CHAPTER FIVE
AIR POLLUTION AND CONTROL

What is Air ?

A continuous, compressible, ideal fluid.

It is a mixture of gases, with numerous suspended particles, some solid and some liquid.

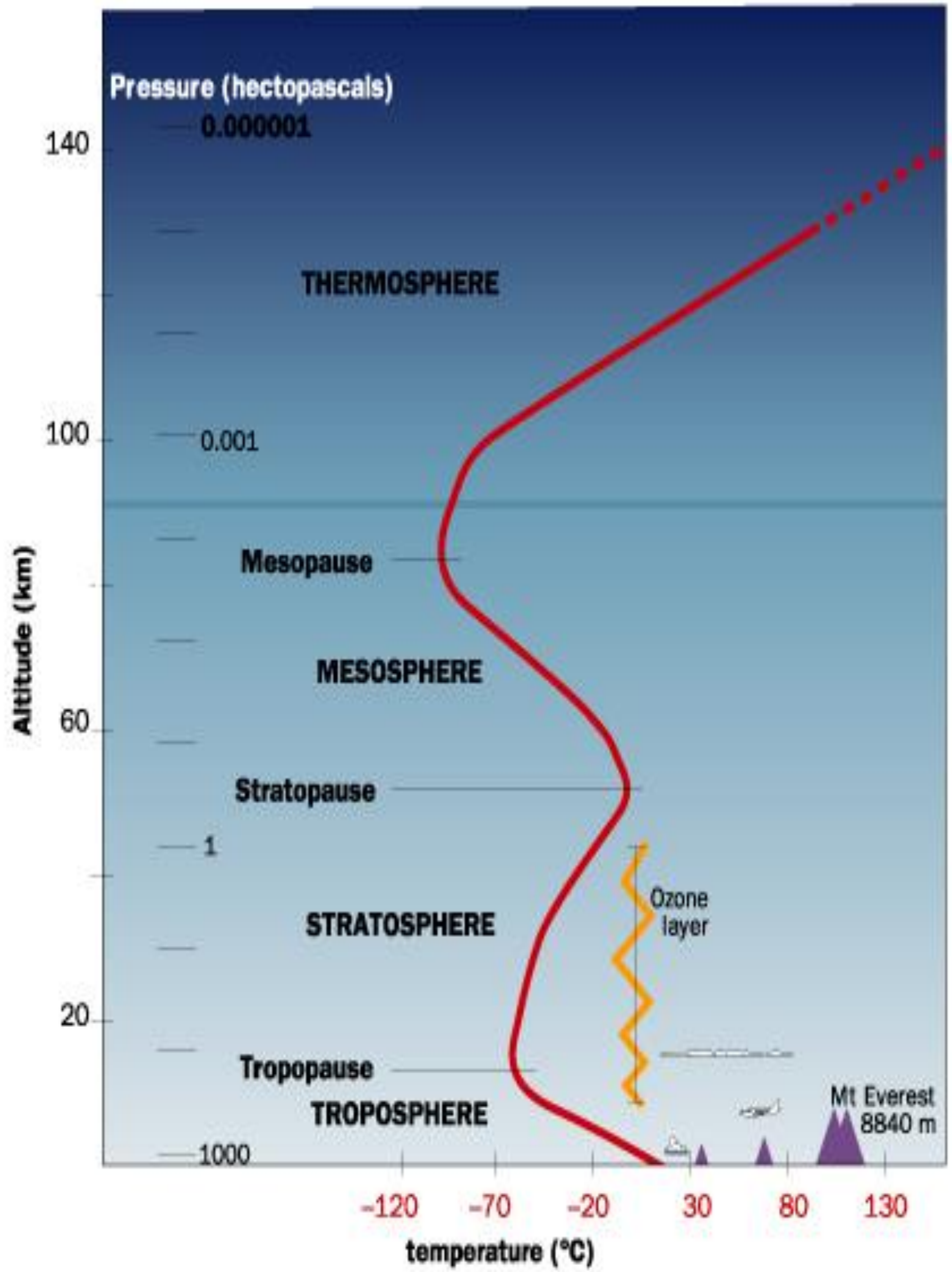
What is Air Pollution ?

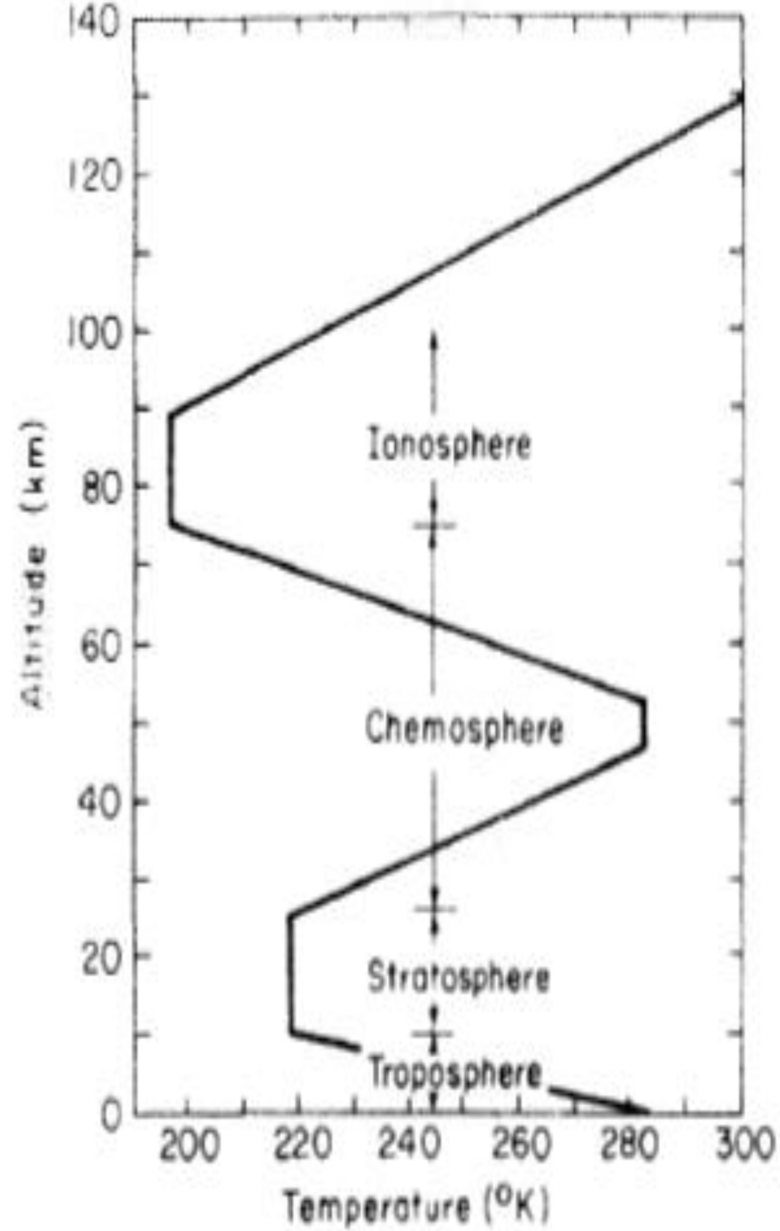
The presence in the air of one or more air contaminants in sufficient quantities, of such characteristics, and of such duration as to be or to threaten to be injurious to human, plant, or animal life or to property, or which reasonably interferes with the comfortable enjoyment of life or property.

How to control pollution?

Emission limits or standards are frequently established rather than ambient air quality standards

Structure of the Atmosphere





Composition of the Atmosphere

Gas	Conc., by volume	Conc., % by volume
Nitrogen	280,000	78.09
Oxygen	209,000	20.95
Argon	9,300	0.93
Carbon dioxide	320	0.032
Neon	18	0.0018
Helium	5.2	0.00052
Methane	1.5	0.00015
Krypton	1.0	0.0001
Hydrogen	0.5	0.00005
Dinitrogen Oxide	0.2	0.00002
Carbon monoxide	0.1	0.00001
Ozone	0.08	0.000008

Concentrations in Gasses: ppm ↔ μg/m³

- At 0 °C and 101.325 kPa, one mole of ideal gas occupies 22.414 L.
- A certain mass of gas will occupy different volume under varying temperature & pressure

$$\text{ppm} = \frac{\dfrac{M_p}{GMW} \times 22.414 \times \dfrac{T_2}{273} \times \dfrac{101.325}{P_2}}{V_a \times 1000}$$

M_p = mass of pollutant (μg)
GMW = gram molecular weight (g)
T_2 = temperature of gas (K)
P_2 = pressure of gas (kPa)
V_a = volume of air sample (m^3)

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P_2 = pressure of gas (kPa)
V_a = volume of air sample (m^3)

<u>Example</u>: a 2.5 m^3 sample of air contains 1.25 g of H_2S. Temperature is 34 °C and atmospheric pressure is 0.98 atm.
- What is the H_2S concentration in terms of ppm?

Basic Calculations

Ideal Gas Law:

$$PV = nRT$$

Dalton's Law of Partial Pressure

$$P_t = P_1 + P_2 + P_3 + \ldots\ldots$$

"The total pressure exerted by a mixture of gases is equal to the sum of the pressures that each type of gas would exert if it alone occupied the container."

Units of Measure

Particulates:

High → Low

mg/m^3 → $\mu g/m^3$ or ppm

Gases:

High → Low

% by Vol. → ppm_v, ppb_v or $\mu g/m^3$

Units of Measure

Converting ppm to μg/m³

GMW = Gram Molecular weight

At standard condition (0ºC and 101.325 kPa)

$$\mu g / m^3 = \frac{ppm \times g\,mol\,mass \times 10^3}{L / mol}$$

$$V_p = \frac{M_p}{GMW} \times 22.414\, L / GM$$

For temperatures (T_2) and pressures (P_2) other than standard conditions

$$22.414 \frac{L}{GM} \times \frac{T_2}{273\,K} \times \frac{101.325\,kPa}{P_2}$$

ppm = Vp/Va

Example

A one-cubic-meter sample of air was found to contain 80 $\mu g/m^3$ of SO_2. The temperature and pressure were 25°C and 103.193 kPa when the air sample was taken. What was the SO_2 concentration in ppm?

Solution

Determine GMW of SO_2

GMW of SO_2 = 32.07 + 2(16.00) = 64.07

Convert temperature to absolute temperature

$25^oC + 273\ K = 298\ K$

$$ppm = \frac{\frac{80\mu g}{64.07} \times 22.414 \times \frac{298}{273} \times \frac{101.325}{103.193}}{1.00m^3 \times 1,000L/m^3}$$

= 0.0300 ppm of SO_2

Air pollution

Sources

- Types of sources
  - Natural
  - Man-made
- Location
- Pollution type
  - Gaseous
  - Particulate
- Strength

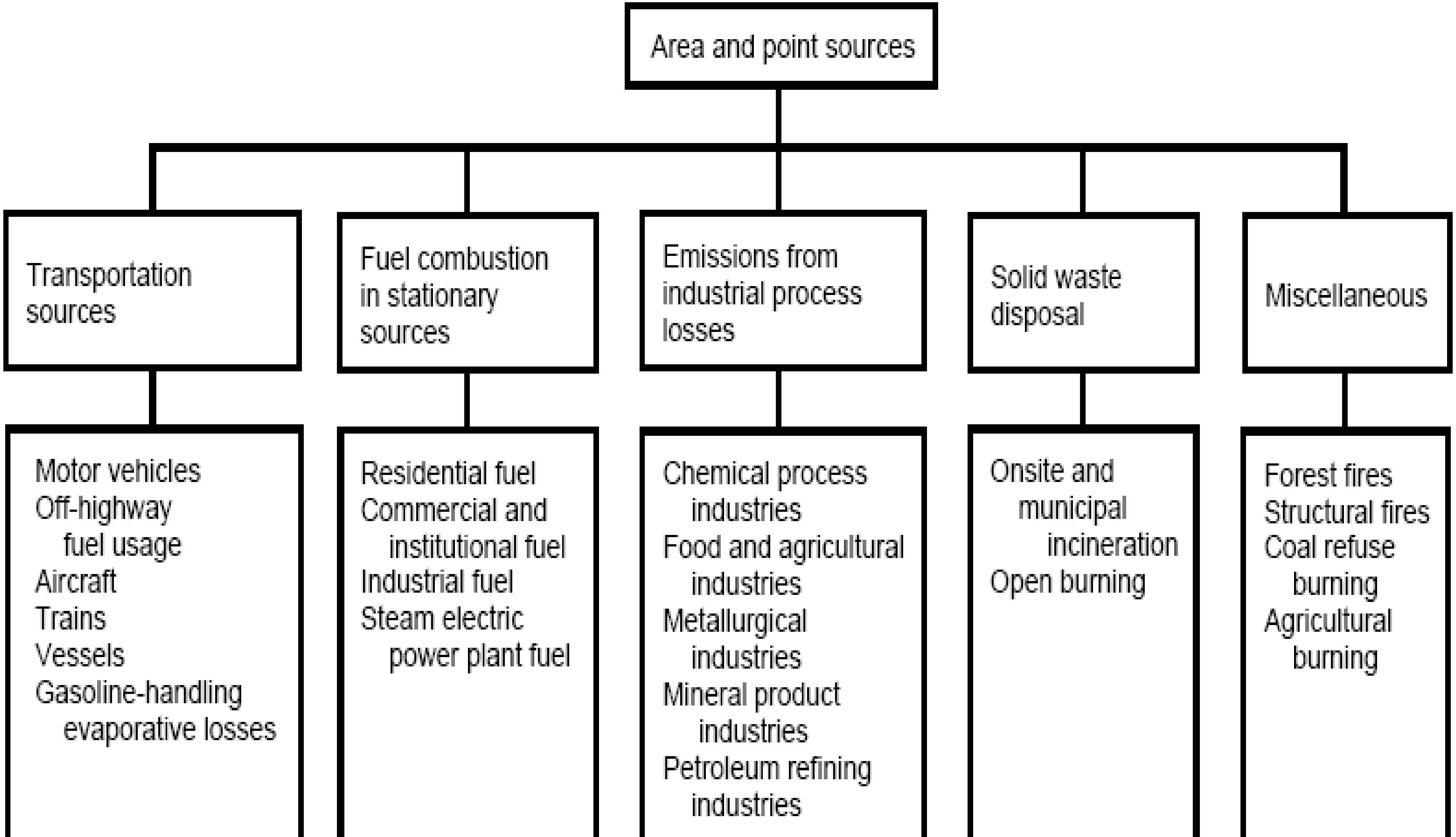
Transport

- Climatology
- Turbulence and diffusion
- Topography

Receptors

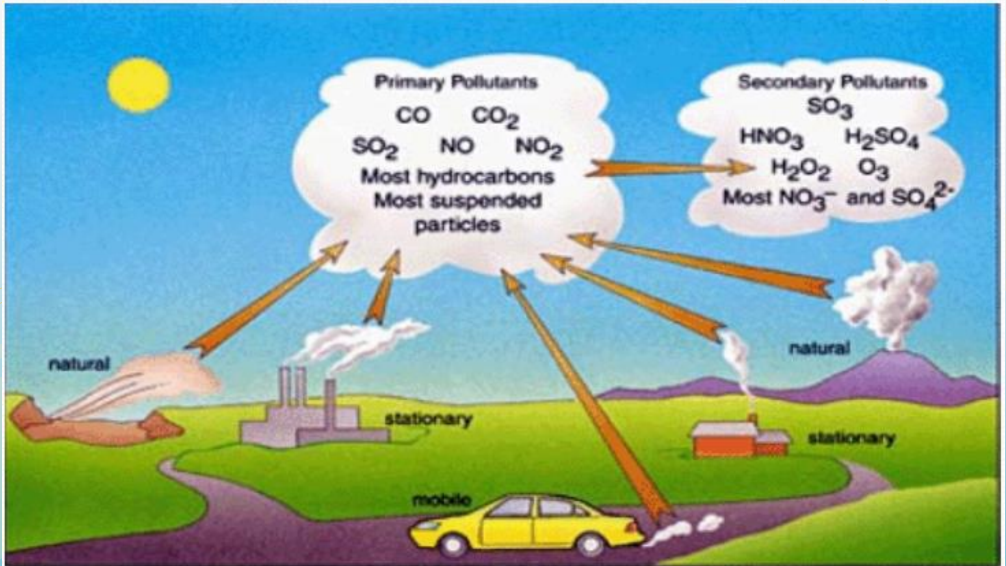
- Man
- Animals
- Plants
- Materials
- visibility

Sources of pollutants



Classification by Origin

- ❑ ***Primary air pollutants*** are pollutants in the atmosphere that exist in the same form as in source emissions.
  - ❑ **carbon monoxide, sulfur dioxide, and total suspended particulates**.
- ❑ ***Secondary air pollutants*** are pollutants formed in the atmosphere as a result of reactions such as hydrolysis, oxidation, and photochemical oxidation.
  - ❑ acidic mists and photochemical oxidants.
- ❑ Air quality management → source control of primary air pollutants.



Classification by state of matter

Major classes	Subclasses	Typical members of subclasses
Particulates	Solid	Dust, smoke, fumes, fly ash
	Liquid	Mist, spray
Gases		
Organic	Hydrocarbons	Hexane, benzene, ethylene,
Inorganic	Aldehydes and ketones	methane, butane, butadiene
	Other organics	Formaldehyde, acetone
	Oxides of carbon	Chlorinated hydrocarbons, alcohols
	Oxides of sulfur	Carbon monoxide, carbon dioxide
	Oxides of nitrogen	Sulfur dioxide, sulfur trioxide
	Other inorganics	Nitrogen dioxide, nitric oxide
		Hydrogen sulfide, hydrogen fluoride, ammonia

Classification by Chemical Composition

- **organic or inorganic**.
  - carbon and hydrogen, and
  - many also contain elements such as oxygen, nitrogen, phosphorus, and sulfur.

  Hydrocarbons are organic compounds containing only carbon and hydrogen

- ***Inorganic materials*** found in contaminated atmosphere
  - carbon monoxide (CO),
  - carbon dioxide (CO_2),
  - carbonates,
  - sulfur oxides,
  - nitrogen oxides,
  - ozone,
  - hydrogen fluoride, and
  - hydrogen chloride.

Air Pollution Regulations

The Clean Air Act established two types of air quality standards.

- ***Primary standards*** set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children, and the elderly.
- ***Secondary standards*** set limits to protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings.

Criteria Air Pollutants

- The Clean Air Act characterizes **five primary pollutants** and **one secondary pollutant** as **criteria air pollutants**.
- **Primary criteria pollutants** include the gases
  - *sulfur dioxide* (SO_2),
  - *nitrogen oxides* (NO_x),
  - *carbon monoxide* (CO)
  - solid or liquid *particulates* (smaller than 10 µm, PM-10) and
  - *particulate lead.*
- **Secondary criteria pollutant** *Ozone* (O_3) is the regulated under Clean Air Act.

