$. This is actually what happens under irrigation, as optimum water application to olive trees is some 60% of PET, i.e. 720 to 900 mm, including rains (Le Houérou 1959b; Damagnez and De Villèle 1961; De Villèle 1965). Detailed studies have revealed that rain-fed arid zone olive crops yield an average of 40–60 kg per tree per annum (800–1,200 kg ha^{-1}≈180–260 kg oil ha^{-1}) on deep coarse sands in central and southern Tunisia, under a mean annual rainfall of 200–250 mm (Le Houérou 1959a, b). On sandy silts, however, average yield decreases to 20–30 kg tree^{-1}, and even further to 10–20 kg on silt and below 10 kg on loam, all other conditions remaining identical. Thus, olive rain-fed farming has been (and still is) economically feasible and commercially rewarding in deep coarse sands, marginally feasible on a subsistence farming basis in sandy silt, and unfeasible in economic terms on silt and loam—without an additional water resource such as the use of runoff, wadi diversion or classical irrigation.

Moreover, production is much more regular and reliable on sandy soils than on silt and loam. The coefficient of variation (CV) of annual yields was 40–75% on sandy soils vs. 80–120% on silt and 150% on loam, for a uniform rainfall CV of 40–50%. The ratio between the rain and production variabilities was thus 0.8–1.5 on sandy soils, 1.6–1.9 on sandy silt, 2.0–3.0 on silt, and 3–4 on loam (Le Houérou et al. 1988; Le Houérou 1992a). The same remarks apply to many perennial crops, forest trees and agro-forestry.

Similar findings have been reported by various authors investigating arid zone rangeland productivity. Range productivity was found to be higher and more regular on deep sandy soils with rain-use efficiency (RUE) factors of 5–8 kg DM ha^{-1} year^{-1} mm^{-1} vs. 2–3 kg on silty, and 1–2 kg on loamy and on shallow soils (Le Houérou 1969, 1984b, 1988b; Le Houérou and Hoste 1977; Floret and Pontanier 1982, 1984; Le Houérou et al. 1988). On a worldwide arid zone basis, the production to rain variability ratio (RPVR = CVR/CVP) was found to be 1.2–1.5 in rangelands on sandy soils, 1.5–2.0 on silty soils, and 2.0–3.0 on loamy soils (Le Houérou 1988b, 1999b; Le Houérou et al. 1988; Guevara et al. 1997).

Many more examples of the local influence of soil on the impact of climatic parameters on plants could be cited. For example, cassava, a tropical crop needing 180–300 days of growing season characteristic of humid tropical lowlands, is successfully grown in the southern Sahel and northern Sudanian ecological zones under a mean annual rainfall as low as 600 mm with a *P*/ETo ratio of 30% and 100–120 days of rainy season, as long as the soil is deep and sandy (at Segou and Markala in central Mali, for instance; Le Houérou 1989a, b).

The distribution of soil taxonomic categories is shown in Table A12 for the continent as a whole (Le Houérou and Popov 1981, compiled from Higgins et al. 1979, World Soil Resources Report 48, vol. 1, pp. 59–61). It should be noted, however, that soil genetic classifications are not necessarily relevant in terms of the evaluation of agronomic or ecological potential, since a major ecological factor for plants is hardly accounted for in genetic classifications (which is one of their major weaknesses, in ecologists' and agronomists' views), i.e. the soil water budget.

Table T18 shows the global radiation (kcal cm^{-2} year^{-1}) received at the soil surface at 36°N, as a function of slope and aspect (Le Houérou 1972). The corresponding data for potential evapotranspiration are given in Table T19.

These data show that, at 36°N (Tangiers, Oran, Algiers, Tunis), global radiation and ETo may differ by factors of almost 1 to 3, depending on slope and aspect (131,150/44,000 = 2.98; 1,115/374 = 2.98). The *P*/ETo ratio (hence, climatic aridity) may therefore vary by the same proportions, this being essentially the maximum slope/aspect effect one may encounter in Africa. These facts play an overriding role in extra-tropical Africa in terms of development planning, such as in the selection of species for afforestation, pasture development or crop species/cultivar selection.

1.3.9 Impact of Agro-hydraulic Works

Some agro-hydraulic works aimed at improving the production potential of the land have exerted a catastrophic impact on the environment, due to careless management. This is particularly the case of the Senegal River Valley that, in a lapse of 15 years, has undergone a proliferation of hydrophilous vegetation and, as a result, of freshwater gastropods, vectors of various parasites for both livestock and humans (Handschumacher et al. 1992; Duvail et al. 1998; Le Houérou 1999a). The lower Senegal valley has thus become the main hotspot of vesicular schistosomiasis in Africa, not to mention other diseases previously very rare or unknown to the area.

Table T18 Effect of aspect and slope on global radiation at the soil surface at 36°N

Aspect	Slope (°)				
	5	15	25	35	45
S	117,400	125,950	*130,150*	130,150	130,150
SW/SE	115,600	121,850	125,300	126,200	123,850
W/E	111,500	110,600	108,600	105,600	101,300
NW/NE	107,100	96,850	85,850	74,750	64,500
N	105,100	90,700	73,900	57,700	*44,000*

Table T19 Effect of aspect and slope on potential evapotranspiration at 36°N (ETo, mm year^{-1}≈0.0085 R_g, kcal cm^{-2} year^{-1}; Le Houérou 1972)

Aspect	Slope (°)				
	5	15	25	35	45
S	998	1,027	*1,115*	1,111	1,106
SW/SE	983	1,036	1,066	1,072	1,053
W/E	948	940	923	898	861
NW/NE	910	823	730	35	548
N	893	770	628	490	*374*

1.3.10 Land-Use Patterns, Agricultural Systems and Crop Distribution

1.3.10.1 General

Land-use patterns depend, to a large extent, on aridity and temperature but not only on these natural conditions—they also are influenced, at least to some extent, by socio-cultural traditions, demography and density of population, i.e. by the "pressure on the land". The impact of socio-cultural traditions and demography is particularly clear in semi-arid and sub-humid zones, which may locally be linked, or not, with farming or focus only on pastoralism. Even in humid and hyper-humid zones, traditional systems of clearing cultivation and abandonment, i.e. shifting cultivation, may or may not have developed over the centuries. Despite these reservations, it is fair to say that, by and large, land-use patterns reflect the following impacts tied to agro-bioclimatic factors.

1.3.10.2 The Hyper-arid Agro-bioclimatic Zone

The hyper-arid zone occupies some 9.2×10^6 km^2, i.e. 30.6% of the continent (Tables T23–26, T28, T31, and Figs. 14, 32). The desert or hyper-arid zones are characterized by spatially shifting pastoralism, either transhumance or nomadism, and the absence of rain-fed cultivation, due to the vagaries of rainfall. Nomadism refers to random movements within the desert governed only by rainfall and the presence of green grazing and water. Transhumance, conversely, refers to regular pendulum-like movements governed by seasons, such as from plain to mountain and from semi-arid zones to desert. There are, however, many kinds of situations in deserts. The Dankali desert of Ethiopia, Eritrea and Djibouti, for instance, is characterized by mixed pastoralism of cattle, small stock and camels. Cattle are unusual in deserts but in this particular situation, cattle husbandry results from the presence of permanent and temporary rivers originating in the nearby highlands of Ethiopia. These produce good perennial grazing in the water-spreading areas of their lower reaches. These rivers come from the humid and sub-humid Ethiopian highlands 1,500–2,500 m higher up and 10–200 km to the west. The same situation occurs in the coastal and sub-coastal deserts of Djibouti and Somaliland, likewise resulting from temporary rivers coming from the semi-arid Harar and Somali plateaus 800–2,400 m higher up. An rather similar situation exists in the Namib desert where the 50–150 km wide rainless coastal plain is crossed by a number of temporary rivers, born on the Namib escarpment and constituting as many linear E–W natural oases utilized by both livestock and wildlife, and where a lion can meet (and eat) a seal, an otherwise not so common opportunity!

1.3.10.3 The Arid Agro-bioclimatic Zone

The arid zone covers some 3.6×10^6 km^2, i.e. 12% of the continent (Tables A1, A16–A18, and Figs. 14, 32). The arid zone is defined as having no commercial rainfed farming (with the worldwide exception mentioned in Sect. 1.3.7). Arid zones are essentially used only for nomadic or transhumant pastoralism and ranching in Namibia and South Africa. Increasingly, however, pastoralism is complemented by subsistence farming of staple cereals, particularly pearl millet in the tropics and barley in the extra-tropical zone, and also some retreat flooding cultivation of sorghum and, occasionally, cotton or vegetables such as watermelon.

Agricultural/livestock production systems are numerous and complex. There are many levels varying between purely pastoral systems and mixed pastoral-farming systems, long-range and short-range transhumance, and also some settled animal husbandry.

1.3.10.4 The Semi-arid Agro-bioclimatic Zone

The semi-arid zones occupy almost 3×10^6 km^2, i.e. 10% of the continent (Table A16 and Figs. 14, 32). This is an area of competition and conflict between pastoralism and farming. Commercial farming is often feasible, in particular for peanut, pearl millet and sorghum in the tropics, and wheat, barley, grapes and fruit-tree crops in the extra-tropical zone. The semi-arid zone also includes commercial ranching, such as in Kenya and southern Africa (Botswana, Namibia, South Africa), and occasionally game ranching. Range reseeding is technically feasible, contrary to the arid zone, but rather uncommon because it is economically marginal. Other industrial crops of moderate extent in the tropics are sesame and safflower (Sudan) and cashew nuts; subsistence crops are pigeon pea, sorghum, millet, cowpea and Guinea sorrel (Karkadeh).

Afforestation is limited by low productivity of 2–5 m^3 ha^{-1} year^{-1} of timber. Contrary to most of the arid zone, the semi-arid regions are usually densely inhabited; pastoralism therefore tends to be increasingly excluded as natural vegetation is progressively cleared for farming, with the exception of bare rock outcrops and hardpans (iron pans in the tropics and calcrete in the extra-tropical zones). This situation often generates acute conflicts between farmers and pastoralists. Rural population densities of 75–100 inhabitants per km^2 are not unusual, as in northern Africa, and parts of West and East Africa, such as in the "Peanut Basin" of Senegal. In turn, such relatively high densities raise very acute socio-economic and land-use problems resulting from overcultivation, erosion, floodings, aeolian deposits, and loss of fertility and productivity, as the traditional fallow is reduced or even cancelled due to excessive pressure on the land. The climatic requirements of semi-arid zone crops are shown at the top of Table A19. In general, pastoralism tends to be increasingly replaced by agro-pastoralism, in which the fodder production system is based mainly on farming by-products and crop residues, complemented by some grazing on non-arable land during the rainy season (Le Houérou 1989b).

1.3.10.5 The Sub-humid Agro-bioclimatic Zone

This zone covers an area of 2.9×10^6 km^2, i.e. 9.5% of the continent (Tables A1, A14, A16, and Figs. 14, 32). This is usually the most diversified ecological zone in Africa, with sometimes very high population densities of 100–500 inhabitants per km^2, such as in parts of the Sudanian zone of northern Nigeria, northern Africa, and the East African Highlands of Eritrea, Ethiopia, Kenya, Tanzania, Rwanda, Burundi and eastern Zaire. Animal husbandry is often hindered in the lowlands and lower midlands by the presence of tsetse flies and trypanosomiasis (Figs. 34, 35). For this reason, trypano-tolerant taurine cattle are preferred to the zebu cattle that, in turn, are better adapted to arid and semi-arid zones, and to heat and tick-borne diseases.

Fodder crops and timber production are feasible, as well as a number of staple and industrial crops (Tables A19, T24, T30, T34). Long-cycle sorghum cultivars, maize, cassava, cowpea, tobacco, soybean, mango, cashew nuts, cotton and groundnuts are the usual main cash crops in the lowland tropics; tobacco and sunflower are found in the midlands; wheat, grapes and olive grow in the extra-tropics, and wheat and barley in the tropical highlands. Typical subsistence crops are sorghum, maize, banana, and rain-fed upland rice in flooding areas. Fodder crops and sown pastures include Guinea grass (*Panicum maximum*), elephant grass (*Pennisetum purpureum*), Bahia grass (*Paspalum notatum*), Para grass (*Brachiaria mutica*), Pangola grass (*Digitaria decumbens*), *Pueraria, Desmodium, Centrosema, Calopogonium* and oxley stylo (*Stylosanthes guyanensis*). Timber production includes several *Eucalyptus* species, *Gmelina, Teak, Grevillea*, and various exotic tropical species of pine in the mid and lower highlands. Timber yields may be as high as 10–20 m^3 ha^{-1} year^{-1}.

1.3.10.6 The Humid Agro-bioclimatic Zone

The humid agro-bioclimatic zone occupies some 3.6×10^6 km^2, i.e. 12% of the continent. This is an area of either densely cultivated cleared forest or derived savanna. A number of crops are developed that hardly exist in the sub-humid zone, such as yam, pineapple, rain-fed rice, sugarcane and cassava. Timber production has high yields of 20–40 m^3 ha^{-1} year^{-1}; animal production is restricted due to generalized trypanosomiasis infestation; river blindness is not uncommon along the drainage network.

1.3.10.7 The Hyper-humid Agro-bioclimatic Zone

This zone occupies an area of 7.8×10^6 km^2 in Africa, i.e. 25% of the continent, only second in size to the hyper-arid zone. This is the area of rainforest with 1,500–4,000 mm of average annual rainfall and 2 months, or less, of dry season. Some crops are restricted to this zone: Para rubber, oil palm, clove, raphia, cocoa, as shown at the bottom of Table A19. The hyper-humid zone is often sparsely inhabited, e.g. Cameroon, Gabon, Zaire, Congo, Central African Republic, southern

Sudan and northern Uganda. This is where most of the African agricultural development potential rests under intermediate to high inputs (Higgins et al. 1984).

1.3.11 Rangelands, Pasture Production and Yields

Range production is low and most irregular in the hyper-arid zone, and always spatially limited to depressions, river valleys, water-spreading zones, and areas subjected to infrequent showers.

In the arid rangelands, production is still low and irregular; as explained above, production is higher and less irregular on deep sandy soils as long as the sand is bound and "clothed" with a perennial cover of vegetation.

Productivity is higher in the extra-tropics and in East Africa, compared to the Sahel (Le Houérou and Hoste 1977; Le Houérou 1982a, 1984b). Rain-use efficiency (RUE) averages 3 kg DM ha^{-1} $year^{-1}$ mm^{-1} in northern Africa, 2.7 in the Sahel, and 4.0 in East Africa. The seasonality of rainfall plays an important role in this respect (Le Houérou 2006c). Bimodal rainfall patterns, as in N. Africa and E. Africa, favour the development of perennial grazing species, particularly grasses, whereas monomodal patterns, as in the Sahel, tend to promote annual grasses. Furthermore, bimodal rains generate two growing seasons in North Africa and East Africa, vs. one single, very short growing season in the Sahel (30–90 days).

In southern Africa, the situation is again more favourable, due to the fact that the rainy season is longer for a given mean and elevation, which lowers temperature and ETo. The arid grazing lands of the Kalahari and of Namibia are thus covered with perennial grasses and are more productive than their counterparts of the Sahel, although developed on similar sandy soils.

The semi-arid rangelands are made of more or less open savanna in the tropics, dominated by *Acacia* spp., *Combretaceae*, and a mixture of annual and perennial grasses (Le Houérou 1977). Productivity and RUE average 4 kg DM ha^{-1} $year^{-1}$ mm^{-1} in the Sudanian ecological zone, and 5–6 in East Africa (Lamprey and Yusuf 1981; Braun 1982; Lamprey 1983).

Contrary to the arid zone, the semi-arid zone is suitable for pasture reseeding but the number of successful species is limited to a few hardy plants (*Cenchrus ciliaris, Urochloa mosambicencis, Andropogon gayanus, Macroptilium atropurpureum, M. lathyroides, Stylosanthes hamata*; Le Houérou 1989b).

In the sub-humid and humid tropics, grazing is impaired by trypanosomiasis. Nevertheless, pasture development may be successfully achieved via a number of high-productivity perennial grasses and legumes: *Panicum maximum, Brachiaria* spp., *Digitaria decumbens, Pennisetum purpureum, Stylosanthes guyanensis*, sometimes in conjunction with fodder shrubs such as *Leucaena leucocephala* and *Glyciridia sepium*. Such "tame pastures" may be very productive (10,000–20,000 kg DM ha^{-1} $year^{-1}$ with RUE factors of 8–10, i.e. a stocking rate of 3–5 tropical livestock units (TLU) ha^{-1} $year^{-1}$, corresponding to 750–1,250 kg Lwt (live weight) per hectare per year.

1.3.12 Native Flora

The African flora includes some 68,500 vascular plant species with ca. 41,600 endemics (61%; Le Houérou 1991b, 1997a, 2005b; Lebrun and Stork 2003). This flora is most unevenly distributed, as shown in Table T20.

This flora includes some 25 common species of native cultivated plants (yams, taro, sorghum, oil palm, teff, ensete, nugh, wheat, barley, olive, grape, castor bean, qat, Arabica coffee, Robusta coffee, kapok, coconut, shea butter, date palm, clove, beet, fig, roselle, floating rice, bambara nut, and a number of minor local crops). African species make up some 72% of the gene pool of world tropical pasture grasses (elephant grass, Guinea grass, buffel grass, Rhodes grass, golden foxtail, Kikuyu grass, Bermuda grass, etc.), and some 27% of the world tropical fodder legume gene pool (*Canavalia, Clitoria, Desmanthus, Hedysarum, Lotus, Macrotyloma, Medicago, Melilotus, Rhynchosia, Trifolium, Vicia, Vigna*). There are, in addition, some 400 common browse species (Le Houérou 1983, 1991b).

1.3.13 Vegetation

A sketch of the vegetation types is given in Fig. 45. The distribution of some common and dominant species of plants and wildlife in West Africa is shown in Tables A14, A15.

The hyper-arid zone is characterized by "contracted" vegetation, clustered along the drainage network, and bare pediments and interfluves (Kilian 1925; Monod 1954; Le Houérou 1959a, b, 2006a).

The arid zone includes steppic formations in the extra-tropical regions with either perennial grasses or dwarf shrubs, e.g. the steppes of northern Africa or the Karroo formation of South Africa. There are some inter-tropical deviations, such as the *Duospermum-Vernonia* dwarf shrub steppe of N. Kenya, but these are rather the exceptions to the rule. In inter-tropical Africa, the arid zone vegetation is made up

Table T20 African flora: number of vascular species (Le Houérou 1988a, 1997a)

Region	Number	Region	Number
The Sahara	2,800	West Africa	7,500
The Sahel	1,500	S. Africa	24,000 (19,000 endemics)
East Africa	10,000	Central Africa	12,000
S.E. Africa	6,500	N. Africa	7,200 (3,000 endemics)
The Horn	8,000	Madagascar	10,000 (8,000 endemics)
(Ethiopia, Somalia Djibouti)		Offshore islands	13,000 (2,000 endemics)
Inter-tropical Africa	30,000 spp., of which 12,000 are endemics		
Whole continent	ca. 68,500 spp., of which ca. 41,600 are endemics (61%)		

of an open scrub of Mimosoideae dominated by *Acacia* spp. with *Balanites* spp., *Commiphora* spp., *Ziziphus* spp. (Le Houérou 2004e), with a carpet of short annual (Sahel) and perennial grasses (East Africa, the Horn, the Kalahari, Namibia, South Africa; Le Houérou 1977, 1994d), and the *Acacia-Commiphora* bush of E. Africa (Trapnell and Griffiths 1960; Trapnell and Langdale-Brown 1962; Trapnell et al. 1966; Pratt and Gwynne 1977).

The semi-arid zone of extra-tropical Africa has a forest vegetation of sclerophyllous species in winter-rain areas, which is often degraded into sclerophyll shrubland such as the garrigue and maquis of N. Africa, or the fynbos of South Africa (Le Houérou 2005a). In the inter-tropical zone predominates an *Acacia*-Combretaceae savanna and/or woodland with annual and perennial grasses such as *Andropogon gayanus* and *Hyparrhenia* spp.

The sub-humid zone is represented by savanna and dry deciduous woodland (the so-called tropophilous, i.e. "wet-and-dry", forest), with Combretaceae (*Combretum, Tenninalia*) and other trees such *Khaya, Bombax, Ceiba, Acacia, Parkia, Butyrospermum*, and a discontinuous layer of tall grasses mostly of the Andropogonoideae tribe (*Andropogon* spp., *Hyparrhenia* spp.). The S.E. African Miombo woodland bears many similarities with the Sudanian West African savanna, except for the fact that the dominant trees are legumes (*Brachystegia* spp., *Julbemardia* spp., *Colophospermum mopane*; Malaisse 1978; Lawton 1980). The climate is also fairly different due to elevation; this particular point is discussed in Chapter 2 (Sect. 2.3.2).

The humid zone is the domain of semi-deciduous forest and woodlands (*Daniellia, Isoberlinia, Uapaca, Vitex, Lophira, Syzygium*).

In the East African highlands, forest and shrublands are dominated by sclerophyllous Mediterranean-like species: *Juniperus procera, Podocarpus* spp., *Olea africana, Barbeya oleoides, Dodonaea viscosa, Buxus hildebrandtii*, etc. (Le Houérou 1984a, 2003), with cactoid spurges (*Euphorbia* spp.; cf. Sect. 1.3.2.8).

The hyper-humid zone is covered mostly by the rainforest of the Guinean, Congolian and Zambezi phytogeographic phytochoria (White 1983). This is an area of timber production and high agricultural potential under intermediate and high inputs (Higgins et al. 1984). Human and livestock diseases and parasitism are common.

1.3.14 Livestock Species and Breeds

The distribution of cattle species and breeds, and the density of cattle in inter-tropical Africa are shown in Fig. 36. The constraints to livestock distribution are of various types but disease and parasitism play a leading role (Dicko et al. 2006; Hiernaux and Le Houérou 2006).

Camel (dromedaries) are sensitive to diseases and parasitism (tick-borne diseases as well as trypanosomiasis); for this reason, they are restricted to hyper-arid and arid (occasionally semi-arid) zones; nowhere in Africa are they found above the 600 mm isohyet of MAR, and often not beyond 400 mm.

Zebu or humped cattle (*Bos indicus*) are tolerant to drought, heat and, to some extent, to tick-borne diseases (TBDs; heartwater, anaplasmosis, babesiasis (= redwater = piroplasmosis), East Coast Fever). TBDs are an important constraint to cattle husbandry in eastern and southern Africa but not so in West Africa, perhaps because of the very low air humidity and of the long dry season in the livestock production zones (Sahel and N. Sudanian zones), although some outbreaks are known to occur every now and then in various areas, such as the inland delta of the Niger River (Le Houérou 1989b). A few outbreaks of East Coast Fever occurred in Senegal and Mauritania in the 1980s, perhaps linked with the Senegal River Basin hydrological works (Handschumacher et al. 1992; Duvail et al. 1998; Le Houérou 1999a). Tick-borne diseases also used to constitute a significant constraint in N. Africa until the generalization of synthetic insecticides in the 1950s—hence, the early import of Indo-Pakistani zebu breeds, e.g. Nellore, Red Sindi, Sahiwal, Brahma.

Conversely, humped cattle are very sensitive to trypanosomiasis (sleeping sickness) and, therefore, do not penetrate deep into the tropical sub-humid zone lowlands (unless tsetse flies have been eradicated). In the tsetse-infested zones (Fig. 34–36), i.e. roughly above the 800 mm isohyet of MAR and below 1,200 m elevation, trypano-tolerant taurine cattle (*Bos taurus*), such as the N'dama breed from the Fouta-Djalon (Guinea) or West African short-horns (Muturu, Baoulé, Méré), the Kuri and Sanga/Ankolé, tend to replace the zebu in trypano-infested regions. The same phenomenon is observed in small stocks of the West African achondroplasic (i.e. dwarf) goats and sheep (Djallonké), which are ±trypano-tolerant and are the only breeds kept in the humid and hyper-humid zones. The upper altitudinal limit of tsetse fly distribution is about 1,200 m of elevation at the equator. The upper midlands and highlands are thus free of trypanosomiasis, i.e. when the mean annual temperature is below 22°C, and the mean minimum of the coldest month below 15°C.

It thus appears that livestock distribution is indirectly controlled in Africa by agro-bioclimatic factors such as rainfall, air moisture, and temperature through the impact of these parameters on vectors and parasites.

1.3.15 Wildlife

The zoning of the distribution of 138 species of mammals in Africa between the equator and the Tropic of Cancer is shown in Table A15.

The distribution of mammals is controlled by the same factors as that of livestock, i.e. feed, shelter, water, predation, diseases and parasitism, all more or less governed by climate. This time-honoured balance, however, was abruptly offset by the introduction from Egypt of rinderpest to East Africa in the late 1880s and, hence, to the whole continent. Rinderpest had a very severe impact on the bovid ungulate populations; some species, like the buffalo, were at the verge of extinction but have slowly recovered, with unknown consequences for the food chains. Other bovids, such as eland and other large antelopes and gazelles, suffered less than did buffalo.

Large mammals, unfortunately, are on the verge of extinction outside national parks, with the exception of southern Africa (Botswana, Zimbabwe, Namibia and South Africa). In the Sahel in 1980, for instance, the order of magnitude of the stocking of wild mammals was 5 kg km^{-2}, essentially hares, rodents, and small carnivores such as jackal and fox (Le Houérou 1989b). In the Kalahari, conversely, the rate of stocking of large mammals was still 400 kg km^{-2} in the early 1980s (Le Houérou 1989b). Nevertheless, this also is now on the decline (Le Houérou 1994b).

In assessing the stocking rate of wild ungulates in the Sahelian zone of N. Darfur (Rep. of Sudan), an aerial survey over a territory of 250,000 km^2 in 1977 found a biomass of 1.0 kg Lwt km^{-2}, with local concentrations of 8.0 to 11.0 kg in limited areas. However, another aerial survey in the Sudanian zone of S. Darfur (Rep. of Sudan), again in 1977, found 28 kg km^{-2} over an area of 160,000 km^2, for 49 species of large mammals (Watson et al. 1977; Le Houérou 1989b). In the semi-arid and sub-humid zones of Kenya, the wildlife biomass was 21 kg ha^{-1} for 15 spp. in the Kadjado, Samburu, Narok and Taïta districts (36,000 km^2) in 1969, versus a livestock population of 32 kg ha^{-1} in the same area (Casebeer 1971; Le Houérou 2006c). In N. Kenya again, between Lake Turkana and Marsabit, a census carried out by a UNESCO project in 1980, over an area of 23,000 km^2, found the following biomasses: 900 kg km^{-2} of livestock and 97.5 kg of wildlife (Le Houérou 2006c). This is the kind of stocking rate of wild large mammals the Sahel is suspected to have borne 100–150 years ago (Coe et al. 1976; Bourlière 1978; Le Houérou 1989b; Palmer et al. 2006), and perhaps the Sahara 4,000–5,000 years ago (Le Houérou 1997b). This kind of past wildlife stocking rate approximately corresponds with the present livestock stocking of 2.5–5.0 kg Lwt ha^{-1} (Le Houérou 1989b). Table A15 shows the distribution of wild mammals between the equator and the Tropic of Cancer.

1.3.16 Human and Animal Diseases and Parasites

There are four major human parasitic diseases in Africa that are closely linked to climatic factors, namely water, temperature and air moisture. These are malaria, bladder and vesicular shistosomiasis, trypanosomiasis, and river blindness, all lowland diseases. The limit to malaria corresponds with the lower limit of the highlands, i.e. 18°C mean annual temperature and a mean daily minimum temperature of the coldest month around 11°C, corresponding approximately to an elevation of 1,800 m between 10°N and 10°S, and with the approximate latitudinal lapse rate of ca. 1°C per km of change in elevation (Sect. 1.2.4).

The limit of shistosomiasis (bilharziosis) would be approximately the same but, here, the situation seems less clear to me, as there are particular conditions of transmission and reinfestation that I am not familiar with. As a consequence of the hydrological works carried out in the Senegal River Basin in the 1990s, the lower part of this basin has become the hotspot of this disease in Africa (Handschumacher et al. 1992; Duvail et al. 1998; Le Houérou 1999a). We have seen above the case of trypanosomiasis for livestock. It would seem that the situation is somewhat more complex for humans. In W. Africa, sleeping sickness is provoked by *Trypanosoma gambiense* transmitted by *Glossina palpalis*, a species of the warm hyper-humid lowlands of the Gulf of Guinea and the Congo River Basin, with probably an upper limit at 500–600 m elevation between 10°N and S. In E. Africa, sleeping sickness is provoked by *T. rhodesiense*, transmitted by *G. morsitans*, a savanna species found at elevations reaching about 1,200 m with an average annual rainfall exceeding 800 mm.

River blindness, or onchocerchiasis, is provoked by a filaria (*Onchocerca volvulus*) transmitted by small flies, the simulies concentrated in moist habitats with running oxygenated waters, in warm humid lowlands, probably limited by mean annual temperatures of around 25°C and below 500 m of elevation between 10°N and S.

1.3.17 Human Comfort

It is a well-known fact that comfort in any given temperature above 22.5°C (the neutral temperature for lightly clothed humans) is inversely related to relative humidity, and directly related with wind speed. I have tried to illustrate this in a somewhat more concise manner in Figs. 15 and 16, taken from research papers by architects. These data tend to show that comfort needs a temperature below 27.5°C, irrespective of air moisture, and that wind velocity above 3 m s^{-1} (10.8 km h^{-1}) hardly improves comfort when sitting in the sunshine under temperatures between 17 and 27°C.

Chapter 2
Bioclimatic Classification

Abstract Chapter 2 deals with the bioclimatic classification of Africa within its main bioclimatic divisions, as defined in Chapter 1: Mediterranean and Subtropical to Tropical, and Equatorial. The Sahara is considered apart, as it experiences a Mediterranean bioclimate to the north and a tropical bioclimate to the south. The other African deserts are considered within their general families (Tropical and Equatorial). Fourteen large tables show the various bioclimates with their corresponding climatic, agronomic and biological characteristics. Two detailed tables show the distribution of some 200 key plant species in the various bioclimatic entities identified, between the equator and the Tropic of Cancer. A similar table shows the distribution of some 170 species of mammals in the same zone. Another table shows the distribution of crop species as a function of elevation in eastern Africa. An extensive table shows the surface areas of the main bioclimatic zones identified. Yet another table shows the main bioclimatic requirements of 53 African crops. A colour figure shows the ordination of the climatic, biologic and agronomic parameters in the bioclimatic zoning for the complex case of Kenya.

2.1 General

The criteria and parameters used in the present classification have been discussed in the preceding chapter and shown in the related tables and figures. These criteria show basic distribution patterns where analogous agro-bioclimates are experienced. Each agro-bioclimatic zone is thus a region in which a significant uniformity of the basic criteria is observed. Such an idealized situation is, however, subject to a number of constraints and limitations that have, as much as possible, to be taken into consideration.

First of all, it is obviously not possible to analyze all the many agro-bioclimatic elements that could be of significance in all of the 962 weather stations of the database utilized, be it independently or in relation to each other. Secondly, there is in any region a number of microclimatic situations that may depart significantly from the overall zonal representative value and pattern, for one or several elements. Thirdly, due to the variety and specificity of agronomic and environmental factors, and their relationships to climate and climatic variability, it was not possible to account for all these factors, otherwise the task would have become too complex to be of practical usefulness in an overall classification at continental scale. Fourthly, some parameters that may be of high local significance, such as wind, foehn effect, hail pathways and occult precipitation, are not accounted for either, because they are insufficiently documented or not amenable to generalization. Some simplifying assumptions had therefore to be made. The overall result of the classification is shown in Fig. 32. Various parameters that were used to reach this end result are shown in various tables and figures, as indicated below.

2.2 Extra-tropical African Bioclimates, Particularly Mediterranean

Extra-tropical agro-bioclimates are those occurring beyond the tropics, i.e. north of the Tropic of Cancer and south of the Tropic of Capricorn. They are characterized by a number of attributes that differentiate them from inter-tropical agro-bioclimates.

A. Extra-tropical agro-bioclimates exhibit a fairly strong seasonal thermoperiodism; there is an approximate 25.0 °C difference between the mean daily maximum of the hottest month (*M*) and the mean daily minimum temperature of the coolest month (*m*). This is the mean extreme range of annual temperature (Figs. 23–26, 28, 31, 50 and 51), considered as representative of continentality (Emberger 1930; Debrach 1953). This range is much smaller in tropical agro-bioclimates, and still more so under equatorial agro-bioclimates that are thermally more homogenous (see the ombrothermal diagrams of Figs. 23–26).
B. Seasonal photoperiodism is also fairly differentiated. The difference in photoperiods between the summer and winter solstices is 3 h 20 min at the tropics, 3 h 52 min at 30° latitude, and 5 h 44 min at 40° latitude. Thermal and photoperiodisms play an important role in plant life, in particular in the specificity of cereal cultivars such as millet and sorghum (Vaksman and Traoré 1991; Traoré et al. 1993). Some pearl millet and sorghum cultivars are sensitive to a daily difference of even a few minutes in photoperiodism at some stages of their life cycle.
C. Extra-tropical agro-bioclimates are, in general, subjected to frost hazard, with the exception of a narrow littoral belt where *m* exceeds 7.5 to 8 °C (Figs. 28, 31, 51).

2.2.1 Mediterranean Bioclimates (Weakly Bimodal Rainfall Regime, in Africa)

These are characterized by winter rains and summer drought (Le Houérou 2005a, b). The rainfall regime is variable but predominantly bimodal in northern Africa, with fall and spring peaks. The rainy season(s) correspond(s) with the short days–cool temperature period (November–April in the northern hemisphere and May–October in the southern hemisphere). This category includes hyper-humid to hyper-arid agro-bioclimates, with mean annual rainfalls of 2,330mm between Bou Noghra and Zitouna on the Collo peninsula, N.E. Algeria, or 1,530mm at Ain Draham in N.W. Tunisia (Fig. 23a) decreasing to virtually zero in the central–eastern Sahara (Aswan, Dakhla, Farafra, Kharga, Kufra, Tazerbo). Mean annual temperature may vary from less than 10°C in the highlands of Algeria/Morocco (and less in the high Atlas Mountains) to some 25°C in the north and central Sahara (Fig. 51). Mean annual temperature is below 18–19°C in the non-Saharan part of northern Africa. Frost-free areas are limited to a narrow strip along the Atlantic, Mediterranean and Red Sea shores. The elements of classification of extra-tropical Africa north of the Tropic of Cancer are shown in Tables T1–T4, and in Figs. 17 and 23a–h, 27, 29, 30, 33, 50, 51.

Mediterranean climate also prevails at the S.W. tip of the continent along the shores of the Atlantic, from the Cape of Good Hope to Luderitz on the southern Namibia coast. Some 20% of the territory of the Rep. of South Africa receives 60 to 90% of winter rains, and may therefore be regarded as Mediterranean (Figs. 29, 30, 46–48; Le Houérou 1994d, 2005a, b).

2.2.2 The Sahara

The Sahara (Figs. 1 and 2, Tables T21–T23) occupies an area of ca. 8.5×10^6 km^2 supporting a population of some 5 million inhabitants: 0.7 inhab. per km^2 (excluding Egypt: 1×10^6 km^2, 70×10^6 inhab.). The Sahara thus occupies 29% of the continental area of Africa, harbouring 0.8% of its population (Le Houérou 1990a, 2007a; Bisson 2003; Figs. 1 and 2). Winter temperatures are shown on Figs. 28 and 31. Freezing occurs regularly every winter above ca. 1,000m elevation. The lowest temperature recorded in the Asekrem station (2,710m a.s.l.) in the Ahaggar mountains is −11°C (Dubief and Bücher 2001). The number of freezing days per annum is 11 in Borj Omar Driss (formerly Fort Flatters) at 650m a.s.l., 5 in Tamanrasset at 1,378m a.s.l., and 5 in Adrar at 263m a.s.l. The mean daily minimum temperature of January, with respect to elevation, is given in Table T21, from north to south (Frère and Popov 1984).

Table T21 Temperature in various Saharan weather stations

Station	Elevation	m^a	M	Station	Elevation	m	M
Biskra	122	6.0	40.0	Laghouat	765	2.2	36.0
Ain Sefra	1,072	–0.1	37.5	Touggourt	69	3.5	41.6
Ghardaïa	450	4.5	42.5	Bechar	773	1.7	39.8
Ouargla	141	4.3	42.7	El Golea	397	2.7	41.6
Adrar	263	3.8	46.0	In Salah	293	6.0	45.0
Tindouf	431	5.0	45.0	Djanet	1,054	6.0	37.7
Tamanrasset	1,378	3.8	35.0	Ghadamès	338	2.8	42.7

[a]Definitions: m, mean daily minimum temperature of January, °C; M, mean daily maximum temperature of July, °C. Note that $M - m$ represents the degree of continentality, and $M + m/2$ is close to the mean annual temperature ± 1°C

Table T21 shows that the relationship between elevation and temperature is not simple and straightforward—it depends on other parameters such as latitude, degree of continentality, distance from large bodies of water, and other local situations.

The geographic Sahara is circumscribed within the isohyet of 100 ± 50 mm of mean annual precipitation, which is correlated with a number of physical and biological criteria (Le Houérou 1959a, b, 1975). The Sahara is multiple. It may be separated into orthogonal zones according to latitude and longitude (Figs. 1 and 2; Le Houérou 1995a, 2001a–c). There is a northern Sahara under a Mediterranean rainfall regime north of the Tropic of Cancer (Maire 1933, 1940; Emberger 1930, 1955, 1971; Dubief 1950, 1953, 1959; Quézel 1965, 1971, 1978). The southern Sahara, south of the Tropic of Cancer, in turn, exhibits a tropical rainfall regime with strictly summer rains. Flora and vegetation are also typically of tropical kinship in the southern Sahara. The central Sahara lower plains, around the tropic, with an average annual rainfall below 25 mm, shows no distinct rainfall regime; the scanty rains may occur at any season due to the extreme position of advance and retreat of the polar front air masses and of the Inter-tropical Convergence Zone (ITCZ) respectively.

The Saharan flora includes 2,800 species of vascular plants, 25% of which are endemic. It should be noted that the Sahara shares 50% of its flora with the Arabian Peninsula (Le Houérou 1995a). Fifteen percent of this flora (mostly endemics) belong to the so-called Rand Flora (Christ 1892; Le Houérou 1995a), with a strong taxonomic kinship to the Cape flora in South Africa.

Contrary to a commonly held opinion, the Sahara has important water resources (Table T22), particularly in its northern part. Both surface waters and aquifers originate, for a large part, in the Atlas Mountains (Gischler 1976; Dubost 1992, 2002; Margat 1992; Le Houérou 2004b, 2007a).

Surprisingly, Table T22 shows that surface waters represent nearly 1/4 of the resources of the Sahara, outside Egypt (note that $1\,m^3\,s^{-1} = 32 \times 10^9\,m^3\,year^{-1}$). Water sources are drawn from ca. 700 foggaras (drainage galleries) in the Continental Intercalary (CI) outcrops (W. Algerian Sahara) and 7,500 boreholes (artesian, sub-artesian and non-artesian, >100 m deep) in the three main aquifers, excluding surface wells (depth < 100 m).

Table T22 Water resources of the Sahara, yields as of the year 2000

	$m^3\,s^{-1}$	%	Area covered ($10^6\,km^2$)
Aquifers			
Continental Intercalary	18.7	48.3	1.4
Terminal Complex	15.0	38.8	0.8
Nubian Sandstone	5.0	13.2	1.8
Subtotal	38.7	100.0	4.0
Surface waters (excl. Nile)	16.0	23.4	–
Nile	52.4	76.6	–
Subtotal	68.4	100.0	–

The CI is considered as one of the very largest aquifers on the planet. It covers an area of some 1.4×10^6 km^2 in E. Algeria, S. Tunisia and W. Libya. It has been fed mainly by runoff from the Saharan Atlas Mountains during the Pleistocene epoch to the Holocene and present time; the waters in this aquifer are aged ca. 8,000 years. The containing terrain dates back to the Middle Cretaceous (Albian: 100–120 Ma). The output is $9.5\,m^3 s^{-1}$, of which $2.7\,m^3 s^{-1}$ is natural discharge (springs, sebkhas, salt lakes, 700 foggaras). About $6.8\,m^3 s^{-1}$ is drawn from some 110 boreholes 250–1,500 m deep, dug over the past 70 years. These waters have TDS values of 3,000 to 6,000 ppm. Salinity, depth and temperature increase from west to east. The amount of water stored is estimated at 6×10^{13} m^3, or 60 km^3.

The Complexe Terminal (CT) is partly fed by the CI underneath, contained in sandy sediments of Mio-Pliocene age (5–15 Ma). The CT yields ca. $21.5\,m^3 s^{-1}$ of water aged 3,000 to 4,000 years. Of this, $8.5\,m^3 s^{-1}$ comes from 2,000 largely artesian boreholes, and $13.5\,m^3 s^{-1}$ from natural discharge in the Great Salt Lakes (Chotts Melhrir, Rharsa, Djerid, Fedjej, etc.). The recharge is estimated at $18\,m^3 s^{-1}$, from runoff in the Saharan Atlas and deep percolation from the Eastern Sand Sea. This aquifer covers 0.6×10^6 km ^{2} in Algeria, Tunisia and Libya.

The Nubian Sandstone aquifers (Trias to Quaternary continental terrains) from Libya, Egypt and Sudan cover an area of 1.8×10^6 km^2, and yield $4\,m^3 s^{-1}$ of excellent water (500 to 1,000 ppm of TDS), aged 20,000 to 30,000 years; the estimated storage is 20^3 km^3.

The Sahara may be subdivided as follows (cf. Table T23; Le Houérou 1995d, 1997a). Meridian subdivisions separate the Sahara into West, Central and East territories. The demarcation lines are on the 0 and 19° longitude east (Figs. 1 and 2). Additional subdivisions include the montane Sahara, above 1,000 m elevation, with freezing winters and both winter and summer rains, as well as a trend towards Mediterranean vegetation, including Mediterranean endemics. One can also distinguish an oceanic Sahara in a narrow strip (ca. 50 km wide) along the Atlantic Ocean, characterized by high relative humidity, occasional fog, low ETo, moderate temperatures, a flora and vegetation akin with those of the Canary Islands, a large proportion of succulent and crassulescent species, and a large number of endemic species (Le Houérou 1995d), in contrast with the other parts of this great desert. Figure 1 shows the latitudinal and meridian subdivisions of the Sahara, and Fig. 2 some 26 corresponding phytogeographic subdivisions (Le Houérou 2007a).

2.2.3 The Subtropical Bioclimates of South Africa

Apart from some 20% of the extra-tropical territory mentioned above, South Africa has a subtropical climate with various proportions of winter and summer rains (Fig. 30). The proportion of summer rains increases from south to north, as

Table T23 Climatic parameters for 150 weather stations from the ten Saharan countries (Le Houérou 2007a)

Sub-regions	(1) N. Sah.		(2) S. Sah.		(3) Central plains		(4) Oceanic Sah.		(5) Montane Sah.		(6) Orient. Sah.		(7) Eryth. Sah.	
Parameter	*n*[a]	*x*	*n*	*x*	*n*	*x*	*n*	*x*	*n*	*x*	*n*	*x*	*n*	*x*
P (mm)	36	90	29	61	24	31	10	92	3	90	13	10	8	48
T (°C)	19	19	28	27	14	25	10	20	3	19	24	21	8	25
Evap. Piche (mm)	8	3,150	7	5,830	12	4,120	2	1,720	2	4,500	20	3,786	6	3,851
ETo (mm)	30	1,676	31	2,546	13	2,140	7	1,410	3	1,507	19	2,086	6	1,848
Vap. press. (hPa)	24	12	24	13	25	11	6	17	3	19	23	12	6	22
Rel. hum. (%)	22	46	4	31	17	36	6	75	4	77	20	43	7	62
Sat. def. (hPa)	20	15	23	26	2	23	6	8	2	20	26	15	7	10

[a]Definitions: *n*, number of weather stations/nature and unit of data for the parameter considered; *x*, average value of the parameter

latitude decreases, to reach more than 85% at the Tropic of Capricorn, i.e. 40–70% in the Karroo of the N. Cape Province, 60–75% in the Orange and Natal provinces, and 75–85% in the Transvaal province. Due to elevation, however, most of the region experiences frost hazard (Figs. 31, 51). Frost-free areas are limited to a narrow strip along the Indian and Atlantic Ocean shores. The various elements of the classification are shown in Tables A1–A4, and in Figs. 26e–g, 30, 48, 50, 51 (cf. Tables T24–T27).

