Slide 1

MET 200   Lecture 8 Stability

Slide 2

Quiz 1 Results
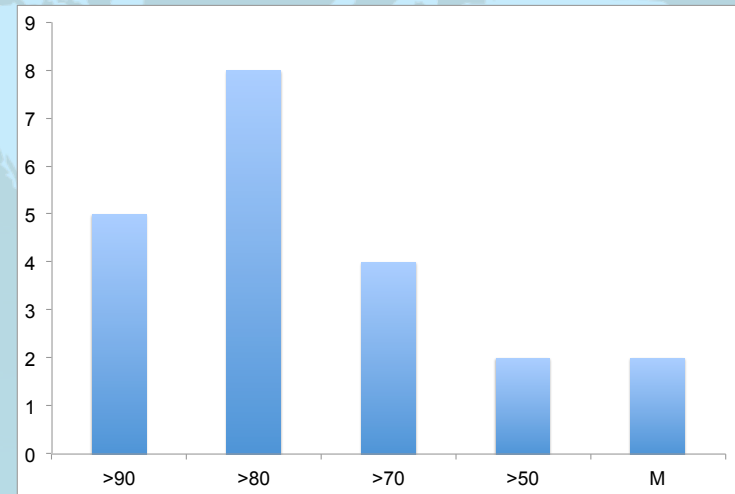
Student Count vs Percent

Slide 3

Previous Lecture

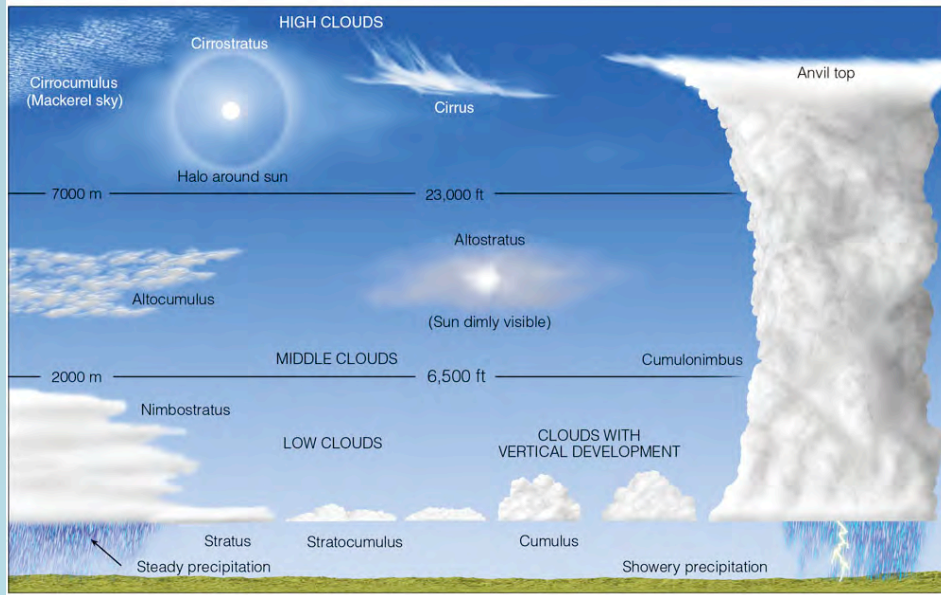Cloud forms and what they tell us.

Slide 4

Cloud classification

Clouds are categorized by their height, appearance, and vertical development

– High Clouds - generally above 16,000 ft at middle latitudes (>6 km)
  • Main types - Cirrus, Cirrostratus, Cirrocumulus
– Middle Clouds – 7,000-23,000 feet (2-6 km)
  • Main types – Altostratus, Altocumulus
– Low Clouds - below 7,000 ft (<2 km)
  • Main types – Stratus, stratocumulus, nimbostratus
– Vertically developed clouds (via convection)
  • Main types – Cumulus, Cumulonimbus

Cloud type summary

HIGH CLOUDS
Cirrostratus
Cirrocumulus (Mackerel sky)
Cirrus
Anvil top
Halo around sun
7000 m — 23,000 ft
Altostratus
(Sun dimly visible)
Altocumulus
MIDDLE CLOUDS
2000 m — 6,500 ft
Cumulonimbus
Nimbostratus
LOW CLOUDS
CLOUDS WITH VERTICAL DEVELOPMENT
Stratus
Stratocumulus
Cumulus
Steady precipitation
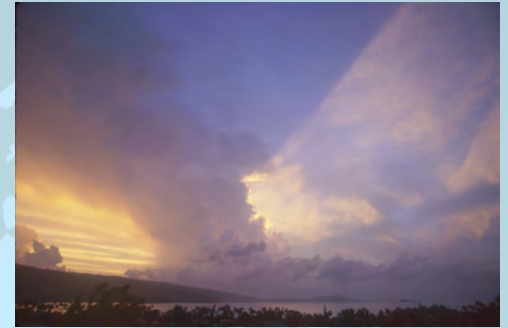Showery precipitation

