Introduction

• **Meteorology** is the study and forecasting of weather changes resulting from large-scale atmospheric circulation

• Characteristics of every air pollution problem
  1. There must be a pollutant emission into atm
  2. The pollutant must be confined
  3. The polluted air must interfere with well-being

• Item #2 occurs during periods of adverse weather that restrict mixing of pollutants
  – Since we can’t control the weather, emissions rates must be controlled so that problems don’t occur when the weather is really bad

Intro, cont’d

• It is imperative to establish the transport and dispersion patterns for given areas
  – Local atmosphere
  – Mathematical modeling

• Dispersion is based on
  – Mean air motion
  – Turbulent fluctuations
  – Diffusion
Solar Radiation

- “Solar Constant” = 1.36 kW/m² at upper boundary of atmosphere
- Maximum intensity at 0.4 μm ≤ λ ≤ 0.8 μm
- Note, visible spectrum: 0.39 μm ≤ λ ≤ 0.7 μm
- Approx. 53% of incident radiation is either
  - Absorbed by high atmosphere
  - Reflected to space by clouds
  - “Back scattered”
  - Reflected by earth’s surface
  - Absorbed by water vapor and clouds

Solar Radiation, cont’d

- Another 47% of incident radiation is absorbed by water and land surfaces
- Earth also radiates
  - Highest intensity: 4 μm ≤ λ ≤ 12 μm
  - Much absorbed by H₂O and CO₂ in atm near earth’s surface
    - These species do NOT absorb short-wave, incident radiation
  - Net result is a potential warming effect
  - Effect of PM emissions?

Earth’s Energy Balance

- Incoming Solar: 174 PW
- Reflected by Clouds: 35
- Reflected by earth’s surface: 7
- Reflected to space by atmosphere: 111
- Reflected back into space: 34
- Absorbed by atmosphere: 53
- Latent heat in water vapor: 12
- Conduction and convection: 9
- Heat absorbed by land and oceans: 89 PW

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Insolation Variability

- Insolation: the quantity of solar radiation reaching a unit area of earth’s surface
  - It varies with
    - Season of year
    - Geographic location
    - Time of day
    - Atmospheric composition

Surface Absorptivity and Albedo

- Not all incident radiation is absorbed
  - Soil, rock, ice, snow, vegetation, etc., all absorb differently
  - The portion reflected by the surface is called the albedo

- **Key Point**: the uneven distribution of energy resulting from latitudinal variations in insolation and from differences in absorptivity leads to the large-scale air motions of the earth

Wind Circulation

- Old adage: “Heat flows from hot to cold”
- So, as energy is transported from the tropics to the poles, the general circulation of the atmosphere is driven
  - This differential heating effect also gives rise to atmospheric pressure gradients
  - Air normally tends to flow from high-pressure regions toward regions of low pressure
    - Not so fast...
Wind, cont’d

• Once air has been set in motion by this “pressure gradient force” (F_{pg}), it undergoes an apparent deflection from its path (as seen by an observer on the earth)
• This deflection is called the Coriolis force (F_{cor}) and is a result of the earth’s rotation
  – F_{cor} is a function of the air velocity and latitude
  – F_{cor} is maximum at poles and zero at equator

Wind, cont’d

• Effects of F_{cor}
  
  ![Diagram of wind deflection due to Coriolis force]

• Example
  – [Link to YouTube video](http://www.youtube.com/watch?v=mcPs_OdQQYu)

Wind, cont’d

• In the upper atmosphere (or above oceans), there is somewhat of a balance between F_{pg} and F_{cor}
• Winds in which the F_{pg} is exactly equal and opposite to the F_{cor} are called geostrophic winds.
• Geostrophic winds flow in a straight path, parallel to the isobars, with velocities proportional to the pressure-gradient force.
Wind, cont’d

• Isobars are usually curved, though
• Winds that blow at a constant speed parallel to curved isobars are called gradient winds
• For air moving in a curve, we must consider
  – Centripetal force: a force which keeps a body moving with a uniform speed along a circular path and is directed along the radius towards the center
  – Centrifugal force: a force that draws a rotating body away from the center of rotation

Wind, cont’d

Flow is counter-clockwise (cyclonic curvature)
Flow is clockwise (anti-cyclonic curvature)