Table T24 Extra-tropical agro-bioclimates, aridity classes in South Africa

No.	Classes	Precipitation (mm year^{-1})	ETo (mm year^{-1})	P/ETo (%)	Rainy period, $P > 0.35$ ETo (days year^{-1})
7	Hyper-arid	0–100	1,800–2,500	0–6	Less than 5
5/6	Arid	100–400	1,300–1,800	6–30	5–100
4	Semi-arid	200–600	1,200–1,500	20–40	100–180
3	Sub-humid	400–800	1,100–1,400	30–70	180–240
2	Humid	600–1,000	1,000–1,200	50–100	240–300
1	Hyper-humid	>1,000	900–1,100	>100	>300

Table T25 Extra-tropical agro-bioclimates: native vegetation and land use

No.	Agro-bioclimatic classes	Ecological zones	Potential land use
7	Hyper-arid	Contracted desert vegetation along the drainage network	No rain-fed farming. Nomadic pastoralism, camels, sheep and goats, wild ungulates
5–6	Arid	Diffuse vegetation of perennial grasses and/or dwarf shrubs	Subsistence rain-fed farming. Settled and nomadic pastoralism, camels, sheep and goats, some cattle. Wildlife ranching
4	Semi-arid	Sclerophyllous forest and woodland	Mixed commercial rain-fed farming. Settled ranching, cattle, sheep and goats and wildlife
3	Sub-humid	Sclerophyllous and malacophyllous forest and woodland	Mixed and industrial commercial rain-fed farming. Settled ranching, dairy production, some timber production, wildlife production
1–2	Humid and hyper-humid	Malacophyllous forest and woodland	Mixed and industrial commercial farming, dairy production, timber production

Table T26 Extra-tropical cold-tolerance zoning, thermal classes

Thermal class[a]	Zone	Annual no. of days of freezing	Description
$m > 13\,°C$	Subtropical	0	No frost under shelter. Most tropical zone crops cultivable. Many tropical species in native vegetation
$13 > m > 9$	Very warm	0	No frost under shelter. Many winter perennial tropical crops cultivable. Some tropical species in vegetation
$9 > m > 7$	Warm winter	0–5	Occasional light frost under shelter. Some perennial tropical crops possible when water requirements are met (sugarcane, banana). Some tropical species in native vegetation
$7 > m > 5$	Mild winter	5–10	Some frost-sensitive crops cultivable, such as citruses, avocado
$5 > m > 3$	Temperate winter	10–20	A few frost-sensitive crops cultivable, such as olive, acacia, cacti. Few tropical species in native vegetation
$3 > m > 1$	Cool winter	15–30	Frost-sensitive plants absent, cold-requiring crop varieties (apple, pear, pistachio, etc.). No tropical species in native vegetation
$1 > m > -1$	Cold winter	20–60	Cold-tolerant crops, and native species, mostly deciduous. Temperate climate crops
$-1 > m > -3$	Very cold winter	40–80	Specialized frost-tolerant species, such as cushion spiny xerophytes and conifer forest
$-3 > m > -5$	Extremely cold winter	60–120	Frost-tolerant species
$-5°C > m$	Mediterraneo-alpine high mountain	100–180	Upper limit of trees at high elevations, tree line ≈–5 °C

[a]*m*, mean daily minimum temperature of the coolest month January in the N. hemisphere, July in the S. hemisphere

2.3 Inter-tropical Bioclimates

Inter-tropical agro-bioclimates are located between the Tropic of Cancer and the Tropic of Capricorn. They include two major subzones: tropical and equatorial. Tropical agro-bioclimates are, by and large, situated between 10°N and the Tropic of Cancer, and between 10°S and the Tropic of Capricorn, while equatorial

Table T27 Extra-tropical agro-bioclimatic classification (Le Houérou 1989a)

Thermal classes			I	II	III	IV	V	VI	VII	VIII
			No frost					Light frost	Hard frost	Severe frost
m (°C)			30–24	24–20	20–15	15–10	10–8	8–4	4–1	1 to −5
Aridity classes			Lowlands	Upper lowlands	Lower midlands	Midlands	Upper midlands	Lower highlands	Upper highlands	Afro-alpine
No.	*P*/ETo (%)									
7	5	Hyper-arid	7-I	7-II	7-III	7-IV	7-V	7-VI	n.a.	n.a.
6	15	Very arid	6-I	6-II	6-III	6-IV	6-V	6-VI	n.a.	n.a.
5	30	Arid	5-I	5-II	5-III	5-IV	5-V	5-VI	n.a.	n.a.
4	45	Semi-arid	4-I	4-II	4-III	4-IV	4-V	4-VI	4-VII	4-VIII
3	75	Sub-humid	3-I	3-II	3-III	3-IV	3-V	3-VI	3-VII	3-VIII
2	100	Humid	2-I	2-II	2-III	2-IV	2-V	2-VI	2-VII	Doubtful
1	>200	Hyper-humid	1-I	1-II	1-III	1-IV	1-V	1-VI	n.a.	n.a.

agro-bioclimates are located between 10°N and 10°S on both sides of the equator (Fig. 32). The inter-tropical zone, as a whole, is characterized by a number of particular conditions that distinguish it from the extra-tropical zones:

A. Mean annual temperature is above 20 °C in the lowlands.
B. Thermoperiodism is moderate to weak ($M - m$ = 15 to 20°C).
C. Seasonal and daily photoperiodism is weak and almost nonexistent under the equator, and fairly weak at the tropics (zero at the equator, 70 min at 10°lat., 2 h 07 min at 15°lat., 3 h 04 min at 20°lat., 3 h 20 min at the tropics at 23°27′).
D. All lowlands and midlands are frost-free.
E. Rains occur either year round in the humid and hyper-humid ecozones, or are concentrated around the summer solstice in the tropical zone or at the equinoxes in the equatorial zone.
F. Both tropical and equatorial agro-bioclimates have hyper-arid to hyper-humid variants, e.g. in East Africa.
G. Both tropical and equatorial agro-bioclimates have frost-free and frost-occurring zones; both have lowlands, midlands, highlands and montane, i.e. Afro-alpine and Afro-subalpine, zones.
H. Both families of inter-tropical climates may be classified in a specific, but similar, orthogonal matrix, as a function of two main parameters: an aridity index (P/ETo) and a thermal condition index linked to frost hazard (m); both indices link intensity and length of favourable and unfavourable (stress) conditions.

2.3.1 Tropical Agro-bioclimates

Tropical agro-bioclimates are characterized primarily by a monomodal (unimodal) type of rainfall distribution pattern, i.e. there is only one annual peak in the rainy season, coincidental with the summer solstice (with a 1–2 month time lag; see Figs. 24a–h, 46, 47). The Sahel ecozone occupies 3.0×10^6 km^2 while the Sudanian ecozone covers another 3×10^6 km^2. In East Africa, the arid lands cover some 3.2×10^6 km^2, and the Miombo 3.7×10^6 (Le Houérou 2006c). We have thus a total of about 13×10^6 km^2 of tropical savannas, i.e. 10% of the surface area of the continent. The overall regional values are as follows (for a detailed estimate of surface areas, see Table A16):

- *Inter-tropical climates* (10^6 km^2)

West Africa: 5.8; Central Africa: 5.2; East Africa: 5.8; southern Africa: 4.1; subtotal: 20.9.

- *Extra-tropical climates* (10^6 km^2)

Southern Africa: 1.7; northern Africa: 6.0; subtotal: 7.7.

- *Madagascar*: 0.590 *grand total*: 29.2 (10^6 km^2).

Although there is one single rainy season and one dry season in the tropical agro-bioclimates, Fulani pastoralists and farmers in the Sahelian-Sudanian ecozone recognize four seasons: the rainy season, “Nduggu”; the deferred post-rainy season, “Kaulé”; the “cool” dry season, “Dabundé”; and the hot pre-rainy season, “Tchedio”. These are fully justified from the plant-life and animal-life viewpoints (Le Houérou 1989b). Analogous seasons are recognized by Ethiopian and Somali pastoralists in their equatorial bioclimates (see Sect. 2.3.3).

Seasonal photoperiodism varies between 70 min difference in day length at the solstices of summer and winter at lat. 10°, and 3 h 20 min at the tropics.

Thermoperiodism (M–m) varies between 20 and 25 °C, vs. 25 °C and above in the extra-tropical zone and 10–15 °C in the equatorial agro-bioclimate zone.

On the other hand, in terms of aridity, tropical climates may be hyper-arid, as in the southern Sahara, arid, as in the Sahel ecozone, and up to hyper-humid, as in the Guinea zone (Figs. 26, 27, 29, 30, 32).

Moreover, tropical agro-bioclimates may or may not be subjected to frost hazard, depending on latitude and elevation, as in the southern Sahara mountains, Aïr, Jebel Marra, etc. The various climatic, agronomic and biological classification criteria and their intensity levels are shown in Tables T28–35, and Figs. 3, 5–8, 11–14, 19, 20, 24a–d, 25g, h, 26a–d, 28, 32–36, 45–48, 50–53, 55.

The midland and highland tropical agro-bioclimates are particularly well represented in the southern hemisphere, i.e. the Miombo savanna woodland, and on Madagascar. They occupy very limited areas north of the equator (eastern and western parts of the Rep. of Sudan, Djebel Marra and the southern Sahara mountains: Adrar of Mauritania, Adrar of Iforas, Aïr, Ennedi, Tibesti, Gourgeil, Marra).

2.3.2 The Southern African Miombo Savanna and Woodland Zone

The Miombo zone is the counterpart in East, S.E. and S.W. Africa of the Sudanian ecological zone above 5°N. The Miombo zone is located between 5–10°S and the Tropic of Capricorn in S.E. Congo, Tanzania, Malawi, Zimbabwe, Zambia, Mozambique and eastern Angola (Fig. 32); it occupies some 3.8×10^6 km^2. It is essentially a more or less wooded savanna of the semi-arid, sub-humid and humid zones, the larger part being sub-humid. Rainfall amounts to 600–1,200 mm year^{-1} (Fig. 1). Seasonal rainfall distribution is of a monomodal type (Fig. 25g, h), and the rainy season is typically 6–8 months long (Fig. 6). This is very similar to the rainfall conditions in the Sudanian ecological zone between 5 and 15–18°N (depending on longitude, as rain belts are E-W-orientated, i.e. a given isohyet is further north in the western part of the continent in the northern hemisphere (Figs. 3–6).

The main differences between the Miombo and the Sudanian ecozone lie in the temperature, Eto, and relative humidity/saturation deficit. The Miombo zone is

Table T28 Tropical agro-bioclimates, aridity classes

No.	Classes	Ecological zones	Rainfall (mm $year^{-1}$)	Eto (mm $year^{-1}$)	*P*/ETo (%)	Rainy period, *R* > 0.35 ETo (days $year^{-1}$)
7	Hyper-arid	Saharan	<100	2,300–3,000	0–5	0–5
6a	Very arid	Saharo-Sahelian	100–200	2,000–2,500	5–20	5–60
6b		Sahelian	200–400	1,800–2,300	10–30	60–90
5	Arid	Sudano-Sahelian	400–600	1,500–2,200	20–40	90–120
4	Semi-arid	Northern Sudanian, southern Miombo	600–800	1,300–2,100	30–60	120–150
3	Sub-humid	Southern Sudanian, northern Miombo	800–1,200	1,200–2,000	40–80	150–240
2	Humid	Northern Guinean, derived savanna	1,200–1,500	1,100–1,700	60–120	210–270
1	Hyper-humid	Southern Guinean, rainforest	>1,500	1,000–1,500	>80	>270

Table T29 Tropical agro-bioclimates, thermal classes (summer rain, monomodal distribution patterns)

Class	m^a (°C)	Ecological/altitudinal zones	Thermal limitation to crops and vegetation
VIII	<1	Afro-alpine and subalpine	Yearlong night frost hazard. No cropping. Transhumant grazing. No permanent settlements
VII	4–1	Upper highlands	30–120 days frost hazard. Evergreen montane forest and woodland. Temperate climate crops (wheat, barley, etc.). No frost-sensitive crops
VI	8–4	Lower highlands	0–30 days of light frost hazard. Evergreen montane forest and woodland. Some frost-sensitive crops (citruses) and temperate crops
V	10–8	Upper midlands	No frost under shelter. Tropical forest and woodlands, temperate and tropical crops
IV	15–10	Midlands	Tropical forest and savanna. Temperate and tropical crops

Table T29 (continued)

Class	m^a (°C)	Ecological/altitudinal zones	Thermal limitation to crops and vegetation
III	20–15	Lower midlands	Tropical forest and savanna. Some temperate crops (wheat), most tropical crops (e.g. Robusta coffee)
II	24–20	Upper lowlands	Tropical forest and savanna, no temperate crops, cold-sensitive crops
I	30–24	Lowlands	Tropical forest and savanna. Very cold-sensitive crops (cocoa, coconut, cashew, clove, hevea, raphia, etc.)

[a] *m*, mean daily minimum of the coldest month in °C

Table T30 Tropical agro-bioclimates, native vegetation and land use

Zone, no.	Sub-climates	Vegetation and livestock kinds	Land-use patterns
7	Hyper-arid	Clustered–contracted vegetation, perennial grasses present. Camels, goats, few sheep, no cattle	Long-range nomadism, no cultivation without irrigation
6	Very arid	Diffuse vegetation, sparse Mimosaceae scrub–perennial grasses present, sheep, goats and camels. Rare cattle (zebu)	Nomadism, transhumance. No cultivation without irrigation
5	Arid	Mimosaceae scrub, annual grasses dominant, rare perennial grasses; cattle (zebu), sheep, goats, camels	Transhumance, some retreat flood cultivation of millet in depressions
4	Semi-arid	Combretaceae savanna–annual grasses dominant, perennial grasses present not dominant. Cattle (zebu) sheep, goats, camels uncommon	Pastoralism and millet farming. Rain-fed cultivation of millet, sorghum, cowpeas, some groundnuts. No fodder crops nor sown pastures possible
3	Sub-humid	*Parkia-Butyrospermum-Khaya*. Woodland, parkland and savanna. *Andropogon gayanus. Brachystegia* and *Julbernardia*, Miombo. *Daniellia–Detarium*. Open forest, perennial grasses. Cattle (zebu and taurines), goats, (dwarf), sheep (dwarf). Light tsetse infestation in woodlands and savanna, permanent riverine infestation	Pastoralism and sedentary livestock. Farming groundnuts, cassava, cowpea, and sown pastures possible (stylos and others). Grazing limited by mild trypanosomiasis infestation. Millet, sorghum, maize, cotton, sweet potatoes, tobacco, groundnuts, rain-fed rice, soy, mango, cashew nuts. Sown pastures, fodder crops, some timber production

(*continued*)

Table T30 (continued)

Zone, no.	Sub-climates	Vegetation and livestock kinds	Land-use patterns
2	Humid	Forest, woodland, so-called derived or secondary savanna. Taurine cattle mostly. Dwarf sheep and goats. Heavy permanent tsetse infestation	Most tropical crops; sorghum, maize, cassava, yam, banana, pineapple, sugarcane, rice, timber production
1	Hyper-humid	Rainforest	Palm-oil groves, coconut, hevea, cocoa, coffee, cassava, taros, yam, banana, pineapple, rice, maize, sugarcane, timber production

situated above 500 m elevation, mostly between 1,000 and 1,500 m. The Sudanian zone is almost entirely below 500 m. Mean annual temperature is around 18–22 °C (vs. 26–28 °C in the Sudanian zone; Fig. 12). Light freezing may occur in winter time (Tables A1, A10, A11, A16–A18). ETo varies from 1,200 to 1,500 mm, vs. 1,750–2,500 mm in the Sudanian zone. The *P*/ETo ratio varies between 50 and 100%, vs. 40–75% in the Sudanian zone. Relative humidity averages 63% and saturation deficit 10 hPa, vs. 52% and 17 hPa respectively in the Sudanian ecozone (cf. Sect. 1.3.7.1).

Vegetation physiognomy is similar to that of the Sudanian ecozone, and the incidence of bushfires is likewise devastating. The savanna-woodland of the Miombo is dominated by *Caesalpinioidae* small legume trees mainly of the genera *Brachystegia, Julbernardia, Colophospermum*, with Combretaceae: *Terminalia, Combretum*, etc. Caesalpinioideae legume trees are by no means rare in the Sudanian ecozone—*Burkea, Isoberlinia, Cynometra, Detarium, Baikiaea, Tamarindus, Afzelia, Danniellia, Griffonia, Piliostigma, Bauhinia, Cassia, Pterolobium, Peltophorum* and *Cordyla*—but these are usually isolated trees and therefore do not play a dominant physiognomic role, as they do in the Miombo savanna. Between the Miombo trees is a layer of tall perennial grasses, mainly Andropogonoideae: *Hyparrhenia* spp., *Themeda triandra* and *Heteropogon contortus*, and from other tropical tribes, *Loudetia* spp., *Andropogon* spp., *Setaria anceps, Pennisetum* spp. and *Chloris* spp. (Rattray 1960; Le Houerou 1977; Lawton 1980).

The Miombo thus appears as more "mesic" with less harsh climatic conditions and is, therefore, much more amenable to agricultural development, with a much broader spectrum of agronomic options, than its western African Sudanian counterpart ecozone.

2.3.3 The Equatorial Agro-bioclimates

The equatorial agro-bioclimates are characterized by a bimodal (occasionally trimodal) rainfall distribution pattern, i.e. there are two peaks in the rainy season

Table T31 Tropical agro-bioclimatic classification

Thermal classes			I	II	III	IV	V	VI	VII	VIII
			No frost					Light frost	Hard frost	Severe frost
m (°C)			30–24	24–20	20–15	15–10	10–8	8–4	4–1	1 to −5
Aridity classes			Lowlands	Upper lowlands	Lower midlands	Midlands	Upper midlands	Lower highlands	Upper highlands	Afro-alpine
No.	*P*/ETo (%)									
7	5	Hyper-arid	7-I	7-II	7-III	7-IV	7-V	7-VI	n.a.	n.a.
6	15	Very arid	6-I	6-II	6-III	6-IV	6-V	6-VI	n.a.	n.a.
5	30	Arid	5-I	5-II	5-III	5-IV	5-V	5-VI	n.a.	n.a.
4	45	Semi-arid	4-I	4-II	4-III	4-IV	4-V	4-VI	4-VII	4-VIII
3	75	Sub-humid	3-I	3-II	3-III	3-IV	3-V	3-VI	3-VII	3-VIII
2	100	Humid	2-I	2-II	2-III	2-IV	2-V	2-VI	2-VII	Doubtful
1	>200	Hyper-humid	1-I	1-II	1-III	1-IV	1-V	1-VI	n.a.	n.a.

(but not necessarily two dry seasons in the wetter areas, if the low-rainfall period does not fall below $P < 0.35$ ETo).

In the sub-humid, semi-arid, arid and hyper-arid ecozones, however, there are two dry seasons. In the Horn of Africa, for instance, the following seasons are recognized by the Galla and Somali pastoralists: "Gu", which is the main rainy season in March–May, "Dhair", the short rainy season in September–October, "Jilal", the long dry season from November to February, and "Hagai", the small dry season from June to August (see above, Sect. 2.3.1 for the "Fulani seasons" in W. Africa).

Seasonal thermoperiodism is very weak ($M - m = 10$ to 15°C), and the monthly mean temperatures do not differ by more than 2.5–5°C throughout the year (Figs. 24e–h, 25a–f).

Photoperiodism is little differentiated: 0 at the equator, 35′ at latitude 5°, and 70′ at latitude 10°, at the solstices.

Equatorial agro-bioclimates may be hyper-arid (E. Ethiopia, N. Somalia, Red Sea shores, Chalby desert, E. of Lake Turkana, ex Rudolf; Fig. 25b), semi-arid (Fig. 25c), sub-humid (Fig. 25d–f), humid (Fig. 25a) or hyper-humid. Characteristics of equatorial agro-bioclimates may or may not include frost hazard, depending on elevation and latitude (Tables A10, A16, A18, T32–T35, Figs. 24e, h, 25c, d, 32, 43, 44, 46, 48, 49, 55).

Table T32 Equatorial agro-bioclimates, aridity classes

No.	Classes	Ecological zones/ vegetation	Precipitation (mm year $^{-1}$)	Eto (mm year $^{-1}$)	P/ETo (%)	Rainy period, $P > 0.35$ ETo (days year $^{-1}$)
7	Hyper-arid	Eco-climatic zone no. VII of East Africa: North Somalia, S.E. and N.E. Ethiopia, N. Kenya, Djibouti, Eritrea. Desert thorn dwarf scrub, dwarf shrub *Duosperma, Indigofera, Vernonia* steppe land[a]	<100	2,300–3000	0–10	0–5
6	Very arid	Eco-climatic zone no. VI/V of East Africa. *Acacia-Commiphora* woodland	100–400	1,700–2,500	10–30	5–100

Table T32 (continued)

No.	Classes	Ecological zones/ vegetation	Precipitation (mm year $^{-1}$)	Eto (mm year $^{-1}$)	*P*/ETo (%)	Rainy period, *P* > 0.35 ETo (days year $^{-1}$)
5	Arid	Eco-climatic zone no. V of East Africa. *Acacia-Commiphora* woodland, E. and S.E. Africa	400–600	1,500–2,200	20–40	100–160
4	Semi-arid	Eco-climatic zone no. IV of E.–S.E. Africa. *Acacia-Commiphora* woodland	600–800	1,200–2,000	30–80	160–210
3	Sub-humid	Eco-climatic zone no. IV/III of East Southeast Africa. *Brachystegia-Terminalia* woodland	800–1,200	1,100–1,700	50–90	210–270
2	Humid	Eco-climatic zone no. II/III of East, Central and West Africa. Evergreen forest and derived savanna	1200–1,500	1,000–1,500	60–100	250–300
1	Hyper-humid	Central and West Africa. S. Guinean, Congol and Zambesi rainforest	>1,500	900–1,300	<80	>300

[a]In particular: *Duosperma eremophilum, Vernonia cinerascens* and *Indigofera spinosa*

Table T33 Equatorial agro-bioclimates, thermal classes (bimodal rainfall distribution pattern; see also Fig. 49)

Class	*m*[a] (°C)	Ecological/altitudinal zones	Thermal limitation to crops (see also Tables T25, T27, T28, T34 and Fig. 49) and to native vegetation
VIII	$1 > m > -5$	Afro-alpine and subalpine	Yearlong night frost hazard. Heath shrublands. No cropping. Transhumant grazing. No permanent settlements

(*continued*)

Table T33 (continued)

Class	m^a (°C)	Ecological/altitudinal zones	Thermal limitation to crops (see also Tables T25, T27, T28, T34 and Fig. 49) and to native vegetation
VII	$4 > m > 1$	Upper highlands	30–120 days frost hazard. Evergreen montane forest and woodland. Temperate climate crops, montane crops (teff, ensete, qat). No frost-sensitive crops
VI	$8 > m > 4$	Lower highlands	0–30 days of light frost hazard. Evergreen and deciduous montane forest and woodland. Some frost-sensitive crops (citruses) and temperate crops
V	$10 > m > 8$	Upper midlands	No frost under shelter. Tropical forest and woodlands, temperate and tropical crops
IV	$15 > m > 10$	Midlands	Tropical forest and savanna. Temperate and tropical crops
III	$20 > m > 15$	Lower midlands	Tropical forest and savanna. Some temperate crops (wheat), most tropical crops (e.g. Robusta coffee)
II	$24 > m > 20$	Upper lowlands	No temperate crops. Tropical forest and savanna
I	$30 > m > 24$	Lowlands	Tropical forest and savanna. Very cold-sensitive crops (cocoa, coconut, cashew, clove, raphia, etc.)

[a] *m*, mean daily minimum temperature of the coldest month in °C

Table T34 Equatorial agro-bioclimates (lowland), native vegetation and land use

Zone, no.	Sub-climates	Vegetation types/livestock	Land-use patterns
7	Hyper-arid	Contracted. Camels, goats, some sheep, rare cattle	Grazing, nomadism, no cultivation without irrigation
6	Very arid	Diffuse shrubland and open bushland–perennial grasses, camels, goats, sheep, some cattle (zebu)	Grazing, nomadism, virtually no rain-fed cultivation
5	Arid	Bushland and open woodland, perennial grasses, cattle, sheep, goats, rare camels	Grazing, nomadism and settled pastoralists, some subsistence farming (millet, sorghum, cow pea)

(*continued*)

Table T34 (continued)

Zone, no.	Sub-climates	Vegetation types/livestock	Land-use patterns
4	Semi-arid	Woodlands, savanna, grassland, crop land, light tsetse infestation, cattle (zebu) sheep, goats	Settled animal husbandry farming, millet, sorghum, cowpea, groundnuts, sweet potatoes, pigeon pea; sown pasture and range reseeding possible
3	Sub-humid	Woodland, savanna, grassland, crop land, heavy tsetse infestation in woodland and savanna (*G. morsitans*)	Limited animal husbandry, sorghum, maize, sugar-cane, banana, rice, yam, cassava, cotton, tobacco; sown pasture and range reseeding
2	Humid	Forest, woodland, savanna, crop land, taurine cattle and dwarf goats. Perennial tsetse riverine infestation	Restricted animal husbandry, farming as above, timber production
1	Hyper-humid	Rainforest, taurine cattle and dwarf goats, permanent heavy tsetse infestation	Restricted animal husbandry, oil palm, cocoa, coffee, coconut, hevea, timber production

2.3.4 Overall Classification Sketch

1. Extra-tropical agro-bioclimates
   - Winter rains

   7 aridity classes × 10 thermal classes = 70 theoretical combinations
   - Summer rains

   7 aridity classes × 10 thermal classes = 70 theoretical combinations
2. Tropical agro-bioclimates

   7 aridity classes × 8 thermal classes = 56 theoretical combinations
3. Equatorial agro-bioclimates

   7 aridity classes × 8 thermal classes = 56 theoretical combinations.

   Total: 252 theoretical combinations

In fact, some combinations never occur, for various reasons (e.g. cold hyper-arid zones). The actual number of combinations occurring is about 200. Some of these occupy very large areas, such as the hyper-humid equatorial lowlands (some 9×10^6 km^2), and the extra-tropical, winter rains, cold hyper-arid zone (some 5×10^6 km^2). Other combinations cover very small areas, such as the afro-alpine and Mediterraneo-alpine ecozones, the equatorial hyper-arid midland ecozone, etc.

The present classification thus differs in nature from previous attempts such as Köppen's, which recognizes some 15 types of climatic ecozones in Africa, or UNESCO's (1977/1979), which differentiates some 20 kinds, excluding the humid

Table T35 Equatorial agro-bioclimatic classification (bimodal rainfall pattern; see also Fig. 49)

Thermal classes			I	II	III	IV	V	VI	VII	VIII
			No frost					Light frost	Hard frost	Severe frost
m (°C)			30–24	24–20	20–15	15–10	10–8	8–4	4–1	1 to −5
Aridity classes			Lowlands	Upper lowlands	Lower midlands	Midlands	Upper midlands	Lower highlands	Upper highlands	Afro-alpine
No.	*P*/ETo (%)									
7	5	Hyper-arid	7-I	7-II	7-III	7-IV	7-V	7-VI	n.a.	n.a.
6	15	Very arid	6-I	6-II	6-III	6-IV	6-V	6-VI	n.a.	n.a.
5	30	Arid	5-I	5-II	5-III	5-IV	5-V	5-VI	n.a.	n.a.
4	45	Semi-arid	4-I	4-II	4-III	4-IV	4-V	4-VI	4-VII	4-VIII
3	75	Sub-humid	3-I	3-II	3-III	3-IV	3-V	3-VI	3-VII	3-VIII
2	100	Humid	2-I	2-II	2-III	2-IV	2-V	2-VI	2-VII	Doubtful
1	>200	Hyper-humid	1-I	1-II	1-III	1-IV	1-V	1-VI	n.a.	n.a.

and hyper-humid ecozones. Subdivisions within the hyper-arid ecozone have been purposely ignored in the map of Fig. 32, although some types of deserts, such as the coastal fog deserts associated with cold offshore upwelling, could have been highlighted, such as in Namibia, Morocco-Mauritania, and the Red Sea coastal plains and uplands.

2.4 Relations to Other Classifications

The number of bioclimatic, agro-climatic, eco-climatic and biogeographic classifications is indeed very large. Some are of general use, while others are only of local or regional scope. I have given the equivalences of the present classification with those of Köppen and Bagnouls-Gaussen, which are of general usage; the latter scheme has been somewhat improved and systematized by Walter and Lieth (1960) and Walter et al. (1975; see Sect. 1.2.3 and Fig. 55). The reason why I did not use these classifications is mainly because they are based on the empirical and somewhat obsolete, albeit fairly efficient, relationship between precipitation and temperature as a criterion of water stress/water availability, and on mean annual temperature as a criterion of cold or heat stress—this lacks accuracy, sensitivity and efficiency.

Other classifications, such as Thornthwaite's, Meig's and Holdrige's, are liable to similar shortcomings, due to the fact that their method of evaluation of PET yields values that are far from realistic, either as measured in lysimeters or as evaluated via more sophisticated equations such as Penman's or Monteith's; moreover, their temperature criterion, being the annual mean, likewise lacks sensitivity and accuracy. Emberger's system is efficient and broadly accepted for Mediterranean climates but inappropriate, in Emberger's own words, for both the temperate and inter-tropical climates. However, the cold-stress criterion selected by Emberger, the mean daily minimum temperature of the coldest month, is a very sensitive, accurate and efficient one, and I have used it as the discriminating parameter for the estimate of the impact of altitude on plant growth and distribution, i.e. winter-cold stress or the absence of such stress.

The eco-climatic classification of East Africa by Pratt et al. (1966) does not serve my purpose, as it is based uniquely on a moisture index, without any consideration of thermal conditions.

My classification is closest to UNESCO's for arid regions, where the water-stress criterion is the rainfall/evapotranspiration ratio, *P*/ETo. Nevertheless, I felt that this was not enough, as the length of the rainy and dry seasons should not be ignored for assessments of water requirements. The UNESCO classification (1977/1979) relies on the mean temperature of the coldest month as a criterion of temperature constraint. This is better than the annual mean but still inadequate in terms of sensitivity, accuracy and precision because this parameter, unlike the mean daily minimum of the coldest month, is rather poorly correlated with frost hazard (Le Houérou 1975).

The classification of Cochemé and Franquin (1967) for the Sahel is based on the length of the rainy season, when $P>0.5$ PET, but is not appropriate for the highlands nor for extra-tropical Africa—again, potential cold stress is not accounted for. Moreover, the 0.5 PET threshold appears somewhat too high.

The classification used by Braun (1982) and by Jätzold and Schmidt (1982) for Kenya is very close to the present one, the equivalence being given in Tables A16–A18 and Fig. 49. Yet again, the temperature criterion lacks sensitivity, accuracy and precision; furthermore, although well adapted to East Africa, it is much less so for West, South and North Africa. It thus does not really represent plant requirements in these regions, which may be very different from those in East Africa for various reasons such as annual temperature amplitude (2–5°C in E. Africa; 10–15 in the Sahel and the Kalahari; 15–20°C at 30°N and S).

Similarly, relative humidity, saturation deficit, rainfall variability, and day length are tied to latitude—e.g. the seasonal variations in day length in E. Africa are only a few minutes, vs. 2 h in the Sahel and the Kalahari, and 5–6 h at 30–35° lat. in N. and S. Africa. This factor of photoperiodism is not directly taken into consideration in the present classification but it is indirectly considered via the major differentiation at the climate family level of classification: subtropical (i.e. extra-tropical), tropical and equatorial. Some plant species and cultivars are very sensitive to photoperiodism, such as grain sorghum and bulrush millet, since even a few minutes' difference in day length may result in success or failure of a given cultivar in a different location (Vaksman and Traoré 1991; Traoré et al. 1993).

Overall, I have tried to use the most simple, rational and reliable parameters to represent water and temperature requirements and constraints. The discriminating values of these parameters have been selected on the basis of agronomic and ecological criteria of the distribution of native vegetation, wildlife, crops and livestock, in an attempt to make this classification realistic and utilizable for the continent as a whole, with the aim of producing a framework that could be safely used by agronomists, foresters, range and livestock specialists, ecologists, land-use and development planners and also, hopefully, teachers and trainers.

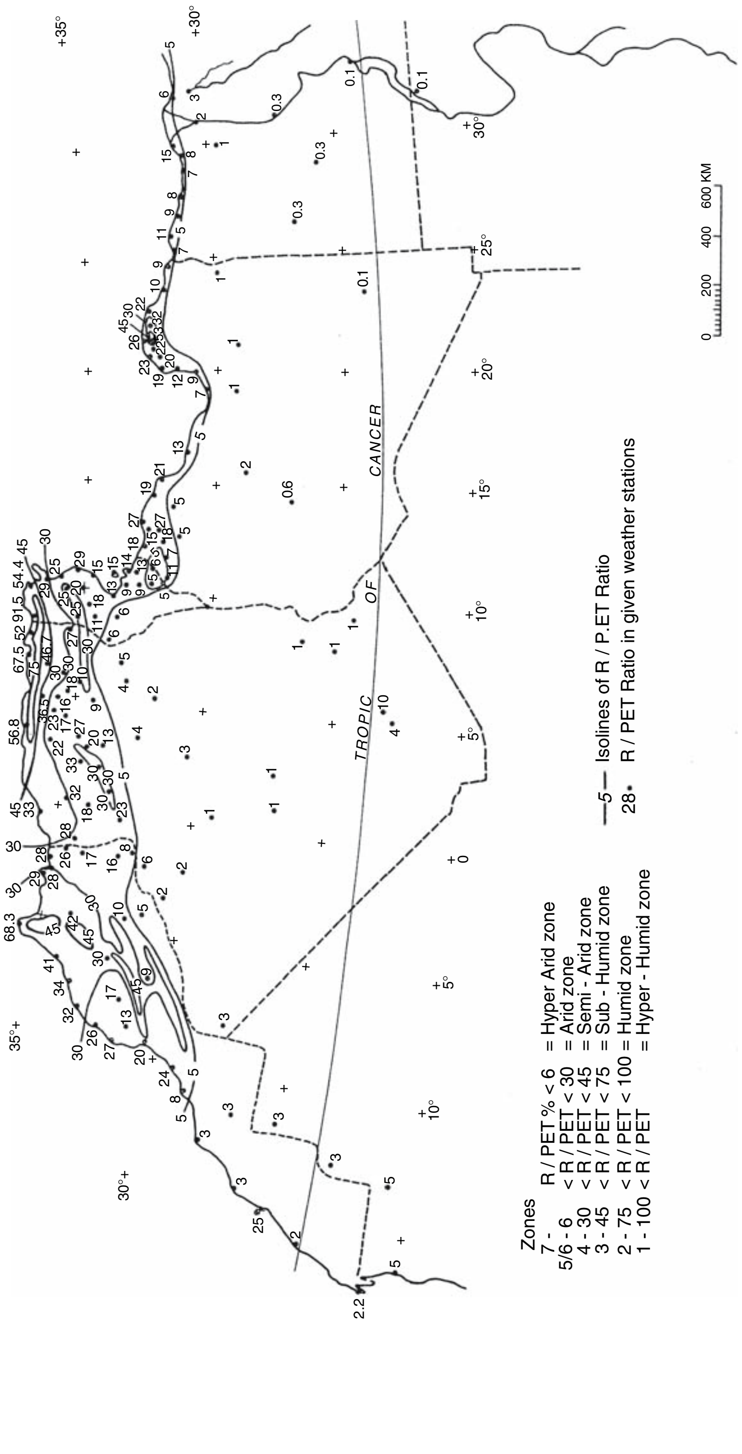


Fig. 27 Distribution of the index of aridity zoning (P/ETo×100) in northern Africa and the Sahara (Le Houérou 1995a)

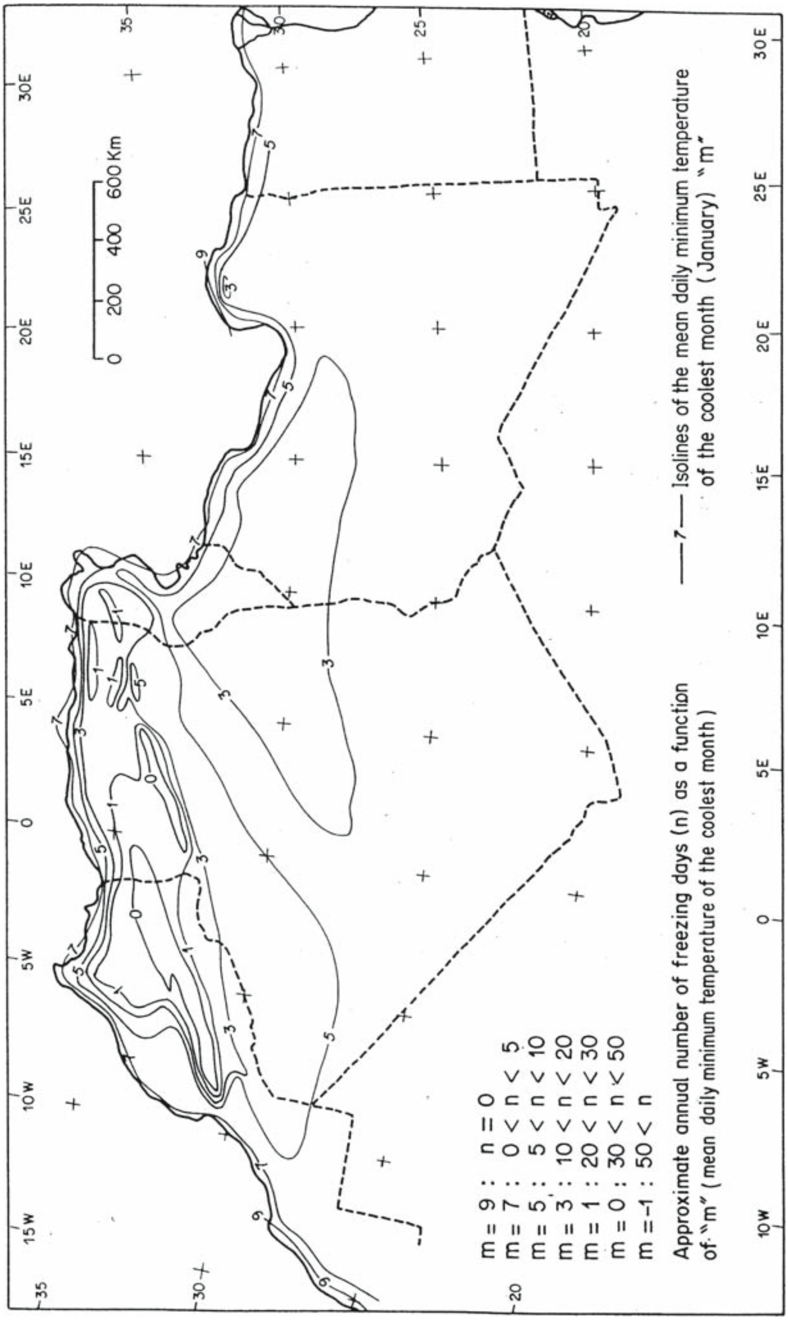


Fig. 28 Distribution of winter temperature (*m*) in northern Africa and the Sahara (Le Houérou 1995a)

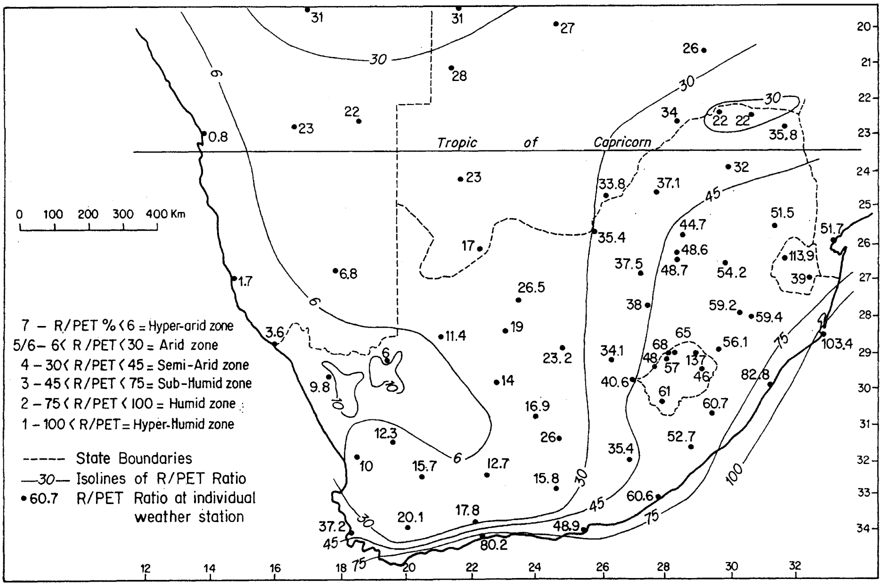


Fig. 29 Aridity zoning in southern Africa (*P*/ETo × 100, Le Houérou 1994b)

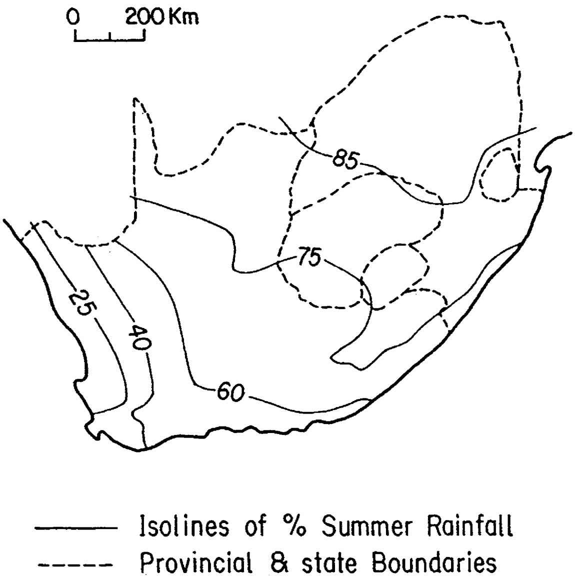


Fig. 30 Proportions of winter and summer rainfall in the annual total in South Africa (Cox, cited in Adamson 1938)

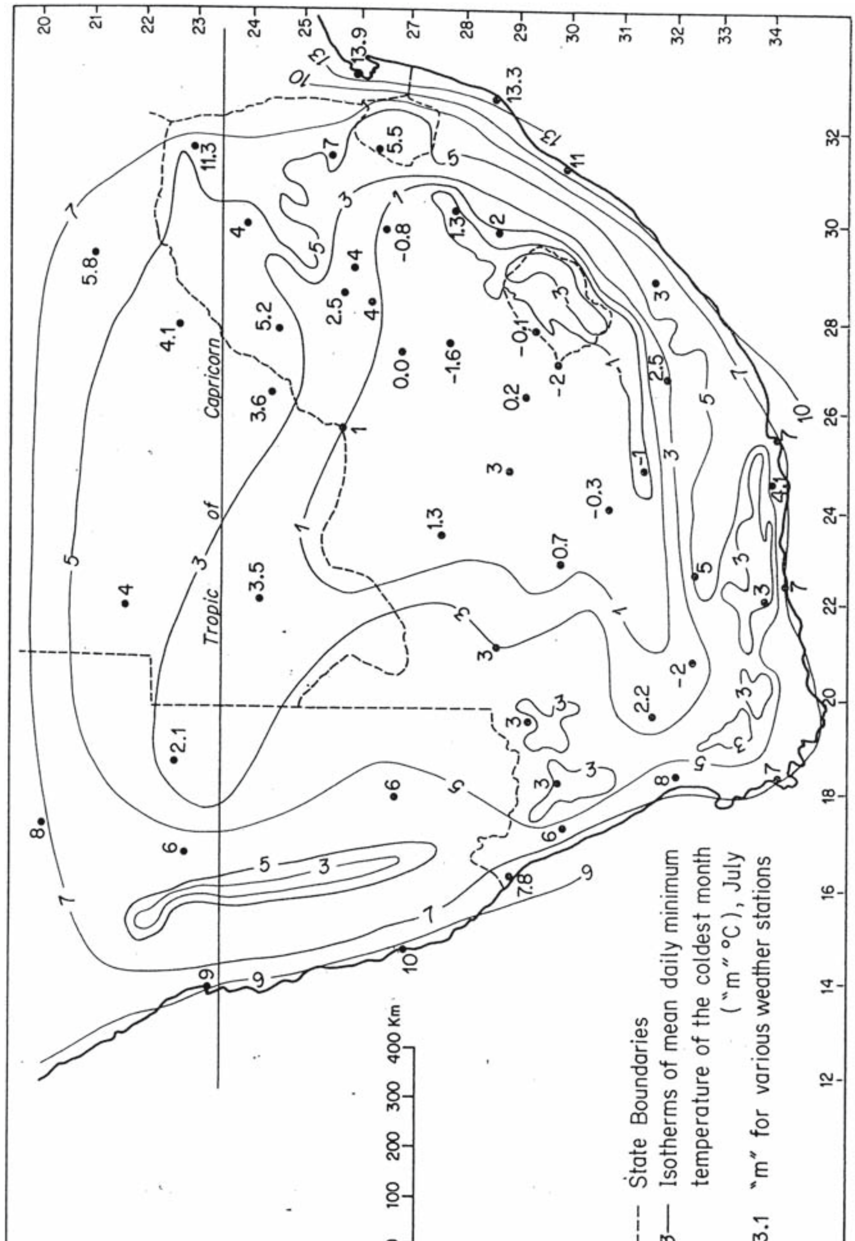


Fig. 31 Map of winter temperature (*m*) in southern Africa (Le Houérou 1994b)

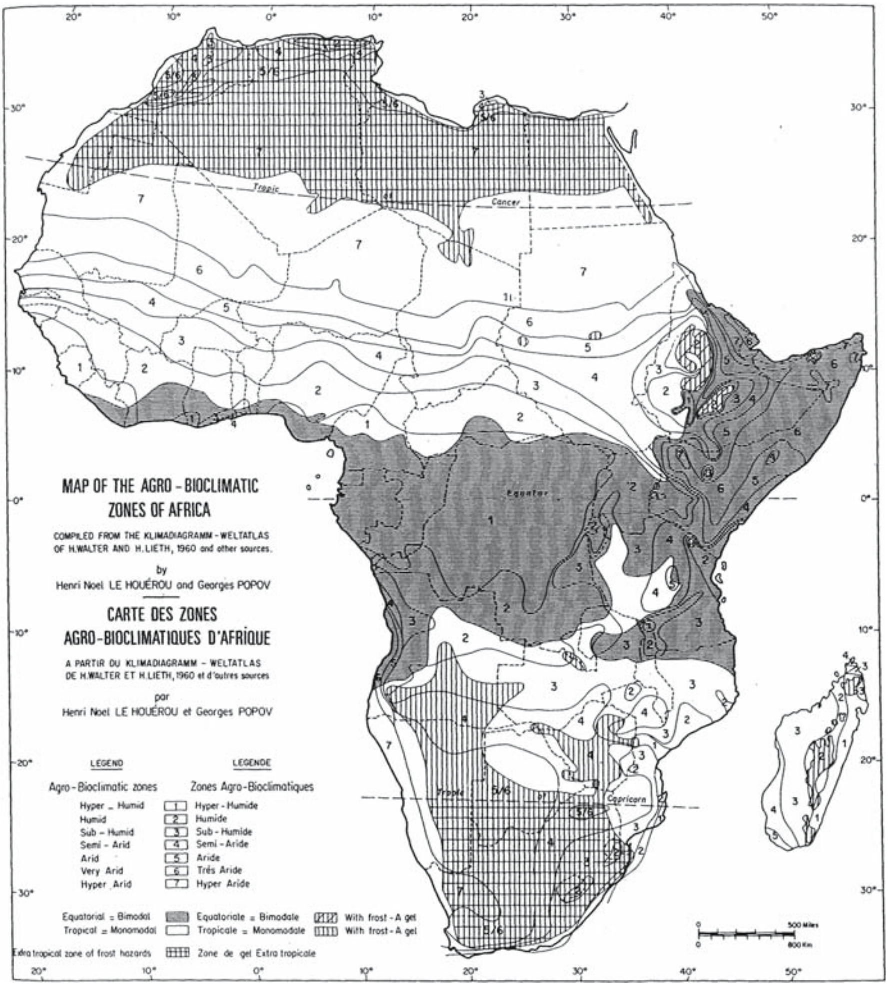


Fig. 32 Map of the agro-bioclimates of Africa (Le Houérou et al. 1993)

