Introduction & Transport Of Air Pollution

Contents…

History of Air pollution and episodes, Sources of air pollution and types, Introduction to meteorology and transport of air pollution: Global winds, Headley cells, wind rose terrestrial wind profile, Effects of terrain and topography on winds, lapse rate, maximum mixing depths, plume rise

Air Pollution Episodes

Introduction:-

- ✓ introduction of chemicals, particulate matter, or biological materials that cause harm or discomfort to humans or other living organisms, or damages the natural environment, into the atmosphere.
- ✓ Above background level.
- ✓ Source : anthropogenic & natural

History:

- ✓ In AD 61 Roman philosopher Seneca reported : "the heavy air of Rome and from the stink of the smoky chimneys thereof, which, being stirred, poured forth whatever pestilential vapors and soot they had enclosed in them, I felt an alteration of my disposition".
- ✓ Coal burning caused air pollution in England under King Henry II. Coal burning prohibited in 1306.
- ✓ Next due to industrial revolution

A Few Well-Known Air Pollution Episodes Around the Globe in the 20th Century.

Region affected	*Date*	*Cause*	*Pollutant*	*Effects*
Meuse valley, Belgium	December 1930	Temperature inversion	SO_2	63 deaths
Los Angeles, USA	July 1943	Low wind circulation	smog	unknown
Donora, PA, USA	October 1948	Weather inversion	SO_2	20 deaths
London, England	December 1952	Subsidence inversion	SO_2, smog	3,000 excess deaths
New York City, USA	December 1962	Shallow inversion	SO_2	269 excess deaths
Bhopal, India	December 1984	Accident	methyl iso-cyanate	> 2,000 deaths
Chernobyl, Ukraine	April 1986	Accident	Radioact i-vity	31 immediate deaths, > 30,000 ill
Lake Nyos, Africa	April 1986	Natural	CO_2	1,700 deaths
Kuala Lampur, Malaysia	September 1997	Forest fire	CO, soot	Unknown

Meuse Valley, 1930

- ✓ Occurred in the first week of December 1930,
- ✓ A thick mist lay over large parts of Belgium. The area around Engis was the worst affected.
- ✓ On December 3rd, 4th and 5th, several thousand cases of acute pulmonary attacks. 60 deaths were reported..
- ✓ Cause was poisonous products in the waste gas of the many factories in the valley(majorly SO_2 , in conjunction with unusual climatic conditions.
- ✓ Resulted in above freezing point during day while at night it measured up to 10°C below, while the wind speed was only 1-3km/hr.

Los Angeles Smog,1943

- ✓ LosAngeles,California 6 July.
- ✓Becomes one of the first cities in the U.S. to experience severe air pollution problems then called “gas attacks”.
- ✓Accumulation of auto exhaust and emissions from local petroleum refineries resulting into smog.

Cleveland Gas Explosion,1944

- ✓ Occurred on the afternoon of Friday, October 20, 1944.
- ✓ Result gas leak, explosion and fires .
- ✓ killed 130 people and destroyed a one square mile area on Cleveland, Ohio's east side.
- ✓ Storage tank number 4, holding liquefied natural gas in the East Ohio Gas Company's tank farm, emit a vapour that poured from a seam on the side of the tank.
- ✓ The tank was located near Lake Erie and winds from the lake pushed the vapour into a mixed use section of Cleveland, where it dropped into the sewer lines via the catch basins located in the street gutters.
- ✓ As the gas mixture flowed and mixed with air and sewer gas, the mixture ignited. In the ensuing explosion, manhole covers launched skyward as jets of fire erupted from depths of the sewer lines.

Donora Smog,1948

✓**1948** Air pollution kills in Donora, Pennsylvania.

✓Dispersal of fluoride emissions from zinc smelting and blast furnaces.

✓Other sources containing sulphur, carbon monoxide and heavy metal dusts that were trapped by weather conditions.

✓Out of a total population of 14,000 people, 20die within 14 hrs, 600 others become ill, and 1400 seek medical attention.

Mexico, Poza Rica, 1950

✓ City of 22,000 people located about 210 km northeast of Mexico leading oil-producing district and the site of several oil field installations, including a sulphur-recovery plant.

✓ A catastrophic exposure episode involving the release of large quantities of hydrogen sulfide in November 1950

✓Malfunction of the waste gas flare resulted in the release of large quantities of unburned hydrogen sulfide into the atmosphere.

✓ The unburned gas, aided by a low-level temperature inversion and light early morning breezes, was carried to the residential area adjacent to the plant area.

✓Within a matter of 3 hours, 320 persons were hospitalised and 22 were killed.

Great Smog ,London 1952

- ✓ collected airborne pollutants mostly from the use of coal to form a thick layer of smog over the city.
- ✓ caused major disruption due to the effect on visibility, and even penetrated indoor areas.
- ✓ Medical reports estimated that 4,000 had died prematurely and 100,000 more were made ill due to effects on the human respiratory tract.
- ✓ considered the worst air pollution event in the history of the United Kingdom, and the most significant in terms of its impact on environmental research, government regulation, and public awareness of the relationship between air quality and health

Bhopal Disaster, 1984

- ✓ In the mid night of 2nd - 3rd December 1984,
- ✓ A poisonous vapour burst from the tall stacks of the Union Carbide pesticide plant.
- ✓ forty tons of toxic gases had leaked from the Carbides Bhopal plant and spread throughout the city.
- ✓ The cause was the contamination of Methyl Isocyanate (MIC) storage tank with water carrying catalytic material.
- ✓ Of the million people living in Bhopal at that time, more than 2,000 died immediately (one fourth of actual figures) and as many as 300,000 were injured. In addition, about 7,000 animals were affected, of which about 1000 were killed.

Chernobyl disaster ,1986

- ✓ The Chernobyl accident in 1986 was the result of a flawed reactor design that was operated with inadequately trained personnel.
- ✓ The resulting steam explosion and fires released at least 5% of the radioactive reactor core into the atmosphere and downwind.
- ✓ Two Chernobyl plant workers died on the night of the accident, and a further 28 people died within a few weeks as a result of acute radiation poisoning

Lake Nyos, Africa 1986

- ✓ A sudden outgassing of CO_2 had occurred at Lake
- ✓ On August 21, 1986, a limnic eruption occurred at Lake Nyos which triggered the sudden release of about 1.6 million tonnes of CO_2;
- ✓ This cloud rose at nearly 100 kilometres (62 mi) per hour. The gas spilled over the northern lip of the lake displacing all the air and suffocating the living beings.
- ✓ Some 1,700 people within 25 kilometres (16 mi) of the lake, mostly rural villagers, as well as 3,500 livestock.

Lake Nyos as it appeared less than two weeks after the eruption; August 29, 1986.

A cow suffocated by gases from Lake Nyos

Malaysia Haze, 2005

- ✓ A week-long choking smog-like haze over Malaysia .
- ✓ The haze was at its worst on August 11, 2005. This was a comeback of the haze crisis which last hit Malaysia in September 1997.
- ✓ Caused by "hotspots" (zones with high temperature levels as seen via satellite imagery) in Malaysia and Indonesia.
- ✓ Lingering smoke from forest fires on the Indonesian island of Sumatra are identified as the primary cause. Farmers regularly burn scrub and forest to clear land during the dry season for agricultural purposes.

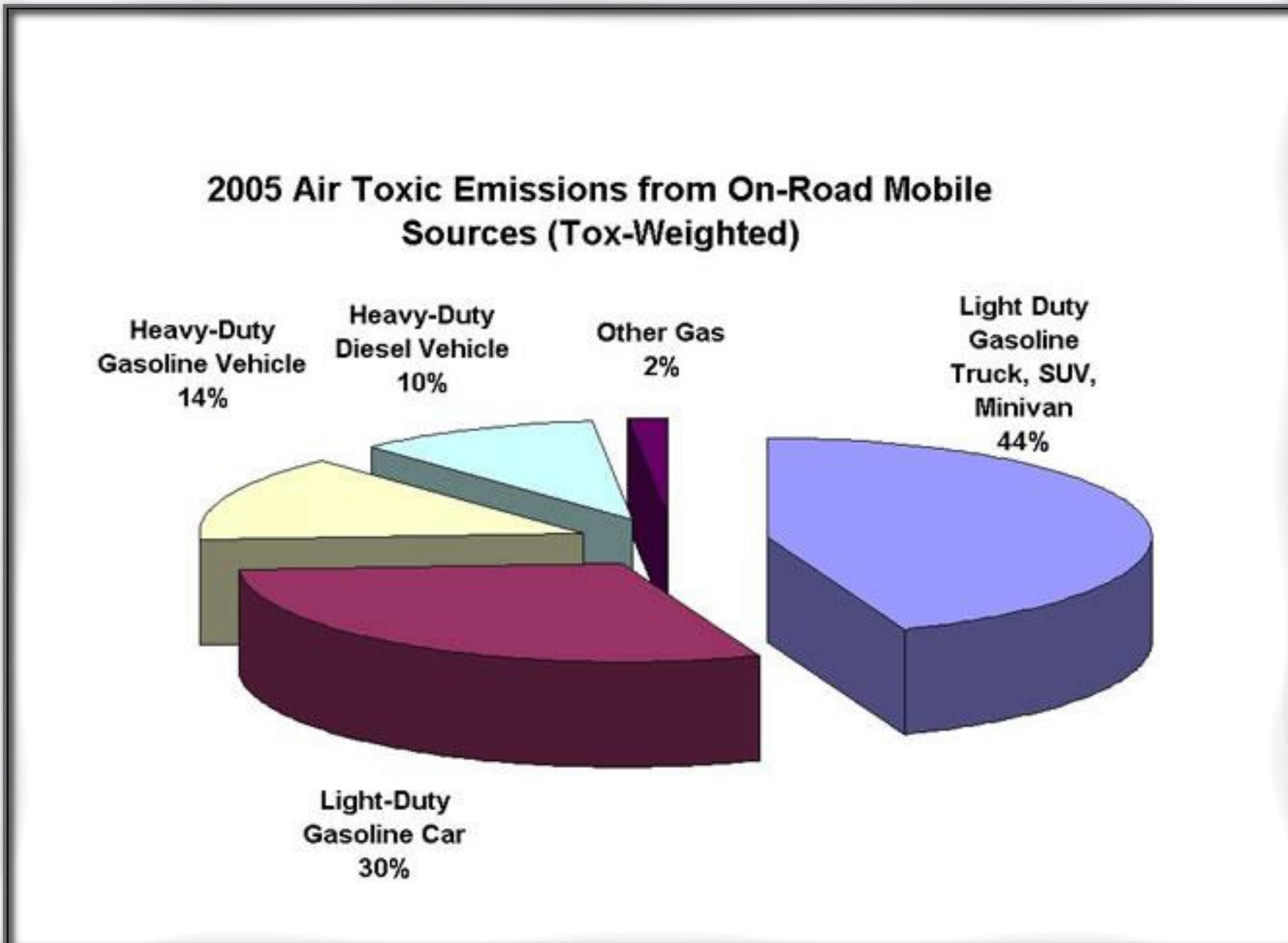
Source and classification

- ✓Natural
- ✓Man- made or anthropogenic

- ✓Natural- pollen grains, volcanic eruptions, forest fires, dust storms, spores, bacteria and other microorganisms.
- ✓Man- made- industrial units, thermal power plants, automobile exhausts, fossil fuel burning, mining, nuclear explosions,

- ✓ Stationary
- ✓ Mobile

  - Point source- large stationary source
  - Area source- small stationary source and mobile source with indefinite routes
  - Line source- mobile source with definite routes


2005 Air Toxic Emissions from On-Road Mobile Sources (Tox-Weighted)
Heavy-Duty Gasoline Vehicle 14%
Heavy-Duty Diesel Vehicle 10%
Other Gas 2%
Light Duty Gasoline Truck, SUV, Minivan 44%
Light-Duty Gasoline Car 30%

Air pollutants

- ✓ Substance dwelling temporarily or permanently in the air.
- ✓ Alters the environment by interfering with the health, the comfort, or the food chain, or by interfering with the property values of people.
- ✓ A pollutant can be solid (large or sub-molecular), liquid or gas .
- ✓ It may originate from a natural or anthropogenic source (or both).

- ✓ It is estimated that anthropogenic sources have changed the composition of global air by less than 0.01%.
- ✓ Even a small change can have a significant adverse effect on the climate, ecosystem and species on the planet.

Classification of pollutants

✓ Pollutants can be grouped into two categories:

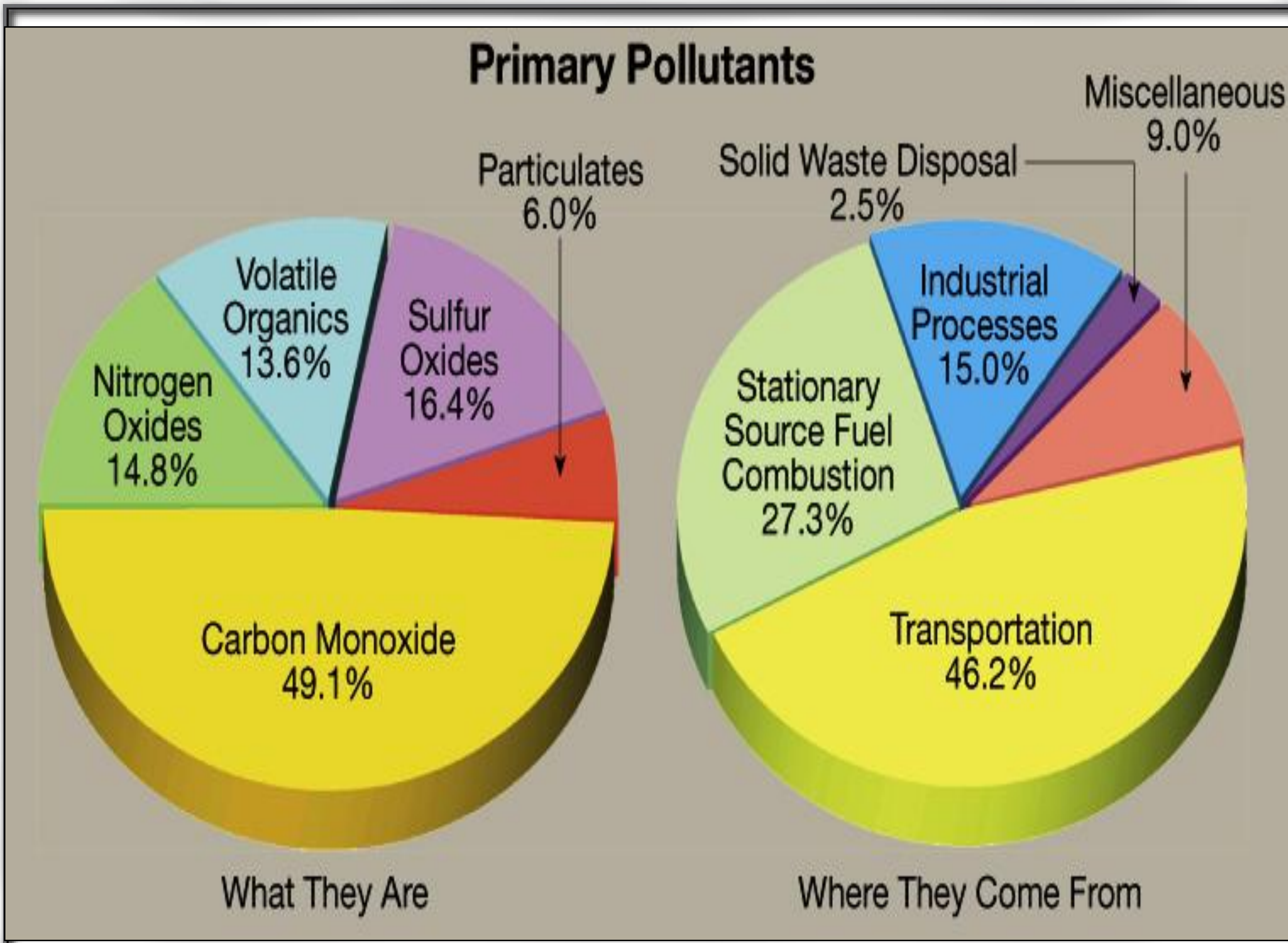
(1) **primary pollutants**, which are emitted directly from identifiable sources, and

(2) **secondary pollutants**, which are produced in the atmosphere when certain chemical reactions take place among primary pollutants.