Vertically developed clouds

Cumulus
- Puffy "cotton"
- Flat base, rounded top
- More space between cloud elements than stratocumulus

Cumulonimbus
- Thunderstorm cloud
- Very tall, often reaching tropopause
- Individual or grouped
- Large energy release from water vapor condensation

Lecture 8 Stability

Defining Stability

Buoyancy in the atmosphere (hot air rises)
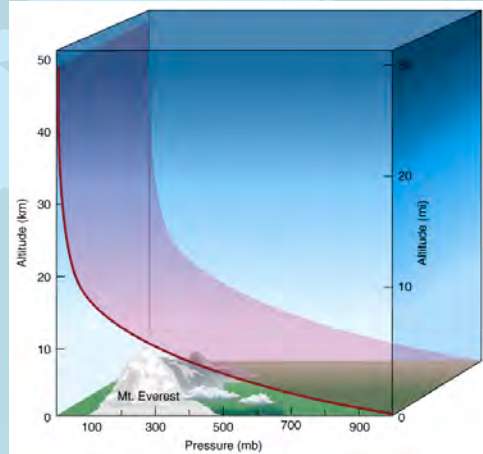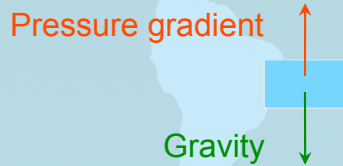
Environmental vs Parcel Lapse Rates

Hot Air Rises

Hydrostatic Balance

What keeps air from rising despite the strong upward pressure gradient force?

A balance between gravity and the pressure gradient force.

Pressure gradient

Gravity

Hydrostatic Equation

The vertical component of the momentum equation can be rewritten after elimination of small terms.

$$\frac{\partial p}{\partial z} = -\rho g$$

Since g is a constant, this equation tells us that the rate of change of pressure with height is dependent on air density or temperature: it is greater for cold dense air than for warm less dense air.

This equation is used to diagnose altitude above the ground based on the pressure distribution.

Stability in the Atmosphere

An Initial Perturbation

Stable Returns

Unstable Keeps Going

Neutral Stays at new level

How do we diagnose stability in the atmosphere? What assumptions are implicit to our analysis of soundings for stability?

Stability in the Atmosphere

Warm (cold) air relative to its surroundings will rise (sink). To determine the atmosphere's stability for vertical motions we need to compare the temperature of rising/sinking air parcels with the temperature of the air in the surrounding environment.

Lapse Rates

A lapse rate is a change of temperature with height in the atmosphere. There are three kinds of lapse rates:

1. Environmental Lapse Rates are measured by a thermistor on a weather balloon.

2. Dry adiabatic lapse rate is the change of temperature that a dry or clear air parcel experiences when it moves up or down. An adiabatic process assumes no heat exchange occurs across the parcel's boundary.

3. Moist adiabatic lapse rate occurs in a cloud because latent heat is released, so the temperature cools more slowly in a rising air parcel.

Derive the Dry Adiabatic Lapse Rate

Start with 1st law of thermodynamics, the total energy of an isolated system is constant. The change in the internal energy of a closed system is equal to the amount of heat supplied to the system from the outside, minus the amount of work derived from the system.

Derive the Dry Adiabatic Lapse Rate

Start with 1st law of thermodynamics, energy added = change in internal energy - work. Then make adiabatic assumption, and assume hydrostatic balance.

1st Law of Thermodynamics : $dq = c_p dT - \alpha dp$

Adiabatic assumtion: $c_p dT = \alpha dp$

Hydrostatic assumption: $\alpha dp = -g dz$

Combining these two equations to eliminate the pressure, one arrives at the result for the DALR:
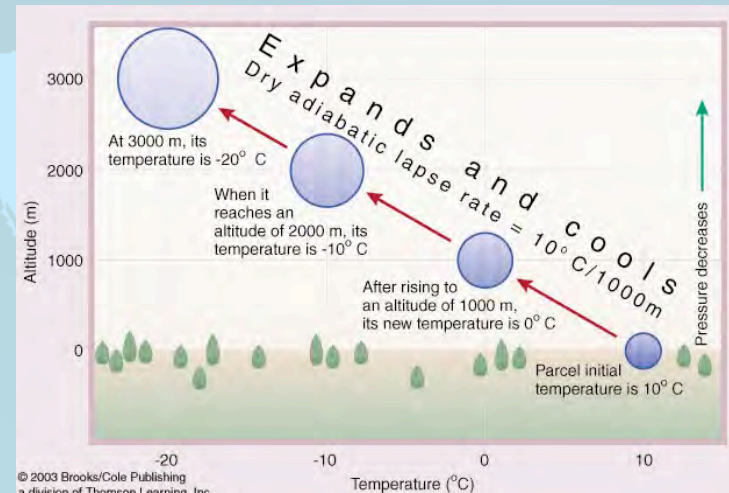
$$c_p dT = -g dz$$