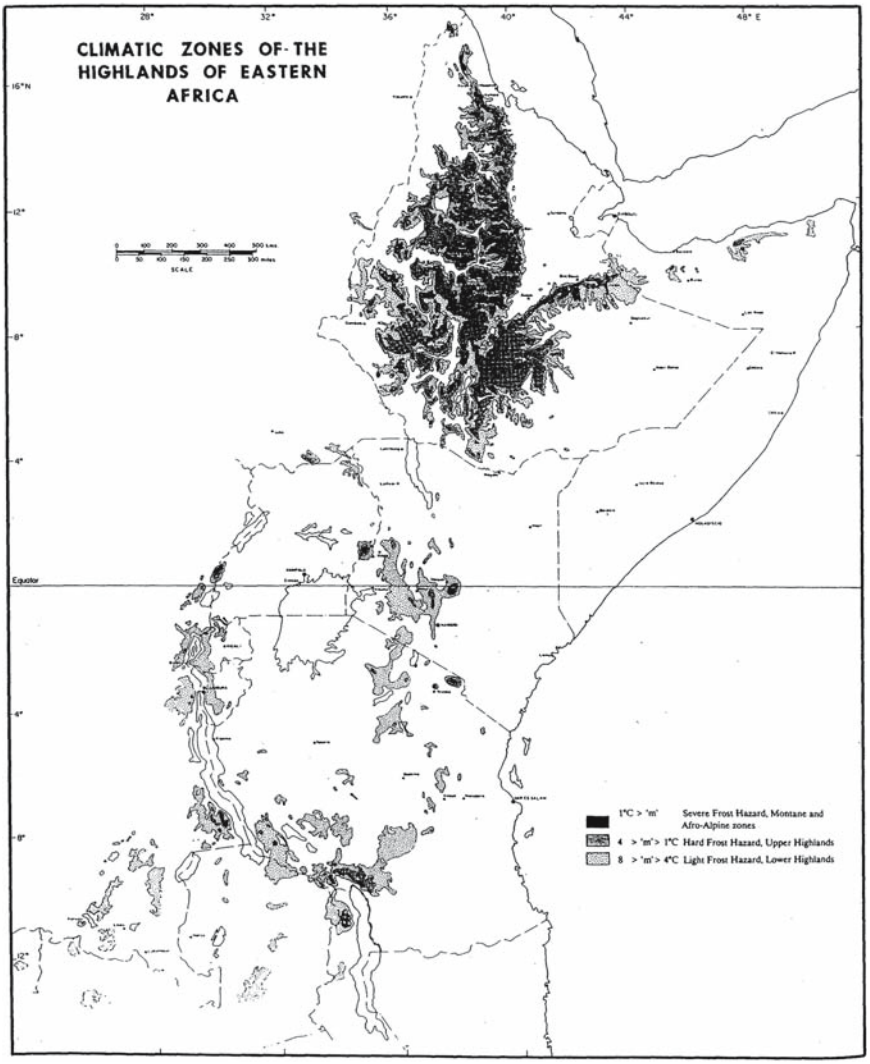


Fig. 33 Geographic distribution of the highlands of East Africa, in relation with winter temperature (*m*; Le Houérou and Popov 1981)

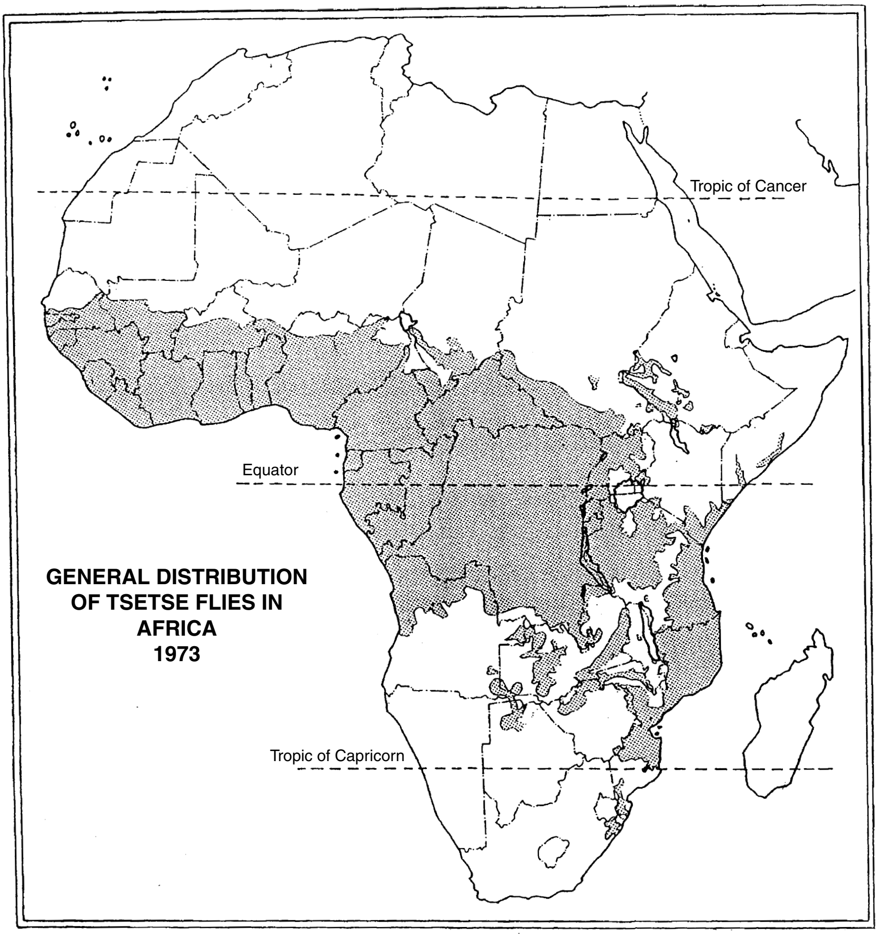


Fig. 34 Simplified map of the distribution of tsetse flies in inter-tropical Africa (Ford and Katondo 1976; Le Houérou and Popov 1981)

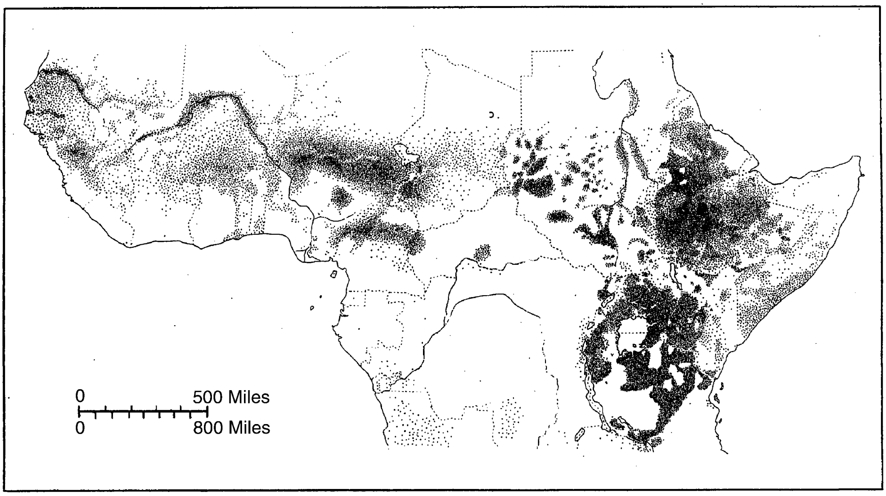


Fig. 35 Geographic distribution of cattle in inter-tropical Africa (N'derito and Adeniji 1976, cited in Le Houérou and Popov 1981). *One dot* corresponds to 5,000 heads of adult cattle

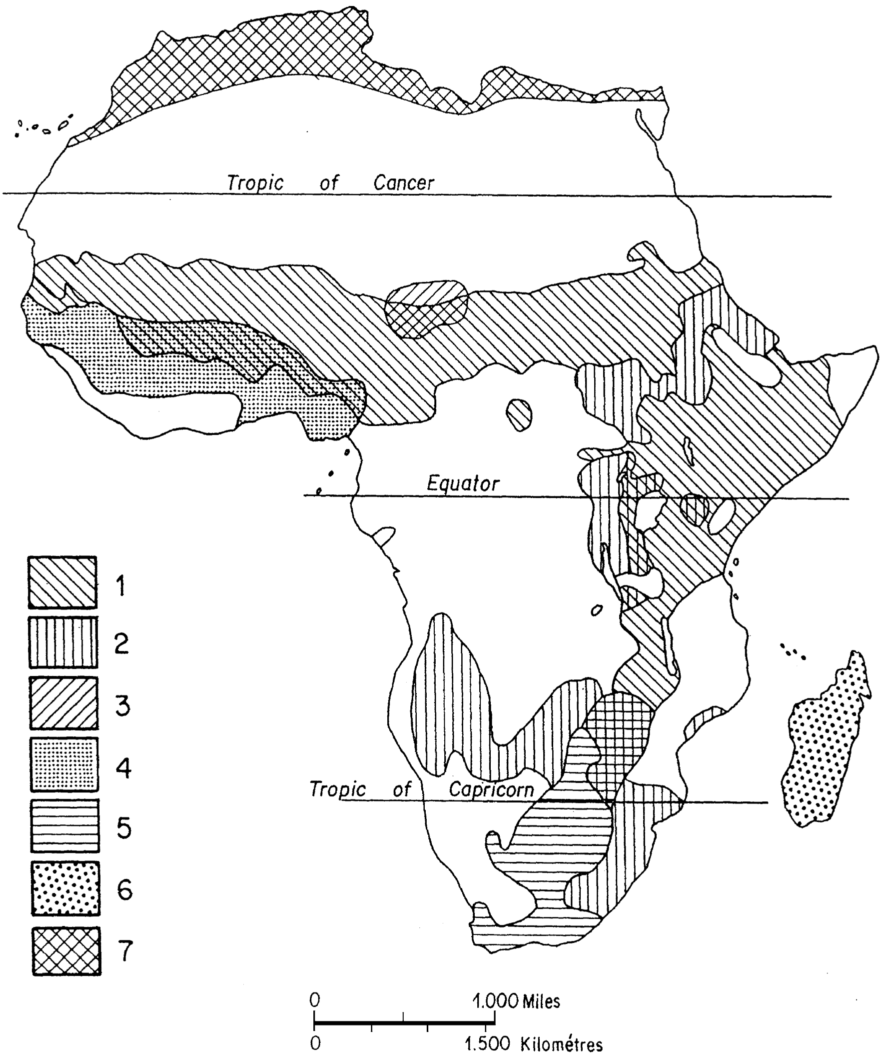


Fig. 36 Geographic distribution of cattle breeds in Africa (partly from N'Derito and Adeniji 1976, cited in Le Houérou and Popov 1981). *1* East and West African zebus (*Bos indicus*). *2* Sanga and Ankolé (*B. taurus x B. indicus*). *3* Kuri (*Bos taurus*). *4* N'Dama and West African short horn (*Bos taurus*). *5* Afrikander (*Bos taurus x B. indicus*). *6* Madagascar zebu (*B. indicus*). *7* North African Atlas brown (*B. taurus*)

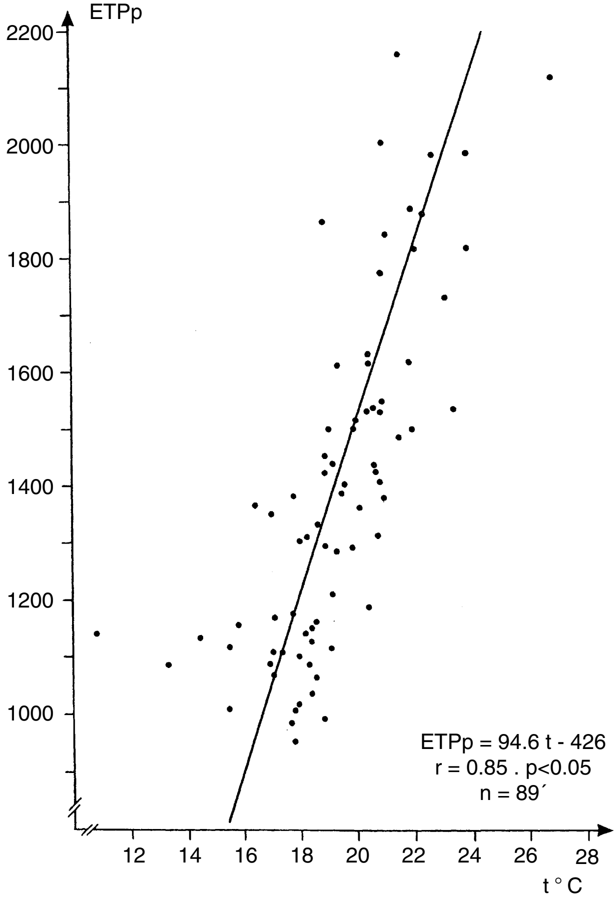


Fig. 37 Relationship between mean annual temperature and ETPp (Penman standard) in northern Africa (Le Houérou 1995a)

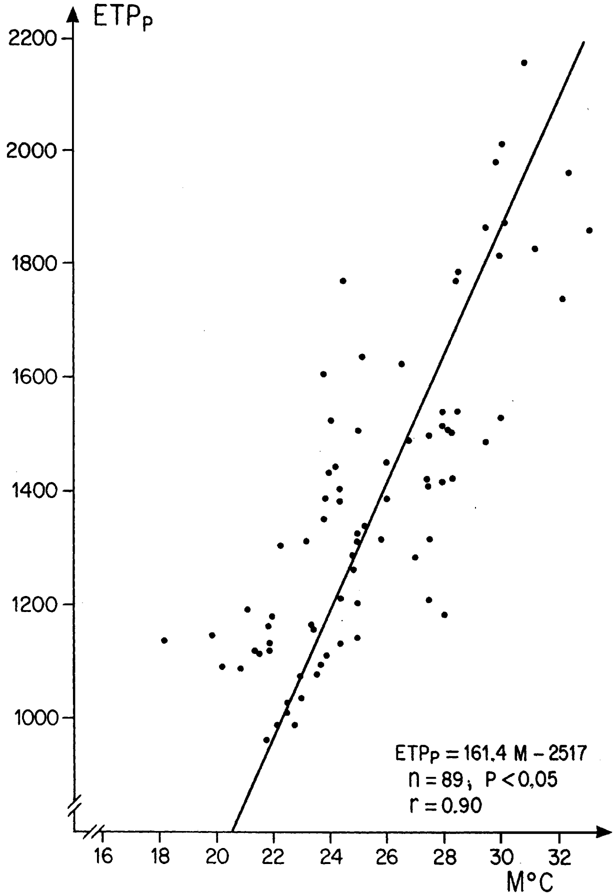


Fig. 38 Relationship between mean maximum annual temperature and ETPp (Penman standard) in northern Africa (Le Houérou 1995a)

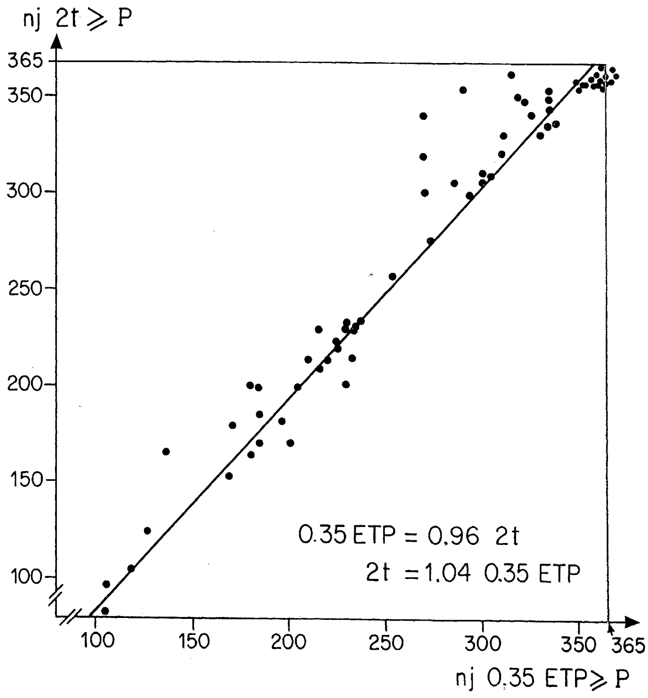


Fig. 39 Relationship between two criteria of assessment of the length of the dry and rainy seasons ($P = 2t$ and $P = 0.35$ ETo) in northern Africa (Le Houérou 1995a)

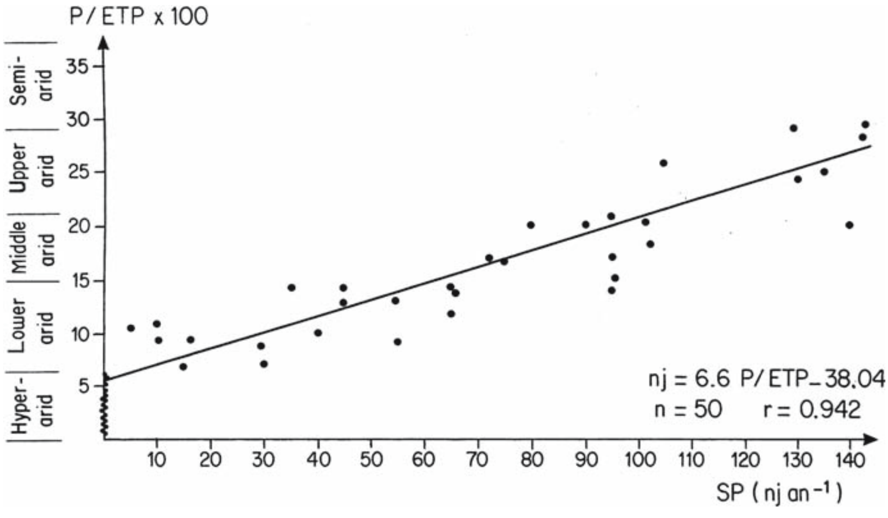


Fig. 40 Relationship between the aridity index (P/ETo) and the length of the dry season ($P < 0.35$ ETo) in the arid zones of northern Africa (Le Houérou 1995a)

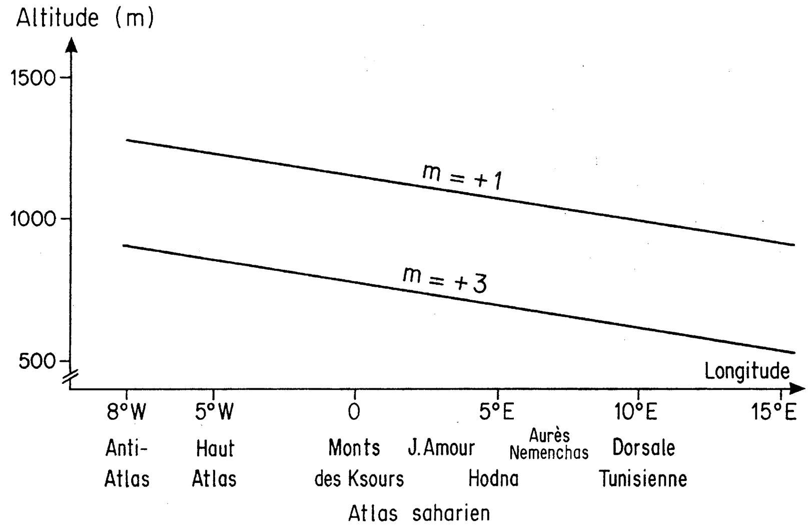


Fig. 41 Geographic and longitudinal variation in the elevation of some critical winter isotherms (*m*) in northern Africa, as a function of distance from the Atlantic Ocean (Le Houérou 1998a)

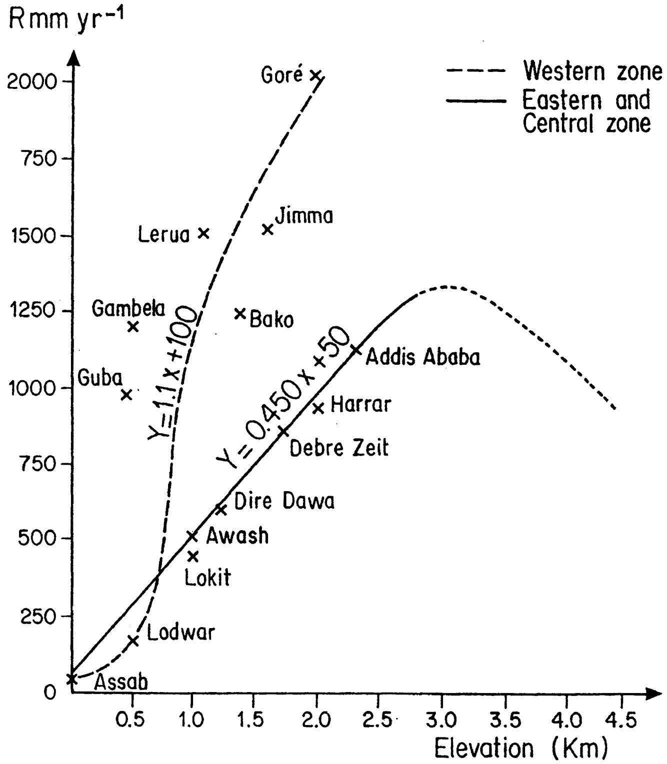


Fig. 42 Relationship between elevation and mean annual rainfall in Ethiopia (Le Houérou 1984a)

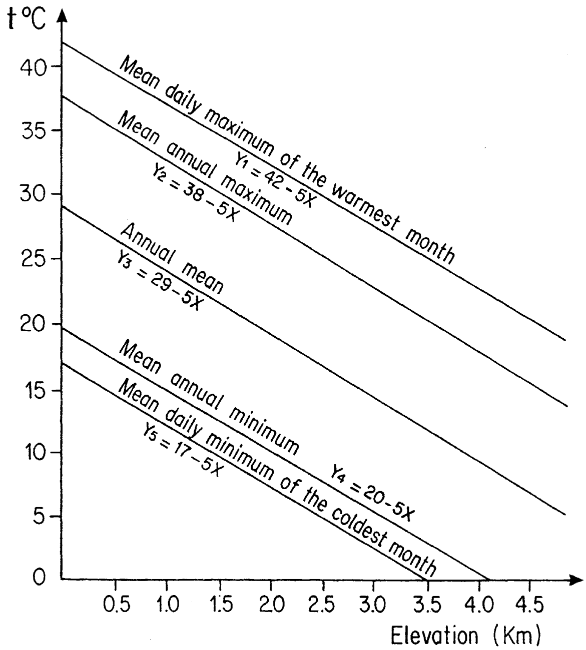


Fig. 43 Relationship between mean annual temperature and elevation in Ethiopia (Le Houérou 1984a)

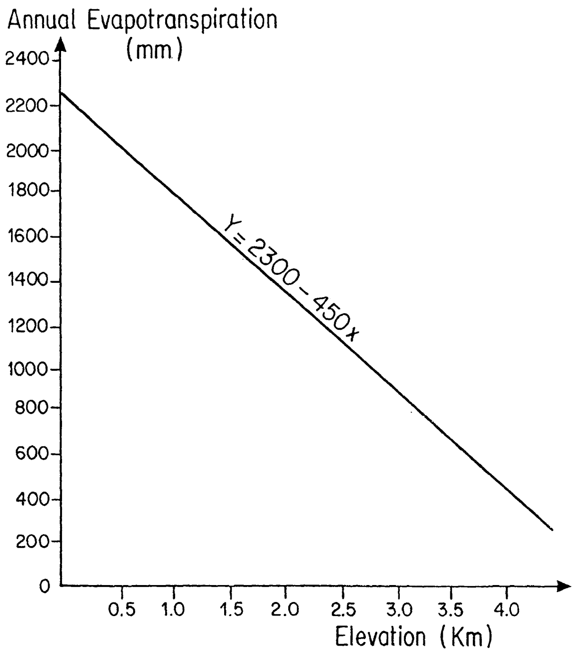


Fig. 44 Relationship between elevation and PET in Ethiopia (Le Houérou 1984a)

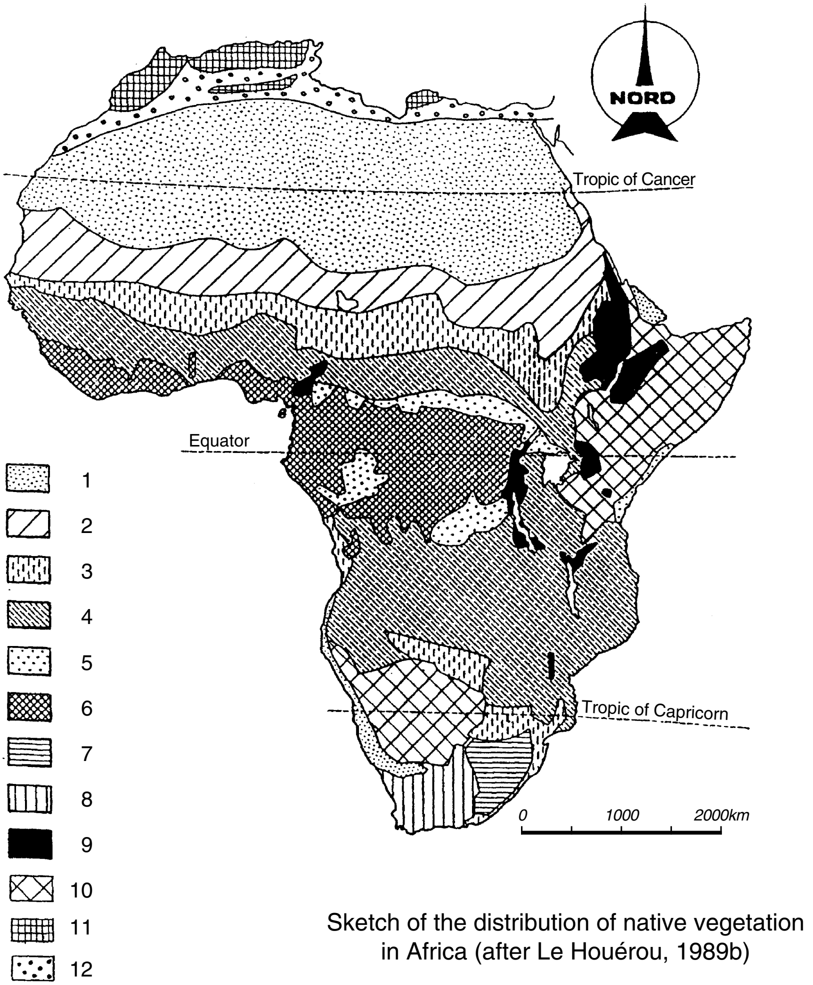


Fig. 45 Sketch of the geographic distribution of natural vegetation in Africa (Le Houérou 1989b). *1* Sahara and Namib deserts: contracted perennial vegetation. *2* Sahel: Mimosoideae scrub (*N*) and Combretaceae savanna *(S)*. *3* Northern Sudanian savanna. *4* Southern Sudanian savanna. *5* Mixed forest, woodland and savanna. *6* Guinean and Congolian rainforest. *7* Subtropical and temperate grassland. *8* Mixed shrubland and grassland. *9* Montane and Afro-alpine mixed formations. *10 Acacia-Commiphora* scrub and Combretaceae savanna with perennial grasses (E. Africa and the Kalahari). *11* Sclerophyllous and acicular Mediterranean forest and shrubland. *12* Perennial grass and dwarf shrub Mediterranean steppe

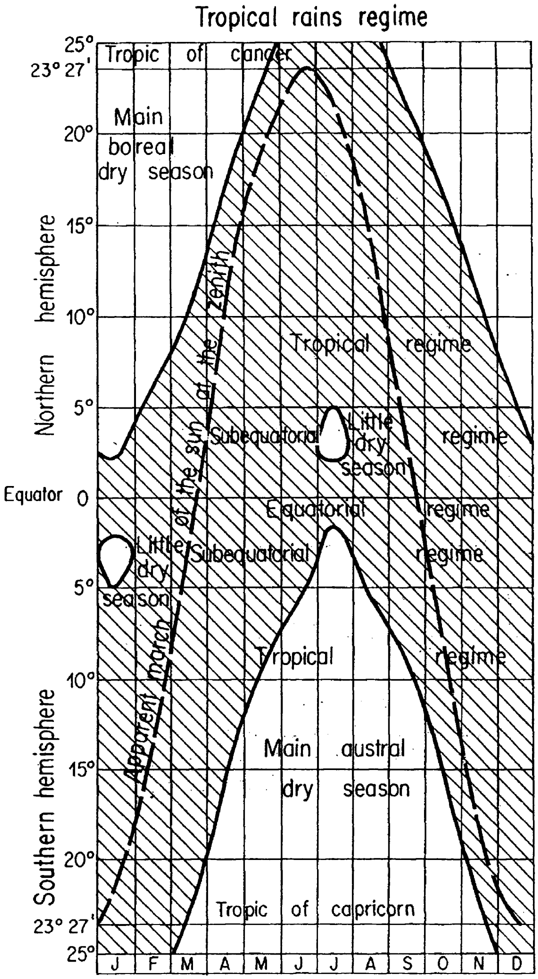


Fig. 46 Distribution of dry and rainy seasons in the inter-tropical zone of Africa (De Martonne 1926; Aubréville 1949)

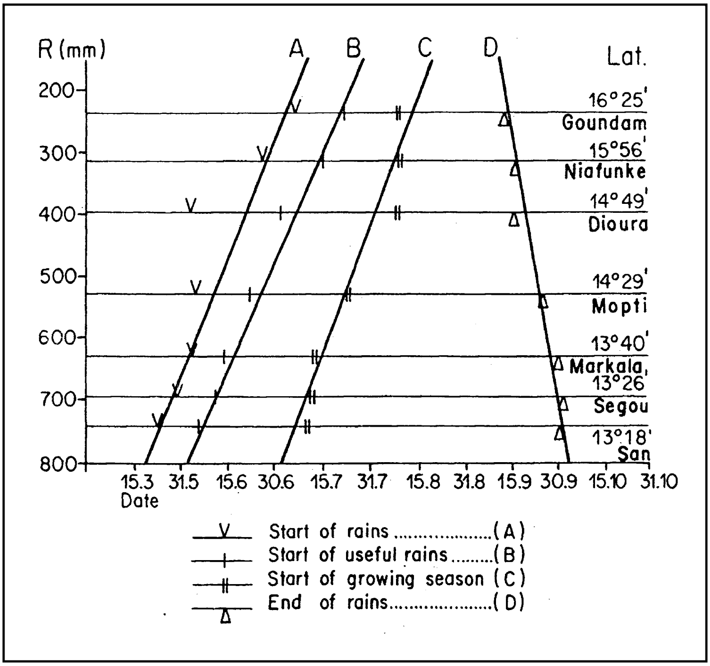


Fig. 47 Initiation and end of the rainy season in Mali, as a function of latitude (Wilson 1982, cited in Le Houérou 1989b)

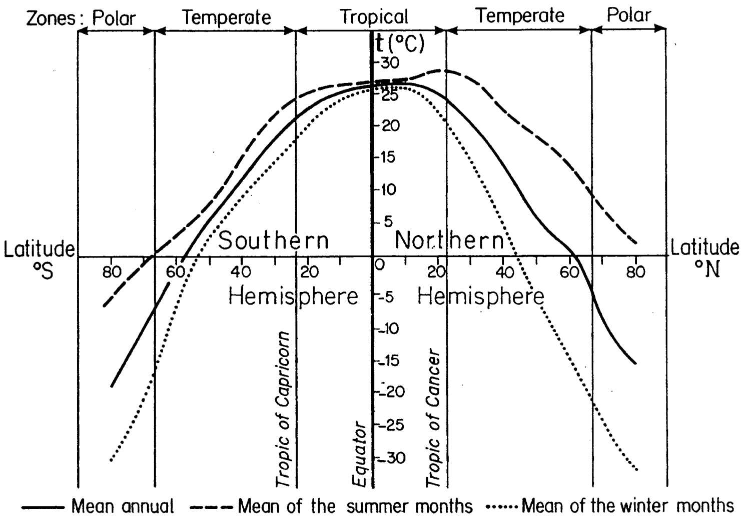


Fig. 48 Mean annual temperature as a function of latitude in both hemispheres of inter-tropical Africa (Hann et al., cited in De Martonne 1927a, b, modified)

	Belts of Z. \ Main Zones	0 (perhumid)	1 (humid)	2 (subhumid)	3 (semi-humid)	4 (transitional)	5 (semi-arid)	6 (arid)	7 (perarid)
G	**TA** Tropical Alpine Zones Ann. mean 2-10° C	Glacier Mountain swamps	I. Cattle-Sheep Zone	II. Sheep Zone				High altitude deserts	
F	UH Upper Highland Zones Ann. mean 10-15° Seasonal night frosts	Forest Zones	Sheep-Dairy Zone	Pyrethrum-Wheat Zone	Wheat-Barley Zone	U. Highland Ranching Zone	★ U.H. Nomadism Zone [4]		
E	LH Lower Highl. Zones Ann. mean 15-18° M. min. 8-11° norm. no frost		Tea-Dairy Zone	Wheat/Maize[2] - Pyrethrum Zone	Wheat/(M)[2]- Barley Zone	Cattle-Sheep-Barley Zone	L. Highland Ranching Zone	★ L.H.Nomadism Zone [4]	
D	**UM** Upper Midland Zones Ann. mean 18-21° M.min. 11-14°		Coffee-Tea Zone	Main Coffee Zone	Marginal Coffee Zone	Sunflower-Maize [3] Zone	Livestock-Sorghum Zone	U. Midland Ranching Zone	U. Midland Nom. Zone [4]
C	**LM** Lower Midland Zones Ann. mean 21-24° M. min. > 14°	★	L. Midl Sugar-cane Zone	Marginal Sugarcane Zone	L. Midland Cotton Zone	Marginal Cotton Zone [6]	L. Midland Livestock-Millet Zone	L. Midland Ranching Zone	L. Midland Nom. Zone [4]
B	**L** Lowland Zones **IL** Inner Lowland Z. Ann. mean > 24° Mean max. > 31°	★	★ Rice-Taro Zone	★ Lowland Sugarcane Zone	★ Lowland Cotton Zone	★ Groundnut Zone	Lowland Livestock-Millet Zone	Lowland Ranching Zone	Lowland Nom. Zone [4]
A	**CL** Coastal Lowl.Z. [5] Ann. mean > 24° Mean max. < 31°	★	★ Cocoa-Oilpalm Zone	Lowland Sugarcane Zone	Coconut-Cassava Zone	Cashewnut-Cass. Zone	Lowland Livestock-Millet Zone	Lowland Ranching Zone	Lowland Nom. Zone [4]

1) Inner Tropics, different zonation towards the margins. The T for Tropical is left out in the thermal belts of zones (except at TA), because it is only necessary if other climates occur in the same country. The names of potentially leading crops were used to indicate the zones. of course these crops can also be grown in some other zones, but they are then normally less profitable.
2) Wheat or maize depending on farm scale, topography, a.o.
3) Maize is a good cash crop here, but maize also in LH 1, UM 1-3, LM and L 1-4;
4) Nomadism, semi-nomadism and other forms of shifting grazing
5) An exception because of the vicinity of cold currents are the tropical cold Coastal Lowlands cCL in Peru and Namibia. Ann. mean there between 18 and 24°
6) In unimodal rainfall areas growing periods may be already too short for cotton. Then the zone could be called Lower Midland Sunflower-Maize Zone.
★ Not in Kenya

Fig. 49 Agro-bioclimatic zoning in Kenya (Jäzold and Schmidt 1982, modified)

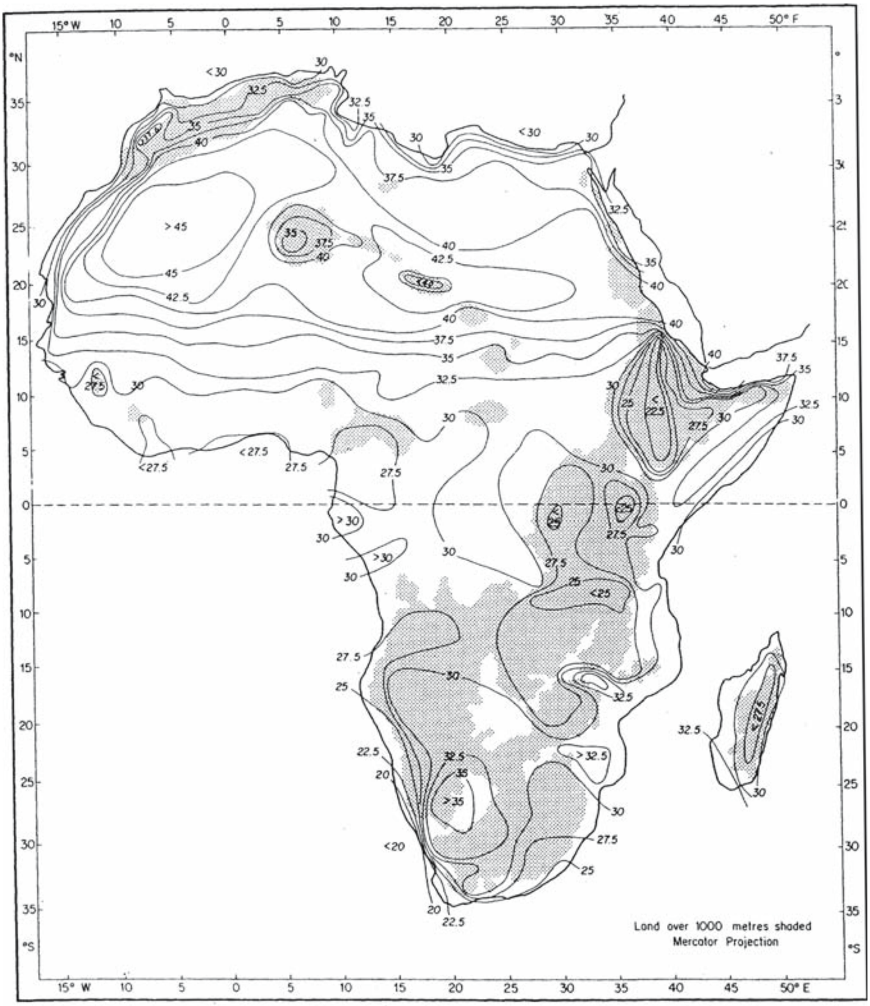


Fig. 50 Mean daily maximum temperature of the hottest month (°C, July in the northern hemisphere, January in the southern hemisphere; Thompson 1965)

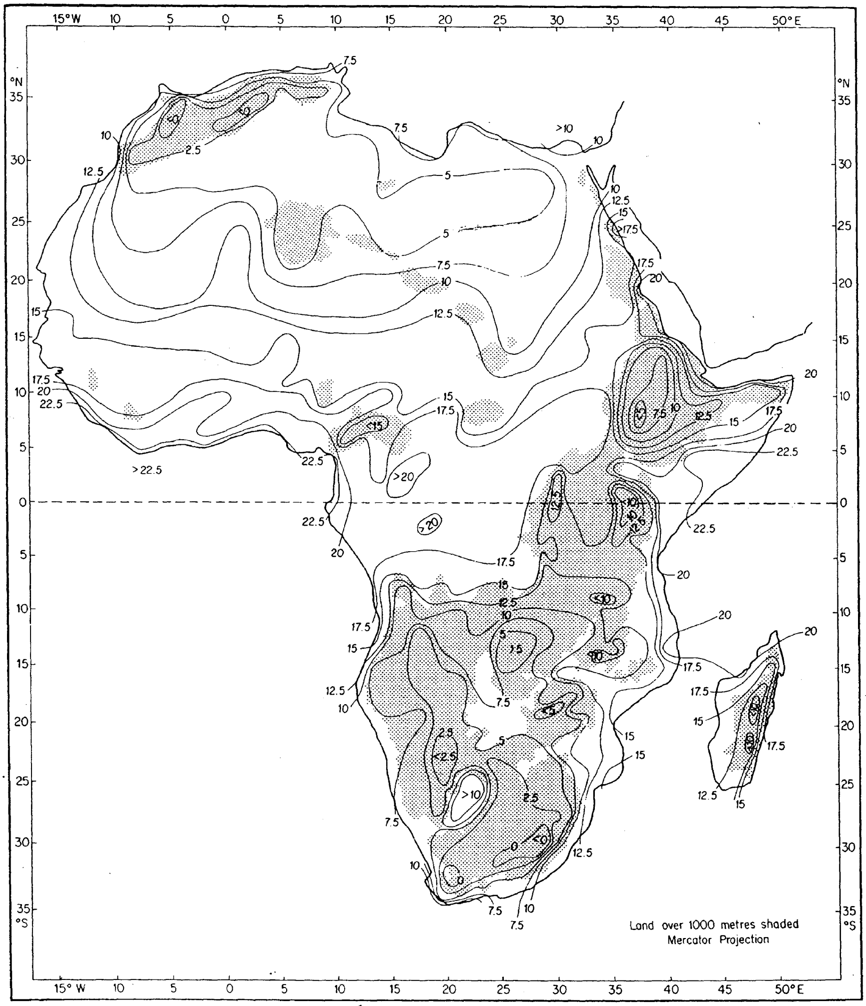


Fig. 51 Mean daily minimum temperature of the coolest month (°C) in Africa (Thompson 1965). Note: $M + m/2 \approx T$

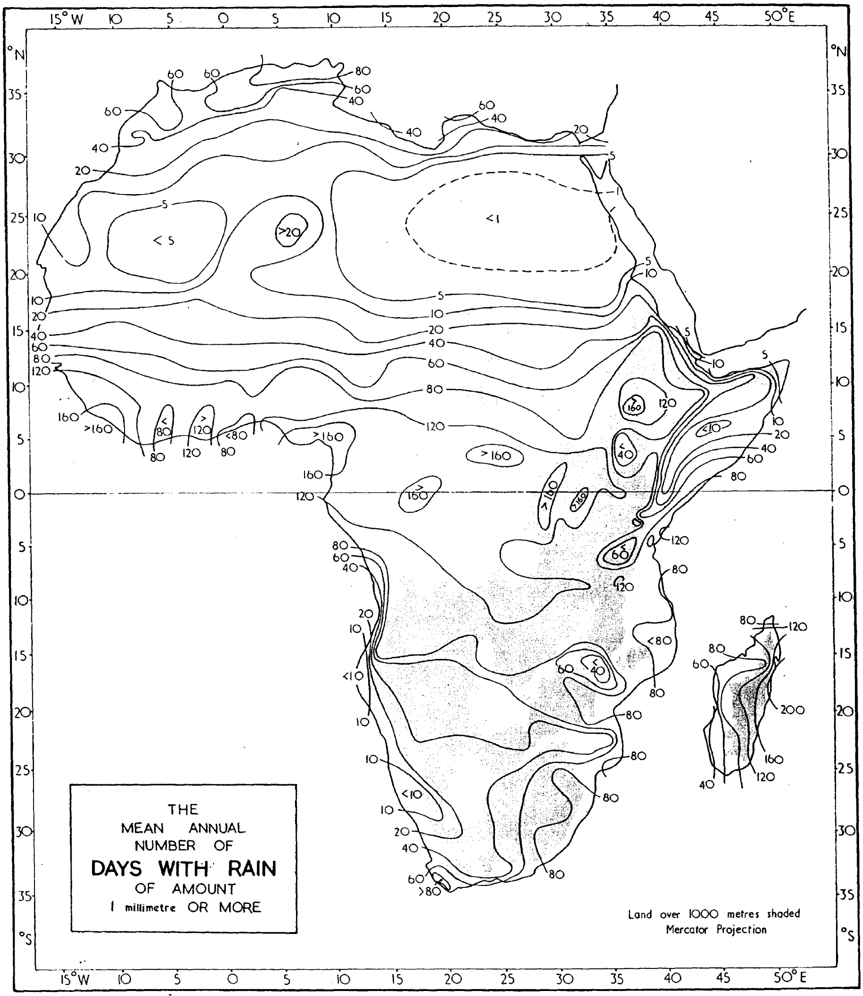


Fig. 52 Mean annual number of days with rain (>1 mm) in Africa (Thompson 1965)

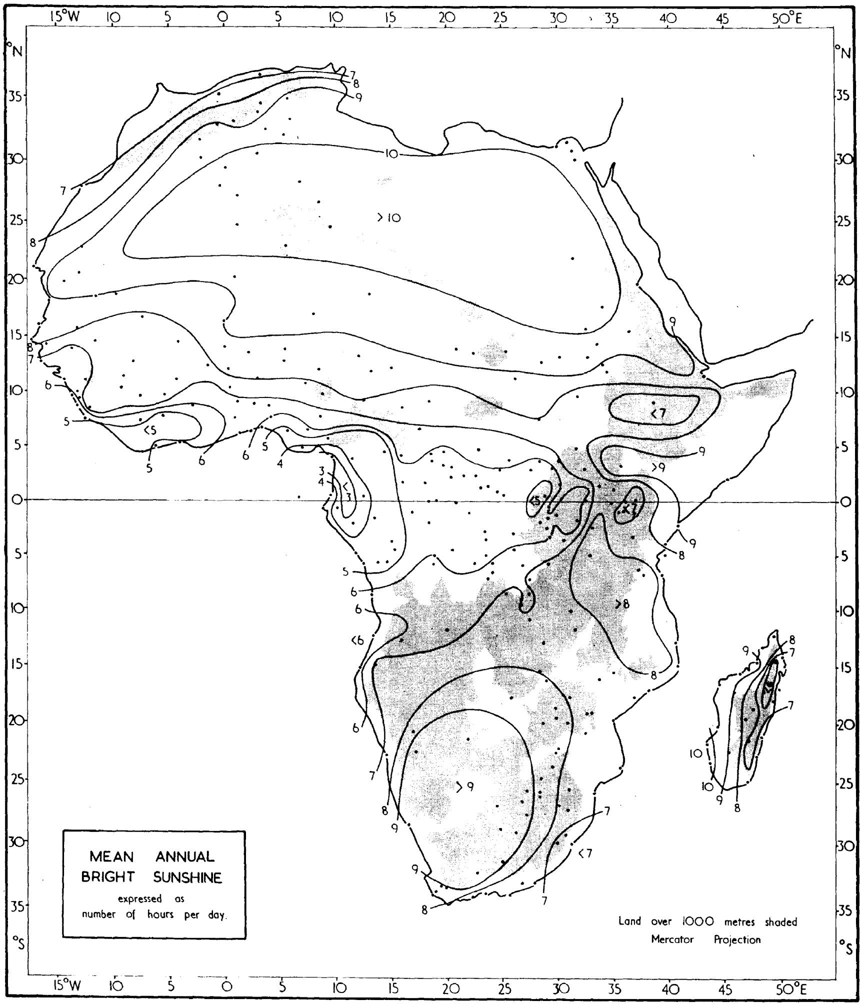
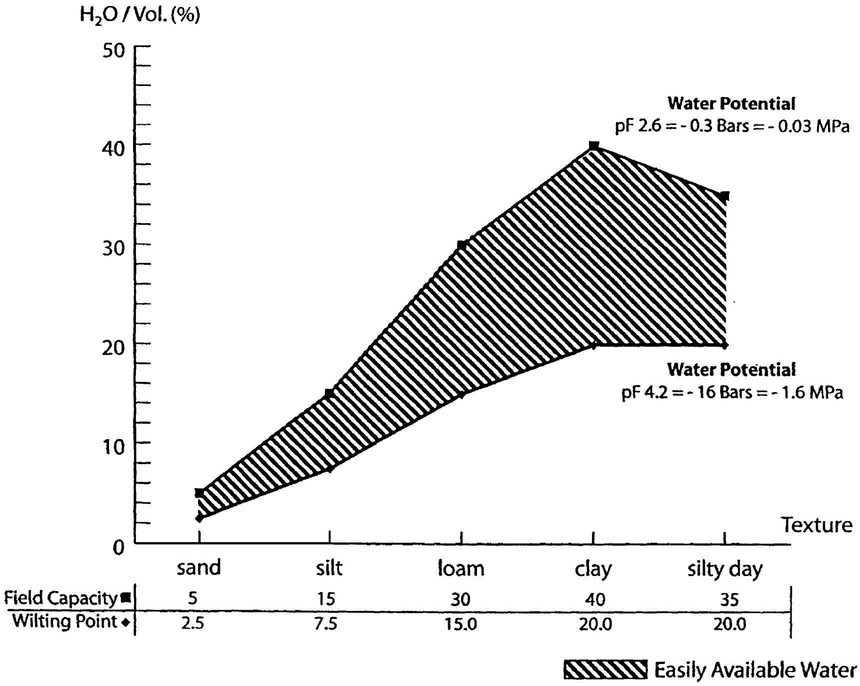


Fig. 53 Mean annual number of hours per day with bright sunshine in Africa (Thompson 1965)

3 h day^{-1} = 1,095 h $year^{-1}$	7 h day^{-1} = 2,555 h $year^{-1}$
4 h day^{-1} = 1,460 h $year^{-1}$	8 h day^{-1} = 2,960 h $year^{-1}$
5 h day^{-1} = 1,825 h $year^{-1}$	9 h day^{-1} = 3,285 h $year^{-1}$
6 h day^{-1} = 2,190 h $year^{-1}$	10 h day^{-1} = 3,650 h $year^{-1}$



Soil water content, potential and retrieval as a function of texture. Original.