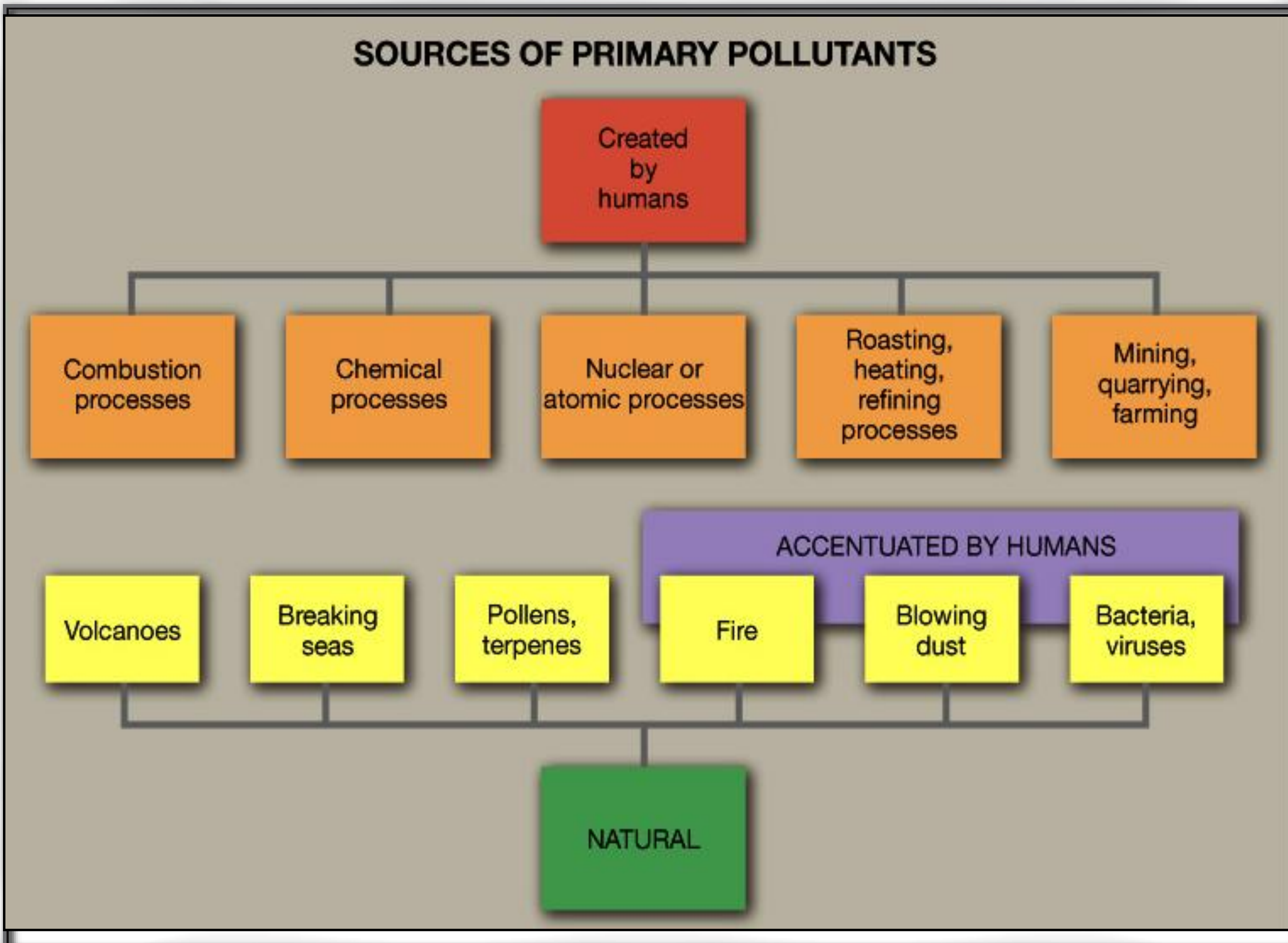
Primary Pollutants

The major primary pollutants include:

- particulate matter (PM),
- sulfur dioxide,
- nitrogen oxides,
- volatile organic compounds (VOCs),
- carbon monoxide, and
- lead.

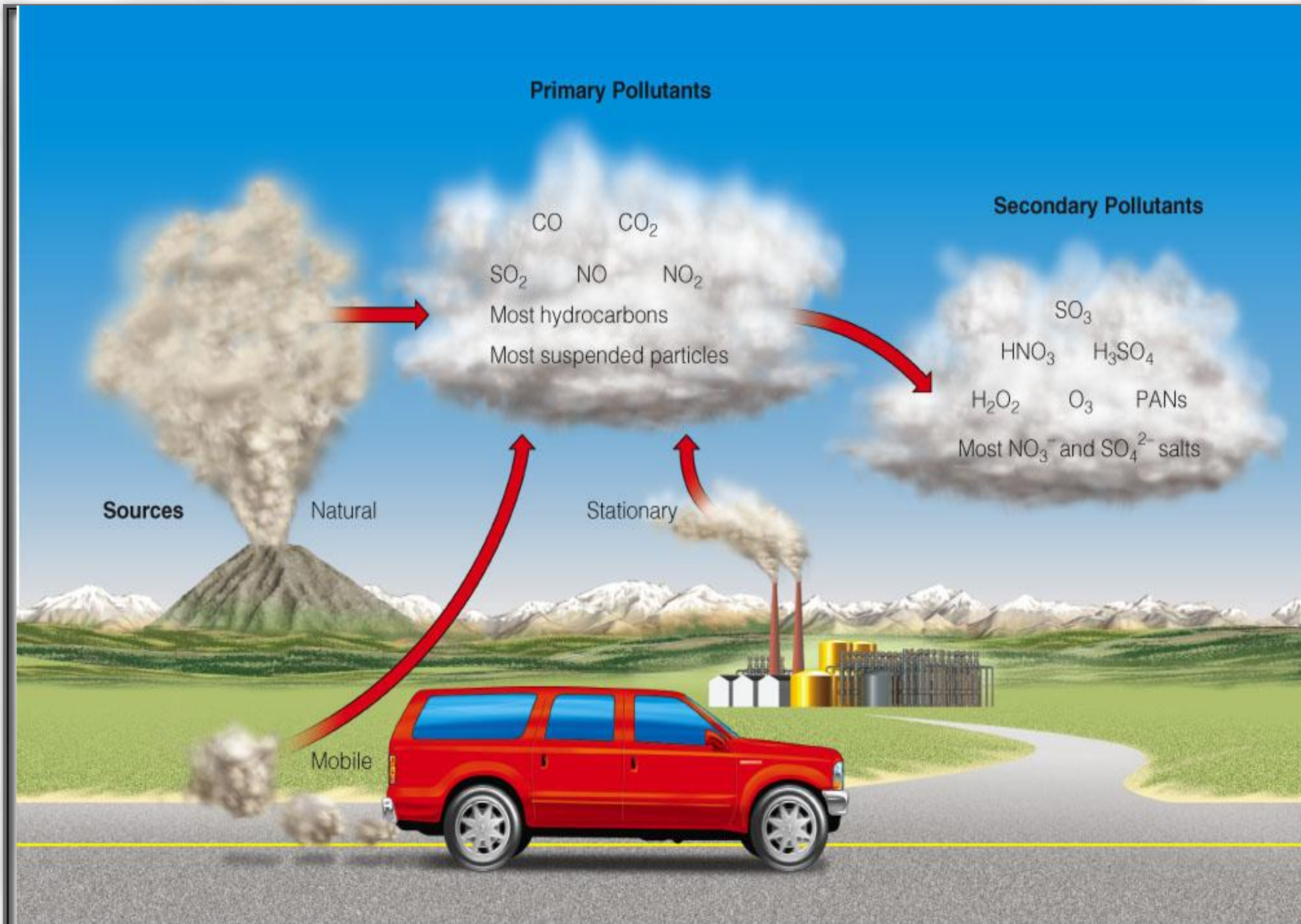


Primary Pollutants
Particulates
6.0%
Volatile
Organics
13.6%
Sulfur
Oxides
16.4%
Nitrogen
Oxides
14.8%
Carbon Monoxide
49.1%
What They Are
Miscellaneous
9.0%
Solid Waste Disposal
2.5%
Industrial
Processes
15.0%
Stationary
Source Fuel
Combustion
27.3%
Transportation
46.2%
Where They Come From


SOURCES OF PRIMARY POLLUTANTS
Created by humans
Combustion processes
Chemical processes
Nuclear or atomic processes
Roasting, heating, refining processes
Mining, quarrying, farming
ACCENTUATED BY HUMANS
Volcanoes
Breaking seas
Pollens, terpenes
Fire
Blowing dust
Bacteria, viruses
NATURAL

Secondary Pollutants

Some primary air pollutants react with one another or with other chemicals to form secondary pollutants.


Primary Pollutants
CO CO_2
SO_2 NO NO_2
Most hydrocarbons
Most suspended particles
Secondary Pollutants
SO_3
HNO_3 H_2SO_4
H_2O_2 O_3 PANs
Most NO_3^- and SO_4^{2-} salts
Sources
Natural
Stationary
Mobile

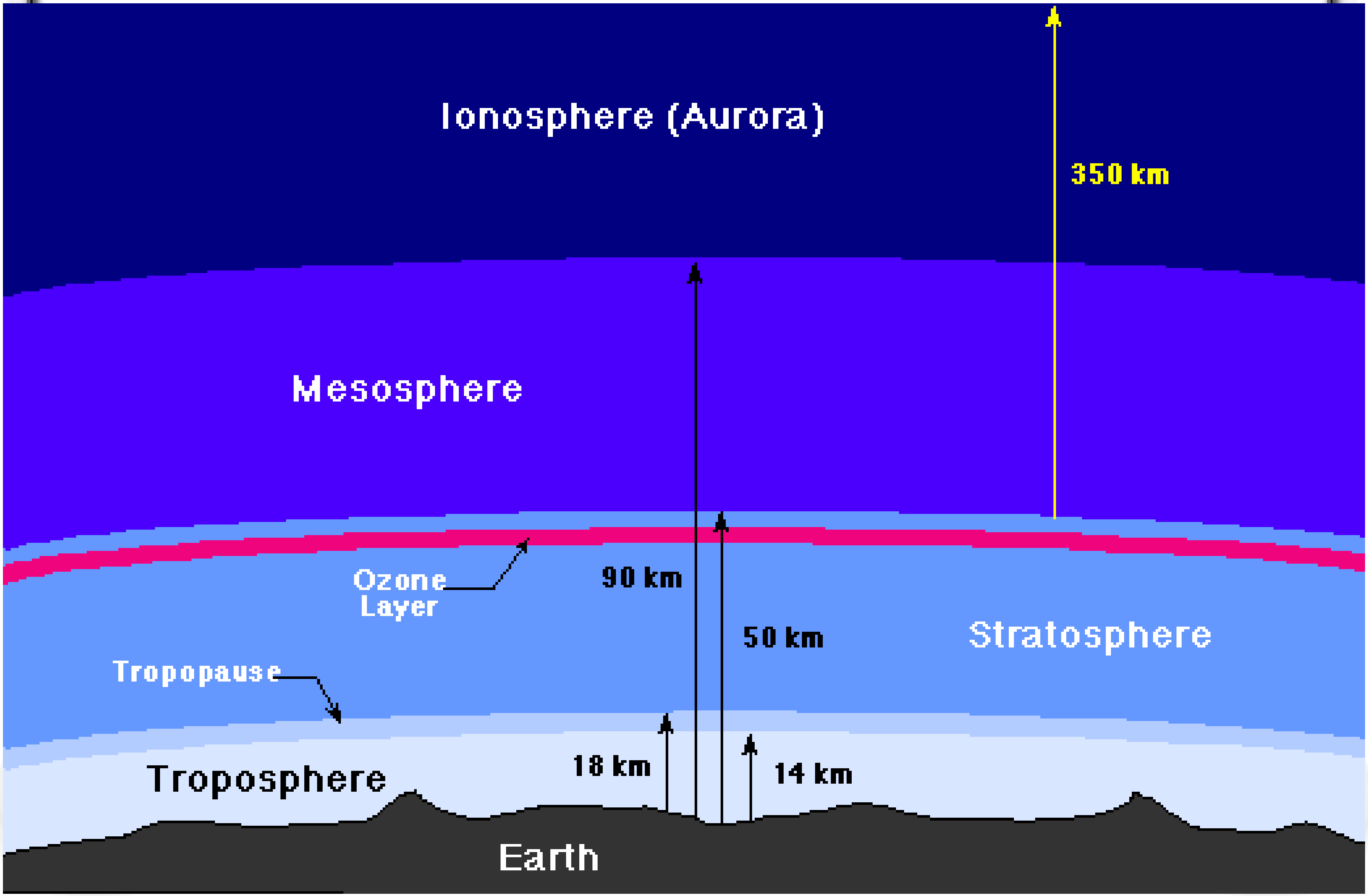
- ✓ Atmospheric **sulfuric acid** is one example of a secondary pollutant.
- ✓ Air pollution in urban and industrial areas is often called **smog**.
- ✓ **Photochemical smog**, a noxious mixture of gases and particles, is produced when strong sunlight triggers **photochemical reactions** in the atmosphere.
- ✓ The major component of photochemical smog is **ozone**.

meteorology and transport of air pollution

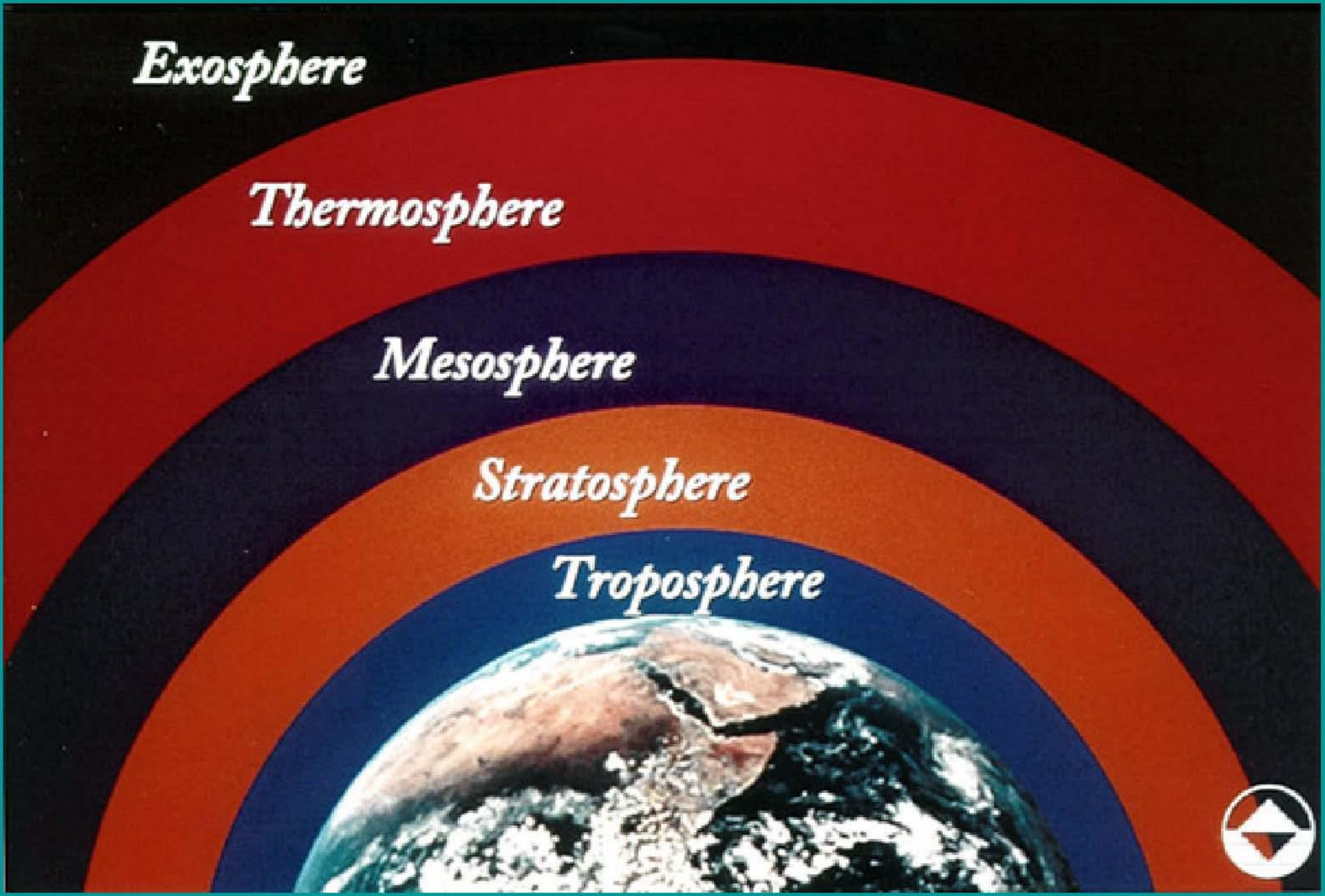
Introduction

- ✓ Once emitted pollutants:
  - Transported
  - Dispersed
  - concentrated
- ✓ By meteorological conditions

Layer nomenclature in the atmosphere



BACK NEXT



- **Major Subdivisions of the Atmosphere**

Main Menu

- The *stratosphere*, the next layer of the air, extends from the troposphere to approximately 31 miles (50 km) above the earth. While this layer contains very little moisture it does contain another very important component: ozone.