Therefore $\Gamma_d = dT/dz = -g/c_p$

Parcel Lapse Rates:Why Rising Air Cools

At 3000 m, its temperature is -20° C

When it reaches an altitude of 2000 m, its temperature is -10° C

After rising to an altitude of 1000 m, its new temperature is 0° C

Parcel initial temperature is 10° C

Expands and cools
Dry adiabatic lapse rate = 10° C/1000m

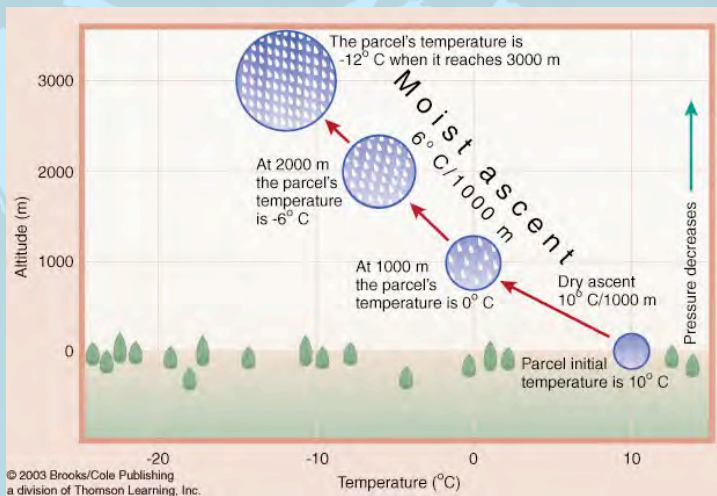Pressure decreases

Altitude (m)

Temperature (°C)

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- Rising air parcels expand.
- Work done by air molecules in the parcel pushing outward consumes energy and lowers the parcel temperature.
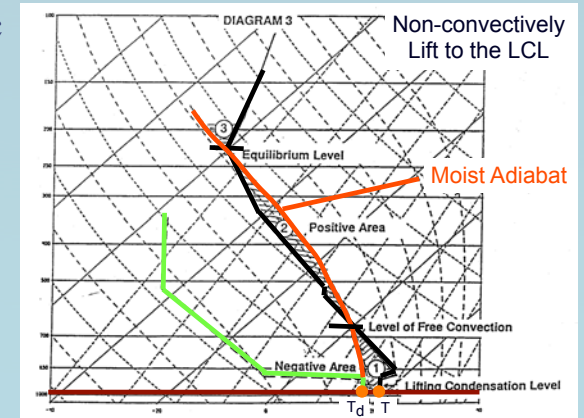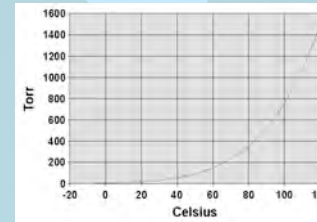
Parcel Lapse Rates: Why Rising Air Cools

A saturated rising air parcel cools less than an unsaturated parcel because latent heat is released when drops form.

Saturated Adiabatic Lapse Rate Varies with Height

- Average SALR in lower troposphere is ~ 6° C/km
- SALR depends on saturation vapor pressure which depends on T and P.
- Since saturation vapor pressure varies exponentially with increasing temperature, the saturated adiabatic LR is not constant, rather it varies from ~ 3-9° C/km.
- Thus, the SALR is curved, approaching the DALR in the upper troposphere as the temperature of the parcel drops.

Saturated Adiabatic Lapse Rate

$$\Gamma_w = g \frac{1 + \dfrac{L_v r}{R_d T}}{c_p + \dfrac{L_v^2 r \varepsilon}{R_d T^2}}$$

where:

Γ_w = Saturated adiabatic lapse rate, K/m

g = Earth's gravitational acceleration = 9.8076 m/s^2

L_v = Heat of vaporization of water, J/kg

r = Mixing Ratio: The ratio of the mass of water vapor to the mass of dry air, kg/kg

R_d = Specific gas constant of dry air = 287 J kg^{-1} K^{-1}

ε = The dimensionless ratio of the specific gas constant of dry air to the specific gas constant for water vapor = 0.6220

T = Temperature of the saturated air, K

c_p = The specific heat of dry air at constant pressure, J kg^{-1} K^{-1}

Determining Convective Cloud Bases

- Dry air parcels cool at the dry adiabatic rate (about 10°C/km)
- Dew point decreases at a rate of ~ 2°C/km
- This means that the dew point approaches the air parcel temperature at a rate of about 8°C/km
- If the dew point depression were 4°C at the surface, a cloud base would appear at a height of 500 meters
  - Cloud base occurs when dew point = temp (100% RH)
- Each one degree difference between the surface temperature and the dew point will produce an increase in the elevation of cloud base of 125 meters