Fig. 54 Easily retrievable soil-water content as a function of texture (Le Houérou 2005b)

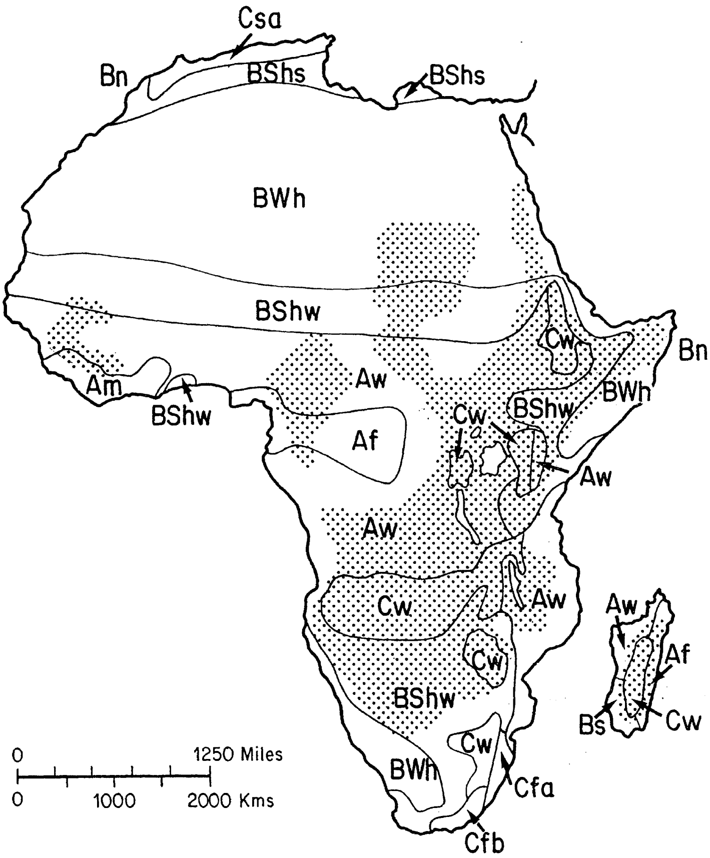


Fig. 55 The bioclimates of Africa according to Köppen's classification. Note that land above 500 m elevation is *shaded* in the inter-tropical zone (Köppen and Geiger 1930). *A* = tropical climates: Af = tropical wet, rainforest, Am = monsoon, one short dry season, Aw = tropical wet-and-dry, savanna; *B* = dry climates: BS = dry semi-arid, steppe, BShs = summer drought, subtropical, BShw = winter drought, tropical, Bn = coastal desert with fog; *C* = temperate climates: Cf = no distinct dry season, Cfa = hot summer, Cfb = cool summer, Cs = summer drought, subtropical, Cw = winter drought, tropical, upland savanna

Chapter 3
Land Degradation, Desertization and Rehabilitation

Abstract Chapter 3 discusses the problems of Land Degradation, Desertization and Rehabilitation, and their relationships to human total and rural populations and to livestock populations. The main points discussed are: Present and potential sustainable human populations, Evolution with time of human and livestock populations, Food production indices, GDP and economic evaluation, Desertization phenomena and their expansion, Rehabilitation efforts and potentials. It is clear that desertization is the consequence not only of droughts but also of mismanagement of the environment. Convincing evidence is provided based on, inter alia, large areas under relative protection during the great Sahel drought of the 1970–1980s, which survived ecologically unharmed through this historical dry period.

3.1 Causes of Land Degradation

Land degradation is widespread in Africa, increasing by the day as the pressure on the land augments due to fast demographic growth. The human population of Africa was 217 million in 1950, 642 in 1990, and 832 million in 2000, corresponding to a 3.5-fold increase in 40 years, i.e. a net growth rate of 2.2% per annum, with a doubling period of 32 years for this last 50-year period (Table T36). The present growth rate is 20 million per annum, i.e. 3.1% annually over the last decade. The population-supporting capacity under low to intermediate inputs was already below actual population density in the hyper-arid, arid and semi-arid zones in 1975 (Kassam et al. 1979). Only the sub-humid, humid and hyper-humid ecological zones had a supporting capacity clearly above the actual population density in 1975, as shown in Tables A13, T36–T40. However, the population has grown by almost 41% since 1980, and by 55% since 1975.

Table T36 Evolution of the human population in Africa (in millions; source: FAO production yearbooks)

1950	1960	1970	1980	1990	2000	2007	2010[a]
217	280	354	477	642	832	950	1075

[a] Projection

Table T37 Evolution of livestock populations in Africa (in millions): 1950–2000

Year, stock heads	1950	1960	1970	1980	1990	2000
Cattle	92	120	153	173	190	225
Camels	7	8	10	13	14	15
Sheep	115	130	160	180	209	239
Goats	80	106	134	147	183	214
Total TLU equivalents	117	146	196	211	230	276

Table T38 Evolution of the human/livestock populations ratios (TLU per person; data compiled from FAO production yearbooks)

1950	1960	1970	1980	1990	2000	2010[a]
0.54	0.52	0.55	0.44	0.36	0.33	0.25

[a] Projection

Table T39 Proportion of rural population relative to the overall population for the period 1950–2000

1950	1960	1970	1980	1990	2000
76	74	70	65	61	61

Table T37 shows the evolution of livestock populations in Africa (in millions) for the period 1950–2000 (computed from FAO production yearbooks; conversion factors: cattle 0.81, camels 1.16, sheep 0.18, goats 0.16 TLU; 250 kg Lwt at maintenance requirements). The data demonstrate that the overall growth of livestock numbers has increased by an exponential 1.75% per annum, vs. 2.2% for humans over the same period of 50 years.

Table T38 shows a clear-cut decline in human/livestock populations ratios; a large part of the decline seems due to the droughts of the 1970s and 1980s. It is worth noting that 54% of the livestock population is located in the arid, semi-arid and hyper-arid zones, 21% in the sub-humid and 10% in the humid zones, and 13% in the highlands (Figs. 35–36; Le Houérou 1977).

Table T39 shows the proportion represented by the rural population in the period 1950–2000 (source: FAO production yearbooks).

Average present and potential human population densities are shown in Table T40, extracted from Kassam et al. (1979) and Higgins et al. (1984) for the period as of 1975, and from Gorse (1984) for West Africa as of 1980. The two latter independent estimates are in good agreement; they both show that arid and semi-arid zones were already grossly overpopulated by 1975 and 1980. However, as mentioned above, the population has increased by some 41% since 1975, a fact that has been incorporated into these tables.

Table T41 shows the actual and sustainable populations in the Sahel and Sudan ecological zones of W. Africa.

The data in Table T42 show that the decline in food production per inhabitant is much less steep than the decrease in livestock/human population ratio; this is probably due to the fact that food production comes to a large extent from areas that

Table T40 Present and potential human population densities under low and intermediate inputs as of 1975 (source: Higgins et al. 1984)

Length growing season days ($P > 0.5$ Eto)	Present no. people per ha	Potential under low input	Potential under intermediate input
365	0.10	1.60	5.6
330–364	0.20	1.37	4.5
300–329	0.27	1.40	4.0
270–299	0.23	0.85	3.9
240–239	0.22	0.82	3.0
210–239	0.24	0.59	2.5
180–209	0.19	0.46	2.15
150–179	0.19	0.47	1.54
120–149	0.24	0.16	1.20
90–119	0.20	0.13	0.15
75–89	0.15	0.06	0.10
1–74	0.07	0.03	0.08
0	0.05	0.07	0.05
Weighted mean	0.13	0.39	

Table T41 Actual and sustainable human populations in the Sahel and Sudan ecological zones of W. Africa (source: Gorse 1984)

Ecological zone	Sustainable population, no. per km^2			Actual population, no. per km^2	Sustainable fuel, per km^{2a}	Actual fuel, per km^2
	Crops	Livestock	Total			
Saharan	–	0.3	0.3	0.3	–	0.3
Sahelo-Saharan	–	0.3	0.3	2.0	–	2.0
Sahelian	5	2.0	7.0	7.0	1.0	7.0
Sahelo-Sudanian	10	5.0	15.0	20.0	10.0	23.0
Sudanian	15	7.0	22.0	17.0	20.0	21.0
Sudano-Guinean	25	10.0	35.0	9.0	20.0	10.0

[a] Based on a consumption of 2 kg DM per person per day

Table T42 Food production indices per capita for the period 1950–2000 (source: FAO production yearbooks)

1950	1960	1970	1980	1990	2000
95	104	100	90	85	100

were much less drought-stricken (sub-humid and humid zones) than were the livestock production areas (primarily arid and semi-arid zones). Foreign food aid also plays a role in this discrepancy.

On the other hand, it has been established that the tropical African forest is currently receding at a rate of 1.5% annually (FAO 1992). A study on five forested countries from Central and West Africa found an annual mean recession rate of 1.37% between 1980 and 1990 (Le Houérou 1991a, unpublished data). Again, the two independent evaluations are in very good agreement. There is virtually no more fuel wood available within a radius of 100–150 km around many African cities and larger towns; indeed, clearing for cultivation increases steadily.

Essentially, the cause of land degradation is the increased pressure on the ecosystems by exponentially growing populations of humans and livestock (Tables T36 and T37). At the same time, production techniques have evolved little over the past 50 years; they are not suitable for the new demographic situation. Production increase has so far come essentially from clearing of new land. However, there is no more land available outside humid and hyper-humid zones. Henceforth, most of the increase of production should therefore come from the intensification of the production processes. As there is no more land available for clearing (except in the humid and hyper-humid zones), the fallow period is reduced or cancelled—hence, the decline in fertility and yields, which is not compensated for by artificial fertilization because fertilization is very expensive, largely due to very high transport costs. Fertilization cost is thus not commensurate with the market value of staple crops and, therefore, not feasible. Mixed farming–animal production systems can, to some extent, compensate via livestock manuring but many farmers keep only few livestock, if any.

Population densities in the highlands of Ethiopia, Kenya, Rwanda and Burundi often exceed 500 people per km^2, 70–80% of them living on agriculture (cf. Table T39). A study of human-induced soil degradation (Oldeman et al. 1990) showed that soil degradation in Africa is, by and large, more acute in arid and semi-arid zones and in the highlands, i.e. the North African arid zone, the South African arid zone, the Sahel, the East African Highlands of Ethiopia, Kenya, Tanzania and Lesotho. It was found to be moderate to stable in the humid and hyper-humid zones, with the exception of Madagascar where deforestation is very active.

In terms of land degradation, the conclusion of this study for Africa may be summarized in Table T43 (hyper-arid zone excluded). Thus, 70% of soil degradation occurs in arid and semi-arid zones, and the overall degraded soils represented some 28% of the non-desert land in the 1980s. Soil degradation results from various factors: water erosion, wind erosion, secondary waterlogging and salinity, fertility (chemical) exhaustion, soil-structure degradation, crusting and sealing.

Table T43 Land degradation (source: ISRIC and UNEP 1992, World Atlas of Desertification, modified)

Zones	Total km² (%)	Non-degraded	Degraded	Light	Moderate	Strong	Extreme	% of degraded land
Arid & semi-arid	4,650 (21.7)	466 (10)	4,184 (90)	1,546 (40)	1,666 (40)	926 (22)	46 (1)	70.5
Sub-humid, humid & hyper-humid	16,796 (78.3)	15,048 (10)	1,748 (10)	557 (3.2)	646 (3.6)	528 (3.1)	17 (0.1)	29.5
Total	21,446 (100)	15,514 (72.3)	5,932 (27.7)	2,103 (9.8)	2,312 (10.8)	1,454 (6.8)	63 (0.3)	
Hyper-arid	9,200							

3.2 Land Desertization

Desertization is the irreversible extension of desert-like conditions to areas where they did not occur in the recent past (Le Houérou 1958, 1962a, 2002a, b). It affects arid lands and essentially results from the destruction of natural vegetation, leaving the top soil bare and unprotected against erosion by wind and water. When perennial plant canopy cover is reduced below about 5%, perennial vegetation tends to concentrate in the low parts of the topography benefiting from runoff. Perennial above-ground plant biomass decreases below 100–200 kg DM ha^{-1}. The soil surface becomes either sealed and impervious, resulting in increased runoff, or it is blown away to form various types of drifting sand deposits, leaving behind desert pebble pavements, hard pans or hard geological substrates where perennial plant life becomes impossible due to the loss of water storage capacity, combined with the shortage of nutrients. All these conditions tend to make recovery impossible even after 25 years of total protection (Floret and Pontanier 1982, 1984).

The primary causes of vegetation destruction and, therefore, the indirect causes of desertization are the clearing of land unsuitable to cultivation, prolonged overstocking and overgrazing, and the destruction of woody species by excessive collection of firewood. Vegetation destruction and deforestation may, in turn, lead to seepage, secondary salinity and waterlogging in the lower parts of the topography.

Desertization differs from “desertification” inasmuch as the latter term does not only apply to arid lands, is not necessarily irreversible, and does not necessarily lead to desert landscapes. “Desertification”, according to UNEP and other organizations, is equated with land degradation as examined above. Desertization is thus a specific and well-defined case of land degradation at the margins of true climatic deserts.

A number of detailed long-standing research projects, covering several hundred thousand hectares each in either northern Africa, the Sahel, East Africa or southern Africa, have shown beyond any doubt that the areas newly affected by desertization represented some 0.6% of African arid lands annually (Le Houérou 1992c). These surveys usually result from field measurements combined with aerial and orbital remote sensing; the conclusions are thus indisputable.

Surprisingly, the same order of magnitude of 0.6–0.7% was found in the former USSR (Khalmoukia, Turkmenistan, Kazaksthan, Uzbekistan), and in N.W. China and Inner Mongolia by Russian and Chinese scientists (Le Houérou 1987, 2005b).

Desertization does not stem primarily from drought but, of course, drought enhances and accelerates the phenomenon. All ranches managed in terms of reasonable stocking rates in N. Africa, the Sahel, E. Africa and S. Africa went unharmed through long periods of drought. In the Sahel, for instance, the state ranches of Dahra and Doli in Senegal, Niono in Mali, Markoye in Burkina Faso, Toukounous in Niger and Wadi Rimé in Chad survived an almost continuous 20-year drought without substantial harmful effects to the vegetation, and with no symptoms of desertization or land degradation—on the contrary, they are conspicuous on satellite images, contrasting strongly with the surrounding desertizing rangeland (Tluczykont and Gningue 1986; Achard and Chanono 2006).

Unsound pastoral water development and the lack of subsequent rational range management have led to range destruction in many parts of Africa, including the Sahel, S. and E. Ethiopia, Somalia and N. Kenya (Bernus 1974; Le Houérou 1998e).

National, international and bilateral "development" financing organizations bear a heavy burden of responsibility in the ecological disaster-generating pastoral water-development projects. Some 20 billion US $ have been spent on these types of arid rangeland and livestock development projects from 1965 to 1985, with the only unquestionable net result that many million hectares of productive rangelands have been turned into desert wasteland within a period of 3–5 years at various times during these 20 years. The rangelands around unregulated boreholes or other permanent water resources may be destroyed within a 20–25 km radius (i.e. 125,000 to 200,000 ha) over a time span of 3–5 years because of the livestock concentration they induce during the dry season (Bernus 1974; Le Houérou 1998c, e, 2006b).

3.3 Land Rehabilitation

Land rehabilitation may have several facets, particularly "restoration", which is the return of vegetation and environment to pristine or near-pristine status, while "rehabilitation" means the upgrading of ecological conditions via various ways that may include man-made re-introduction of native species or the introduction of exotics, and the utilization of various techniques of improvement of soil and water intake into soil, such as soil and water conservation techniques, pasture reseeding, afforestation and re-afforestation, the creation of national parks, and various environmental protection measures. These topics have been dealt with in many studies (Boudet 1972, 1974; Le Houérou 1989a, 2007c; Roose 1994; Toutain et al. 2006).

This is not the place to discuss these various methods used so far in Africa. Let us only mention that the most common, cheap and efficient method is land protection or "exclosure", which has usually beneficial consequences and a relatively low cost. However, it is often difficult to establish for societal reasons (Le Houérou 2007c).

Range reseeding and afforestation are restricted to semi-arid to humid bioclimates because of the vagaries of rainfall that restrict their utilization in arid zones.

Chapter 4
Conclusions

I have recapitulated some of my recent basic findings, notably dealing with the statistical equivalence between the $P = 2t$ and $P = 0.35$ ETo criteria to differentiate between dry and rainy seasons. The relationship between mean annual temperature and the reference potential evapotranspiration can be estimated by the equation 1°C = 77.5 mm ETo at low wind speed (<5 m s^{-1}). It follows that an increase of 1°C in mean annual temperature corresponds with an increase of 77.5 ± 2.5 mm of ETo. An increase in temperature thus corresponds with a measured decrease in the *P*/ETo ratio, i.e. a quantified climatic aridification.

I have provided evidence of agro-bioclimatic similarities and differences between various regions of Africa. Moreover, these have been compared with tropical and subtropical regions on other continents, such as the Indian subcontinent, S.E. Asia and South America.

The term and the geographic notion of "Sahel" has recently been extended, in some administrative circles, to include also the East African Arid Lands (EAAL; Le Houérou 2006b), i.e. the arid zones of the Republic of Sudan, Eritrea, Ethiopia, Djibouti, Somalia, Kenya and Uganda (but, surprisingly, not Tanzania). One can thus now hear or read about a so-called western Sahel (from Mauritania and Senegal to Chad) and an eastern Sahel (from Sudan to Kenya). This may be practical from some non-scientific viewpoints but is most inappropriate from scientific, biogeographic and agro-bioclimatic standpoints. It is true that the Sahel and the EAAL bear some similarities in terms of drought occurrence, and of broad and purely physiognomic vegetation patterns. The Mimosaceae Sahel scrub, for instance, bears some physiognomic similarity with the EAAL *Acacia-Commiphora* bushland but there are some 3,000 plant species in the EAAL, vs. barely 1,500 in the Sahel—phytogeographers have never made any confusion here (e.g. AETFAT 1938; Pichi-Sermolli 1957; Keay 1959; White 1983; Le Houérou 2006b), neither have ecologists, meteorologists, climatologists and agronomists. Evidently, this is a concept developed by bureaucrats for reason of administrative convenience.

The Sahelian ecological zone is characterized by a unimodal rainfall pattern and, therefore, belongs to the tropical family of climates. EAAL have a bimodal rainfall distribution with two rainy and two dry seasons and, therefore, belong to the equatorial family of climates. The Sahelian rains occur around the boreal summer solstice (with a 2-month time lag in the peak), whereas the EAAL receive spring and autumn rains, i.e. equinoxial rains. Furthermore, rainfall variability in the Sahel is substantially lower than in the EAAL, contrary to many published statements. Mean relative humidity (RH) is twice as large in the EAAL as in the Sahel, averaging 60–70 vs. 35–40% respectively on an annual basis. Conversely, the saturation deficit (SD) is twice as high in the Sahel: 24 vs. 12 hPa as an annual average, with extremely low values in the Sahel between December and April (RH below 5–10% every afternoon for 4–5 months). Correspondingly, SD may then rise to a mean seasonal value of some 40 hPa, probably the highest on earth for a broad ecological region.

Annual ETo is of the order of 2,200–2,800 mm in the Sahel, whereas it seldom rises above 2,200 mm in the EAAL (with the exception of the Red Sea shores). Mean annual temperature in the Sahel is 27–28°C (occasionally, 30°C) vs. 25–26°C in the EAAL, again with the exception of the Red Sea shores where it is similar to that of the Sahel (but with 70, vs. 35% RH). Temperature seasonality in the Sahel spans an amplitude of 10–15°C between the mean monthly values for the coolest (January) and the hottest (May) months, whereas this range does not exceed 2–5°C in the EAAL, typical for equatorial climates characterized by thermal homogeneity, in addition to a bimodal rainfall distribution pattern.

The same applies to day length, which varies with season in the Sahel but is fairly constant in the EAAL, typical for equatorial climates. Sahelian rangelands are essentially characterized by annual grasses, whereas perennial grasses are largely dominant in non-depleted EAAL rangelands. Successful pearl millet cultivation requires a mean zonal annual rainfall of 400 mm in the Sahel, while 600 mm are necessary in the EAAL, although pearl millet is hardly cultivated in the latter.

Furthermore, the "eastern Sahel" is climatically most heterogeneous; the arid zone of the Republic of Sudan (8–16°N) belongs to the "true Sahel", with unimodal rainfall and exhibiting all the attributes of the Sahelian climate reported above. By contrast, the other countries of the EAAL have a typically equatorial climate.

There are several other differences between the Sahel and the EAAL, particularly in terms of afforestation potential, livestock diseases, and parasitism (tick-borne diseases). The East Coast Fever was virtually nonexistent in the Sahel until the 1990s when it appeared in Senegal and Mauritania, apparently as a consequence of the hydrological works carried out in the lower Senegal River Basin (Le Houérou 1999a).

It follows from this detailed comparison that the two regions have profound differences in climate and agro-bioclimatic potential, and that it would be most hazardous to extrapolate or interpolate research and development findings from one region to the other without a careful and detailed agro-bioclimatic analysis. This is why "amalgams" based on superficial observations are very risky and conducive to potential ecological and development disasters, such as the afforestation activities in S.W. Mauritania (Trarza) in the 1980s.

The same type of rationale applies when comparing the Kalahari and the Sahel, or the Kalahari and the EAAL. The Kalahari bears superficial similarities to the Sahel and to the EAAL; it shares with the Sahel a typical tropical climate with strictly unimodal summer rains, and the fact that it was a former desert with sandy soils, a dune geomorphology, and a vegetation of perennial grassland dotted with more or less sparse, small thorny trees (*Acacia-Commiphora* bushland). It is also periodically swept by bushfires, as is the Sahel. However, the Kalahari is located at about 1,000 m elevation and, therefore, enjoys mild temperatures, the annual mean varying from 18 to 22 vs. 28°C in the Sahel. Due to the similarity in latitude, the annual thermal amplitude is comparable to that of the Sahel: 10–15°C between the mean of the coolest (July) and of the hottest (January) month. The central and southern Kalahari experience light winter freezing almost every year, and there is a 2–3 month plant winter rest from cold stress, unlike the Sahel where temperature practically never falls below 10°C. ETo in the Kalahari varies from 1,200 to 1,500 mm, vs. 2,200–2,800 mm in the Sahel. The length of the rainy season is 6–7 months in the Kalahari, vs. 2–4 in the Sahel. Relative humidity in the Kalahari is about 70% as an annual average, vs. 35% in the Sahel, and SD averages 6 hPa in the Kalahari, vs. 24 in the Sahel. Compared with the EAAL, the Kalahari has a different rainfall distribution pattern, much lower and contrasting temperatures, much lower ETo, a longer growing season, and a somewhat lower rainfall variability. There is, therefore, no more a would-be "southern Sahel" than there is an "eastern Sahel"!

A similar comparison may be made for the extra-tropical zones of northern and southern Africa. Northern Africa has a typical Mediterranean type of climate, with over 80% of the rains occurring during the short-day cool temperature half-year. In southern Africa, the situation is more complex, as the region receives both winter and summer rains. Only a small portion of the territory at the S.W. tip of the continent along the Atlantic shore receives over 80% of winter rains and is, thus, climatically comparable to N. Africa, north of the Tropic of Cancer. About 90% of the territory south of the Tropic of Capricorn receives 40 to 85% of summer rains, as shown in Fig. 30. Conversely, winters are by and large cooler in southern Africa, due to elevation, again with the exception of the S.W. tip (Fig. 31). Annual ETo is rather similar in the two regions.

Again, extrapolation or interpolation between the two regions are, therefore, most hazardous, with the exception of the S.W. tip that bears similarities with S.W. Morocco (low rainfall, winter regime, high air moisture, relatively low ETo, mild winter temperatures (it never freezes), mild summer temperatures, frequent fogs, etc.). This situation is, to a large extent, due to the cold upwelling associated with the Benguela and Canary currents respectively.

The exchange of genetic material between the two zones has been small; exceptions include *Acacia karroo*, extensively used in N. Africa as defensive hedge. Similarly successful introductions from other continents have occurred in both zones: fodder cacti, *O. ficus-indica, O. robusta, O. fusicaulis* and *Agave americana*, from the Mexican highlands, and the saltbush *Atriplex nummularia* from Australia; also, some 300 species of the archaic xerophytic "Rand flora" (Christ 1892) are common in N. Africa and the Sahara, particularly Crassulaceae, Aizoaceae and Mesembrianthemaceae (Le Houérou 1995a).

The Sudanian ecological zone, south of the Sahel, is also quite different from its counterpart, the Miombo savanna-woodland, which is found in an analogous geographical location in the southern hemisphere. Both ecozones are subject to a semi-arid to humid tropical climate, with a monomodal rainfall type amounting to 600–1,200 mm $year^{-1}$. Both have a more or less typical woody savanna vegetation, impacted by devastating bushfires, and dominated by Caesalpimoideae legume trees in the case of the Miombo, and by various Combretaceae and other families including Caesalpinioideae in the Sudanian ecozone. Both are dominated by semi-deciduous or deciduous mesophyll-malacophyll tree species.

However, there are large differences between the two zones in terms of agro-bioclimatic characteristics. Mean annual temperatures in the Miombo are typically ca. 20°C vs. 26–27 in the Sudanian zone. Light winter freezing occurs in the Miombo (located at elevations of 500–1,500 m a.s.l.) but never in the Sudan, due to the absence of highlands in this geographic zone, north of the equator. ETo is 1,200–1,500 mm in the Miombo vs. 1,750–2,500 mm in the Sudan, and the *P*/ETo ratios are 50–100% in the Miombo vs. 40–75% in the Sudan. RH averages 63 and 52% respectively, and SD is 10 and 17 hPa respectively.

On an intercontinental basis, Africa appears as a hotter and drier continent than both South America and the Indian subcontinent, but conditions may be comparable in limited parts of these distinct continents. For example, the Sahel and the Sind-Rajasthan share many features, as do the EAAL, S.E. Madagascar and N.E. Brazil.

The African rainforest of Cameroon, Gabon and Congo and the Congo-Zaire River Basin are very reminiscent of the Amazon Basin rainforest, with similar problems of fertility. As the mineralomass of geobiogene elements and nutrients is sequestered in the woody phytomass, the abrupt destruction of the forest, usually by fire, results in most of the nutrients and geobiogene elements being washed away with the ashes in subsequent runoff and erosion processes. Recovery then becomes most problematic and very slow, unless there is a heavy fertilizer input of geobiogene elements such as Ca, Mg and trace elements. Also, in addition to chemical exhaustion, the processes of water erosion are very aggressive on these denudated and highly unsaturated ferralsols (Ultic Haplorthox).

From the agro-climatic viewpoint, the exchange of gene pools has been most active, particularly with the Indian subcontinent and South America. From the Indian subcontinent, Africa has imported: *Azadirachta indica* (Neem), *Albizzia lebbek*, banana, black pepper, *Cassia siamea, Dialbergia sissoo*, finger millet, ginger, *Gmelina arborea*, hemp (*Hibiscus cannabinus*), jute, mango, *Melia azedarach*, pearl millet, pigeon pea, *Prosopis cineraria*, rice, sesame, sugarcane, tea, and also zebu cattle (*Bos indicus*), introduced ca. 400 A.D. through the strait of Aden.

From South America, Africa has imported: avocado, cassava, cacti, cashew nut, cocoa, "European" bean, groundnut, hevea (Para rubber), Lima bean, maize, pawpaw, pineapple, potato, sweet potato, sisal, soybean, sunflower, tobacco, tomato, most of the tropical fodder legume gene pool—*Calopogonium, Centrosema, Desmodium, Glycine, Macrotyloma, Macroptylium* (Siratro), *Mucuna, Pueraria, Stylosanthes* spp.—and most of the tropical pines used in re-afforestation, particularly in the Miombo, and E. and S. Africa.

From Australia, Africa has introduced *Eucalyptus* spp., wattles (*Acacia* sect. Phyllodinae), *Casuarinas* spp. (Filao, She-oaks), *Grevillea robusta* and saltbushes (*Atriplex* spp.).

To other continents, Africa has exported: Arabica coffee, Robusta coffee, sorghum, fig, olive, oil palm, date palm, sugar beet (in part), cowpea, lablab, wheat (in part), barley (in part), floating rice, yam, taro (in part), grapes (in part), pyrethrum, roselle (Guinea sorrel), some 70–75% of the world's gene pool of tropical fodder grasses—*Andropogono gayanus*, buffel grass, Bermuda grass, blue panic, Sabi grass, Rhodes grass, Guinea grass, elephant grass, kikuyu grass, weeping love grass, signal grass, Para grass, Ruzizi grass, Pangola grass, golden timothy—and some 20–25% of the world gene pool of fodder legumes—*Desmanthus, Canavalia, Rhynchosia*, cowpea, *Lablab, Clitoria tematea, Medicago* spp., *Trifolium* spp., *Hedysarum* spp., *Vicia* spp., *Melilotus* spp. and *Lotus* spp. (Harlan 1987).

Progress in plant breeding is likely, as in the past, to bring about some breakthroughs in agro-climatology, with the creation of new cultivars better adapted to marginal environments. In some instances, however, this may in turn locally prove a double-edged sword. If/when the 75-days GAM dwarf pearl millet is made genetically stable, it would open a large new territory to that crop in the Sahel and in E. Africa (Dancette 1975), i.e. 2.3×10^6 ha in the northern half of Senegal, and some 67.7×10^6 ha in the Sahel as a whole, from the Nile Valley to the Atlantic. This would also be a potential threat of disaster, as has happened in the past and is still occurring today, since cropping would thus be extended to land that is not appropriate due to the high wind erosion hazard. In such an event, as in the pastoral water development discussed in Section 3.2, technology might bring about more desertization and, in the balance, become a disaster.

Research using meteorological satellites has achieved remarkable progress, so that it is now possible to evaluate, in a reliable way, both rainfall and temperature (Assad et al. 1986; Lahuec et al. 1986; Guillot 1992). This will complement information from conventional weather stations, permitting sound interpolation in the many areas where the density of the network and/or the reliability of the records are still unsatisfactory.

Outposted research activities, in an actual concrete production systems context (i.e. outside research stations), have resulted in reliable yield-predictive equations for groundnuts and for staple cereals (bulrush millet, sorghum, maize, and upland rice). These have been generated for the West Africa, S. Sahelian, Sudanian and N. Guinean ecozones using basic climate data in conjunction with appropriate models for the evaluation of ETR (actual ET). These predictions enable a probabilistic approach to a dependable harvest forecast (Franquin and Forest 1977; Forest and Reyniers 1986; Forest et al. 1986).

System research in real-life situations has furthermore indicated that light inputs of land and water conservation practices, associated or not with agro-forestry techniques, are conducive to a substantial increase in crop productivity while restoring and rehabilitating the land (Ruelle et al. 1990; Roose 2004). Weather and drought predictions are making steady progress, so that one may expect, in the not too distant future, to be able to produce and thus take advantage of reliable drought forecasts (Janicot and Fontaine 1993).

I hope that the present attempt to build an overall agro-bioclimatic framework at the continental level will be useful in improving the understanding of the impact of climatic variables on agricultural development planning and on human activities in general. My desire is also that it helps in the extrapolation or interpolation of research and development findings to areas having comparable agro-bioclimatic attributes, either in other African regions or on other continents. Moreover, one may hope that this research has contributed to the strongly needed harmonization of current terminology, since terms such as “semi-arid” have nearly as many meanings as the number of scientists using them.

Appendix

Table A1 Basic annual climatic data for 962 meteorological stations from 54 countries in Africa[a]

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
ALGERIA										
Adrar	–0.17	27.53	263	25	24.3	2,124	1	87.4	1	1
Ain Sefra	–0.36	32.46	1,058	192	16.5	1,525	13	92.4	56	1
Alger	3.00	36.46	60	691	18.3	1,217	57	66.5	227	1
Annaba	7.49	36.50	4	687	17.9	1,314	52	73.4	209	1
Bechar	–2.14	31.37	773	90	21.1	1,737	5	82.3	1	1
Biskra	5.44	34.48	87	129	21.9	1,796	7	82.0	26	1
Constantine	6.37	36.17	694	594	15.7	1,272	47	81.0	226	1
Djanet	9.28	24.33	1,054	26	23.5	1,877	1	79.9	1	2
Djelfa	3.15	34.41	1,144	308	13.4	1,245	25	92.9	143	1
El Golea	2.52	30.34	397	56	21.6	1,700	3	78.7	1	1
Ghardaia	3.49	32.23	450	68	21.4	1,933	3	90.3	1	1
In Salah	2.28	27.12	293	19	25.3	2,002	1	79.1	1	1
Laghouat	2.56	33.46	765	100	17.9	1,353	7	75.6	34	1
Oran	–0.39	35.44	11	402	17.2	1,228	33	71.4	181	1
Ouargla	5.24	31.55	141	39	22.3	2,015	2	90.4	1	1
Setif	5.25	36.11	1,081	469	13.9	1,287	36	92.6	199	2
Sidi Belabbes	–0.38	35.11	486	395	15.5	1,162	34	75.0	189	1
Skikda	6.57	36.56	7	830	17.0	1,229	68	72.3	240	1
Tamanrasset	5.31	22.47	1,378	42	21.1	1,770	2	83.9	1	2
Tebessa	8.08	35.29	813	348	15.6	1,309	27	83.9	204	1
Tlndouf	–8.08	27.40	431	32	23.2	1,886	2	81.3	1	1
Touggourt	6.08	33.07	85	58	21.4	1,920	3	89.7	1	1
N = 22; √N = 4.69										
X				255	19.4	1,586	20.0	81.9	88	–
SD				253	3.4	320	21.0	7.4	95	–
CV(%)				99	17.6	20	10.5	9.0	107	–
SE				54	0.7	68	4.5	1.6	20.3	–

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
ANGOLA										
Cabinda	12.11	−5.33	25	810	24.8	1,145	70.7	46.2	224	1
Chitembo	16.46	−13.32	1,500	1,120	20.2	1,545	72.5	76.5	204	1
Cuemba	18.05	−12.08	1,300	1,348	20.0	1,457	92.5	72.9	221	1
Huambo (Nova Usboa)	15.45	−12.48	1,710	1,369	19.1	1,399	97.9	73.2	227	1
Lobito	13.32	−12.22	3	234	23.7	1,269	18.4	53.5	63	1
Luanda	13.14	−8.51	74	377	24.3	1,382	27.3	56.9	78	1
Luau	22.15	−10.43	1,100	1,335	22.7	1,728	77.3	76.1	211	1
Lubango	13.34	−14.56	1,760	894	18.6	1,500	56.9	80.6	203	1
Luena (Luso)	19.55	−11.47	1,357	1,190	20.7	1,412	84.3	68.2	215	1
Malange	16.22	−9.33	1,139	155	20.8	1,360	84.9	65.4	239	1
Menongue (SE. Pinto)	17.41	−14.39	1,348	868	19.4	1,484	58.5	76.5	176	1
Mocamedes	12.09	−15.12	43	50	20.4	1,208	4.1	59.2	1	1
N’Dalatando	14.55	−9.17	795	1,200	22.4	1,344	89.3	60.0	235	1
Ngiva	15.44	−17.05	1,109	620	22.7	1,748	35.5	77.0	152	1
Nova Gaia	17.33	−10.04	1,260	1,233	20.4	1,424	86.6	69.8	239	1
Saurimo	20.24	−9.39	1,081	1,293	21.9	1,491	86.7	68.1	237	1
Soyo	12.21	−6.07	1	808	26.0	1,260	64.1	48.5	221	1
Sunginge	16.47	−8.46	630	1,253	23.9	1,576	79.5	6.5	241	1
N = 18; √N = 4.24										
X				953	21.8	1,428	66.0	59	228	–
SD				392	2.1	156	40.0	5	33	–
CV(%)				41	7	11	61.0	8	14	–
SE				92	0.5	37	9	1	8	–
BENIN										
Bohicon	2.04	7.10	166	1,172	27.2	1,172	76.8	56.1	261	1
Cotonou	2.23	6.21	5	1,241	27.6	1,241	82.1	54.7	250	2
Kandi	2.56	11.08	290	1,067	27.4	1,067	57.9	67.3	167	1
Natitingou	1.23	10.19	460	1,339	26.5	1,339	83.9	59.8	219	1
Parakou	2.37	9.21	392	1,177	26.2	1,177	71.5	60.2	212	1
Save	2.28	8.02	199	1,146	27.2	1,146	77.6	54.3	256	1
N = 6; √N = 2.45										
X				1,190	27.0	1,900	75	59	228	–
SD				84	5.0	84	9	4	33	–
CV(%)				7	2.0	7	12	7	14	–
SE				34	2.0	33	4	2	13	–
BOTSWANA										
Francistown	27.30	−21.13	1,001	436	20.9	1,690	25.8	81	121	1
Gaborone	25.55	−24.40	983	520	19.7	1,537	33.8	78	166	1
Ghanzi	21.39	−21.42	1,131	454	20.9	1,622	28.0	78	125	1
Mahalapye	26.48	−23.05	991	478	20.5	1,420	33.7	69	150	1
Maun	23.25	−19.59	945	453	21.9	1,672	27.1	76	125	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Shakawe	21.51	−18.22	1,032	501	22.1	1,632	30.7	74	143	1
Tsabong	22.27	−26.03	960	271	19.7	1,600	16.9	81	1	1
T'sahane	21.53	−24.01	1,118	350	20.5	1,552	22.6	76	109	1
N = 8; √N = 2.82										
X				433	20.8	1,590	27	77	117	–
SD				78	0.8	81	5	4	48	–
CV(%)				18	4	5	19	5	41	–
SE				2.8	0.3	29	2	1.4	17	–
BURKINA FASSO										
Bobo-Dioulasso	−4.19	11.10	460	1,037	26.9	1,977	52.5	73.5	172	1
Boromo	−2.56	11.45	270	871	27.8	1,926	45.2	69.3	158	1
Dori	−0.02	14.02	276	486	28.9	2,399	20.3	83.6	96	1
Fada N'Gourma	0.22	12.02	306	831	27.7	2,057	40.4	74.3	144	1
Gaoua	−3.11	10.20	333	1,062	27.5	1,892	56.1	68.8	197	1
Ouagadougou	−1.31	12.21	316	786	28.1	2,120	37.1	75.4	146	1
Ouahigouya	−2.25	13.34	337	605	28.6	1,771	34.2	61.9	122	1
N = 7; √N = 2.64										
X				811	26.5	2,020	42.8	72.4	148	–
SD				195	3.9	187	11.0	6.2	30	–
CV(%)				24	14.7	9	26.0	8.6	21	–
SE				74	1.5	71	4.2	2.3	11	–
BURUNDI										
Bujumbura	29.19	−3.19	782	855	23.1	1,519	56.3	65.8	240	1
Klsozl-Colune	29.41	−3.33	2,155	1,461	15.5	1,229	118.9	79.3	276	1
Luvironza	30.00	−3.43	1,850	1,294	16.5	1,364	94.9	82.7	269	1
Musasa-Plateau	30.21	−3.39	1,260	1,103	20.9	1,497	73.7	71.6	226	1
N = 4;√N = 2										
X				1,178	19.0	1,402	86.0	80	253	–
SD				256	2.6	116	23.4	5	21	–
CV(%)				19	13.6	8	27.2	6	8	–
SE				128	10.0	58	11.7	3	11	–
CABO VERDE										
Mindelo	−25.00	16.53	62	49	22.8	1,785	2.7	78.3	1	1
Ponta-do-Sol	−25.06	17.12	16	161	23.5	1,703	9.5	78.5	37	1
Praia	−23.31	14.54	27	170	25.3	1,806	9.4	71.4	52	1
N = 3; √N = 1.73										
X				127	23.9	1,765	7.2	76.1	30	–
SD				55	1.3	44	3.2	3.3	22	–
CV(%)				43	5.0	2.5	44.4	4.3	73	–
SE				32	0.6	2.5	1.8	1.9	14	–