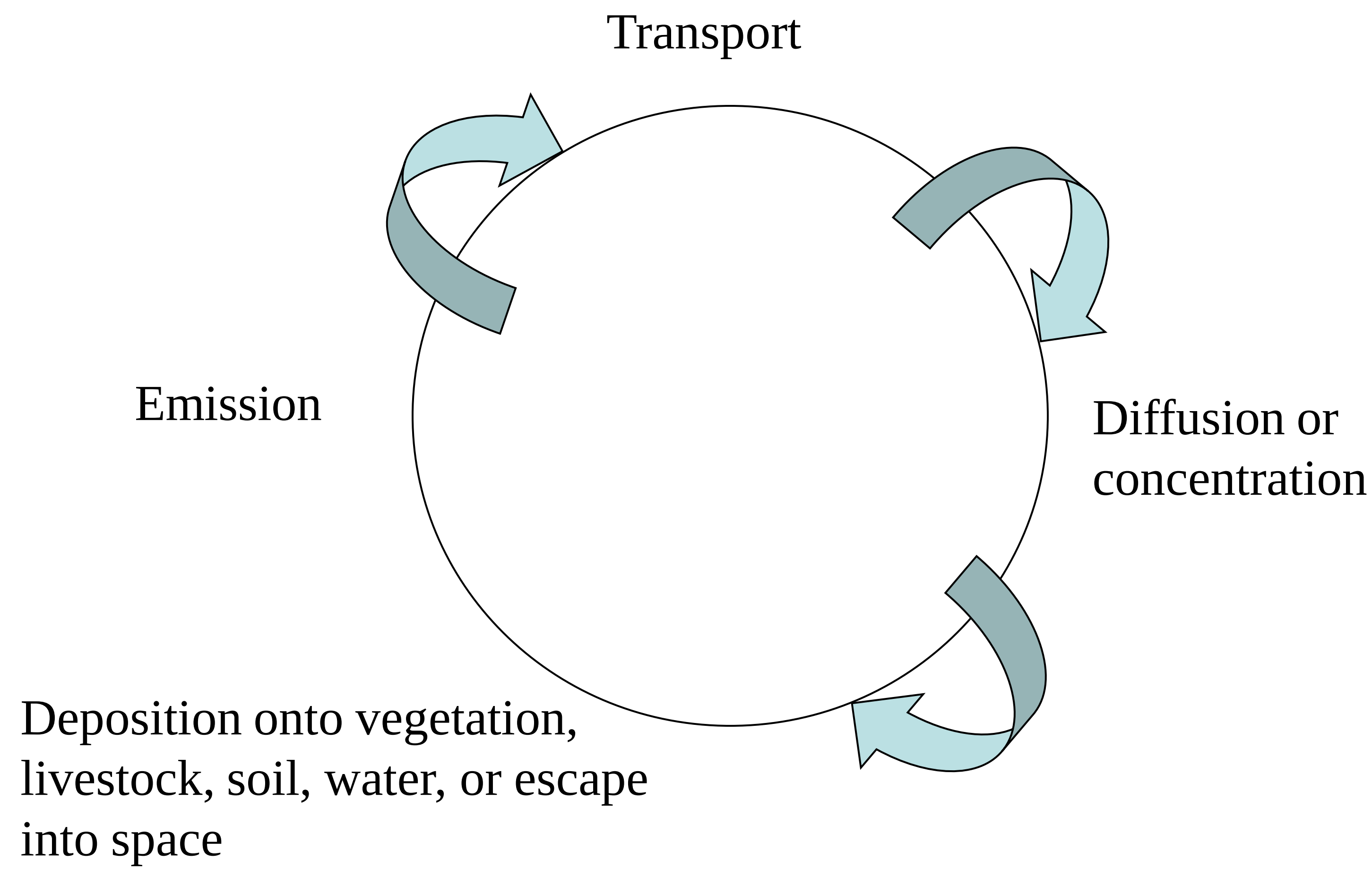
BACK

NEXT

- **Extending from the stratosphere to about 50 miles (80 km) above the earth's surface, is the *mesosphere*, followed by the uppermost layer of the atmosphere, the *thermosphere*. More than 99.9% of the atmospheric gases lie below the thermosphere.**

Main Menu

Air Pollutant Cycle



Transport

- ✓ Pollutants moved from source
- ✓ May undergo physical and chemical changes
  - Smog – interaction of NOx, HC, and solar energy
  - Ozone formation

Concentration & Dispersion

- ✓ Disperse based on meteorological & topographic conditions
- ✓ Concentration --- usually stagnant conditions
- ✓ Dispersion
  - – Topological conditions
    - Affected by presence of large buildings
  - – Meteorological conditions
  - – prevailing wind speed & direction
- ✓ Pollutants disperse over geographic area
- ✓ Any location receives pollutants from different sources in different amounts
- ✓ Need to understand how pollutants disperse to predict concentrations and predict violations at a particular location

Prediction

- ✓ Mathematical models of local atmosphere determine transport and dispersion patterns
- ✓ With emission data – predict concentrations throughout region
- ✓ Should correlate with data from monitoring locations
- ✓ Effect of sources can be estimated & regulations set

Dispersion

- ✓ General mean air motion
- ✓ Turbulent velocity fluctuations
- ✓ Diffusion due to concentration gradients – from plumes
- ✓ Aerodynamic characteristics of pollution particles
  - Size
  - Shape
  - Weight

Meteorological parameters influence air pollution

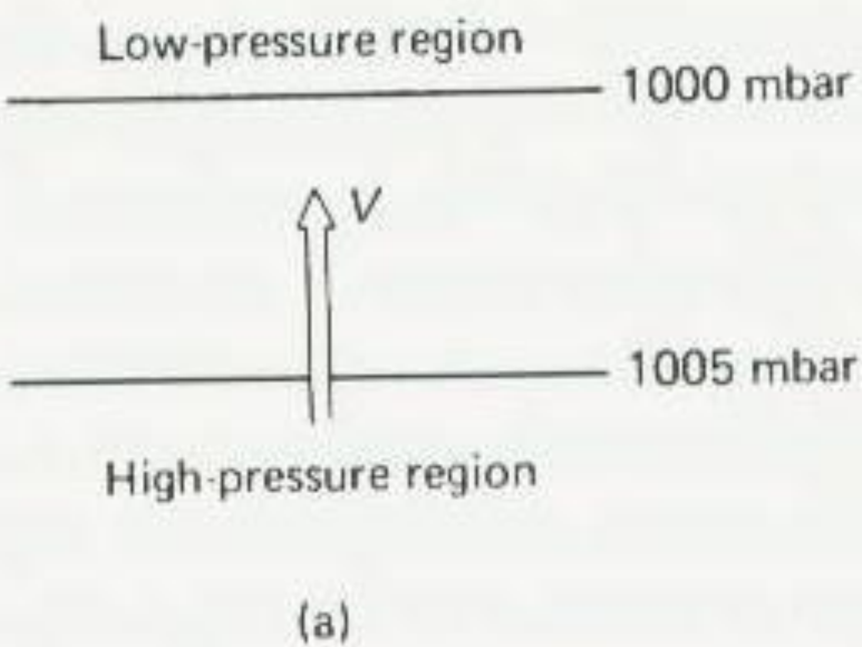
- ✓Wind direction and speed
- ✓Solar radiation
- ✓Atmospheric stability
- ✓Temperature inversion
- ✓Mixing height

Wind direction & speed

- ✓ Average over a year, solar heat flow to the earth's surface at equator is 2.4x that at poles
- ✓ Air moves in response to differences
- ✓ Heat transports from equator to poles
  - Like air circulation from a heater in a room
- ✓ Without rotation
- ✓ Air flows directly from high to low pressure areas (f_p)

Wind Circulation

Air flows directly from high to low pressure areas (f_p)



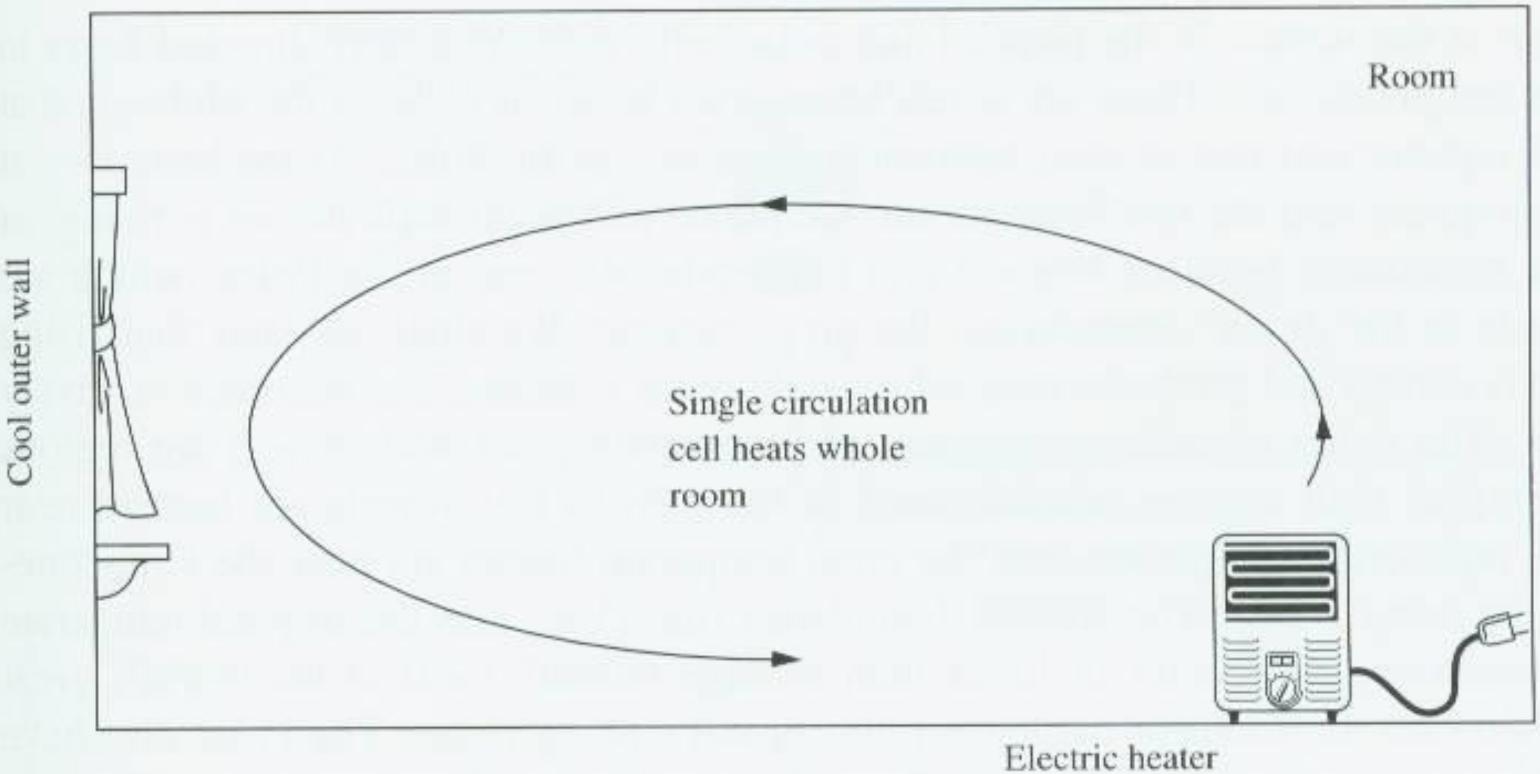
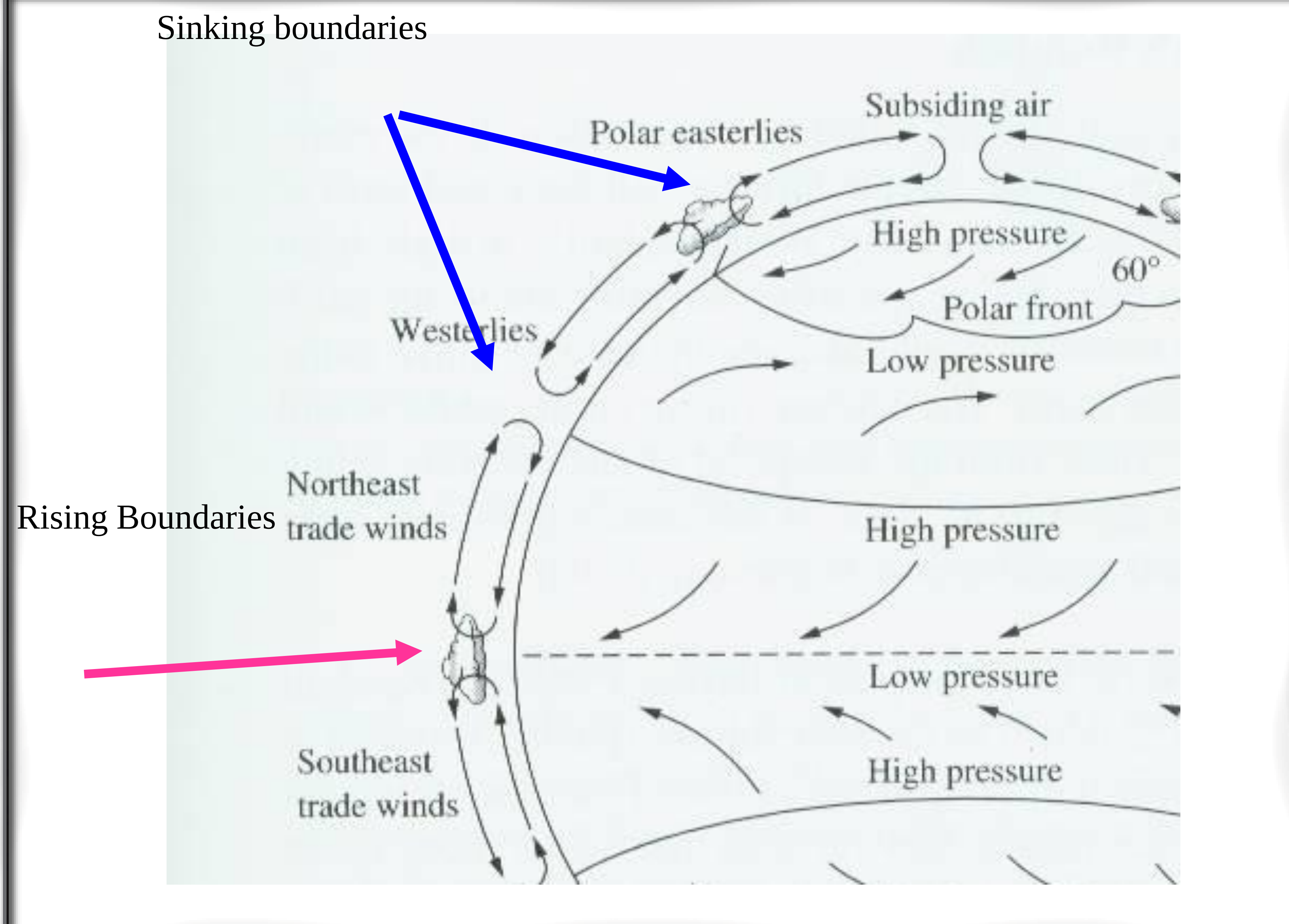


FIGURE 5.1
Air circulation in a room heated by an electric heater. There is a single circulation cell, rising at the heater and descending at the cold wall.

