CHAPTER 5

METEOROLOGY OF AIR POLLUTION

Ch5 deNevers

Atmospheric Dispersion & Transport

- Structure & properties of the atmosphere
- Wind: cause, types, effect on air pollution
- Turbulence
- Ambient Stability & Inversion
- Plume Rise and Transport
- Plume Characteristics
- Long Range Transport

PROPERTIES OF THE ATMOSPHERE

- Troposphere: 0 - 11 km above ground
- Stratosphere: above 11 km
- 99% of atmospheric mass within 30 km
- Equivalent to a large pancake of 25,000 km diameter
- Horizontal movements more pronounced than vertical movements

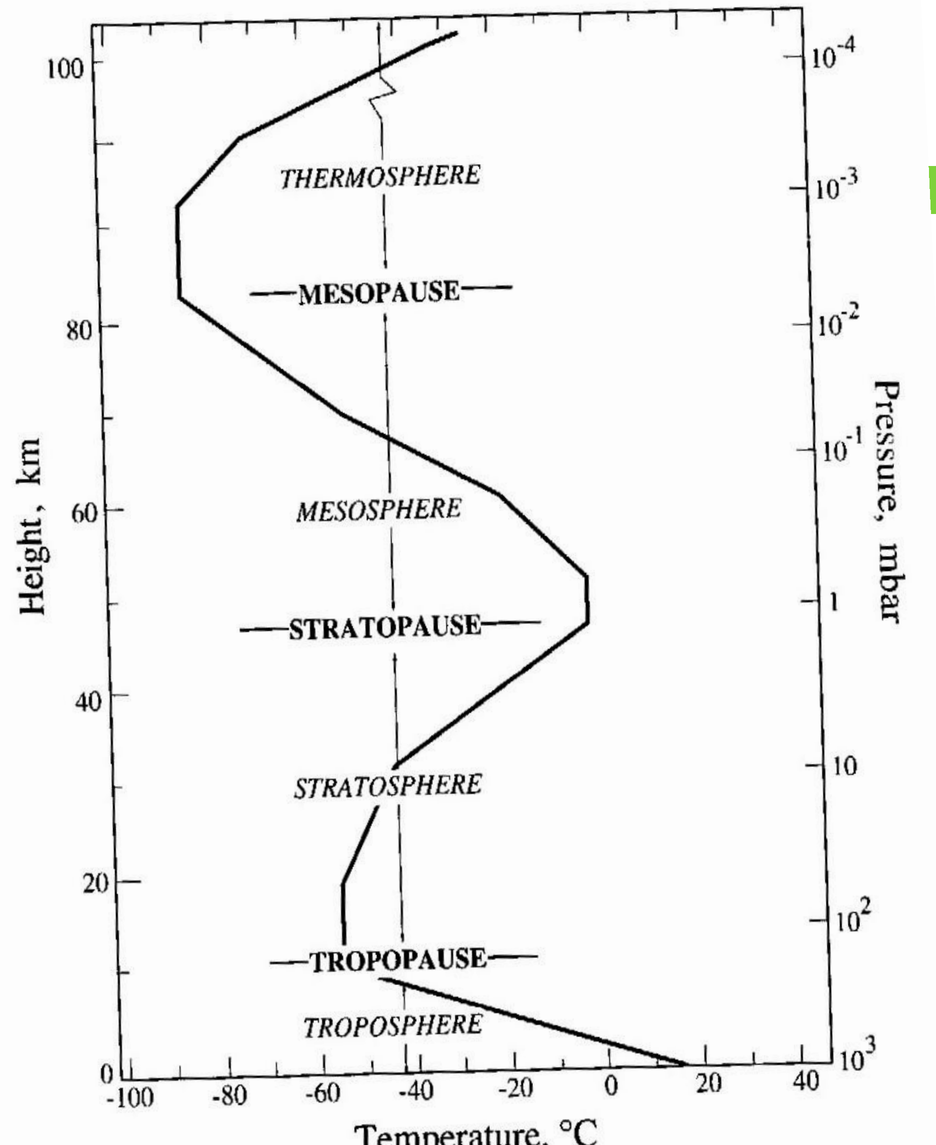


FIGURE 1.1 Layers of the atmosphere.

The Atmosphere as a Sink

- Sink for natural & man-made pollutants sources
- Imperfect sink: limited ability to :
  - carry away (**transport**): air motions carry pollutants from one region of the atmosphere to another
  - dilute (**dispersion**): mixing of pollutants with air
  - remove (**deposition**) : cleansing by wet precipitation and dry pollutants fallout.
- Local or regional overloading
- Topographical barriers
- Atmospheric stability and inversion
- Atmospheric chemical reactions
- Scales of air motion (next)

Effect of Atmosphere in Air Pollution

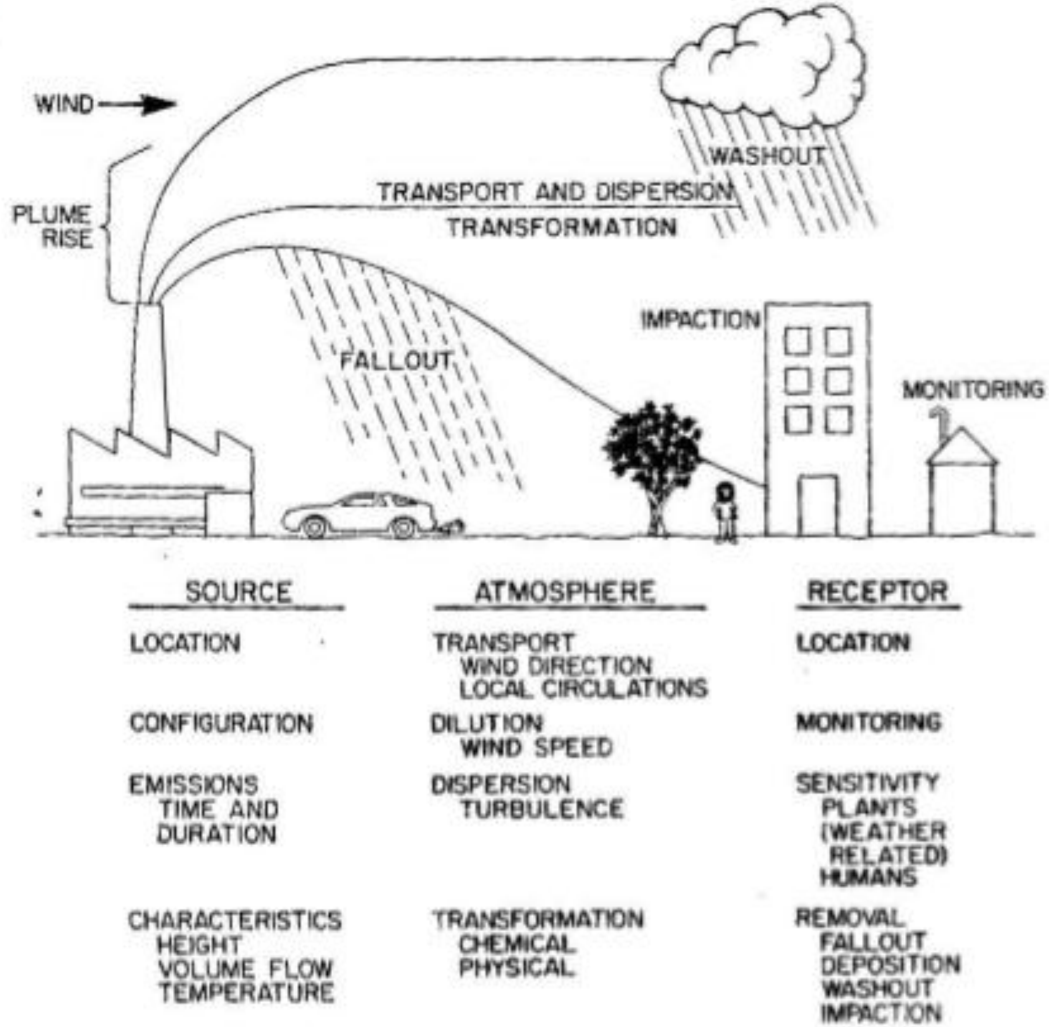


Fig. 18-1. The atmosphere's role in air pollution.

Scales of Air Motion

Table 3.1 Meteorological Scales of Air Motion

Scale	Geographical Area (km^2)	Period	Phenomena
Microscale	2–15	Minutes	Plume behavior Downwash
Mesoscale	15–160+	Hour to days	Sea, lake, and land breezes Mountain valley winds
Synoptic scale large/wide	$>10^6$	Days	Migratory high- and low-pressure systems Cold and warm fronts Semipermanent high-pressure systems
Planetary scale		Weeks to months	Hadley cell flows Tropical storms Jet stream meanders bends Cold and warm fronts

Turbulence

- Circular eddies of air movements (pressure/wind) over short time scales
- Mechanical Turbulence:
  - Caused by air moving over and around structures / vegetation
  - Increases with wind speed
  - Affected by surface roughness
- Thermal Turbulence:
  - Caused by heating/cooling of the earth's surface
  - Flows are typically vertical
  - Convection cells of upwards of 1000 - 1500 meters

- **What is the effect of turbulence on pollution?**
- **Is turbulence desired?**

HORIZONTAL ATMOSPHERIC MOTION -
1. GLOBAL

- Solar heating is maximum at the Equator

  (2.4 X heating at the poles, annual average)
- Atmosphere carries heat from Equator to poles
- Long horizontal distance vs. short height, break-up into:
  - ***tropical, temperate*** **and** ***polar*** **cells**
- Rotation of Earth gives rise to different surface wind patterns in these three zones:
  - Tropical: southeasterly and northeasterly (trade winds)
  - Temperate: westerlies
  - Polar: easterlies

(Figure 5.2 de Nevers)

Figure 5.2 de Nevers

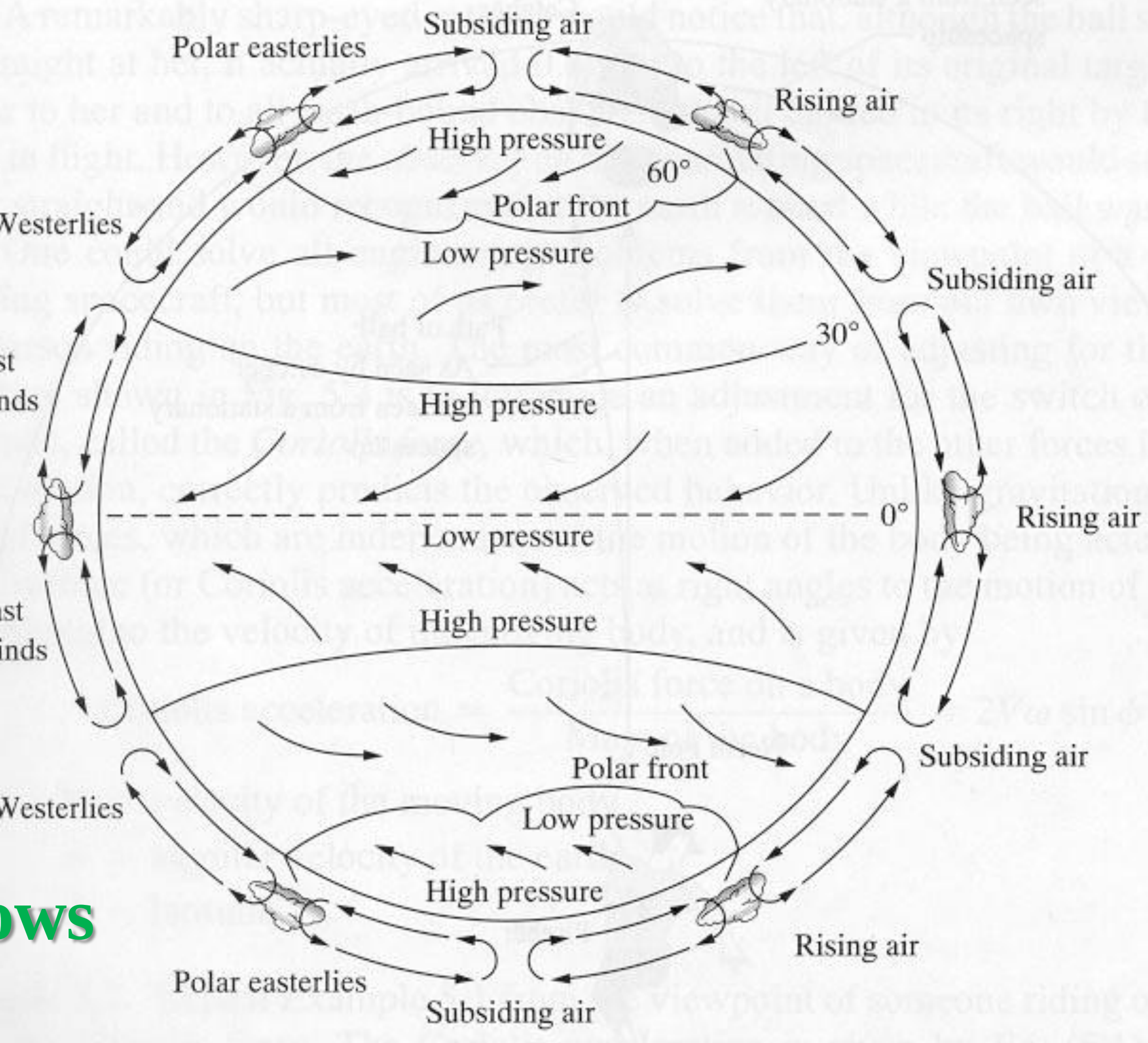


FIGURE 5.2
Schematic representation of the general circulation of the atmosphere. (Frederick K. Lutgens/Edward J. Tarbuck, *The Atmosphere,* 5e, ©1992, p. 170. Reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey.)