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
CAMEROON										
Batouri	1422	4.28	656	1,625	23.8	1,218	133.4	51.2	323	1
Douala Obs.	9.44	4.00	10	4,118	26.4	1,120	367.7	42.4	365	1
Garoua	13.23	9.20	242	1,017	27.2	2,111	48.2	77.6	174	1
Kaele	14.27	10.05	389	878	27.7	2,046	42.9	73.9	149	1
Koundja	10.45	5.39	1,208	2,096	21.3	1,428	146.8	67.0	285	1
Kribi	9.54	2.57	10	3,018	25.7	1,301	232.0	50.6	365	1
Lomie	13.37	3.00	624	1,676	23.4	1,256	133.4	53.7	365	1
Maroua-Salak	14.15	10.27	423	841	27.8	1,940	43.4	70.3	146	1
Ngaoundere	13.34	7.21	1,114	1,605	22.1	1,379	116.4	60.2	238	1
Yaounde	11.31	3.50	751	1,684	23.4	1,197	140.7	51.2	319	1
N = 10; √N = 3.16										
X				1,856	24.9	1,500	140.5	59.8	273	–
SD				969	2.2	361	93.9	11.2	85	–
CV(%)				52	9.1	24	66.8	18.7	26	–
SE				307	0.7	114	29.7	3.5	0.3	–
CENTRAL AFRICAN REP.										
Bambari	20.39	5.51	474	1,500	26.0	1,479	101.4	56.9	273	1
Bangassou	22.50	4.44	499	1,710	25.4	1,401	122.1	55.2	294	1
Bangui	18.31	4.24	365	1,531	25.8	1,358	112.7	57.6	298	1
Berberati	15.48	4.15	582	1,529	24.4	1,334	114.6	54.5	296	1
Birao	22.47	10.17	463	843	26.6	1,587	53.1	59.7	163	1
Bossangoa	17.26	6.29	464	1,440	25.9	1,496	96.3	57.8	232	1
Bouar	15.38	5.58	1,019	1,548	23.6	1,505	102.9	63.8	257	1
Bria	21.59	6.32	583	1,553	25.1	1,367	113.6	54.1	263	1
N'délé	20.39	8.24	510	1,303	26.4	1,495	87.2	56.0	222	1
N = 9;√N = 3.00										
X				1,440	25.5	1,447	100.4	58.8	25.5	–
SD				234	9.2	80	19.5	4	742	–
CV(%)				16	3.6	6	19.5	7	16	–
SE				78	3.1	27	7.0	1.3	14	–
CHAD										
Abeche	20.51	13.51	545	383	28.5	2,452	15.6	86.0	76	1
Am-Timan	20.17	11.02	433	799	27.0	1,755	45.5	65.0	142	1
Ati	18.19	13.13	333	383	28.9	2,150	17.8	74.4	80	1
Bokoro	17.03	12.23	300	483	28.5	1,792	27.0	62.9	104	1
Bol-Berim	14.44	13.26	291	252	26.9	2,100	12.0	78.1	62	1
Bousso	16.43	10.29	334	808	27.7	1,750	46.2	63.2	151	1
Faya	19.10	18.00	235	25	28.2	2,803	0.9	99.4	1	1
Mongo	18.41	12.11	427	700	29.3	1,785	39.2	60.9	127	1
Moundou	16.04	8.37	428	1,126	26.3	1,598	70.5	60.8	191	1
Ndjamena	15.02	12.08	296	529	27.5	1,900	27.8	69.1	104	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Pala	14.55	9.22	467	994	26.7	1,963	50.6	73.5	167	1
Sarh	18.23	9.09	365	991	27.0	1,895	52.3	70.0	166	1
N = 12; √N = 3.46										
X				623	27.7	1,995	33.8	71.9	106	–
SD				321	0.9	326	19.4	11.0	55	–
CV(%)				51	3.3	16	57.4	15.3	51	–
SE				97	0.3	99	5.9	3.3	17	–
COMOROS										
Dzaoudzi/ Pamanzi	45.17	−12.48	8	1,095	26.1	1,648	66.4	63.1	189	1
Moroni Airport	43.14	−11.42	6	2,635	25.4	1,651	159.6	65.0	365	1
Mutsamudu	44.25	−12;10	70	1,900	24.8	1,630	116.6	65.7	365	1
N = 3; √N = 1.73										
X				1,877	25.4	1,643	114	64.6	306	–
SD				629	0.5	9	38	1.1	83	–
CV (%)				34	2.1	6	33	0.2	23	–
SE				0.59	0.3	5	22	0.6	49	–
CONGO										
Brazzaville Mayamaya	5.15	−4.15	319	1,378	24.9	1,300	106.0	52.2	264	1
Djambala	14.46	−2.22	791	2,040	23.1	1,219	167.4	52.8	305	1
Impfondo	12.42	1.37	335	1,764	25.3	1,295	136.2	51.2	365	1
Loubomo	12.42	−4.12	329	1,299	24.6	1,264	102.8	51.4	244	1
M'Pouya	16.13	−2.37	311	1,596	25.6	1,402	113.8	54.8	294	1
Makoua	15.35	−0.01	394	1,815	25.3	1,298	139.8	51.3	349	1
Mouyond	13.55	−3.59	509	1,327	23.5	1,124	118.1	47.8	259	1
Ousso	16.03	1.37	352	1,706	25.4	1,195	142.8	47.0	365	1
Pointe-Noire	11.54	−4.49	17	1,290	25.1	1,203	107.2	47.9	251	1
N = 9; √N = 3.00										
X				1,579	24.8	1,256	126	50.6	300	–
SD				255	0.8	76	21	2.6	46	–
CV(%)				16	3.3	6	16	0.5	15	–
SE				85	0.3	25	7	0.9	15	–
CÔTE d'IVOIRE										
Abidjan	−3.56	5.15	7	2,144	26.4	1,365	157.1	51.7	315	1
Bondoukou	−2.47	8.03	369	1,177	25.9	1,376	85.5	53.1	279	1
Bouake	−5.04	7.44	376	1,109	26.6	1,382	80.2	52.0	273	1
Ferkesse Dougou	−5.05	9.37	350	1,337	26.6	1,477	90.5	55.5	229	1
Gagnoa	−5.57	6.08	205	1,480	26.5	1,267	116.8	47.8	352	1
Korhogo	−5.37	9.25	381	1,384	26.6	1,510	91.7	56.8	242	1
Man	−7.31	7.23	339	1,646	24.8	1,297	126.9	52.3	299	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ETo	ETo/*T*	RD	RS
Odienne	−7.34	7.23	434	1,612	26.6	1,474	109.4	55.4	248	1
Sassandra	−6.05	4.57	62	1,633	25.7	1,362	119.9	53.0	292	1
Tabou	−7.22	4.25	21	2,351	25.8	1,234	190.5	47.8	365	1
N = 10; √N = 3.16										
X				1,587	26.2	1,374	116.9	52.5	279	–
SD				376	0.6	87	33.0	2.9	39	–
CV(%)				24	2.1	6	28.0	5.5	14	–
SE				119	0.2	26	10.4	0.9	12	–
DJIBOUTI										
Djibouti	43.09	11.33	13	132	29.8	1978	6.7	66.4	1	1
EGYPT										
Alexandria	29.57	31.22	32	190	20.3	1,532	12.4	75.5	86	1
Asswan	32.47	32.47	192	1	26.9	2,140	0.0	79.6	1	1
Asyut	31.10	27.12	52	7	21.7	2,142	0.3	98.7	88	1
Baltim	31.06	31.33	1	185	20.8	1,403	13.2	67.5	1	1
Benisuef	31.06	29.04	28	8	21.5	1,679	0.5	78.1	1	1
Bilbeis	31.35	30.24	20	20	20.7	1,622	1.2	78.4	29	1
Borg el Arab	29.33	30.54	20	104	19.2	1,535	6.8	79.9	56	1
Dabaa	28.26	30.56	17	141	19.3	1,651	8.5	85.5	1	1
Dakhla	29.00	25.29	106	0	23.2	2,228	0.0	96.0	0	1
Gemmeiza	31.07	30.43	20	51	19.3	1,332	3.8	69.0	1	1
Giza	31.13	30.03	19	24	19.9	1,673	1.4	84.1	1	1
Helwan	31.20	29.52	139	26	21.9	1,835	1.4	83.8	1	1
Ismailia	32.15	30.36	12	44	21.7	1,619	2.7	74.6	1	1
Kharga	30.32	25.27	78	0	24.0	1,816	0	78.2	0	1
Kom Ombo	35.56	24.29	102	0	25.1	1,964	0	82.9	0	1
Mallawi	30.45	27.42	20	3	21.2	0.2	0	69.6	1	1
Mansoura	31.23	31.03	30	54	19.5	3.7	0	81.5	1	1
Mersa Matruh	27.13	31.20	25	165	21.6	10.4	54	82.4	1	1
Minya	30.44	28.05	37	2	20.7	0.1	0	74.3	1	1
Port Said/El Gamil	32.14	31.17	1	81	19.0	5.3	0	74.7	1	1
Sakha	30.57	31.07	20	88	20.6	6.2	29	87.7	1	1
Salloum	25.11	31.32	40	104	22.7	5.8	0	83.5	1	1
Shandaweel	31.38	26.26	60	1	19.3	0.1	0	83.3	1	1
Sidi Barrani	25.54	31.37	24	143	20.7	8.5	37	87.4	1	1
Siwa	25.31	29.15	3	10	22.6	0.4	0	109.4	1	1
Sohag	31.42	26.34	61	0	20.4	0.0	0	87.9	1	1
Tahrir	30.42	30.39	16	35		2.0	0		1	1
N = 27; √N = 5.19										
X				57	21.3	1,743	3.5	82.1	15	–
SD				62	1.8	247	4.0	8.9	26	–
CV(%)				108	8.5	14	11.5	10.9	1.7	–
SE				12	0.3	48	0.8	1.7	5	–

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ETo	ETo/*T*	RD	RS
EQ. GUINEA										
Bata (Rio Muni)	9.48	1.54	2	2,110	25.1	1,286	1667	50.4	320	1
Malabo	8.46	3.45	50	1,864	25.2	1,060	176	42.1	322	1
N = 2; √N = 1.41										
X				1,987	25.2	1,173	922	46.3	321	–
SD				123	0.05	113	746	4.2	1	–
CV(%)				6	2.0	10	81	9	321	–
SE				88	0.04	81	529	3	0.7	–
ETHIOPIA										
Adaba	39.24	7.01	2,485	838	14.9	1,300	64.5	87.2	286	2
Addis Ababa	38.48	8.59	2,324	1,225	15.9	1,234	99.3	77.6	244	1
Adi Keyih	39.19	14.49	2,490	508	17.8	1,624	31.3	91.2	79	1
Adi Ugri	38.49	14.53	2,022	574	17.4	1,745	32.9	100.3		1
Adola (Kibremengist)	39.05	5.55	2,170	958	19.2	1,328	72.1	69.2	291	1
Adwa	38.54	14.10	1,980	742	19.0	1,629	35.5	85.7	123	1
Agaro	36.38	7.51	1,560	1,657	20.4	1,359	121.9	66.6	305	1
Akaki	38.47	8.52	2,100	910	18.8	1,477	61.6	78.6	206	1
Akordat	37.53	15.33	626	319	29.0	2,031	15.7	70.0	73	1
Alamata	39.41	12.31	2,200	841	21.8	1,539	54.6	70.6	168	2
Alemaya	42.03	9.26	2,125	880	17.1	1,469	59.9	85.9	244	1
Ambo (Hagere Hiwot)	37.52	8.58	2,080	912	18.5	1,444	63.2	78.1	204	1
Arba Minch	37.40	6.04	1,219	789	20.8	1,538	51.3	73.9	258	1
Asela	39.08	7.52	2,450	1,298	14.2	1,237	104.9	87.1	278	1
Asmara	38.55	15.17	2,325	525	16.6	1,585	33.1	95.5	82	1
Asosa	34.31	10.04	1,750	1,116	21.6	1,463	76.3	67.7	196	1
Awassa	38.30	7.04	1,652	961	19.2	1,422	67.6	74.1	276	1
Bahar Dar	37.24	11.36	1,805	1,521	18.3	1,388	109.6	75.8	193	1
Bako Shewa	37.05	9.07	1,590	1,227	19.9	1,452	84.5	73.0	234	1
Barentu	37.36	15.10	980	516	25.1	2,044	25.2	81.4	107	1
Bati	40.03	11.13	1,660	810	20.3	1,539	52.6	75.8	168	2
Bedele	36.23	8.27	2,090	1,966	18.0	1,300	152.1	72.2	290	1
Bokoji	39.15	7.32	2,850	1,203	12.9	1,115	107.9	86.4	323	1
Bonga	36.17	7.13	1,725	1,799	19.7	1,316	136.7	66.8	365	1
Bure	35.06	8.17	1,600	1,143	20.1	1,363	83.9	67.8	244	1
Burji	37.56	5.24	1,960	961	20.5	1,479	65.0	72.1	277	2
Butajira	38.27	8.07	2,100	1,062	17.2	1,350	78.7	78.5	247	1
Chagni (Metekel)	36.26	10.55	1,720	1,909	19.5	1,397	136.6	71.6	200	1
Chefa	39.50	10.54	1,600	1,010	21.2	1,488	67.9	70.2	231	2
Combolcha	39.43	11.05	1,916	1,069	19.1	1,446	73.9	75.7	254	2
Dangila	36.55	11.17	2,180	1,502	17.0	1,436	104.6	87.4	210	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	P (mm)	T (°C)	ETo (mm)	(100 P)/ ETo	ETo/T	RD	RS
Debre Birhan	39.30	9.38	2,820	980	14.4	1,259	77.8	81.6	182	2
Debre Tabor	38.02	11.53	2,410	1,651	16.7	1,363	121.1	76.1	193	1
Debre Zeit (Bishof Tu)	39.02	8.44	1,900	866	18.7	1,423	60.9	77.1	174	2
Debremarcos	37.43	10.21	2,440	1,341	15.2	1,172	114.4	91.6	249	1
Dese	39.40	11.10	2,540	1,175	14.9	1,365	86.1	64.8	236	2
Didesa	36.06	9.00	1,200	1,479	22.5	1,458	101.4	70.6	224	1
Dila	38.18	6.25	1,670	1,253	20.1	1,419	88.3	84.1	293	1
Dire Dawa	41.52	9.36	1,146	576	24.4	1,319	28.1	81.8	107	2
Dixis	39.35	8.08	2,600	1,014	16.5	2,051	75.2	94.9	304	1
Dodola	39.11	6.58	2,540	915	13.9	1,658	69.4	78.6	243	1
Faghena (M. Zagher)	38.54	15.33	1,760	1,048	19.3	1,349	69.1	60.6	314	1
Gambela	34.35	8.15	480	1,327	27.5	1,319	80.0	72.7	222	1
Gewani	40.38	10.05	625	458	24.6	1,517	25.4	61.7	89	1
Gidole	37.29	5.37	2,550	1,171	16.7	1,337	87.6	80.0	335	1
Gimbi	35.47	9.05	1,870	1,920	19.9	1,321	145.3	66.4	220	1
Goba	40.00	7.01	2,700	958	13.0	1,109	86.4	85.3	304	1
Gode	44.35	5.06	320	340	28.7	2,028	16.8	70.7	95	1
Gondar	37.26	12.32	1,966	1,172	19.2	1,524	76.9	79.4	179	1
Gore	35.33	8.10	1,974	2,318	18.1	1,263	183.5	69.8	325	1
Gorgora	37.18	12.15	1,840	1,101	21.5	1,560	72.0	72.6	156	2
Grawa	41.50	9.08	2,250	931	14.6	1,125	82.8	77.1	261	1
Hageré Mariam	38.15	5.38	200	973	18.6	1,422	68.4	76.5	280	1
Hagere Selam	38.31	6.28	2,840	1,228	12.5	1,152	106.6	92.2	337	1
Harer	42.07	9.12	1,856	859	19.7	1,347	63.8	63.4	233	1
Hosaina	37.50	7.35	2,290	1,159	16.6	1,325	87.5	79.8	250	1
Itang	34.15	8.10	550	1,216	26.6	1,637	74.3	61.5	214	1
Jiggiga	42.43	9.20	1,644	885	19.0	1,469	60.2	77.3	234	2
Jimma	36.50	7.40	1,577	1,469	18.8	1,301	112.9	69.2	314	1
Kebridehar	44.18	6.40	450	467	26.9	2,025	23.1	75.3	115	1
Keren	38.26	15.45	1,460	456	23.0	1,808	25.2	78.6	95	2
Kofele	38.47	7.04	2,680	1,170	14.2	1,279	91.5	90.1	306	1
Kokadam	39.10	8.25	1,650	830	20.9	1,533	54.1	73.3	158	1
Kulumsa	39.08	8.08	2,600	823	16.6	1,277	64.4	76.9	246	1
Kurmuk	34.23	10.33	600	1,130	27.7	1,700	66.5	61.4	199	1
Langano	38.40	7.35	1,600	510	20.1	1,459	35.0	72.6	141	1
Maichew	39.32	12.46	2,380	833	16.6	1,429	58.3	86.1	185	1
Makale	39.29	13.30	2,212	563	18.0	1,623	34.7	90.2	86	1
Massawa	39.27	15.37	10	181	29.8	2,033	8.9	68.2	1	2
Melka Werer/ Ambibara	40.23	9.28	737	471	26.3	1,874	25.1	71.3	73	2
Mendi	35.05	9.47	1,650	1,652	20.2	1,339	123.4	66.3	220	1
Metehara	39.47	8.50	1,062	543	24.6	1,721	34.6	70.0	83	1
Metu	35.35	8.19	1,940	1,887	19.2	1,327	142.2	69.1	288	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Midagaloloa	42.07	8.47	1,428	665	21.2	1,526	43.6	72.0	225	2
Mojo (Bery)	39.09	8.37	1,880	919	20.2	1,557	59.0	77.1	193	1
Munesa	38.54	7.35	2,550	1,333	12.6	1,188	112.2	94.3	304	1
Nacfa	38.20	16.40	1,676	224	19.0	1,595	14.0	83.9	31	1
Nazareth	39.17	8.33	1,622	804	20.2	1,435	56.0	71.0	172	2
Neghelli	39.45	5.17	1,455	765	19.1	1,321	57.9	69.2	160	1
Nejo	35.29	9.30	1,800	1,788	18.9	1,271	140.7	67.2	225	1
Nekemti	36.36	9.03	1,950	2,158	17.7	1,245	173.3	70.3	267	1
Poko	34.35	8.15	560	1,042	27.4	1,655	63.0	60.4	210	1
Robe	40.00	7.06	2,450	1,468	23.0	1,544	95.1	67.1	309	2
Sodo	37.43	6.50	2,020	1,333	20.0	1,382	96.5	69.1	273	1
Teseney	36.40	15.07	585	358	28.4	1,928	18.6	67.9	85	1
Ticho	39.32	7.49	2,800	1,265	13.9	1,155	109.5	83.1	328	1
Waldia	39.36	11.49	1,960	1,073	17.9	1,502	71.4	83.9	299	1
Weliso (Ghion)	37.59	8.33	1,960	1,208	18.0	1,361	88.8	75.6	228	1
Wendo (Aleta)	38.25	6.35	1,860	1,566	17.2	1,367	114.6	79.5	348	1
Wenji	39.15	8.25	1,540	804	20.7	1,441	55.8	69.6	211	1
Wush Wush	36.11	7.16	1,950	1,892	18.3	1,274	148.5	69.6	365	1
Yabelo	38.06	4.53	1,740	744	18.9	1,351	55.1	71.5	261	1
Yirgalem	38.23	6.45	1,835	1,216	19.6	1,383	87.9	70.6	320	1
Ziway	38.45	8.00	1,640	642	19.3	1,432	44.8	74.2	181	1
N = 94; √N = 9.69										
X				1,041	19.3	1,445	76.0	75.7	217	–
SD				454	4.3	257	37.3	9.4	81	–
CV(%)				43.6	22.3	18	0.49	12.4	37	–
SE				47	0.4	27	3.8	9.2	8	–
GABON										
Bitam	11.29	2.05	600	1,818	24.2	1,082	168.0	44.7	365	1
Cocobbeach	9.36	1.00	12	3,454	25.7	1,166	296.2	45.4	312	1
Franceville	13.34	−1.36	426	1,833	24.4	1,195	153.4	49.0	296	1
Lambarene	10.14	−0.43	27	1,912	26.1	1,157	165.3	44.3	278	1
Lastoursville	12.43	−0.50	483	1,771	24.1	1,146	154.5	47.6	300	1
Libreville	9.25	0.27	12	3,009	28.9	1,181	254.8	40.9	291	2
Makokou	12.52	0.34	509	1,798	24.0	1,112	161.7	46.3	353	2
Port-Gentil	8.45	−0.42	3	1,951	25.9	1,203	162.2	46.4	270	1
Tchibanga	11.01	−2.51	83	1,539	25.8	1,170	131.5	45.3	257	1
N = 9; √N = 3.00										
X				2,120	25.4	1,157	172.0	45.5	302	–
SD				613	1.5	37	33.3	2.1	34	–
CV(%)				29	5.8	3.1	19.4	4.6	11	–
SE				5	0.5	4.1	11.1	0.7	11	–

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
GAMBIA										
Banjul Yundum	−16.48	13.21	36	960	25.6	1,777	54.0	69.4	137	1
Basse	−14.13	1.19	4	890	27.8	1,980	44.9	71.2	143	1
Georgetown	14.46	13.32	1	796	28.1	1,951	40.8	69.4	138	1
Jenoi	−15.34	13.29	11	753	27.6	1,912	39.4	69.3	129	1
Sapu	−15.56	13.34	2	714	27.6	1,914	37.3	69.3	130	1
N = 5; √N = 2.23										
X				823	27.3	1,547	43.3	69.7	135	–
SD				90	0.9	720	5.9	0.74	5	–
CV(%)				11	3.2	46.5	13.6	1.1	4	–
SE				40	0.4	323	2.6	0.33	2	–
GHANA										
Accra	−0.10	5.36	68	765	26.4	1,471	52.0	55.7	190	1
Ada	0.38	5.47	5	899	27.3	1,453	61.9	53.2	221	1
Akuse	0.07	6.06	17	1,136	27.2	1,510	75.2	55.5	301	1
Axim	−2.14	4.52	38	2,246	26.3	1,359	165.3	51.7	365	1
Bole	−2.29	9.02	299	1,087	26.1	1,537	70.7	58.9	234	1
Ho	0.28	6.36	158	1,430	26.7	1,464	97.7	54.8	330	1
Kete-Krachi	−0.02	7.49	122	1,403	27.5	1,549	90.6	56.3	273	1
Kumasi	−1.36	6.43	287	1,459	25.6	1,327	10.9.9	51.8	318	1
Navrono	−1.06	10.54	201	1,057	28.2	1,771	59.7	62.8	180	1
Saltpond	−1.04	8.12	44	924	26.5	1,444	64.0	54.5	228	2
Sefwi Bekwai	−2.20	6.12	171	1,717	26.6	1,279	134.2	48.1	320	1
Takoradi	−1.46	4.53	5	1,253	25.6	1,334	93.9	52.1	298	1
Tamale	−0.51	9.30	168	1,090	27.8	1,665	65.5	59.9	223	1
Wa	−2.30	10.03	325	1,080	27.2	1,777	60.8	65.3	212	1
Wenchi	−2.06	7.45	339	1,344	25.5	1,427	94.2	56.0	284	1
Yendi	−0.01	9.27	195	1,181	27.4	1,758	67.2	64.2	222	1
N = 16; √N = 4.00										
X				1,254	26.7	1,508	85.4	56.3	262	–
SD				346	0.79	155	29.7	5.0	54	–
CV(%)				28	3.0	10	34.7	8.9	21	–
SE				87	0.2	39	7.4	1.3	14	–
GUINEA										
Conakry	−13.37	9.34	48	4,351	26.4	1,394	312.1	52.8	225	1
Kouroussa	−9.15	10.39	372	1,054	26.0	1,574	95.6	60.5	213	1
Mamou	−12.05	10.22	783	1,963	23.5	1,255	156.4	53.4	246	1
N = 3; √N = 1.73										
X				2,456	25.3	1,408	188	55.6	228	–
SD				1390	1.3	131	91	3.5	14	–
CV(%)				57	5.1	9	48	6.3	6	–
SE				803	0.8	5	53	2.0	8	–

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
GUINEA BISSAU										
Bissau (Aeroport)	−15.39	11.53	39	1,906	26.2	1,628	117.1	62.1	170	1
Bolama	−15.29	11.35	18	2,290	26.7	1,604	142.8	60.1	182	1
Buba	−15.05	11.18	30	2,133	26.0	1,459	46.2	56.1	177	1
Catio	−15.16	11.17	18	2,629	26.7	1,489	176.6	55.8	194	1
Nova Lamego	−14.14	12.17	83	1,502	28.1	1,584	94.8	53.4	174	1
N = 5; √N = 2.23										
X				2,092	26.0	1,553	116	57.5	179	–
SD				377	1.8	67	44	3.1	8	–
CV(%)				18	7.0	4	38	5.5	5	–
SE				169	0.8	30	20	1.4	4	–
KENYA										
Eldoret	35.17	0.32	2,120	1,063	16.6	1,515	70.2	91.3	251	2
Equator	35.33	−0.01	2,762	1,219	13.1	1,342	90.8	102.4	317	1
Galole	40.02	−1.30	100	470	27.2	1,802	26.1	66.3	69	2
Garissa	39.38	−0.28	138	321	26.4	1,959	16.4	69.0	69	2
Habaswein	39.30	1.02	200	218	28.5	2,076	10.5	72.8	29	1
Isiolo	37.35	0.21	1,104	613	23.4	2,019	30.4	86.3	143	2
Kabete Lab.	36.46	−1.15	1,820	931	18.1	1,369	68.0	75.6	226	2
Kabete Obs.	36.45	−1.16	1,820	977	17.9	1,378	70.9	77.0	241	2
Kericho	35.21	−0.22	2,184	1,847	17.6	1,325	139.4	75.3	365	1
Kiambu	36.49	−1.12	1,731	989	18.8	1,454	68.0	77.3	231	2
Kisumu	34.45	−0.06	1,157	1,118	23.1	1,607	69.6	69.6	355	1
Kitale	35.00	1.01	1,890	1,232	18.3	1,414	87.1	77.3	298	1
Kitui (Agric.)	38.01	−1.22	1,090	1,031	21.4	1,662	62.0	77.7	178	2
Lamu	40.50	−2.16	6	895	26.6	1,593	56.2	59.9	134	1
Lodwar	35.37	3.07	506	220	29.3	2,523	8.7	86.1	30	1
Loitoketok D.C.	37.31	−2.56	1,845	767	16.7	1,331	57.6	79.7	217	1
Lokitaung	35.45	4.15	730	395	27.0	2,328	17.0	86.2	47	1
Machakos School	37.17	−1.31	1,680	908	19.3	1,476	61.5	76.5	207	2
Magadi	36.17	−1.53	622	398	29.0	2,042	19.5	70.4	61	2
Makindu	37.50	−2.17	1,000	611	22.7	1,604	38.1	70.7	155	2
Malinci	40.06	−3.14	20	1,148	26.4	1,668	68.8	63.2	219	1
Mandera	41.52	3.56	230	228	28.8	2,140	10.7	74.3	30	1
Maralal	36.42	1.05	1,950	620	16.1	1,340	46.3	83.2	219	2
Marigat	36.02	1.30	1,000	652	24.6	1,823	35.8	74.1	185	3
Marsabit	37.54	2.18	1,219	817	20.0	1,319	61.9	66.0	200	2
Molo Pijr	35.44	−0.14	2,499	1,174	13.7	1,239	94.8	90.4	312	1
Mombasa	39.37	−4.02	57	1,203	26.7	1,649	73.0	61.8	282	1
Moyale	39.03	3.32	1,097	682	22.2	1,581	43.1	71.2	164	2
Muguga	36.38	−1.13	2,096	991	15.9	1,342	73.8	84.4	232	1
Nairobi/ Dagoretti	36.45	−1.18	1,798	920	17.5	1,357	67.8	77.5	234	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Naivasha	36.26	–0.43	1,900	611	17.2	1,258	48.6	73.1	295	1
Nakuru	36.06	–0.16	1,901	877	18.1	1,386	63.3	76.6	272	1
Nanyuki	37.04	0.01	1,948	739	16.1	1,296	57.0	80.5	288	1
Narok	35.50	−1.08	1,890	718	16.5	1,437	50.0	87.1	223	1
Rumuruti (D.C.)	36.33	0.16	1,7770	599	17.7	1,598	37.5	90.3	199	2
South Kinangop	38.40	–0.46	2,600	1,142	11.5	1,106	103.3	96.2	365	1
Subukia	36.09	–0.02	2,100	1,066	16.2	1,303	81.8	80.4	278	1
Thika	37.03	–0.58	1,549	858	19.8	1,453	59.1	73.4	191	2
Voi38.34	–3.24	579	538	25.0	1,707	31.6	68.3	140	2	
Wajir	40.04	1.45	244	254	27.8	1,911	13.3	68.7	51	2
N = 40; √N = 6.32										
X				802	20.9	1,561	55	77.2	204	–
SD				343	5.0	390	28	9.3	97	–
CV(%)				43	23.7	25	51	12.0	48	–
SE				54	0.8	62	4.4	1.5	15	–
LESOTHO										
Buthaz Buthe	28.15	–28.46	1,680	817	14.2	1,203	67.9	84.7	252	1
Leribe (Maputsoe)	28.03	–28.53	1,670	857	15.1	1,327	64.6	87.9	250	1
Maseru	27.29	–29.12	1,510	647	15.2	1,348	48.0	88.7	229	1
Mokhotlong	29.08	–29.16	2,200	575	11.5	1,260	45.6	109.6	224	1
Oxbow	28.37	–28.43	2,650	1,281	7.3	933	137.3	127.8	365	1
Outhing	27.43	–30.25	1,650	799	14.7	1,315	60.8	89.5	278	1
Teyateyaneng	27.44	–29.09	1,690	723	15.0	1,266	57.1	84.4	248	1
Thaba Tseka	28.33	–29.30	2,160	614	11.7	1,115	55.1	95.3	252	1
N = 8; √N = 2.82										
X				789	13.1	1,220	67	96.0	262	–
SD				209	2.6	130	27	14.2	42	–
CV(%)				26	20	11	41	14.8	16	–
SE				74	0.9	15	10	5.0	15	–
LIBERIA										
Greenville	–9.05	5.10	5	4,132	25.2	1,292	319.8	51.3	365	1
Harbel	–10.20	6.20	150	3,259	25.7	1,295	251.7	50.4	345	1
Sakleipie	–8.45	7.00	300	2,166	25.8	1,538	140.8	59.6	307	1
Spriggspayne Air.	–10.45	6.20	8	4,735	25.8	1,378	343.6	53.4	365	1
Suakoko	–9.35	7.00	150	1,880	24.3	1,291	145.6	53.1	320	1
Voinjama	–9.45	8.25	300	2,954	24.8	1,420	235.0	57.3	326	1
N = 6; √N = 2.44										
X				3,188	25.3	1,369	235	54.2	338	–
SD				1,008	0.56	90	78	3.3	22	–
CV(%)				32	2.2	7	33	6.0	7	–
SE				413	22	37	32	1.4	9	–

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
LIBYA										
Agedabia	20.10	30.43	7	122	20.7	1,630	7.5	78.7	71	1
Benina	20.16	32.05	132	258	19.6	1,278	20.2	65.2	122	1
Derna	22.34	32.47	26	256	19.4	1,367	18.7	70.5	125	1
Ghadames	9.30	30.08	357	5	22.2	2,597	0.2	117.0	0	1
Gialo	21.34	29.02	60	1	22.4	1,960	0.0	87.5	0	1
Giarabub	24.32	29.45	−1	8	22.0	1,948	0.4	88.5	0	1
Hon	15.57	29.08	267	37	21.1	2,093	1.8	99.2	0	1
Jamal Abdel Nasser	23.55	31.51	155	96	19.2	1,657	5.8	86.3	0	1
Kufra	23.18	24.13	435	1	23.8	2,014	0.0	84.6	0	1
Misurata	15.03	32.19	32	249	19.9	1,312	19.0	65.9	97	1
Nalut	10.59	31.52	621	113	18.4	1,921	5.9	104.4	13	1
Sebha	14.26	27.01	432	19	22.8	2,408	0.8	105.6	0	1
Shahat	21.51	32.49	625	545	15.9	1,320	41.3	83.0	171	1
Sirte	16.35	31.12	13	186	20.3	1,383	13.4	68.1	91	1
Tazerbo	21.08	25.48	260	1	22.1	1,952	0.1	88.3	0	1
Tripoli (Met.)	13.11	32.54	20	389	19.5	1,554	25.0	79.7	142	1
Zuara	12.05	32.53	3	216	19.4	1,335	16.2	68.8	101	1
N = 17; √N = 10.81										
X				147	20.5	1,733	10.4	84.8	55	–
SD				152	1.9	401	11.4	15.1	60	–
CV(%)				104	9.1	23	109	17.8	109	–
SE				37	2.2	97	2.8	1.4	15	–
MADAGASCAR										
Analalava	47.46	−14.38	105	1,912	26.6	1,847	103.5	69.4	189	1
Antalaha	50.15	−14.53	87	2,103	24.1	1,397	150.5	58.0	365	1
Antananarivo	47.32	−18.54	1,310	1,329	18.3	1,242	107.0	67.9	198	1
Diego-Suarez	19.18	−12.21	114	901	27.0	1,918	47.0	71.0	140	1
Fascene (Nossi-Be)	18.19	−13.19	10	2,347	26.4	1,536	152.8	58.2	365	1
Fianarantsoa	47.06	−21.27	1,115	1,215	18.5	1,130	107.5	61.1	259	1
Fort-Dauphin	46.57	−25.02	8	1,530	22.9	1,418	107.9	61.9	365	1
Lac Alaotra	48.30	−17.45	770	1,148	20.6	1,341	85.6	65.1	174	1
Maintirano	444.02	−18.03	23	940	25.8	1,690	55.6	65.5	149	1
Majunga	46.21	−15.40	26	1,559	27.0	1,841	84.7	68.2	169	1
Mananjary	48.22	−21–12	5	2,795	23.2	1,328	210.5	57.2	365	1
Morondava	44.19	−20.17	7	767	24.9	1,638	46.8	65.8	127	1
Toamasina (Tamatave)	49.24	−18.07	5	3,324	23.6	1,325	250.9	56.1	365	1
Tulear (Toliara)	43.44	−23.23	8	343	23.8	1,544	22.2	64.9	63	1
N = 14; √N = 3.74										
X				1,587	23.8	1,443	109	63.6	235	–
SD				799	2.8	382	62	4.7	105	–

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
CV(%)				50	12	27	57	7.4	45	–
SE				214	0.7	102	17	1.3	28	–
MALAWI										
Bvumbwe	35.04	−15.55	1,145	1,248	19.2	1,289	96.8	66.1	193	1
Chileka	34.58	−15.41	766	847	21.9	1,466	57.8	66.9	166	1
Chitedze	33.38	−13.59	1,149	848	20.2	1,607	52.8	79.6	152	1
Chitipa	33.16	−9.42	1,278	975	21.1	1,647	59.2	78.1	157	1
Karonga	33.53	−9.57	529	1,121	24.8	1,597	70.2	64.4	177	1
Lilongwe	33.42	−13.58	1,136	840	19.4	1,466	57.3	75.6	156	1
Mulanje	34.40	−16.05	628	1,908	21.0	1,328	143.7	63.2	309	1
Mzimba	33.37	−11.53	1,349	870	19.7	1,614	53.9	81.9	152	1
Mzuzu	34.01	−11.27	1,251	1,344	17.6	1,225	109.7	69.6	269	1
Nkhata Bay	34.18	−11.36	500	1,597	23.3	1,481	107.8	63.6	231	1
N = 10; √N = 3.16										
X				1,160	20.8	1,472	80.9	70.9	196	–
SD				348	2.0	141	29.9	6.6	53	–
CV(%)				30	9.6	10	36.9	9.6	27	–
SE				110	0.6	45	33.1	2.1	17	–
MALI										
Bamako-Ville	−8.01	12.38	381	976	27.1	2,163	45.1	79.8	150	1
Bougouni	−7.30	11.25	350	1,124	26.6	2,207	50.9	83.0	172	1
Gao	−0.03	16.16	265	189	29.8	2,939	6.4	98.6	1	1
Hombori	−1.41	15.20	287	333	30.1	2,741	12.1	91.1	62	1
Kayes	−11.26	14.26	47	633	28.9	2,436	26.0	84.3	117	1
Kenieba	−11.14	12.51	132	1,152	28.3	2,234	51.6	78.9	155	1
Kidal	1.21	18.26	458	114	28.7	2,907	3.9	101.3	1	1
Kita	−9.28	13.04	333	933	27.4	2,232	41.8	81.5	146	1
Koutiala	−5.28	12.23	365	897	26.8	2,084	53.0	77.8	148	1
Menaka	2.13	15.52	278	219	29.9	3,174	6.9	106.2	9	1
Mopti	−4.06	14.31	276	467	28.0	2,273	20.5	81.2	96	1
Nioro du Sahel	−9.21	15.14	235	458	28.4	2,604	17.6	91.7	93	1
Same	−11.35	14.29	39	598	29.0	1,953	30.6	67.3	107	1
San	−4.50	13.20	283	696	27.9	2,694	25.8	96.6	114	
Segou	−6.09	13.24	288	635	27.6	2,418	26.3	87.6	109	1
Sikasso	−5.41	11.21	374	1,122	26.4	2,026	55.4	76.7	175	1
Tessalit	0.59	20.12	494	69	28.7	3,001	2.3	104.6	1	1
Timbuktu	−3.00	16.43	263	160	27.8	2,944	5.4	105.9	1	1
N = 18; √N = 4.24										
X				599	27.8	2,502	26.8	88.6	92	–
SD				360	1.9	370	18.3	11.2	62	–
CV(%)				60	6.8	15	68.2	12.6	67	–
SE				85	0.4	87	43.2	2.6	15	–