Wind Circulation

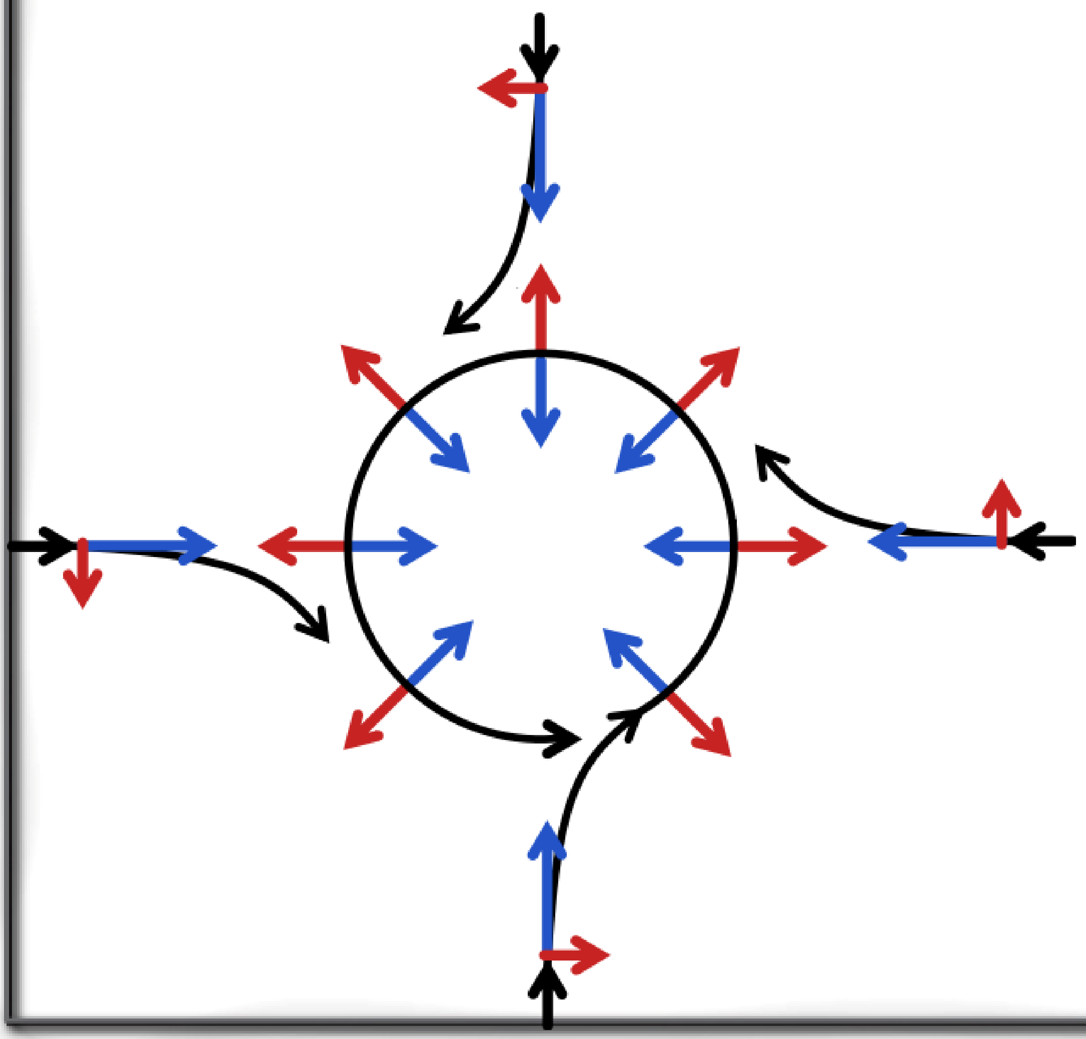
- ✓ Rising air cools & produces rain
- ✓ Sinking air is heated and becomes dry
- ✓ Rising boundaries are regions of of higher than average rainfall
  - Equator
  - Rain forests
  - Temperate forests
- ✓ Sinking boundaries are regions of lower than average rainfall
  - Most of world's deserts
  - Poles – small amounts of precipitation remains due to low evaporation


Sinking boundaries
Rising Boundaries
Subsiding air
Polar easterlies
High pressure
60°
Polar front
Westerlies
Low pressure
Northeast
trade winds
High pressure
Low pressure
Southeast
trade winds
High pressure

Inertial atmospheric rotation

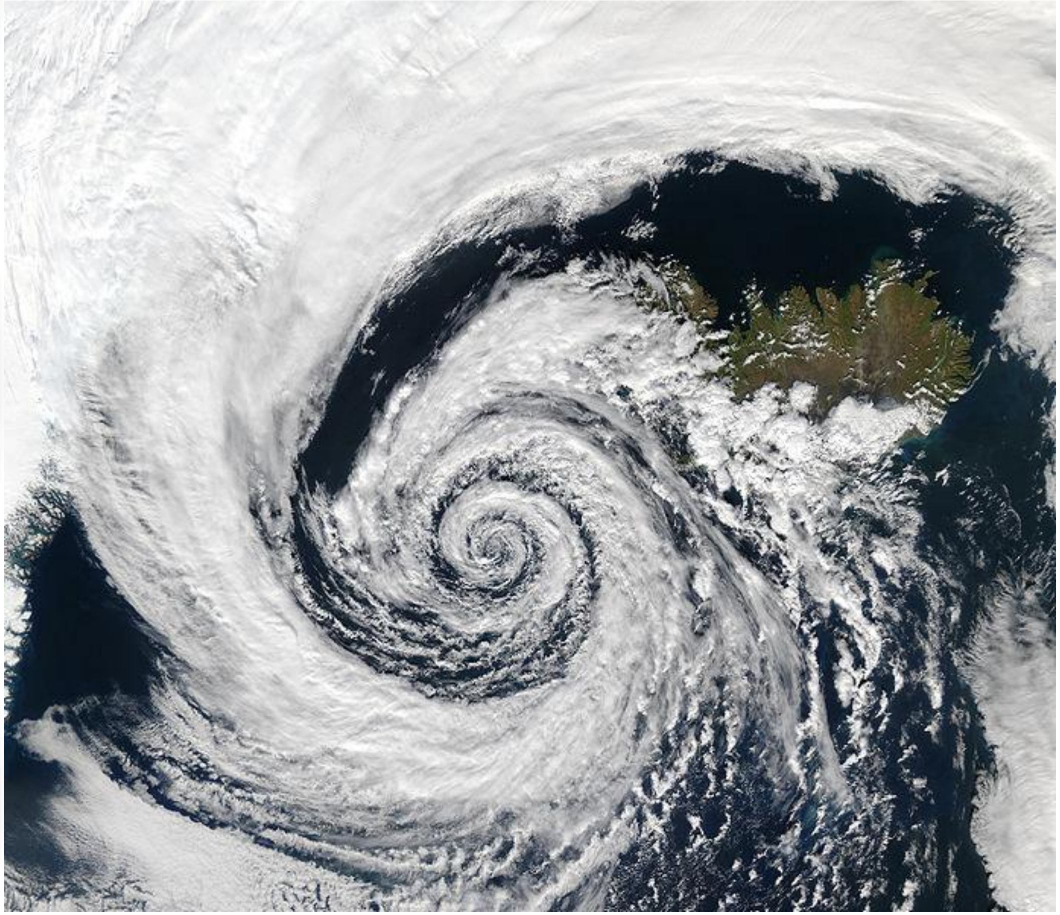
Schematic representation of inertial circles of air masses in the absence of other forces, calculated for a wind speed of approximately 50 to 70 m/s. Note that the rotation is exactly opposite of that normally experienced with air masses in weather systems around depressions.

Low-pressure area flows



Schematic representation of flow around a **low-**pressure area in the Northern hemi-sphere. The pressure-gradient force is represented by blue arrows, the Coriolis acceleration (always perpendicular to the velocity) by red arrows

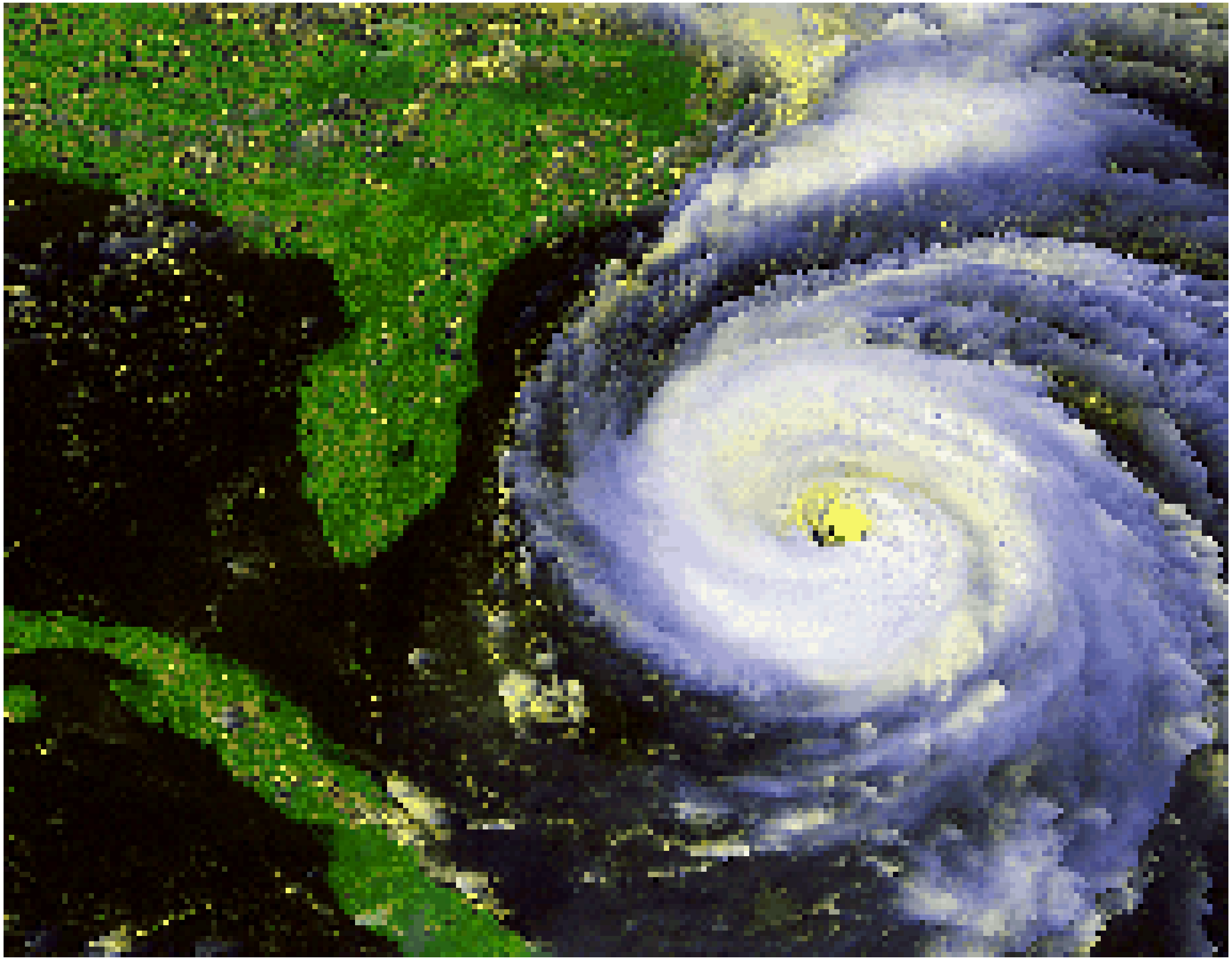
Low-pressure system



If a low-pressure area forms in the atmosphere, air will tend to flow in towards it, but will be deflected perpendicular to its velocity by the Coriolis force.

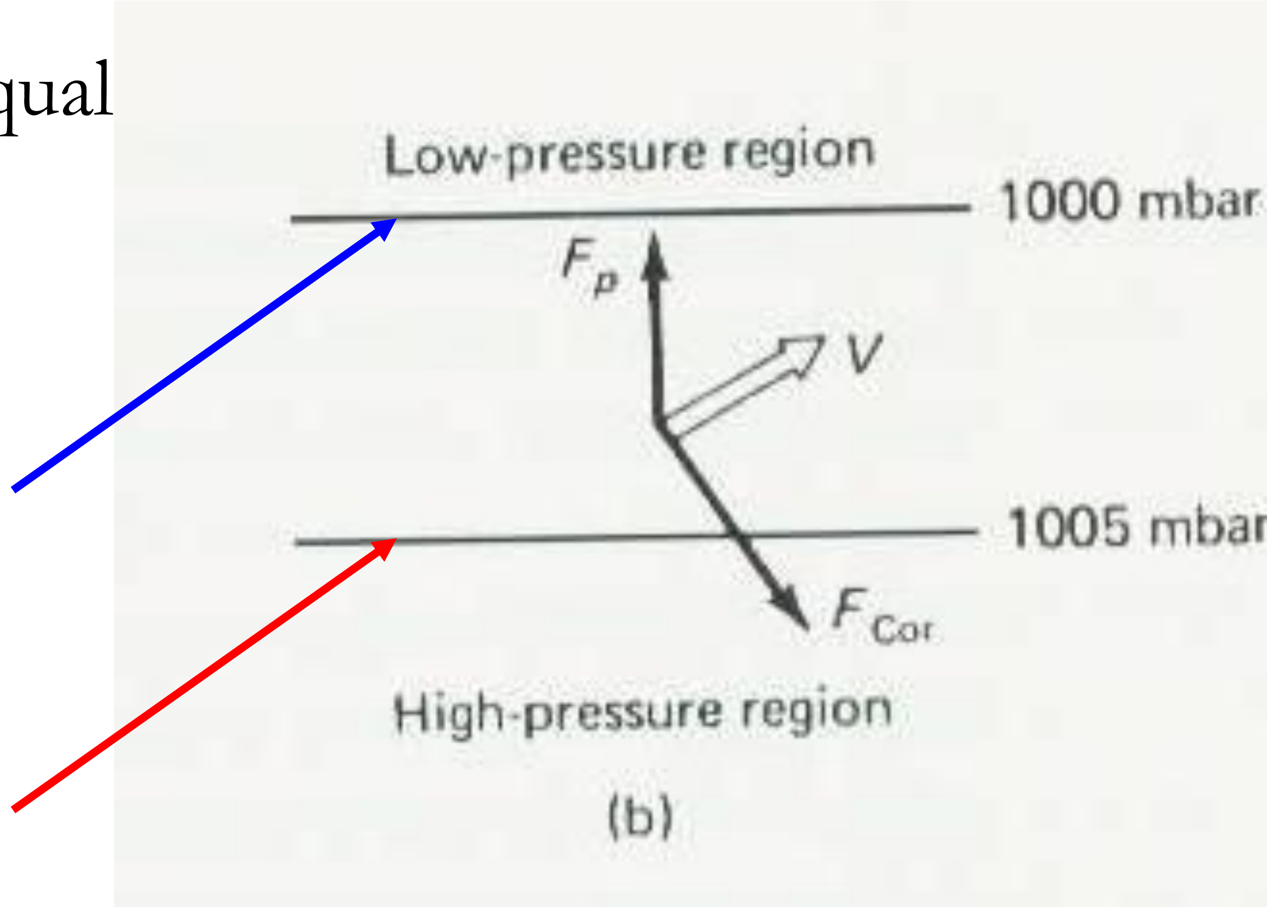
This low pressure system over Iceland spins counter-clockwise due to balance between the Coriolis force and the pressure gradient force.

Hurricane



Isobar

Areas of equal pressure



Influence of Ground & Sea

- In reality, land & water do not respond to solar heating similarly
- Terrain is uneven
  - Highest mountains rise above most of atmosphere
  - Large mountain ranges are major barriers to horizontal winds
  - Even small mountain ranges influence wind patterns

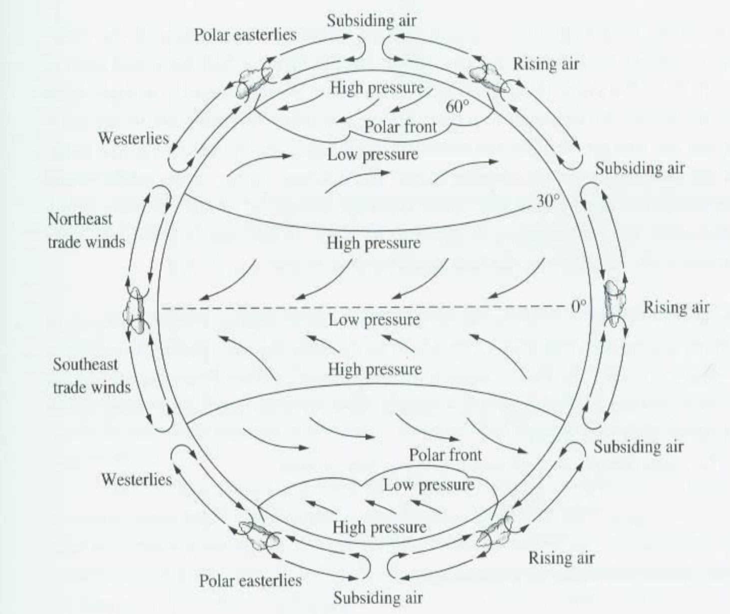


FIGURE 5.2
Schematic representation of the general circulation of the atmosphere. (Frederick K. Lutgens/Edward J. Tarbuck, *The Atmosphere*, 5e, ©1992, p. 170. Reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey.)

