

# EVE 402/502 Air Pollution Generation and Control

## Chapter #3 Meteorology

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### 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

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### Intro, cont'd

- It is imperative to establish the transport and dispersion patterns for given areas
  - Mathematical modeling of local atmosphere
- Dispersion is based on
  - Mean air motion
  - Turbulent fluctuations
  - Diffusion



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## Solar Radiation

- “Solar Constant” = 1.36 kW/m<sup>2</sup> at upper boundary of atmosphere
  - Maximum intensity at  $0.4 \mu\text{m} \leq \lambda \leq 0.8 \mu\text{m}$
  - Note, visible spectrum:  $0.39 \mu\text{m} \leq \lambda \leq 0.7 \mu\text{m}$
  - 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

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## Solar Radiation, cont’d

- Another 47% of incident radiation is absorbed by water and land surfaces
- Earth also radiates
  - Highest intensity:  $4 \mu\text{m} \leq \lambda \leq 12 \mu\text{m}$
  - Much absorbed by H<sub>2</sub>O and CO<sub>2</sub> 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?

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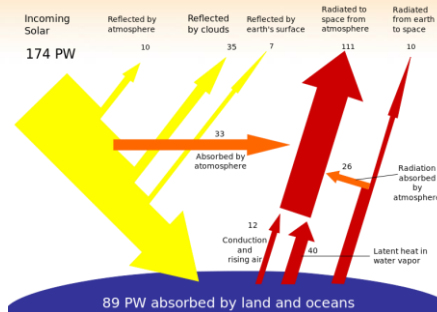
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## Earth’s Energy Balance



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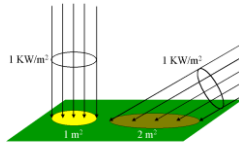
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## Insolation Variability

- 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



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## 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

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## 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...

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## 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

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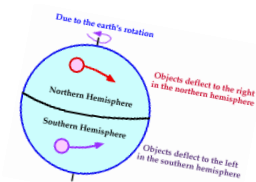
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## Wind, cont'd

- Effects of  $F_{cor}$



- Example

– [http://www.youtube.com/watch?v=mcPs\\_OdQOYU](http://www.youtube.com/watch?v=mcPs_OdQOYU)

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## 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

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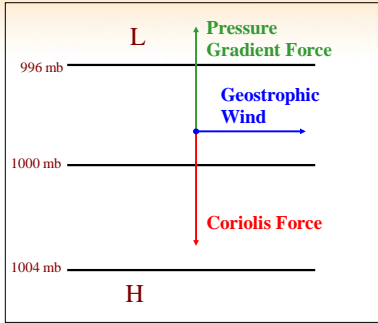
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### Wind, cont'd



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### 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

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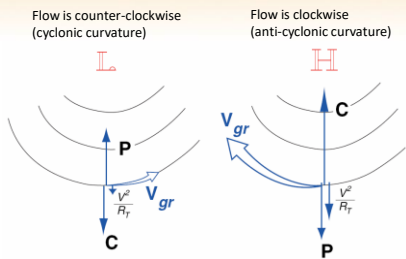
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### Wind, cont'd



Note: Both depictions above are for the Northern Hemisphere

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### 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

Small frictional force



Large frictional force



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### Recap

- Insolation + absorptivity  $\rightarrow$  differential heating
- Differential heating  $\rightarrow F_{pg}$  (flow from H to L)
- Coriolis effect opposes  $F_{pg}$
- Geostrophic winds when  $F_{pg}$  and  $F_{cor}$  are equal and opposite (straight line isobars)
- Isobars are really curved  $\rightarrow$  gradient winds
- Frictional force ( $F_f$ ) also plays a role with wind
  - Terrain “roughness” matters

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### The Frictional Force, cont'd

#### How does friction affect geostrophic balance?

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

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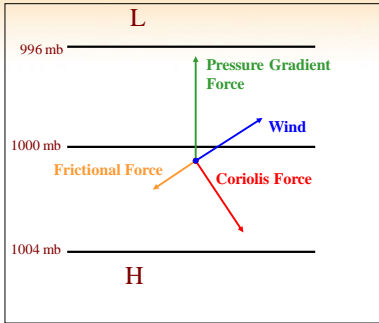
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### Atmospheric Force Balancing with the Frictional Force



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### Atmospheric Force Balancing with the Frictional Force

Notice that, with the presence of friction...