Orographic Clouds
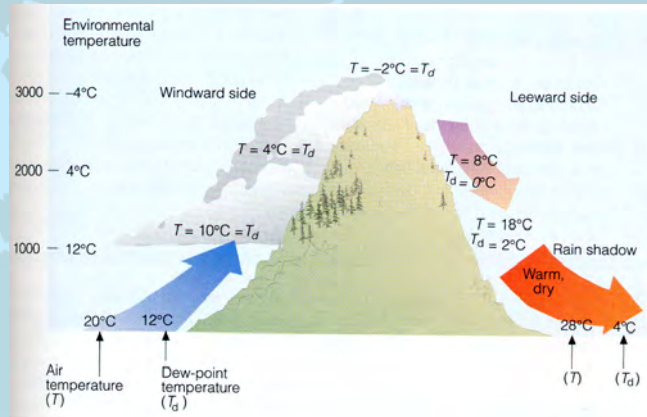
- Forced lifting along a topographic barrier causes air parcel expansion and cooling
- Clouds & precipitation often develop on upwind side of Mts.
- Air dries and warms during descent on downwind side

The Key to Determining Stability

- To test for stability we need to compare the changing temperature of air parcels with their environments.
- Parcel Lapse Rates are fixed by physics.
- Environmental lapse rates are not fixed, they are always changing, depending on wind, sun, etc.
- Therefore, the key to determining atmospheric stability is the slope, or magnitude, of the environmental lapse rate.

## Comparison of Environmental and Parcel Lapse Rates

1. Absolutely stable - if they have a value less than the moist lapse rate.
2. Conditionally unstable - if they fall between the dry and moist adiabatic lapse rates.
3. Absolutely unstable - if they have a value greater than the dry adiabatic lapse rate.
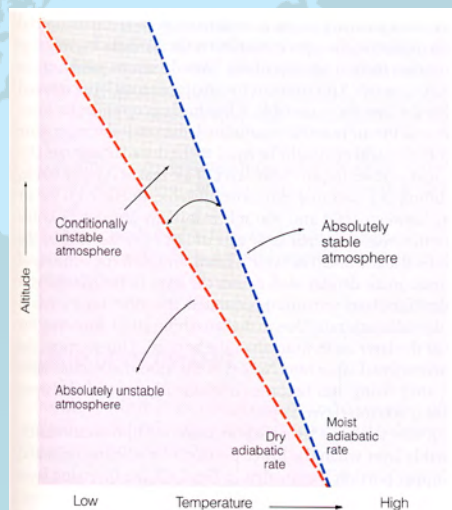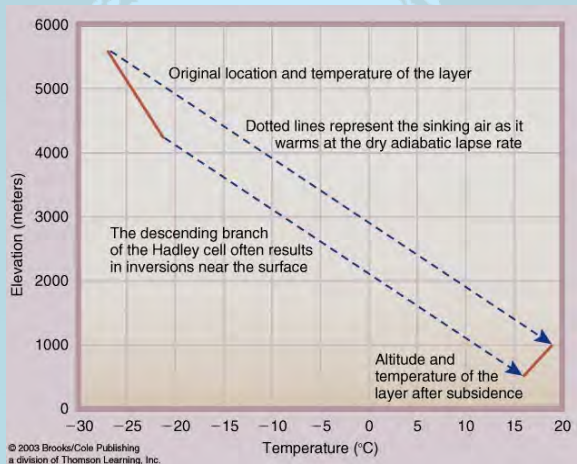
Conditions that contribute to a stable atmosphere

Radiative cooling of surface at night

Advection of cold air near the surface.

Air moving over a cold surface (e.g., snow)