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	P (mm)	T (°C)	ETo (mm)	(100 P)/ETo	ETo/T	RD	RS
MAURITANIA										
Aioun el Atrouss	−9.36	16.42	223	206	29.1	2,391	8.6	82.2	36	1
Akjoujt	−14.22	19.45	123	64	28.8	2,364	2.7	82.1	1	1
Atar	−13.04	20.31	226	71	27.9	2,352	3.0	84.3	1	1
Bir Moghrein	−11.37	25.14	364	35	22.9	1,981	1.8	86.5	1	1
Boutlimit	−14.41	17.32	77	125	28.2	2,381	5.2	84.4	1	1
F'Derik	−12.42	22.41	298	67	26.0	2,553	2.6	98.2	1	1
Aedi	−13.31	16.09	18	391	29.7	2,312	16.9	77.8	1	1
Kiffa	−11.24	16.38	115	265	29.4	1,893	14.0	64.4	61	1
Nema	−7.16	16.36	269	219	30.2	2,577	8.5	85.3	44	1
Nouadhibou	−17.02	20.56	5	16	20.1	1,914	0.8	95.2	1	1
Nouakchott	−15.57	18.06	2	87	24.6	2,283	3.8	92.8	1	1
Rosso	−15.49	16.30	5	222	26.8	2,196	10.1	81.9	59	1
Tidjkja	−11.26	18.34	396	125	28.0	1,963	6.4	70.1	1	1
N = 13; √N = 3.60										
X				146	27.1	2,243	6.4	83.5	16	–
SD				104	2.8	226	4.7	8.9	23	–
CV(%)				71	10.5	10	74.0	10.7	1.5	–
SE				29	0.8	63	1.3	2.5	6.4	–
MAURITIUS										
Pampelmousses	7.34	−20.06	79	1,294	23.7	1,370	94.5	57.8	322	1
Plaisance	57.40	−20.26	55	1,966	23.2	1,257	156.4	54.2	365	1
Union Flacq	57.41	−20.26	146	2,353	22.3	1,211	194.3	54.3	365	1
Vacoas	57.30	−20.18	423	2,135	21.1	1,221	174.9	57.9	365	1
N = 4; √N = 2.00										
X				1,687	22.6	1,265	155	56.1	354	–
SD				369	1.0	63	37	1.8	19	–
CV(%)				22	4	5.0	24	3.2	5	–
SE				185	0.5	32	19	0.9	10	–
MOROCCO										
Agadir	−9.34	30.23	27	219	18.8	1,236	17.7	65.7	107	1
Tarfaya	−13.00	27.58	60	42	19.1	1,117	3.8	58.5	1	1
Casablanca	−7.40	33.34	62	426	17.4	1,076	39.6	61.8	190	1
Ifrane	−5.10	33.30	1,664	1,112	10.8	1,308	85.0	121.1	261	1
Kasba-Tadla	−6.17	33.32	503	409	19.6	1,531	26.7	78.1	184	1
Marrakech	−8.02	31.37	468	243	19.8	1,570	15.5	79.3	100	1
Meknes	−5.32	33.53	576	585	17.1	1,257	46.5	73.5	215	1
Ouarzazate	−6.54	30.56	1,139	123	19.0	1,591	7.7	83.7	1	1
Oujda	−1.56	34.47	468	337	17.1	1,518	22.2	88.8	156	1
Rabat-Sale	−6.46	34.03	84	497	17.7	1,255	39.6	70.9	195	1
Sidi Ifni	−10.11	29.22	58	168	18.8	1,065	15.8	56.6	76	1
Tan-Tan	−11.09	28.27	229	112	19.6	1,454	7.7	74.2	32	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Tangier (Airport)	−5.54	35.44	19	895	18.0	1,436	62.3	79.8	226	1
N = 13; √N = 3.60										
X				321	17.9	1,340	30	76.3	134	–
SD				231	2.2	181	23	16.0	84	–
CV(%)				72	12.6	14	76	20.9	63	–
SE				64	0.6	50	6	4.4	23	–
MOZAMBIQUE										
Alto Molocue	37.41	−15.38	563	1,403	22.9	1,358	103.3	53.3	203	1
Ancuabe	39.51	−12.58	349	1,147	26.0	1,487	77.1	57.2	173	1
Angoche	39.54	−16.13	61	1,074	25.7	1,750	61.4	68.1	236	1
Beira-Observatorio	34.51	−19.50	7	1,493	24.6	1,567	95.3	63.7	274	1
Bela Vista (Maputo)	32.41	−26.20	15	668	22.6	1,489	44.9	65.9	247	2
Caia	35.20	−17.50	44	1,002	25.2	1,553	64.5	61.6	235	1
Catandica	33.10	−18.04	611	1,591	22.3	1,332	119.4	59.7	205	1
Catuane	32.17	−26.50	37	577	22.9	1,531	37.7	66.9	194	1
Cazula	33.38	−15.24	597	1,135	25.0	1,560	72.8	62.4	178	1
Changalane	32.11	−26.17	100	680	22.8	1,501	45.3	65.8	219	1
Chibuto	33.32	−24.41	90	760	24.5	1,540	49.4	62.9	248	1
Chicoa	32.21	−15.36	274	636	26.1	1,719	37.0	65.9	128	1
Chicualacuala	31.41	−22.05	452	493	22.9	1,659	29.7	72.4	128	1
Chigubo	33.31	−22.50	102	592	24.5	1,455	40.7	59.4	121	1
Chimoio	33.28	−19.07	731	1,068	21.5	1,462	73.1	68.0	187	1
Chinde	36.28	−18.35	4	1,200	25.5	1,601	75.0	62.8	264	1
Chiou-Chemba	34.49	−17.14	100	678	26.0	1,531	44.3	58.9	151	1
Chobela	32.44	−25.00	40	687	23.5	1,537	44.7	65.4	181	1
Chokue	33.00	−24.32	33	622	23.6	1,543	40.3	65.4	168	1
Cobue	34.46	−12.08	502	1,177	24.8	1,784	66.0	71.9	154	1
Cuamba	36.32	−14.49	606	934	24.2	1,545	60.5	59.7	154	1
Errego-Ile	37.11	−16.02	533	1,615	23.0	1,374	117.5	62.5	284	1
Espungabera	32.46	−20.28	824	1,533	19.9	1,243	123.3	70.7	365	1
Fingoe	31.53	−15.10	857	1,058	21.9	1,548	68.3	53.3	159	1
Funhalouro	34.23	−23.05	116	588	25.0	1,482	39.7	75.0	145	1
Furancungo	33.36	−14.54	1,260	1,130	19.9	1,493	75.7	62.8	181	1
Goba-Fronteira	32.06	−26.15	418	753	21.9	1,376	54.7	67.8	236	1
Gurue	36.59	−15.30	734	1,997	21.9	1,353	147.6	56.9	314	1
Inhaca	32.56	−26.02	27	899	22.9	1,303	69.0	61.7	329	1
Inhambane	35.23	−23.52	14	954	23.6	1,455	65.6	67.9	281	1
Inhaminga	35.00	−18.24	316	1,093	24.7	1,678	65.1	60.5	180	1
Inharrime	35.01	−24.49	43	845	24.1	1,458	58.0	72.6	285	1
Lichinga	35.15	−13.17	1,364	1,062	19.1	1,387	76.6	61.2	174	1
Lioma	36.46	−15.09	736	1,031	22.7	1,389	74.2	57.9	184	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Lugela	36.45	−16.26	293	1,628	24.7	1,431	113.8	57.6	277	1
Mabote	34.07	−22.03	143	597	24.0	1,382	43.2	66.1	149	1
Macia	33.06	−25.02	56	829	22.2	1,468	56.5	61.6	262	1
Macomia	40.08	−12.12	343	1,198	25.1	1,545	77.5	69.1	173	1
Macanja	37.32	−17.18	70	1,307	25.2	1,742	75.0	70.5	271	1
Malema	37.25	−14.57	625	973	22.0	1,551	62.7	65.4	152	1
Mambone	35.01	−20.59	4	865	24.4	1,595	54.2	64.5	176	1
Manhica	32.48	−25.24	35	807	23.1	1,489	54.2	76.2	258	1
Maniamba	34.59	−12.46	1,093	1,450	20.4	1,555	93.2	63.1	189	1
Manica	32.52	−18.56	723	1,014	21.2	1,337	75.8	60.6	185	1
Manisquenique	33.02	−24.44	13	837	23.6	1,431	58.5	61.8	260	1
Manjacaze	33.53	−24.43	65	703	24.0	1,482	47.4	71.6	256	1
Mapai	32.03	−22.44	254	365	23.8	1,705	21.4	64.6	71	1
Maputo/ Mavalane	32.34	−25.55	39	759	22.7	1,467	51.7	65.3	203	1
Marromeu	35.56	−18.18	20	912	25.3	1,653	55.2	66.9	175	1
Marrupa	37.33	−13.44	836	1,136	22.1	1,478	76.9	62.9	174	1
Massanguena	32.58	−21.33	136	627	24.5	1,540	40.7	67.6	139	1
Massangulo-Missao	35.26	−13.53	1,110	1,094	20.6	1,392	78.6	63.6	175	1
Massinga	35.24	−20.19	109	1,172	23.1	1,470	79.7	65.6	286	1
Maua	37.10	−13.52	594	1,170	24.3	1,594	73.4	61.6	166	1
Mazeminhana	32.15	−26.27	60	586	19.1	1,176	49.8	64.9	221	1
Meconta	39.51	−14.59	235	933	24.0	1,557	59.9	65.5	155	1
Mecufi	40.34	−13.17	10	796	26.9	1,761	45.2	59.6	160	1
Mecula	37.37	−12.06	1,110	1,419	24.5	1,460	97.2	57.6	189	1
Meloco	39.10	−13.29	438	1,162	25.6	1,475	78.8	67.6	173	1
Memba	40.32	−14.11	14	744	25.9	1,752	42.5	69.0	139	1
Messambuzi	32.55	−19.30	906	1,172	20.5	1,414	82.9	63.5	190	1
Milange	35.47	−16.06	745	1,735	22.9	1,454	119.3	68.5	287	1
Moamba	32.14	−25.36	110	633	24.0	1,644	38.5	60.8	179	1
Mocimboa da Praia	40.22	−11.21	27	991	25.3	1,538	64.4	55.9	179	1
Mocuba	36.59	−16.50	134	1,175	24.6	1,374	85.5	67.2	270	1
Mogincual	40.45	−15.34	35	1,008	25.7	1,726	58.4	62.7	231	1
Moma	39.13	−16.46	4	1,167	25.9	1,623	71.9	62.9	251	1
Montepuez	39.02	−13.08	534	944	24.2	1,521	62.1	61.4	158	1
Mopeia	34.52	−17.59	51	1,043	26.3	1,614	64.6	65.6	254	1
Morrumbala	35.35	−17.20	417	1,017	23.5	1,547	65.7	69.6	178	1
Mossuril	40.40	−14.57	15	941	25.2	1,754	53.6	61.6	196	1
Mueda	39.33	−11.40	847	1,093	21.9	1,350	81.0	64.3	177	1
Muite	39.02	−14.02	400	1,044	25.4	1,633	63.9	64.5	159	1
Mungari	33.33	−17.10	535	632	23.9	1,542	41.0	64.5	134	1
Mutarara	35.03	−17.23	88	737	25.9	1,651	44.6	63.7	154	1
Mutuali	37.03	−14.53	570	898	24.3	1,627	55.2	67.0	164	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Namaacha	32.01	−25.29	523	896	21.1	1,307	68.6	61.9	246	1
Namacurra	37.01	−17.30	50	1,169	25.7	1,651	70.8	64.2	260	1
Namapa	39.50	−13.43	200	972	24.9	1,631	59.6	65.5	165	1
Namarroi	36.52	−15.57	603	1,758	23.4	1,383	127.1	59.1	288	1
Nametil	39.21	−15.43	171	1,042	26.1	1,602	65.0	61.4	177	1
Nampula	39.17	−15.06	438	1,033	24.6	1,556	66.4	63.3	179	1
Namuno	38.49	−13.37	495	1,024	24.7	1,484	69.0	60.1	166	1
Nhacoongo	35.11	−24.18	30	1,015	23.6	1,397	72.7	59.2	330	1
Nova Sofala	34.44	−20.09	10	1,028	24.5	1,644	62.5	67.1	171	1
Nungo	37.46	−13.25	610	1,090	23.4	1,637	66.6	70.0	173	1
Pafuri	31.20	−22.27	290	380	24.4	1,650	23.0	67.6	94	1
Palma	40.30	−10.46	60	1,139	26.4	1,536	74.2	58.2	211	1
Panda	34.43	−24.03	150	694	24.1	1,528	45.4	63.4	208	1
Pebane	38.09	−17.16	25	1,225	25.2	1,629	75.2	64.6	264	1
Pemba	40.30	−12.58	49	876	25.9	1,740	50.3	67.2	164	1
Quelimane	36.53	−17.53	11	1,373	24.8	1,568	87.6	63.2	276	1
Quissanga	40.24	−12.26	42	1,000	26.2	1,740	57.5	66.4	173	1
Quissico	34.45	−24.43	147	958	23.3	1,519	63.1	65.2	285	1
Ressano Garcia	34.59	−25.36	145	571	23.5	1,495	38.2	63.6	181	1
Ribaue	38.16	−14.59	535	1,125	23.7	1,423	79.1	60.0	183	1
Sussundenga	33.13	−19.20	635	1,155	21.2	1,465	78.8	69.1	186	1
Tacuane-Madal	36.22	−16.21	400	2,117	23.7	1,371	154.4	57.8	318	1
Tete	33.35	−16.11	123	646	26.5	1,752	36.9	66.1	129	1
Ulongue	34.21	−14.13	1,305	936	19.1	1,545	60.6	80.9	158	1
Umbeluzi	32.23	−26.03	12	715	23.0	1,555	46.0	67.6	188	1
Vila Gamito	32.59	−14.10	958	1,007	22.6	1,755	57.4	77.7	165	1
Vila Machado	34.12	−19.16	57	922	25.5	1,650	55.9	64.7	173	1
Vilanculos	35.19	−22.0	20	832	24.1	1,534	54.2	63.7	191	1
Xai Xai	33.38	−25.03	4	953	22.9	1,412	67.5	61.7	326	1
Zitundo	32.50	−26.45	71	958	22.1	1,382	69.3	62.5	365	1
Zumbo	30.26	−15.37	339	714	25.2	1,695	42.1	67.3	141	1
N = 107; √N = 10.34										
X				998	23.4	1,506	68.2	64.4	198	–
SD				318	1.6	102	24.3	4.5	48	–
CV(%)				32	6.8	6.8	36.6	7.0	23	–
SE				31	0.2	9.9	2.4	0.4	4	–
NAMIBIA										
Gobabis	18.58	−22.28	1,440	375	19.4	1,711	21.9	88.2	93	1
Keetmanshoop	18.07	−26.32	1,067	149	20.8	2,176	6.8	104.6	1	1
Luderitz (Diaz Point)	15.06	−26.38	23	17	15.9	1,000	1.7	62.9	1	1
Swakopmund	14.31	−22.41	12	8	15.2	1,042	0.8	68.6	1	1
Tsumeb	17.43	−19.14	1,311	524	21.9	1,705	30.7	77.9	141	1
Windhoek	17.06	−22.34	1,728	361	19.0	1,595	22.6	83.9	103	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ETo	ETo/*T*	RD	RS
N = 6; √N = 2.44										
X				239	18.7	1,538	14.1	81.0	57	–
SD				194	2.4	409	12	13.6	58	–
CV(%)				81	13	27	82	20.5	102	–
SE				80	1.0	168	5	5.6	24	–
NIGER										
Agadez	7.59	16.58	501	111	27.9	2,941	3.8	105.4	1	1
Bilma	12.55	18.41	355	12	26.6	2,758	0.4	103.7	1	1
Birni-N'Konni	5.15	13.48	272	477	28.7	2,611	18.3	91.0	97	1
Gaya	3.27	11.53	202	796	28.5	2,219	35.9	77.9	143	1
Maine-Soroa	11.59	13.14	338	342	27.8	2,879	11.9	103.6	62	1
Maradi	7.05	13.28	372	864	27.2	2,276	38.0	83.7	123	1
N'Guigmi	13.07	14.15	285	187	27.6	2,746	6.8	99.5	30	1
Niamey-Aero.	2.10	13.29	223	531	29.0	2,670	19.9	92.1	97	1
Tahoua	5.15	14.54	386	359	28.9	3,226	11.1	111.6	61	1
Tillabery	1.27	14.12	209	399	29.6	2,814	14.2	95.1	76	1
Zinder	8.59	13.47	452	411	28.0	2,456	3.4	87.7	78	1
N = 11; √N = 3.31										
X				408	28.2	2,456	16.1	95.6	70	–
SD				248	0.8	733	11.4	9.8	44	–
CV(%)				61	3.0	30	70.8	10.2	62	–
SE				75	0.2	221	3.4	3.0	13.3	–
NIGERIA										
Bauchi	9.49	10.17	591	1,113	25.6	2,294	48.5	89.6	156	1
Benin City	5.36	6.19	79	2,014	26.2	1,286	156.6	49.1	289	1
Enugu	7.33	6.26	140	1,814	26.7	1,379	131.5	51.6	265	1
Gusau	6.42	12.10	463	972	26.3	2,152	45.2	81.8	152	1
Ibadan	3.54	7.26	234	1,227	26.4	1,373	89.4	52.00	267	1
Ibi	9.45	8.11	111	1,137	27.1	1,589	71.6	58.6	220	1
Ilorin	4.35	8.29	308	1,288	26.8	1,367	82.2	51.8	243	1
Jos	8.54	9.52	1,295	1,420	22.2	1,690	84.0	76.1	197	1
Kaduna	7.27	10.36	645	1,275	24.9	1,833	69.6	73.6	193	1
Kano	8.32	12.03	476	832	26.2	2,336	35.6	89.2	129	1
Katsina/ Lagos/Okeja	7.41	13.01	427	737	26.0	1,936	38.1	74.5	122	1
Lokoja	3.20	6.35	40	1,466	26.2	1,321	111.0	50.4	287	1
Maiduguri	6.44	7.48	41	1,168	27.5	1,486	78.6	54.0	233	1
Makurdi	13.05	11.51	354	644	26.8	1,948	33.1	72.7	115	1
Minna	8.37	7.41	113	1,377	27.3	1,485	92.7	54.4	227	1
Nguru	6.32	9.37	262	1,351	27.0	1,701	79.4	63.0	206	1
Port Harcourt	10.28	12.53	343	570	26.8	1,774	32.1	66.2	105	1
Potiskum	7.01	4.51	18	2,492	26.7	1,221	204.1	45.7	329	1
Samaru	11.02	11.42	415	787	26.3	1,927	40.8	73.3	126	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Sokoto	7.35	11.11	685	1,133	24.9	1,882	60.2	75.6	178	1
Yelwa	5.15	13.01	351	730	28.1	2,309	31.6	82.2	123	1
Yola	4.45	10.53	244	970	27.5	2,064	47.0	75.1	176	1
N = 22; √N = 3.87										
X				1,196	26.4	1,699	74	67.9	197	–
SD				443	1.2	469	42	11.8	62	–
CV(%)				37	4.6	28	57	17.4	32	–
SE				92	0.3	98	9	3.0	13	–
RWANDA										
Gabiro	30.24	−1.32	1,472	824	20.4	1,494	55.2	73.2	272	1
Rubona-Colline	29.46	−2.29	1,706	1,182	18.4	1,405	84.1	76.4	284	1
N = 2; √N = 1.41										
X				1,003	19.4	1,450	70	74.8	278	–
SD				179	1.0	45	14	1.6	6	–
CV(%)				18	5	3	21	2.1	2	–
SE				127	0.7	32	10	1.1	4	–
SAO TOME & PRINCIPE										
Sao Tome	6.43	0.23	8	896	25.4	1,262	71.0	49.7	261	1
Santo Antonio	7.25	1.39	5	1,872	24.8	1,198	156	48.3	326	1
N = 2; √N = 1.41										
X				1,354	25.1	1,230	114	49.0	294	–
SD				488	0.3	32	43	0.7	33	–
CV(%)				35	1.2	3	37	1.4	11	–
SE				343	0.2	23	30	0.5	23	–
SENEGAL										
Bambey Meteo	−16.28	14.42	45	516	26.6	2,113	24.4	79.4	100	1
Dakar/Yoff	−17.30	14.44	27	421	23.9	1,728	24.4	72.3	91	1
Diourbel	−16.14	14.39	7	518	26.9	1,663	31.1	61.8	113	1
Guede	−14.47	16.32	8	311	27.3	2,228	14.0	81.6	64	1
Kaolack	−16.04	14.08	6	615	27.5	1,933	31.8	70.3	122	1
Kedougou	−12.13	12.34	178	1,173	28.0	1,663	70.5	59.4	166	1
Kolda	−14.58	12.23	10	990	26.6	1,805	54.8	67.9	151	1
Linguere	−15.07	15.23	20	397	28.4	1,699	23.4	59.8	102	1
Matam	−13.15	15.39	15	369	29.6	1,695	21.8	57.3	92	1
Podor	−14.58	16.39	6	221	28.4	1,910	11.6	67.3	58	1
Sait-Louis	−16.27	16.03	4	262	24.3	1,813	14.5	74.6	74	1
Tambacounda	−13.41	13.46	49	769	28.2	2,141	35.9	75.9	137	1
Thies	−16.57	14.48	76	479	25.6	1,905	25.1	74.4	100	1
Ziguinchor	−16.16	12.33	26	1,236	25.5	1,855	66.6	72.7	148	1
N = 14; √N = 3.74										
X				570	26.9	1,870	32	69.6	108	–
SD				334	1.6	177	18	7.4	32	–

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	P (mm)	T (°C)	ETo (mm)	(100 P)/ ETo	ETo/T	RD	RS
CV(%)				0.6	6	10	57	10.6	29	–
SE				89	0.4	47	5	2.0	9	–
SEYCHELLES										
Seychelles Int. Aero.	55.31	−4.40	3	2,343	26.5	1,645	142.4	62.1	365	1
SIERRA LEONE										
Bo	−11.46	7.57	100	2,919	26.3	1,267	230.4	48.2	294	1
Bonthe	−12.30	4.32	7	3,771	26.8	1,236	305.1	46.1	283	1
Daru	−10.51	7.59	185	2,566	26.0	1,276	201.1	49.1	307	1
Freetown (Falcon B)	−13.14	8.30	11	3,260	26.6	1,334	244.4	50.2	252	1
Kabala	−11.33	9.35	463	2,237	25.3	1,409	158.8	55.7	262	1
Lungi	−13.12	8.37	25	3,653	26.4	1,339	272.8	50.7	257	1
N = 6; √N = 2.44										
X				3,067	2.2	1,310	235	50.0	276	–
SD				553	49	57	47	3.0	20	–
CV(%)				18	1.9	4	0.2	6.0	7	–
SE				227	20	23	19	1.2	8	–
SOMALIA										
Afgoi	45.08	2.09	83	467	27.4	2,006	23.3	73.2	130	2
Afmadu	42.04	0.31	29	550	28.4	1,889	29.1	66.5	139	2
Alessandra	42.46	0.30	24	523	27.6	1,722	30.4	62.4	190	2
Bardera	42.18	2.21	116	384	28.8	2,252	17.1	78.2	71	2
Belet Uen	45.13	4.42	173	206	28.7	1,981	10.4	68.3	26	1
Berbera	45.01	10.25	9	50	29.8	3,189	1.6	107.0	1	1
Bosaso	49.11	11.17	2	19	29.3	2,392	0.8	81.6	1	1
Brava	44.02	1.06	6	376	26.2	1,569	24.0	60.4	104	1
Bulo Burti	45.34	3.15	158	328	28.6	2,171	15.1	75.9	77	2
Chisimaio	42.26	−0.22	10	318	27.0	1,751	18.2	64.9	85	1
El Bur	46.37	4.42	175	174	28.1	2,164	8.0	77.0	1	2
El Mugne	44.46	1.43	12	251	25.9	1,606	15.6	62.0	51	2
Galcayo	47.16	6.51	302	147	27.4	2,260	6.5	82.5	1	1
Gardo	49.05	9.31	812	96	24.6	2,352	4.1	95.6	1	1
Genale	44.45	1.50	69	473	26.5	1,619	29.2	61.1	166	2
Giohar	45.30	2.46	108	798	27.5	1,792	27.8	65.2	129	2
Hargeisa	44.05	9.30	1,326	416	21.8	2,720	15.3	124.8	1	1
Hoddur	43.52	4.11	497	363	26.6	2,193	16.6	82.4	93	2
Iscia Baidoa	43.40	3.08	487	585	26.1	1,804	32.4	69.1	135	2
Jonte	42.28	−0.20	8	383	27.3	1,517	25.2	55.6	101	1
Lug Ganane	42.35	3.45	193	310	30.5	2,338	13.3	78.9	38	1
Mogadiscio	45.21	2.02	9	94	27.0	1,785	22.1	66.1	110	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Obbia	48.34	5.20	10	199	26.6	1,721	11.6	64.7	1	1
Scusciuban	50.14	10.18	344	72	28.6	2,754	2.6	96.3	1	1
N = 24; √N = 4.89										
X				351	27.3	2,064	16.7	75.8	69	–
SD				221	1.8	413	9.5	16.1	60	–
CV(%)				63	6.4	20	56.9	21.2	87	–
SE				45	0.4	84	1.9	3.3	12	–
SOUTH AFRICA										
Alexander Bay	16.32	−28.34	21	44	15.9	1,236	3.6	77.7	1	1
Beaufort West	22.35	−32.21	842	222	17.1	1,752	12.7	110.2	1	1
Bethal	29.29	−26.27	1,663	754	15.0	1,392	54.2	92.8	206	1
Bloemfontein	26.18	−29.06	1,351	547	15.6	1,604	34.1	102.8	155	2
Calvinia	19.46	−31.28	975	209	16.3	1,703	12.3	104.5	23	1
Cape St Lucia	32.24	−28.30	107	1,292	21.5	1,249	103.4	58.1	365	1
Cape Town	18.32	−33.54	17	506	16.5	1,362	37.2	82.5	175	1
De Aar	24.01	−30.39	1,240	288	16.2	1,700	16.9	104.9	54	1
Durban (Louis Botha)	30.57	−29.58	8	1,008	20.5	1,218	82.8	59.4	365	1
East London	27.50	−33.02	125	808	18.6	1,334	60.6	71.7	365	1
Estcourt	29.53	−29.00	1,148	738	16.8	1,315	56.1	78.3	212	1
George Airport	22.23	−34.00	193	860	16.4	1,072	80.2	65.4	365	1
Germiston	28.09	−26.15	1,668	708	16.2	1,456	48.6	89.9	211	1
Grootfontein	25.02	−31.29	1,263	377	14.4	1,448	26.0	100.6	68	1
Jansenville	24.40	−32.56	424	268	19.0	1,695	15.8	89.2	1	1
Johannesburg	28.03	−26.12	1,753	718	16.3	1,474	48.7	90.4	212	1
Kimberley	24.46	−28.48	1,198	415	18.3	1,792	23.2	97.9	66	1
Klaver	18.37	−31.47	42	174	19.2	1,736	10.0	90.4	30	1
Kokstad	29.25	−30.32	1,305	728	15.0	1,200	60.7	80.0	224	1
Kroonstad	27.15	−27.40	1,348	606	16.4	1,595	38.0	97.3	189	1
Kuruman	23.26	−27.28	1,317	420	17.8	1,582	26.5	88.9	107	1
Macuville	29.54	−22.16	522	348	23.3	1,582	22.0	67.9	92	1
Melmoth	31.24	−28.35	770	806	19.2	1,358	59.4	70.7	246	1
Montagu	20.07	−33.47	223	315	17.7	1,569	20.1	88.6	121	1
Nelspruit	30.59	−25.26	671	762	20.2	1,480	51.5	73.3	194	1
Newcastle	29.55	−27.44	1,235	916	17.3	1,547	59.2	89.4	207	1
O'okiep	17.51	−29.35	927	152	17.6	1,548	9.8	88.0	43	1
Oudtshoorn	22.13	−33.34	359	254	17.9	1,423	17.8	79.5	1	1
Pietersburg	29.27	−23.52	1,230	476	17.2	1,486	32.0	86.4	156	1
Pofadder	19.23	−29.08	1,989	98	18.5	1,636	6.0	88.4	1	1
Port Elisabeth	25.36	−33.59	60	576	17.2	1,179	48.9	68.5	281	1
Postmasburg	23.04	−28.19	1,323	325	18.8	1,710	19.0	91.0	41	1
Potchefstroom Agric.	27.04	−26.44	1,350	608	17.0	1,620	37.5	95.3	164	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Pretoria	28.11	−25.44	1,330	715	17.9	1,601	44.7	89.4	207	1
Prieska	22.45	−29.40	938	32	19.3	1,657	14.0	85.9	1	1
Punda Mailia	31.01	−22.41	5,462	590	22.9	1,648	35.8	72.0	159	1
Queenstown	26.52	−31.54	1,094	560	16.8	1,580	35.4	94.0	166	1
Sutherland	20.40	−32.33	1,459	229	12.4	1,454	15.7	117.3	70	1
Thabazimbi	27.25	−24.35	970	671	21.2	1,811	37.1	85.4	169	1
Umtata	28.40	−31.32	742	654	17.6	1,240	52.7	70.5	272	1
Upington	21.16	−28.24	836	196	20.2	1,725	11.4	85.4	1	1
Wepener	27.02	−29.44	1,438	627	13.4	1,543	40.6	115.1	204	1
Zeerust	26.05	−25.33	1,207	601	18.4	1,696	35.4	92.2	161	1
N = 43; √N = 6.56										
X				516	17.7	1,512	36	86.7	148	–
SD				276	2.3	185	22	13.7	108	–
CV(%)				53	12.7	12	61	15.8	73	–
SE				42	0.4	28	3	2.1	16	–
SUDAN										
Abu Hamed	33.19	19.32	312	19	28.9	2,672	0.7	92.5	1	1
Abu Na’ama	34.08	12.44	445	576	28.0	2,233	25.8	79.8	130	1
Akobo	33.01	7.47	400	996	28.1	1,991	50.0	70.3	190	1
Aroma	36.09	15.50	430	181	28.3	2,586	7.0	91.4	1	1
Atbara	33.58	17.42	347	73	29.4	1,461	3.0	83.7	1	1
Aweil	27.24	8.46	415	875	27.3	1,984	44.1	72.7	168	1
Bentiu	29.48	9.14	389	876	27.3	1,990	44.0	72.9	172	1
Bor	31.33	6.12	420	905	27.5	1,832	49.4	66.6	220	1
Damazine	34.23	11.47	474	707	28.1	1,996	35.4	71.0	137	1
Dereisa	22.46	12.41	750	597	25.1	2,073	28.8	82.6	112	1
Derudeb	36.06	17.33	518	117	29.2	2,529	4.6	83.0	1	1
Doka	35.46	13.31	500	680	28.7	2,383	28.5	102.6	122	1
Dongola	30.29	19.10	226	21	27.7	2,843	0.7	73.9	1	1
Dongonab	37.08	21.06	5	37	26.7	1,974	1.9	73.9	1	1
Ed Dueim	32.20	14.00	378	228	29.0	2,143	10.6	80.0	49	1
El Fasher	25.20	13.37	733	211	26.1	2,089	10.1	80.0	48	1
El Obeid	30.14	13.10	574	307	26.5	2,398	12.8	90.5	71	1
En Nahud	28.26	12.42	565	350	27.2	2,148	16.3	79.0	86	1
Gebeit	36.50	18.57	796	127	25.4	2,026	6.3	79.8	1	1
Gedaref	35.24	14.02	599	604	28.4	2,283	26.5	80.4	111	1
Geneina	22.27	13.29	805	445	25.9	2,229	20.0	86.1	90	1
Ghazala Gawzat	26.27	11.28	480	473	27.4	2,290	20.7	83.6	110	1
Haiya	36.22	18.20	640	87	28.2	2,800	3.1	99.3	1	1
Halfa el Gedida	35.36	18.19	451	359	28.7	2,066	17.4	72.0	74	1
Juba	31.36	4.52	460	959	27.3	1,624	59.1	59.5	238	1
Kadugli	29.43	11.00	499	764	26.9	2,126	35.9	79.0	167	1
Karima	31.51	18.33	249	41	28.5	2,751	1.5	96.5	1	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Kass	24.16	12.31	800	581	24.1	2,139	27.2	88.8	115	1
Kassala	36.24	15.28	500	253	29.2	1,953	13.0	67.2	55	1
Katrie	32.47	4.02	1,000	1,541	24.8	1,609	95.8	64.9	265	1
Khartoum	32.33	15.36	382	140	29.5	2,624	5.3	88.9	1	1
Kosti	32.40	13.10	381	344	27.5	2,124	16.1	77.6	81	1
Kurmuk	34.17	10.33	690	982	27.7	2,074	47.3	74.9	184	1
Kutum	24.40	14.21	1,160	316	23.3	2,026	15.6	87.0	64	1
Li Yubu	27.15	5.24	715	1,468	25.0	1,602	91.6	64.1	262	1
Malakal	31.39	9.33	387	782	28.1	2,021	38.7	71.9	175	1
Maridi	29.28	4.35	750	1,411	24.8	1,728	81.7	69.7	256	1
Mlkgur	23.17	11.57	650	657	25.8	2,096	31.3	81.2	128	1
Murundo	23.09	12.49	800	531	24.6	2,206	24.1	89.7	111	1
Na 35.04	8.37	400	816	27.6	2,113	38.6	76.6	174	1	
Nagishot	33.34	4.16	1,980	1,161	18.2	1,324	87.7	86.2	252	1
Nierteti	24.04	12.58	1,000	883	22.6	1,948	45.3	85.7	116	1
Nyala	24.53	12.03	674	401	26.9	2,305	17.4	80.9	95	1
Ourashi	33.17	14.45	440	277	28.5	2,305	12.0	70.8	58	1
Pibor	33.08	6.48	410	935	27.8	1,968	47.5	70.4	209	1
Port Sudan	37.13	19.35	3	75	28.7	2,020	3.7	69.7	1	1
Raga	25.41	8.28	545	1,070	26.1	1,818	58.9	85.1	189	1
Rashad	31.03	11.52	884	723	26.7	2,273	31.8	74.2	147	1
Renk	32.47	11.45	282	528	27.7	2,054	25.7	65.8	128	1
Rumbek	29.42	6.48	420	957	27.3	1,797	53.3	65.8	204	1
Sennar	33.37	13.33	418	430	25.1	2,149	20.0	85.6	101	1
Shambat Observatory	32.32	15.40	380	165	28.6	2,643	6.2	92.4	1	1
Shendi	33.26	16.42	360	136	29.6	2,583	5.3	87.3	1	1
Singa	33.57	1309	430	618	28.7	2,265	27.3	78.9	120	1
Tokar	37.44	18.26	19	70	29.8	2,510	2.8	84.2	1	1
Tonj	28.45	7.16	429	1,077	27.2	1,777	60.6	65.3	205	1
Torit	32.33	4.25	625	988	26.7	1,910	51.7	74.5	226	1
Wad Medani	33.29	14.24	408	307	28.4	2,535	12.1	89.3	60	1
Wadi Halfa	31.29	21.49	183	1	25.6	2,735	1.0	106.8	1	1
Wau	28.01	7.42	438	1,070	27.4	1,807	59.2	65.9	206	1
Yambio	28.24	4.34	650	1,464	24.6	1,431	102.3	58.2	277	1
Yei	30.40	4.05	830	1,373	24.4	1,795	76.5	73.6	258	1
Zalingei	23.29	12.54	900	638	23.8	2,103	30.3	88.4	113	
N = 63; √N = 7.94										
X				584	26.5	2,126	31	77.1	113	–
SD				417	3.6	335	26	16.5	85	–
CV(%)				71	13.6	4.7	83	21.3	75	–
SE				53	0.5	42	3.3	2.1	11	–
SWAZILAND										
Big Bend	31.35	–26.51	120	590	22.0	1,515	38.9	68.9	195	1
Malkerns	31.09	–26.33	786	967	19.5	1,294	74.7	66.4	247	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Nbabane	31.08	−26.19	1,163	1,440	16.9	1,264	113.9	74.8	309	1
Nhulume	31.50	−26.02	272	678	22.1	1,522	44.5	68.9	179	1
N = 4; √N = 2.00										
X				919	20.3	1,399	51	69.8	233	–
SD				332	2.45	120	40	3.1	51	–
CV(%)				36	12	8.6	78	4.4	22	–
SE				166	1.2	60	20	1.6	26	–
TANZANIA										
Amania	38.38	−5.06	911	1904	20.7	1,126	169.1	54.4	365	1
Arusha	36.37	−3.20	1,387	809	19.5	1,203	67.2	61.7	224	1
Biharamulo	31.19	−2.38	1,480	972	20.1	1,521	63.9	75.7	242	1
Bukoba	34.49	−1.20	1,137	2,040	21.1	1,241	164.4	58.8	365	1
Chunya	33.26	−8.32	1,500	1,366	21.1	1,519	89.9	72.0	192	1
Dar es Salaam	39.18	−6.50	14	1,083	25.8	1,525	71.0	59.1	242	1
Dodoma	35.46	−6.10	1,119	578	22.7	1,532	37.7	67.5	146	1
Ilonga	37.02	−6.46	500	1,071	24.5	1,581	67.7	64.5	210	1
Iringa	35.45	−7.40	1,426	743	19.1	1,582	47.0	82.3	163	1
Kigoma	29.38	−4.53	882	977	23.5	1,543	63.3	65.7	221	1
Kilwa Kivinje	39.25	−8.45	10	901	26.7	1,532	58.8	57.4	195	1
Kondoa	35.48	−4.55	1,386	625	21.3	1,633	38.3	76.7	170	1
Kongwa	36.25	−6.12	1,021	544	22.1	1,734	31.4	78.5	149	1
Lindi	39.42	−10.00	41	926	26.1	1,614	57.4	61.8	181	1
Loliondo	35.37	−2.03	2,100	3,023	16.0	1,404	215.3	87.8	365	1
Lumeno	36.37	−8.10	270	1,317	25.2	1,469	89.7	58.3	202	1
Lyamungu	37.15	−3.14	1,250	1,679	19.6	1,199	140.0	61.2	323	1
Mafia/Kilindoni	39.40	−7.55	21	1,877	26.5	1,523	123.2	57.5	283	1
Mbeya	33.28	−8.56	1,704	883	17.6	1,339	65.9	76.1	177	1
Mbulu	35.33	−3.52	1,530	1,074	18.0	1,304	82.4	72.4	244	1
Morogoro	37.39	−6.50	526	892	24.3	1,407	63.4	57.9	216	1
Moshi	37.20	−3.21	854	859	23.5	1,345	63.9	57.2	183	1
Mtwara	40.11	−10.16	113	1,159	25.6	1,705	68.0	66.0	199	2
Musoma	33.48	−1.30	1,147	812	23.1	1,585	51.2	68.8	228	1
Muze	31.33	−7.40	810	919	23.7	1,541	59.6	65.0	185	1
Mwanza	32.55	−2.28	1,139	1,002	22.8	1,688	59.4	74.0	236	1
Nachingwea	38.45	−10.21	463	926	24.6	1,631	56.8	66.3	181	1
Ngomeni	38.54	−5.09	180	1,179	25.2	1,355	87.0	53.8	329	1
Njombe	34.45	−9.25	1,890	1,155	16.4	1,144	101.0	69.8	185	1
Pemba/Karume Airport	39.49	−5.15	25	1,926	25.7	1,282	150.2	49.8	348	1
Same	37.43	−4.05	872	553	13.5	1,572	35.2	66.9	166	2
Sao Hill	35.12	−8.20	1,981	936	16.2	1,395	67.1	86.1	180	1
Songea	35.35	−10.41	1,067	1,118	21.1	1,475	75.8	69.9	175	1
Sumbawanga	31.36	−7.57	1,710	830	17.8	1,710	58.9	79.0	186	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Tabora Airport	32.50	−5.05	1,181	916	22.9	1,768	51.8	77.2	191	1
Tabora Observatory	32.49	−5.02	1,265	892	22.9	1,887	47.3	82.4	188	1
Tanga	39.04	−5.05	39	1,321	26.3	1,446	91.4	55.0	301	1
Ubungo (Dar)	39.12	−6.47	60	1,037	26.1	1,544	67.2	59.2	249	1
Urambo	32.03	−5.04	1,106	946	23.3	1,768	53.5	75.9	195	1
Zanzibar/ Kisauni	39.13	−6.13	15	1,561	26.0	1,596	97.8	61.4	304	1
N = 40; √N = 6.32										
X				1,133	21.7	1,499	77	65.5	227	–
SD				478	4.5	178	41	13.0	63	–
CV(%)				42	21	12	53	19.9	28	–
SE				76	0.7	57	6.5	2.1	10	–
TOGO										
Atakpame	1.07	7.35	400	1375	25.9	1,404	97.9	54.2	272	1
Lome	1.15	6.10	20	925	26.4	1,501	61.6	56.9	203	2
Mango	0.28	10.22	145	1089	28.2	1,603	67.9	56.8	197	1
Sokode	1.09	8.59	386	1414	26.3	1,367	103.4	52.0	238	1
N = 4; √N = 2.00										
X				731	26.7	1,072	82.7	55.5	165	–
SD				665	0.9	612	18	2.0	84	–
CV(%)				91	3.4	57	22	3.6	51	–
SE				333	0.5	306	9	1	42	–
TUNISIA										
Bizerte	9.48	37.15	5	625	18.1	1,148	54.4	63.4	215	1
Cherfech	10.03	36.50	5	436	17.1	1,242	35.1	72.6	188	1
Chott Mariem	10.33	35.55	15	332	17.8	1,138	29.2	69.9	204	1
Gabes	10.06	33.53	4	176	19.3	1,439	12.2	74.6	36	1
Gafsa	8.49	34.25	313	152	19.7	1,463	10.4	74.3	1	1
Hendi Zitoun	10.07	35.51	74	336	17.9	1,483	22.7	82.8	133	2
Jendouba	8.48	36.29	143	477	18.1	1,263	37.8	69.8	218	1
Jerba	10.47	33.35	6	209	20.7	1,648	12.7	79.6	112	1
Kairouan	10.06	35.40	60	288	19.1	1,565	18.4	81.9	129	1
Kelibia	11.05	36.51	29	444	18.5	1,270	35.0	68.6	100	1
Ksar Rheriss	9.50	34.39	25	138	18.3	1,481	9.3	80.9	33	1
Messaoudia	10.06	34.40	70	261	18.7	1,489	17.5	79.6	95	2
Monastir-Skanes	10.45	35.40	2	331	18.4	1,190	27.8	64.7	207	1
Nakta	10.30	34.39	25	149	18.6	1,299	11.5	69.8	39	1
Remada	10.24	32.19	300	52	21.0	1,796	2.9	95.5	1	1
Sfax El-Maou	10.41	34.43	21	197	19.0	1,232	16.0	64.8	89	2
Tabarka	8.45	36.57	20	1,029	18.0	1,125	91.5	68.5	252	1
Tozeur	8.06	33.55	87	89	21.3	1,729	5.1	81.2	1	1
Tunis-Carthage	10.14	36.50	3	443	18.3	1,159	38.2	63.3	211	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ETo	ETo/*T*	RD	RS
N = 19; √N = 4.35										
X				324	18.8	1,292	25.7	74.0	122	–
SD				222	1.1	317	20.4	8.2	81	–
CV(%)				69	5.9	25	81	11.1	66	–
SE				51	0.3	73	4.7	1.9	19	–
UGANDA										
Arua	30.55	3.03	1,204	1,403	22.7	1,677	83.7	73.9	291	1
Butiaba	31.20	1.50	621	765	25.6	1,465	52.2	57.6	272	1
Entebbe Airport	32.27	0.03	1,155	1,537	21.4	1,386	110.9	64.8	365	2
Fort Portal	30.17	0.40	1,539	1,530	19.1	1,313	116.5	88.7	365	1
Gulu	32.20	2.45	1,104	1,585	23.1	1,758	90.2	76.1	280	1
Hoima	31.22	1.26	1,158	1,435	22.6	1,401	102.4	62.0	336	2
Jinja	33.11	0.27	1,175	1,272	22.1	1,422	89.5	64.3	365	1
Kabale	29.59	−1.15	1,867	986	16.7	1,158	85.1	69.3	316	1
Kampala	32.37	0.19	1,144	1,180	21.9	1,543	76.5	70.5	352	1
Kitgum	32.53	3.17	937	1,262	24.5	1,932	65.3	78.9	257	1
Lira	32.54	2.15	1,085	1,364	23.3	1,755	77.7	75.3	276	1
Masindi	31.43	1.41	1,146	1,308	22.8	1,510	86.6	66.2	323	1
Mbale	34.09	1.06	1,340	1,145	22.8	1,631	70.2	71.6	289	1
Mbarara	30.39	−0.37	1,412	924	20.3	1,332	69.4	65.6	309	2
Moroto	34.46	2.33	1,347	888	22.4	1,595	55.7	71.2	233	1
Mpanga	32.18	0.12	1,250	1,376	21.1	1,331	103.4	63.1	365	1
Mubende	31.22	0.35	1,553	1,223	20.4	1,532	79.8	75.1	334	1
Namulonge	32.37	0.32	1,148	1,264	21.7	1,431	88.3	65.9	365	1
Orichinga	30.47	−0.52	1,280	1,391	19.9	1,225	113.6	64.6	332	1
Soroti	33.37	1.43	1,132	1,311	24.2	1,765	74.3	72.9	266	1
Tororo	34.10	0.41	1,170	1,475	22.5	1,521	97.0	67.6	365	1
N = 21; √N = 4.58										
X				1,235	22	1,509	85	66.4	317	–
SD				319	1.9	191	17	15.2	41	–
CV(%)				26	9	13	21	23.0	13	–
SE				70	0.4	42	4	3.3	9	–
WESTERN SAHARA										
El Aayun	−13.12	27.09	63	25	20.0	1,617	1.5	80.9	1	1
Dakhla (Villa Cisneros)	−15.52	23.42	10	29	20.3	1,575	1.8	77.6	1	1
N = 2; √N = 1.41										
X				27	20.2	1,596	1.7	79.3	1	–
SD				2	0.2	21	0.15	1.7	0	–
CV(%)				7.4	10	1.3	9	2.1	0	–
SE				1.4	0.1	15	0.1	1.2	0	–

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ETo	ETo/*T*	RD	RS
ZAIRE (R.D. Congo)										
Bafwasende	27.08	1.05	524	1,862	23.7	1,291	144.2	54.4	365	1
Bambesa	25.43	3.27	621	1,759	24.4	1,367	128.7	56.6	344	1
Banana	12.35	−6.00	2	826	25.2	1,291	64.0	51.2	226	1
Bandundu	17.21	−3.18	324	1,661	25.2	1,368	121.4	54.3	588	1
Basankusu	19.48	1.13	360	1,995	24.3	1,285	155.3	52.9	365	1
Basoko	23.36	1.15	410	1,680	24.6	1,352	124.3	51.2	365	1
Binga	20.30	2.18	400	1,920	24.2	1,312	146.3	54.2	365	1
Boende	20.51	−0.13	3,510	2,132	24.5	1,303	163.6	53.2	365	1
Boketa	19.46	3.11	475	1,677	23.8	1,335	125.7	56.0	347	1
Bokondji	21.26	−0.43	365	2,054	23.8	1,298	158.2	54.5	365	1
Bongabo	20.32	3.06	450	1,808	24.0	1,337	135.2	55.7	335	1
Bukavu	28.51	−2.31	1,612	1,326	18.8	1,275	104.0	67.8	310	1
Bumba	22.33	2.11	361	1,657	24.3	1,349	122.8	55.9	365	1
Buta	24.47	2.47	410	1,571	24.2	1,328	118.3	54.9	328	1
Butembo	29.16	0.08	1,840	1,468	16.6	1,134	129.5	68.3	365	1
Eala	18.18	0.03	350	1,813	24.7	1,310	138.4	53.0	365	1
Gandajika	23.57	−6.45	780	1,425	23.3	1,460	97.6	62.7	273	1
Gemena	19.47	3.17	475	1,739	24.2	1,328	130.9	54.9	365	1
Gimbi-Plateau	13.22	−5.31	480	1,127	22.1	1,145	98.4	51.8	249	1
Goma	29.14	−1.41	1,552	1,205	18.8	1,348	89.4	71.7	326	1
Ilebo	20.35	−4.20	465	1,598	24.4	1,319	121.2	54.1	296	1
Inongo	18.16	−1.58	300	1,666	25.5	1,335	124.8	52.4	327	1
Irumu	29.52	1.27	955	1,351	22.0	1,349	100.1	61.3	365	1
Isiro	27.39	2.46	806	2,138	22.7	1,303	164.1	57.4	343	1
Kalemie	29.11	−5.53	790	1,149	23.1	1,503	76.4	65.1	235	1
Kamina	25.00	−8.44	1,105	1,343	22.5	1,452	92.5	64.5	230	1
Kamina/Base	25.15	−8.38	1,088	1,352	21.7	1,516	89.2	69.9	232	1
Kananga	22.25	−5.53	654	1,571	23.7	1,350	116.4	57.0	296	1
Kaniama	24.09	−7.25	949	1,560	22.4	1,491	104.6	66.6	262	1
Kibangula	27.04	−4.52	685	1,440	23.2	1,405	102.5	60.6	270	1
Kikwit	18.48	−5.02	518	1,604	24.1	1,365	117.5	56.6	290	1
Kindu	25.55	−2.57	497	1,614	24.4	1,322	122.1	54.2	332	1
Kinshasa/Binza	15.15	−4.22	445	1,328	23.5	1,283	103.5	54.6	262	1
Kinshasa/N'Djili	15.26	−4.23	309	1,420	24.6	1,303	109.0	53.0	266	1
Kisanga-Plateau	27.25	−11.44	1,187	1,285	19.1	1,261	101.9	66.0	186	1
Kisangani	25.11	0.31	415	1,750	24.6	1,313	133.3	53.4	365	1
Kiyaka-Plateau	18.57	−5.16	739	1,616	23.2	1,402	115.3	60.4	290	1
Kolwezi	25.27	−10.43	1,405	1,122	19.4	1,470	76.3	75.2	207	1
Kondo	12.58	−5.34	230	1,221	23.7	1,108	110.2	46.8	249	1
Kongolo	27.00	−5.21	561	1,220	24.1	1,484	82.2	61.6	258	1
Kutubongo	19.53	4.37	550	1,794	24.5	1,406	127.6	57.4	307	1
Libenge	18.38	3.38	380	1,564	24.4	1,358	115.2	55.7	327	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Lisala	21.34	2.19	463	1,621	24.1	1,310	123.7	54.4	365	1
Lodja	23.28	−3.29	479	1,749	24.1	1,298	134.7	53.9	365	1
Loekalomela	22.42	2.12	380	1,818	23.9	1,312	138.6	54.9	365	1
Lubarika	23.17	−2.18	427	1,942	24.1	1,246	155.9	51.7	365	1
Lubumbashi-Luano	28.57	−2.50	980	1,212	23.0	1,421	85.3	61.8	264	1
Ludi-Plateau	27.29	−11.40	1,276	1,234	20.3	1,546	79.8	76.2	181	1
Ludolela	13.06	−5.37	350	1,164	23.1	1,087	107.1	47.1	245	1
Luputa	17.12	−1.03	318	1,606	24.9	1,332	120.6	53.5	350	1
Lusambo	23.44	−7.08	880	1,809	22.8	1,370	132.0	60.1	281	1
M'Vuazi-Poste	23.26	−4.58	424	1,615	24.2	1,350	119.6	55.9	317	1
Manono	14.54	−5.27	505	1,479	23.2	1,270	116.5	54.7	258	1
Mbandaka	27.26	−7.17	614	1,138	25.0	1,732	65.7	69.3	215	1
Mitwaba	18.16	0.03	345	1,666	24.4	1,279	130.3	52.4	365	1
Mont Hawa	27.20	−8.36	1,579	1,200	19.2	1,397	85.9	72.8	230	1
Mukumari	30.45	2.49	1,350	1,502	21.0	1,531	98.1	72.9	298	1
Mulungu Bukulumisa	23.11	−2.50	535	1,823	23.4	1,280	142.4	54.7	365	1
Mulungu	28.43	−2.20	2,378	1,803	13.8	1,016	177.5	73.6	350	1
Nyamunyunye	28.48	−2.18	1,703	1,532	16.7	1,045	146.6	62.6	328	1
Mulungu-Molehe	28.47	−2.18	1,731	1,572	18.2	1,153	136.3	63.4	325	1
Mulungu-Tshibinda	28.45	−2.19	2,055	1,859	15.3	1,153	189.5	64.1	365	1
Mutsora	29.44	0.19	1,330	1,421	20.7	981	115.7	59.3	365	1
N'Dihira	29.10	−0.16	2,190	1,324	14.0	1,228	131.5	71.9	365	1
Nioka-Drusi	30.39	2.09	1,678	1,366	18.1	1,007	103.6	72.9	326	1
Opala	24.21	−0.35	398	1,883	24.2	1,270	148.3	52.5	365	1
Rumangabo	29.22	−1.21	1,620	1,856	18.5	1,220	152.1	65.9	365	1
Rwindi	29.17	−0.47	1,040	891	22.7	1,608	55.4	70.8	365	1
Tshkapa	20.51	−6.25	521	1,431	24.5	1,490	96.0	60.8	277	1
Watsa	29.30	3.04	985	1,678	22.2	1,409	1409	63.5	311	1
Yaligimba	22.51	2.17	435	1,766	24.1	1,331	132.7	55.2	365	1
Yangambi E.C.P.	24.31	0.53	491	1,828	23.4	1,227	149.0	52.4	365	1
Yangambi Km 5	24.29	0.49	470	1,823	23.7	1,303	139.9	55.0	365	1
N = 73; √N = 8.54										
X				1,562	22.6	1,322	138	59.1	318	–
SD				280	2.7	132	154	9.8	62	–
CV(%)				18	12	10	110	14.0	19	–
SE				30	0.3	15	18	0.85	7	–
ZAMBIA										
Chipata	22.35	−13.33	1,028	1,014	21.5	1,604	63.2	74.6	165	1
Choma	27.04	−16.50	1,213	705	18.2	1,400	50.4	76.9	161	1
Kabompo	24.12	−13.36	1,075	1,042	20.4	1,326	78.6	65.0	174	1

(*continued*)

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Kabwe	28.28	−14.27	1,206	970	21.7	1,665	58.3	76.7	155	1
Kafue Polder	27.55	−15.46	978	824	20.6	1,652	49.9	80.2	131	1
Kaoma	24.48	−14.48	1,213	938	20.4	1,488	63.0	72.9	165	1
Kasama	31.08	−10.13	1,382	1,288	19.8	1,610	80.0	81.3	182	1
Kasempa	25.51	−13.32	1,234	1,140	19.3	1,385	82.3	71.8	176	1
Kawambwa	29.05	−9.48	1,323	1,299	21.0	1,403	92.6	66.8	211	1
Livingstone	25.49	−17.49	985	644	21.5	1,606	40.1	74.7	149	1
Lundazi	33.12	−12.17	1,143	892	20.1	1,463	61.0	72.8	152	1
Lusaka City Airport	28.19	−15.25	1,280	804	19.6	1,714	46.9	87.4	149	1
Mansa	28.51	−11.06	1,259	1,065	19.8	1,473	72.3	74.4	179	1
Mbala	31.20	−8.51	1,672	1,219	18.1	1,474	82.7	81.4	191	1
Mongu	23.09	−15.15	1,052	985	22.5	1,774	55.5	78.8	165	1
Mpika	31.26	−11.54	1,400	1,065	18.8	1,440	74.0	76.6	162	1
Mwinilunga	24.26	−11.45	1,361	1,377	20.1	1,292	106.6	64.3	215	1
Ndola	28.39	−13.00	1,269	1,147	19.7	1,540	74.5	78.2	168	1
Petauke	31.17	−14.15	1,035	953	22.6	1,468	64.9	65.0	158	1
Samfya	29.32	−11.21	1,172	1,432	20.7	1,430	100.0	69.1	178	1
Serenje	30.13	−13.14	1,384	1,185	19.2	1,430	82.9	74.5	165	1
Sesheke	24.18	−17.28	949	700	20.9	1,557	45.0	74.5	152	1
Solwezi	26.22	−12.10	1,386	1,368	19.7	1,290	106.0	65.5	194	1
Zambezi	23.07	−13.32	1,077	1,008	21.1	1,485	67.9	70.4	176	1
N = 24; √N = 4.89										
X				1,044	20.3	1,499	67	73.9	170	–
SD				216	1.2	125	23	5.8	19	–
CV(%)				21	6	8	35	7.9	11	–
SE				44	0.2	26	5	1.2	4	–
ZIMBABWE										
Beitbridge	30.00	−22.13	456	320	23.0	1,661	19.3	72.2	48	1
Bulawayo Goetz Obs.	28.37	−20.09	1,343	594	18.6	1,731	34.3	91.6	146	1
Chibero	30.40	−18.06	1,335	785	18.5	1,587	49.5	85.8	173	1
Chipinge	32.37	−20.12	1,131	1,119	18.1	1,496	74.8	82.7	188	1
Chirundu Sugar Est.	28.54	−16.00	392	628	25.1	1,762	35.6	70.2	131	1
Enkeldoorn	30.53	−19.02	1,459	710	17.4	1,651	43.0	94.9	154	1
Gatooma Cotton R.I.	29.53	−18.19	1,157	730	20.4	1,929	37.8	94.6	146	1
Gokwe	28.56	−18.13	1,282	791	19.8	1,621	48.8	81.9	156	1
Grand Reef	32.27	−18.59	1,018	718	19.4	1,535	46.8	79.1	161	1
Gwaai	27.42	−19.17	999	627	21.1	1,751	35.8	83.0	143	1
Gweru	29.51	−19.27	1,428	643	17.1	1,661	38.7	97.1	152	1
Harare (Belvedere)	31.01	−17.50	1,471	814	18.2	1,550	52.5	85.2	162	1

Table A1 (continued)

Country/station	Long.	Lat.	Alt. (m)	*P* (mm)	*T* (°C)	ETo (mm)	(100 *P*)/ ETo	ETo/*T*	RD	RS
Hernderson	30.58	−17.35	1,290	875	17.8	1,436	60.9	80.7	166	1
Inyanga Exp. Stat.	32.45	−18.17	1,878	1,120	14.1	1,268	88.3	89.9	193	1
Kariba	28.53	−16.31	518	677	24.2	1,777	38.1	73.4	128	1
Karoi	29.37	−16.50	1,343	855	18.9	1,610	53.1	85.2	161	1
Kwekwe	29.50	−18.56	1,213	656	19.4	1,710	38.4	88.1	144	1
Marandellas Res. Stat.	31.30	−18.10	1,646	924	16.3	1,399	66.0	85.8	179	1
Matopos Nursery	28.30	−20.23	1,347	586	17.5	1,554	37.7	88.8	152	1
Mount Darwin	31.35	−16.47	965	780	20.3	1,512	51.6	74.5	149	1
Nyamandhlovu Exp. Stat.	28.11	−19.57	1,219	544	19.7	1,730	31.4	98.0	137	1
Nyanyadzi	32.25	−19.45	530	489	22.5	1,617	30.2	71.9	116	1
Sabi Valley Exp Stat.	32.20	−20.21	448	470	22.3	1,565	30.0	70.2	130	1
Tjolotjo	27.46	−19.45	1,100	564	20.6	1,764	32.0	85.6	134	1
Trelawney Res. Stat.	30.20	−17.35	1,326	836	19.1	1,475	56.7	77.2	170	1
Triangle Hill	31.22	−20.57	421	586	21.8	1,550	37.8	71.1	150	1
Umtali	32.40	−18.58	1,119	756	19.7	1,414	53.5	71.8	161	1
Umvukwes	30.51	−17.02	1,481	865	17.4	1,402	61.7	80.6	165	1
Victoria Falls	25.51	−18.06	1,061	716	20.7	1,674	42.8	80.9	145	1
Wankie	26.30	−18.22	782	567	24.7	1,743	32.5	70.6	130	1
Wankie Main Camp	26.57	−18.44	1,077	632	20.3	1,566	40.4	77.1	143	1
West Nicholson	29.22	−21.03	860	481	20.2	1,422	32.2	70.4	136	1
N = 32; √N = 5.65										
X				702	19.3	1,551	44.8	81.6	148	–
SD				172	4.0	293	14.3	8.4	25	–
CV(%)				25	20.5	18.9	31.9	10.3	17	–
SE				30	0.7	51.9	2.5	1.5	4	–

[a] Long. = longitude, in degrees and minutes; Lat. = latitude, in degrees and minutes; the minus sign (–) denotes long. W or lat. S; Alt. = altitude, m; *P* = mean annual precipitation, mm; *T* = mean annual temperature, °C; ETo = mean annual reference potential evapotranspiration (Penman/Monteith), mm; (100 *P*)/ETo = annual aridity index; Eto/*T* = relationship between annual reference potential evapotranspiration and annual temperature; RD = annual number of rainy days ($P \geq 1$ mm); RS = annual number of rainy seasons(s) ($P < 0.35$ ETo); X = mean of a given parameter; SD = standard deviation of the mean; CV (%) = coefficient of variation of the mean, expressed as a percent thereof (100×SD/X); N = number of weather stations in the database for a given country; SE = standard error on the mean (SD/√*N*)

Table A2 Relationship between mean annual rainfall and its coefficient of variation (%) in Africa (source: Le Houérou 1986, 1988b, 1992a; Nicholson et al. 1988)

Mean annual rainfall	Average coefficient of variation of annual rainfall % (SD/mean)			
	West Africa	East Africa	Southern Africa	North Africa
0–50	96	-	100	108
50–100	57	95	70	62
100–200	43	50	60	53
200–300	37	40	50	40
300–400	32	35	45	29
400–500	30	30	40	30
500–600	27	29	35	26
600–700	27	28	32	22
700–800	21	26	30	22
800–900	19	24	25	20
900–1,000	18	22	20	20
1,000–2,000	17	16	20	18
2,000–4,000	16	15	15	15

Table A3 Relationship between mean annual rainfall and dependable annual rainfall ($p = 0.8$, %) in Africa

Mean annual rainfall	Dependable annual rainfall ($p = 0.8$, mm)[a]			
	Coefficient of variation of annual rainfall, % (SD/mean)			
	West Africa	East Africa	Southern Africa	North Africa
50	20	20	20	20
100	58	39	45	52
200	133	124	108	122
300	213	206	180	213
400	296	291	257	300
500	380	376	342	382
600	464	456	431	479
700	560	541	518	571
800	666	632	616	659
900	760	726	730	749
1,000	840	840	800	800
1,500	1,270	1,298	1,280	1,260
2,000	1,650	1,664	1,706	1,723
3,000	2,600	2,600	n.a.	n.a.