The six so-called "Criteria Pollutants"

Criteria Pollutant	Primary / Secondary	Source(s)	Effect(s)
CO *Carbon Monoxide*	P	Incomplete combustion	Impairs oxygen-carrying capacity of blood
NO_2 *Nitrogen Dioxide*	S	From NO in combustion	Respiratory irritant Visibility impairment Acid deposition
O_3 *Ozone*	mostly S	From NO and NO_2	Coughing, Chest pain Lung damage
SO_2 *Sulfur Dioxide*	P	Sulfur in fuels, esp. coal	Lung irritant Acid deposition
PM_{10} and $PM_{2.5}$ *Particulate Matter*	both P and S	Industrial combustion Other industrial activities	Visibility impairment Respiratory impairment
Pb *Lead*	P	Industrial processes Lead pipes, solder	Blood poisoning Kidney damage Mental retardation

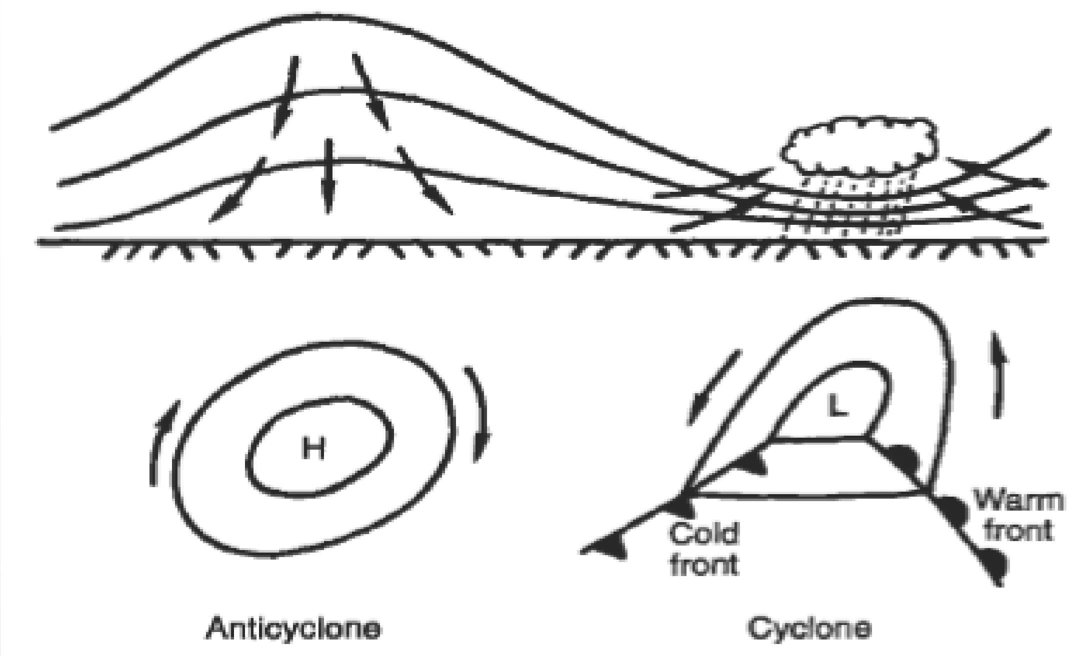
Allowable Limit

	Concentration in ambient air in microgram/m³			
Pollutant	*Time weighted average*	*Industrial area*	*Residential, rural and other areas*	*Sensitive area*
Sulphur dioxide	Annual Avg.* 24 hours**	80 120	60 80	15 30
Oxides of nitrogen as NO_2	Annual Avg. 24 hours	80 120	60 80	15 30
Suspended particulate matter	Annual Avg. 24 hours	360 500	140 200	70 100
Respirable particulate matter (size less than 10 mm)	Annual Avg. 24 hours	120 150	60 100	50 75
Lead(Pb)	Annual Avg. 24 hours	1.0 1.5	0.75 1.0	0.5 0.75
Carbon monoxide	8 hours 1 hours	5.0 10.0	2.0 4.0	1.0 2.0

Transport of pollutants

Basic Metrology

- Air movement is caused by solar radiation and the irregular shape of the earth and its surface, which causes unequal absorption of heat by the earth's surface and atmosphere.
- Low- and high-pressure systems, commonly called cyclones and Anticyclones



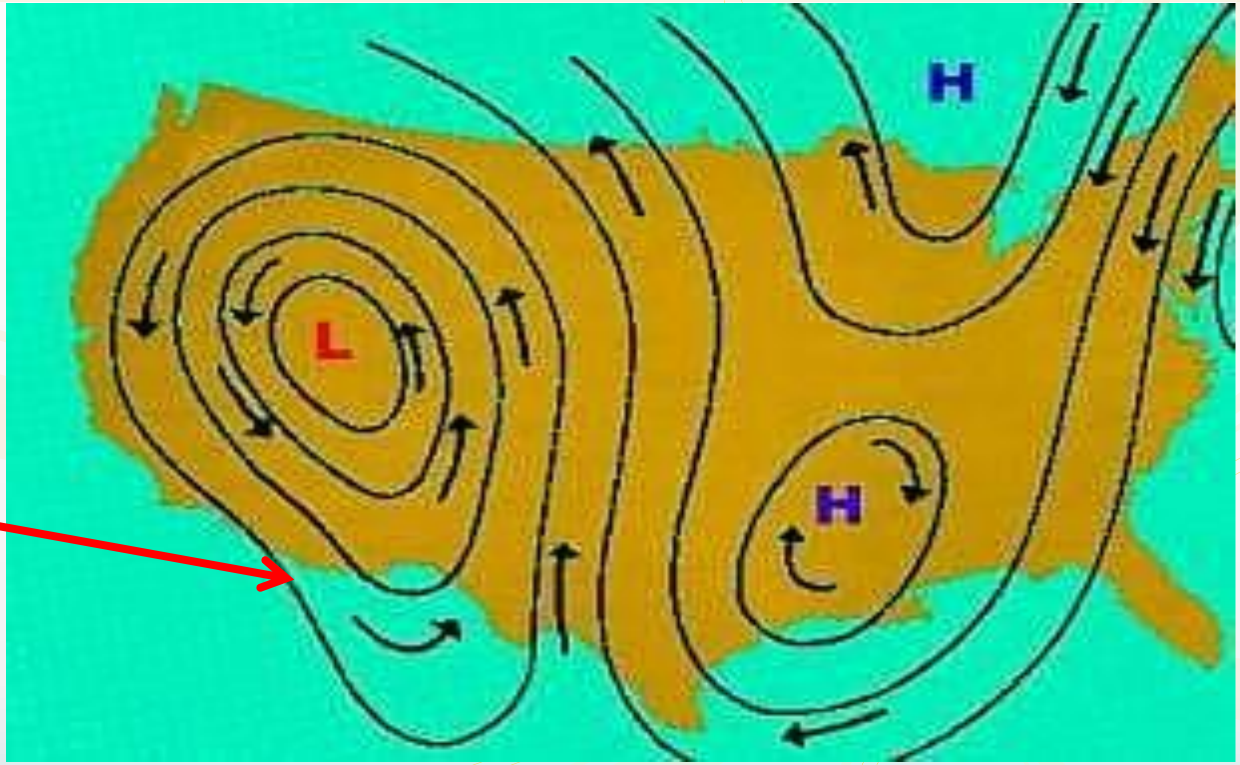
Good weather

Foul weather
Tornadoes
Hurricanes

Highs and lows

- Air pressure is the weight of air resting on a given area of the Earth's surface
- Low pressure occurs when air is warm, expands, gets lighter and rises.
- High pressure occurs when air gets cold, contracts, becomes heavier (denser) and sinks (falls).
- Air flows from regions of high pressure (highs) to low pressure (lows) as it tries to equalize the difference between the two, known as the pressure gradient.
- This movement of air is wind.

Highs and lows



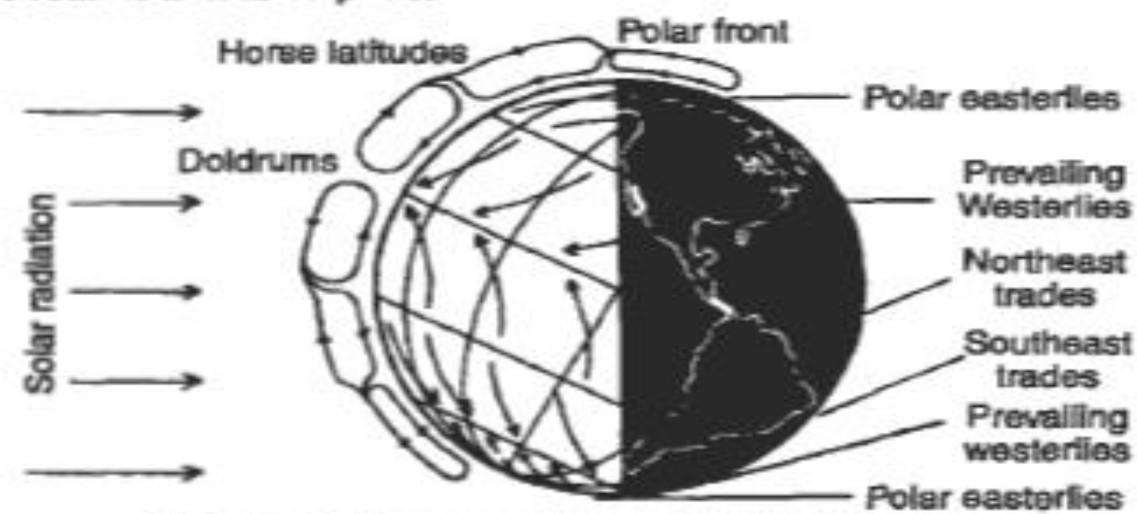
isobars

The greater the difference between the high and the low pressure, the greater the wind speed.

The closer the isobars on a weather map are together, the stronger the winds.

Air Pollution Meteorology

A. If the earth did not turn, the air would circulate in a fixed pattern



B. The earth turns, creating variable wind patterns

Turbulence

Turbulence: Atmospheric turbulence is characterized by different sizes of eddies, which are primarily responsible for diluting and transporting pollutants injected in to the atmosphere.

Mechanical Turbulence

Caused by air moving over and around structures/ vegetation

Mechanical turbulence serves to enhance dispersion of pollutants by increasing the eddies around building edges

Affected by surface roughness

- Thermal Turbulence

Caused by heating/cooling of the Earth's surface

Flows are typically vertical

Rising density current

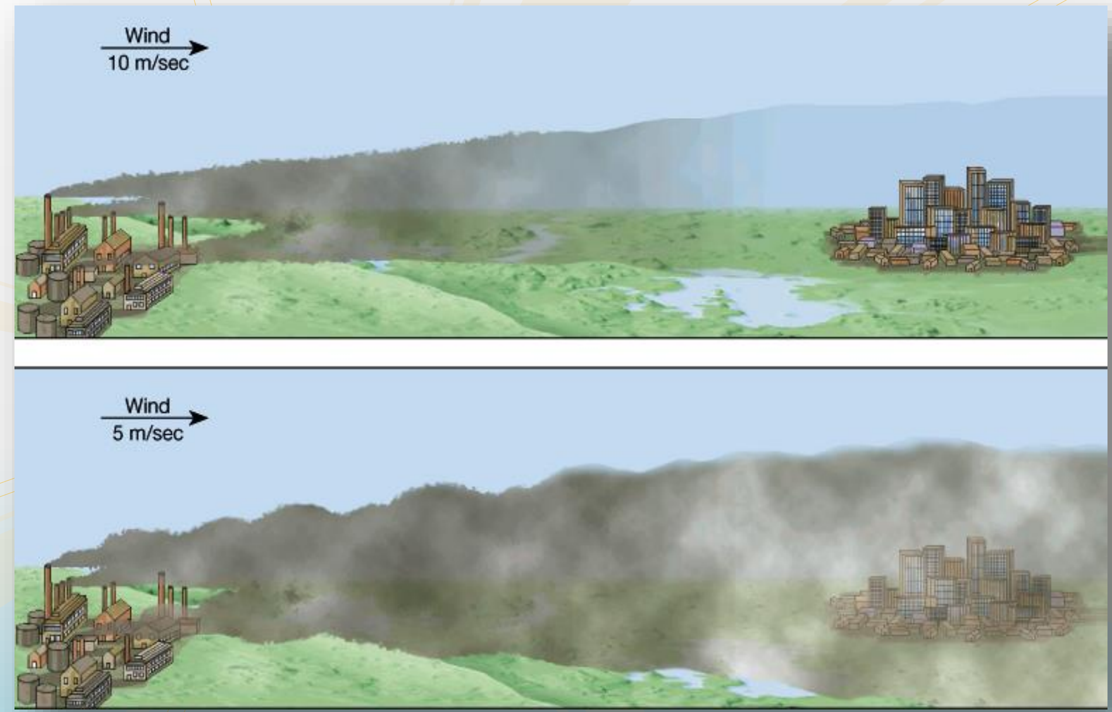
Sinking density current

Transport of pollutants

Horizontal Air Movement

The direction of the wind and its speed, have a significant effect on movement and dilution of air pollutants.

In the presence of an elevated inversion, the surface wind speed and direction may be the predominant dispersal process.

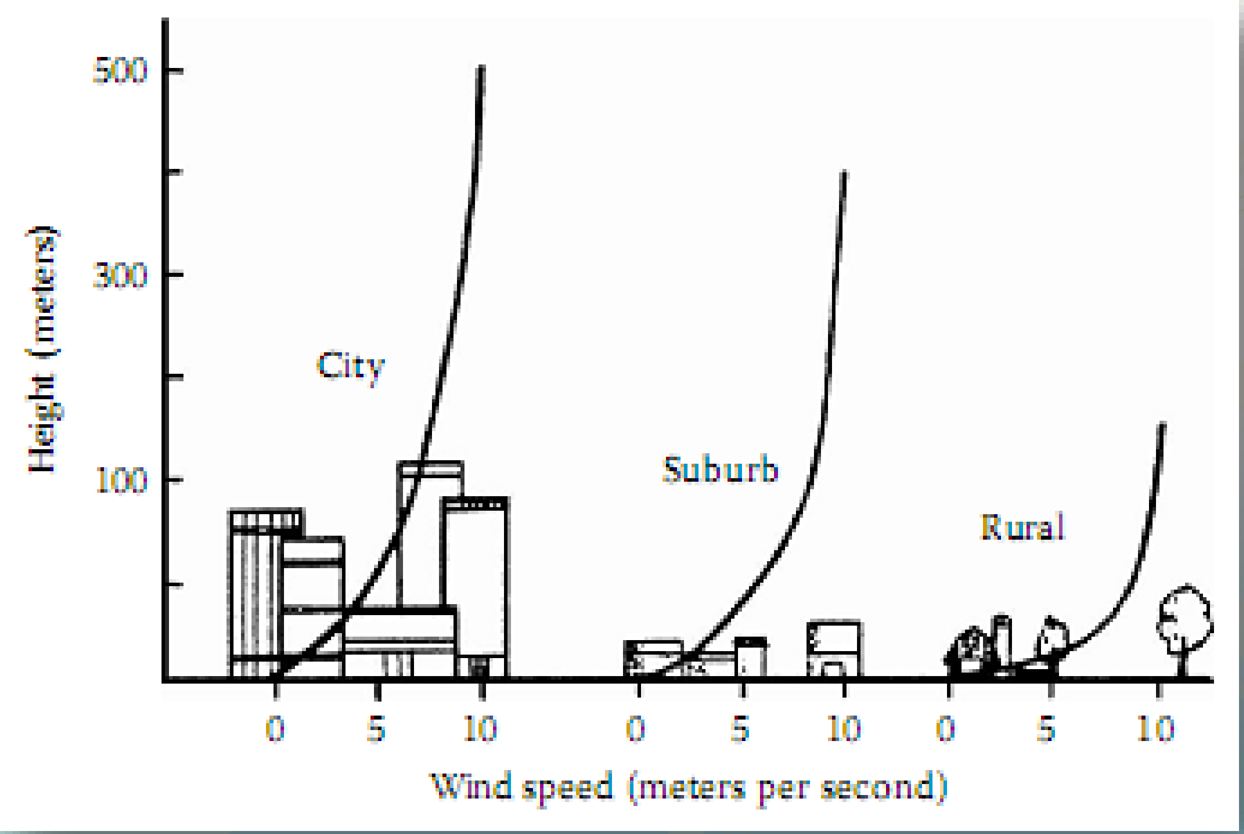


- Strong wind-provide better mixing both horizontally and vertically

- Doubling of the wind speed decreases pollutant levels by 50%

Terrain Effects

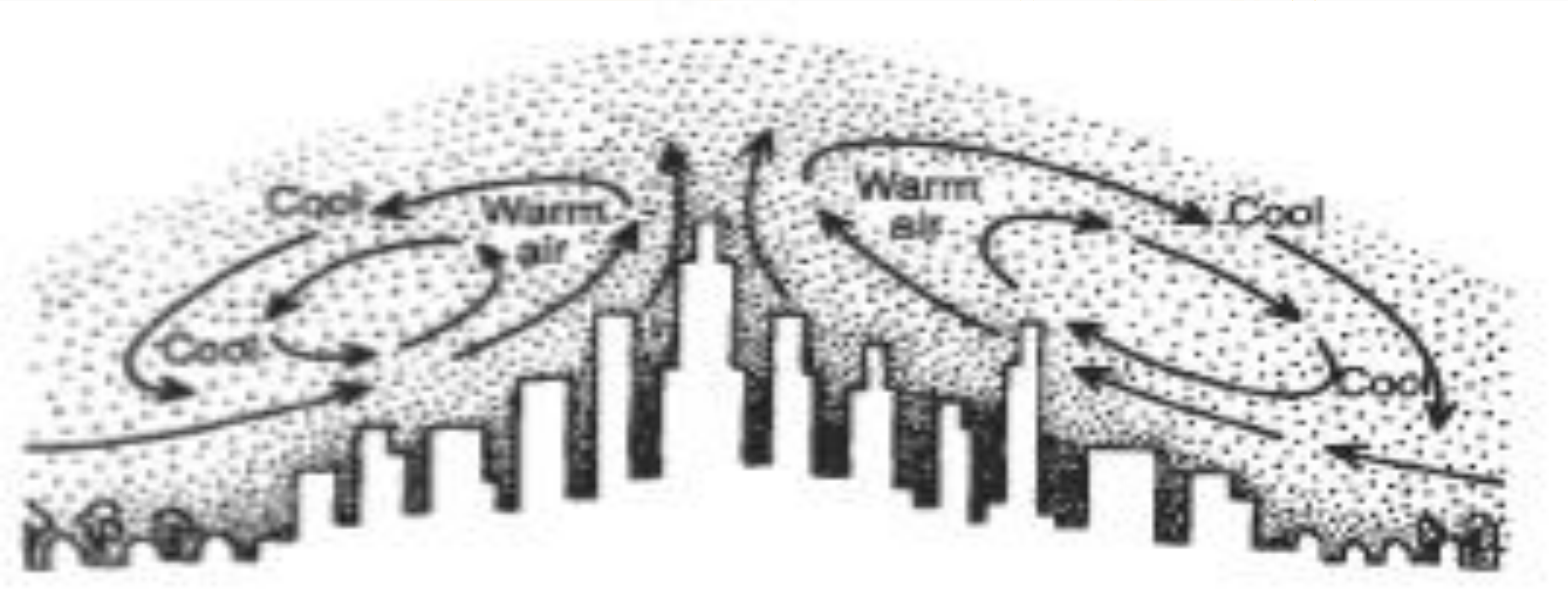
Terrain effects, or surface roughness and built up areas, may significantly affect the speed of the wind across a given geographic location.



Terrain Effects

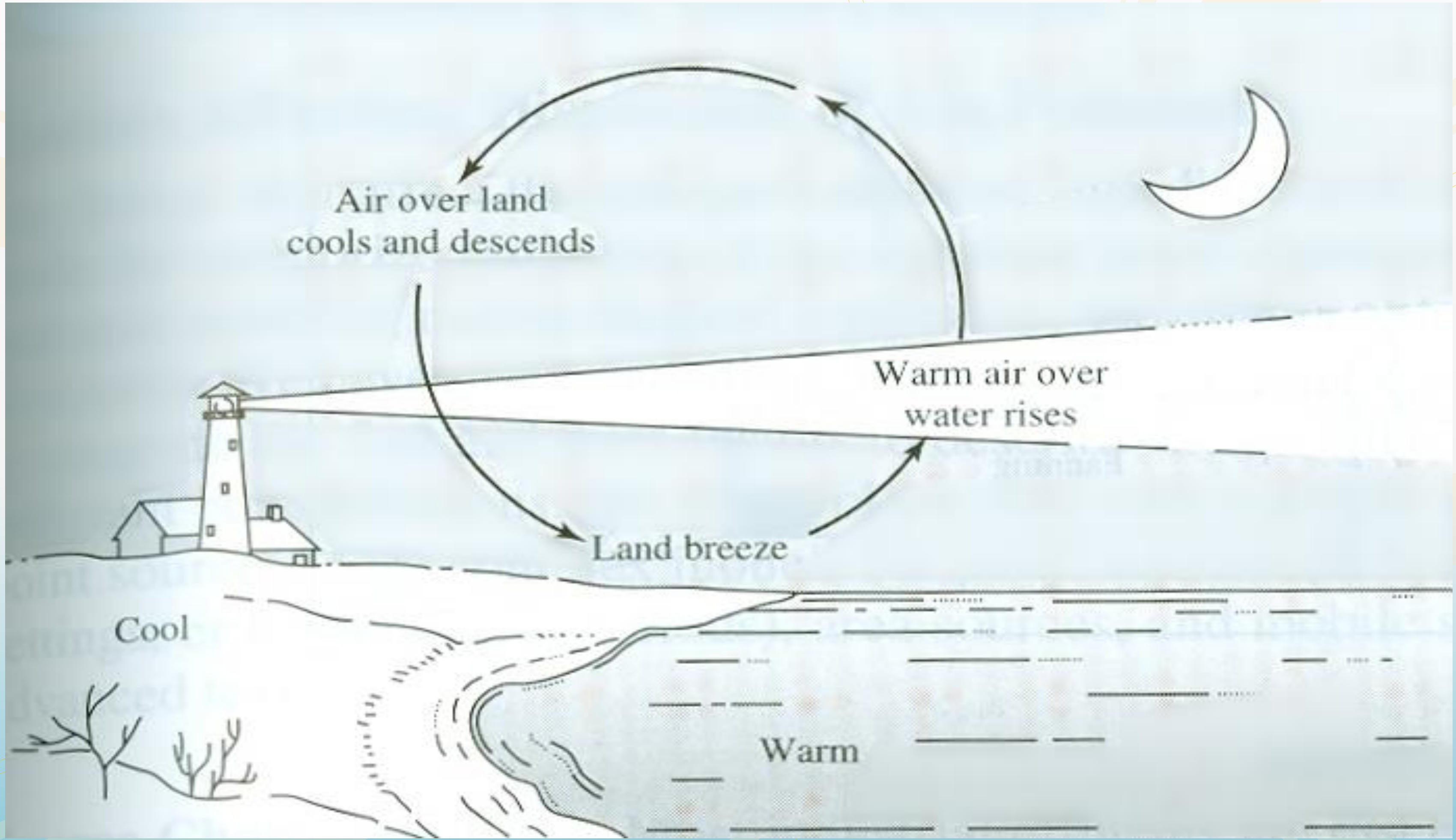
In cities, brick and concrete buildings absorb heat during the day and radiate it at night, creating Heat Islands

- Absorbs or radiates heat at a greater rate than the surrounding
- The atmosphere becomes more stable



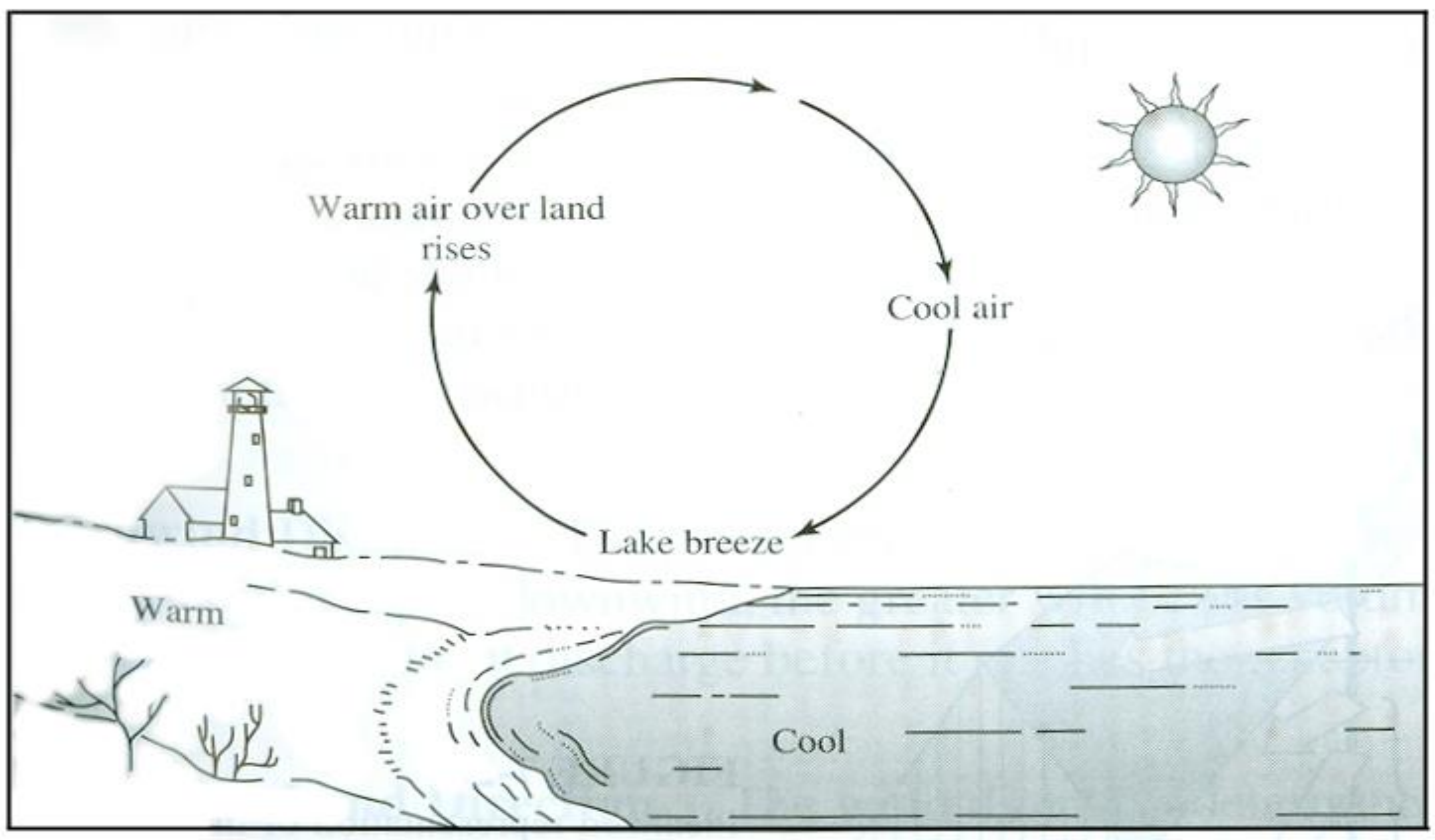
Terrain Effects-Land Breath

- During night , the land cools more rapidly than the water.