Hadley cell flows

HORIZONTAL ATMOSPHERIC MOTION - 2. LOCAL

- Land surface heats and cools faster than ocean/lake surface.
- Daily and seasonal differences result in wind patterns between land and water bodies.

(Figure 5.13 de Nevers)

- “Random” wind patterns between high pressure (anticyclone) and low pressure (cyclones) zones superimposed on global and land-water winds.

Figure 5.13 de Nevers

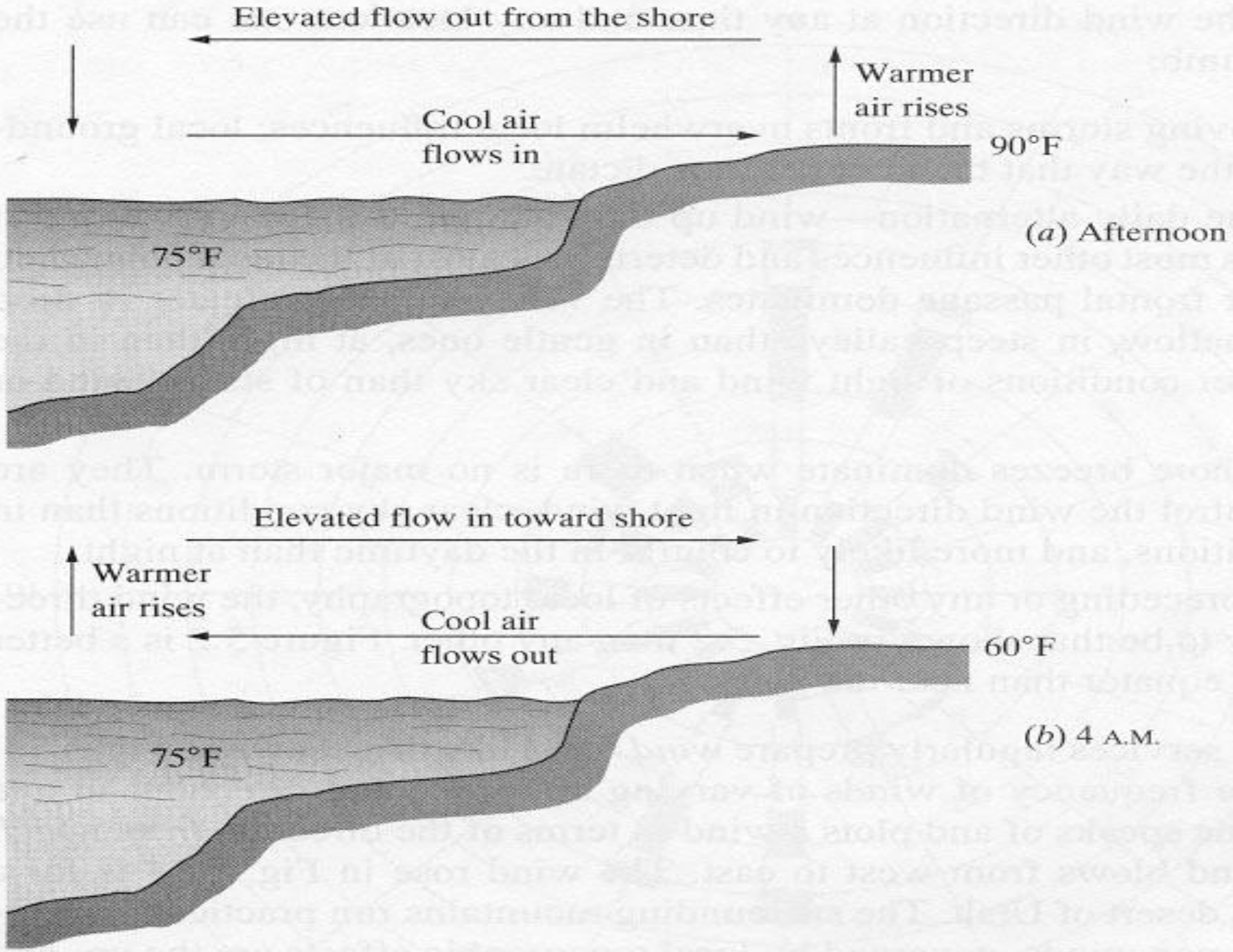


FIGURE 5.13
Onshore sea breezes in the day and offshore land breezes at night.

HORIZONTAL ATMOSPHERIC MOTION - LOCAL

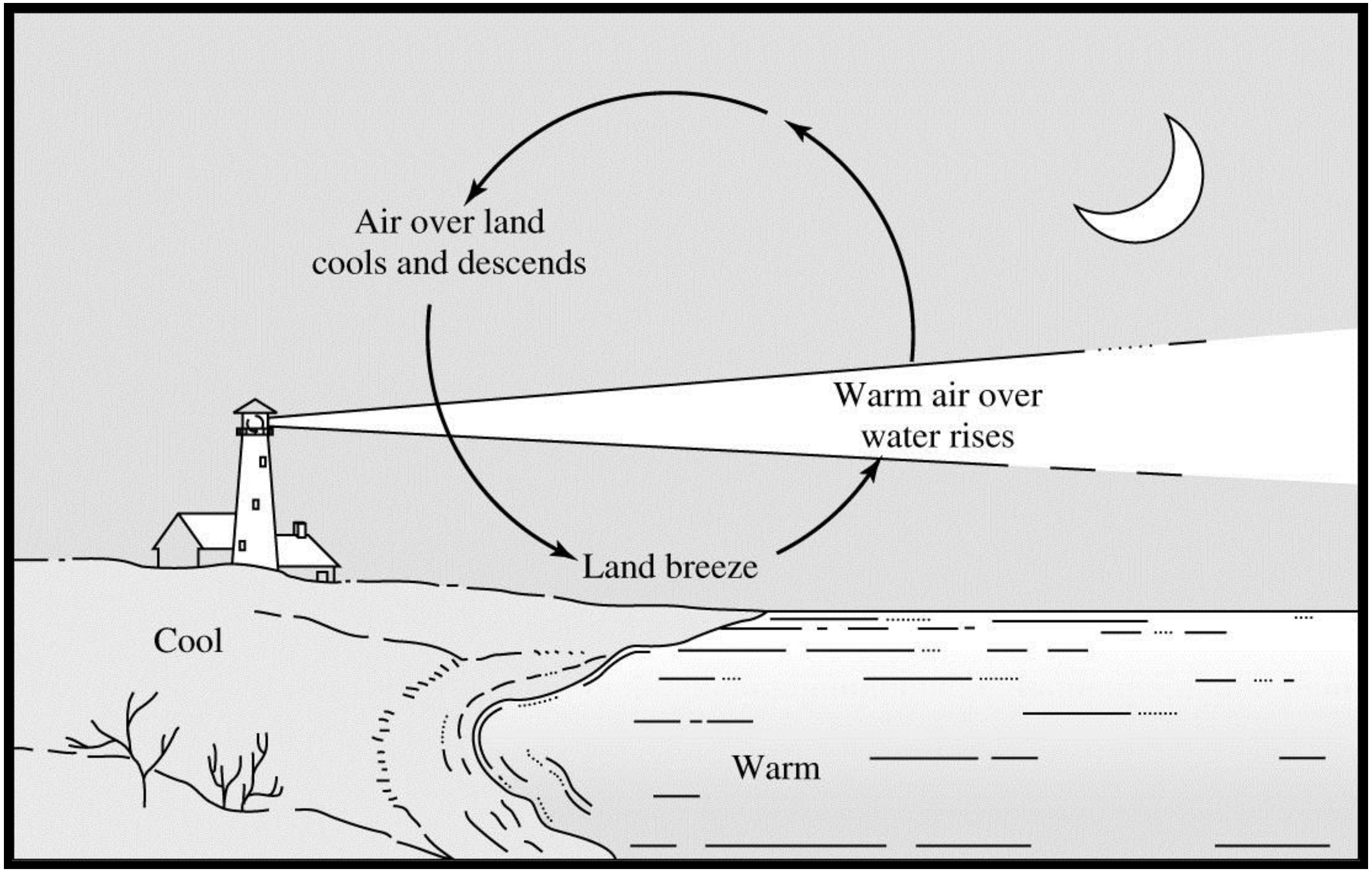


Fig 7-17: Land Breeze during night

HORIZONTAL ATMOSPHERIC MOTION - LOCAL

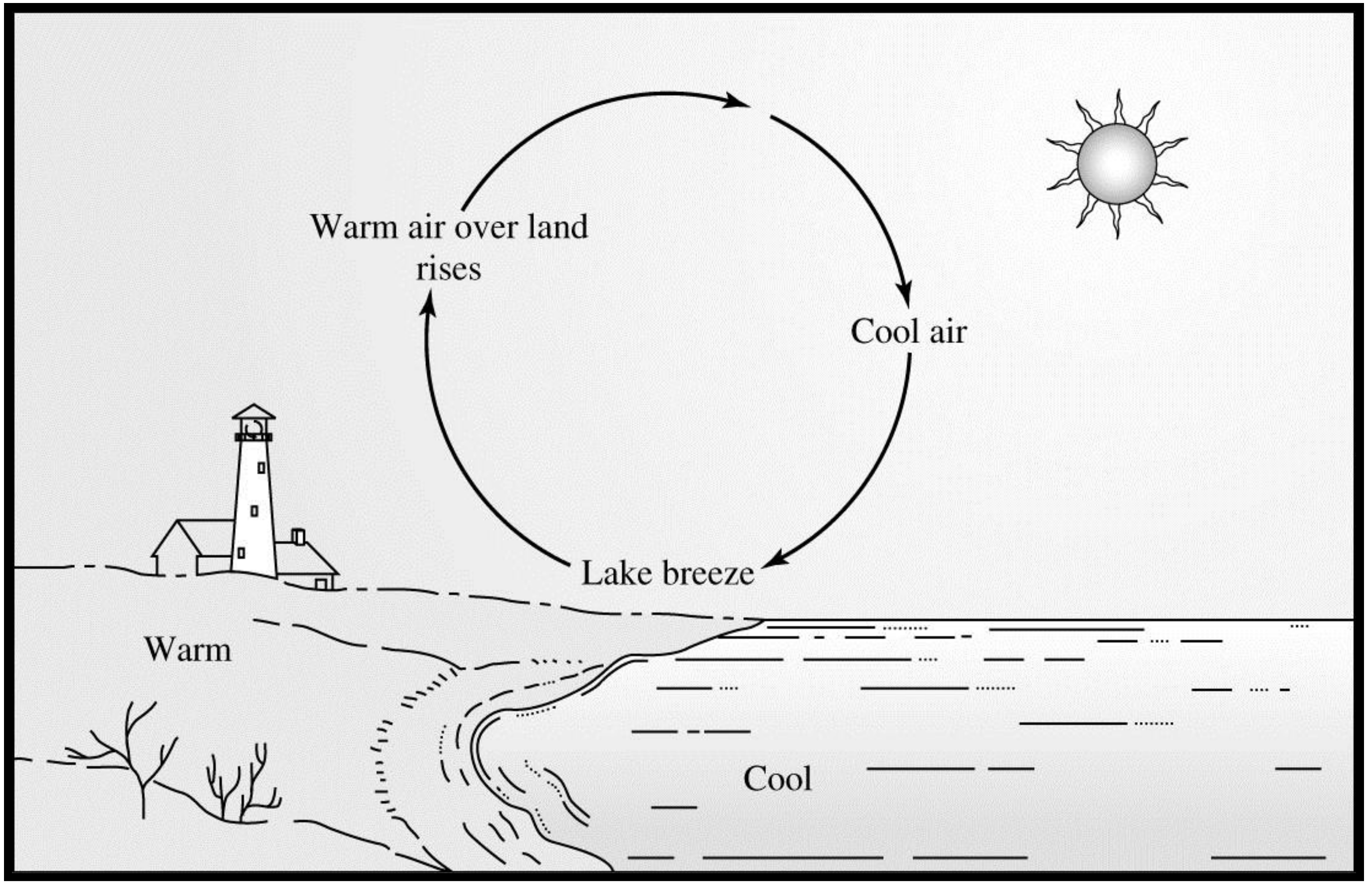


Fig 7-18: Land Breeze during day

ANTICYCLONES - HIGH PRESSURE

- An anticyclone is a weather Phenomenon
  - large-scale circulation of winds around a central region of **high** atmospheric pressure
  - clockwise in the Northern Hemisphere,
  - anticlockwise in the Southern Hemisphere
  - 1020 - 1030 mbar
  - Sinking air near the ground
  - Evaporating moisture, clearing sky