Influence of Ground & Sea

- ✓ Water adsorbs and transfer heat differently than rock & soil
- ✓ Rock and soil radiate heat differently summer to winter

Vertical Motion

- ✓ Any parcel of air less dense than surrounding air will rise by buoyancy
- ✓ any parcel more dense will sink
- ✓ Most vertical movement is due to changes in air density
- ✓ The pressure at any point in the atmosphere = pressure required to support everything above that point

Solar Radiation

- ✓ At upper boundary of atmosphere, vertical solar radiation = 8.16 J/cm^{2}min (solar constant)
- ✓ Maximum intensity at λ = 0.4 to 0.8 μm = visible portion of electromagnetic spectrum
- ✓ ~ 42% of energy
  - – Absorbed by higher atmosphere
  - – Reflected by clouds
  - – Back-scattered by atmosphere
  - – Reflected by earth's surface
  - – Absorbed by water vapor & clouds
- ✓ 47% adsorbed by land and water

- ✓ Depending on location, solar radiation pronounced effect on type and rate of chemical reactions in atmosphere.
- ✓ E.g. Photochemical smog formation at Los Angeles

Lapse Rate

- ✓ Important characteristic of atmosphere is ability to resist vertical motion: stability
- ✓ Affects ability to disperse pollutants
- ✓ When small volume of air is displaced upward
  - Encounters lower pressure
  - Expands to lower temperature
  - Assume no heat transfers to surrounding atmosphere
  - Called adiabatic expansion

Adiabatic expansion

To determine the change in temp. w/ elevation due to adiabatic expansion

- Atmosphere considered a stationary column of air in a gravitational field
- Gas is a dry ideal gas
- Ignoring friction and inertial effects

$$(dT/dz)_{\text{adiabatic perfect gas}} = \frac{-v p g}{C_p}$$

T = temperature

z = vertical distance

g = acceleration due to gravity

p = atmospheric density

v = volume per unit of mass

C_p = heat capacity of the gas at constant pressure

Adiabatic expansion

- ✓ If the volume of a parcel of air is held constant and an incremental amount of heat is added to the parcel, temperature of the parcel will rise by an amount dT
- ✓ Resultant rise in temperature produces a rise in pressure according to ideal gas law
- ✓ If the parcel is allowed to expand in volume and have a change in temperature, while holding the pressure constant, the parcel will expand or contract and increase or decrease in temp.
- ✓ Parcel rises or falls accordingly

Adiabatic expansion

SI:

$$(dT/dz)_{\text{adiabatic perfect gas}} = -0.0098°C/m$$

American:

$$(dT/dz)_{\text{adiabatic perfect gas}} = -5.4°F/ft$$

Change in temp. with change in height

- ✓ Lapse rate is the negative of temperature gradient
- ✓ Dry adiabatic lapse rate =

Metric:

$\Gamma = -\ 1°C/100m$ or

SI:

$\Gamma = -\ 5.4°F/1000ft$

International Lapse Rate

SI:

$\Gamma = -\ 6.49°C/km$ or $0.65\ °C/100m$

American:

$\Gamma = -\ 3.45°F/1000ft$

About 66% of adiabatic lapse rate

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:

$5.5105 \times 6.49 = 35.76°$

Original temp was 15°, temp at 5.5105 km =

$15° - 35.76° = -20.76°C$

Temperature change due to atmospheric height

- ✓ Lapse rate for "standard atmosphere"
- ✓ Troposphere:
  - 0 to 36,150 feet
  - Temperature decreases linearly
  - 75% of atmospheric mass
- ✓ Not applicable above troposphere
- ✓ Stratosphere
  - 36,150 to 65,800 feet
  - Temperature does not decrease further with increasing height
  - Chemical reaction occur to absorb heat from the sun
  - Adiabatic assumption is not followed

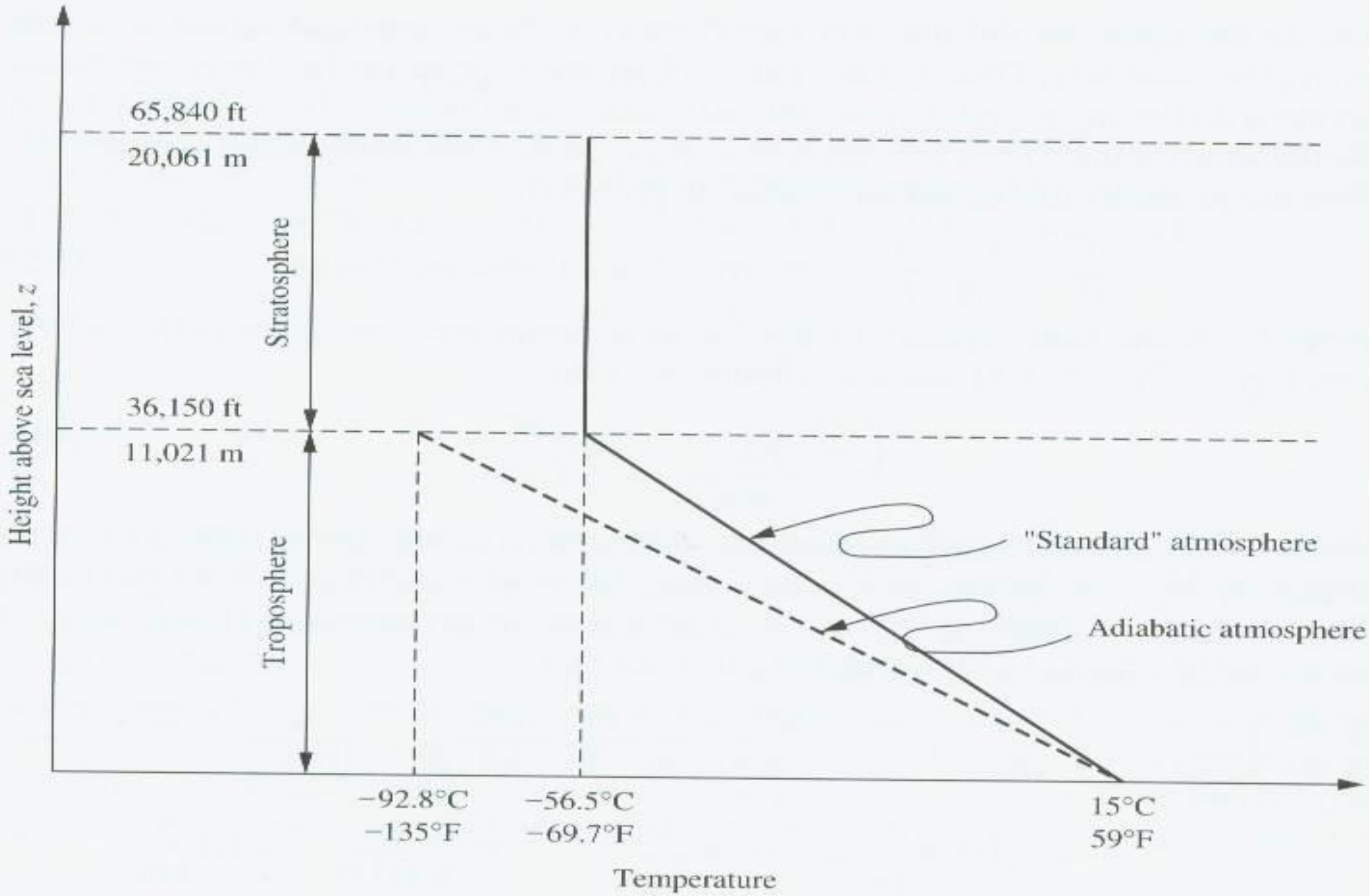
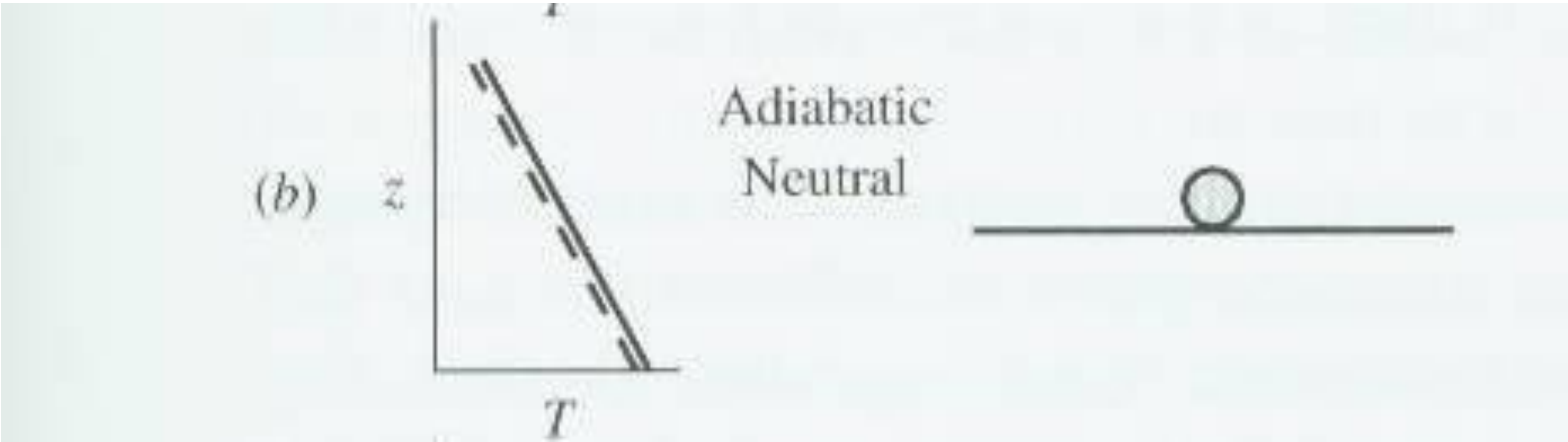


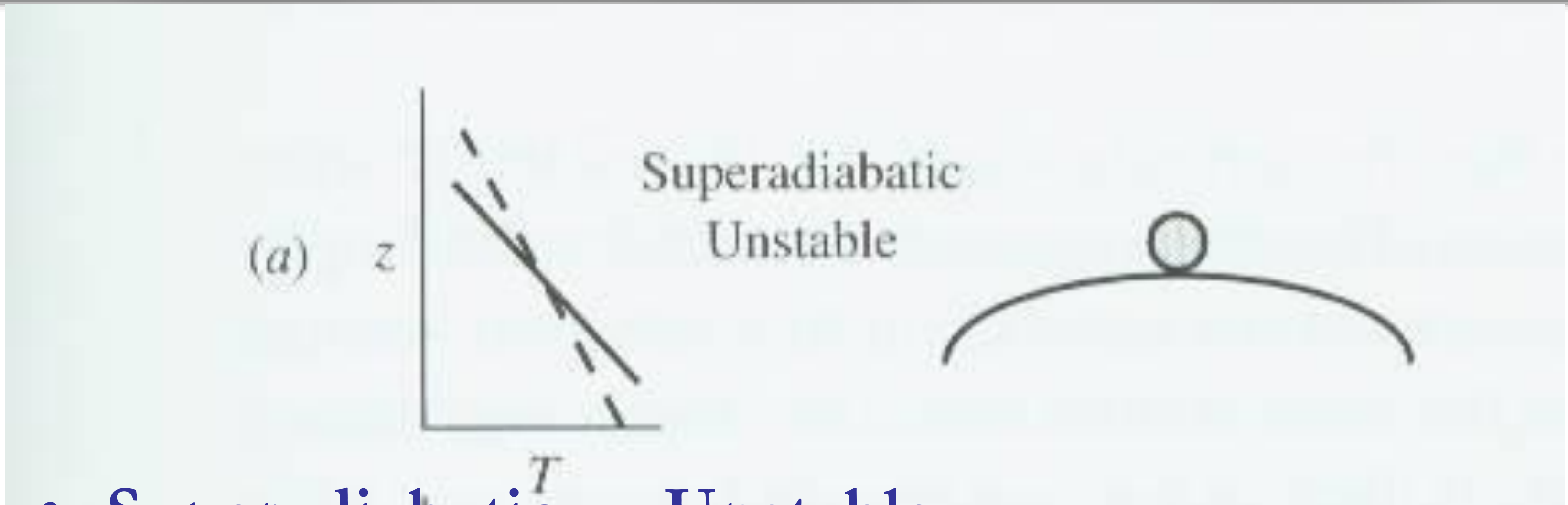
FIGURE 5.5
Comparison of the temperature-elevation relations in the adiabatic atmosphere and the standard atmosphere.

Atmospheric Stability

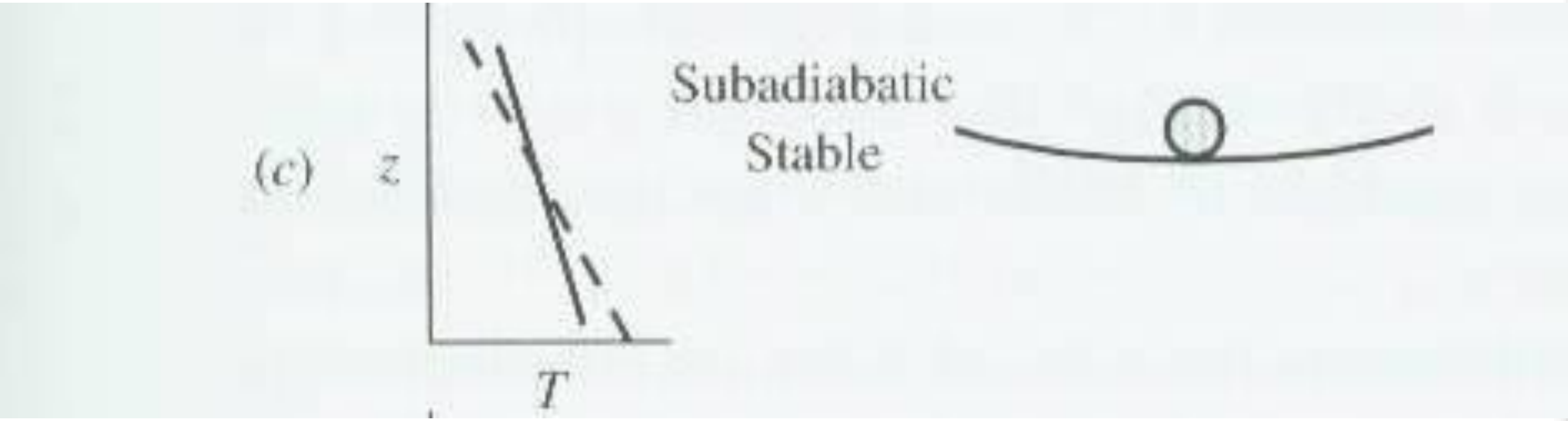
- ✓ Affects dispersion of pollutants
- ✓ Temperature/elevation relationship principal determinant of atmospheric stability
- ✓ Stable
  - Little vertical mixing
  - Pollutants emitted near surface tend to stay there
  - Environmental lapse rate is same as the dry adiabatic lapse rate
- ✓ 4 common scenarios



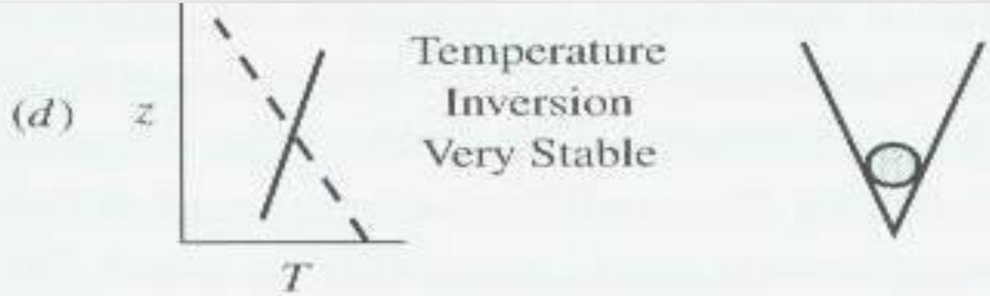
- **Neutral**
  - Environmental lapse rate is same as the dry adiabatic lapse rate
  - A parcel of air carried up or down will have same temp as environment at the new height
  - No tendency for further movement



- **Superadiabatic --- Unstable**
  - Environmental lapse rate > Γ
  - i.e. Actual temp. gradient is more negative
  - Small parcel of air displaced approximates adiabatic expansion
  - Heat transfer is slow compared to vertical movement
  - At a given point, $T_{parcel} > T_{surrounding\ air}$
    - less dense than surrounding air
  - Parcel continues upward



- **Subadiabatic --- Stable**
  - Environmental lapse rate < Γ
  - greater temp. gradient
  - No tendency for further vertical movement due to temp. differences
  - Any parcel of air will return to its original position
  - Parcel is colder than air above – moves back



Note: In all of these plots the dashed line represents the adiabatic lapse rate, $dT/dz = -5.4°F/1000$ ft ($dz/dT = -185$ ft/°F).