- ...the wind blows ACROSS isobars  
Thus, the flow can not be geostrophic (gradient)
- ...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

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## 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

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## Atmospheric Stability, cont'd

- 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

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## Temperature Change in the Lower Atmosphere – Adiabatic Lapse Rate

- First Law of Thermodynamics (in terms of enthalpy)

$\nearrow = 0$  for adiabatic expansion

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

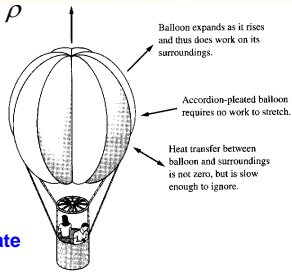
- Barometric Equation

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

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

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

Lapse Rate



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## Calculate the Dry ALR( $\Gamma$ )

- Negative of the temperature gradient in the atmosphere

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

$$c_p = 1005 \frac{J}{kg \cdot K}$$

$$-\Gamma = \frac{g}{c_p} = \frac{9.81 \frac{m}{s^2}}{1000 \frac{J}{kg \cdot K}} = 0.0098 \frac{K}{m}$$

$$-\Gamma \approx 1 \frac{K}{100m}$$

$$-\Gamma \approx 1 \frac{^\circ C}{100m} \approx 5.4 \frac{^\circ F}{1000ft}$$

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## 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

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## Environmental Lapse Rate, cont'd

Example:



$$\text{ELR} = -[(T_B - T_T) / (z_B - z_T)]$$

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

$$\text{ELR} = 2^\circ\text{C} / 100 \text{ m}$$

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## Stability Conditions

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

- Adiabatic lapse rate
- \_\_\_\_\_ Environmental lapse rate

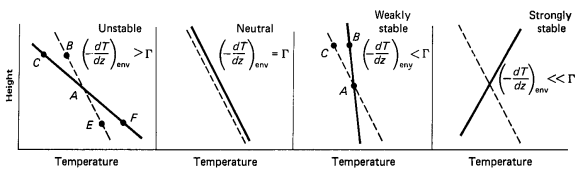


Figure 3-8. Lapse rate as related to atmospheric stability

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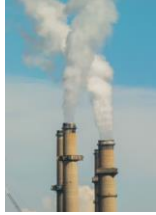
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### Superadiabatic Lapse Rates (Unstable)

- Temperature decreases are greater than  $+1^{\circ}\text{C}/100\text{m}$
- Occur on sunny days
- Characterized by intense vertical mixing
- Excellent dispersion conditions



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### 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

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### Isothermal Lapse Rates (Weakly Stable)

- Characterized by no temperature change with height
- Atmosphere is somewhat stable
- Dispersion conditions are moderate

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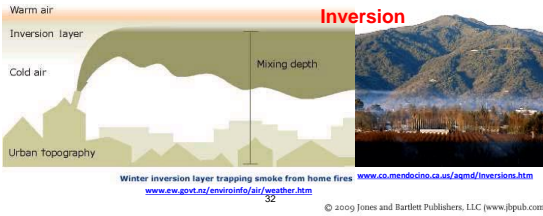
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## Inverted Lapse Rates (Strongly Stable)

- Characterized by increasing temperature with height

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




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## Inversion

- Definition: temperature increases with altitude

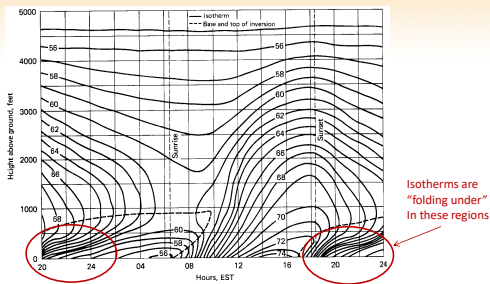


Figure 3-11 Time cross section of average temperature (°F) up to 5000-ft altitude, September, October, 1950, Oak Ridge, Tenn. (Source: U.S. Weather Bureau, Meteorological Survey of the Oak Ridge Area, Report ORO-99, Oak Ridge, Tenn.: AEC, 1953.)

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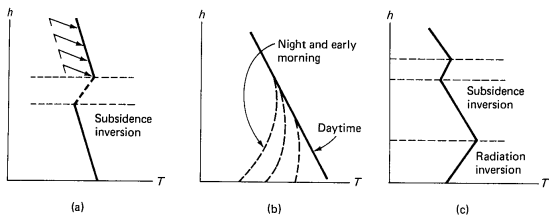
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## Inversion

- 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



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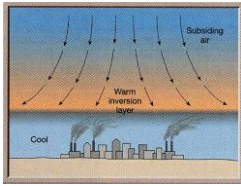
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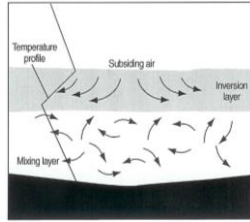
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### Subsidence Inversion

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



[apollo.bsc.vsc.edu/~jrmog\\_var\\_geo.html](http://apollo.bsc.vsc.edu/~jrmog_var_geo.html)



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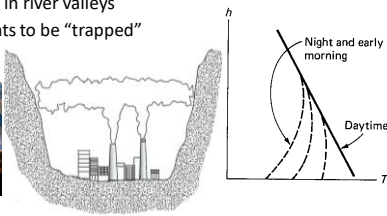
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### Radiational Inversions