CYCLONES - LOW PRESSURE

- A **cyclone** is an area of closed, circular fluid motion rotating in the same direction as the Earth.
  - Winds rotate counter clockwise in the Northern Hemisphere and Clockwise in the Southern Hemisphere.
  - most large-scale cyclonic circulations are centered on areas of **low** atmospheric pressures.
  - largest low-pressure systems are cold-core polar cyclones and extra-tropical cyclones

CYCLONES - LOW PRESSURE (Cont'd)

- warm-core cyclones include tropical cyclones, mesocyclone, and polar lows.
- 980 - 990 mbar
- Rising air near the ground
- Condensing moisture, clouds & precipitation
- Strong winds, inward toward center, counter-clockwise in the northern hemisphere

CYCLONE (Low Pressure)

(ANTI-CYCLONE (High Pressure)

WINDS

- Affected by:
  - Horizontal pressure gradients
  - Horizontal temperature gradients
  - Friction related to surface roughness

Maximum height of wind profiles indicate where effects of surface roughness end and where gradient wind begins

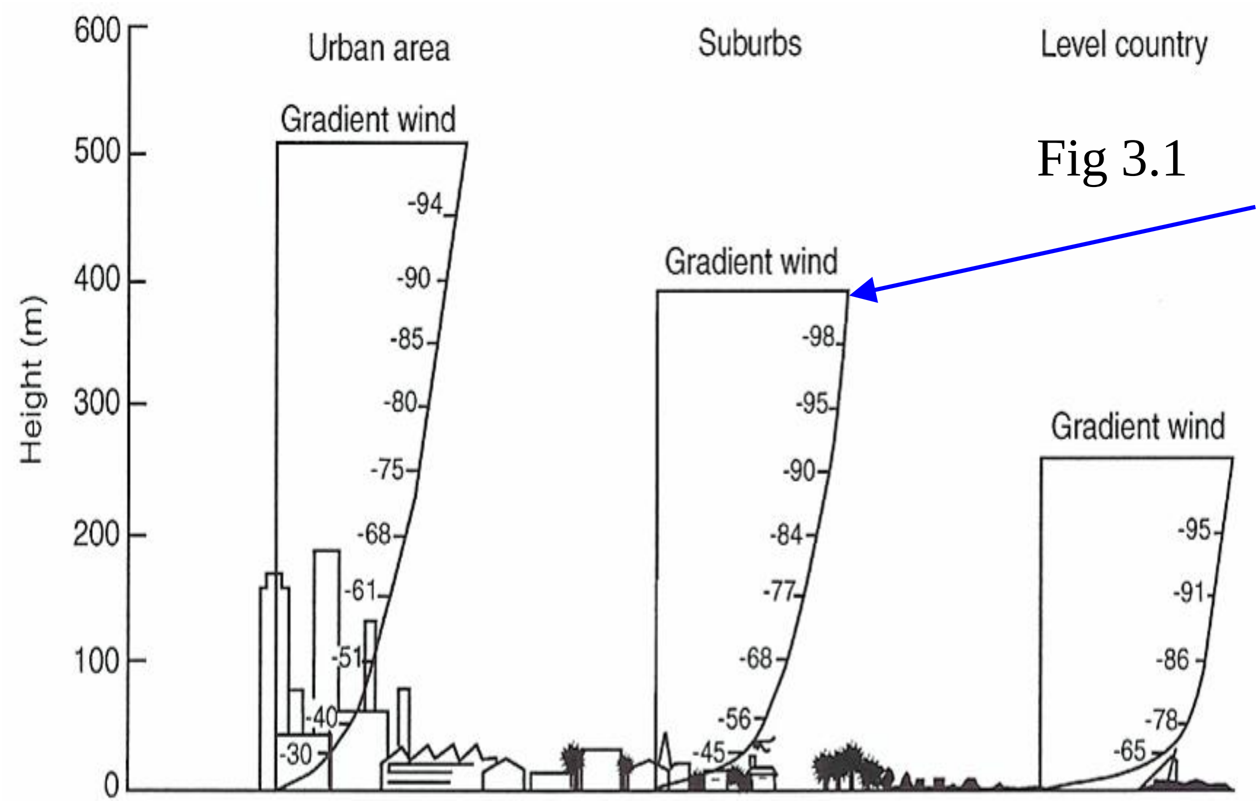


Fig 3.1

<u>Gradient wind:</u>
Horizontal wind with NO friction

WINDS

- **GROUND LEVEL**:
  - Maximum, tornadoes: 200 mph (90 m/s)
  - Typical: 10 mph (4.5 m/s)
  - Frictionless velocity above ~ 500 m
  - Wind rose used for reporting annual wind speed and direction variation

(Figure 5.14 de Nevers)

Wind

Meteorological Station

- **Wind speed:**
  - Effect of wind on emission / dilution of plume: Doubling of the wind speed decreases pollutant levels by 50 %
- **Wind Direction**
  - Prevailing flows
  - Anti- Cyclonic flows
  - Effects of topography
    - In a valley
    - Along sea and lake coasts

Wind Rose

A **wind rose** is a graphic tool used by meteorologists to give a view of how wind speed and direction are typically distributed at a particular location.

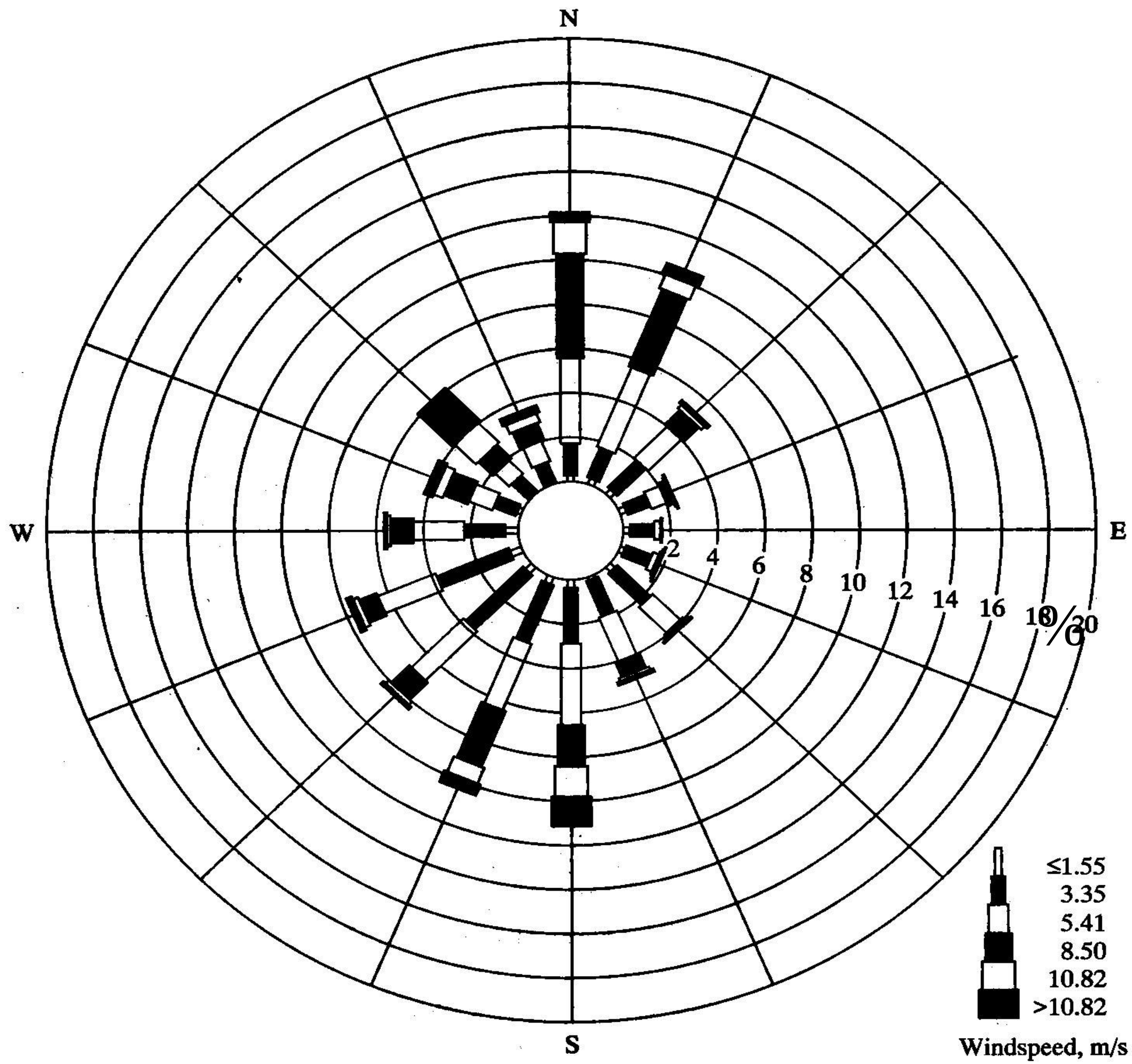


FIGURE 5.14
Wind rose for 1988 at Newfoundland, Utah. The concentric circles represent frequencies. For example, the wind blew from the south 11 percent of the time. It blew from the south with wind velocity > 10.82 m/s about 1 percent of the time; about $3\frac{1}{2}$ percent of the time it blew from the south with velocities between 3.35 and 5.41 m/s.

Atmospheric Stability

- Concept that describes (non-) movement of air near the surface
- Characterized by vertical temperature gradients (Lapse Rates)
  - Dry adiabatic lapse rate (Γ) = 0.0976 °C/m ~ 9.8 °C/km
  - International **standard lapse rate = 6.5 °C/km**

1. Does dry or moist air have a larger temperature change for the same change in elevation?
   - Lapse rate : 4-8 ‹ adiab)
   - Dry air : sensible heat only Wet air: latent & sensible heat
2. Does lapse rate have anything to do with air quality?