[a] DR = R–0.84 SD, where DR = dependable rainfall, SD = standard deviation of annual rainfall and R = mean annual rainfall

Table A4 Rainfall parameters in the CILSS countries (1951–1980)

Class of mean annual rainfall	Cap Verde				Mauritania				Senegal				Gambia				Guinea Bissau			
	n[a]	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$	n	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$	n	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$	n	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$	n	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$
0–50	-	-	-	-	2	33	2.667	27	-	-	-	-								
50–100	2	89	2.530	32	5	80	1.752	48	-	-	-	-								
100–200	-	-	-	-	4	155	1.528	53	-	-	-	-								
200–300	3	221	1.931	43	7	256	1.229	63	2	293	1.003	71								
300–400	-	-	-	-	4	341	0.900	71	-	-	-	-								
400–500	-	-	-	-	2	407	0.724	77	16	458	1.055	68								
500–600	3	575	1.878	44	1	572	0.730	76	7	547	0.774	74								
600–700	-	-	-	-					9	649	0.806	73								
700–800	-	-	-	-					5	737	0.722	76								
800–900	-	-	-	-					4	842	0.671	78								
900–1,000	-	-	-	-					2	918	0.747	77	4	957	0.609	80				
1,000–1,200	-	-	-	-					4	1,144	0.627	80	2	1110	0.717	77				
1,200–1,400	1	1,224	1.766	47					5	1,311	0.641	79								
1,400–1,600									1	1,480	0.642	79					5	1,762	0.565	82
1,600–2,000																	5	2,269	0.479	84
2,000–2,600																				

(*continued*)

Table A4 (continued)

Class of mean annual rainfall	mALI				Burbina Faso				Nigar				Gambia				Chad			
	n^a	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$	n	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$	n	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$	n	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$	n	$\bar{X}$	IV	$\frac{0.8}{\bar{X}}\%$
0–50	-	-	-	-	-	-	-	-	1	15	2.727	27	2	30	2.632	34				
50–100	1	81	1.353	58	-	-	-	-	1	54	1.469	56	1	79	2.169	39				
100–200	1	169	0.877	70	-	-	-	-	2	141	0.988	64	-	-	-	-				
200–300	6	258	0.746	76	-	-	-	-	4	254	1.161	64	3	239	1.080	65				
400–500	6	451	0.655	78	3	459	0.651	79	23	460	0.710	77	5	445	0.646	80				
500–600	11	556	0.572	81	4	552	0.633	81	12	558	0.651	78	2	577	0.610	80				
600–700	12	645	0.524	83	7	662	0.487	83	7	633	0.662	81	6	657	0.484	86				
700–800	9	748	0.516	84	5	479	0.470	84	-	-	-	-	8	763	0.443	85				
800–900	12	857	0.435	85	16	841	0.706	87	1	841	0.474	84	10	870	0.364	88				
900–1,000	10	962	0.457	85	10	940	0.400	86	-	-	-	-	57	972	0.398	86				
1,000–1,200	12	1,071	0.450	85	14	1,109	0.418	86	-	-	-	-	27	1,076	0.399	87				
1,200–1,400	9	1,268	0.462	85	2	1,349	0.542	85	-	-	-	-	3	1,272	0.452	85				

[a] *n* = number of weather stations per class and per country; X = mean annual rainfall in the class/country; IV = index of variability, i.e. (*P* 0.10–*P* 0.90)/*P* 0.50

Table A5 Variability of annual rainfall in the CILSS countries of West Africa[a]

Class of mean annual rainfall (mm)	Number of weather stations	Annual mean of class	Variability index[b]	Dependability ratio[c] (*p* 0.8/*R*)	Coefficient of variation[d] (%)
0–50	5	33	2.665	0.30	82
50–100	8	78	2.331	0.49	60
100–200	13	160	1.113	0.63	40
200–300	23	257	1.044	0.68	38
300–400	33	345	0.772	0.75	30
400–500	40	455	0.796	0.75	29
500–600	40	556	0.644	0.79	26
600–700	40	648	0.597	0.81	23
700–800	35	745	0.524	0.80	20
800–900	45	850	0.456	0.85	17
900–1,000	32	953	0.467	0.84	17
1,000–1,200	62	1,089	0.440	0.83	17
1,200–1,400	24	1,293	0.516	0.83	19
1,400–1,600	5	1,480	0.642	0.79	21
1,600–2,000	4	1,762	0.564	0.82	21
2,000–4,000	5	2,269	0.479	0.84	18
Total stations	414				

[a]VI = 2.7 CV, CV = 0.37 VI, $n = 414$, $r^2 = 0.97$. The CILSS countries are Burkina Faso, Cape Verde, Chad, Guinea Bissau, Gambia, Mali, Mauritania, Niger and Senegal (database: Morel 1992).

[b] Variability index = (*P* 0.10–*P* 0.90)/*P* 0.50, as determined by the gamma distribution law of restricted probability (Pearson III) and computed by Morel (1992). This variability index was first used by Fitzpatrick and Nix (1970) and Nix (1983) in Australia.

[c] The dependability ratio is the quotient between the rainfall under probability 0.8 (or decile 0.2) to the mean. Dependable rains are herein defined in a slightly different way from that of Hargreaves (1975a, b, 1977), i.e. rains occurring during 4 of 5 years, rather than 3 of 4, as defined by Hargreaves.

[d] Computed from Morel's database 1951–1980 (Bartaire and Reyniers 1983).

Table A6 Comparison of annual rainfall variability in the 138 weather stations of the CILSS countries for two reference periods: long-term and 1951–1980[a]

Class of annual rainfall (mm)	Number of weather stations	A: long-term				B: 1951–1980			
		Mean of class (mm)	±SE	CV (%)	±SE	Mean of class (mm)	±SE	CV (%)	±SE
0–50	5	30	9.7	105	12.3	29	6.5	82	5.3
50–100	8	73	5.6	66	3.4	77	5.9	60	5.0
100–200	10	157	7.8	44	2.4	161	2.4	40	3.2
200–300	16	261	8.1	44	2.7	262	7.6	41	2.5
300–400	12	345	8.7	34	1.8	346	12.7	30	1.8

(*continued*)

Table A6 (continued)

Class of annual rainfall (mm)	Number of weather stations	A: long-term				B: 1951–1980			
		Mean of class (mm)	±SE	CV (%)	±SE	Mean of class (mm)	±SE	CV (%)	±SE
400–500	18	456	7.9	30	1.0	460	9.7	28	1.5
500–600	16	549	7.5	27	1.4	565	9.3	25	1.5
600–700	12	630	8.6	27	2.0	643	15.0	23	1.7
700–800	10	754	10.4	21	1.5	760	21.0	20	1.9
800–900	10	841	6.3	21	2.7	868	9.4	17	0.8
900–1,000	8	927	14.9	20	1.1	928	8.8	18	1.2
1,000–1,200	13	1,089	15.5	17	1.0	1,092	17.5	18	1.1
Total	138								

[a] Long-term is understood as from the inception of the records (1830 for St Louis, Senegal, to 1930 generally) to 1984, as reported by Nicholson et al. (1988). The 1951–1980 series is the AGRHYMET database as published by Morel (1992). One can see that the CV is systematically and consistently lower (by an average 5 percentage points from 0 to 1,000 mm mean) in the 1951–1980 series relative to the long term. This shows that, in the area concerned and below a mean of 1,000 mm, variability cannot be accurately assessed over a 30-year period. On a monthly basis, the situation should still be more pronounced as the monthly variability is far above annual. It would thus seem that probability studies should be based on at least 50 years of records, if some accuracy is sought. As expected, the discrepancy between the two series increases as the mean decreases, and as variability increases (23 percentage points for 0–510 mm mean to 2 percentage points for 900–1,000 mm mean). One should add that the 1951–1980 series includes an above average (1950–1969) and a below average period (1970–1980). It so happens that the rainy and dry spells have the same length in the AGRHYMET database. This tends to reinforce the strength of the statements made above (see also Tables T16–T19, T21–T23, and Figs. 2, 3, and 5–8 on the problems of annual rainfall variability)

Table A7 Evolution of annual rainfall in the CILSS countries from 1950 to 1985, by rainfall class and by country from west to east

Class of annual rainfall (mm) as of 1951–1980	Number of weather stations	Class average 1950–1967, A	Class average 1951–1980, B	Class average 1968–1985, C	C/A	C/B
0–50						
Mauritania	2	42	34	21	0.50	0.62
Niger	1	18	15	11	0.61	0.73
Chad	2	37	30	21	0.57	0.70
Weighted average		35	28	19	0.54	0.66
50–100						
Cap Verde	2	71	89	51	0.72	0.57
Mauritania	3	103	85	60	0.58	0.71
Mali	1	99	81	52	0.53	0.64

Table A7 (continued)

Class of annual rainfall (mm) as of 1951–1980	Number of weather stations	Class average 1950–1967, A	Class average 1951–1980, B	Class average 1968–1985, C	C/A	C/B
Niger	1	62	54	44	0.71	0.81
Chad	1	108	79	48	0.44	0.61
Weighted average		102	81	58	0.52	0.66
100–200						
Mauritania	4	190	155	102	0.54	0.66
Mali	6	195	169	133	068	0.79
Niger	2	178	141	94	0.53	0.67
Weighted average		175	151	116	0.66	0.77
200–300						
Cap Verde	3	293	221	141	0.48	0.64
Mauritania	6	301	260	188	0.62	0.72
Senegal	3	329	288	210	0.64	0.73
Niger	4	299	255	192	0.64	0.74
Mali	6	291	258	211	0.73	0.82
Chad	3	308	272	212	0.69	0.79
Weighted average		291	259	194	0.67	0.75
300–400						
Mauritania	4	396	334	242	0.61	0.72
Niger	12	404	354	274	0.68	0.77
Mali	6	374	331	311	0.73	0.83
Chad	7	396	343	270	0.68	0.79
Weighted average		395	344	268	0.68	0.78
400–500						
Mauritania	2	468	407	315	0.67	0.78
Senegal	9	555	457	338	0.61	0.74
Niger	21	522	471	360	0.69	0.76
Mali	4	525	460	363	0.69	0.79
Burkina Faso	3	524	459	324	0.62.	0.71
Chad	6	488	431	356	0.72	0.83
Weighted average		523	448	352	0.67	0.78
500–600						
Cape Verde	3	757	575	319	0.42	0.55
Mauritania	1	687	572	433	0.63	0.76
Senegal	8	636	544	429	0.67	0.79
Burkina Faso	4	629	552	428	0.68	0.78
Mali	10	614	556	466	0.75	0.84
Niger	12	679	606	523	0.77	0.94
Chad	3	639	572	473	0.74	0.83
Weighted average		636	564	437	0.69	0.78

Table A8 Evolution of annual rainfall in the CILSS countries: annual number of rainy days from 1950 to 1985

Class of annual rainfall (mm) as of 1951–1980	Number of weather stations in common	Class average 1950–1967, A	Class average 1951–1980, B	Class average 1968–1985, C	C/A	C/B
0–50	5	35	28	19	0.54	0.66
50–100	8	102	81	58	0.52	0.66
100–200	12	175	151	116	0.66	0.77
200–300	25	291	259	194	0.67	0.75
300–400	29	395	344	268	0.68	0.78
400–500	45	523	448	352	0.67	0.78
500–600	41	636	564	437	0.69	0.78
600–700	37	725	647	515	0.71	0.80
700–800	27	815	745	640	0.78	0.86
800–900	42	909	854	754	0.82	0.88
900–1,000	30	1,028	953	823	0.80	0.86
1,000–1,200	61	1,152	1,074	934	0.81	0.87
Overall	362	806	727	629	0.78	0.865

Table A9 Change in mean annual rainfall in the CILSS countries between 1950 and 1985 by country from west to east

Class of annual rainfall (mm) as of 1951–1980	Number of weather stations in common	Class average 1950–1967, A	Class average 1951–1980, B	Class average 1968–1985, C	C/A	C/B
Cape Verde	9	544	421	237	0.44	0.56
Mauritania	26	268	228	166	0.62	0.73
Senegal	62	797	707	572	0.72	0.81
Gaùboa	6	1,206	1,003	905	0.75	0.90
Guinea Bissau	22	1,890	1,810	1,583	0.84	0.87
Mali	110	794	724	618	0.78	0.85
Burkina Faso	62	924	866	771	0.83	0.89
Niger	62	511	454	362	0.71	0.80
Chad	95	836	804	728	0.87	0.91

Table A10 Frost hazard occurrence in Africa

Country	Weather station	T^a	*m*	LFH	HFH	SFH	TFOH
ALGERIA	Adrar	24.2	3.8	90	0	0	90
	Ain Sefra	16.4	−0.1	90	30	60	180
	Alger	18.2	9.2	0	0	0	0
	Annaba	17.9	7.8	30	0	0	30
	Bechar	20.2	1.7	60	60	0	120
	Biskra	21.8	6.0	60		0	60
	Constantine	15.6	2.8	150	30	0	180
	Djanet	23.5	6.0	30	0	0	30
	Djelfa	13.3	−0.5	120	30	90	240
	El Glea	21.6	2.7	60	30	0	90
	Gardaïa	21.3	4.5	120	0	0	120
	In Salah	25.3	6.0	60	0	0	60
	Laghouat	17.2	2.2	90	0	0	150
	Oran	18.4	9.0	0	0	0	0
	Ouargla	22.2	4.3	90	0	0	90
	Setif	13.9	0.3	90	30	60	180
	Sidi Bel Abbès	15.5	1.8	150	30	0	180
	Skikda	17.0	7.1	60	0	0	60
	Tamanrasset	21.0	3.8	90	0	0	90
	Tebessa	15.8	1.8	90	90	0	180
	Tindouf	23.2	5.0	90	0	0	90
	Toggourt	21.4	3.5	90	0	0	90
ANGOLA	Chitembo	20.2	7.2	30	0	0	30
	Cyemba	20.0	3.1	60	30	0	90
	Huambe	19.1	7.8	60	0	0	60
	Lubango	18.6	7.8	30	0	0	30
	Menongue	19.5	6.1	60	0	0	60
	N’Guiva	22.7	6.5	60	0	0	60
BOTSWANA	Francistown	20.9	5.7	90	0	0	90
	Gaborone	20.0	3.6	120	30	0	150
	Ghanzi	25.0	4.0	135	0	0	135
	Mahalapye	20.4	4.1	120	0	0	120
	Maun	22.1	7.0	90	0	0	90
	Shakane	22.1	6.0	90	0	0	90
	Tsabong	19.6	1.0	90	30	60	180
	Tshane	20.5	3.5	90	60	0	150
EGYPT	Alexandria	20.2	9.2	0	0	0	0
	Asyut	22.9	6.7	60	0	0	60
	Aswan	26.9	9.5	0	0	0	0
	Baharyia	21.5	4.6	90	0	0	90

(*continued*)

Table A10 (continued)

Country	Weather station	T^a	m	LFH	HFH	SFH	TFOH
	Baltim	20.8	12.0	0	0	0	0
	Deni Suef	21.5	5.0	90	0	0	90
	Bilbeis	20.7	8.0	30	0	0	30
	Borg El Arab	19.2	6.3	60	0	0	60
	Dabaa	19.3	7.3	60	0	0	
	Dakhla	23.1	4.3	90	0	0	90
	Gemmeiza	20.4	5.2	90	0	0	90
	Giza (Cairo)	20.5	6.3	60	0	0	60
	Helwan (Cairo)	21.9	8.8	0	0	0	0
	Ismaïlia	20.7	7.0	60	0	0	60
	Kharga	24.0	8.8	60	0	0	60
	Kom Ombo	25.1	7.7	30	0	0	30
	Mallawi	20.8	2.5	90	30	0	120
	Marsa Matruh	19.2	8.0	30	0	0	30
	Mansourah	20.9	7.0	60	0	0	60
	Minya	21.1	4.0	90	30	0	120
	Port Saïd	21.0	11.3	0	0	0	0
	Sarkha	19.2	9.0	90	0	0	90
	Salloum	20.5	935	0	0	0	0
	Shandaweel	22.5	4.6	60	30	0	90
	Sidi Barrani	19.3	8.5	0	0	0	0
	Siwa	20.6	3.8	90	30	0	120
	Sohag	22.6	5.3	90	0	0	90
	Tahrir	20.4	7.8	60	0	0	60
ETHIOPIA	Adaba	14.9	3.7	270	60	0	330
	Addis Ababa	16.0	6.9	90	0	0	90
	Adigrat	16.0	3.6	165	30	0	195
	Adi Ugri	17.4	3.5	270	60	0	330
	Adwa	19.1	6.5	90	0	0	90
	Alabe Kolito	19.0	7.9	30	0	0	30
	Asela	14.2	4.9	180	0	0	180
	Asendabo	19.2	7.3	60	0	0	60
	Asmara	16.6	7.2	60	0	0	60
	Bahirdar	18.3	5.6	90	0	0	90
	Bedele	18.0	6.7	30	0	0	30
	Borkodji	12.9	5.1	300	0	0	300
	Chefa	21.2	7.9	30	0	0	30
	Dabat	13.0	3.7	300	30	0	330
	Dangila	16.8	4.2	180	0	0	180
	Debré Birhan	14.4	5.0	180	0	0	180
	Debré Markos	15.6	6.7	90	0	0	90

Table A10 (continued)

Country	Weather station	T^a	m	LFH	HFH	SFH	TFOH
	Debré Tabor	16.8	6.7	120	0	0	120
	Desé	14.9	2.9	180	60	0	240
	Dixis	16.5	4.0	300	30	0	330
	Dodola	13.9	2.0	215	50	0	365
	Fiche	12.9	3.3	270	60	0	330
	Fincha	15.7	4.9	210	0	0	210
	Goha Tsion	16.2	7.8	30	0	0	30
	Goba	13.0	3.7	335	30	0	365
	Guder	17.4	5.1	105	0	0	105
	Hagere Selam	12.5	6.9	240	0	0	240
	Hosaina	16.6	7.0	90	0	0	90
	Jijigga	19.0	6.1	120	0	0	120
	Kofele	14.2	6.2	90	0	0	90
	Kulumba	16.6	7.5	30	0	0	30
	Kuyera	17.4	6.9	30	0	0	30
	Maöichew	16.7	4.8	150	0	0	150
	Munesa	12.6	2.1	305	60	0	365
	Ticho	13.9	5.0	180	0	0	180
	Waldia	17.9	7.9	560	0	0	60
	Wendo	17.2	4.1	120	0	0	120
	Yrga Chefe	17.6	6.3	60	30	0	60
KENYA	Equator	13.1	7.6	240	0	0	240
	S. Kinangop	11.5	6.2	180	0	0	180
	Molo	13.7	5.8	300	0	0	300
	Nakuru (Airfield)	16.8	6.9	150	0	0	150
	Nanyuki	16.1	7.1	90	0	0	90
	Narok	16.5	7.7	180	0	0	180
	Rumuruti	17.7	6.7	60	0	0	60
LESOTHO	Butha Buthe	14.0	−1.5	90	30	90	210
	Guthing	14.7	1.0	90	60	30	180
	Leribe	15.1	0.3	90	60	30	180
	Maseru	15.1	−0.1	45	60	60	165
	Mohale's Hoek	15.8	2.9	120	30	0	150
	Mokhotlong	11.6	−5.0	105	60	120	285
	Oxbow	7.3	−5.9	185	30	150	365
	Tayateyeneng	15.2	1.4	90	60	0	150
	Thaba Tseka	11.9	−0.8	120	60	60	240
LIBYA	Agedabia	20.7	6.6	75	0	0	75
	Benina Airport (Benghazi)	19.6	8.0	30	0	0	30
	Derna	19.9	11.0	0	0	0	0

(*continued*)

Table A10 (continued)

Country	Weather station	T^a	m	LFH	HFH	SFH	TFOH
	Ghadamès	22.2	2.8	90	30	0	120
	Gialo	22.4	5.5	120	0	0	120
	Giarabub	22.0	6.6	120	0	0	120
	Hon	21.1	2.7	120	30	0	150
	Kufra	23.8	6.0	30	0	0	30
	Misurata	20.8	8.0	30	0	0	30
	Nalut	18.3	2.7	60	60	0	120
	Nasser Airport (Tobruk)	19.2	6.3	105	0	0	105
	Sebha	22.8	5.0	120	0	0	120
	Shahat (Cyrene)	15.9	4.3	150	0	0	150
	Sirte	20.2	8.0	30	0	0	30
	Tazerbo	22.1	4.1	120	0	0	120
	Tripoli Meteo	19.6	8.0	30	0	0	30
	Zwara	19.4	7.1	75	0	0	75
MALAWI	Chitedzi	19.4	7.2	30	0	0	30
	Lilongwe	19.4	6.0	90	0	0	90
MOROCCO	Agadir	18.4	9.0	0	0	0	0
	Casablanca	17.8	9.0	0	0	0	0
	Tarfaya (Cape Juby)	19.1	13.1	0	0	0	0
	Dakhla (Villa Cisn)	20.4	13.6	0	0	0	0
	El Ayayoun	20.0	9.6	0	0	0	0
	Ifni	18.8	11.9	0	0	0	0
	Ifrane	10.8	−5.0	60	60	150	270
	Kasba Tadla	19.6	3.8	90	30	0	120
	Marrakech	19.1	7.0	90	0	0	90
	Meknes	17.1	4.3	120	0	0	120
	Ouarzazate	19.0	1.0	60	60	30	150
	Oujda	17.1	5.0	180	0	0	180
	Rabat	17.4	9.0	0	0	0	0
	Tanger	18.0	9.0	0	0	0	0
	Tan-Tan	19.60	9.6	0	0	0	0
MOZAMBIQUE	Manica	21.2	7.3	30	30	0	30
	Mazeminhana	19.1	7.0	60	60	0	60
	Via Gamito	21.8	6.8	60	60	0	60
NAMIBIA	Gobabis	19.4	2.14	90	60	0	150
	Keetmanshoop	20.8	6.0	120	0	0	120
	Luderitz Bay	15.9	10.0	0	0	0	0
	Swakopmund	15.2	9.0	0	0	0	0
	Tsumeb	22.0	8.1	0	0	0	0
	Windhoek	19.0	6.0	60	0	0	60

Table A10 (continued)

Country	Weather station	T^{a}	m	LFH	HFH	SFH	TFOH
SOUTH AFRICA	Alexander Bay	15.3	7.8	60	0	0	60
	Beaufort West	18.1	5.0	150	0	0	150
	Bethal	14.9	–0.8	90	60	60	210
	Bloemfontein	16.0	0.2	45	60	60	165
	Calvinia	16.1	2.0	90	90	0	180
	Cape St Lucia	21.4	13.3	0	0	0	0
	Cape Town	16.6	7.0	90	0	0	90
	De Aar	16.1	–0.3	90	60	60	210
	East London	18.5	10.0	0	0	0	0
	Estcourt	19.1	9.1	0	0	0	0
	Germiston	16.2	4.0	120	30	0	150
	Grootfontein	14.4	–1.0	90	75	90	255
	Jansenville	18.5	4.1	135	0	0	135
	Johannesburg	16.2	4.0	120	30	0	150
	Kimberley	18.4	3.0	105	60	0	165
	Klaver	19.2	8.0	30	0	0	30
	Kokstad	14.9	0.6	90	30	60	180
	Kroonstad	16.3	–1.6	90	60	60	210
	Kuruman	17.7	1.3	90	90	0	180
	Messina	23.4	11.0	0	0	0	0
	Melmoth	19.1	9.1	0	0	0	0
	Montagu	17.6	3.6	120	60	0	180
	Nelspruit	20.3	7.0	90	0	0	90
	Newcastle	17.2	1.3	90	60	0	150
	O'okiep	17.7	6.0	135	0	0	135
	Oudtshoorn	17.7	3.0	120	60	0	180
	Pietersburg	18.1	4.0	120	0	0	120
	Pofadder	18.5	4.0	120	30	0	150
	Port Elizabeth	17.1	7.0	90	0	0	90
	Postmastburg	18.7	5.0	120	0	0	120
	Potchefstroom Agr.	17.0	0.0	90	60	60	210
	Pretoria	17.9	2.5	90	60	0	150
	Prieska	19.2	0.7	90	60	30	180
	Punda Milia	22.8	11.5	0	0	0	0
	Queenstown	16.4	2.5	120	60	0	180
	Sutherland	12.4	–2.0	90	60	90	240
	Thabazimbi	21.2	5.2	90	0	0	0
	Umtata	17.6	3.0	105	60	0	165
	Upington	20.3	3.0	60	60	0	120

(*continued*)

Table A10 (continued)

Country	Weather station	T^a	m	LFH	HFH	SFH	TFOH
	Wepener	15.5	−2.0	90	30	90	210
	Zeerust	18.5	1.0	90	30	30	150
SUDAN	Dereisa	25.1	7.0	90	0	0	90
	Murundo	24.6	5.3	120	0	0	120
	Sennar	25.1	6.0	75	0	0	75
	Zalingei	23.8	6.3	105	0	0	105
SWAZILAND	M'babane	16.8	5.5	105	0		105
TANZANIA	Igeri	13.6	4.6	195	0	0	195
	N'Gorongoro	13.5	6.7	90	0	0	90
	N'Jombe	16.4	7.0	105	0	0	105
TUNISIA	Bizerte	18.0	7.7	60			60
	Cherfech	17.1	6.0	135	0	0	135
	Chott Meriem	17.8	7.2	75	0	0	75
	Gabès	19.3	6.0	105	0	0	105
	Gafsa	19.0	4.0	90	30	0	120
	Henri Zitoun	17.9	4.6	135	0	0	135
	Jendouba	18.1	5.0	195	0	0	195
	Jerba	20.7	7.0	120	0	0	120
	Kairouan	19.1	7.3	150	0	0	150
	Kelibia	18.5	4.6	165	0	0	165
	Ksar Rheriss	18.3	5.5	120	0	0	120
	Messaoudia	18.7	5.7	75	0	0	75
	Monastir-Skanès	18.4	7.2	60	0	0	60
	Nakta	18.6	5.5	120	0	0	120
	Remada	20.4	5.5	120	0	0	120
	Sfax-el Maou Airport	18.6	6.0	75	0	0	75
	Tabarka	17.8	7.7	60	0	0	60
	Tozzeur	20.5	4.5	120	0	0	120
	Tunis-Carthage Airport	18.5	7.0	90	0	0	90
ZAMBIA	Choma	18.2	3.2	90	60	0	150
	Kabompo	20.4	7.1	90	0	0	90
	Kafue Polder	20.6	7.3	45	0	0	45
	Kaoma	20.4	5.5	90	0	0	90
	Kasempa	19.7	6.0	105	0	0	105
	Livingstone	21.5	6.5	120	0	0	120
	Lundazi	19.9	7.0	90	0	0	90
	Mwinnilunga	19.8	6.2	90	0	0	90
	N'Dola	19.7	6.3	105	0	0	105
	Serenje	18.5	8.0	30	0	0	30

Table A10 (continued)

Country	Weather station	T^a	m	LFH	HFH	SFH	TFOH
	Sesheke	20.9	3.8	90	60	0	150
	Solwezi	18.6	4.5	150	0	0	150
	Zambezi	1.0	8.0	30	0	0	30
ZIMBABWE	Binga	24.7	14.7	0	0	0	0
	Beitbridge	23.0	7.9	30	0	0	30
	Bulawayo Gz Obs.	18.6	6.9	90	0	0	90
	Chibere	18.5	5.1	120	0	0	120
	Chipinge	18.1	9.9	0	0	0	0
	Chirungu Sug. Est.	24.3	10.8	0	0	0	0
	Enkeldoorn	17.4	5.9	90	0	0	90
	Gatooma Cott. R.I.	20.4	8.4	0	0	0	0
	Gokwe	19.8	8.4	0	0	0	0
	Grand Reef	19.4	6.7	90	0	0	090
	Gwai	21.1	3.2	90	60	0	150
	Gweru	17.1	4.0	120	30	0	150
	Harare Belved.	18.1	6.5	120	0	0	120
	Hernderson	17.8	2.8	120	60	0	180
	Inynaga Exp. St.	14.1	5.5	150	0	0	150
	Kariba Airport	24.2	10.8	0	0	0	0
	Karoi	18.9	8.3	0	0	0	0
	Kwekwe	19.4	5.7	120	0	0	120
	Marandellas Res. St.	16.3	5.1	135	0	0	135
	Matopos Nursery	17.5	2.7	90	60	0	105
	Mount Darwin	20.3	6.5	105	0	0	90
	Nyamandhlove Exp. St.	19.7	7.6	90	0	0	120
	Nyanda	18.9	5.4	120	0	0	0
	Nyandadzi	22.5	8.0	0	0	0	0
	Nakoholi	18.6	6.2	90	0	0	90
	Sabi Valley Exp. St.	22.3	7.8	30	0	0	30
	Tjolotjo	20.6	6.4	90	0	0	90
	Trelawney Res. St.	19.1	7.2	90	0	0	90
	Triangle Hill	21.8	6.0	120	0	0	120
	Umtali	19.7	9.0	0	0	0	0
	Umvukwe	17.4	6.5	90	0	0	90
	Victoria Falls	21.7	5.8	90	0	0	90
	Wankie	24.7	10.5	0	0	0	0
	Wankie Main Camp	20.3	4.1	150	0	0	150
	West Nicholson	20.3	1.9	120	0	0	120

(*continued*)

Table A10 (continued)

Country	Weather station	T^a	m	LFH	HFH	SFH	TFOH
MADAGASCAR[b]	Ambatolampy (10.22°S, 47.26°E, 1,625 m)	21.9	5.2	180	-	-	180
	Ambohibary (19.37°S, 47.07°E, 1,640 m)	23.0	5.1	150	-	-	150
	Antsirabé (19.52°S, 47.01°E, 1,506 m)	23.3	5.7	150	-	-	150
	Faratsiho (18.53°S, 47.33°E, 1,259 m)	22.9	6.4	120	-	-	120
	Nanisana (19.31°S, 47.92°E, 2,020 m)	24.5	7.8	75	-	-	75
	Nanokely (19.10°S, 46.45°E, 1,575 m)	20.0	3.8	150	60	-	190
	Soavinandrina (19.24°S, 46.57°E, 1,750 m)	23.5	7.4	75	-	-	75
	Tsinjoarivo (19.37°S, 47.42°E, 1,640 m)	21.3	7.1	105	-	-	105

[a] T = mean annual temperature, °C; m = mean daily minimum temperature of the coolest month (usually July in the southern hemisphere); LFH = light frost hazard, $4 < m < 8$°C, days year^{-1}; HFH+ = hard frost hazard, $1 < m < 4$°C, days year^{-1}; SFH = severe frost hazard, $m < 1$°C, days year^{-1}; TFOH = total frost occurrence hazard, $m < 8$°C, days year^{-1}

[b] Frost hazard occurrence in Madagascar (source: Oldeman 1990), liminar remarks: frost generally occurs above 1,500 m of elevation a.s.1. but locally it can occur at around 1,200 m; hard frost usually occurs above 2, 000 m. Total area of frost hazard occurrence: about 116,000 km^2—114,000 of LFH, 1,500 of HFH, and 500 km^2 of SFH

Table A11 Crop distribution in East Africa between 10°N and 10°S (Le Houérou 1984b; other sources: Acland 1971; Westphal 1975; Le Houérou 1979; Braun 1982; Jätzold and Schmidt 1982)

Elevation (m)		0.0	500	1,000	1,500	2,000	2,500	3,000	3,500	4,000
Mean annual temp.	°C±10%	28.0	27.0	25.0	22.2	19.5	16.8	14.0	11.2	8.5
Frost occurrence:	None	00000000000000000000000000000000000								
	Light					XXXXXXXX				
	Hard						XXXXXXXXXXXXXX			
	Severe								XXXXXXX	
Anacardium occidentale		_________								
Cashew nut										
Cocos nucifera		___________…								
Coconut										
Penisetum glaucum		_____________…								
Pearl millet, Bulrush millet										
Saccharum officinarum		_________________…								
Sugarcane										
Mangifera indica		_________________…								
Mango										
Arachis hypogea		_________________…								
Groundnut										
Vigna unguiculata		_________________…								
Cowpea										
Psicium guava		___________________…								
Guava										

(*continued*)

Table A11 (continued)

Elevation (m)		0.0	500	1,000	1,500	2,000	2,500	3,000	3,500	4,000
Mean annual temp.	°C±10%	28.0	27.0	25.0	22.2	19.5	16.8	14.0	11.2	8.5
Frost occurrence:	None	000000000000000000000000000000000000								
	Light					XXXXXXXX				
	Hard						XXXXXXXXXXXXXX			
	Severe								XXXXXXX	
Gossypium hirsutum		____________________…								
Cotton										
Colocasia esculenta		______________________…								
Taro										
Carica papaya		______________________…								
Pawpaw										
Agave sisalana		______________________…								
Sisal										
Musa X paradisiaca		______________________…								
Banana										
Manihot esculenta		______________________…								
Cassava										
Sesamum indicum		________________________…								
Sesame										
Citrus spp.		________________________…								
Citruses										
Dioscorea spp.		________________________…								
Yam										
Ricinus communis		___________________________…								
Castor bean										

Cajanus cajan	…
Pigeon pea	
Dioscorea batatas	…
Sweet potato	
Ananas comosus	…
Pineapple	
Eleusine coracana	
Finger millet	
Sorghum bicolor	
Grain sorghum	
Zea mais	…
Maize, corn	
Helianthus annuus	…
Sunflower	
Coffea robusta	
Robusta coffee	
Phaseolus spp.	
Bean	
Nicotiana tabacum	
Tobacco	
Coffea arabica	
Arabica coffee	
Eucalyptus camaldulensis	…
Red river gum	

(*continued*)

Table A11 (continued)

Elevation (m)		0.0	500	1,000	1,500	2,000	2,500	3,000	3,500	4,000
Mean annual temp.	°C±10%	28.0	27.0	25.0	22.2	19.5	16.8	14.0	11.2	8.5
Frost occurrence:	None	00000000000000000000000000000000000								
	Light					XXXXXXXX				
	Hard						XXXXXXXXXXXXXX			
	Severe								XXXXXXX	
Eucalyptus globulus				______________________________…						
Blue gum										
Catha edulis					_____________________________					
Qat										
Ensete ventricosum					…..____________________…					
Ensete										
Eragrostis tef					…..____________________…					
Teff										
Brassica oleracea					…..______________________….					
Cabbage										
Camellia sinensis					…..___________________…					
Tea										
Cicer arietinum					__________________…					
Chick pea										
Coleus edulis					_______________					
Galla potato										
Lupinus albus					__________________….					
Lupin										
Guizotia edulis					________________……					

Nugh	
Vicia faba	
Horse bean	
Triticum vulgare	
Soft wheat	
Hordeum vulgare	…
Barley	
Solanum tuberosum	…
Potato (Irish)	
Chrysantemum ciner-ariifolium	…
Pyrethrum	

Table A12 Soil distribution in the main ecological zones of Africa (in 10^3 ha)[a]

Soils/zones	7	6	5	4	3	2	1	Cold ($T < 5\,°C$)	Total	Percent
	Desert	Arid	Semi-arid	Dry sub-humid	Sub-humid	Humid	Hyper-humid			
Acrisols	-	5	5 358	10 646	16 686	37 749	20 598	11	92 575	3.05
Cambisols	6,272	14,794	12,208	21,118	14,655	24,395	12,266	1,425	111,564	368
Ferralsols	-	760	2,311	15,267	32,495	136,218	121,947	22	335,970	11.08
Gleysols	1,259	5,892	11,367	18,252	20,465	26,906	42,895	-	133,720	4.41
Lithsols	3,058	23,753	25,311	87,845	62,197	51,131	2,427	1,265	397,667	13.12
Fluvisols	30,029	18,092	10,238	9,747	9,719	12,896	6,021	128	101,910	3.36
Luvisols	3,058	23,753	25,311	87,845	62,197	51,131	2,427	1,265	256,988	8.48
Nitosols	-	2,313	3,059	9,596	14,678	38,625	-	757	99,316	3.28
Arenosols	15,783	108,723	67,394	34,428	19,947	51,065	30,255	2	331,033	10.92
Regosols	102,503	83,270	22,371	24,577	11,999	19,202	5,055	478	264,707	8.73
Vertisols	1,552	21,748	18,439	39,303	13,920	8,812	706	487	104,967	3.46
Xerosols	22,807	52,701	18,202	5,461	825	146	-	766	100,908	3.33
Yermosols	312,624	55,305	5,283	264	32	-	-	266	373,774	12.33
Solontchaks	20,043	18,783	6,541	2,833	903	1,582	578	62	51,325	1.69
Others	194,487	53,214	13,864	23,885	9,096	8,209	41,505	820	274,697	9.06
Total	901,738	530,093	248,855	341,220	255,754	447,091	220,545	9,674	3,031,118	99.98
Percent	29.75	17.49	8.21	11.26	8.44	14.75	9.59	0.32	99.81	

[a] *Source*: FAO (1978) World Soil Resources Report 48, vol. 1: Report on the agro-ecological zones project, methodology and results for Africa

Table A13 Average present and potential human population densities (in nos. of people per ha, as of 1975)[a]

Eco-climatic zones	Length of growing season (days)[a]	Average present population density	Potential population-supporting capacities	
			Under low inputs	Under intermediate inputs
7–Hyper-arid	0	0.03	0.01**	0.02
6–Very arid	1–74	0.06	0.03**	0.04
5–Arid	75–119	0.16	0.07**	0.20
4–Semi-arid	120–179	0.20	0.32	1.54
3–Sub-humid	180–209	0.16	0.49***	2.15
2–Humid	210–299	0.19	0.82***	3.90
1–Hyper-humid	300	0.21	1.46***	5.61

[a] Based on the relation $P > 0.5$ ETP.

** Critical zones: actual population densities greater than supporting capacity potential;

*** non-critical zones: present population densities far below supporting capacity potential. Source: compiled from Kassam and Higgins (1980) Report on the second FAO/UNFPA Expert Consultation on Land Resources for Populations of the Future, AGLS, FAO, Rome.