Adiabatic warming due to compression from subsidence (sinking).
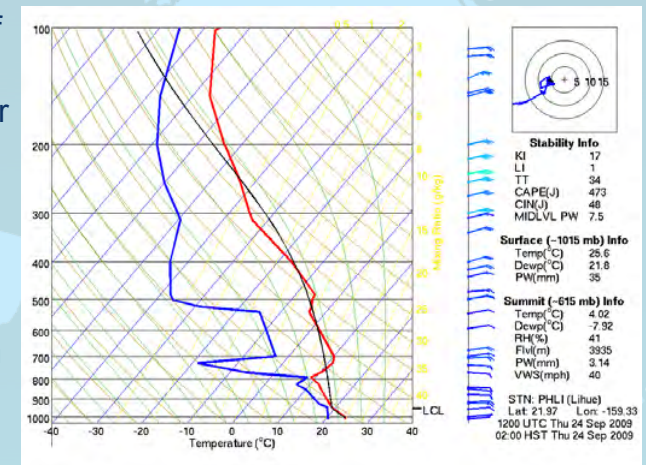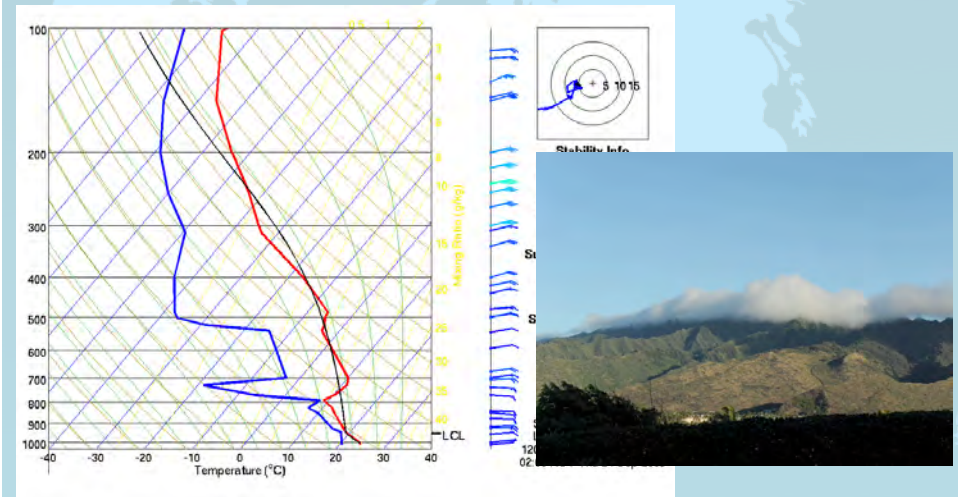
Conditions that contribute to a stable atmosphere

When a layer of air sinks an inversion forms below. This is the cause of the tradewind inversion common over Hawaii.

Original location and temperature of the layer

Dotted lines represent the sinking air as it warms at the dry adiabatic lapse rate

The descending branch of the Hadley cell often results in inversions near the surface

Altitude and temperature of the layer after subsidence

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Cloud Loop for 9/24/09

Lihue Temperature Chart from 9/24/09 (AKA Skew-T Chart)

Radiation Inversion

• Radiation inversions feature increasing T with height above ground

• Occur on most clear, calm
• nights (nocturnal inversion)

Are strongest when
• Winds are calm
• Air is dry and cloud free
  • Less IR absorption
 • Less latent heat release from fog/ dew formation

• Night is long

Windy night

Calm night

FIGURE 3.16
Vertical temperature profiles just above the ground on a windy night and on a calm night. Notice that the radiation inversion develops better on the calm night.
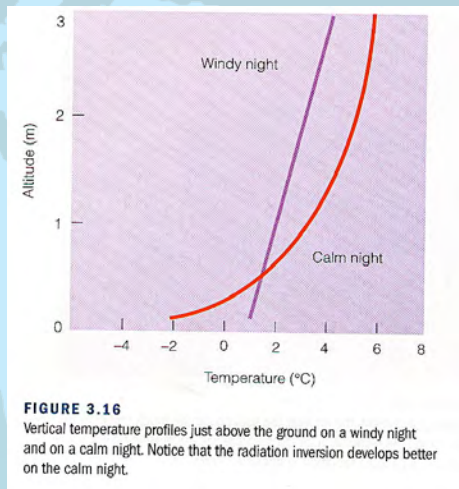
Temperature Inversions

• A temperature inversion is simply a layer in the atmosphere in which the temperature increases with height.

• All temperature inversions are absolutely stable.

• Temperature inversions prevent vertical mixing of air and can contribute to pollution episodes.
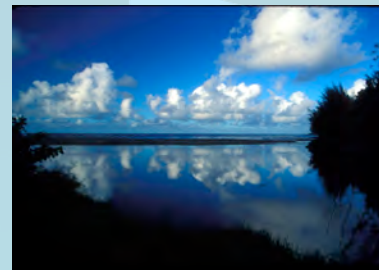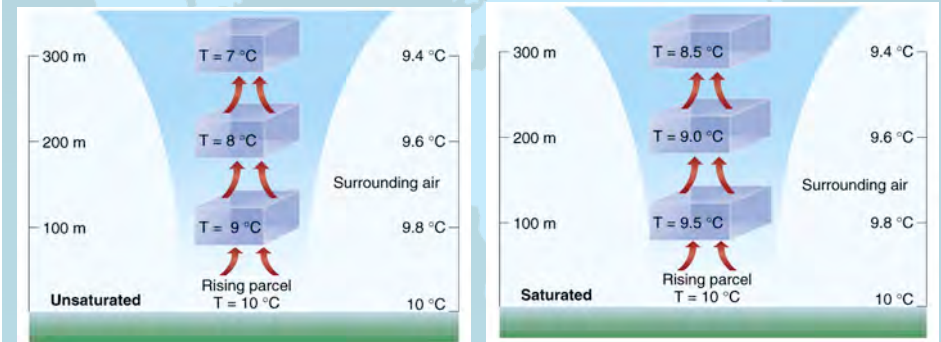
Absolutely Stable