First Law of Thermodynamics

= 0 for adiabatic expansion

$$\cancel{dq} = dh - \upsilon dP = C_p dT - \frac{1}{\rho} dP$$

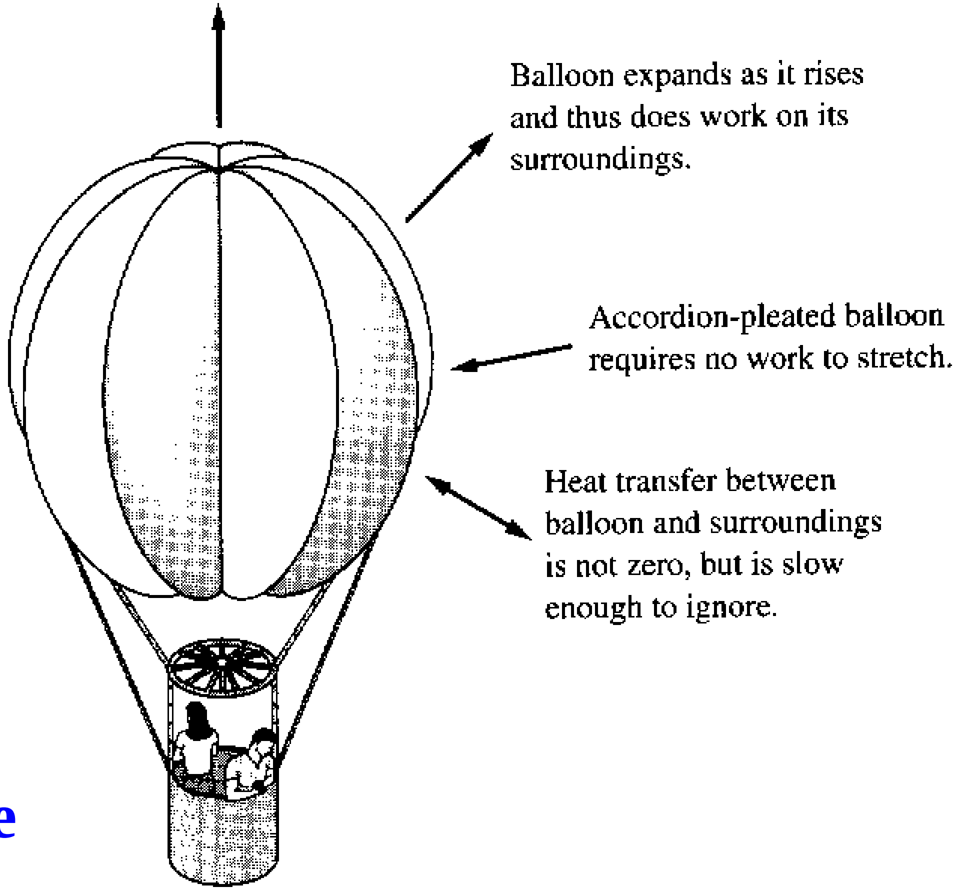
Barometric Equation

$$\frac{dP}{dZ} = -\rho g$$

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

$$\Rightarrow \frac{dT}{dZ} = -\boxed{\frac{g}{C_p}}$$

Lapse Rate



How much is dT/dZ if $C_p = 1.0034\times10^3$ m²/s²-K?
What if $C_p = 1.856\times10^3$ m²/s²-K? (for dry air and moist air, respectively)

Physical Properties of Planetary Gases

	Gas	M kg/ mole	Cp $m^2 s^{-2} K^{-1}$	g $m s^{-2}$	-dT/dz K / km
Venus	CO_2	44 x 0.001	850	8.87	10.4
Earth	O_2 , N_2	29 x 0.001	1003	9.81	9.8
Mars	CO_2	44 x 0.001	850	3.71	4.4

The dry adiabatic lapse rate is

$-dT/dz = M.g/Cp_m$ (Cpm = molar heat capacity @const. P)

$= (29.0 \times 10^{-3}$ kg/mol * 9.8 m/s^2)/29.0 J/(K.mol)

$= 9.8 \times 10^{-3}$ K/m (1K = 1ºC)

= 9.8 K/km (*approximately 10 degrees/meter*)

Lapse Rate Example

Assuming the surface temperature is 15 at the surface of the earth, what is the temperature at 5510.5 m?

$\Gamma = 6.49$ C/km

Solution:

5510.5 m = 5.5105 km

For each km the temperature decreases 6.49

So the temperature decreases:

5.5105 x 6.49 = 35.76

Original temp was 15 , temp at 5.5105 km =

15 - 35.76 = -20.76 C

TEMPERATURE LAPSE RATE
1. THE STANDARD ATMOSPHERE

- Compared with soil and water, the atmosphere is relatively transparent to infrared radiation
- Soil and water surface absorb solar radiation, heat up and heat the adjacent air by convection
- Atmospheric temperature decreases from temperatures of 20ºC at the surface, to around - 50ºC at the troposphere-stratosphere boundary
- *"Standard" atmospheric lapse rate: 6.5 ºC/km*

  (average over day and night, summer and winter)
- A positive value is quoted for lapse rate although temperature decreases with increasing height.

(Figure 5.7, de Nevers)

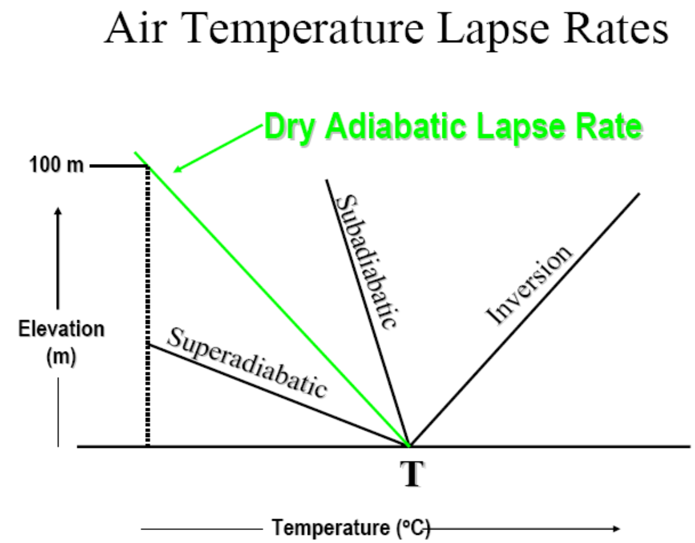
2. SUPERADIABATIC LAPSE RATE

- Lapse rate more than the adiabatic 9.8 ºC/km, e.g. 12 ºC/km
- Small adiabatic displacements in the vertical direction are enhanced by existing temperature profile
- *UNSTABLE conditions*, leading to effective mixing and dispersion
  - Favorable for pollutant dispersion…

3. SUBADIABATIC LAPSE RATE

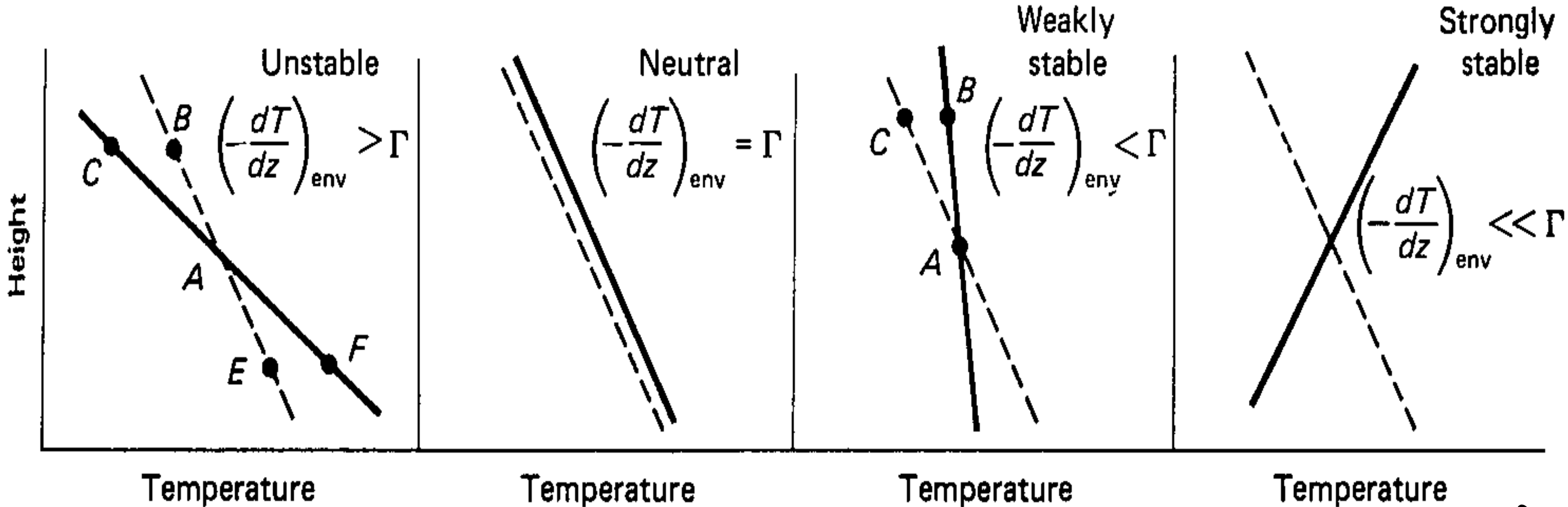
- Lapse rate less than the adiabatic 9.8 ºC/km, e.g. 8 ºC/km
- Small adiabatic displacements in the vertical direction are inhibited by existing temperature profile
- *STABLE conditions*, leading to poor mixing and dispersion
  - Not favorable for pollutant dispersion…

Stability Conditions



------- Adiabatic lapse rate

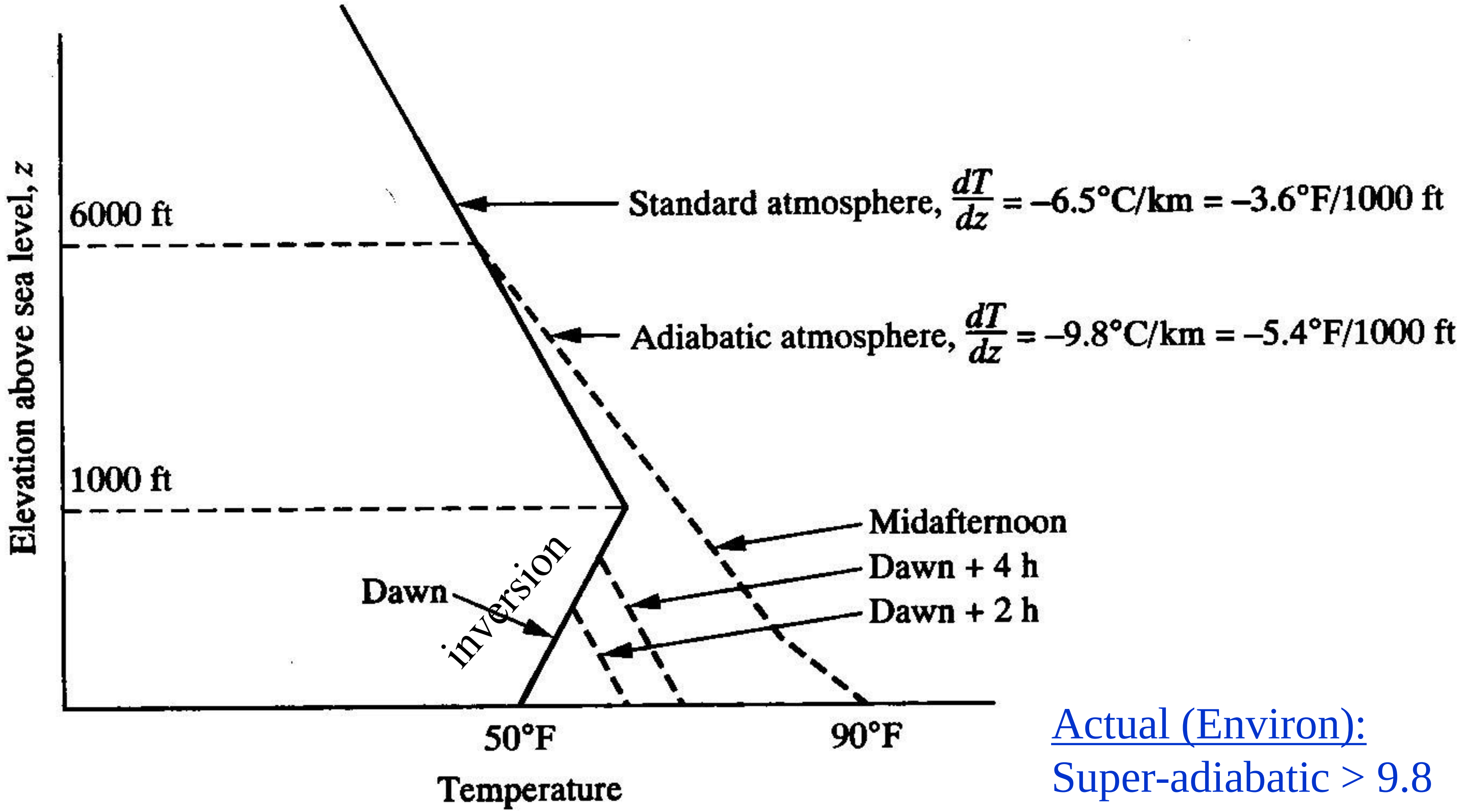
—— Environmental (actual) lapse rate



inversion

Stability Conditions

Figure 5.7 de Nevers



Actual (Environ):

Super-adiabatic > 9.8

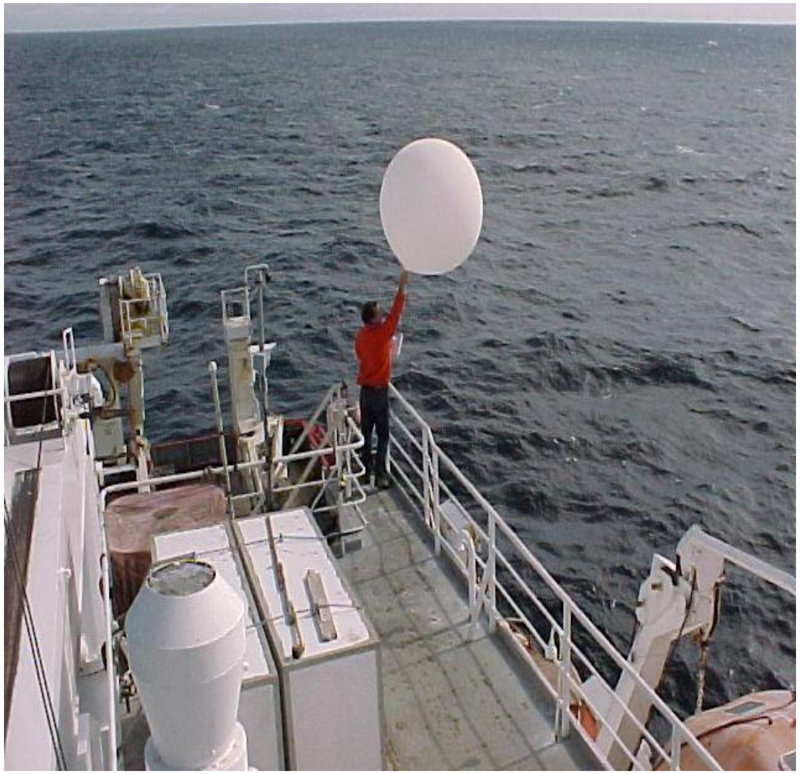
Subadiabatic < 9.8

FIGURE 5.7

Vertical temperature distribution at various times on a cloudless day with low or average winds in a dry climate.