Terrain Effects-Sea Breath

- During the morning the land heats faster than water.
- sea breeze (cooler) make the air mass in coastal areas more stable – trap air pollutant in the city.



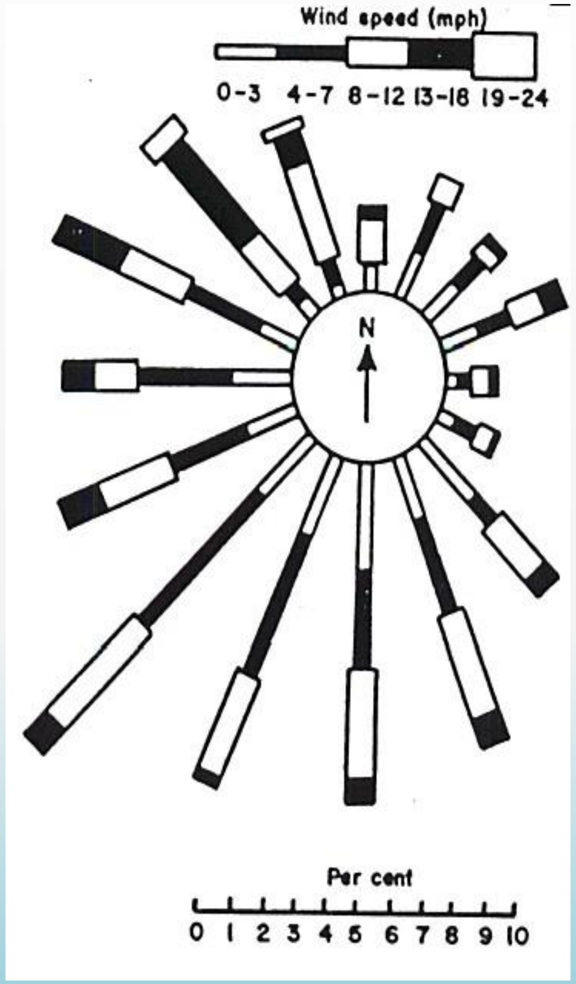
Wind Rose

Wind velocity data are plotted as a wind rose, a graphic picture of wind velocities and the direction from which the wind came.

The three features of a wind rose are:

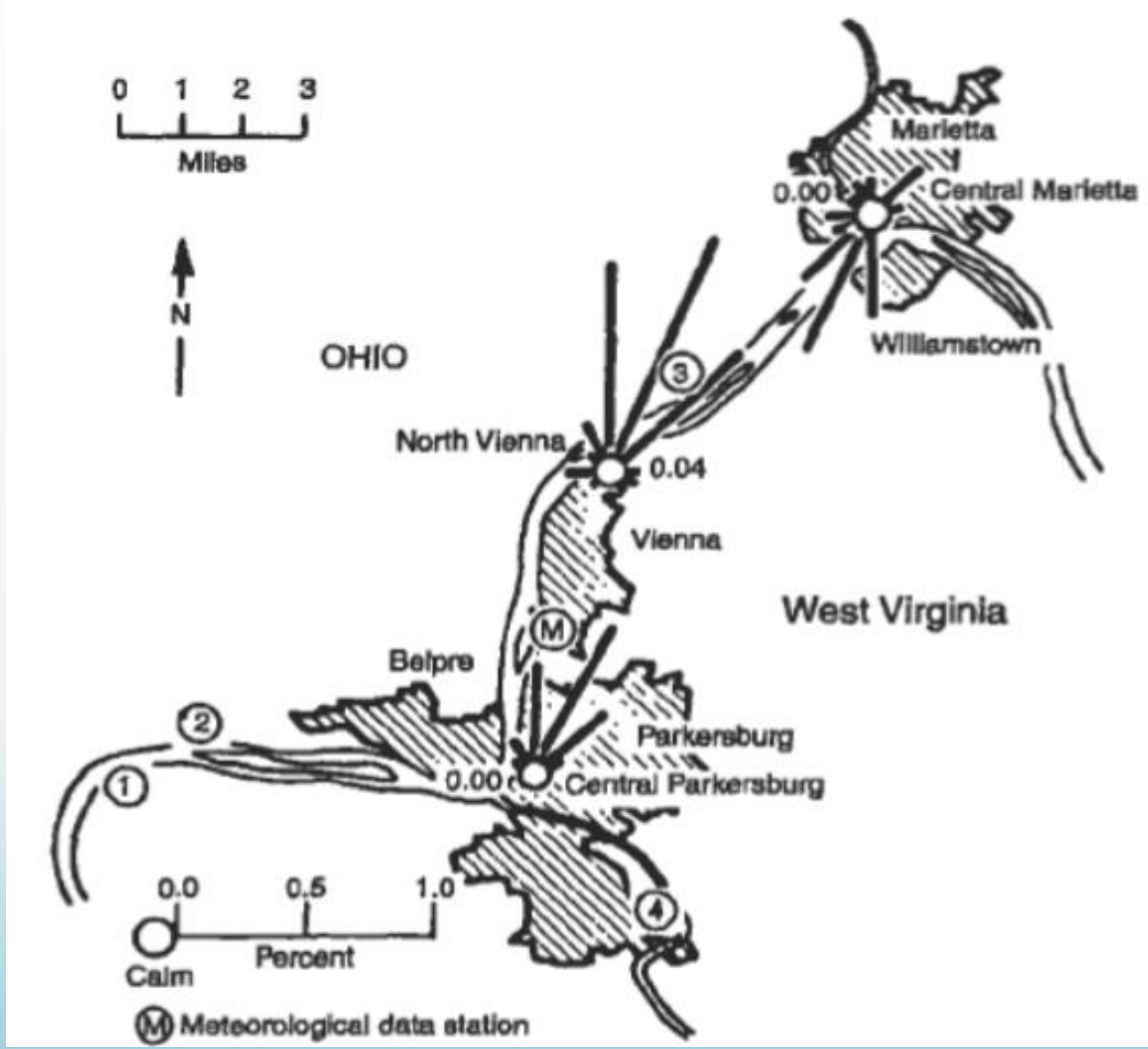
1. The orientation of each segment, which shows the direction from which the wind came
2. The width of each segment, which is proportional to the wind speed
3. The length of each segment, which is proportional to the percent of time that wind at that particular speed was coming from that particular direction.

The wind rose in Fig. shows that the prevailing winds were from the southwest.



Wind rose

- Helps to identify source of pollutant when the air contamination level exceeds a given amount.
- The four chemical plants are the suspected sources of pollution, but the roses clearly point to Plant 3, identifying it as the primary culprit.



Vertical motion

- As the horizontal motion, vertical motion is equally important – determine how much air for pollutant dispersal
- The movement of air in the vertical dimension is enhanced by large temperature differences. The greater the temperature difference between the surface and higher, the more vigorous the convective and turbulent mixing of the atmosphere will be.
- Likewise, the greater the area of the vertical column over which turbulent mixing occurs, the more effective the dispersion process will be.

A parcel of air is relatively well-defined body of air which is self-contained & does not mix with surrounding air

As a parcel of air in the earth's atmosphere rises through the atmosphere, it experiences decreasing pressure and thus expands.

This expansion lowers the temperature of the air parcel, and therefore the air cools as it rises.

In short, warm air rises and cools, while cool air descends and warms

If parcel's temperature >surrounding, it will rise. If cooler, it will descend.

If temperature of parcel = surrounding, parcel will neither rise or descend (unless influenced by wind)

Lapse rate: The rate at which air temperature changes with height.

- Actual lapse rate varies approximately from – 6 to -7 oC per km in the troposphere.
- Negative lapse rate: temperature decrease with height
- Positive lapse rate: temperature increase with height

Dry adiabatic lapse rate:

The rate at which dry air cools as it rises is called the dry adiabatic lapse rate

and is independent of the ambient air temperature.

Adiabatic Expansion and Compression

- An adiabatic process is one that takes place with no addition or removal of heat and with sufficient slowness, so that the gas can be considered to be in equilibrium at all times.
- With the first principle of thermodynamics we have:

Heat added To gas = Increase in thermal energy + External work done by or on the gas

zero (adiabatic process)

$$= c_p dT - \frac{1}{\rho} dP$$

From Hydrostatic Equation: $\frac{dp}{dz} = -\rho . g$

$$\Rightarrow c_p dT = \frac{1}{\rho} dP = -g dZ$$

$$\Rightarrow \frac{dT}{dZ} = -\frac{g}{c_p}$$

Lapse Rate

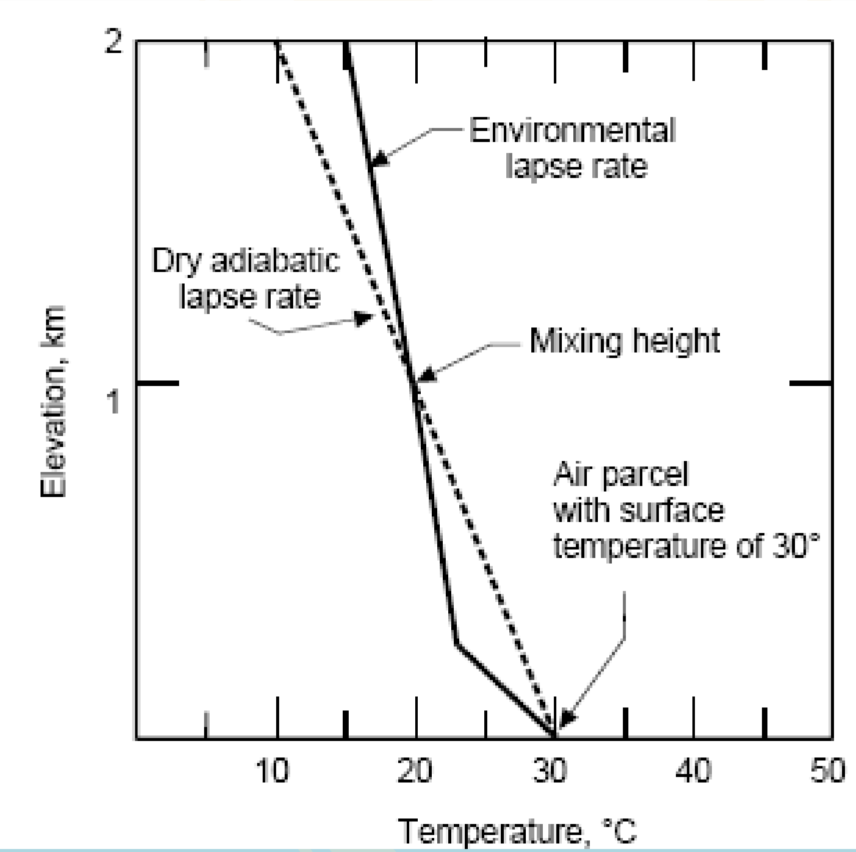
$$\left(\frac{dT}{dz}\right)_{\text{adiabatic, perfect gas}} = -\frac{g}{c_p} = \frac{9.81\,\mathrm{m/s^2}}{1.003\,\mathrm{kJ/kg.K}}$$

$$= -0.00978\frac{K}{m} = -9.78\frac{°C}{km} \approx -10\frac{°C}{km}$$

- The dry adiabatic lapse rate is calculated from basic physical principles and thermodynamics as

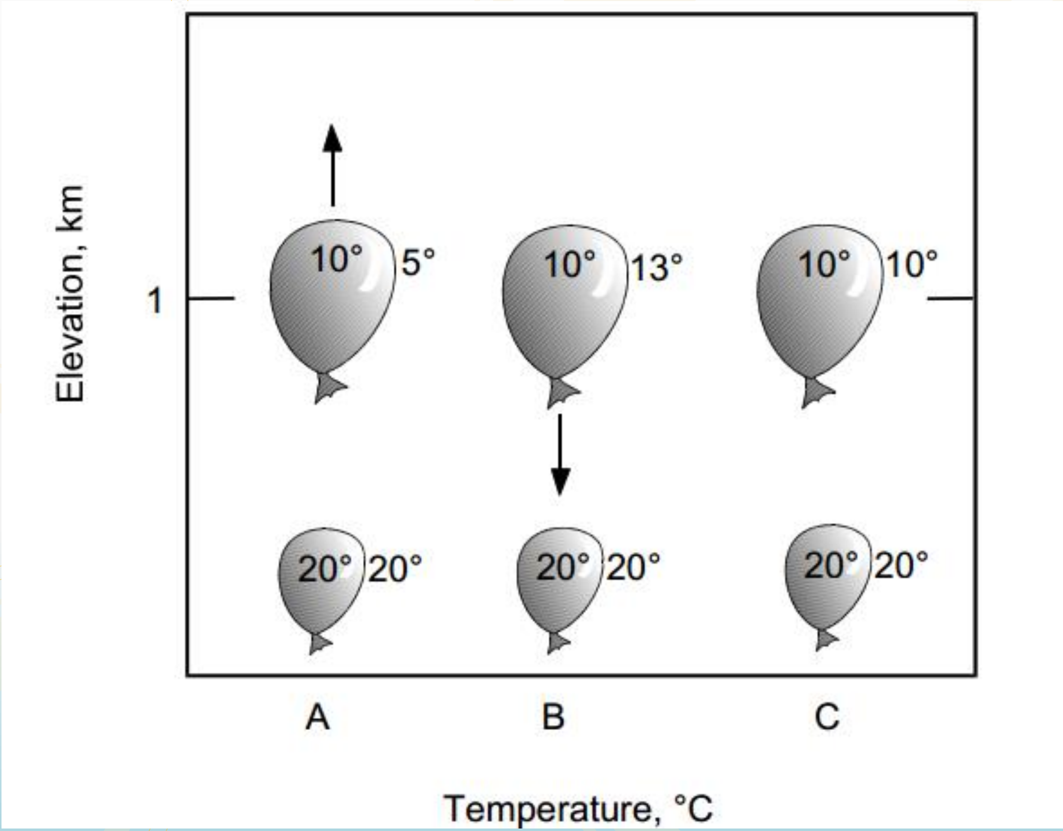
  dT/dz = -1.00oC/100 m

- The actual measured rate at which air cools as it rises is called the ambient or prevailing lapse rate.
- The elevation the air parcel cooling at the dry adiabatic lapse rate intersects the ambient temperature profile "line" is known as the 'mixing height'.



MIXING HEIGHT

- Mixing height is the maximum level of ascendance. There is no corresponding upward flow above the mixing height.
- The air below the mixing height is the mixing layer – the deeper the layer, the greater volume of air into which pollutant can be dispersed.
- Thermal buoyancy determines depth of convective mixing depth



Example

A stack loo m tall emits a plume whose temperature is 20°C. The temperature at the ground is 19°C. The ambient lapse rate is -4.5 °C /km up to an altitude of 200 m. Above this the ambient lapse rate is +20°C /km. Assuming perfectly adiabatic conditions, how high will the plume rise

Solution

Assuming the mixing height is greater than 200

Ambient temperature= Parcel temperature

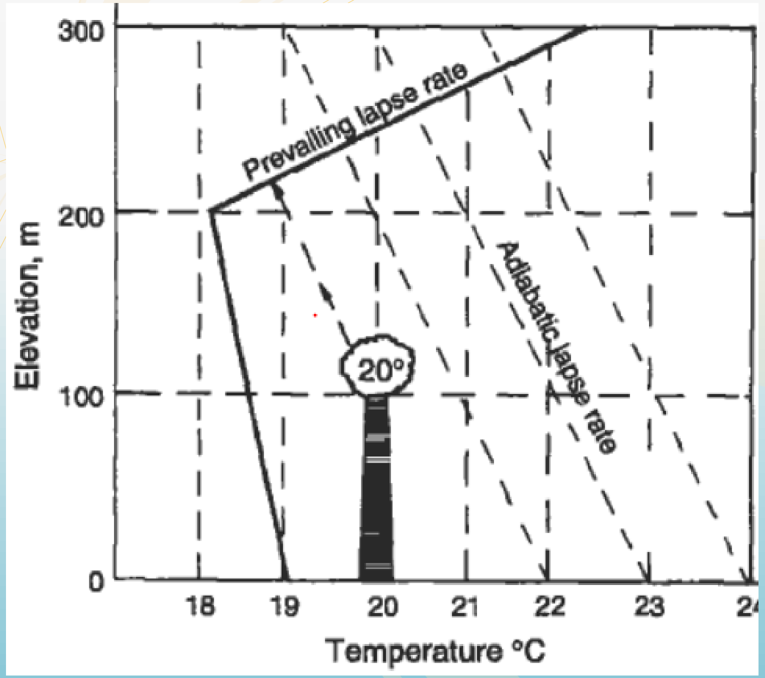
$$19 - \frac{(4.5*200)}{1000} + \frac{(20*(H-200))}{1000} = 20 - \frac{(1*(H-100))}{100}$$

$$14.1+.02H=21-.01H$$

0.03H=6.9

H=230

(as assumed H is greater than 200m)



Stability

The relationships between the ambient lapse rate and the dry adiabatic lapse rate essentially determine the stability of the air and the speed with which pollutants will disperse.

Stability is the tendency of the atmosphere to resist or enhance vertical motion/turbulence.