- When the environmental lapse rate is less than the moist and dry adiabatic lapse rates, the atmosphere is absolutely stable.
- Temperature inversions (increasing temperature with height) are absolutely stable, and result in reduced mixing.
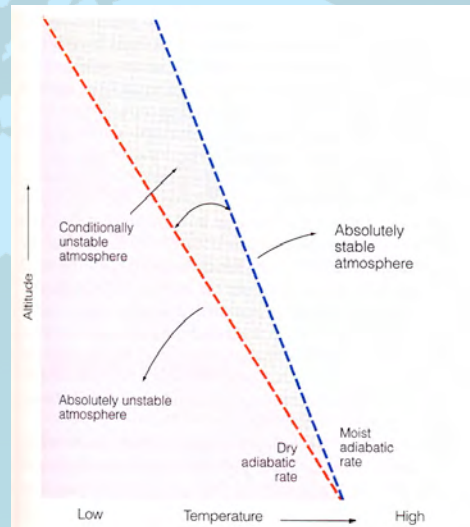

Absolutely Stable Air

In clear air   In cloudy air

## Conditions that Enhance Atmospheric Instability?

- Cooling of air aloft
  – Cold advection aloft
  – Radiative cooling of air/clouds aloft
- Warming of surface air
  – Solar heating of ground
  – Warm advection near surface
  – Air moving over a warm surface (e.g., a warm body of water)
    • Contributes to lake effect snow
- Lifting of a layer of air
  – Especially if bottom of layer is moist and top is dry
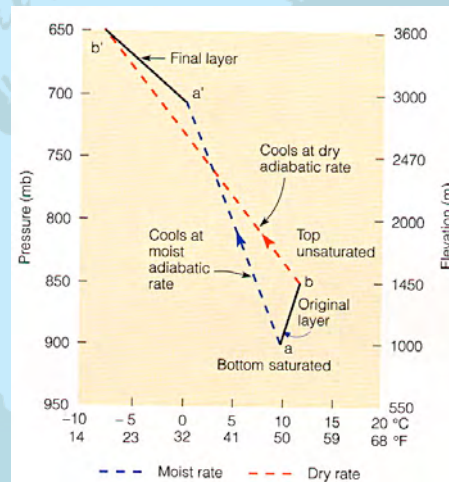
Conditionally Unstable Air

- What if the environmental lapse rate falls between the moist and dry adiabatic lapse rates?
  – The atmosphere is unstable for saturated air parcels but stable for unsaturated air parcels
  – This situation is termed conditionally unstable
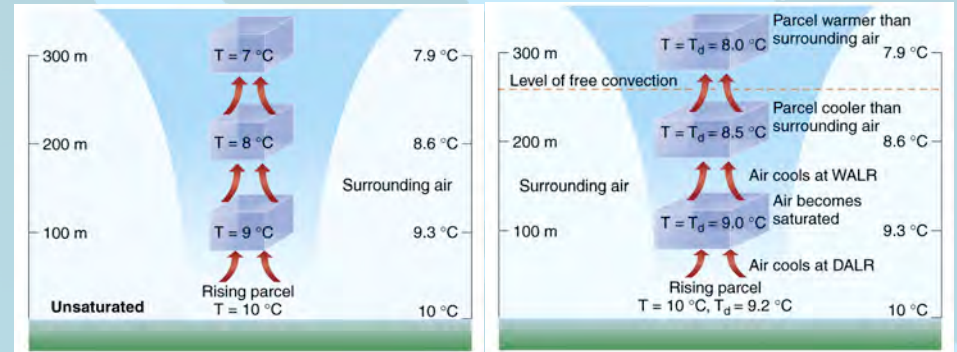- This is the typical situation in the atmosphere
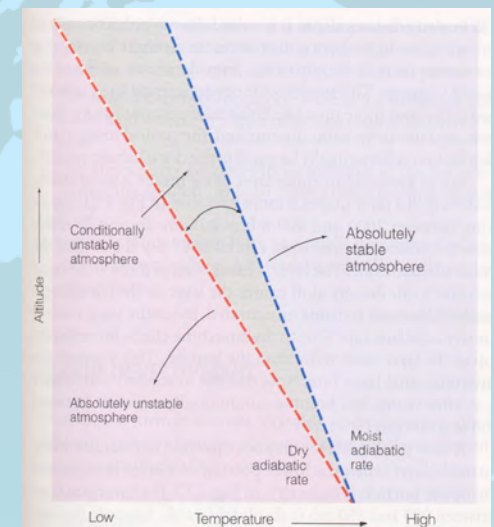
Cumulonimbus