Environmental Lapse Rates

- Actual measured rate of change of temperature with height
- Measured by balloons



<u>Actual (Environ):</u>

- Super-adiabatic > 9.8
- Subadiabatic < 9.8

Thermal Inversions: Types

- *Radiative*

1. Earth cools during night by radiating thermal energy into space.
2. In morning, air near surface will be cooler than air above creating thermal inversion.
3. Daily occurrence due to cooling of ground surface at night
4. Less problematic and persistent.

- *Subsidence (High pressure)*

large regions of high-pressure cold air sinking from above due to weather patterns, heating at adiabatic lapse rate is compressed and heated, causing thermal inversion some distance above ground.

- *Drainage inversion:*

due to horizontal motions, cold air *sliding in under* warm air, or warm air *riding up on* cold air

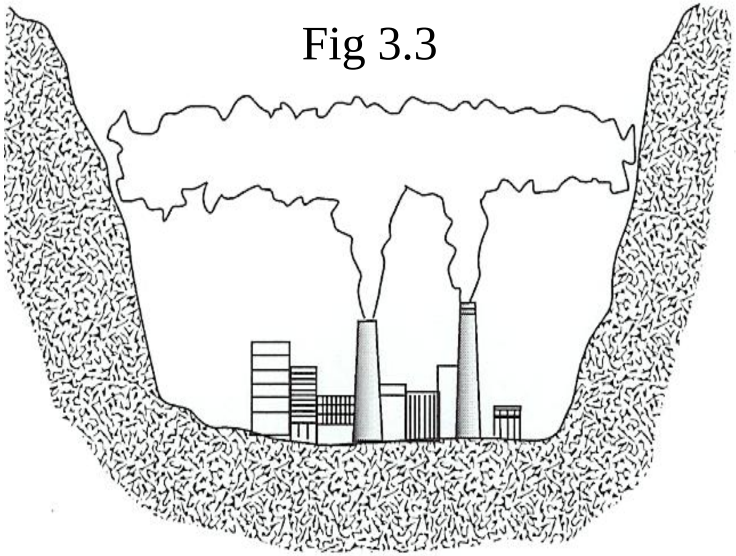
Inversion above Large City

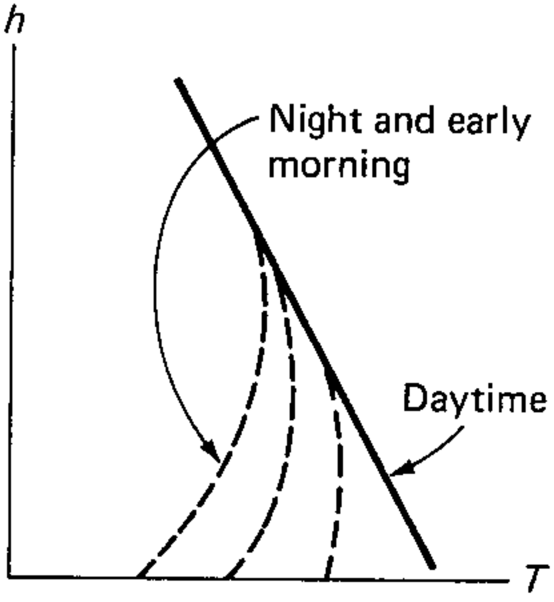
Inversion at Four Corners power plant

Radiational Inversions

- Result from radiational cooling of the ground
- Occur on cloudless nights – nocturnal
- Typically surface based
- Are intensified in river valleys
- Cause pollutants to be "trapped"
- Related to diurnal cycle of cooling /heating

Fig 3.3





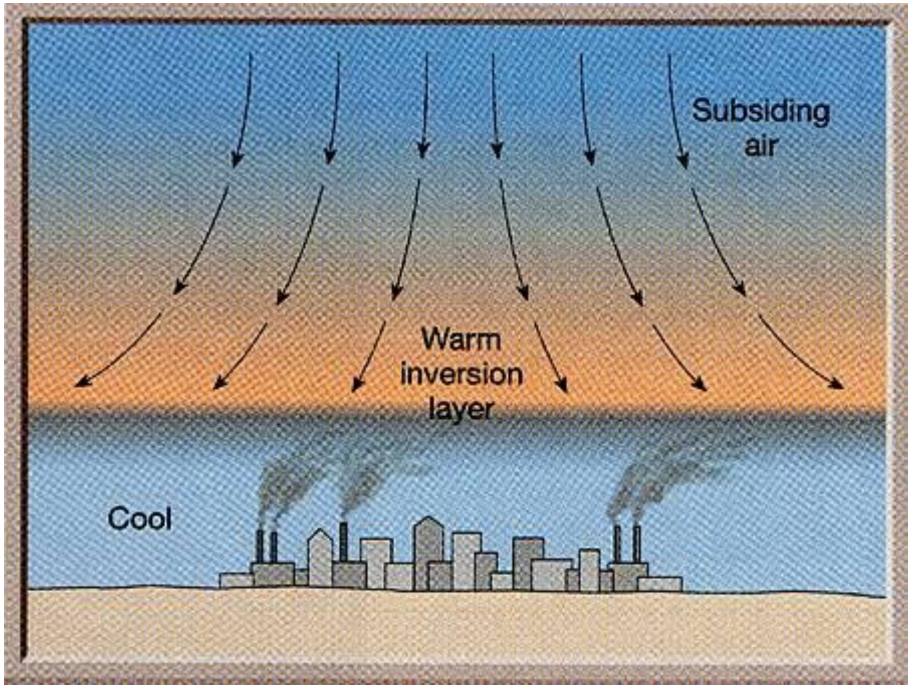
Radiational Inversions

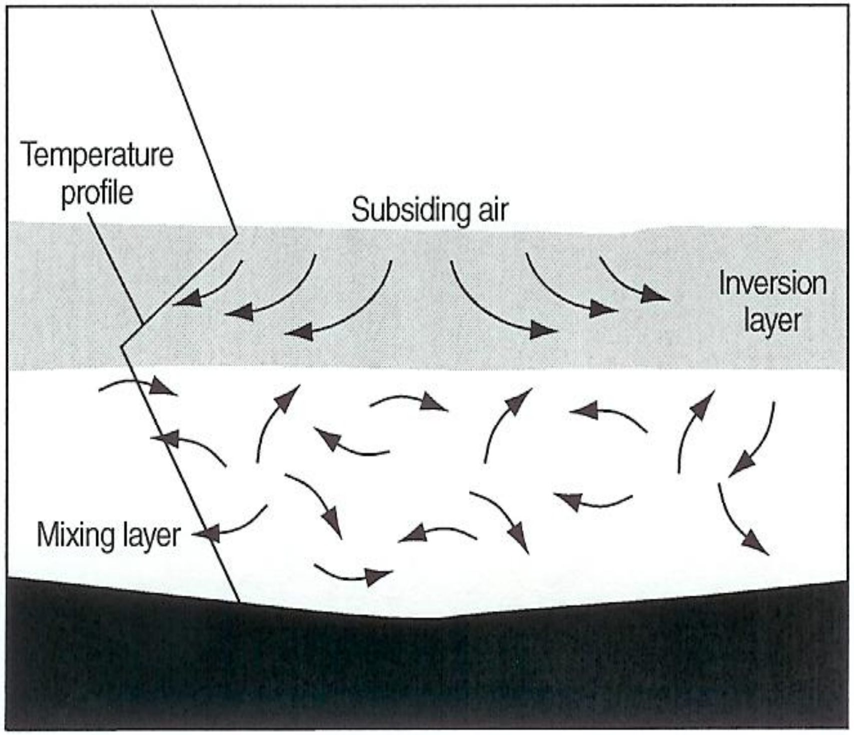
What happens to inversion when sun rises?

- Inversion breaks up after sunrise
- Breakup results in elevated ground level concentrations
- Breakup described as a **fumigation**

Subsidence Inversion

- Associated with high-pressure systems
- Inversion layer is formed aloft *(higher, above)*
- Covers hundreds of thousands of sq.kms.
- Persists for days





MIXING HEIGHT (MH)

- Superadiabatic lapse rate found near ground in early afternoon under a strong sun causes **UNSTABLE** well mixed layer, above which there can be an adiabatic (**NEUTRAL**) or subadiabatic (**STABLE**) atmosphere: Figure 5.9.

1. **DEFINITION of MH**: Height of air that is relatively vigorously mixed and where dispersion occurs
2. Pollutants released at ground level dispersed in this *well-mixed layer.*
3. The lower the mixing height, the higher the resultant pollutant concentration
4. MH: Lower at night than during the day **AND** Lower in the winter than in the summer
5. Can be strongly influenced by weather patterns
6. Typical values, 0 - 2000 m