Three categories of stability:

- ➔Neutral
- ➔Unstable
- ➔Stable

Stability and Lapse rate

Superadiabatic, Strong, Unstable

Temperature Reduction > 1 °C/100m

Subadiabatic, Weak, Stable

Temperature Reduction < 1 °C/100m

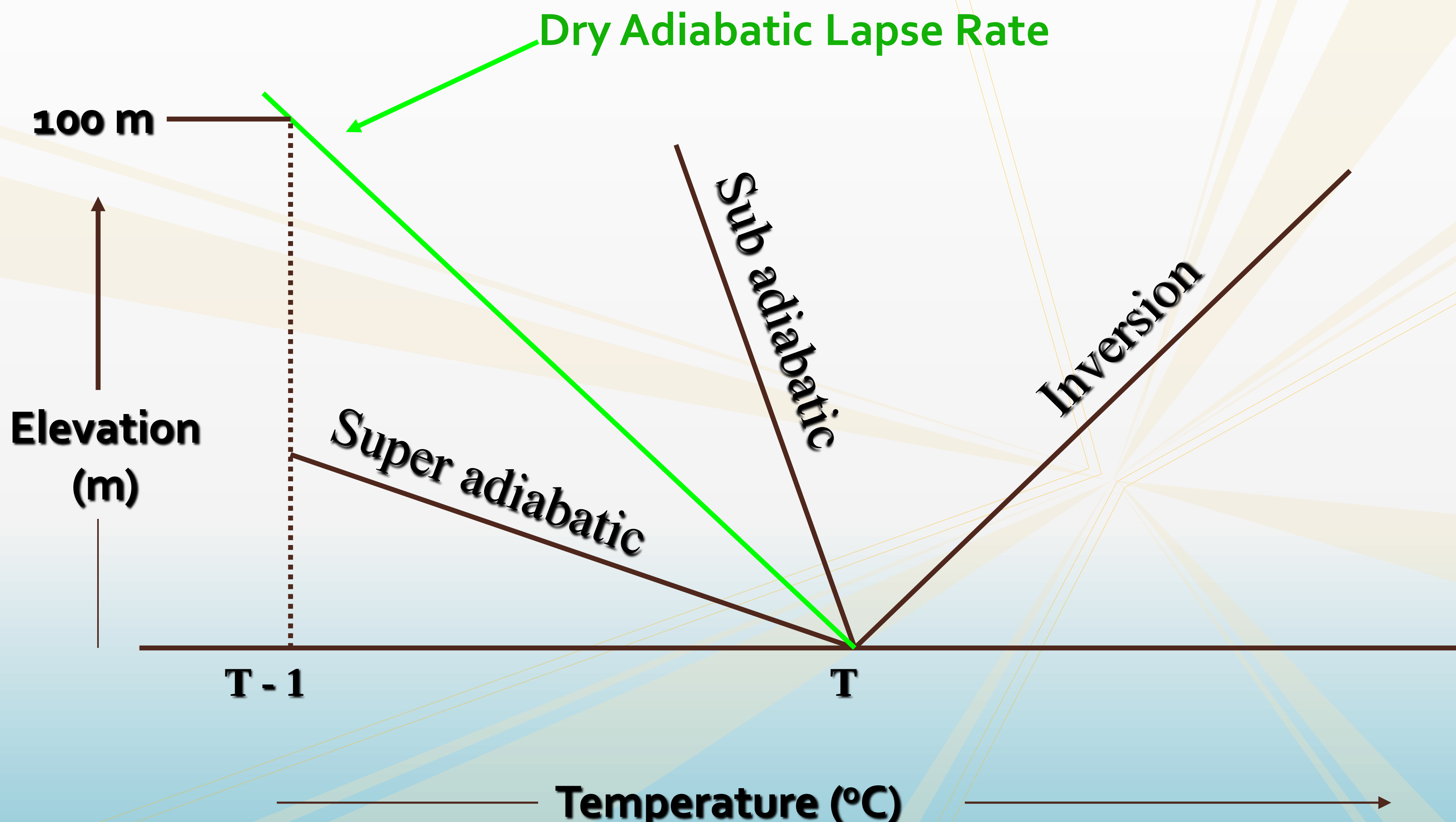
Neutral

Temperature Reduction = 1 °C/100m

Inversion (Extreme Subadiabatic)

Temperature Increase with Height

Lapse Rates



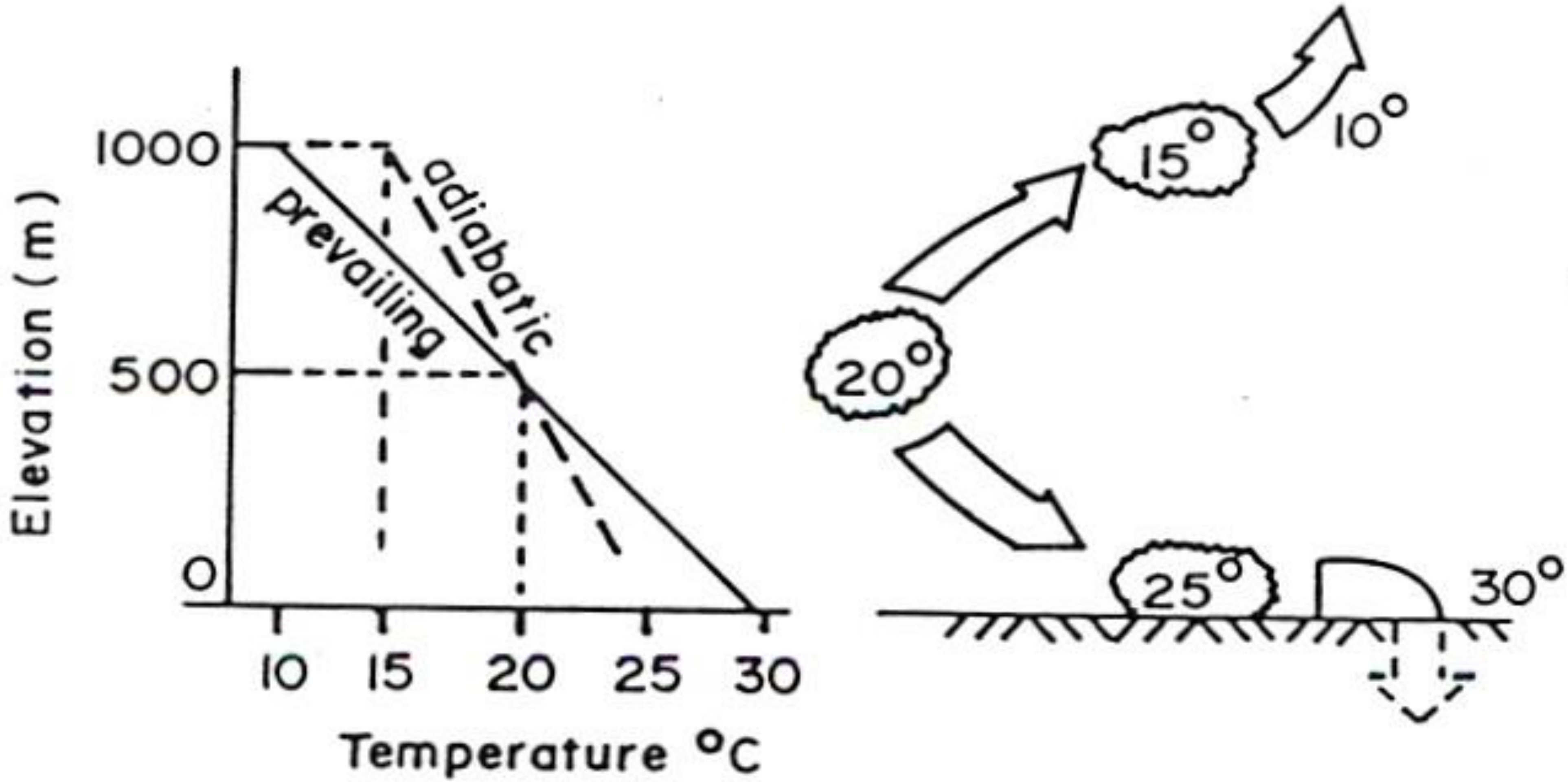
Dry Adiabatic Lapse Rate
100 m
Elevation (m)
Super adiabatic
Sub adiabatic
Inversion
T - 1
T
Temperature (ºC)

Atmosphere stability

➢ Unstable

- Assumed that surrounding has a lapse rate greater than adiabatic lapse rate (cooling at more than –9.8°C/1000m).->super-adiabatic lapse rate
- Develop on sunny days with low wind speeds where strong insulation is present, which is characterized by intense vertical mixing
- If air parcel rises, it follows adiabatic lapse rate. It become hotter as compared with the surrounding air. It tends to move upward away from its original position.
- If air parcel is forced to move downward, it follows the adiabatic lapse rate. It become cooler as compared with the surrounding air. It tends to move downwards away from its original position.

Super-adiabatic – Unstable



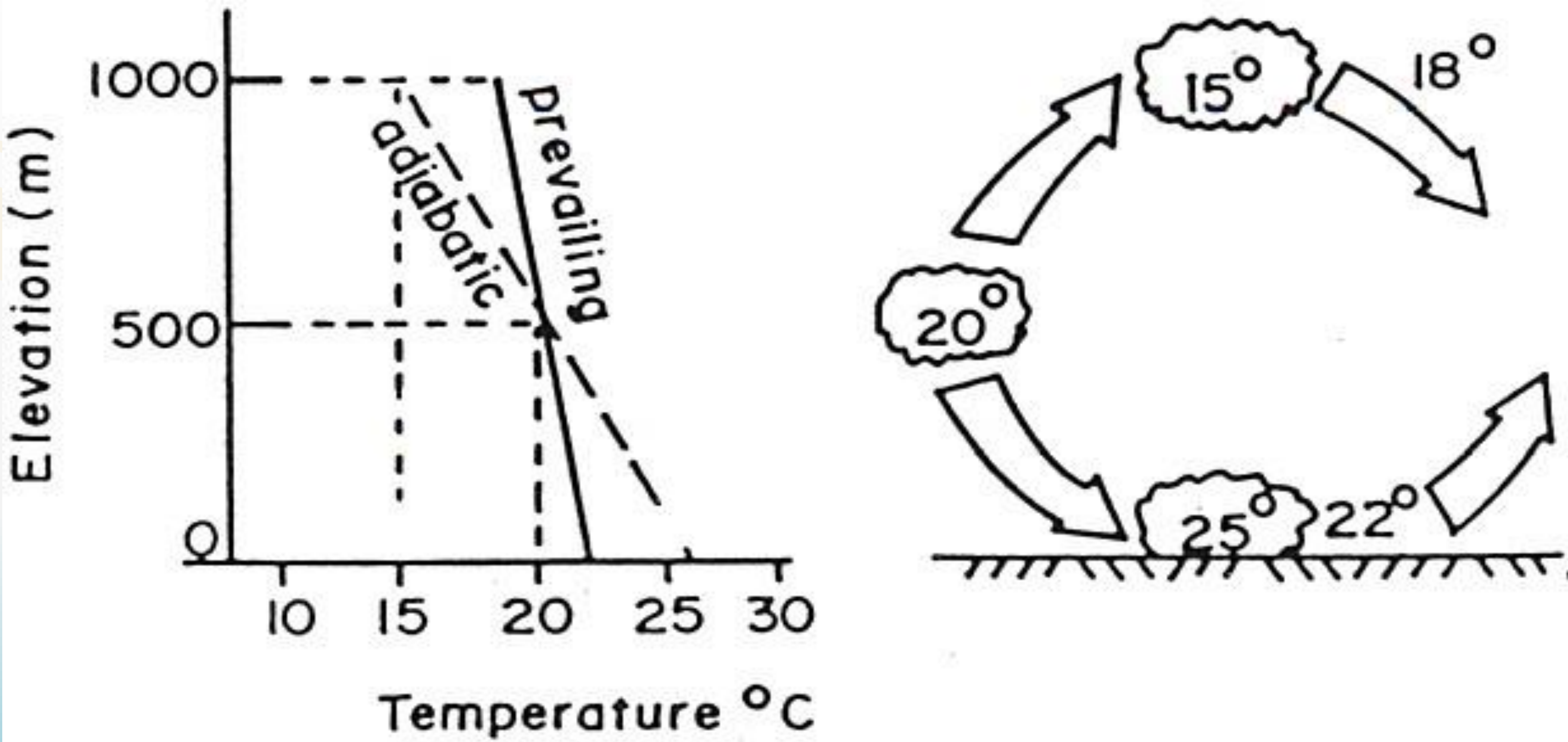
A. Superadiabatic conditions (unstable)

Subadiabatic – Stable

➢ Stable

- When the environmental lapse rate is less than the adiabatic lapse rate (cools at less than 9.8^{o}C/1000m), the air parcel is stable and resists vertical motion. This is a sub-adiabatic lapse rate.
- Air lifted vertically will remain cooler, and therefore more dense than the surrounding air.
- Once the lifting force is removed, the air that has been lifted will return to its original position.
- Stable conditions occur at night when there is little or no wind.

Subadiabatic – Stable



B. Subadiabatic conditions (stable)

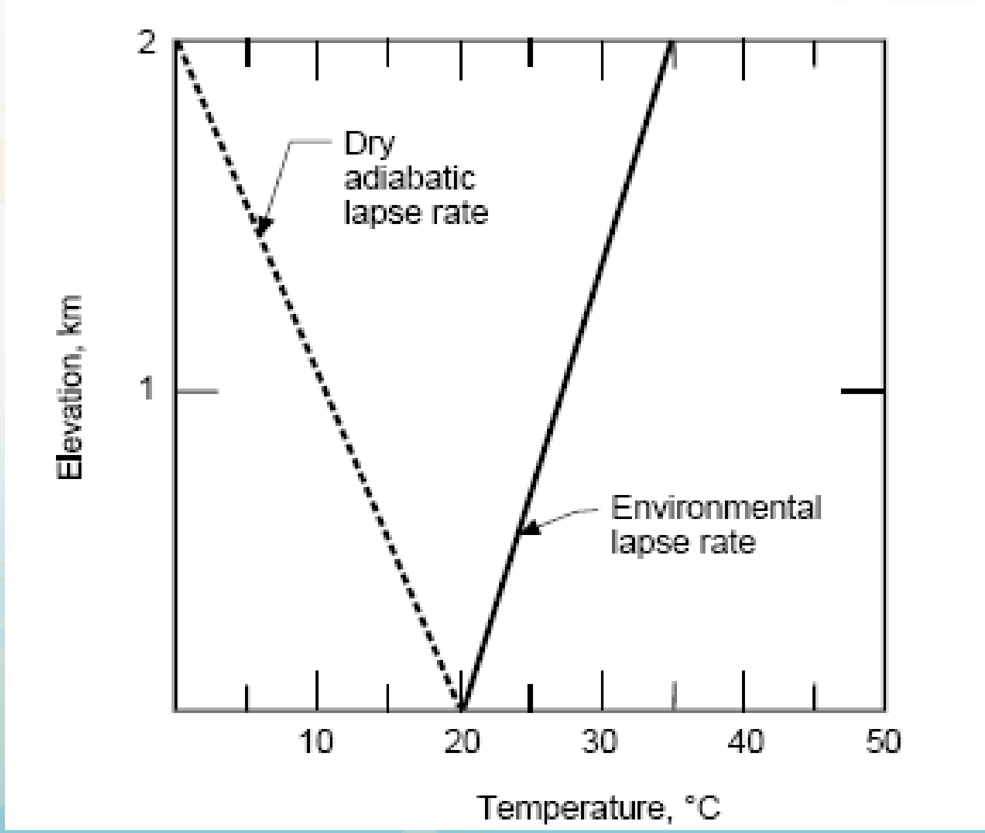
Atmosphere stability

➢ Inversion

- An inversion occurs when air temperature increases with altitude.
- Plumes emitted into air layers that are experiencing an inversion (inverted layer) do not disperse very much as they are transported with the wind.
- Plumes that are emitted above or below an inverted layer do not penetrate that layer, rather these plumes are trapped either above or below that inverted layer.
- High concentrations of air pollutants are often associated with inversions since they **inhibit plume dispersion**.

Inversion

When an inversion exists and winds are light, diffusion is inhibited and high pollution concentrations are to be expected in areas where pollution sources exist.



Example

Given the following temperature and elevation data, determine the stability of the atmosphere.

Elevation, m	Temperature, °C
2.00	14.35
324.00	11.13

Solution

Determine the existing lapse rate

$$\frac{\Delta T}{\Delta Z} = \frac{T_2 - T_1}{Z_2 - Z_1} = \frac{11.13 - 14.35}{324.00 - 2.00} = -0.0100^o C / m = -1.00^0 C / 100m$$

➔ The atmospheric stability is neutral

Stability and Plume Behavior

- The combination of vertical air movement and horizontal air flow influences the behaviour of plumes from point sources (stacks).

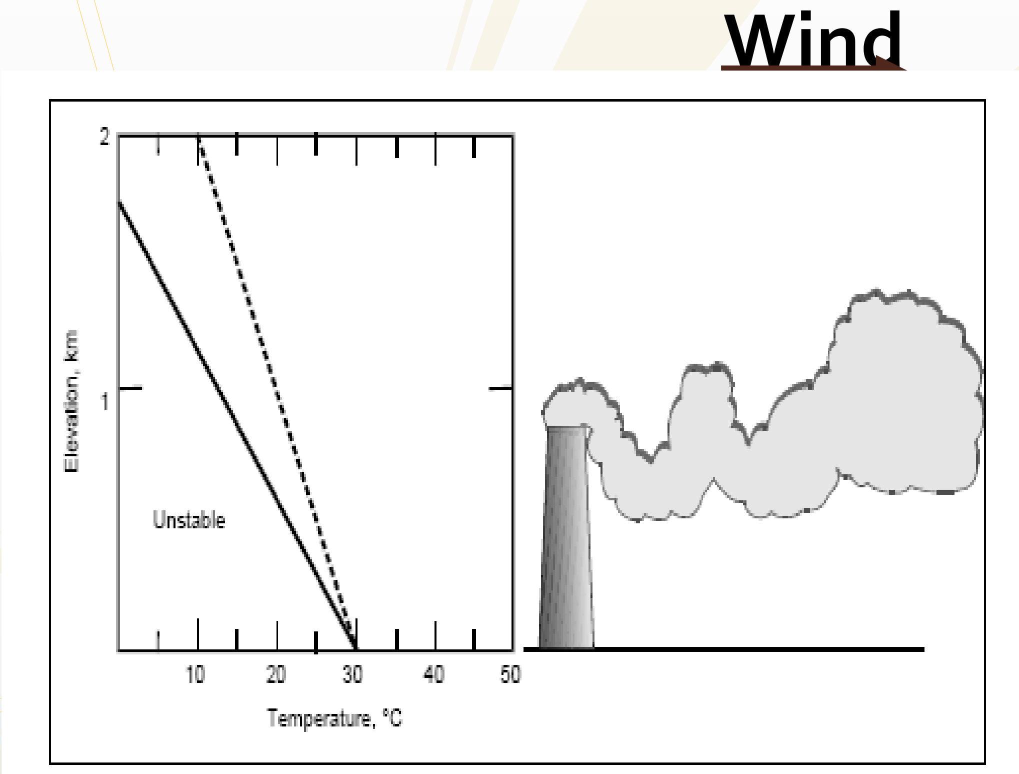
- Pollutants that cannot be dispersed upward may be dispersed horizontally by surface winds.

Strong Lapse Condition (Looping)

Occurs under conditions of:

- High degree of convective turbulence
- **superadiabatic lapse rate** - - strong instability conditions

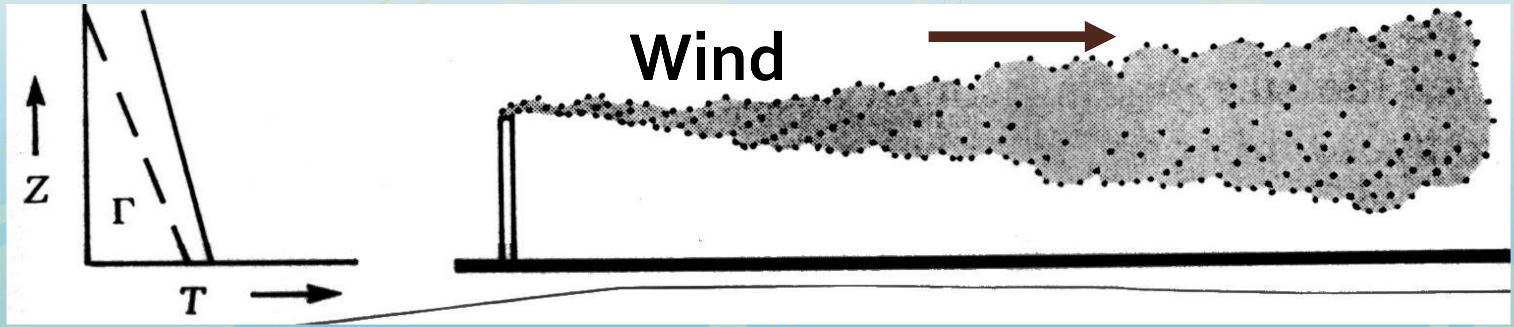
Associated with clear daytime conditions accompanied by strong solar heating & light winds



Causes momentary high ground-level concentrations when portion of the plume loops downward to the surface.