- 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”



[www.co.mendocino.ca.us/agmd/inversions.htm](http://www.co.mendocino.ca.us/agmd/inversions.htm)



**What happens to inversion when sun rises?**

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### Relationship Between Atmospheric Stability and Wind Speed

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

| Wind Speed,<br>10 m (m/sec) | Day<br>Incoming Solar Radiation |          |        | Night<br>Thinly Overcast |            |
|-----------------------------|---------------------------------|----------|--------|--------------------------|------------|
|                             | Strong                          | Moderate | Slight | >4/8 Cloud               | <3/8 Cloud |
| <2                          | A                               | A-B      | B      | E                        | F          |
| 2-3                         | A-B                             | B        | C      | D                        | E          |
| 3-5                         | B                               | B-C      | C      | D                        | D          |
| >6                          | C                               | D        | D      | D                        | D          |

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## 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

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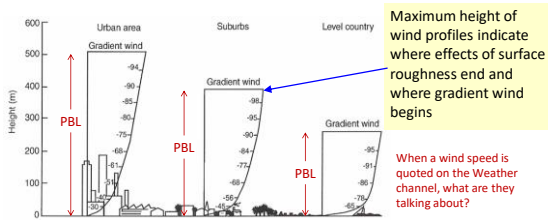
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## Relationship Between Wind Speed and Surface Roughness

- 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



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## Predicting wind speeds at other heights (Deacon's Power Law)

$$u = u_1 \left( \frac{z}{z_1} \right)^p$$

$u$  = unknown windspeed at height  $z$   
 $u_1$  = known windspeed at height  $z_1$   
 $p$  = positive exponent shown below

Value of Exponent,  $p$

| 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           |

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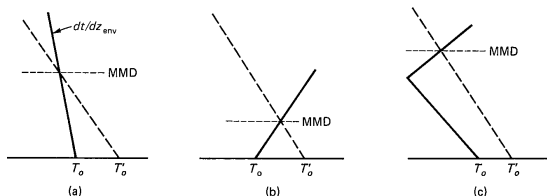
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## Mixing Height (MH)

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



Note: MMD = maximum mixing depth

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## Mixing Height (MH)



Figure 3.6 Average summertime MHs for selected U.S. cities.

- How does mixing height vary diurnally?
- How does mixing height vary seasonally?

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## Dispersion from Point Sources

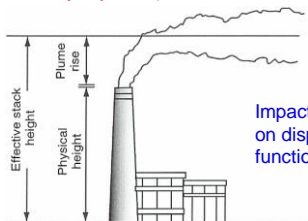
- Pollutants emitted in plume form

Why does plume expand downwind?

What are the factors that influence the history of plume (how it behaves over time)?



[www.epa.gov/.../muncpl/landfill/w\\_combst.htm](http://www.epa.gov/.../muncpl/landfill/w_combst.htm)



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

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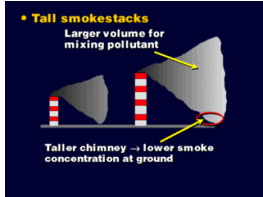
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## Dispersion from Point Sources

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



[www.atmos.ucla.edu/~jchimney/plumes/Notes03.html](http://www.atmos.ucla.edu/~jchimney/plumes/Notes03.html)

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

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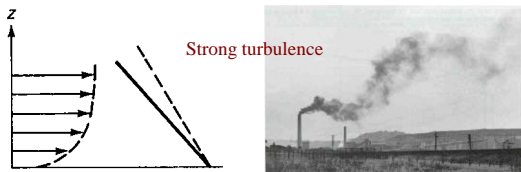
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## Plume Category: “Looping”

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



<http://www.aesd.usf.edu/~spos03>  
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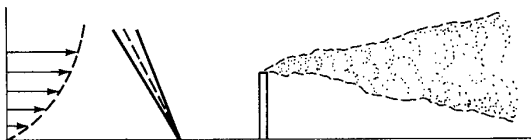
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## Plume Category: “Coning”

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



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### 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



<http://www.med.usf.edu/~npsor/4>  
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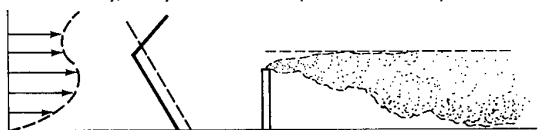
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### Plume Category: "Fumigation"

- 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)



(d)

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### 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.



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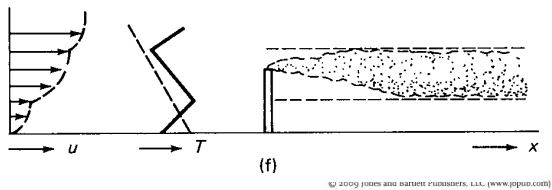
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### Plume Category: "Trapping"

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



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