Mixing Height

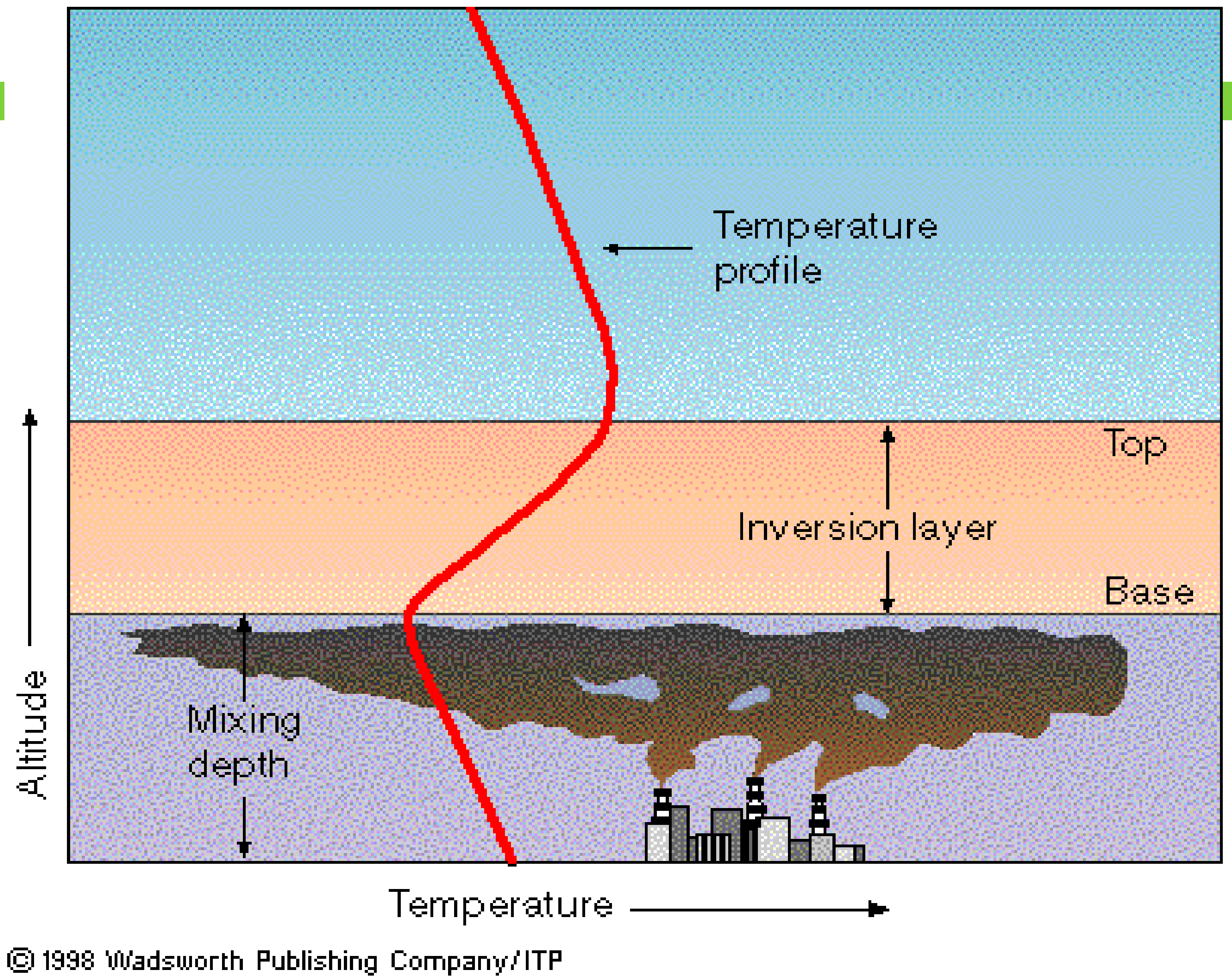
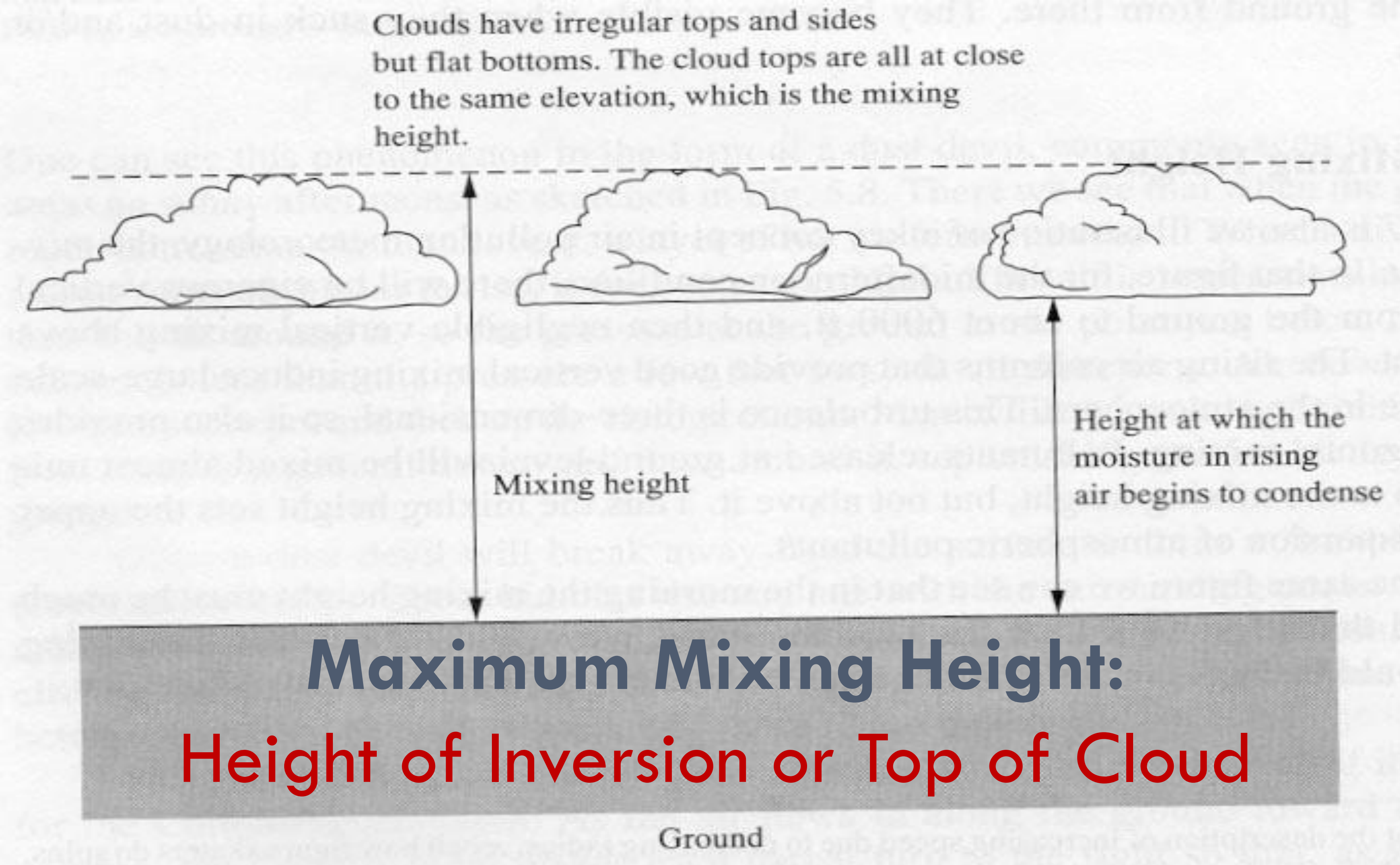


Figure 5.9 de Nevers



Maximum Mixing Height:

Height of Inversion or Top of Cloud

FIGURE 5.9
During the day many small clouds with a common top elevation show the height of the mixing layer. The flat bottoms show the elevation at which condensation begins (see Section 5.3.5).

Maximum Mixing Height:
Height of Inversion or Top of Cloud

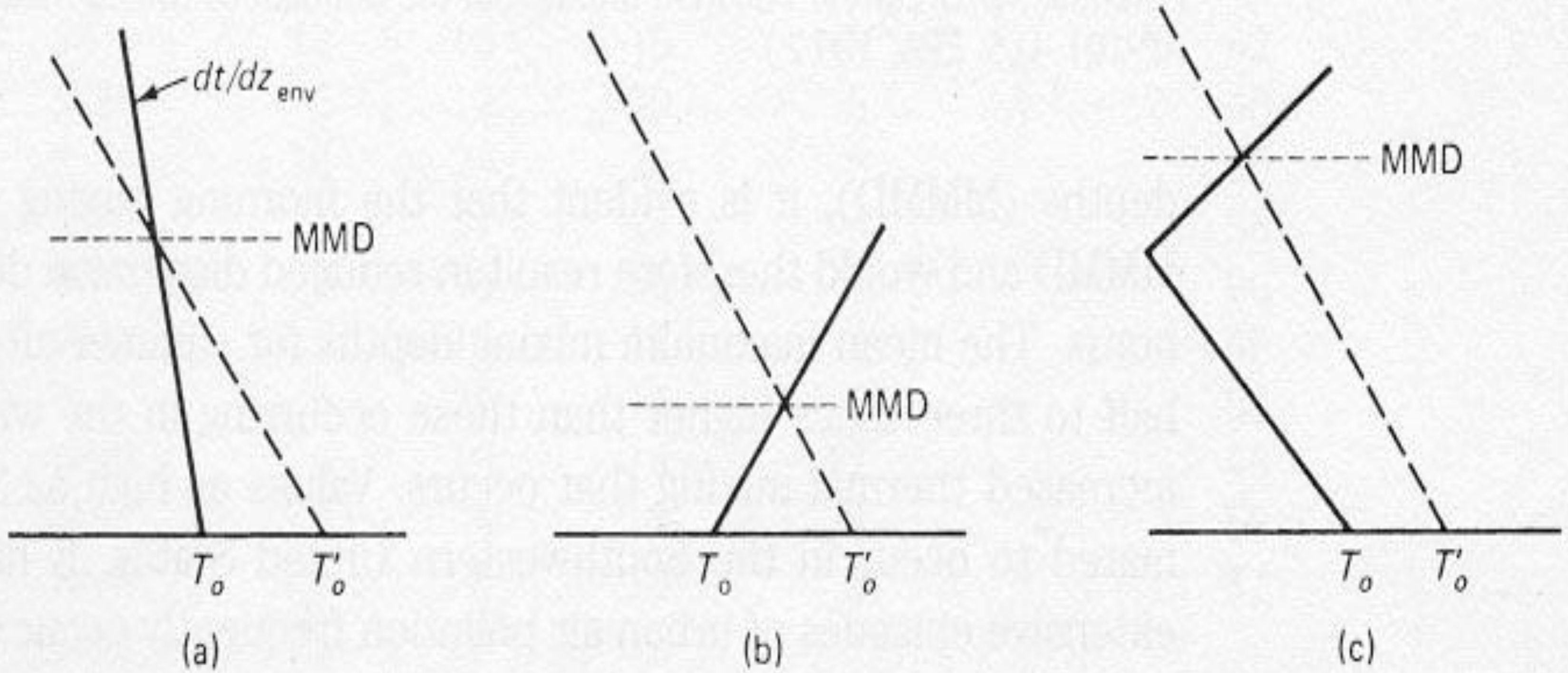
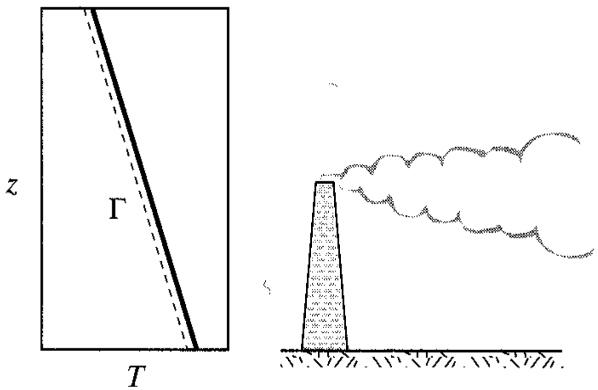


FIGURE 3-14 Establishment of the maximum mixing depth (MMD) under various atmospheric conditions (adiabatic profile - - -, environmental profile—).

Plume types

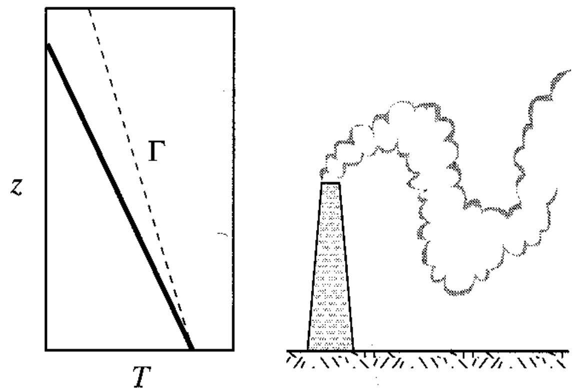
- The smoke trail or plume from a tall stack located on flat terrain has been found to exhibit a characteristic shape that is dependent on the stability of the atmosphere.
- There are six types of plume behavior as shown in the Figure (next).
- In each case, the reference lapse rate, Γ, is given as a broken line to allow comparison with the actual lapse rate, which is given as a solid line.