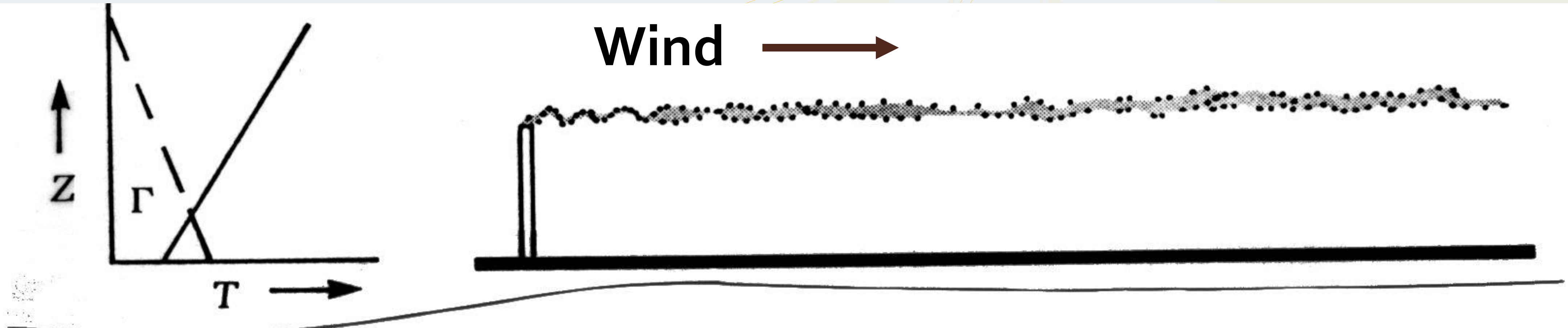
Weak Lapse Condition (Coning)

- The coning plume is characteristic of neutral conditions or slightly stable conditions. It is likely to occur on cloudy days or on sunny days between the break-up of an inversion and the development of unstable daytime conditions.
- Pollutants travel fairly long distances before reaching ground level in significant amounts



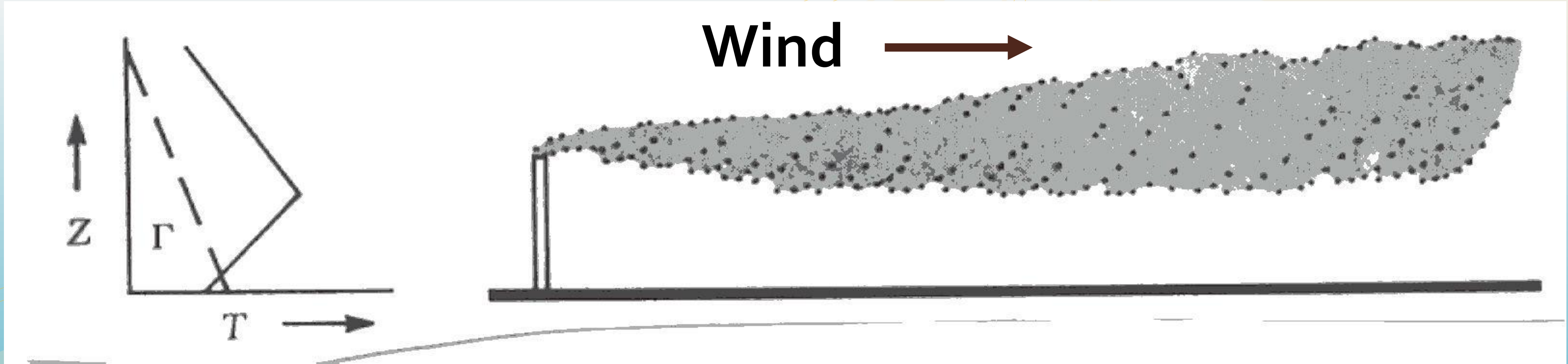
Inversion Condition (Fanning)

- Occurs under extremely stable atmosphere conditions
- The inversion lapse rate discourages vertical motion without prohibiting horizontal motion, and the plume may extend downwind from the source for a long distance.
- Fanning plumes often occur in the early morning during a radiation inversion



Inversion Below, Lapse Aloft (Lofting)

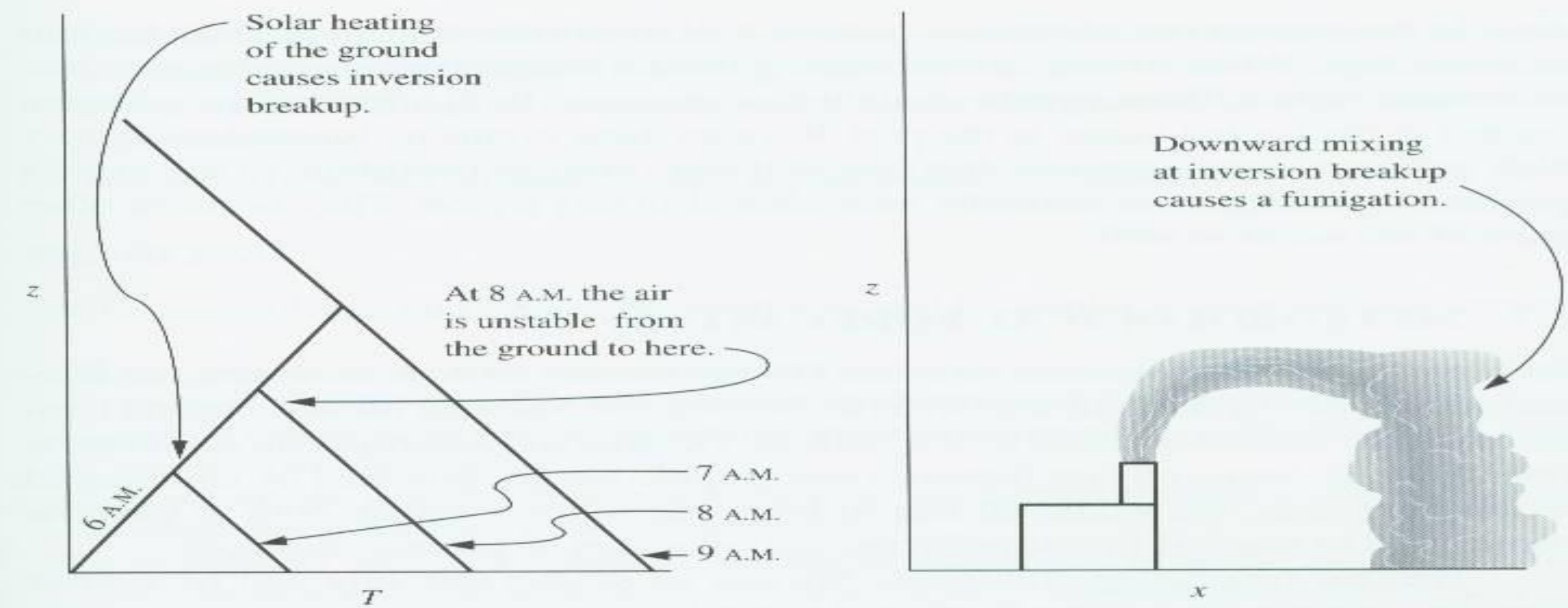
When conditions are unstable above an inversion, the release of a plume above the inversion results in effective dispersion without noticeable effects on ground level concentrations around the source. This condition is known as lofting.



Lapse Below, inversion Aloft (Fumigation)

- Occurs when atmospheric conditions are stable above the plume and unstable below.
- As the ground warms in the morning, air below an inversion layer becomes unstable. When the instability reaches the level of the plume that is still trapped below the inversion layer, the pollutants can be rapidly transported down toward the ground.
- Most dangerous plume: contaminants are all coming down to ground level.
- Sufficiently tall stacks can prevent fumigation in most cases.

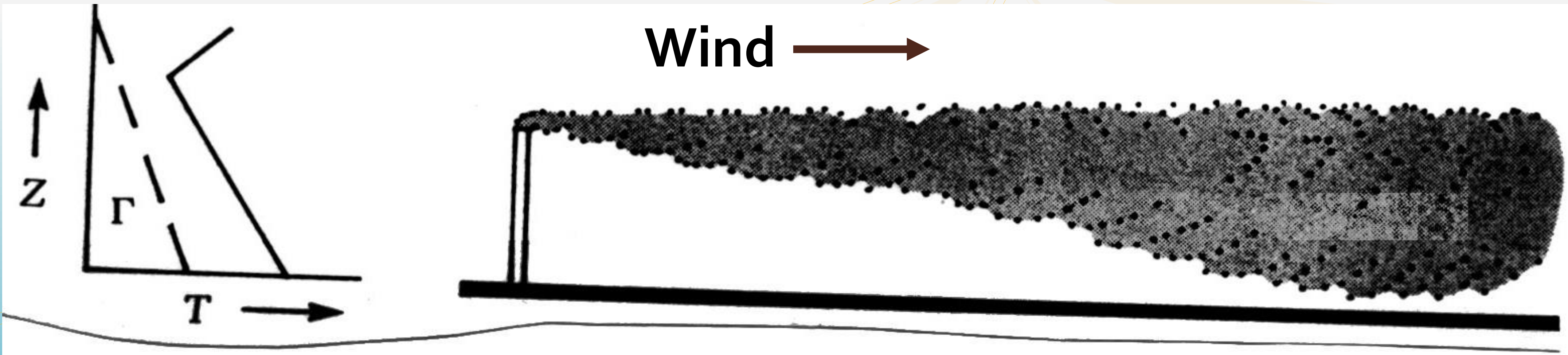
Lapse Below, inversion Aloft (Fumigation)



The development of a *fumigation*. The figure at the left shows the vertical temperature profile at various times. At 6 A.M. there is an inversion that is slowly destroyed by solar heating. On the right, the plume from a factory is shown inside an inversion. It flows horizontally with little mixing or dispersion due to the strong stability of the inversion. When the unstable mass of air from the heated ground reaches the plume, it mixes it to the ground, often at a high concentration, producing a short-term fumigation. This is most likely to occur with clear skies and light winds.

Weak Lapse Below, Inversion Aloft (Trapping)

Occurs when the plume effluent is caught b/n two inversion layers
The diffusion of pollutants is restricted to the unstable layer between the two stable regions (inversions layers).
Trapping also may be associated with subsidence inversions lasting for several days, where almost all emissions are trapped below the inversion layer thus creating one of the worst pollution situations.

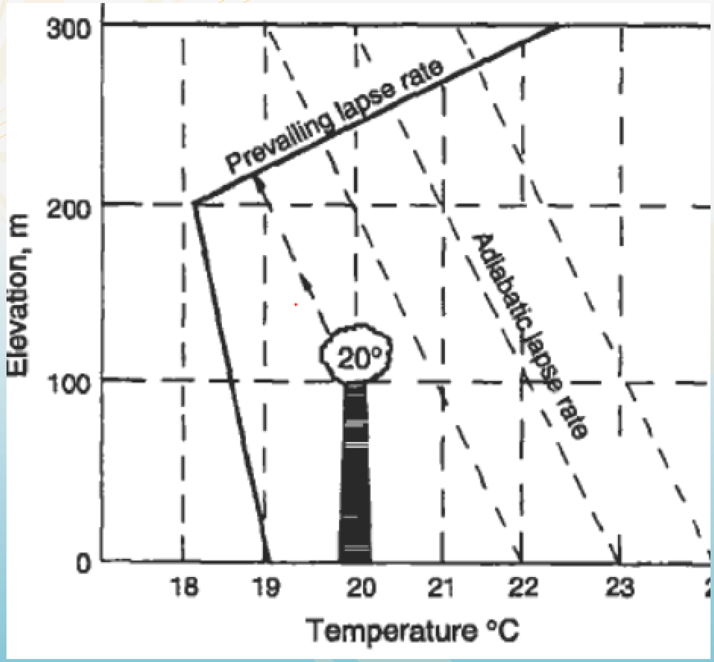


Example

A stack loo m tall emits a plume whose temperature is 20°C. The temperature at the ground is 19°C. The ambient lapse rate is -4.5 °C /km up to an altitude of 200 m. Above this the ambient lapse rate is +20°C /km. Assuming perfectly adiabatic conditions, how high will the plume rise and what type of plume will it be?

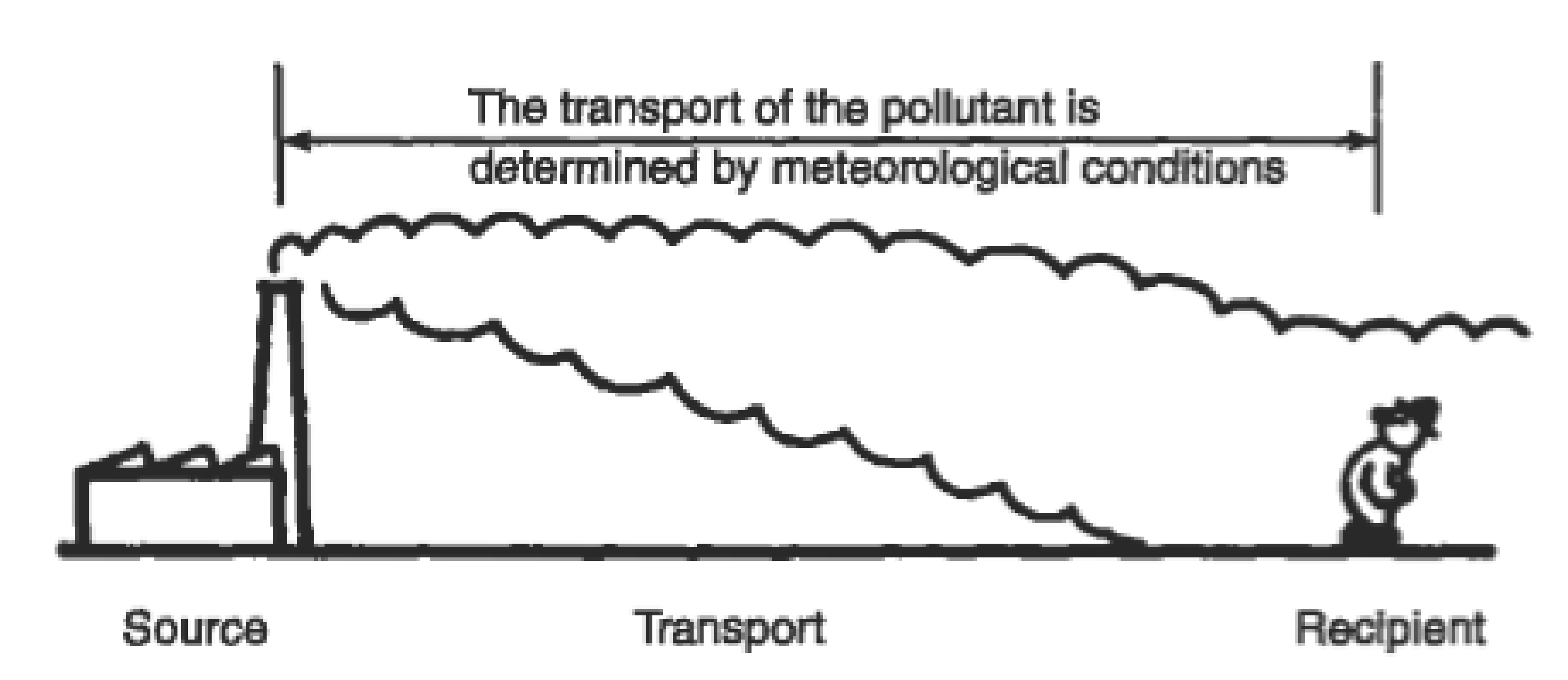
solution

The ambient lapse rate below 200 m is sub adiabatic the surrounding air is cooler than the plume, so it rises, and cools as it rises. Below 230 m, the plume would have been slightly coning. It would not have penetrated 230 m.



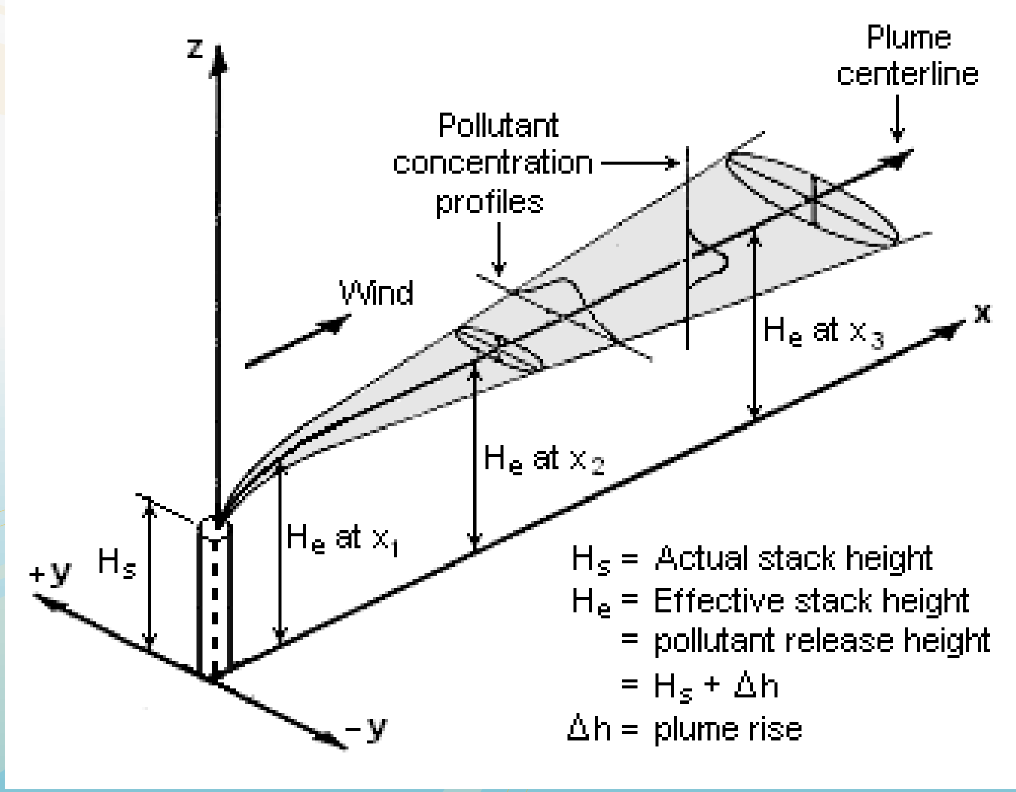
Atmospheric Dispersion

Dispersion is the process by which contaminants move through the air and a plume spreads over a large area, thus reducing the concentration of the pollutants it contains.

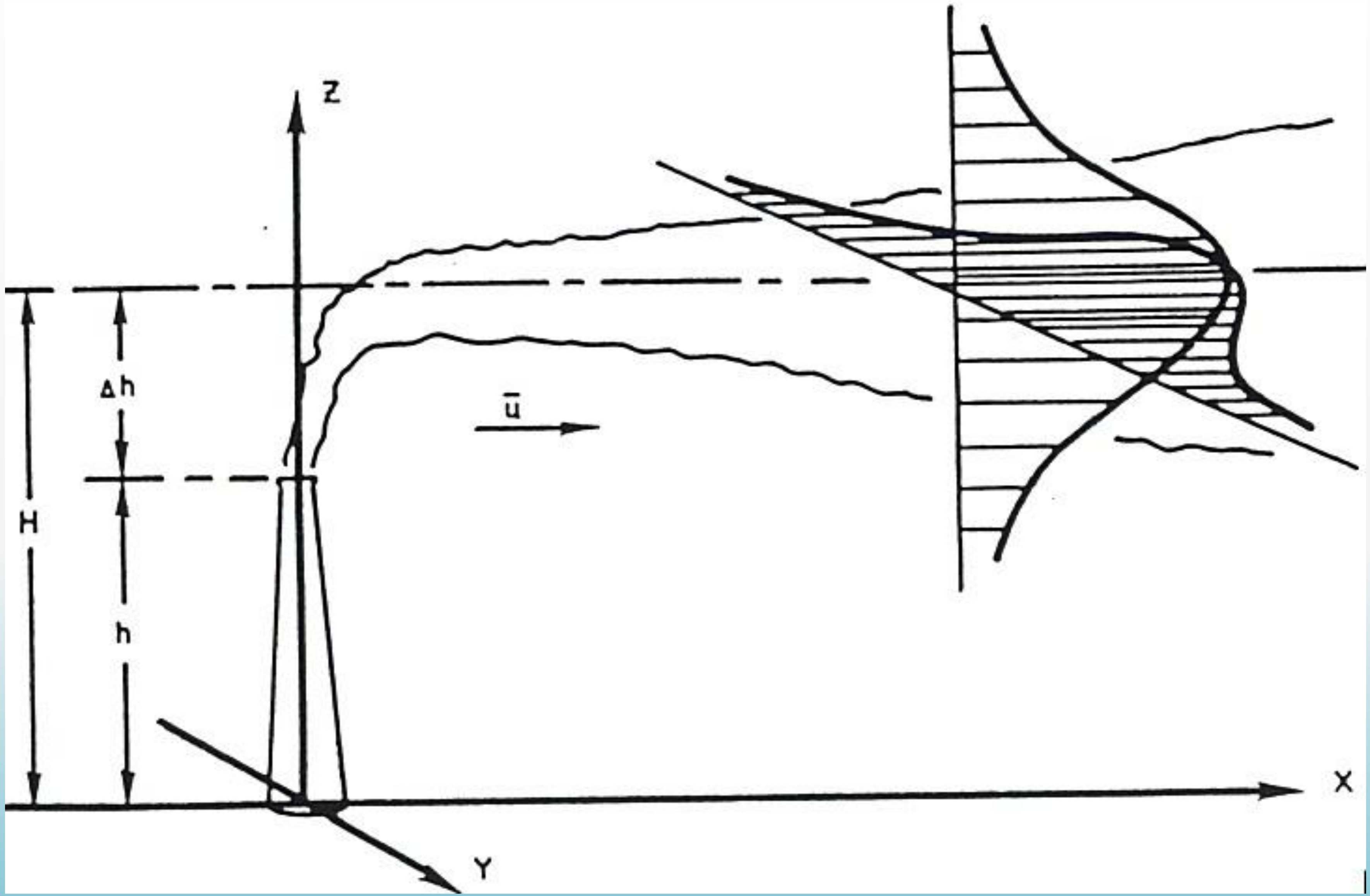


Atmospheric Dispersion

- The plume spreads both horizontally and vertically.
- If it is a gaseous plume, the motion of the molecules follows the **laws of gaseous diffusion.**



Gaussian Dispersion Model



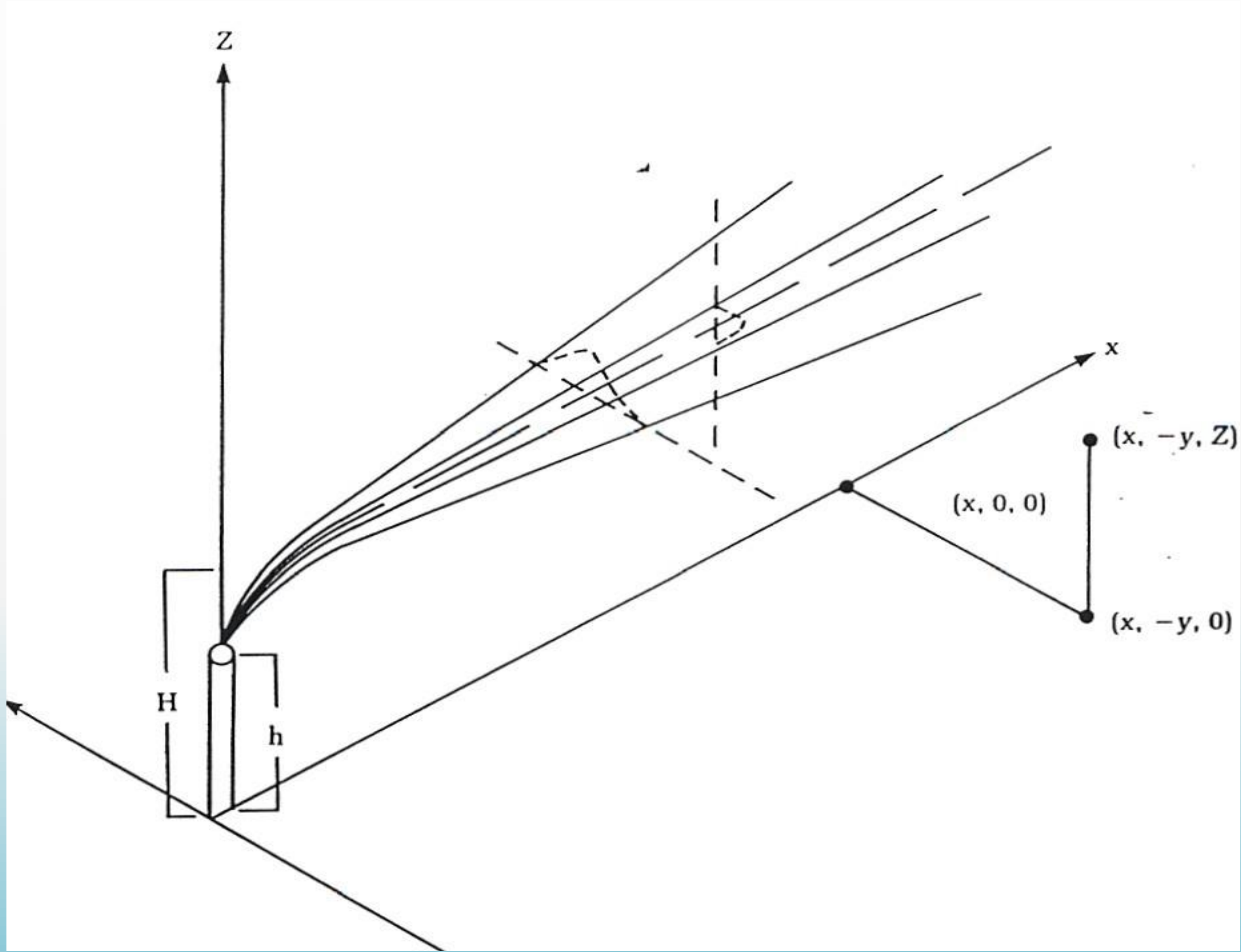
Dispersion Model Assumptions

- The predominant force is the wind.
- The greatest concentration of the pollutant molecules is along the plume centerline.
- The process is a steady state process.