Conditionally Unstable Air

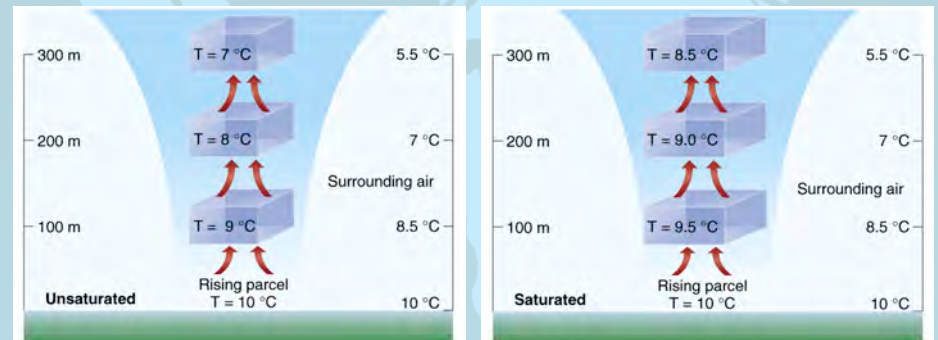Clear Air - Stable   Cloudy Air - Unstable

Absolutely Unstable

- The atmosphere is absolutely unstable if the environmental lapse rate exceeds the moist and dry adiabatic lapse rates.
- This situation is not long-lived.
  - Usually results from surface heating and is confined to a shallow layer near the surface.
  - Vertical mixing can eliminate it.
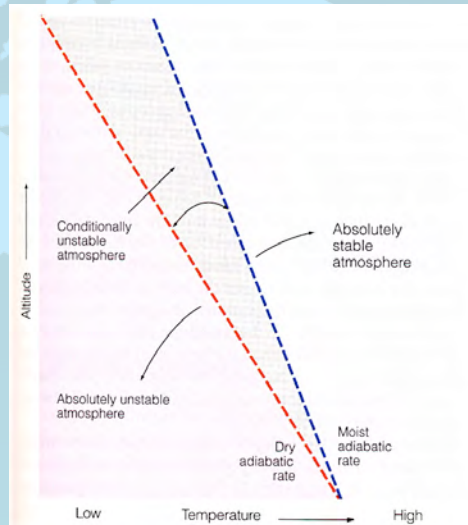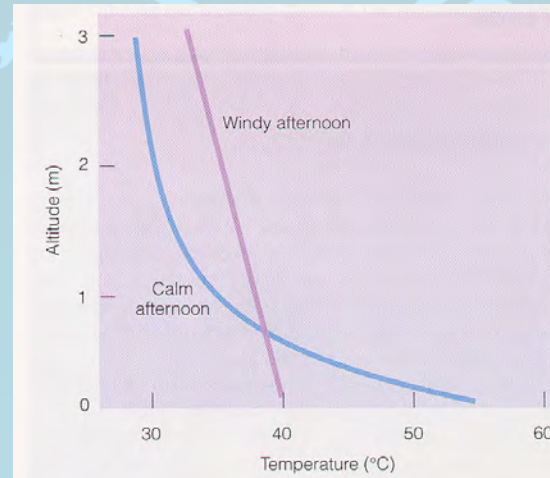
Absolutely Unstable Air

In clear air   In cloudy air

Mirage and Absolute Instability

Absolute Instability (example)

FIGURE 3.13
Vertical temperature profiles above an asphalt surface for a windy and a calm summer afternoon.

Jogger on calm, summer day may have 122 F at their feet and 90 F at their waist!