- **Inversion --- Strongly Stable**
  - Environmental lapse rate is negative
  - Temp. increases with height
  - No tendency for further vertical movement due to temp. differences
  - Any parcel of air will return to its original position
  - Parcel is colder than air above – moves back
  - Concentrates pollutants

Inversions

- Stability lessens exchange of wind energy between air layers near ground and high altitude winds
- Horizontal & vertical dispersions of pollutants are hampered
- Influenced by:
  - Time of year
  - Topography
  - Presence of water or lakes
  - Time of day

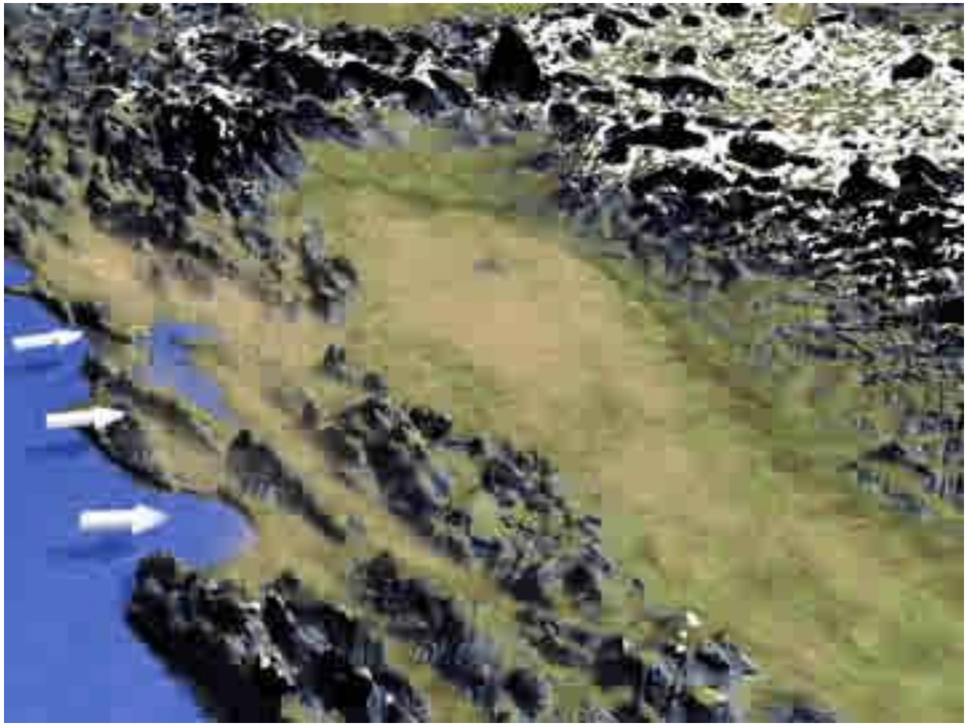


Image and text source: http://www.sparetheair.org/teachers/bigpicture/IIIA1a.html

From San Francisco Bay area: “Pollutants are carried from the ocean through mountain passes on an almost daily basis during the summer months”

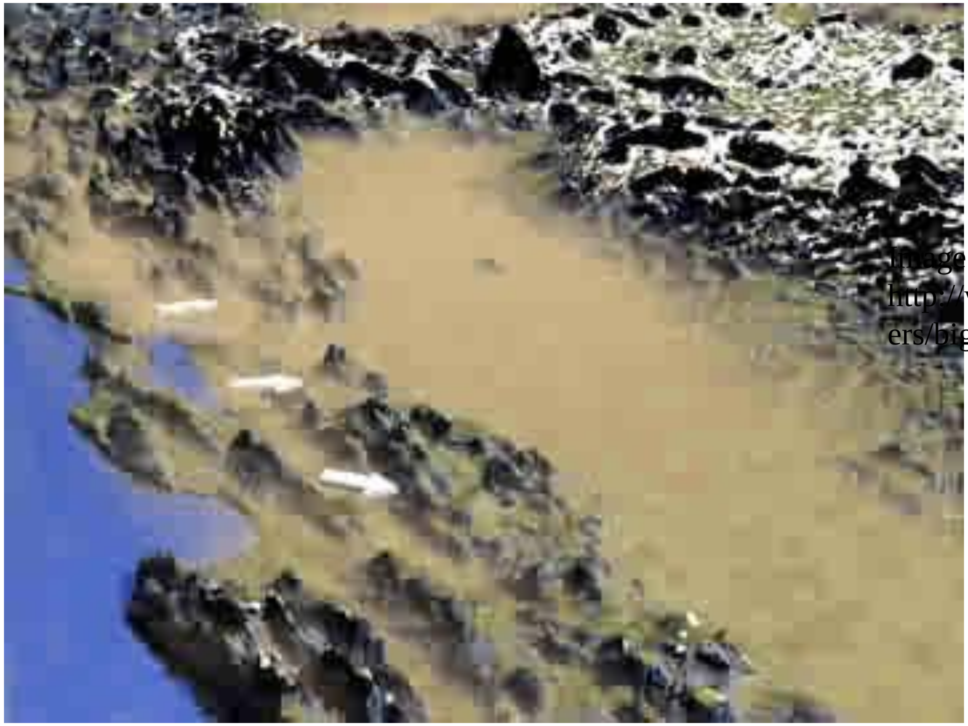


Image and text source: http://www.sparetheair.org/teachers/bigpicture/IIIA1a.html

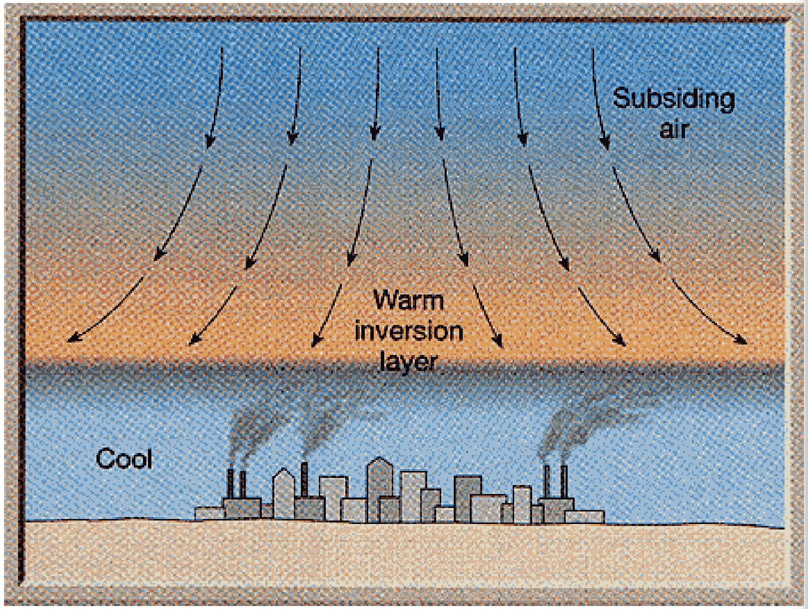
“Streams of air carrying Bay Area emissions mix with locally generated pollution from automobile traffic, small engine exhaust, industry, and agriculture in the Valley and are diverted both north and south”

Image and text source: http://www.sparetheair.org/teachers/bigpicture/IIIA1a.html

“A warm inversion layer acts like a blanket on the smog layer, preventing it from dissipating higher in the atmosphere. Because of high pressure, the Central Valley regularly experiences these thermal inversions. The Valley, which is nearly at sea level, often fills at night with cool heavy air underneath a layer of warmer air. The cool air layer grows through the night reaching up to 3000 feet thick. “

Two Types of Inversion

- Radiation Inversion
  - Surface layers receive heat by conduction, convection, and radiation from earth's surface
- Subsidence Inversion
  - Cloud layer absorbs incoming solar energy or high-pressure region with slow net downward flow or air and light winds
  - Sinking air mass increases in temp and becomes warmer than air below it
  - Usually occur 1,500 to 15,000 feet above ground & inhibit atmospheric mixing
  - Common in sunny, low-wind situations



Subsidence Inversion

Image Source:
http://apollo.lsc.vsc.edu/classes/met130/notes/chapter17/fav_conditions.html

Two more Types of Inversion

- ✓ Cold Air Flowing Under
  - Nighttime flow of cold air down valleys
  - Col air flows under warm air
  - Winter
  - Presence of fog blocks sun and inversion persists
  - Sea or lake breezes also bring cold air under warm air
- ✓ Warm Air Flowing Over
  - Same as above but warm air flows over cold trapping it
  - Warm air frequently overrides colder more dense air

Stability Classes

- ✓ Developed for use in dispersion models
- ✓ Stability classified into 6 classes (A – F)
  - A: strongly unstable
  - B: moderately unstable
  - C: slightly unstable
  - D: neutral
  - E: slightly stable
  - F: moderately stable

TABLE 3-1 Key to Stability Classes[a]

Surface Wind Speed at 10 m (m/s)	Day: Incoming Solar Radiation			Night: Cloud Cover	
	Strong	Moderate	Slight	Thinly Overcast or ≥50% Clouds	Mostly Clear or $\leq \frac{3}{8}$ Clouds
<2	A	A–B	B	—	—
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]The neutral class, D, should be assumed for overcast conditions during day or night.
Source: D. B. Turner. *Workbook of Atmospheric Dispersion Estimates.* Washington, D.C.: HEW, 1969.

Wind Velocity Profile

- ✓ Friction retards wind movement
- ✓ Friction is proportional to surface roughness
- ✓ Location and size of surface objects produce different wind velocity gradients in the vertical direction
- ✓ Area of atmosphere influenced by friction – planetary boundary layer – few hundred m to several km above earth's surface
- ✓ Depth of boundary layer > unstable than stable conditions

Wind Velocity Profile

- ✓ Wind speed varies by height
- ✓ International standard height for wind-speed measurements is 10 m
- ✓ Dispersion of pollutant is a function of wind speed at the height where pollution is emitted
- ✓ But difficult to develop relationship between height and wind speed

Wind Velocity Profile

- Power law of Deacon

$$u/u_1 = (z/z_1)^p$$

U: wind speed at elevation z

z: elevation

p: exponent based on terrain and surface cover and stability characteristics

Wind Velocity Profile

TABLE 3-3 Value of Exponent, *p*, in Equation (3-13)

Stability Category	Rural exponent	Urban Exponent
A	0.07	0.15
B	0.07	0.15
C	0.10	0.20
D	0.15	0.25
E	0.35	0.30
F	0.55	0.30

Source: User's Guide for the ISC3 Dispersion Models, Vol. II, EPA-454/B-95-003b, U.S. EPA, September, 1995. Available on TTNWeb SCRAM.

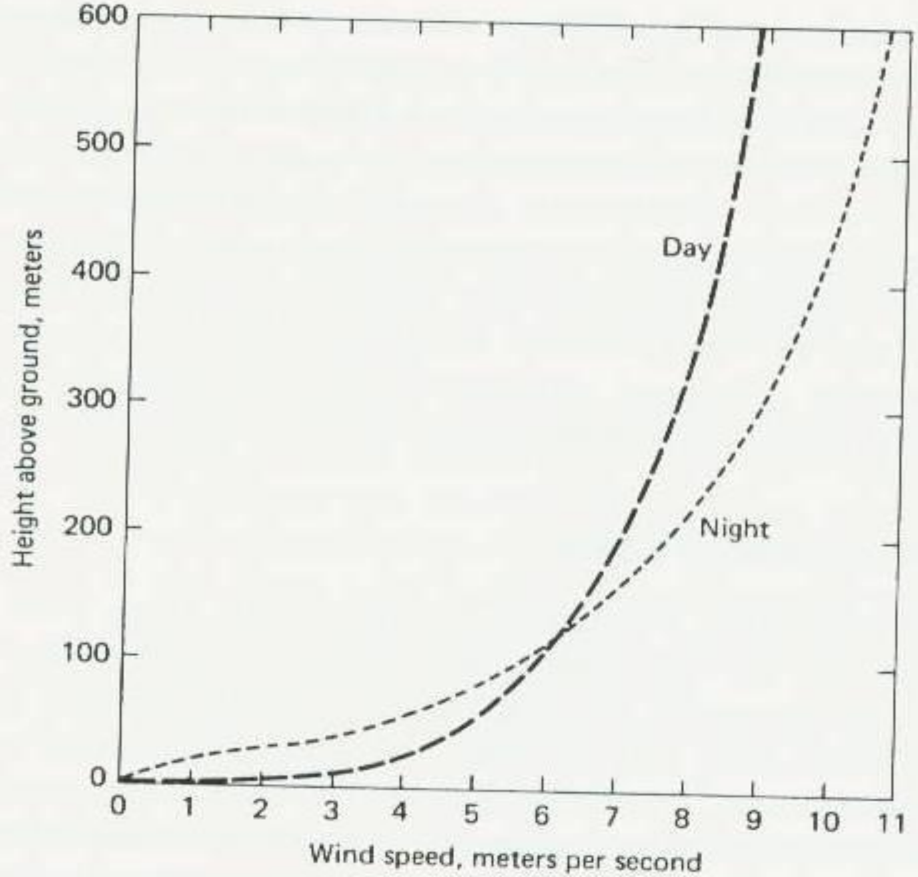


FIGURE 3-12 Change of wind-speed profile with stability. (Source: D.B. Turner, *Workbook for Atmospheric Dispersion Estimates*, Washington, D.C.: HEW, 1969.)

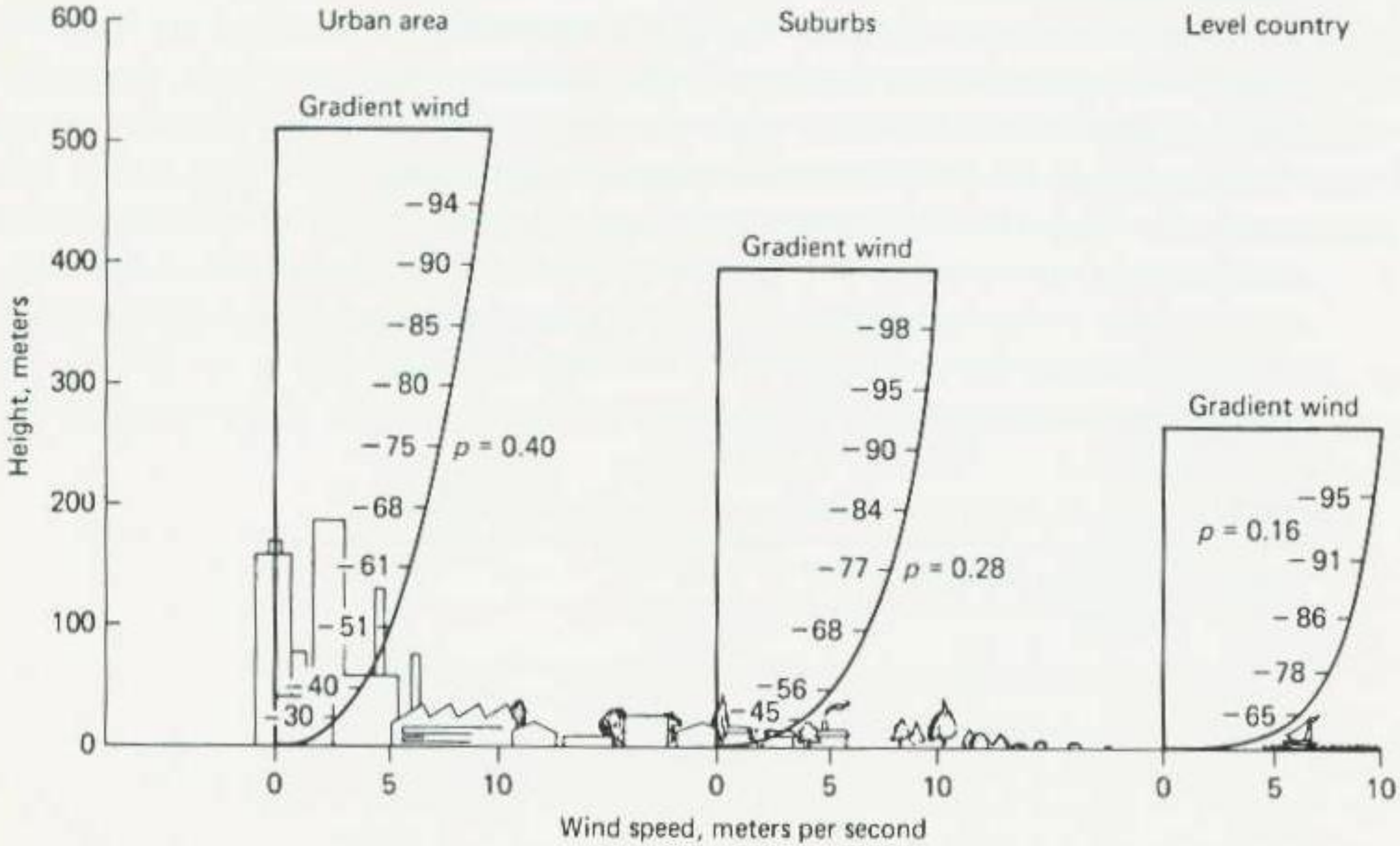


FIGURE 3-13 Effect of terrain roughness on the wind-speed profile. Values along curves represent percentages of gradient wind value. (Source: D.B. Turner. *Workbook for Atmospheric Estimates*. Washington, D.C.: HEW, 1969.)