Dispersion Model Construction

- Plume travels horizontally in x-direction
- Plume disperses horizontally (y) and vertically (z)
- Concentration inside the plume follows Gaussian Distribution
- Concentration ($C_{(x,y,z)}$) is proportional to:
  - Source strength (Q)
  - Inverse of wind speed (1/U)
  - Normalized Gaussian distribution function in the y and z directions that is dependent on weather conditions

Plume Dispersion Coordinate System



Gaussian Dispersion Model

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)\right),$$

where

$C(x, y, z)$ is the concentration at some point in space with coordinates x, y, z, and
$Q =$ the emission rate of the pollution source (in g/s),
$u =$ the average wind speed in (m/s),
$\sigma_y =$ the standard deviation of the plume in the y direction (m), and
$\sigma_z =$ the standard deviation of the plume in the z direction (m).

At ground level, we have z=0, thus

$$C(x, y, 0) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{(H)^2}{2\sigma_z^2}\right)\right).$$

Gaussian Dispersion Model

The greatest value of the ground level concentration in any direction, and this is the concentration along the plume centerline; that is, for y = o. We have

$$C(x, 0, 0) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(\frac{-H^2}{2\sigma_z^2}\right).$$

Finally, for a source *of emission at ground level, H = o, and the ground level concentration* of pollutant downwind along the plume centerline is given by

$$C(x, 0, 0) = \frac{Q}{\pi u \sigma_y \sigma_z}.$$

Maximum ground level conc.

By differentiating the Gaussian concentration formula and setting it equal to zero, an equation for maximum concentration can be derived:

$$C_{max} = \frac{2Q}{\Pi u e H^2} \frac{\sigma_Z}{\sigma_y}$$

For a release above ground level the maximum downwind ground level concentration occurs along the plume centerline when the following condition is satisfied:

$$\sigma_Z = \frac{H}{\sqrt{2}}$$

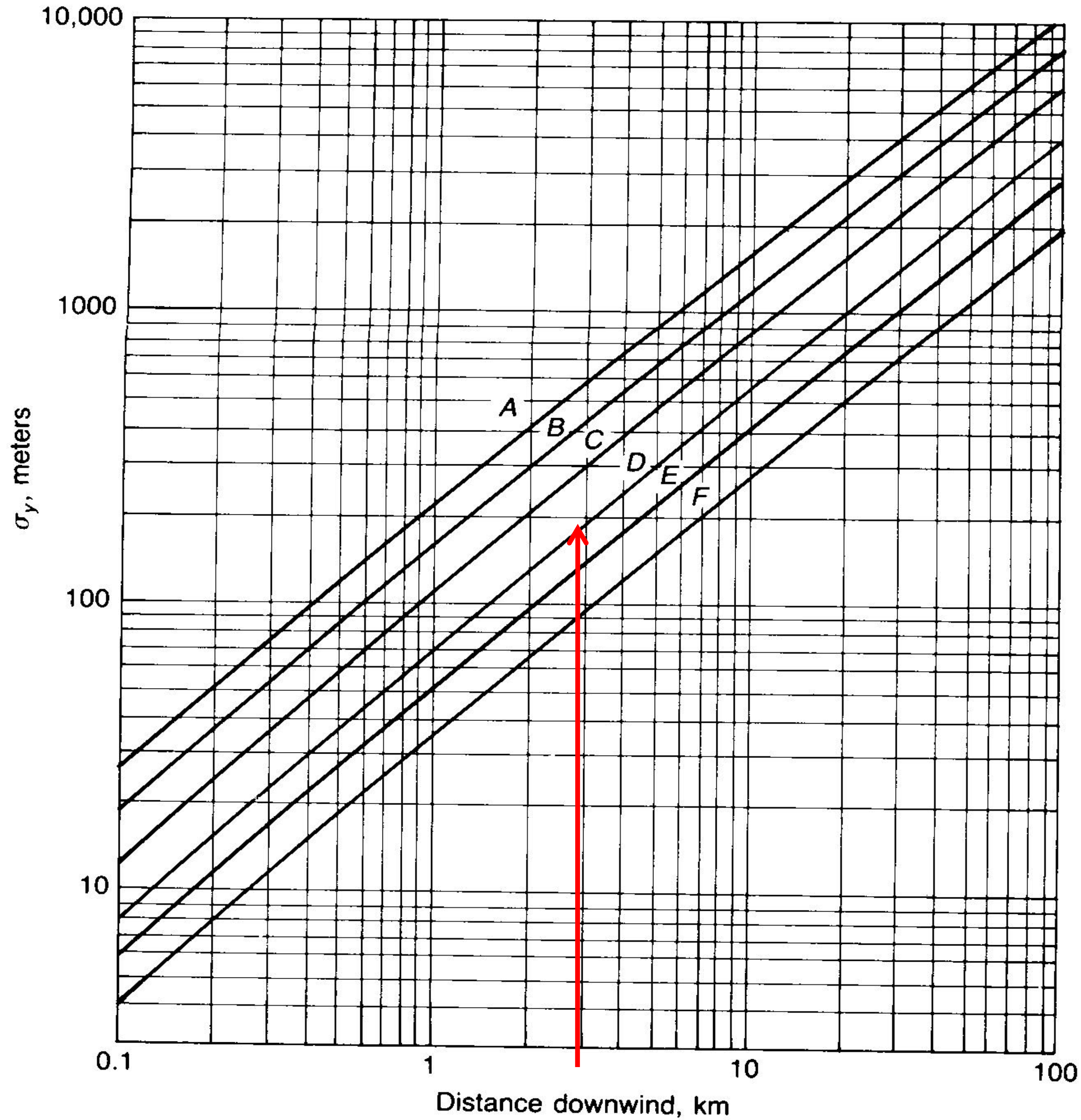
Key to Stability Categories

Surface Wind Speed[a] m/s	Day Incoming Solar Radiation			Night Cloudiness[e]	
	Strong[b]	Moderate[c]	Slight[d]	Cloudy (≥4/8)	Clear (≤3/8)
<2	A	A–B[f]	B	E	F
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

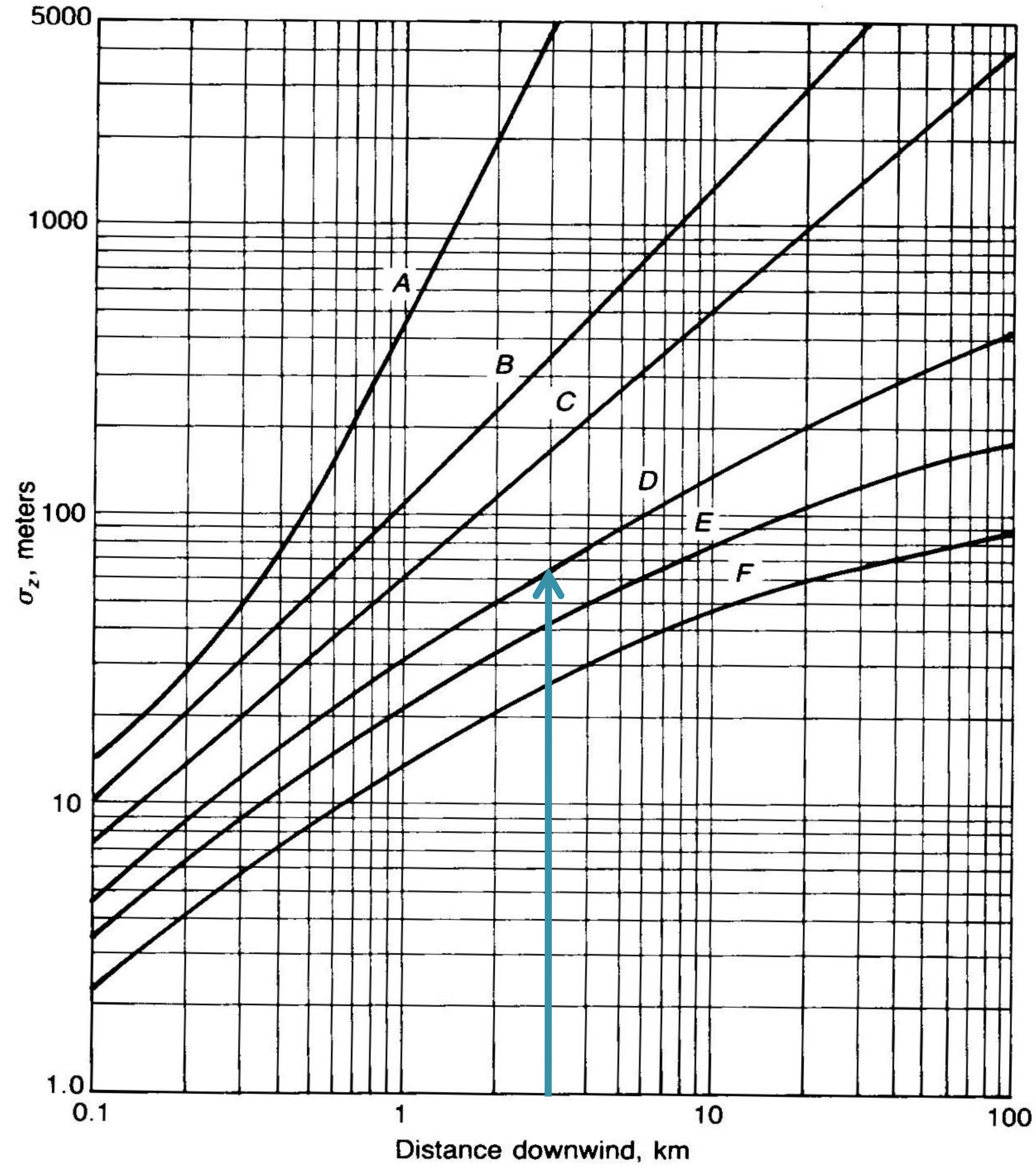
[a] Surface wind speed is measured at 10 m above the ground.
[b] Corresponds to clear summer day with sun higher than 60° above the horizon.
[c] Corresponds to a summer day with a few broken clouds, or a clear day with sun 35-60° above the horizon.
[d] Corresponds to a fall afternoon, or a cloudy summer day, or clear summer day with the sun 15–35°.
[e] Cloudiness is defined as the fraction of sky covered by clouds.
[f] For A–B, B–C, or C–D conditions, average the values obtained for each.

* A = Very unstable　　D = Neutral
B = Moderately unstable　　E = Slightly stable
C = Slightly unstable　　F = Stable
Regardless of wind speed, Class D should be assumed for overcast conditions, day or night.

Horizontal Dispersion Coefficients



Vertical Dispersion Coefficients



Formulas for Horizontal & Vertical Dispersion Coefficients

$$s_y = ax^{0.894}$$

$$s_z = cx^d + f$$

Values of a, c, d, and f for calculating s_y and s_z

Stability class		$x \leq 1$ km			$x > 1$ km		
	a	c	d	f	c	d	f
A	213	440.8	1.941	9.27	459.7	2.094	−9.6
B	156	100.6	1.149	3.3	108.2	1.098	2
C	104	61	0.911	0	61	0.911	0
D	68	33.2	0.725	−1.7	44.5	0.516	−13.0
E	50.5	22.8	0.678	−1.3	55.4	0.305	−34.0
F	34	14.35	0.74.0	−0.35	62.6	0.18	−48.6

Effective Stack Height

- Carson and Moses Equation

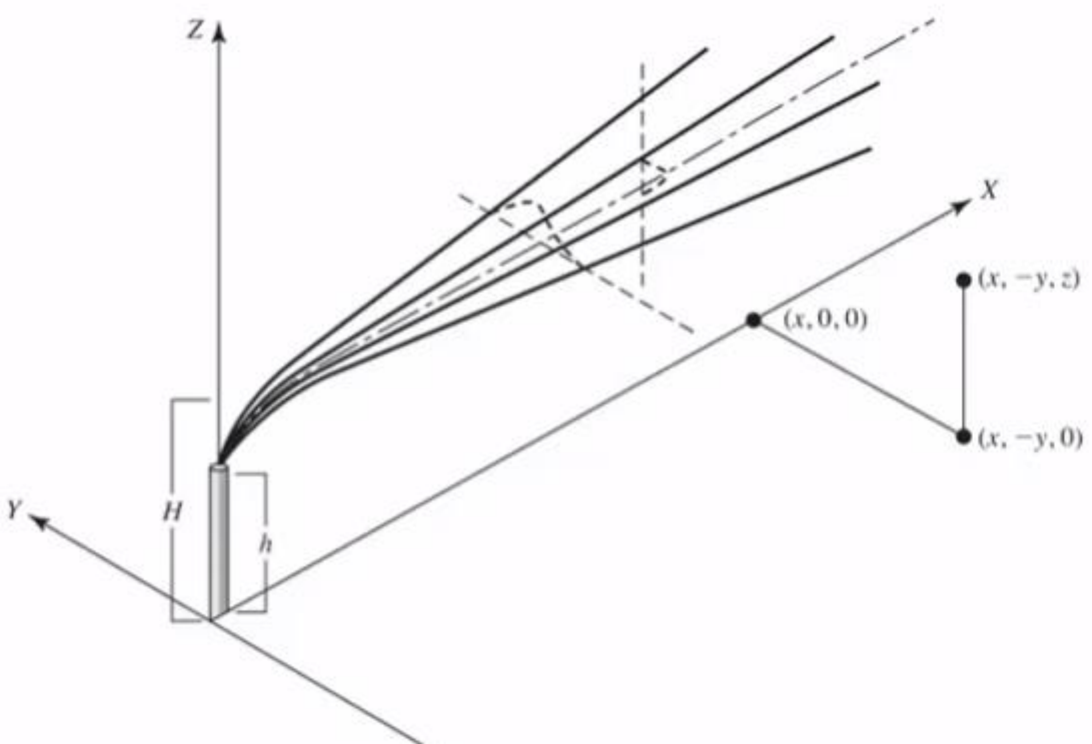
Superadiabatic Stability	$\Delta h = 3.47 \frac{V_s d}{u} + 5.15 \frac{Q_h^{0.5}}{u};$
Neutral Stability	$\Delta h = 0.35 \frac{V_s d}{u} + 2.64 \frac{Q_h^{0.5}}{u};$
Subadiabatic Stability	$\Delta h = -1.04 \frac{V_s d}{u} + 2.24 \frac{Q_h^{0.5}}{u},$

V_s = stack gas exit speed (in *m/s*) ,
d = stack diameter (in m), and
Q_h = heat emission rate from the stack (in kJ/s).

Effective Stack Height

- Holland Formula

$$\Delta H = \frac{v_s d}{u}\left[1.5 + \left(2.68\times10^{-2}(P)\left(\frac{T_s - T_a}{T_s}\right)d\right)\right]$$



H = *effective* stack height (m)

ΔH = plume rise (m)

h = *physical* stack height

v_s = stack velocity (m/s)

d = stack diameter (m)

u = wind speed (m/s)

T_s = stack temperature (K)

T_a = air temperature (K)

P = pressure (kPa)

We begin by determining the effective stack height (H).

$$\Delta H = \frac{(10.0 \text{ m} \cdot \text{s}^{-1})(1.20 \text{ m})}{4.50 \text{ m} \cdot \text{s}^{-1}} \left\{1.5 + \left[2.68 \times 10^{-2}(95.0)\left(\frac{588 \text{ K} - 298 \text{ K}}{588 \text{ K}}\right)(1.20 \text{ m})\right]\right\}$$

$$= 8.0 \text{ m}$$

$$H = 120.0 + 8.0 = 128.0 \text{ m}$$

Since it is overcast condition stability Class D is used

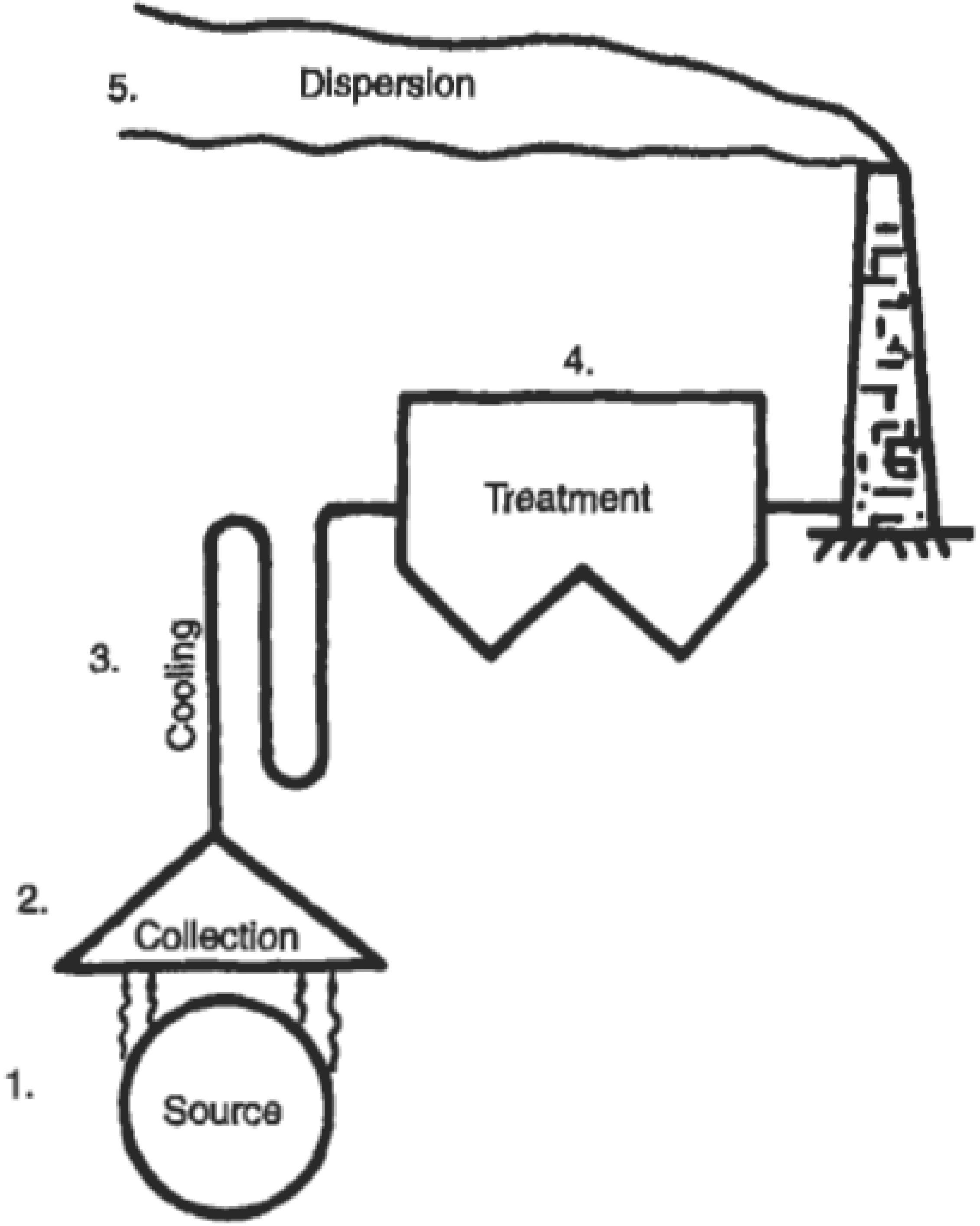
$$s_y = 68(3)^{0.894} = 181.6 \text{ m}$$

$$s_z = 44.5(3)^{0.516} - 13 = 65.4 \text{ m}$$

$$\chi = \left[\frac{1656.2}{\pi(181.6)(65.4)(4.50)}\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{0}{181.6}\right)^2\right]\right\}\left\{\exp\left[-\frac{1}{2}\left(\frac{128.0}{65.4}\right)^2\right]\right\}$$

$$= 1.45 \times 10^{-3} \text{ g} \cdot \text{m}^{-3}, \text{ or } 1.5 \times 10^{-3} \text{ g} \cdot \text{m}^{-3} \text{ of } SO_2$$

Air Pollution Control



Source Correction

- Changing or eliminating a process that produces a polluting **air effluent** is often easier than trying to trap the effluent.
- A process or product may be needed or necessary, but could be changed to control emissions.
- For example, **automobile exhaust** has caused high **lead** levels in urban air.
- Elimination of lead from gasoline, which was needed for proper catalytic converter operation, has also resulted in reducing lead in urban air.
- Similarly, removal of sulfur from coal and oil before the fuel is burned reduces the amount of **SO_2 emitted into the air**.