Note: Both depictions above are for the Northern Hemisphere
The Frictional Force ($F_f$)

- Certain terrain is especially rough, like cities or forests
- Generally, friction is lower over oceans or large lakes
- This is why it is much windier over large bodies of water

Since $F_f$ acts in the opposite direction of the wind, it reduces wind speed

Reduction in speed $\rightarrow$ reduction in $F_{cor}$

$F_f + F_{cor} \neq F_{pg} \rightarrow$ no longer have geostrophic balance; winds can cross isobars from high to low pressure

Applies near surface but not at upper levels where friction is insignificant

Atmospheric Force Balancing with the Frictional Force
Atmospheric Force Balancing with the Frictional Force

Notice that, with the presence of friction...

- ...the wind blows ACROSS isobars
  Thus, the flow cannot be geostrophic
- ...the wind is slightly weaker than it would be without friction
- ...the frictional force is always in the exact opposite direction of the wind
- ...the Coriolis force, however, is still always 90° to the right of the wind (in the northern hemisphere)

This kind of atmospheric flow is common at Earth's surface

Atmospheric Stability

Atmospheric stability refers to the tendency for air parcels to move vertically.

Basic concept – when the temperature of the air parcel is greater than the temperature of the surrounding environment, then it will rise, and when the temperature of the air parcel is less than the surrounding environment, then it will sink.

Dry adiabatic lapse rate (DALR)

- Meteorologists normally assume that unsaturated air parcels (i.e. air outside clouds) change temperature in an adiabatic process as they rise or sink.

- The Dry Adiabatic Lapse Rate (DALR) is the rate at which an unsaturated air parcel cools as it rises.
Temperature Change in the Lower Atmosphere
– Adiabatic Lapse Rate

- First Law of Thermodynamics
  \[ dq = dh - \tau dP = C_p dT - \frac{1}{\rho} dP \]
- Barometric Equation
  \[ \frac{dP}{dZ} = -\rho g \]
  \[ \Rightarrow \frac{C_p}{\rho} = -\frac{1}{\rho} dP = -gdZ \]
  \[ \Rightarrow \frac{dT}{dZ} = -\frac{g}{C_p} \]

Lapse Rate

Calculate the Dry ALR(Γ)

- Negative of the temperature gradient in the atmosphere

Assume \( g = 9.8 \frac{m}{s^2} \), and

\[ c_p = 10^5 J \frac{kg}{K} \]

\[ -\Gamma = \frac{g}{c_p} = \frac{9.8 \frac{m}{s^2}}{10^5 \frac{J}{kgK}} = 0.0098 \frac{K}{m} \]

\[ -\Gamma = \frac{K}{100m} \approx 54 \frac{F}{1000ft} \]

Environmental Lapse Rate

The Environmental Lapse Rate (ELR) is the negative of the rate at which the measured temperature of the air in the environment decreases with height.

We send up balloons with instrument packages called radiosondes to measure the temperature at different levels above the Earth’s surface.
Environmental Lapse Rate, cont’d

Example:

\[ z_t = 200 \text{ m} \quad \text{top} \quad T_t = 18^\circ C \]
\[ z_b = 100 \text{ m} \quad \text{bottom} \quad T_b = 20^\circ C \]

**ELR** = \( -\left(\frac{T_B - T_T}{z_B - z_T}\right) \)

**ELR** = \( -\left[(20^\circ C - 18^\circ C) / (100 \text{ m} - 200 \text{ m})\right] \)

**ELR** = \( 2^\circ C / 100 \text{ m} \)

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Stability Determination

In order to determine the stability of the air, we compare the Environmental Lapse Rate (ELR) to the Dry Adiabatic Lapse Rate (DALR).

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Stability Conditions

- Adiabatic lapse rate
- Environmental lapse rate

![Figure 3-8: Lapse rate as related to atmospheric stability](image)

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Superadiabatic Lapse Rates (Unstable)
- Temperature decreases are greater than -1°C/100m
- Occur on sunny days
- Characterized by intense vertical mixing
- Excellent dispersion conditions

Neutral Lapse Rates
- Temperature decreases are similar to the adiabatic lapse rate
- Results from:
  - Cloudy conditions
  - Elevated wind speeds
  - Day/night transitions
- Describes good dispersion conditions

Isothermal Lapse Rates (Weakly Stable)
- Characterized by no temperature change with height
- Atmosphere is somewhat stable
- Dispersion conditions are moderate
Inverted Lapse Rates (Strongly Stable)

• Characterized by increasing temperature with height

Does it occur during the day or at night? Does it improve or deteriorate air quality?