Wind Direction

- ✓ Does the wind blow from my house towards a smelly feedlot or the other way?
- ✓ High and low-pressure zones
  - – Formed from large scale instabilities
  - – Often near boundaries of circulation zones
  - – Air is rising or sinking
  - – Major storms often associated with low-pressure
- ✓ Topography
  - – Air heats and cools differently on different surfaces, causes air from
  - – Lake to shore, etc.
  - – Mountains block low-level wind

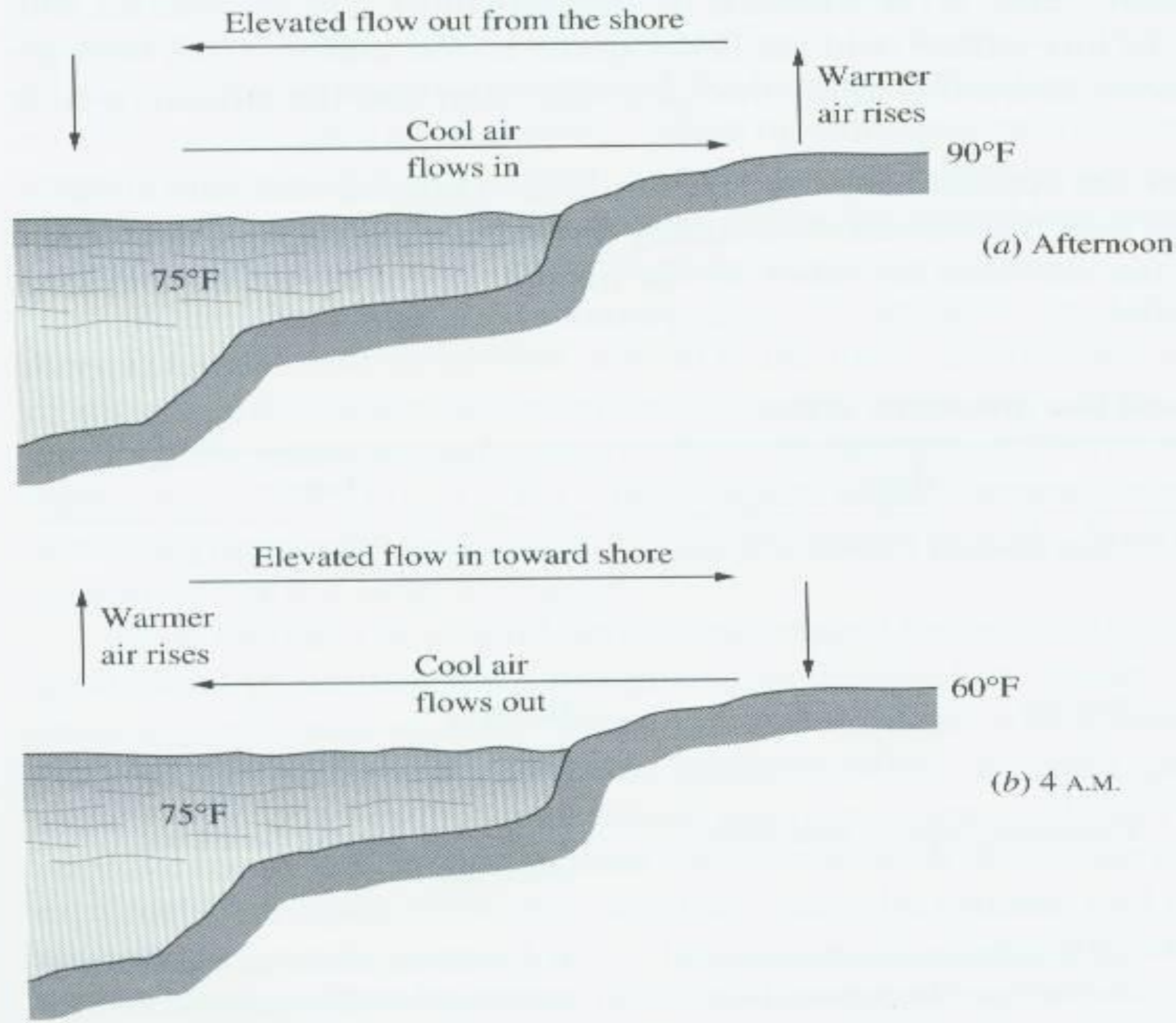
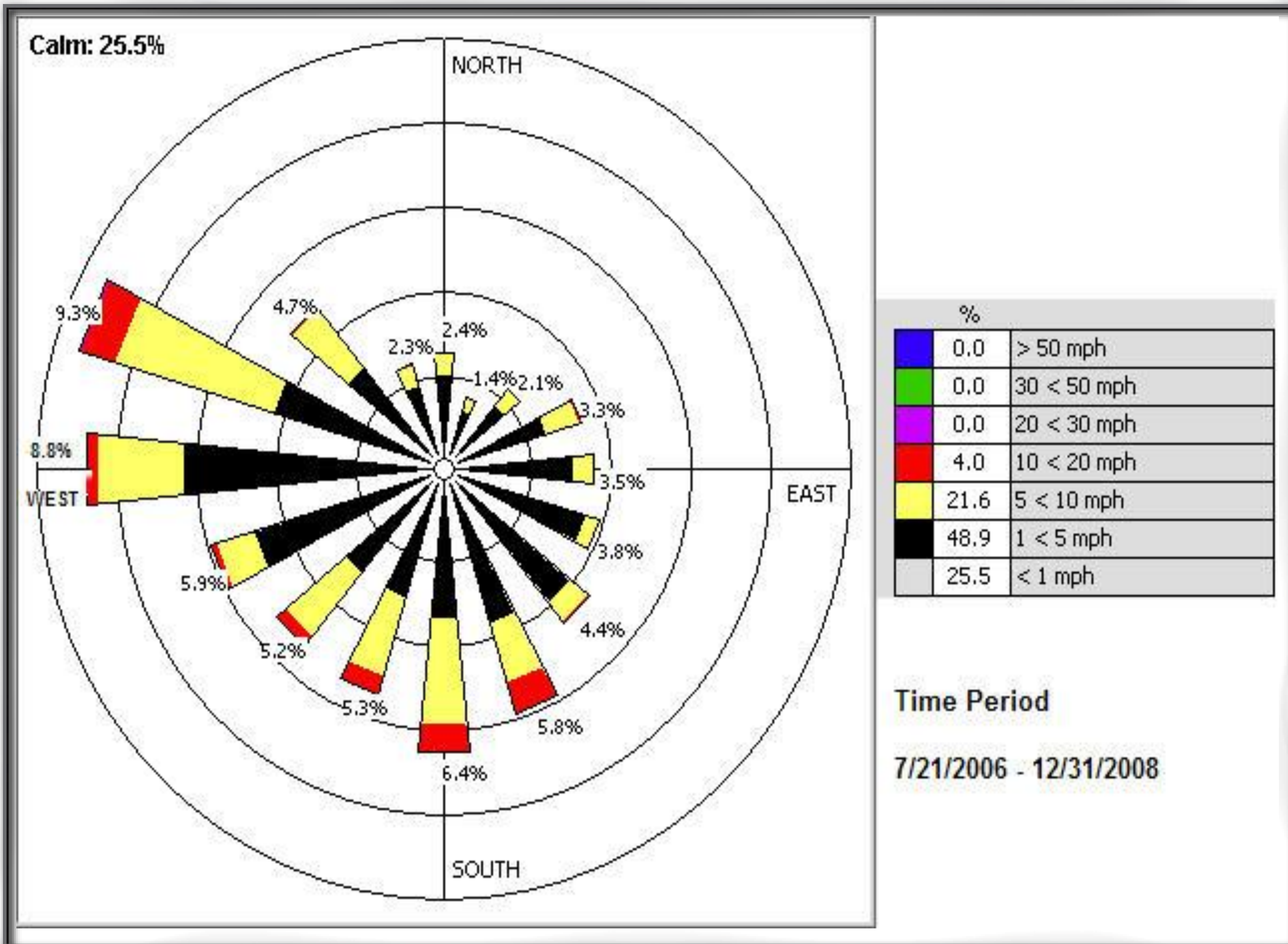


FIGURE 5.13
Onshore sea breezes in the day and offshore land breezes at night.

Predicting Wind Direction

- ✓ Need to know distribution of wind direction for estimating pollution concentrations
- ✓ Need speed and direction
- ✓ Wind Rose
  - Average of wind speed and direction over time
  - Shows
    - Frequency
    - Speed
    - direction
  - Wind direction is direction from which the wind is coming


Calm: 25.5%
NORTH
SOUTH
EAST
WEST
9.3%
8.8%
4.7%
2.3%
2.4%
1.4%
2.1%
3.3%
3.5%
3.8%
4.4%
5.8%
6.4%
5.3%
5.2%
5.9%
%
0.0 > 50 mph
0.0 30 < 50 mph
0.0 20 < 30 mph
4.0 10 < 20 mph
21.6 5 < 10 mph
48.9 1 < 5 mph
25.5 < 1 mph
Time Period
7/21/2006 - 12/31/2008

- length of each "spoke" around the circle is related to the frequency that the wind blows from a particular direction per unit time.
- Each concentric circle represents a different frequency, from zero at the centre to increasing frequencies at the outer circles.
- A wind rose plot may contain additional information, in that each spoke is broken down into colour-coded bands that show wind speed ranges.
- Wind roses typically use 16 cardinal directions, such as north (N), NNE, NE, etc

- ✓ In terms of angle measurement in degrees, North corresponds to 0°/360°, East to 90°, South to 180° and West to 270°.

- ✓ Compiling a wind rose is one of the preliminary steps taken in constructing airport runways, as aircraft perform their best take-offs and landings pointing into the wind.

- ✓ Industrial area development

Mixing Height

- ✓ Vigorous mixing to a certain height (z) and little effect above that
- ✓ Rising air columns mix air vertically & horizontally
- ✓ Rising air mixes and disperses pollutants
- ✓ Only mixes to "mixing" height or above it
- ✓ Different in summer vs winter, morning vs evening
- ✓ For inversions, mixing height can be close to 0
- ✓ Thermal buoyancy determines depth of convective mixing depth

Mixing Height

- ✓ Usually corresponds to tops of clouds
- ✓ Different shapes but reach about same height
- ✓ Up to mixing height unstable air brings moisture up from below to form clouds – above mixing height there is no corresponding upward flow
- ✓ Strong delineation at stratosphere/troposphere boundary
- ✓ Stratosphere very stable against mixing
  - Where commercial air lines fly, air clear and non turbulent
  - Very clear boundary

Mixing Height

TABLE 5.1
Typical values of the mixing height for the contiguous United States

	Mixing height, m	
	Range	Average
Summer morning	200–1100	450
Summer afternoon	600–4000	2100
Winter morning	200–900	470
Winter afternoon	600–1400	970

Source: Ref. 4.