Effect of Lapse Rate on Plumes



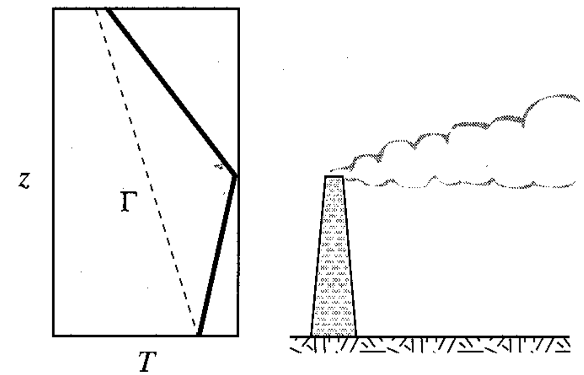
Coning

(*a*)



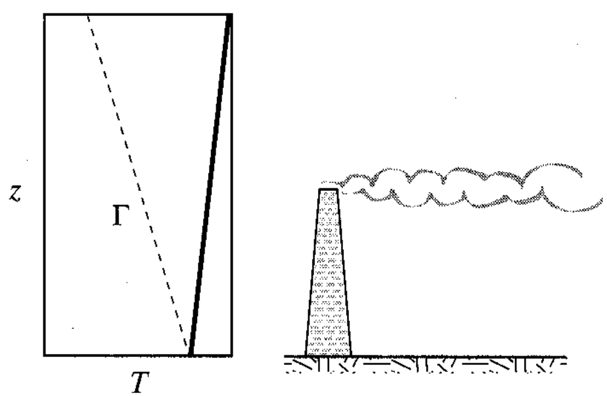
Looping

(*b*)



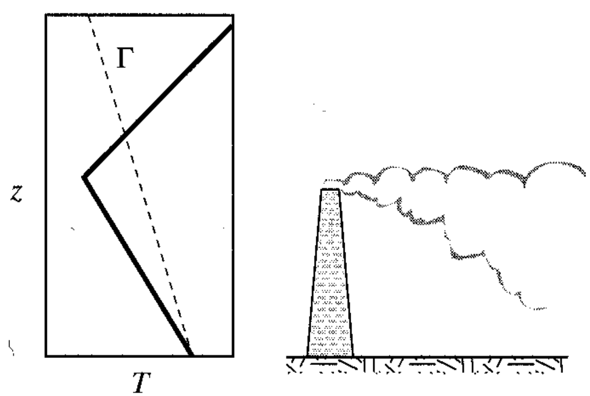
Lofting

(*e*)



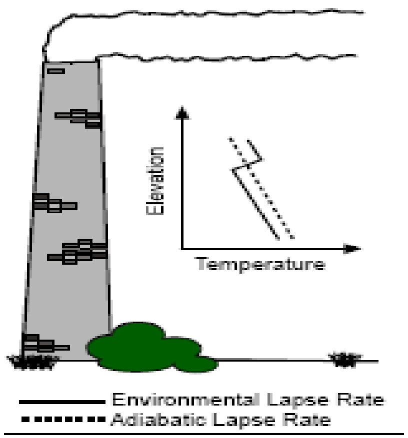
Fanning

(*c*)



Fumigation

(*d*)



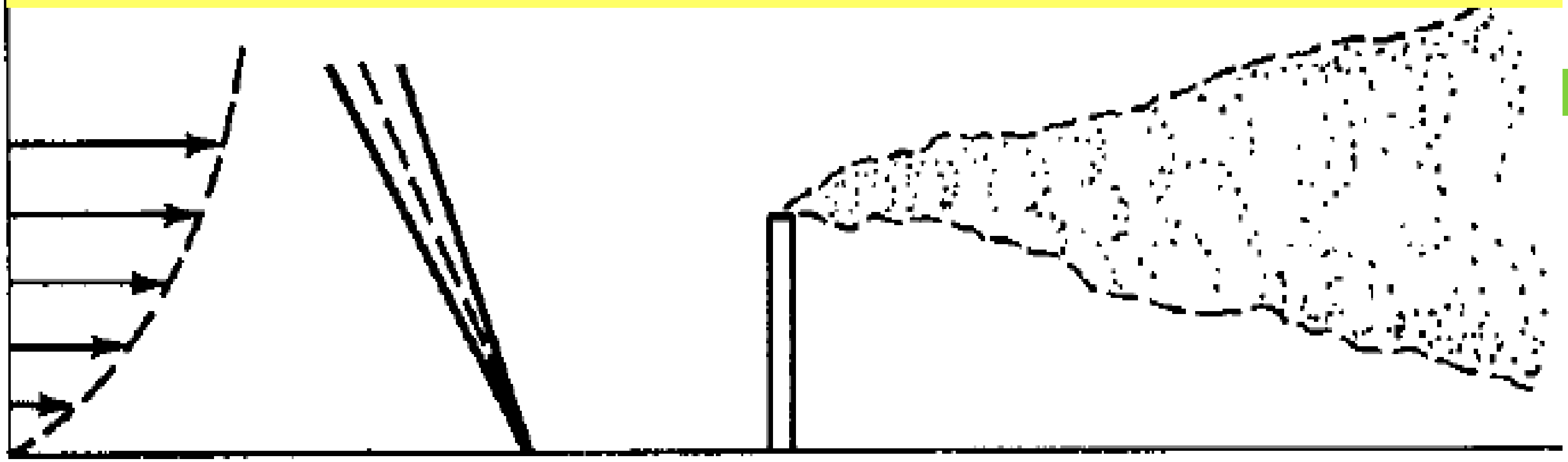
Trapping

(f)

(a) CONING PLUMES.

1. *Neutral or slightly* unstable conditions create a coning plume that is distinguished by large billows or puffs of pollutants.
2. Coning plumes are typically formed on partly cloudy days when there is an alternate warming and cooling of the atmosphere.
3. Warm gases released into cool, ambient air mix, expand, and rise into the upper atmosphere

Stack Plume: Coning



(b) Strong wind, no turbulence

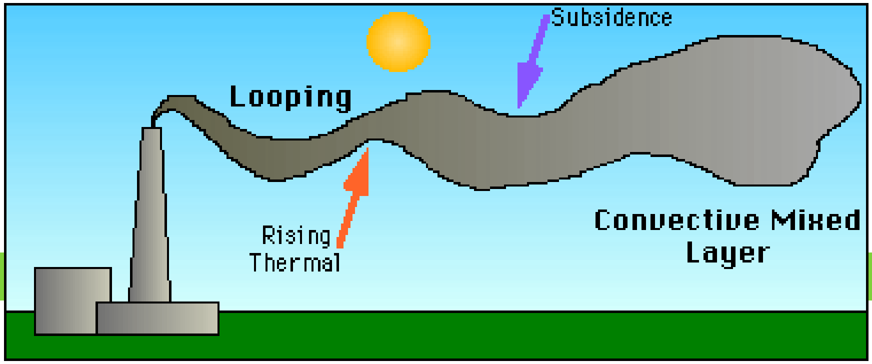
What is the stability class? (dashed line is adiabatic lapse rate) c

Is there good vertical mixing? OK

On sunny or cloudy days? Partly cloudy

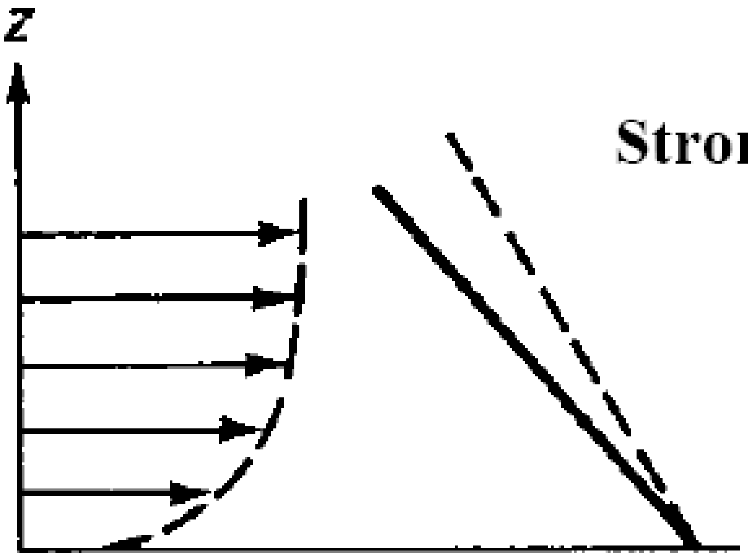
Good for dispersing pollutants? OK

(b) LOOPING PLUMES.

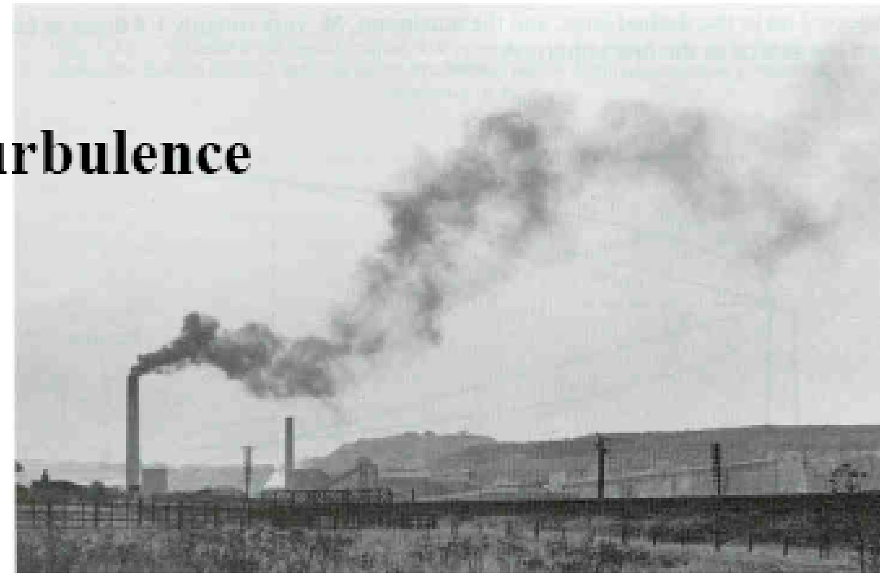


1. Pollution that is released into an *unstable atmosphere* forms looping plumes.
2. Rapid changes in temperature and pressure may result in plumes that appear billowing and puffy.
3. Unstable conditions are usually favorable for pollutant dispersion.
   - However, high concentrations of air pollution forced down by cooling air can be harmful if trapped at ground level.
   - This can occur on sunny days with light to moderate winds, which combine with rising and sinking air to cause the stack gases to move up and down in a wavy pattern producing a looping plume

Stack Plume: Looping



Strong turbulence



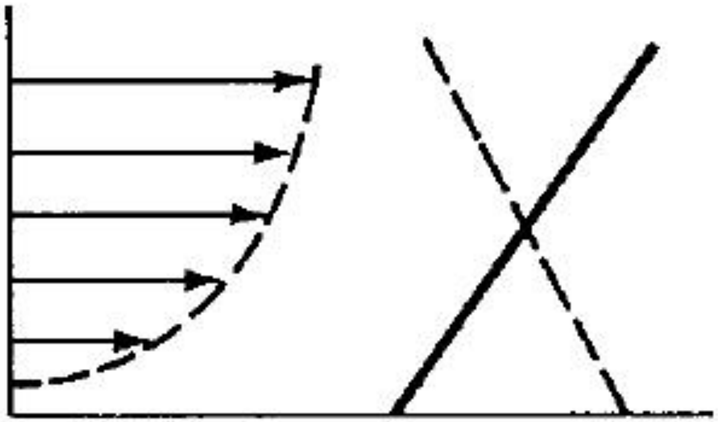
http://www.med.usf.edu/~npoor/3

Is it at stable or unstable condition? Unstable
High or low wind speed? Low wind speed.
Does it happen during the day or night? Day
Is it good for dispersing pollutants? Yes

(c) FANNING PLUMES.

1. A fanning plume occurs during *stable conditions* and is characterized by long, flat streams of pollutant emissions.
2. Because atmospheric pressure is stable, there is neither a tendency for emissions to rise nor descend permitting (horizontal) wind velocity to transport and disperse the pollutant.
3. Fanning plumes are usually seen during the early morning hours just before the sun begins to warm the atmosphere and winds are light

Stack Plume: Fanning



http://www.med.usf.edu/~npoor/4

What is the stability class? (solid line is actual air temperature with altitude air temp lapse rate)

What is the top view of the plume?

(d) Fumigating plumes

1. In the early morning, if the plume is released just below the inversion layer, a very serious air pollution episode could develop.
2. When pollutants are released below the inversion layer, gaseous emissions quickly cool and descend to ground level.
3. This condition is known as fumigation and results in a high concentration of pollution that can be damaging to both humans and the environment alike.
4. This atmospheric condition characterizes the most destructive type of air pollution episodes

FUMIGATION

1. The daily radiation inversion starts breaking up near the ground as the ground heats.
2. This can lead to a sandwich phenomenon with an inversion layer bounded by a stable layer above and an unstable layer below.
3. As the unstable layer from below reaches the height of a pollutant plume in the inversion layer the plume mixes downward, producing temporary but high ground level concentrations.