Table A14 Distribution of some dominant or common trees, shrubs and perennial grasses in the various eco-climatic zones north of the equator and south of the Sahara in Africa (eco-climatic zones are as defined by Le Houérou and Popov 1981)

	1	2	3	4	5	6	7	8
	Saharan	Saharo-Sahelian	Sahelian	Sudano-Sahelian	Northern Sudanian	Southern Sudanian	Guinean	Montane
Trees & shrubs								
Balanities aegyptiaca	(+)	+	+	+	+	–	–	+
Calotropis procera	+	+	+	+	+	+	(+)	+
Acacia tortilis	+	+	+	(+)	–	–	–	+
Capparis decidua	+	+	(+)	(+)	–	–	–	(+)
Leptadenia pyrotechnica	+	+	(+)	–	–	–	–	(+)
Ochradenus baccatus	+	+	(+)	–	–	–	–	(+)
Grewia tenax	+(+)	+	(+)	–	–	–	–	(+)
Hyphaene thebaica	+	+	+	–	–	–	–	–
Maerua crassifolia	+	+	+	(+)	–	–	–	+
Acacia ehrenbergiana	+	+	+	(+)	–	–	–	+
Acacia laeta	–	+	+	(+)	–	–	–	+
Acacia senegal	–	(+)	+	(+)	–	–	–	+
Salvadora persica	+	+	+	(+)	–	–	–	+
Cordia sinensis	(+)	+	+	(+)	–	–	–	+
Boscia senegalensis	–	+	+	(+)	–	–	–	+
Cadaba farinose	–	(+)	+	+	–	–	–	+
Cadaba glandulosa	–	(+)	+	+	–	–	–	+
Dobera glabra	–	(+)	+	+	–	–	–	+
Euphorbia balsamifera	–(+)	+	+	+	(+)	–	–	+
Combretum aculeatum	–	(+)	+	+	(+)	–	–	+
Commiphora africana	–	(+)	+	+	(+)	–	–	+

Adenium obesum	–	(+)	+	+	(+)	–	–	+
Ziziphus mauritiana	–	(+)	+	+	+	–	–	+
Ziziphus mucronata	–	(+)	+	+	+	–	–	+
Feretia apodanthera	–	(+)	+	+	+	–	–	+
Acacia meliffera	–	(+)	+	+	+	(+)	–	+
Faidherbia albida	–	(+)	+	+	+	+	–	+
Acacia nilotica	–	(+)	+	+	+	+	–	+
Bauhinia rufescens	–	(+)	(+)	+	+	(+)	–	
Acacia nubica	–	(+)	+	+	+	–	–	+
Grewia bicolour	–	(+)	+	+	+	+	–	+
Boscia salicifolia	–	–	(+)	+	+	+	–	+
Maerua angustifolia	–	–	(+)	+	+	(+)	–	+
Crataeva andansoni	–	–	+	+	+	(+)	–	+
Combretum cordofanianum	–	–	(+)	+	+	+	–	+
Combretum glutinosum	–	–	(+)	+	+	(+)	–	(+)
Combretum micranthum	–	–	(+)	+	+	(+)	–	(+)
Guiera senegalensis	–	–	(+)	+	+	(+)	–	+
Mitragyna inermis	–	–	(+)	+	+	+	–	+
Anogeissus leiocarpus	–	–	(+)	+	+	+	+	+
Celtis integrifolia	–	–	(+)	+	+	+	+	+
Maytenus senegalensis	–	–	(+)	+	+	+	–	+
Stereospermum kunthianum	–	–	(+)	+	+	+	–	+
Diospyros mespiliformis	–	–	(+)	+	+	+	(+)	+
Adansonia digitata	–	–	(+)	+	+	+	(+)	+
Bombax costatum	–	–	(+)	+	+	+	(+)	+

(*continued*)

Table A14 (continued)

	1	2	3	4	5	6	7	8
	Saharan	Saharo-Sahelian	Sahelian	Sudano-Sahelian	Northern Sudanian	Southern Sudanian	Guinean	Montane
Hymenocardia acida	–	–	(+)	+	+	+	(+)	+
Sclerocarya birrea	–	–	(+)	+	+	+	(+)	+
Sterculia setigera	–	–	(+)	+	+	+	–	+
Pterocarpus lucens	–	–	(+)	+	+	(+)	–	–
Lannea acida	–	–	(+)	+	+	+	–	–
Leptadenia hastata	–	–	(+)	+	+	(+)	–	+
Terminalia brownii	–	–	(+)	+	+	+	(+)	+
Acacia seyal	–	–	(+)	+	+	(+)	–	+
Acacia ataxacantha	–	–	(+)	+	+	(+)	–	+
Dalbergia melanoxylon	–	–	(+)	+	+	(+)	–	+
Grewia flavescens	–	–	(+)	+	+	+	(+)	(+)
Grewia mollis	–	–	(+)	+	+	+	(+)	+
Grewia villosa	–	–	(+)	+	+	(+)	–	+
Maerua oblongifolia	–	–	(+)	+	+	(+)	–	+
Maerua angustifolia	–	–	(+)	+	+	(+)	–	+
Capparis corymbosa	–	–	–	+	+	(+)	(+)	+
Capparis tomentosa	–	–	–	+	+	(+)	(+)	+
Combretum racemosum	–	–	–	(+)	+	+	+	–
Combretum nigricans	–	–	–	+	+	+	–	+
Combretum getonophyllum	–	–	–	(+)	+	+	(+)	–
Combretum molle	–	–	–	+	+	+	(+)	+
Combretum ghazalense	–	–	–	+	+	+	–	–
Borassus aethiopum	–	–	–	+	+	+	+	(+)

Khaya senegalensis	–	–	–	+	+	+	(+)	–
Parkia biglobosa	–	–	–	+	+	+	(+)	(+)
Butyrospermum paradoxum	–	–	–	+	+	+	(+)	–
Ceiba pentandra	–	–	–	(+)	+	+	+	–
Xeroderris stuhlmanni	–	–	–	(+)	+	+	–	–
Piliostigma thonningii	–	–	–	(+)	+	+	(+)	+
Cassia sieberiana	–	–	–	(+)	+	+	(+)	+
Pterocarpus erinaceus	–	–	–	(+)	+	+	+	–
Cordyla pinnata	–	–	–	(+)	(+)	+	+	–
Entada africana	–	–	–	(+)	+	+	+	+
Ozoroa insignis	–	–	–	(+)	+	+	+	+
Albizia chevalieri	–	–	–	(+)	+	+	+	–
Albizia amara	–	–	–	(+)	+	+	–	+
Ximenia americana	–	–	–	(+)	+	+	+	+
Strychnos spinosa	–	–	–	(+)	+	+	+	+
Tamarindus indica	–	–	–	(+)	+	+	(+)	+
Parinari macrophylla	–	–	–	(+)	+	+	+	–
Crossopterix febrifuga	–	–	–	(+)	+	+	+	–
Daniellia oliveri	–	–	–	–	(+)	+	+	+
Isoberlinia doka	–	–	–	–	(+)	+	+	–
Lonchocarpus laxiflorus	–	–	–	–	(+)	+	+	–
Oxytenanthera abyssinica	–	–	–	–	(+)	+	+	–
Cussonia kirkii	–	–	–	–	(+)	+	+	–
Cussonia barteri	–	–	–	–	(+)	+	+	(+)
Gardenia erubescens	–	–	–	–	(+)	+	+	+

(*continued*)

Table A14 (continued)

	1	2	3	4	5	6	7	8
	Saharan	Saharo-Sahelian	Sahelian	Sudano-Sahelian	Northern Sudanian	Southern Sudanian	Guinean	Montane
Gardenia terrifolia	–	–	–	–	(+)	+	+	+
Acacia dudgeoni	–	–	–	–	(+)	+	+	+
Moringa oleifera	–	–	–	–	(+)	+	+	–
Vitex doniana	–	–	–	–	–	+	+	–
Vitex madiensis	–	–	–	–	–	+	+	+
Lophira lanceolata	–	–	–	–	–	(+)	+	+
Trema guineensis	–	–	–	–	–	(+)	+	+
Ficus capensis	–	–	–	–	–	+	+	+
Ficus glumosa	–	–	–	–	–	+	+	+
Ficus thonningii	–	–	–	–	–	+	+	+
Cola cordifolia	–	–	–	–	–	+	+	+
Bridelia ferruginea	–	–	–	–	–	+	+	+
Burkea africa	–	–	–	–	–	+	+	+
Ficus asperifolia	–	–	–	–	–	+	+	–
Albizia zygia	–	–	–	–	–	+	+	(+)
Annona senegalensis	–	–	–	–	–	+	+	–
Terminalia macroptera	–	–	–	–	–	+	+	(+)
Newbouldia laevis	–	–	–	–	–	–	+	–
Aspilia latifolia	–	–	–	–	–	–	+	–
Spondias mombin	–	–	–	–	–	–	+	–
Cyclodicus gabonensis	–	–	–	–	–	–	+	–
Perocopsis laxiflora	–	–	–	–	–	–	+	–
Uapaca togoensis	–	–	–	–	–	–	+	(+)

Harungana madascariensis	–	–	–	–	–	–	+	(+)
Syzygium guineense	–	–	–	–	–	–	+	(+)
Perennial grasses								
Stipagrostis pungens	+	(+)	–	–	–	–	–	–
Stipagrostis ciliata	+	(+)	–	–	–	–	–	+
Stipagrostis plumosa	+	(+)	–	–	–	–	–	+
Panicum turgidum	+	(+)	–	–	–	–	–	+
Lasiurus hirsutus	+	+	–	–	–	–	–	+
Cymbopogon schoenanthus	+	+	–	–	–	–	–	+
Aristida pallida	+	+	(+)	–	–	–	–	+
Aristida papposa	–	+	(+)	+	–	–	–	+
Cymbopogon proximus	–	+	(+)	+	–	–	–	–
Aristida longiflora	–	–	(+)	+	–	–	–	+
Andropogon gayanus	–	–	–	(+)	+	+	(+)	+
Hyperthelia dissoluta	–	–	–	(+)	+	+	+	+
Cymbopogon giganteus	–	–	–	(+)	+	+	–	+
Hyparrhenia rufa	–	–	–	–	(+)	+	+	(+)
Hyparrhenia smithiana	–	–	–	–	–	+	+	–
Andropogon ascinodis	–	–	–	–	–	+	+	–
Andropogon tectorum	–	–	–	–	–	+	(+)	–
Diheteropogon amplectens	–	–	–	–	–	+	+	–
Loudetia simplex	–	–	–	–	–	+	–	
Loudetia arundinacea	–	–	–	–	–	+	–	
Panicum phragmitoides	–	–	–	–	–	+	+	
Panicum maximum	–	–	–	–	–	+	–	

(*continued*)

Table A14 (continued)

	1 Saharan	2 Saharo-Sahelian	3 Sahelian	4 Sudano-Sahelian	5 Northern Sudanian	6 Southern Sudanian	7 Guinean	8 Montane
Pennisetum purpureum	–	–	–	–	–	+	–	
Hyparrhenia diplandra	–	–	–	–	–	+	–	
Hyparrhenia filipendula	–	–	–	–	–	+	–	
Imperata clindrica	–	–	–	–	–	+	–	
Andropogon macrophyllus	–	–	–	–	–	+	–	
Themeda triandra	–	–	–	–	–	–	+	
Heteropogon contortus	–	–	–	–	–	–	+	
Hyparrhenia cymbaria	–	–	–	–	–	–	+	
Chloris gayana	–	–	–	–	–	–	+	
Cenchrus ciliaris	–	–	–	–	–	–	+	
Botriochloa pertusa	–	–	–	–	–	–	+	
Chrysopogon plumulosus	–	–	–	–	–	–	+	
Antephora hochstetteri	–	–	–	–	–	–	+	
Dichanthium annulatum	–	–	–	–	–	–	+	
Sprobolus ioclados	–	–	–	–	–	–	+	
Eremopogon foveolatus	–	–	–	–	–	–	+	
Enneapogon brachystachyus	–	–	–	–	–	–	+	
Sehima ischaemodies	–	–	–	–	–	–	+	
Schmidtia pappophoroides	–	–	–	–	–	–	+	
Hyparrhenia hirta	–	–	–	–	–	–	+	

Table A15 Zonal distribution of 140 species of mammals in the lowlands of Africa between the equator and the Tropic of Cancer[1] (Le Houérou 1989a)

Species	Eco-climatic zones[2]						
	Saharan	Saharo-Sahelian	Sahelian	Sudano-Sahelian	Northern Sudanian	Southern Sudanian	Guinean/Congolian
Mammals (excl. rodents)							
Fennecus zerda	+	–	–	–	–	–	–
Vulpes rupelii	+	+	–	–	–	–	–
Addax nasomaculatus	(+)	(+)	(+)	–	–	–	–
Oryx dammah	(+)	(+)	(+)	–	–	–	–
Ammotragus lervia	+	+	+	(+)	–	–	–
Capra ibex	(+)	+	+	–	–	–	–
Vulpes pallida	(+)	(+)	(+)	–	–	–	–
Gazella leptoceros	(+)	(+)	(+)	–	–	–	–
Gazella dama	(+)	+	+	(+)	–	–	–
Felis margarita	(+)	+	+	+	–	–	–
Gazella dorcas	(+)	+	+	+	–	–	–
Lepus capensis	(+)	+	+	+	+	+	
Pelictis libyca	(+)	+	+	+	+	+	–
Canis aureus	(+)	+	+	+	+	+	–
Hyaena hyaena	(+)	+	+	+	+	+	–
Felis libyca	(+)	+	+	(+)	+	+	–
Acinonyx jubatus	(+)	+	+	(+)	–	–	–
Procavia capensis	+	+	+	+	–	–	–
Gazella rufifrons	–	(+)	+	+	–	–	–
Zorilla striatus	–	(+)	+	+	+	+	–
Lepus crawshayi	–	+	+	+	+	+	–
Felis caracal	–	(+)	+	+	(+)	(+)	–
Lyacaon pictus	–	(+)	+	+	–	–	–
Panthera leo	–	(+)	+	+	–	–	–
Galago senegalensis	–	–	+	+	–	–	–
Erythrocebus patas	–	–	(+)	+	+	+	–
Cercopithecus aethiops	–	–	(+)	+	(+)	(+)	–
Crocuta crocuta	–	–	+	+	+	+	–
Canis adustus	–	–	+	+	+	+	–
Ichneumia albicauda	–	–	+	+	+	+	–
Herpestes ichneumo	–	–	+	+	+	+	–
Xerus erythropus	–	–	+	+	(+)	(+)	–
Genetta genetta	–	–	+	+	+	+	–
Giraffa camelopardais	–	–	+	+	+	+	–
Felis serval	–	–	+	+	+	+	–

(*continued*)

Table A15 (continued)

Species	Eco-climatic zones[2]						
	Saharan	Saharo-Sahelian	Sahelian	Sudano-Sahelian	Northern Sudanian	Southern Sudanian	Guinean/Congolian
Hyppotragus equinus	–	–	(+)	+	+	+	–
Redunca redunca	–	–	(+)	+	+	+	–
Alcephalus cama	–	–	(+)	+	+	+	–
Damaliscus korrigum	–	–	(+)	+	+	+	–
Kobus defassa	–	–	(+)	+	+	+	–
Papio anubis	–		(+)	+	+	+	
Orycteropus afer	–	–	+	+	+	+	+
Phacochaerus aethiopicus	–	–	+	+	+	+	+
Kobus kob	–	–	–	(+)	+	+	+
Alcephalus buselaphus	–	–	–	(+)	+	+	+
Sylvicapra grimmia	–	–	–	+	+	+	+
Panthera pardus	–	–	–	(+)	+	+	+
Loxodonta africana	–	–	–	(+)	+	+	+
Hypopotamus amphibius	–	–	–	(+)	+	+	+
Syncerus caffer	–	–	–	(+)	+	+	+
Ourebia ourebi	–	–	–	(+)	+	+	+
Taurotragus derbyanus	–	–	–	(+)	+	+	+
Tragetaphus strepticeros	–	–	–	(+)	+	+	+
Tragbelaphus scriptus	–	–	–	–	+	+	+
Cephalophus rufilatus	–	–	–	–	(+)	+	+
Potamochaerus porcus	–	–	–	–	–	+	+
Naudinia binotata	–	–	–	–	–	+	+
Genetta tigrina	–	–	–	–	–	+	+
Genetta servalina	–	–	–	–	–	–	+
Potamogale velox	–	–	–	–	–	–	+
Manis gigantea	–	–	–	–	–	–	+
Periodictius potto	–	–	–	–	–	–	+
Galagoides demidovii	–	–	–	–	–	–	+
Cercocebus spp.[3]	–	–	–	–	–	–	+
Cercopithecus spp.[4]	–	–	–	–	–	–	+
Gorilla gorilla	–	–	–	–	–	–	+
Papio sphinx	–	–	–	–	–	–	+
Pan troglodytes	–	–	–	–	–	–	+
Colobus spp.[5]	–	–	–	–	–	–	+
Aonyx congica	–	–	–	–	–	–	+

Table A15 (continued)

Species	Eco-climatic zones[2]						
	Saharan	Saharo-Sahelian	Sahelian	Sudano-Sahelian	Northern Sudanian	Southern Sudanian	Guinean/Congolian
Polona richardsonii	–	–	–	–	–	–	+
Bdeogale nigripes	–	–	–	–	–	–	+
Herpestes naso	–	–	–	–	–	–	+
Crossarcus obscurus	–	–	–	–	–	–	+
Dendrohyrax arboreus	–	–	–	–	–	–	+
Hylochaerus meinetzageni	–	–	–	–	–	–	+
Okapia hohnstoni	–	–	–	–	–	–	+
Boocercus euryceros	–	–	–	–	–	–	+
Tragelaphus spekei	–	–	–	–	–	–	+
Cephalophus spp.[6]	–	–	–	–	–	–	+
Rodents							
Ctednodactylus goundi	+	+	–	–	–	–	–
Gerbillus nanus	+	(+)	–	–	–	–	–
Gerbillus gerbillus	+	(+)	–	–	–	–	–
Gerbillus pyramidum	+	(+)	–	–	–	–	–
Jaculus jaculus	+	(+)	–	–	–	–	–
Meriones libycus	+	(+)	–	–	–	–	–
Pachyuromys duprasi	+	(+)	–	–	–	–	–
Psammonys obesus	+	(+)	+	–	–	–	–
Teterillus arenarius	+	+	+	–	–	–	–
Desmodilliscus braueri	(+)	+	+	+	(+)	–	–
Hystrix costata	(+)	+	+	+	+	–	–
Taterillus pygargus	–	(+)	+	+	+	–	–
Arvicanthis niloticus	–	(+)	+	+	+	–	–
Mus haussa	–	(+)	+	+	+	–	–
Mastomys huberti	–	–	+	+	+	+	–
Euxerus erythropu	–	–	+	+	+	+	–
Taterillus gracilis	–	–	(+)	+	+	+	–
Mastomys erythroleucus	–	–	+	+	+	+	+
Tatera guineae	–	–	–	–	+	+	+
Heliosciurus gamblanus	–	–	–	–	+	+	+
Cricetemys gambianus	–	–	–	–	+	+	+
Steatomys caurinus	–	–	–	–	+	+	+

(*continued*)

Table A15 (continued)

Species	Eco-climatic zones[2]						
	Saharan	Saharo-Sahelian	Sahelian	Sudano-Sahelian	Northern Sudanian	Southern Sudanian	Guinean/Congolian
Mus mattheyi	–	–	–	–	+	+	+
Mus muscoloides	–	–	–	–	+	+	+
Rattus rattus	–	–	–	–	+	+	+
Lemnicomys barbarus	–	–	–	–	+	+	+
Myomys daltoni	–	–	–	–	+	+	+
Mastromys erythroleucus	–	–	–	–	+	+	+
Graphiurus murinus	–	–	–	–	+	+	+
Tatera gambiana	–	–	–	–	+	+	+
Cricetomys emini	–	–	–	–	+	+	+
Thryonomys swinderianus	–	–	–	–	+	+	+
Thryonomys gregorianus	–	–	–	–	–	–	+

[1] An interpretation of the indications given by Dekeyser (1955), Dorst and Dandelot (1970), Poulet (1972), Happold (1973), Delany and Happold (1979), Haltenorth et al. (1985).

[2] Eco-climatic zones as defined by Le Houérou and Popov (1981).

[3] *Cercocebus aterrimus, C. galeritus, C. torquatus, C. albigena*.

[4] *Cercopithecus ascanius, C. cephus, C. neglectus, C. nictitans, C. diana, C. erythrogaster, C. mona, C. mitis, C. neglectus*.

[5] *Colobus angolensis, C. badius, C. guereza, C. pennanti, C. satanas*.

[6] *Cephalophus callipygus, C. dorsalis, C. leucogaster, C. niger, C. nigrifons, C. monticolola, C. silvicultor*.

Table A16 Surface areas of distribution of agro-bioclimatic zones (Le Houérou and Popov 1981)

Zones & countries	Total adjusted km^2	Frost hazard	Equator	Tropical	Frost hazard	Equator	Tropical
Inter-tropical continental Africa		1–Hyper-humid			2–Humid		
Western Africa							
Benin	110,640	-	7,138	21,415	-	3,568	67,812
Burkina Faso	273,771	-	-	7,020	-	-	168,474
Côte d'Ivoire	317,870	-	135,264	175,843	-	-	6,763
Gambia	10,002	-	-	-	-	-	9,526
Ghana	229,973	-	67,075	73,464	-	15,970	67,076
Guinea	246,000	-	-	246,600	-	-	-
Guinea Bissau	28,026	-	-	28,026	-	-	-
Liberia	96,317	-	38,527	57,790	-	-	-
Mali	1,181,316	-	-	52,895	-	-	151,631
Mauritania	858,748	-	-	-	-	-	-
Niger	1,266,556	-	-	-	-	-	-
Nigeria	910,362	-	98,319	353,221	-	-	247,618
Senegal	191,934	-	-	36,401	-	-	33,092
Sierra Leone	71,621	-	-	71,621	-	-	-
Togo	53,578	-	-	26,790	-	3,348	20,092
Total western Africa	5,846,714	-	346,323	1,150,486	-	22,886	777,084
%			5.92	19.67		0.39	13.21
Central Africa							
Angola	7,138	-	5,710	-	-	1,428	-

(*continued*)

Table A16 (continued)

Zones & countries	Total adjusted km²	Frost hazard	Equator	Tropical	Frost hazard	Equator	Tropical
Cameroon	469,598	-	208,711	197,529	-	-	29,816
Central African Rep.	623,045	-	95,559	481,617	-	-	45,869
Chad	1,259,127	-	-	74,310	-	-	173,388
Congo	341,647	-	340,184	1,463	-	-	-
Equatorial Guinea	28,046	-	28,046	-	-	-	-
Gabon	257,664	-	257,664	-	-	-	-
Zaire	2,267,367	3,542	2,104,401	28,342	3,542	95,655	31,885
Total central Africa	5,253,632	3,542	3,040,275	783,261	3,542	97,083	280,958
%		0.07	57.87	14.90	0.07	1.85	5.35
Eastern Africa							
Burundi	25,638	-	17,092	-	-	8,546	-
Ethiopia	1,100,988	126,640	34881	127,044	19,026	88,789	114,158
Kenya	569,371	-	104,409	2,088	-	48,724	4,872
Rwanda	25,052	-	25,052	-	-	-	-
Somalia	627,306	-	-	-	-	-	-
Sudan	2,375,776	-	61,737	79,894	-	-	268,737
Tanzania	886,054	3,421	61,579	3,421	-	424,211	229,211
Djibouti	21,990	-	-	-	-	-	-
Uganda	199,657	-	170,078	7,395	-	-	11,092
Total eastern Africa	5,831,832	130,465	474,828	219,842	19,026	570,270	628,070
%		2.23	8.14	3.76	0.36	9.78	10.77
Southern Africa							
Angola	1,239	17,779	298,698	199,132	142,237	99,566	141,237
Botswana	406,578	-	-	-	-	-	-

Malawi	94,047	-	-	-	-	25,079	56,428
Mozambique	697,368	3,289	36,184	7,565	-	88,816	348,689
Namibia	523,896	-	-	-	-	-	-
Zimbabwe	387,573	3,418	-	-	34,178	-	37,595
Zambia	740,721	3,292	79,010	79,010	36,213	79,010	381,884
Total southern Africa	4,098,779	27,778	384,263	353,800	212,628	292,471	966,828
%		0.68	9.37	8.63	5.19	7.14	23.59
Total inter-tropical Africa	21,030,957	161,583	4,315,689	2,507,187	235,196	982,710	2,652,940
Inter-tropical continental Africa			1–Hyper-humid			2–Humid	
Western Africa							
Benin		-	-	10,707	-	-	-
Burkina Faso		-	-	68,178	-	-	35,099
Côte d’Ivoire		-	-	-	-	-	-
Gambia		-	-	476	-	-	-
Ghana		-	6,388	-	-	-	-
Guinea		-	-	-	-	-	-
Guinea Bissau		-	-	-	-	-	-
Liberia		-	-	-	-	-	-
Mali		-	-	148,105	-	-	109,316
Mauritania		-	-	9,039	-	-	120,525
Niger		-	-	55,586	-	-	170,726
Nigeria		-	-	207,563	-	-	6,641
Senegal		-	-	49,638	-	-	52,948

(*continued*)

Table A16 (continued)

Zones & countries	Total adjusted km²	Frost hazard	Equator	Tropical	Frost hazard	Equator	Tropical
Sierra Leone		-	-	-	-	-	-
Togo		-	3,348	-	-	-	-
Total western Africa			9,736	544,292	-	-	492,255
%			0.17	9.31			8.42
Central Africa							
Angola		-	-	-	-	-	-
Cameroon		-	-	29,816	-	-	3,726
Central African Rep.		-	-	-	-	-	-
Chad		-	-	123,848	-	-	107,335
Congo		-	-	-	-	-	-
Equatorial Guinea		-	-	-	-	-	-
Gabon		-	-	-	-	-	-
Zaire		-	-	-	-	-	-
Total central Africa		-	-	153,664	-	-	111,061
%				2.93			2.11
Eastern Africa							
Burundi		-	-	-	-	-	
Ethiopia		634	117,329	25,369	-	133,184	-
Kenya		-	90,487	-	-	153,131	19,026
Rwanda		-	-	-	-	-	-
Somalia		-	39829	-	3,319	126,125	-
Sudan		-	-	493,894	5,810	-	-
Tanzania		6,842	116,316	34,211	-	-	246,947
Djibouti		-	-	-	-	-	6,842

Uganda	-	-	11,092	-	-	-
Total eastern Africa	130,465	363,961	564,566	9,129	412,440	272,815
%	2.23	6.24	9.68	0.16	7.07	4.68
Southern Africa						
Angola	184,908	14,224	21,336	28,448	99,566	7,112
Botswana	1,974	-	85,526	-	-	190,789
Malawi	-	-	2,540	-	25,079	-
Mozambique	-	26,316	46,053	72,368	88,816	-
Namibia	10,974	-	19,737	-	-	6,579
Zimbabwe	123,039	1,367	123,038	27,342	-	3,417
Zambia	6,584	-	105,347	-	79,010	-
Total southern Africa	418,479	41,907	413,578	267,996	128,158	207,897
%	10.21	1.02	10.09	6.54	3.12	5.07
Total inter-tropical Africa	425,955	415,604	1,676,100	277,125	540,598	1,084,028
Inter-tropical continental Africa	1–Hyper-humid			2–Humid		
Western Africa						
Benin	-	-	-	-	-	-
Burkina Faso	-	-	-	-	-	-
Côte d’Ivoire	-	-	-	-	-	-
Gambia	-	-	-	-	-	-
Ghana	-	-	-	-	-	-
Guinea	-	-	-	-	-	-
Guinea Bissau	-	-	-	-	-	-
Liberia	-	-	253,895	-	-	465,474

(*continued*)

Table A16 (continued)

Zones & countries	Total adjusted km²	Frost hazard	Equator	Tropical	Frost hazard	Equator	Tropical
Mali		-	-	343,500	-	-	385,684
Mauritania		-	-	262,046	-	-	778,198
Niger		-	-	-	-	-	-
Nigeria		-	-	19,855	-	-	-
Senegal		-	-	-	-	-	-
Sierra Leone		-	-	-	-	-	-
Togo		-	-	-	-	-	-
Total western Africa		-	-	879,296	-	-	1,629,356
%				15.04			27.87
Central Africa							
Angola		-	-	-	-	-	-
Cameroon		-	-	-	-	-	-
Central African Rep.		-	-	-	-	-	-
Chad		-	-	247,697	49,540	-	480,009
Congo		-	-	-	-	-	-
Equatorial Guinea		-	-	-	-	-	-
Gabon		-	-	-	-	-	-
Zaire		-	-	-	-	-	-
Total central Africa		-	-	247,697	49,540	-	480,009
%				4.72	0.94		9.13
Eastern Africa							
Burundi		-	-	-	-	-	-
Ethiopia		-	88,789	44,395	-	152,221	9,513
Kenya		-	146,171	-	-	17,401	-

Rwanda		-	-	-	-	-	-
Somalia		-	219,059	-	-	238,974	-
Sudan		5,810	-	334,106	-	-	878,841
Tanzania		-	-	-	-	-	-
Djibouti		-	9,424	-	-	12,566	-
Uganda		-	-	-	-	-	-
Total eastern Africa		5,810	463,433	378,501	-	421,152	88,354
%		0.10	7.95	6.49		7.22	15.23
Southern Africa							
Angola		-	32,033	21,336	-	2,134	24,891
Botswana		9,868	-	-	-	-	-
Malawi		-	-	-	-	-	-
Mozambique		-	-	-	-	-	-
Namibia		101,974	-	46,053	-	-	144,737
Zimbabwe		-	-	-	-	-	-
Zambia		-	-	-	-	-	-
Total inter-tropical southern Africa		111,842	32,033	67,399	-	2,134	169,628
%		2.73	0.78	1.64		0.05	4.14
Total inter-tropical Africa		117,652	459,446	157,288	49,540	423,286	3,170,347
Inter-tropical continental Africa			1–Hyper-humid			2–Humid	
Southern Africa (south of Tropic of Capricorn)							
Namibia	291,000	-	-	-	-	-	-

(*continued*)

Table A16 (continued)

Zones & countries	Total adjusted km²	Frost hazard	Equator	Tropical	Frost hazard	Equator	Tropical
South Africa, Lesotho and Swaziland	1,161,000	-	-	-	-	-	50,000
Botswana	193,794	-	-	-	-	-	-
Mozambique	85,632	-	-	-	-	-	5,632
Total southern Africa	1,731,426	-	-	-	-	-	55,632
%	100						3.2
Northern Africa (north of Tropic of Cancer)							
Algeria	2,381,740	4,375	-	-	4,375	-	-
Egypt	1,001,450	-	-	-	-	-	-
Libya	1,759,740	-	-	-	-	-	-
Morocco (including West Sahara)	712,550	3,000	-	-	10,000	-	-
Tunisia	163,610	700	-	-	5,500	-	-
Total northern Africa	6,019,090	8,075	-	200,000	19,875	-	-
%	100	0.1		33.9	0.3		
Madagascar	590,000	31,000	-	169,000	85,000	-	45,000
%	100	5.2		28.6	14.4		4.6
Inter-tropical continental extra-tropical Africa		3–Sub-humid			4–Semi-arid		
Southern Africa (south of Tropic of Capricorn)							
Namibia		-	-	-	-	-	-
South Africa, Lesotho and Swaziland		365,000	-	-	425,000	-	-

Botswana	-	-	-	22,500	-	-
Mozambique	-	-	80,000	-	-	-
Total southern Africa	365,000	-	80,000	447,500	-	-
%	21.1		4.6	25.8		
Northern Africa (north of Tropic of Cancer)						
Algeria	7,500	-	-	164,750	-	-
Egypt	-	-	-	-	-	-
Libya	200	-	-	600	-	-
Morocco (including West Sahara)	30,000	-	-	154,000	-	-
Tunisia	4,800	-	-	26,000	-	-
Total northern Africa	42,500	-	-	345,350	-	-
%	0.7			5.7		
Madagascar	-	-	100,000	-	-	90,00
%			17.0			15.2
Extra-tropical & continental Africa		3–Sub-humid			4–Semi-arid	
Southern Africa (south of Tropic of Capricorn)						
Namibia	183,000	-	-	-	-	108,000
South Africa, Lesotho and Swaziland	223,000	-	-	-	-	98,000
Botswana	171,294	-	-	-	-	-
Mozambique	-	-	-	-	-	-

(*continued*)

Table A16 (continued)

Zones & countries	Total adjusted km^2	Frost hazard	Equator	Tropical	Frost hazard	Equator	Tropical
Total southern Africa		577,294	-	-	-	-	206,000
%		33.4					11.9
Northern Africa (north of Tropic of Cancer)							
Algeria		200,00	-	-	2,000,740	-	-
Egypt		31,450	-	-	970,000	-	-
Libya		90,000	-	-	1,667,740	-	-
Morocco (including West Sahara)		120,000	-	-	395,750	-	-
Tunisia		55,000	-	-	71,610	-	-
Total northern Africa		496,450	-	-	5,105,840	-	-
%		8.3			584.9		
Madagascar		-	-	70,000	-	-	-
%				11.9			

Table A17 Aridity zoning in East Africa between 10°N and 10°S

Zones	P/ETo = Q	Designation in Kenya[a]	Approximate equivalence[b]	Class
VIII	$Q < 0.05$	n.a.	Hyper-arid	7
VII	$0.05 < Q < 0.15$	Very arid	Very arid	6
VI	$0.15 < Q < 0.25$	Arid	Arid	5
V	$0.25 < Q < 0.40$	Semi-arid	Semi-arid	4
IV	$0.40 < Q < 0.50$	Semi-arid to semi-humid	Dry sub-humid	
III	$0.50 < Q < 0.65$	Semi-humid	Sub-humid	3
II	$0.65 < Q < 0.80$	Sub-humid	Humid	2
I	$0.80 < Q < 1.20$	Humid	Very humid	1
0	$1.20 < Q$	n.a.	Wet	

[a] Braun (1982), Jätzold and Schmidt (1982).

[b] Table XVIII in Le Houérou and Popov (1981) Thermal zoning in East Africa between 10°N and 10°S.

Table A18 Thermal zoning in East Africa (Le Houérou et al. 1993)

Zones	Elevation (m a.s.1.)	Mean annual temperature°C (°C)	Designation (Braun 1982)	Deisgnation in Kenya (Jätzold and Schmidt 1982)	Designation in Ethiopia (Le Houérou and Popov 1981)
10	E>3500	8 >t	Very cold	Afro-alpine	Afro-alpine = Woortch (m < 1°C)[a]
9	3,500 > E > 3,000	10 > ← t >8	Cold	Sub-alpine	Montane = Dega (1 < m < 8°C)
8	3,000 > E > 2,700	12 > ← t >10	Very cool	Upper highlands	
7	2,700 > E > 2,400	14 > ← t >12	Cool	Upper highlands	
6	2,400 > E > 2,100	16 > ← t >14	Fairly cool	Lower highlands	Highlands = Woina Dega (8 < m < 10°C)
5	2,100 < E < 1,800	18 > ← t >16	Cool temperature	Lower highlands	
4	1,800 > E > 1,500	20 > ← t >18	Warm temperature	Upper midlands	Midlands = upper Kolla (10 < m < 20°C)
3	1,500 > E > 1,200	22 > ← t >20	Fairly warm	Upper midlands	
2	1,200 > E > 900	24 > ← t > 22	Warm	Lower midlands	Lower Kolla (15 < m < 20°C)
1	900 > E > 900	30 > ← t > 24	Hot	Lowlands	Lowlands = Bereha (20°C < m)

[a] m = mean daily minimum temperature of the coolest month (January in the N. hemisphere, July in the S. hemisphere)

Table A19 Broad climatic requirements of some 80 African crops (Le Houérou et al. 1993)

Species	Carboxyl pathway	Length of cycle days (depending on cultivar)	Precipition required per cycle	Optimum growth 1 °C	Zero growth 1 °C	kg of water for 1 kg DM production (WUE)
Sesame (*Sesamum indicum*)	C3	50–70	250–600	20 ± 5	8	300–700
Giant/old man saltbush (*Atriplex nummularia*)	C4	60–180	200–400	30 ± 5	12	150–250
Finger millet (*Eleusine coracana*)	C4	70–90	400–800	30 ± 5	15	150–300
Foxtail millet (*Setaria italica*)	C4	70–90	400–800	25 ± 5	10	150–350
Common millet (*Panicum miliaceum*)	C4	70–100	400–800	25 ± 5	10	150–350
Pearl millet (*Pennisetum typhoides*)	C4	75–120	400–800	25 ± 5	15	150–350
Tobacco (*Nicotiana tabacum*)	C3	70–150	600–1,200	20 ± 5	10	300–700
Soybean (*Glycine max*)	C3	75–170	600–1,200	25 ± 5	10	300–700
Sorghum (*Sorghum bicolour*)	C4	90–240	600–1,200	30 ± 5	15	150–350
Sudan grass (*Sorghum sudanense*)	C4	45–60	360–500	30 ± 5	15	150–300
Fonio (*Digitaria exilis*)	C4	90–130	300–600	25 ± 5	15	150–350
Maize (*Zea mays*)	C4	80–130	600–1,200	25 ± 5	15	30–700
Groundnut (*Arachis hypogea*)	C3	90–120	600–1,200	25 ± 5	15	400–800
Field mustard (*Brassica campestris*)	C3	80–90	400–600	15 ± 5	10	400–800
Chickpea (*Cicer arietinum*)	C3	90–150	600–800	20 ± 5	5	300–700
Potato (*Solanum tuberosum*)	C3	90–180	600–800	20 ± 5	10	400–800
Lentil (*Lens esculenta*)	C3	90–240	400–800	18 ± 5	10	400–800
French bean (*Phaseolus vulgaris*)	C3	90–200	500–700	20 ± 5	10	300–700
Rape (*Brassica napus*)	C3	100–110	600–800	18 ± 3	5	400–800
Cabbage (*Brassica oleracea*)	C3	100–120	600–800	18 ± 3	5	400–800
Barley (*Hordeum vulgare*)	C3	90–240	300–800	18 ± 3	10	400–800
Sunflower (*Helianthus annuus*)	C3	100–160	500–600	18 ± 3	5	300–700

Cashew nut (*Anacardium occidentale*)	C3	100–200	600–2,000	30 ± 5	20	300–700
Spring wheat (*Triticum aestivum*)	C3	100–240	400–800	18 ± 3	5	400–800
Flax (*Linum usitatissimum*)	C3	100–180	600–800	18 ± 3	5	400–800
Safflower (*Carthamus tinctorius*)	C3	110–130	300–600	20 ± 5	10	400–800
Rice (*Oryza sativa, Oryza spp.*)	C3	110–180	1,000–2,000	25 ± 5	10–15	300–700
Tomato (*Lycopersicum esculentum*)	C3	110–140	600–800	18 ± 3	10	400–800
Oats (*Avena sativa*)	C3	110–180	500–700	18 ± 3	5	400–800
Rye (*Secale cereale*)	C3	110–170	400–600	18 ± 3	5	400–800
Cowpea (*Vigna unguiculata*)	C3	110–180	400–1,200	25 ± 5	15	300–700
Pigeon pea (*Cajanus cajan*)	C3	120–180	400–800	25 ± 5	15	400–800
Hyacinth bean (*Lalblab purpureus*)	C3	110–210	300–700	25 ± 5	15	300–700
Roselle (*Guinea sorrel*) (*Hibiscus sabdariffa*)	C3	120–150	400–800	25 ± 5	15	300–700
Hemp (*Hibiscus cannabinus*)	C3	120–150	600–800	25 ± 5	18	300–700
Fig (*Ficus carica*)	C3	120–150	300–1,000	20 ± 5	15	300–700
Cotton (*Gossypium hirsutum*)	C3	130–180	700–1,500	30 ± 5	15	300–700
Jute (*Corchorus capsularis*, *C. olitorius*)	C3	120–150	1,500–2,000	30 ± 5	20	
Sweet potato (*Ipomaea batatas*)	C3	120–210	600–1,200	25 ± 5	12	300–700
Castor bean (*Ricinus communis*)	C3	150–180	700–1,200	25 ± 10	12	300–700
Lima bean (*Phaseolus lunatus*)	C3	150–210	800–1,200	25 ± 5	15	300–700
Grape (*Vitis vinifera*)	C3	160–180	400–1,200	18 ± 5	10	400–800
Cassava (*Manihot esculenta*)	C3	180–300	1,200–1,500	28 ± 5	18	300–700
Sugar beet (*Beta vulgaris*)	C3	160–240	600–800	20 ± 5	10	400–800
Pyrethrum (*Chrysanthemum cinerariifolium*)	C3	180–365	800–1,500	15 ± 5	5	400–800
Mango (*Mangifera indica*)	C3	180–200	800–1,500	25 ± 5	15	300–700

(*continued*)

Table A19 (continued)

Species	Carboxyl pathway	Length of cycle days (depending on culti-var)	Precipition required per cycle	Optimum growth 1 °C	Zero growth 1 °C	kg of water for 1 kg DM production (WUE)
Pawpaw (*Caricapapaya*)	C3	182–260	800–1,500	25 ± 5	15	300–700
White yam (*Dioscorea rotundata*)	C3	200–240	1,200–2,000	25 ± 5	15	300–700
Guava (*Psidium guava*)	C3	200–300	800–1,200	20 ± 5	10	300–700
Avocado (*Persea americana*)	C3	200–300	600–1,200	20 ± 7	10	300–700
Olive (*Olea europaea*)	C3	210–240	200–800	20 ± 5	10	300–700
Shea butter (*Butyrospermum paradoxa*)	C3	180–240	600–1,200	30 ± 5	15	300–700
Guinea fan palm (*Borassus aethiopum*)	C3	180–240	800–1,500	30 ± 5	15	400–800
Kapok (*Ceiba pentandra*)	C3	180–240	800–1,500	30 ± 5	15	300–700
Lemon (*Citrus limon*)	C3	240–365	800–1,200	20 ± 5	10	400–800
Black pepper (*Piper nigrum*)	C3	240–280	2,000–3,000	25 ± 5	15	RH>80%; 400<Alt.<1,000
Sisal (*Agave sisalana*)	CAM	200–300	700–1,500	20 ± 5	10	100–300
Fruit/Fodder Cactus (*Opuntia ficus-indica*)	CAM	180–300	200–600	20 ± 5	12	150–300
Vanilla (*Vanilla spp.*)	C3	280–300	1,200–1,500	20 ± 5	15	150–300
Sugarcane (*Saccharum officinarum*)	C4	275–335	1,200–2,000	25 ± 5	15	300–700
Greater yam (*Dioscorea alata*)	C3	270–300	1,500–3,000	25 ± 5	15	RH>80%; Alt.<600
Para rubber (*Hevea brasiliensis*)	C3	330–365	1,500–3,000	25 ± 5	15	RH>80%; Alt.<600
Oil palm (*Elaeis guineensis*)	C3	330–365	1,500–3,000	25 ± 5	20	RH>75%; Alt.<600
Clove (*Eugenia caryophyllus*)	C3	365	1,500–2,000	26	20	RH>80%; Alt.<600
Pineapple (*Ananas comosus*)	CAM	300–365	1,200–1,500	25 ± 5	15	WUE: 50–200
Qat (*Catha edulis*)	C3	180–240	800–1,200	20 ± 5	10	300–700
Ensete (*Ensete ventricosum*)	C3	200–260	100–1,500	25 ± 5	12	300–700
Sweet orange (*Citrus sinensis*)	C3	240–300	1,500–3,000	18 ± 5	8	300–700

Arabica coffee (*Coffea arabica*)	C3	240–300	1,200–3,000	20 ± 5	12	300–700
Robusta coffee (*Coffea canephora*)	C3	280–365	>2,000	25 ± 5	15	300–700
Banana/Plantain (*Musa spp.*)	C3	280–330	1,000–2,000	25 ± 5	12	150–300
Coconut (*Cocos nucifera*)	C3	200–365	1,500–3,000	25 ± 5	18	300–700
Taro (*Colocasia antiquorum*)	C3	280–365	1,500–3,000	25 ± 5	15	Lat.<10°; Alt.<1000
Tea (*Camellia sinensis*)	C3	280–330	1,500–4,000	20 ± 5	12	400–800
Cola nut (*Cola acuminata, C. nitida*)	C3	280–365	>2,000	25 ± 5	15	Lat.<10°
Cocoa (*Theobroma cacao*)	C3	270–300	>2,000	25 ± 5	15	300–700
Cinnamon (*Cynnamum zeylanicum*)	C3	365				
Cardamon (*Eletteria cardamomum*)	C3	365				-
Ginger (*Zingiber officinale*)	C3	365				-

Table A20 Countries of Africa: population, surface area, population density, GNP per inhabitant as of 2000 (source: Atlaseco 2006)

Order	Country/territory	No. of inhab. (10^6)	Annual popul. increase (%)	Surface area (10^3 km^2)	Density (inhab. km^{-2})	GNP per inhab. (US \$ year^{-1})
1	South Africa	42	1.8	1,221	34	2,900
2	Algeria	30	2.1	2,382	13	1,400
3	Angola	12	2.9	1,247	10	160
4	Benin	6	2.8	113	3	370
5	Botswana	1.6	1.9	582	2.8	2,940
6	Burkina Faso	11	2.4	2,075	40	230
7	Burundi	6.6	2.0	28	255	100
8	Cameroon	14	2.7	475	31	560
9	Cape Verde	0.42	2.9	4	103	1,190
10	Central Africa	3.5	1.8	623	6	290
11	Comores	0.5	2.5	2.2	238	370
12	Congo (Brazaville)	2.8	2.7	342	8	100
13	Congo (Kinshasa)	48	3.2	2,344	21	590
14	Ivory Coast	14.4	2.0	322	46	700
15	Djibouti	0.64	1.9	23	27	810
16	Egypt	61	1.7	1,001	62	1,480
17	Eritrea	3.9	2.8	118	30	160
18	Ethiopia	61	2.5	1,104	61	100
19	Gabon	1.2	2.4	268	5	3,980
20	Gambia	1.2	2.9	11	122	330
21	Guinea	7	2.3	246	81	400
22	Guinea Bissau	1.2	2.1	36	29	330
23	Equatorial Guinea	0.43	2.6	28	41	140
24	Kenya	29	2.4	583	15	330
25	Lesotho	2.1	2.2	30	51	490
26	Liberia	3.0	2.7	111	31	240
27	Libya	5.3	2.2	1,760	3	6,560
28	Madagascar	14.6	3.1	587	25	240
29	Malawi	10.4	2.5	118	89	150
30	Mali	10.6	2.9	1,240	9	240
31	Mauritius	1.2	1.0	2.0	571	3,730
32	Mauritania	2.5	2.7	1,025	2	340
33	Mayotte	0.13	?	0.374	351	3,030
34	Morocco	28	1.7	711	39	1,200
35	Mozambique	17	1.9	799	22	220
36	Namibia	1.7	2.4	825	2	1,830

Table A20 (continued)

Order	Country/territory	No. of inhab. (10^6)	Annual popul. increase (%)	Surface area (10^3 km^2)	Density (inhab. km^{-2})	GNP per inhab. (US \$ year^{-1})
37	Niger	10	3.4	1,267	8	190
38	Nigeria	121	2.6	924	133	330
39	Uganda	21	2.8	236	89	300
40	Réunion	0.7	1.4	2.5	281	7,600
41	Rwanda	8.1	2.6	26	329	230
42	St Helena	0.07	?	0.12	58	4,920
43	Sao Tomé & Principe	0.141	2.3	1.0	148	290
44	Senegal	9	2.7	197	47	510
45	Seychelles	0.79	1.3	0.454	175	6,710
46	Sierra Leone	4.9	2.2	71.7	68	130
47	Somalia	9.1	3.4	638	14	150
48	Sudan	28.3	2.2	2,505	12	310
49	Swaziland	1	3.0	17	57	1,270
50	Tanzania	32	2.6	945	36	240
51	Tchad	7.3	2.8	1,284	6	210
52	Togo	4.5	2.6	56.6	79	330
53	Tunisia	9.4	1.3	162	60	1,980
54	Zambia	9.7	2.3	753	13	270
55	Zimbabwe	11.7	1.9	391	30	340
Total, arithmetic mean, weighted mean		723,484	2.4	32,103	22.5	1,083

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