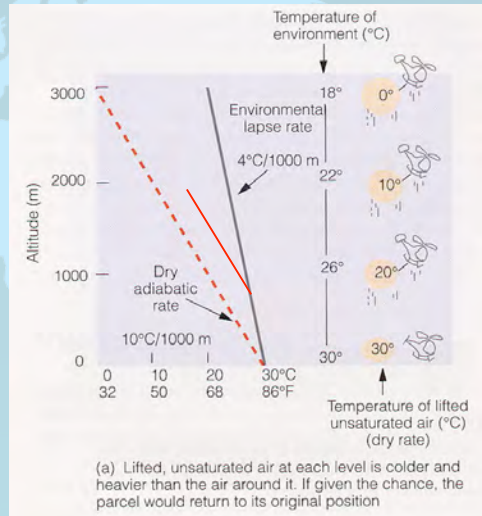# Cumulus

Schematic for a Trade Wind Cumulus Cloud
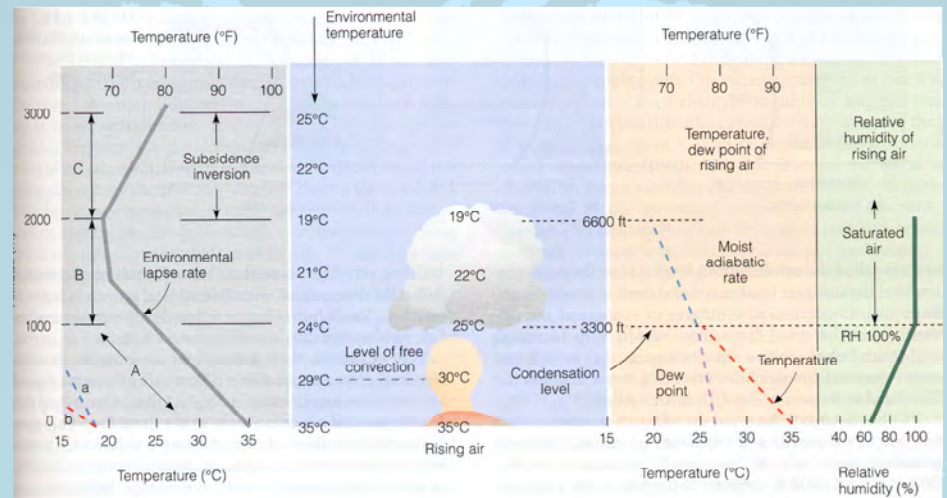
Stability of Dry (Clear) Air

Atmospheric stability

depends on the environmental lapse rate

– A rising unsaturated air parcel cools according to the dry adiabatic lapse rate

– If this air parcel is
  • warmer than surrounding air, it is less dense and buoyancy accelerates the parcel upward.
  • colder than surrounding air, it is more dense and buoyancy forces oppose the rising motion.

(a) Lifted, unsaturated air at each level is colder and heavier than the air around it. If given the chance, the parcel would return to its original position

A saturated rising air parcel cools less than an unsaturated parcel

- If a rising air parcel becomes saturated condensation occurs and a cloud forms.
- Condensation warms the air parcel due to the release of latent heat.
- So, a rising parcel cools less if it is saturated (e.g., in cloud).
- Define a moist adiabatic lapse rate
  – ~ 5° C/1000 m
  – Not constant (varies from ~ 3-9° C)
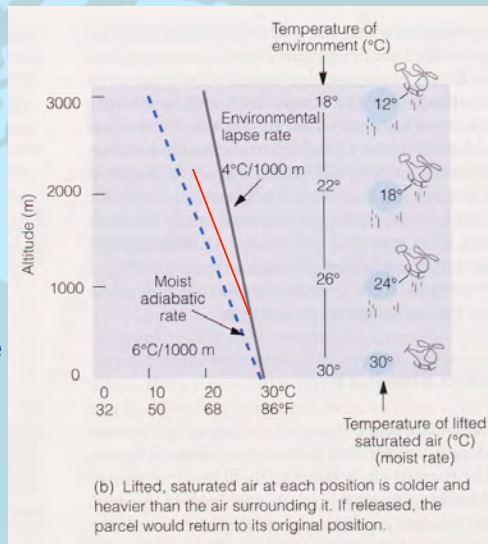 – depends on saturation vapor pressure which depends on T and P.
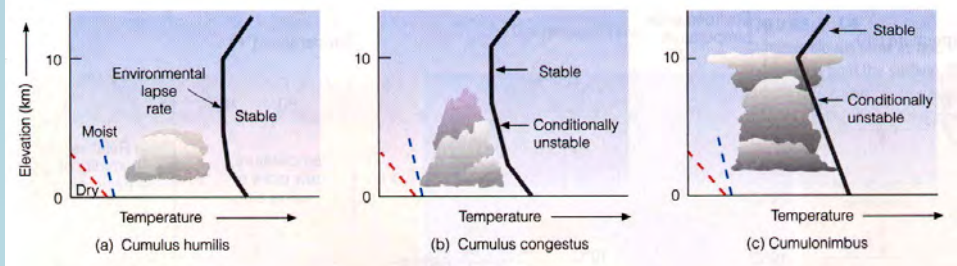
Stability of Cloudy Air Parcels

Atmospheric stability

depends on the environmental lapse rate

– A rising saturated air parcel cools according to the moist adiabatic lapse rate

– When the environmental lapse rate is smaller than the moist adiabatic lapse rate, the atmosphere is termed absolutely stable. Recall that the dry adiabatic lapse rate is larger than the moist lapse rate.

(b) Lifted, saturated air at each position is colder and heavier than the air surrounding it. If released, the parcel would return to its original position.

What conditions support taller cumulus development ?

(a) Cumulus humilis (b) Cumulus congestus (c) Cumulonimbus

- A less stable atmospheric (steeper lapse rate) profile permits greater vertical motion
- Lots of low-level moisture permits latent heating to warm parcel, accelerating it upward
- To forecast changing weather you have to predict how the environmental lapse rate will change in time.

Questions?