Inversion

• Definition: temperature increases with altitude

Isotherms are “folding under” in these regions

Inversion

• Two major types of inversion:
  – Subsidence Inversion: descent of a layer of air within a high pressure air mass
  – Radiational Inversion: radiation at night from the earth’s surface into the local atmosphere
Subsidence Inversion

- Associated with high-pressure systems
- Inversion layer is formed aloft
- Covers hundreds of thousands of square km
- Persists for days

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”

Relationship Between Atmospheric Stability and Wind Speed

- Six stability classes (A most unstable, F most stable)

<table>
<thead>
<tr>
<th>Wind Speed, 10 m (m/sec)</th>
<th>Day</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Incoming Solar Radiation</td>
<td>Thinly Overcast</td>
</tr>
<tr>
<td>&lt;2</td>
<td>Strong (A)</td>
<td>A-B</td>
</tr>
<tr>
<td>2-3</td>
<td>Moderate (B)</td>
<td>B-C</td>
</tr>
<tr>
<td>3-5</td>
<td>Slight (C)</td>
<td>C-D</td>
</tr>
<tr>
<td>&gt;6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

What happens to inversion when sun rises?
Notes on Stability Table

• The neutral class (D) should be assumed for overcast conditions, both day and night
• Strong insolation refers to clear skies; solar angle > 60° above the horizon
• Slight insolation refers to a sunny fall afternoon, solar angle between 15° and 35°
• Night refers to the period between 1 hour before sunset and 1 hour after sunrise

Relationship Between Wind Speed and Surface Roughness

• Planetary boundary layer (PBL): the region between the earth’s surface and the level of the atmosphere where gradient winds dominate
  - Wind speeds are decreased due to surface roughness

<table>
<thead>
<tr>
<th>Stability Category</th>
<th>Rural exponent</th>
<th>Urban exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.07</td>
<td>0.15</td>
</tr>
<tr>
<td>B</td>
<td>0.07</td>
<td>0.15</td>
</tr>
<tr>
<td>C</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>D</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>E</td>
<td>0.15</td>
<td>0.30</td>
</tr>
<tr>
<td>F</td>
<td>0.55</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Mixing Height (MH)

- Height of air that is relatively vigorously mixed and where dispersion occurs

Note: MMD = maximum mixing depth

Dispersion from Point Sources

- Pollutants emitted in plume form

Why does plume expand downwind?

What are the factors that influence the history of plume?

Impact on air quality depends on dispersion, which is a function of plume height

How does mixing height vary diurnally?

How does mixing height vary seasonally?

Figure 3.6 Average summertime MHs for selected U.S. cities.
Dispersion from Point Sources

- Plume rise affects transport
  - Effects maximum ground level concentrations (MGLCs)
  - Effects distance of MGLCs

Under what conditions can we have a higher Effective Stack Height?

Plume Category: “Looping”

- Superadiabatic lapse rate – strong instabilities
- Dispersal over a wide area
  - High, localized ground concentration possible
- Warm, clear conditions

Plume Category: “Coning”

- Neutral atmospheric stability; small-scale turbulence
- Overcast skies (day or night)
- Plume half-angle: approximately 10°
- Plume carried far prior to reaching ground
Plume Category: “Fanning”

- Large, negative lapse rate; strong inversion
- Plume often travels downwind at constant elevation
- Difficult to predict downwind concentrations
- Little pollutant reaches ground

Plume Category: “Fumigation”

- Summertime, with two important conditions
  - Stable layer of air lies a short distance above release point
  - Unstable layer of air beneath
- High ground-level concentrations reached
- Usually, very short-lived (< 30 minutes)

Plume Category: “Lofting”

- The opposite of fumigation
  - Stable layer of air beneath release point
  - Unstable layer of air above
- A favorable situation
  - Downwind dispersion with little ground conc.
Plume Category: “Trapping”

- Inversions exist both above and below stack height
- Dispersion severely restricted to region between stable layers