(Figure 5.15 de Nevers, next)

Figure 5.15 de Nevers

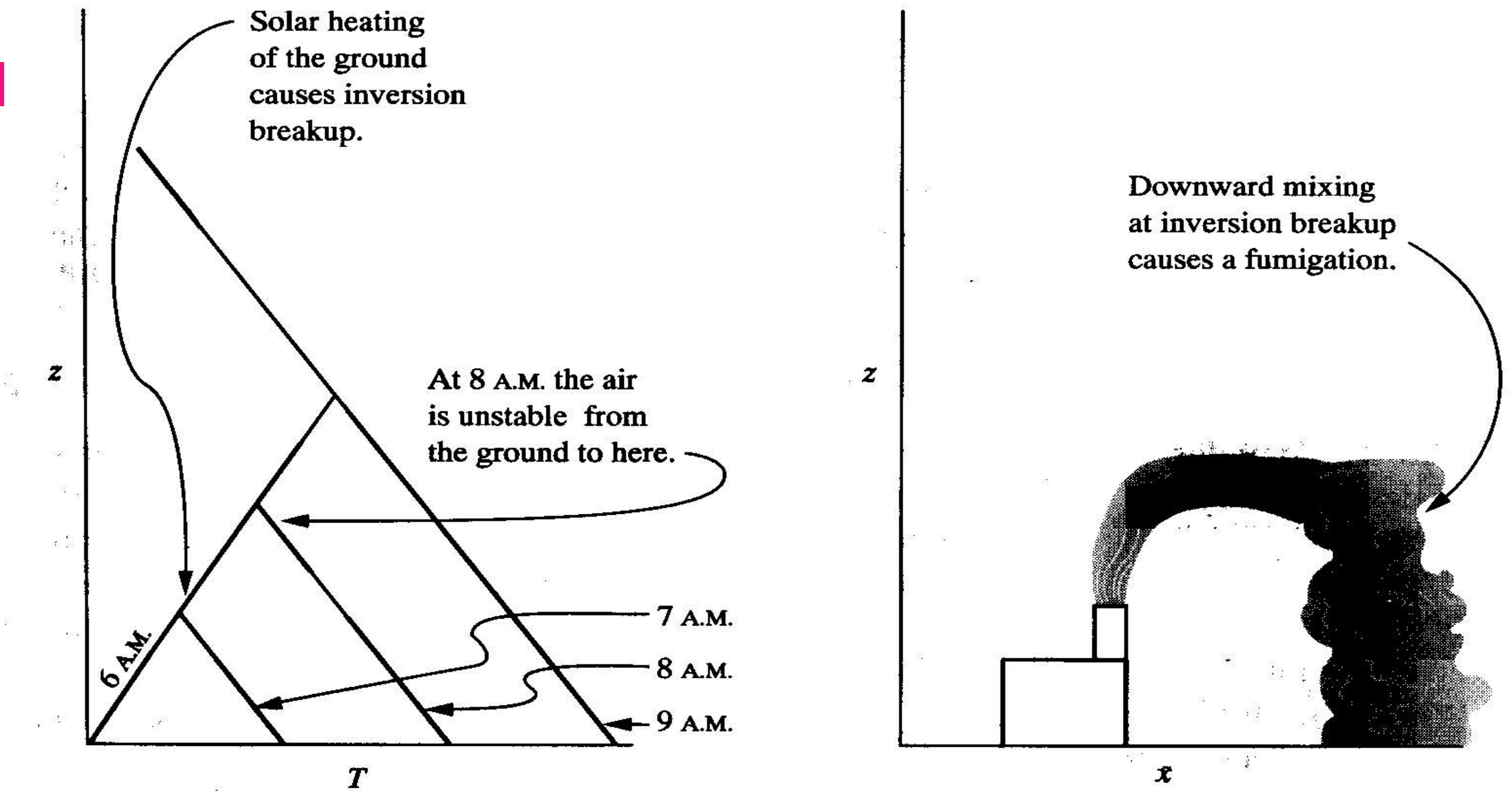


FIGURE 5.15
The development of a *fumigation*. The figure at the left shows the vertical temperature profile at various times. At 6 A.M. there is an inversion that is slowly destroyed by solar heating. On the right, the plume from a factory is shown inside an inversion. It flows horizontally with little 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.

Building downwash

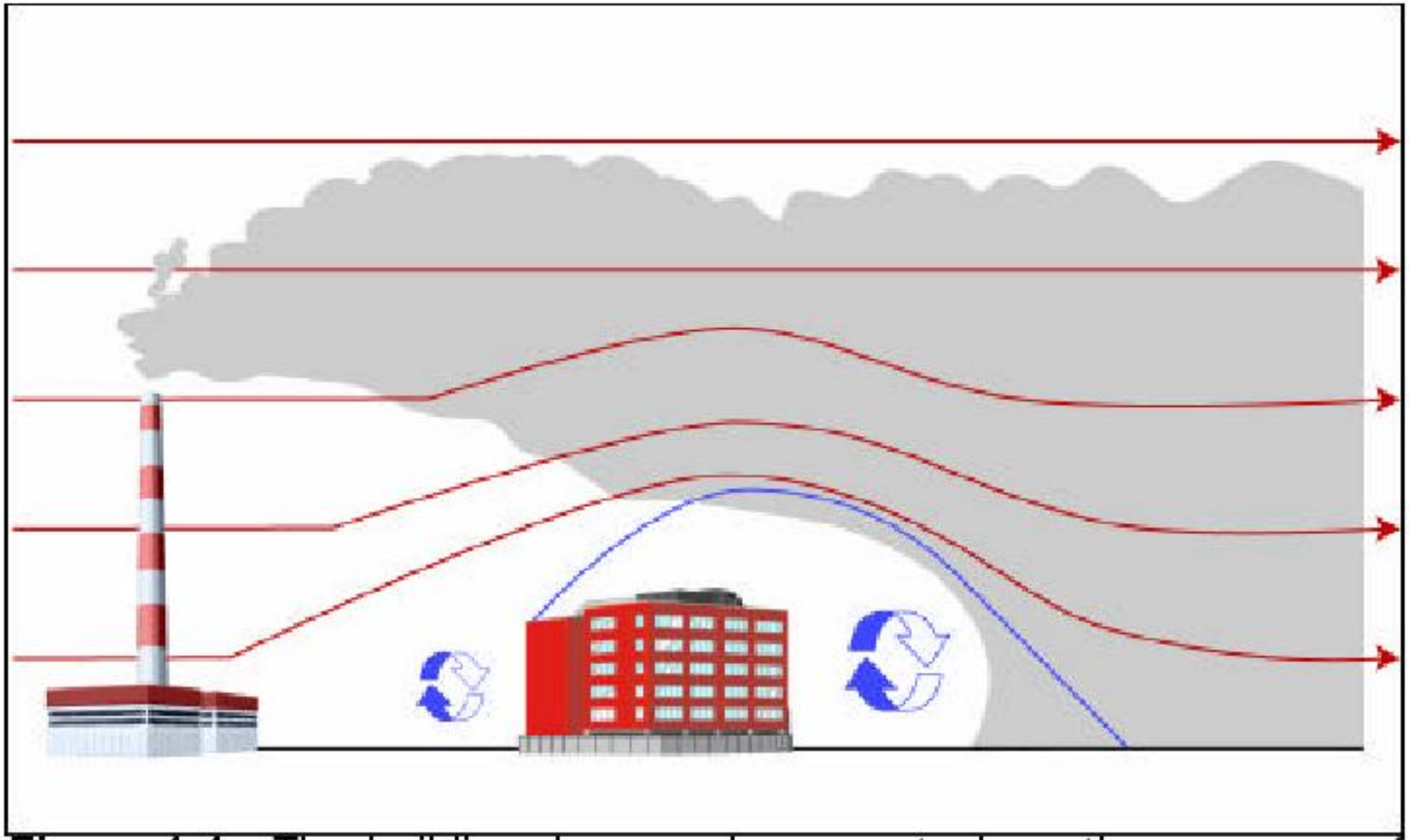
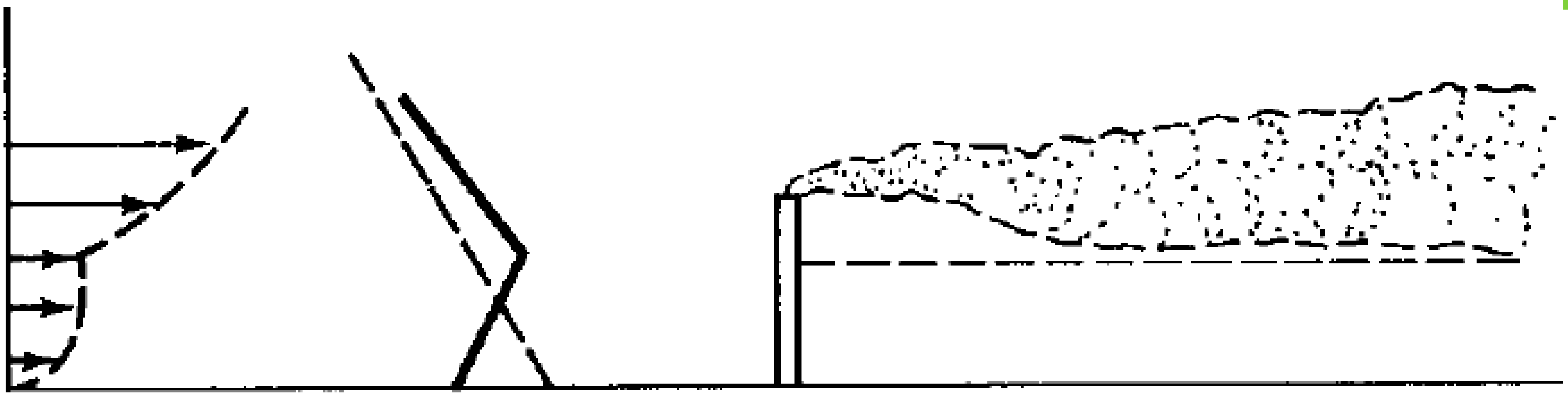


Figure 4.4 - The building downwash concept where the presence of buildings forms localized turbulent zones that can readily force pollutants down to ground level.

(e) LOFTING PLUMES.

1. When the atmosphere is relatively *stable*, warm air remains above cool air and creates an inversion layer.
2. Pollutants released below the inversion layer will remain trapped at ground level and, in the absence of any atmospheric instability, prevent the upward transport of the pollutant.
3. When there is little or no vertical mixing, pollutants tend to form in high concentrations at ground level.
4. When conditions are unstable or neutral above the inversion layer, stack gases above that level form a lofting plume that can effectively disperse the pollutant into the upper atmosphere

Stack Plume: Lofting



Why can't the pollutants be dispersed downward?

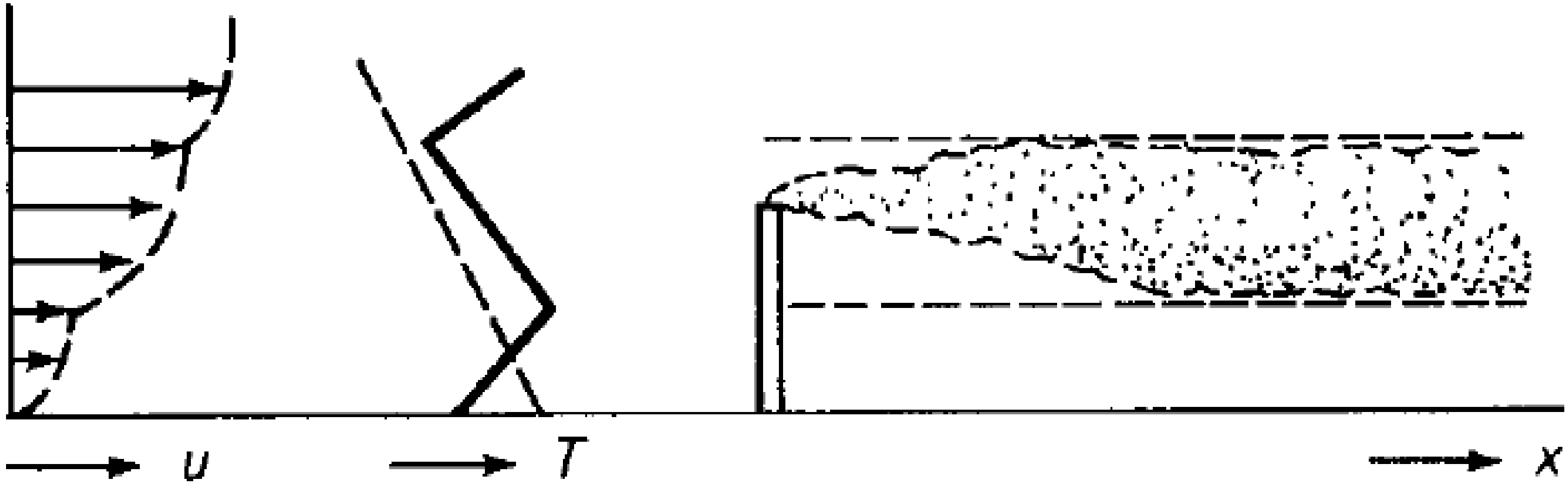
What time of the day or night does this happen?

Evening – night as radiation inversion forms

(f) TRAPPING PLUMES.

1. A trapped plume, on the other hand, is produced on clear, sunny days or clear nights with light winds.
2. A trapped plume is the result of an *unstable air mass that* creates an inversion layer both above and below the plume.
3. A trapped plume, in contrasted with a fumigating plume, is one of the most favorable types of plume for pollutant dispersion.
4. Temperature inversions, both above and below the plume, protect ground sources from potential exposure while winds at altitude disperse and dilute the pollutant

Stack Plume: Trapping



(f)

What weather conditions cause plume trapping?

Radiation inversion at ground level, subsidence inversion at higher altitude (evening – night)