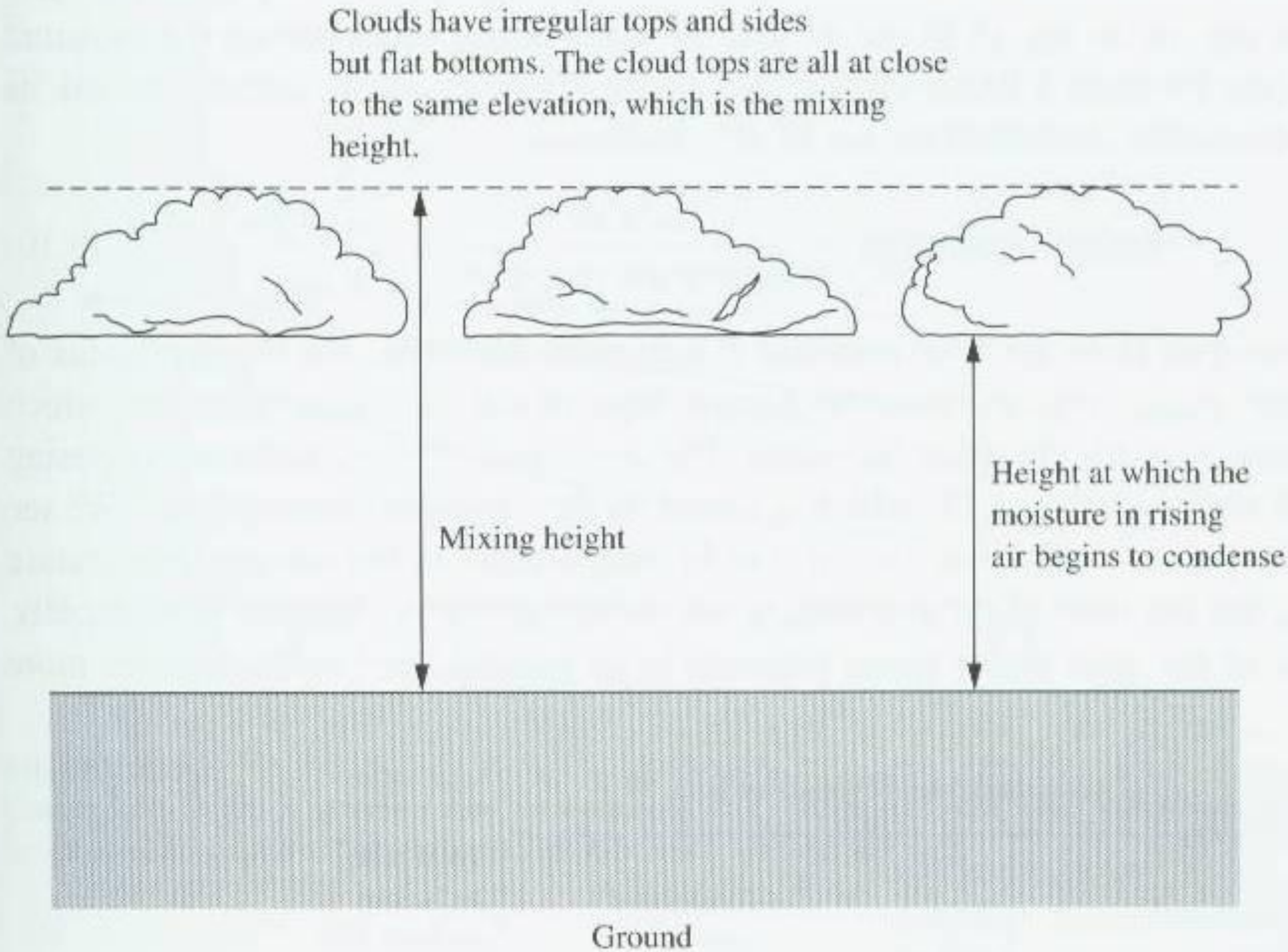


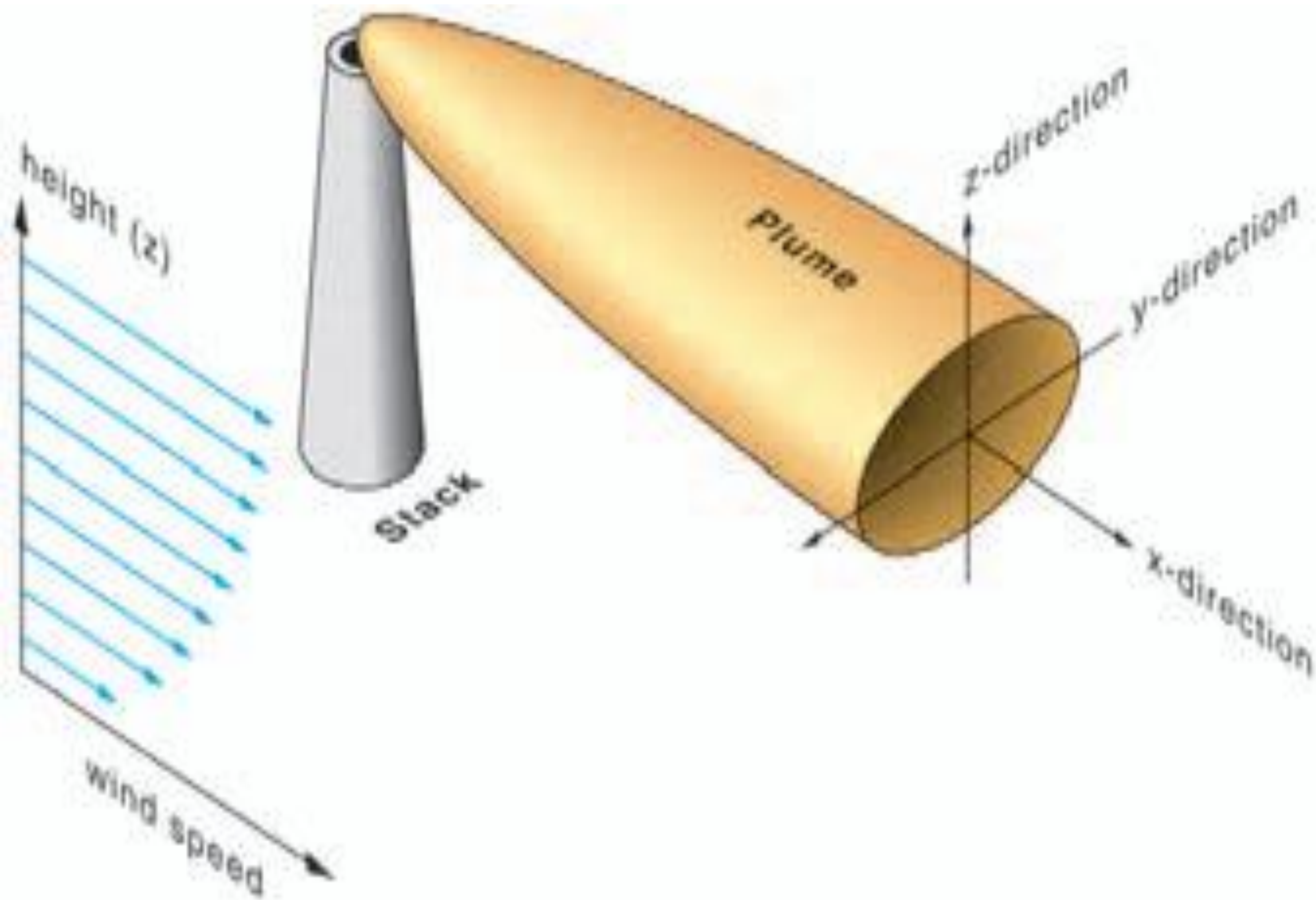
FIGURE 5.9
During the day many small clouds with a common top elevation show the height of the mixing layer. The flat bottoms show the elevation at which condensation begins (see Sec. 5.3.5).

Mechanics of Mixing Height

- ✓ Parcel heated by solar radiation at earth's surface
- ✓ Rises until temperature T' = T
- ✓ T' = particle's temp
- ✓ T = atmospheric temp
- ✓ Achieves neutral equilibrium, no tendency for further upward motion

Plume rise

- ✓ Effluent plumes from the chimney stacks are released in to the atmosphere at elevated temperatures.
- ✓ The rise of the plume after release to the atmosphere is caused by buoyancy and the vertical momentum of the effluent

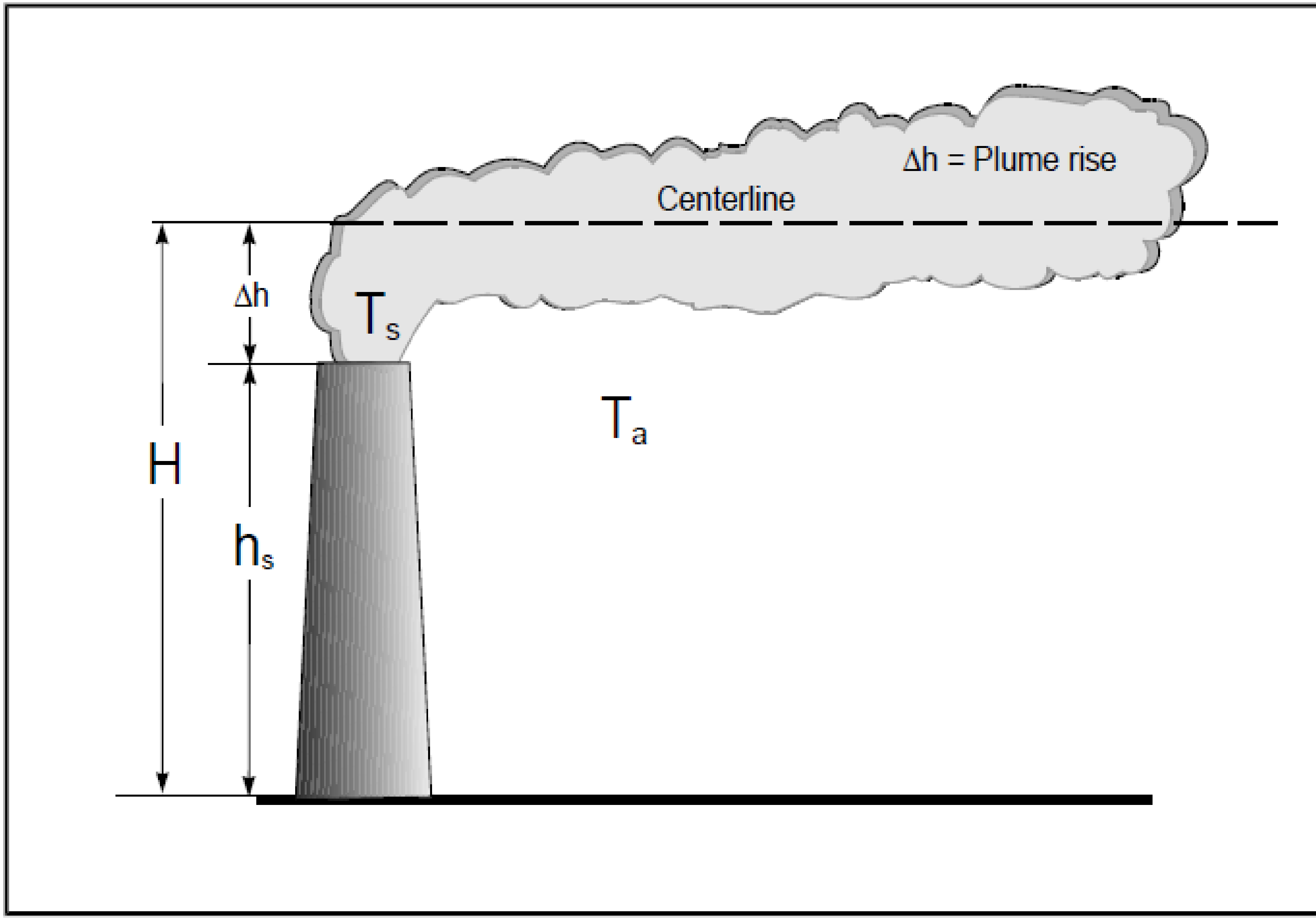


height (z)
Stack
Plume
z-direction
y-direction
x-direction
wind speed

- ✓ Under windless conditions, the plume rises vertically but more often it is bent as a result of the wind that is usually present.

- ✓ This rises of the plume adds to the stack an additional height ΔH, the height H of the virtual origin is obtained by adding the term ΔH, the plume rise, the actual height of the stack, Hs.

- ✓ The plume centre line height $H = Hs + \Delta H$ is known as the effective stack height.



Δh = Plume rise
Centerline
Δh
Ts
Ta
H
hs

✓ Types of Plume

- **Continuous Plume:** The release and the sampling time are long compared with the travel time.

- **Puff Diffusion / Instantaneous Plume:** The release time or sampling time is short when compared with the travel time

✓ Types of Plume Rise

- **Buoyancy Effect:** Rise due to the temperature difference between stack plume and ambient air.

- **Momentum Rise:** Rise due to exit velocity of the effluents (emissions).

Plume Rise Models

- ✓ Semi empirical equations based on heat flux
- ✓ Analytical solutions
- ✓ Numerical models

- Buoyancy Flux (F):

$$F = \frac{g.V_s.d^2.\Delta T}{4.T_s}$$

$$\Delta T = T_s - T_a$$

- Momentum Flux (F_m):

$$F_m = (T_a / T_s) * V_s^2 * d^2 / 4$$

g = Acceleration due to gravity
V_s = Stack exit velocity
d = Exit gas diameter
T_s = Stack gas exit temperature
T_a = Ambient air temperature

Stability Parameter

$$S = \frac{g \cdot \frac{\partial \theta}{\partial z}}{T_a}$$

Where,

$$\frac{\partial \theta}{\partial z} = Ambient Potential Temperature$$

$$\frac{\partial \theta}{\partial z} = \left(\frac{\Delta T}{\Delta z} \right) - \Gamma_d$$

$$where, \ \Gamma_d = -0.0098\ K/m$$

Analytical Solutions

- Momentum Sources
  - For Unstable and Neutral conditions

$$\Delta h = \frac{3dV_s}{U_s}\text{...} for V_s / U_s > 4$$

  - For Stable conditions

$$\Delta h = 1.5\left(\frac{V_s^2 d^2 T_a}{4T_s U_s}\right)^{1/3} S^{-1/6}$$

$$\Delta h = \frac{3dV_s}{U_s}\text{...} for V_s / U_s > 4$$

  - The lower value of the above equations is used for the concentration calculations.

Analytical Solutions

- Buoyant plumes
  - For Unstable and Neutral conditions

$$\Delta h(x) = \text{Const. } F^{1/3} * U_s^{-1} * X^{2/3}$$

$$\Delta h = \frac{1.6 * F^{1/3} * (3.5x^*)^{2/3}}{U_S}$$

- $x^* = 14 F^{5/8}$ when $F <= 55 \; m^4/sec^3$
- $x^* = 34 F^{2/5}$ when $F > 55 \; m^4/sec^3$
- $3.5x^*$ = Downwind distance to the point of final rise

- For Stable conditions $\Delta h = 2.6 * (\frac{F}{U_s * S})^{1/3}$

- The distance to final rise is given by $X_f = \frac{(2.0715 * U_s)}{S^{0.5}}$

Determination of the Type of Plume (Momentum or Buoyant)

Crossover Temperature (DT_c)

Unstable or Neutral case

$$\Delta T_c = 0.0297 * T_s \frac{V_s^{2/3}}{d_s^{1/3}} \qquad for\ F < 55\, m^4/\sec^3$$

$$\Delta T_c = 0.00575 * T_s \frac{V_s^{1/3}}{d_s^{2/3}} \qquad for\ F >= 55\, m^4/\sec^3$$

Buoyancy rise if DT >= DT_c or is assumed to be Momentum

Stable case $\quad \Delta T_c = 0.019582 * T_s V_s \sqrt{S}$

- The above calculations are valid for cases with stack exit temperature T_s greater than or equal to ambient temperature T_a.

Plumes Under Calm Conditions and Jets

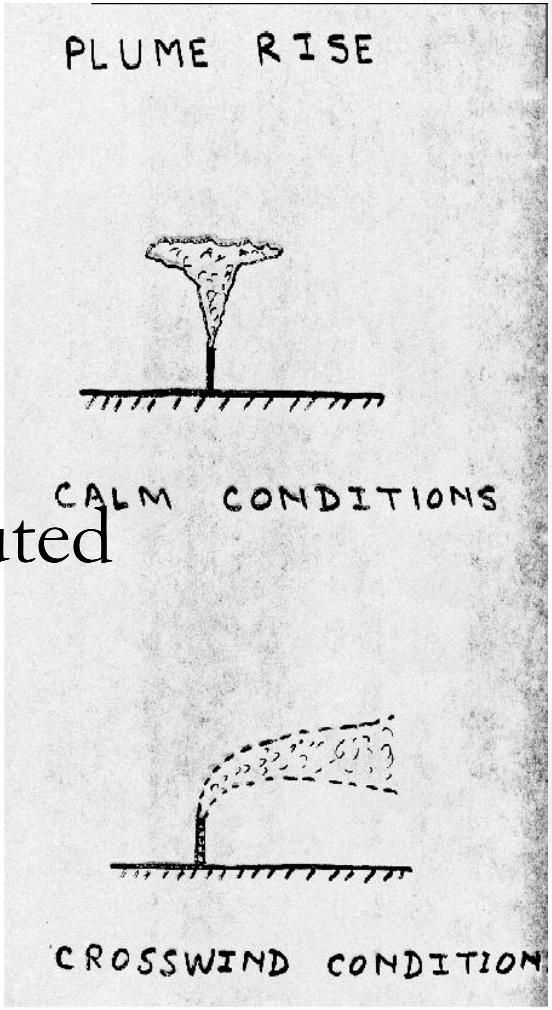
– For Calm Conditions

$$\Delta h = 5.0 \frac{F^{1/4}}{S^{3/8}}$$

For wind speeds < 1 m/sec

- The plume rise for a jet is computed as follows:

$\Delta h = 4.0\ F_m^{\ 1/4}\ S^{\ -1/4}$



Semi-Empirical Equations

- Most of the plume rise equations in this category are based on the following equations

$$\Delta h(x) = const.Q_h^a X^b U^c$$

where,

- Q_h is the heat emission rate of the source
  - $Q_h = Q_m C_p (T_s - T_a)$

where,

- Q_m is the total mass emission rate
  - $Q_m = (\Pi/4) \rho_s d^2 V_s$

Numerical Models

- Conservation of Mass

$$\frac{d}{dt}\left(v_p R^2 \rho_p\right) = \frac{2v_e}{R} v_p R^2 \rho_a$$

- Conservation of Moisture

$$\frac{d}{dt}\left(v_p R^2 \rho_p (\Delta q + \sigma)\right) = -G v_p R^2 \rho_p w$$

- Conservation of Energy (Heat)

$$\frac{d}{dt}\left(v_p R^2 \rho_p \left(\Delta T^* - \frac{L\sigma}{c_p}\right)\right) = v_p R^2 \rho_p w(\Gamma - \Gamma_d)$$

- Conservation of Momentum

$$\frac{d}{dt}(v_p R^2 \rho_p) = v_p R^2 \rho_p g\left(\frac{\Delta T^*}{T_a^*} - \sigma - \psi\right) + W_e \frac{d}{dt}(V_p R^2 \rho_p)$$

Numerical Models

✓ Conservation of Horizontal Momentum

$$\frac{d}{dt}(v_p R^2 \rho_p (v_x - u)) = c_d (u - v_x)^2 R |Sin\theta| \rho_a v_p$$

✓ Conservation of Solid Particles

$$\frac{d}{dt}(v_p R^2 \rho_p \Psi) = 0$$

- Relationship between Plume Rise z, Downwind Distance x and Time t

$$\frac{dz}{dt} = w$$

$$\frac{dx}{dt} = v_x$$

$$\frac{dP}{dt} = \rho_a g w$$

- Hydrostatic Environment - No Liquid or Solid Particulate Matter
- Assumptions made in developing the above equations
  - Boussinesq approximation has not been used
  - Solid body effects are included only in the horizontal direction
  - Downwash is neglected during computations i.e. $W_e = 0$

Thanks to all…