- **Controls:** raw material substitution, and equipment modification to meet emission standards
- **Abatement** ***:*** devices and methods for decreasing the quantity of pollutant reaching the atmosphere, **once it has been generated by the source**.
- For simplicity, however, we will refer to all of the procedures as controls.

COLLECTION OF POLLUTANTS

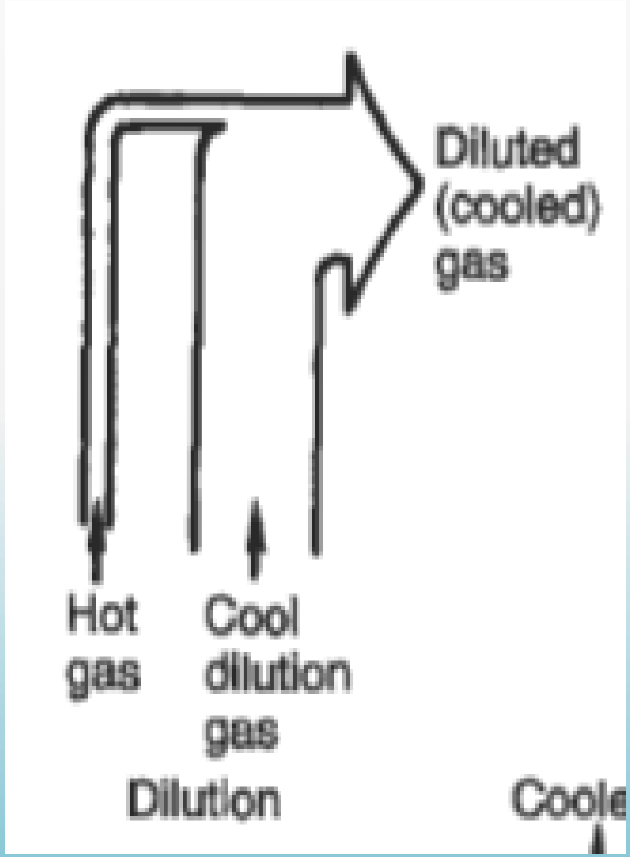
Collection of pollutants for treatment is the most serious problem in air pollution control.

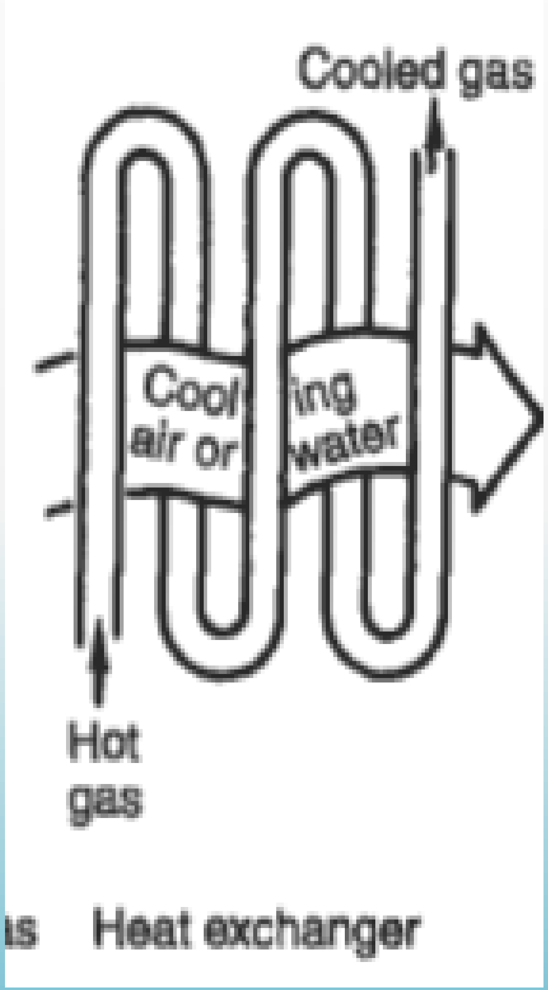
Air Pollution Control Technologies

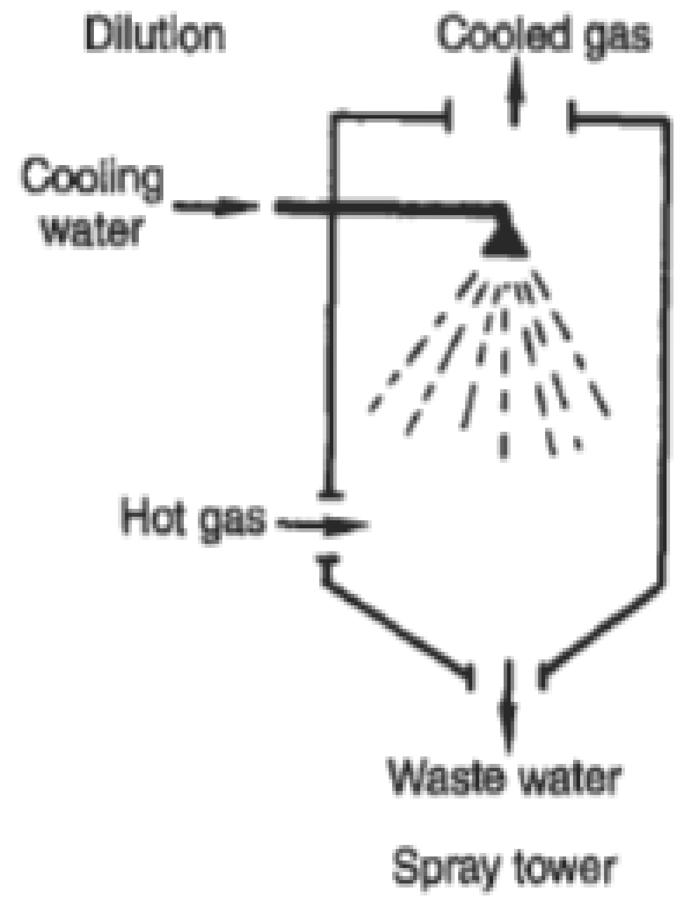
- Control of Particulate Emission
  - Settling
  - Cyclone separation(mechanical collector)
  - Wet scrubbing
  - Baghouse filtration (fabric filtration)
  - Electrostatic precipitation (ESP)
- Control of Vapor-phase Emissions
  - Wet scrubbing
  - Activated carbon adsorption
  - Incineration

COOLING

- The exhaust gases to be treated are sometimes too hot for the control equipment, and must first be cooled.

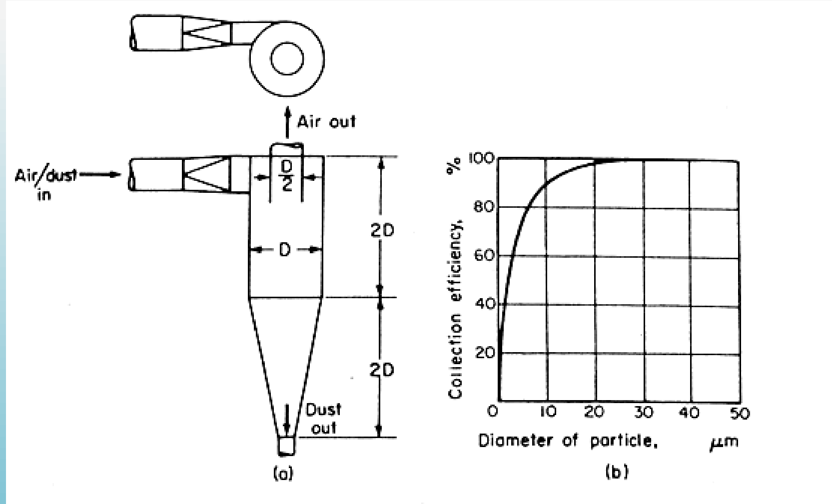


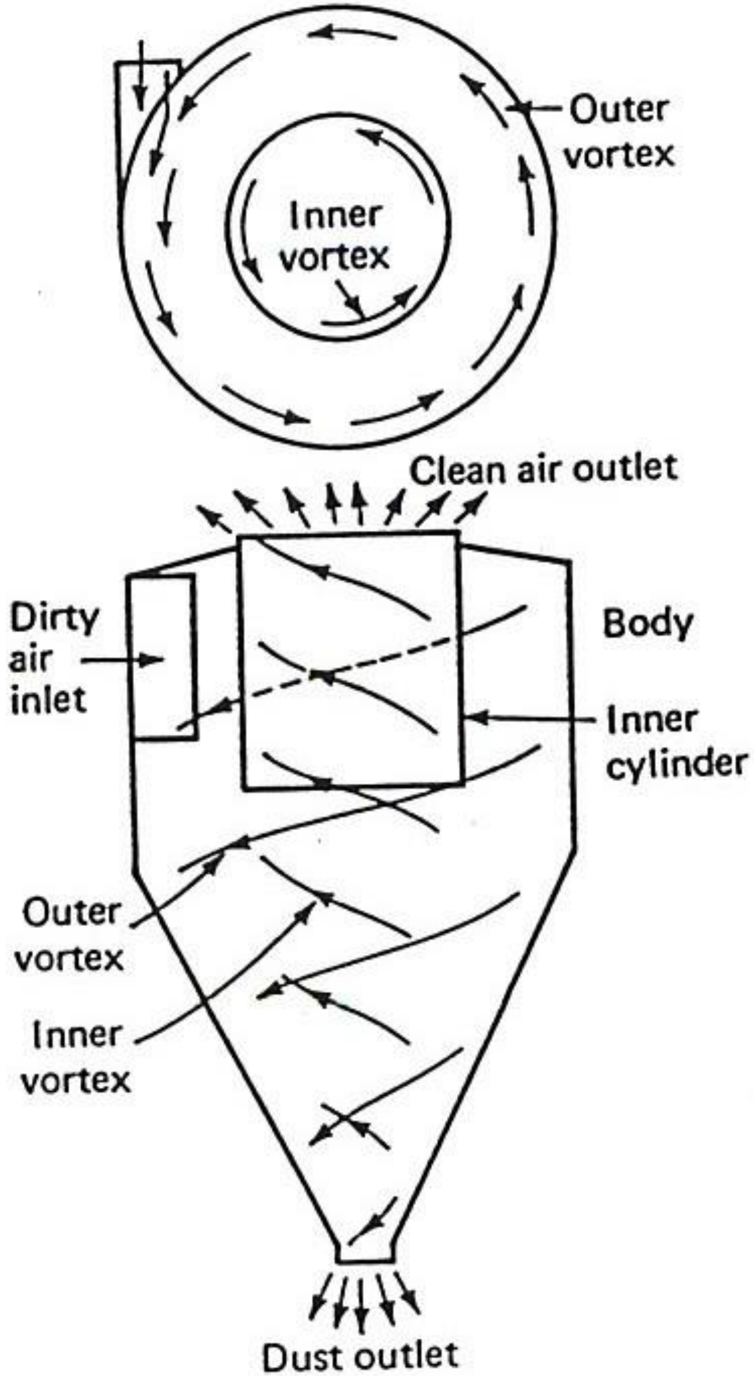




Cyclone

- use centrifugal force to separate particles
- Used as precleaners
- >90% efficiency for > 5μm
- In expensive and maintenance free
- an external device, such as a blower or other source of pressure, is required to move the gas stream





Cyclones

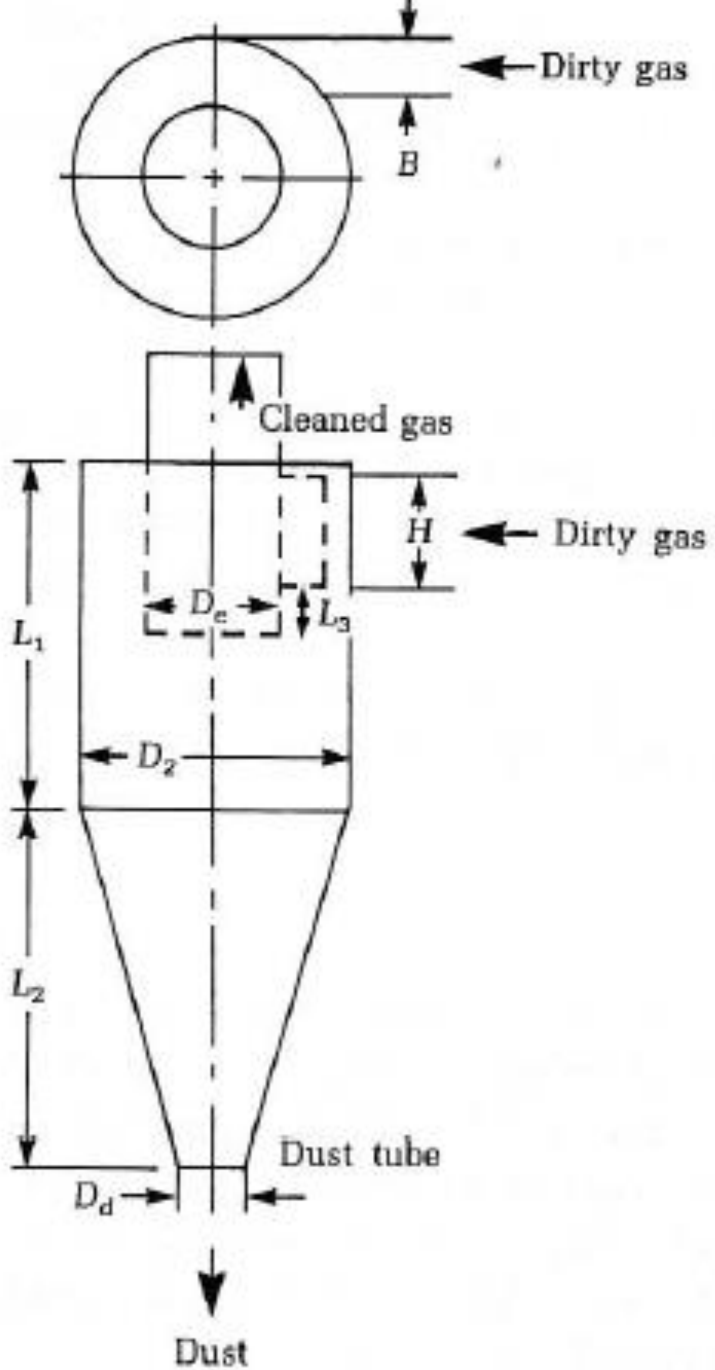


FIGURE 7-35

Standard reverse flow cyclone proportions.

Note: Standard cyclone proportions are as follows:

Length of cylinder, $L_1 = 2D_2$

Length of cone, $L_2 = 2D_2$

Diameter of exit, $D_e = 0.5D_2$

Height of entrance, $H = 0.5D_2$

Width of entrance, $B = 0.25D_2$

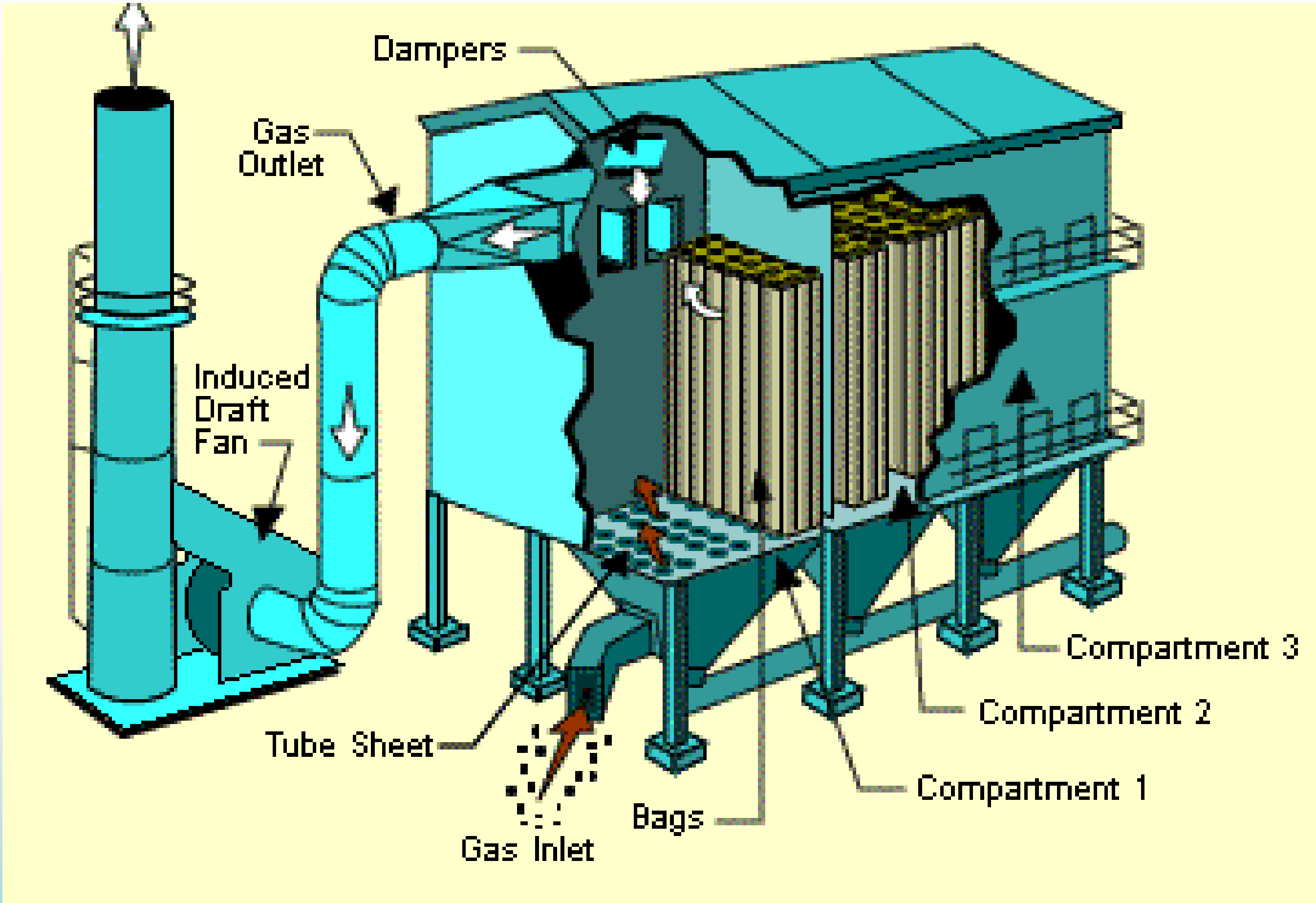
Diameter of dust exit, $D_d = 0.25D_2$

Length of exit duct, $L_3 = 0.125D_2$

(*Source:* Crawford, 1976.)

Fabric Filters

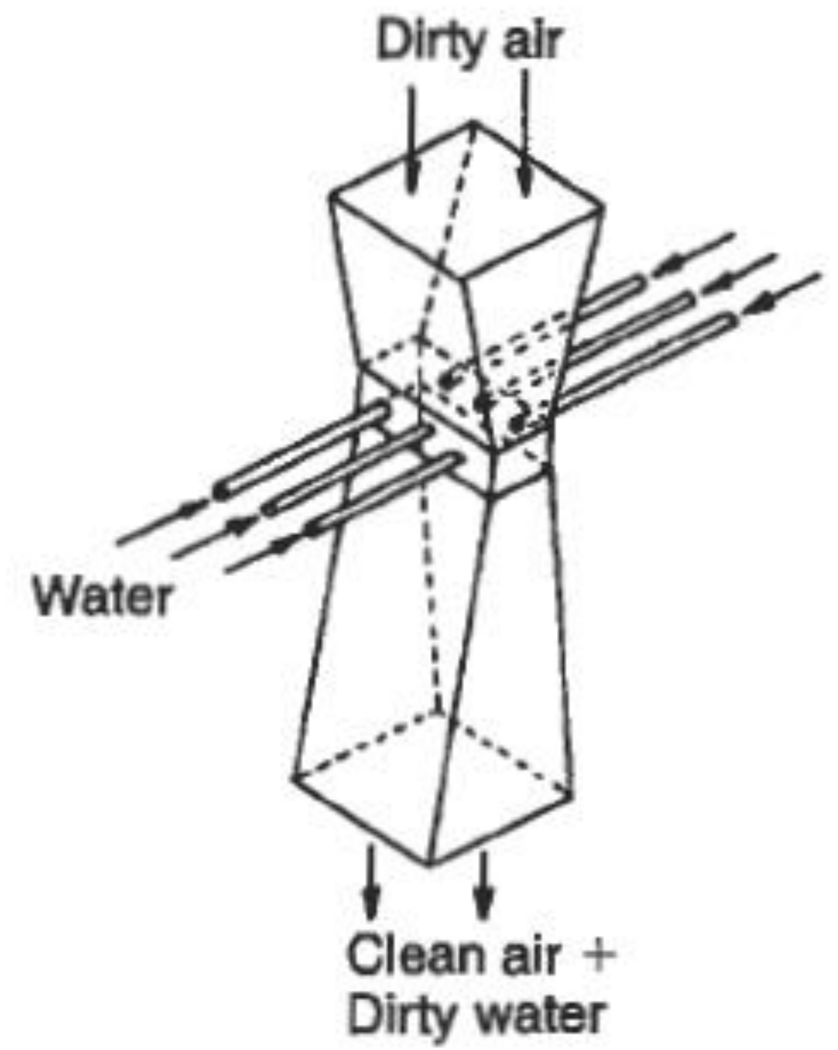
- known as baghouses
- Control particulates
- efficient and cost effective
- 99% efficient for very fine particulates (<1µm).



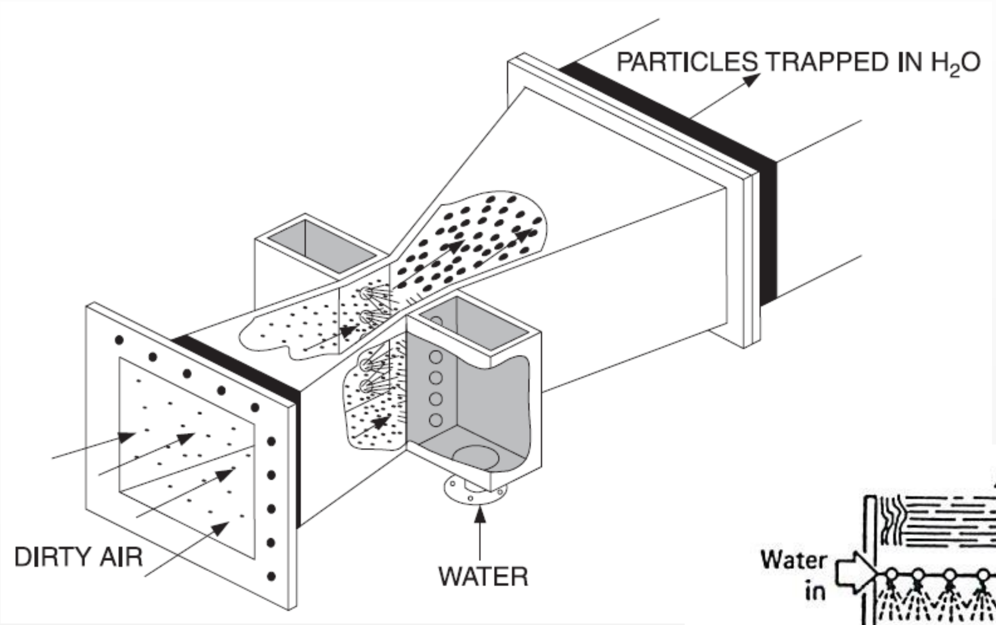
Baghouses

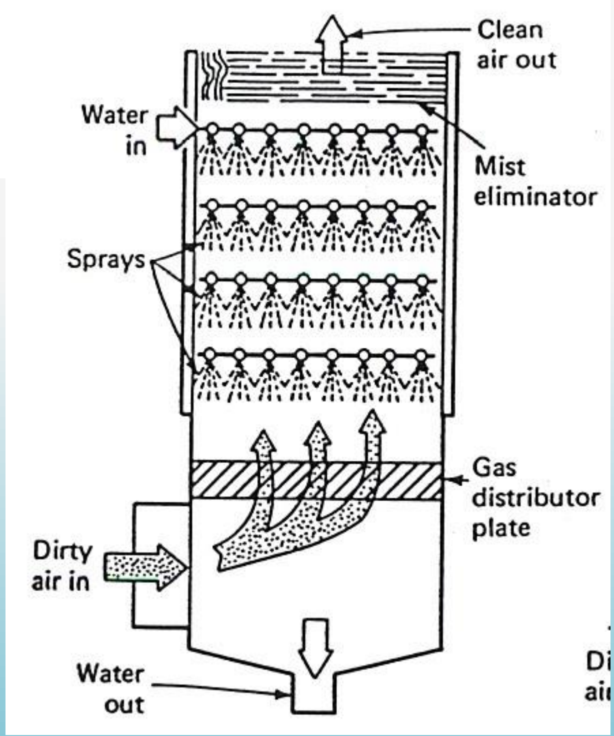
Wet Collectors

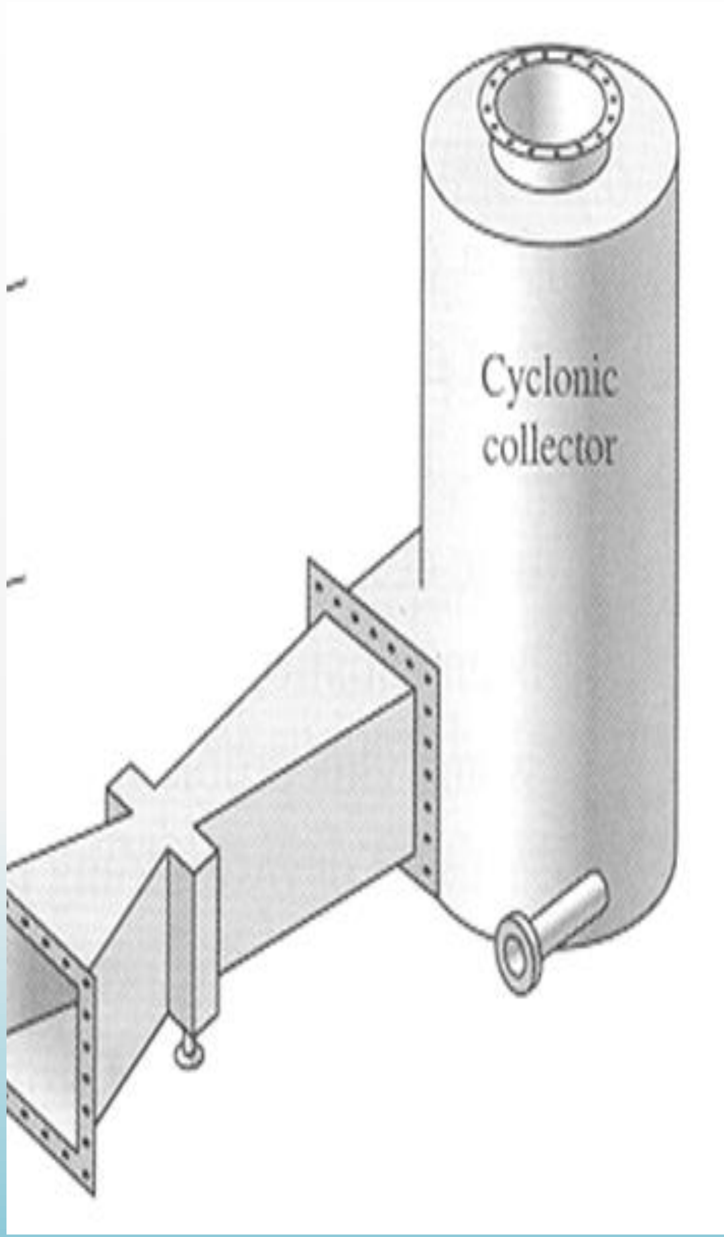
- The spray tower or scrubber
- Remove larger particles effectively
- can remove both gases and particulate matter.
- *A venturi scrubber is a frequently* used high-energy wet collector.
  - 100% efficient in removing particles >5 *pm*



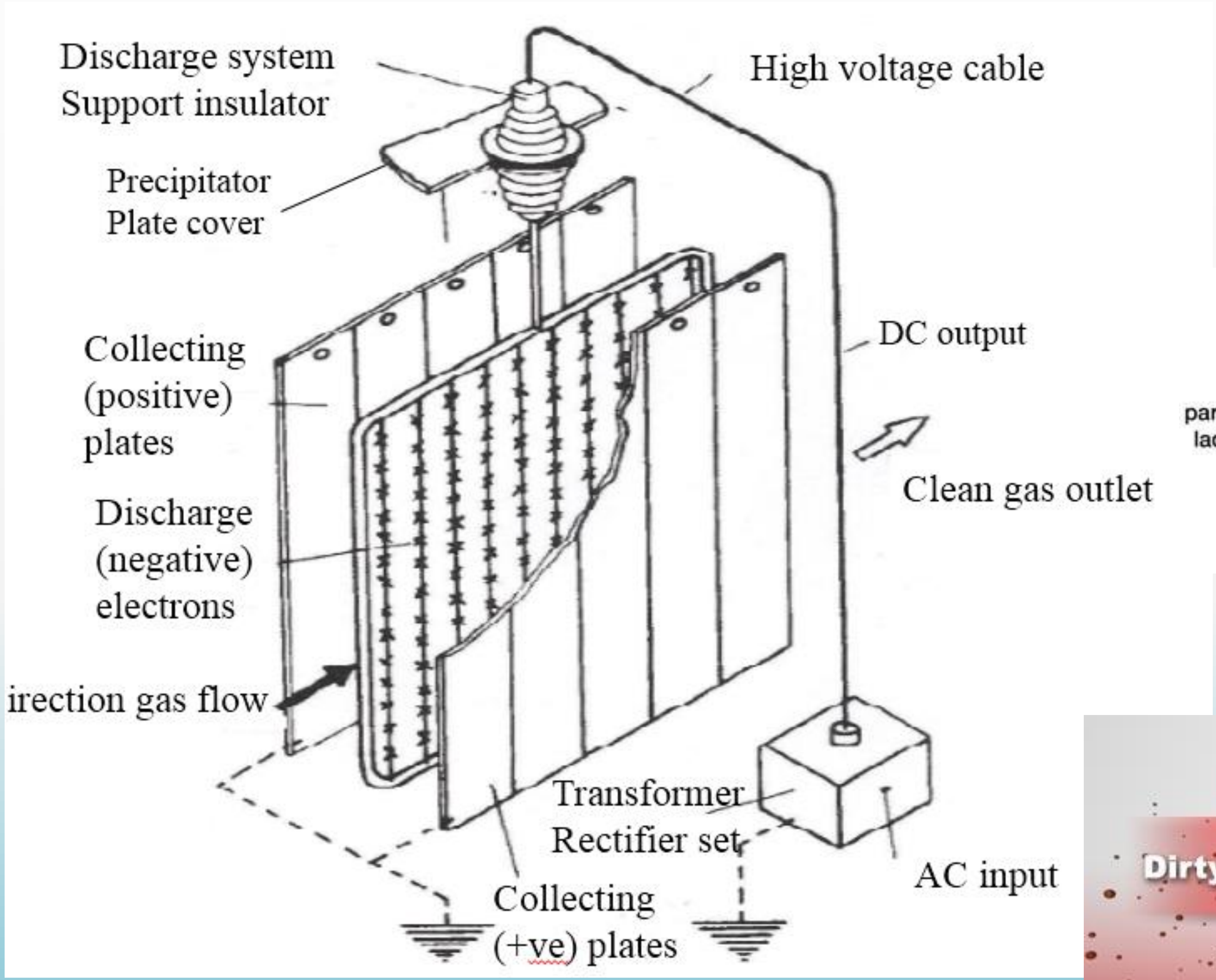
Wet collectors

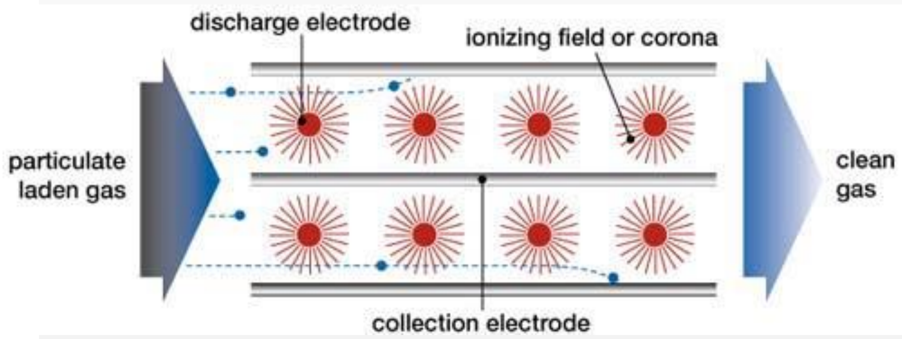


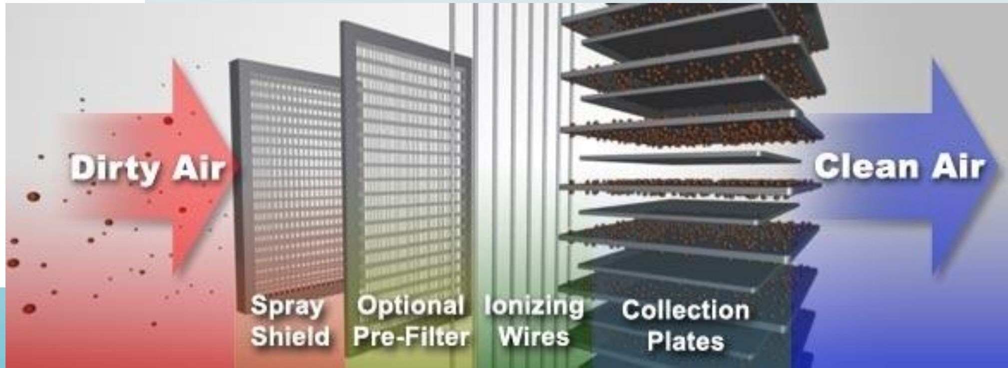




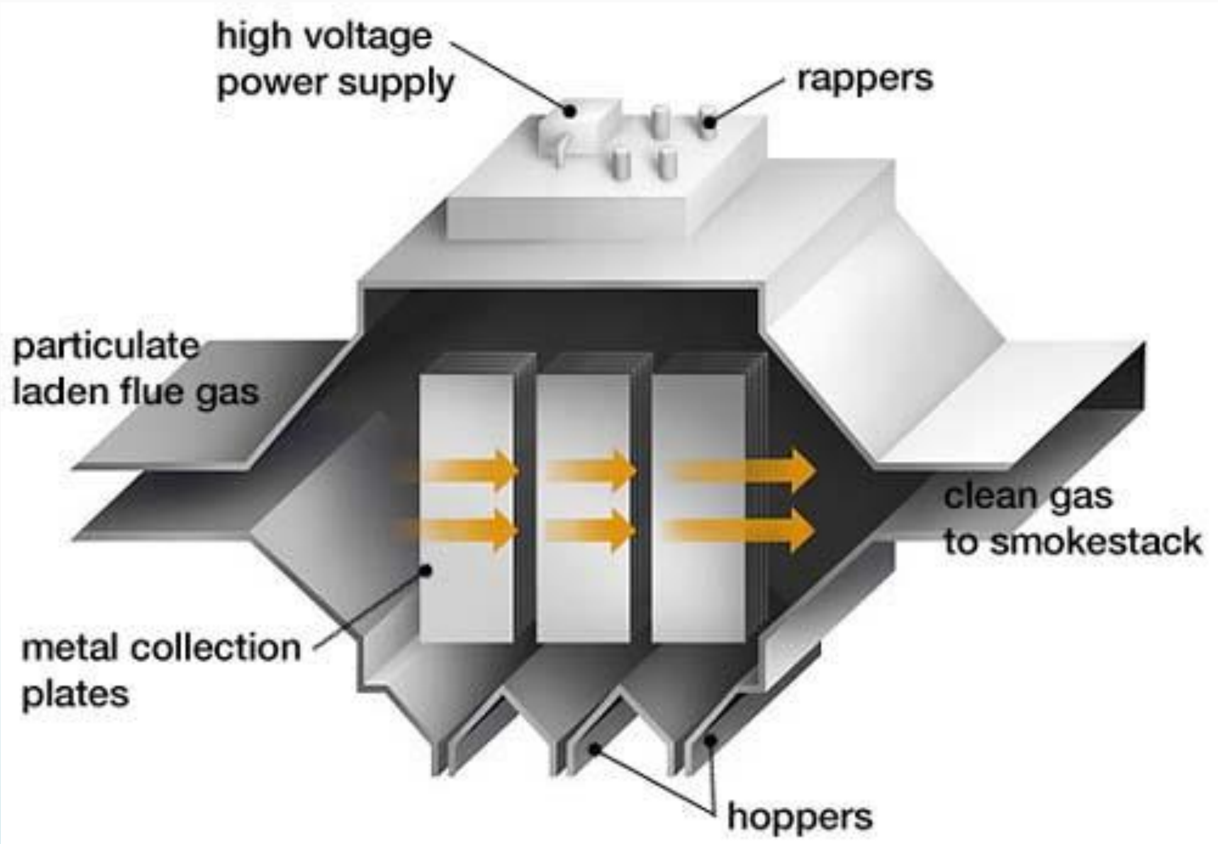
Electrostatic Precipitators







Electrostatic Precipitators

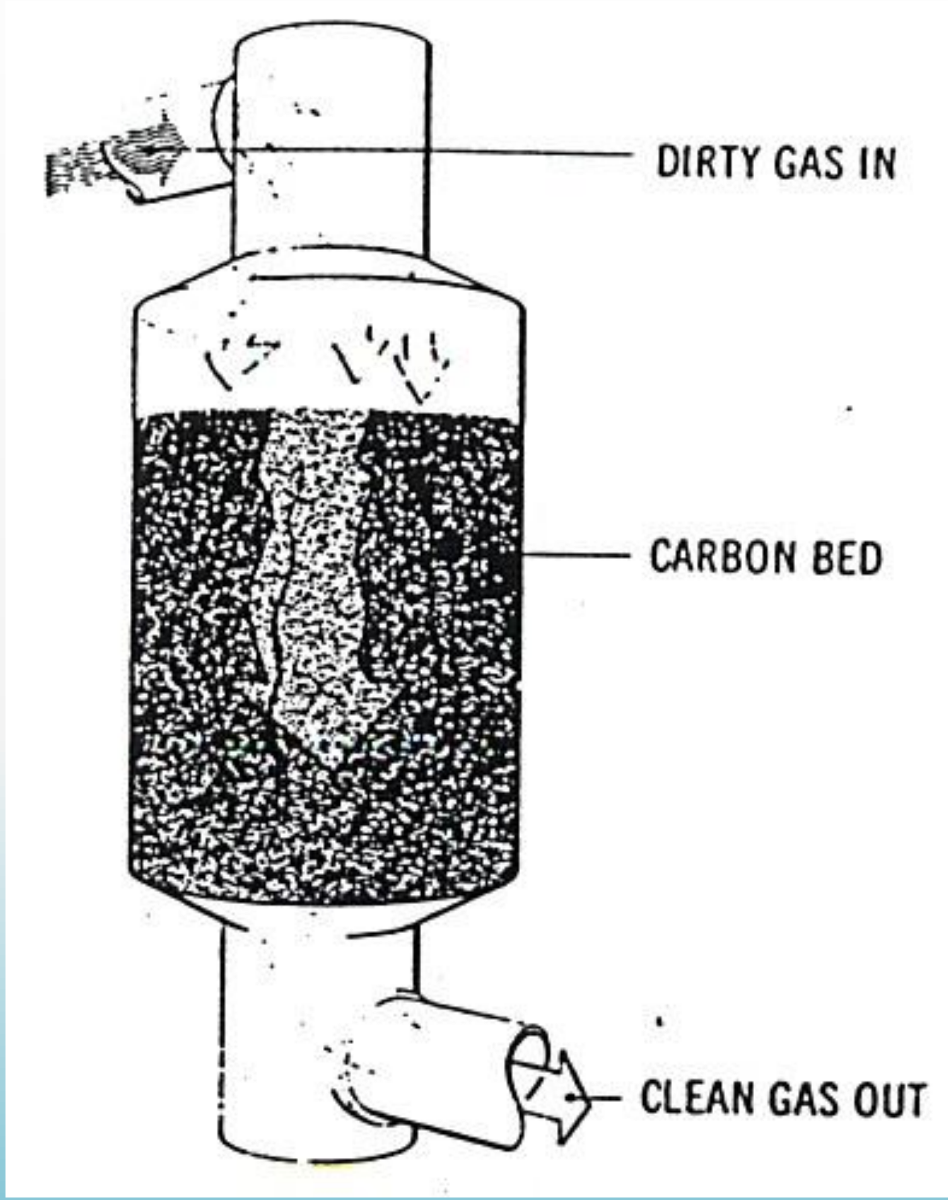


CONTROL OF GASEOUS POLLUTANTS

- *Wet scrubbers:* can remove pollutants by dissolving them in the scrubber solution. Ex. SO_2 and NO_2 in power plant .
- Packed scrubbers, spray towers packed with glass platelets or glass frit, more efficient. Ex. removal of fluoride from aluminum smelter exhaust gases.

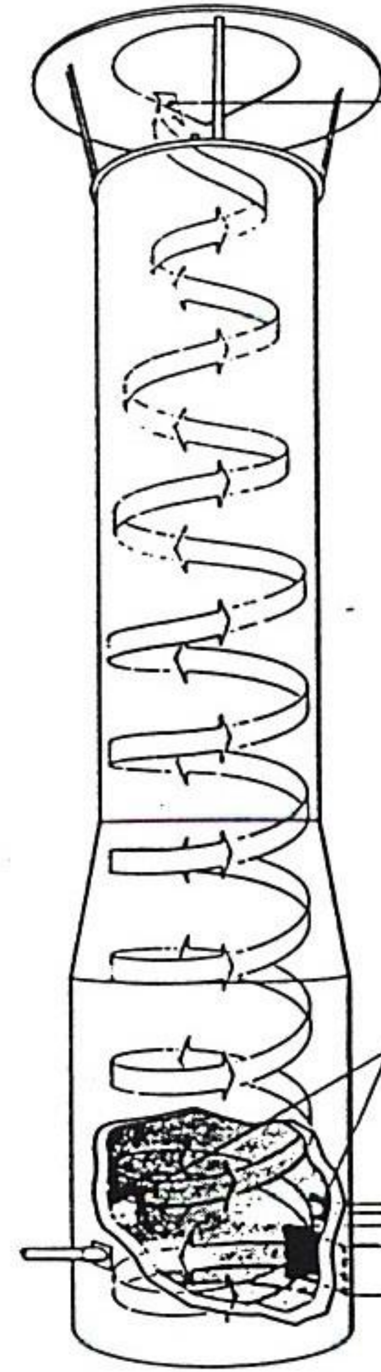
Activated Carbon Adsorber

- Removal of organic compounds with an adsorbent like activated charcoal.



Incinerator

- Incineration, or flaring, is used when an organic pollutant can be oxidized to CO_2 and water, or in oxidizing H_2S to SO_2.
- Catalytic combustion is a variant of incineration in which the reaction is facilitated energetically and carried out at a lower temperature by surface catalysis,



Effectiveness of Technologies