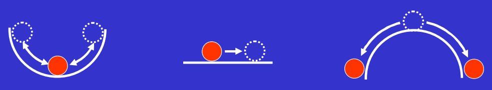
MTO 412E Physics of Cloud and Precipitation

Static Stability and Cloud Development



Objectives

- Be able to provide the definition of stability
- Be able to describe the two methods by which air is displace
- Be able to identify the types of clouds that form during either forced ascent or auto-convective ascent
- Be able to determine if the atmosphere is potentially unstable

Static Stability and Environmental Lapse Rate (ELR)

- **Static Stability**
- **Absolutely Unstable Air**
- **Absolutely Stable Air**
- **Conditionally Unstable Air**

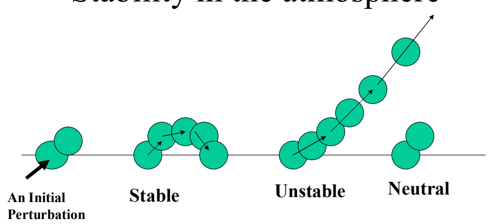
Why is stability important?

- Vertical motions in the atmosphere are a critical part of energy transport and strongly influence the hydrologic cycle
- Without vertical motion, there would be no precipitation, no mixing of pollutants away from ground level - weather as we know it would simply not exist.
- There are two types of vertical motion:
  - **forced motion** such as forcing air up over a hill, over colder air, or from horizontal convergence
  - **buoyant motion** in which the air rises because it is less dense than its surroundings - **stability** is especially important here

Static Stability

- Static stability – The air's susceptibility to lift.
  - Unstable – Air will continue to rise if given an initial upwards push
  - Stable – Air resists the upward displacement and sinks back to original level.
  - Neutral – Air will neither rise on its own or sink back to its original level.

Stability in the atmosphere



If an air parcel is displaced from its original height it can:

Return to its original height - Stable
Accelerate upward because it is buoyant - Unstable
Stay at the place to which it was displaced - Neutral

Buoyancy

- An air parcel rises in the atmosphere when it's density is less than its surroundings
- Let ρ_{env} be the density of the environment. From the Equation of State/Ideal Gas Law
  $\rho_{env} = P/RT_{env}$
- Let ρ_{parcel} be the density of an air parcel. Then
  $\rho_{parcel} = P/RT_{parcel}$
- Since both the parcel and the environment at the same height are at the same pressure
  - when $T_{parcel} > T_{env}$ $\rho_{parcel} < \rho_{env}$ (positive buoyancy)
  - when $T_{parcel} < T_{env}$ $\rho_{parcel} > \rho_{env}$ (negative buoyancy)

Buoyancy

Static Stability is Related to Buoyancy

Parcel of Air

Less dense Than Surrounding Air: Positive Buoyancy

Tends to Rise (Warmer)

More dense Than Surrounding Air: Negative Buoyancy

Tends to Sink if Not Lifted(Colder)

A Rising Parcel of Air

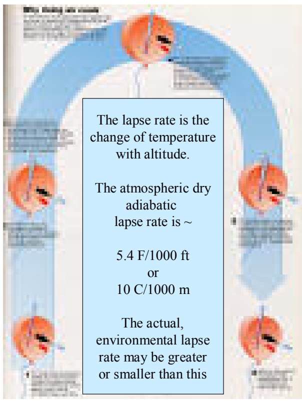
Stops Rising When It Cools to Surrounding Air

Sinks When It Becomes Colder Than Surrounding Air

This Suppresses Uplift

Rising Air Cools

- Rising air parcels expand
- Work done by air molecules in the parcel pushing outward consumes energy and lowers the parcel temperature



What is lapse rate?

- The lapse rate is the change of temperature with height in the atmosphere
- There are two kinds of lapse rates:
  - Environmental Lapse Rate
    - What you would measure with a weather balloon
  - Parcel Lapse Rate
    - The change of temperature that an air parcel would experience when it is displaced vertically
    - This is assumed to be an *adiabatic process* (*i.e.*, no heat exchange occurs across parcel boundary)

Lapse Rates

Lifted Parcel of Air

Cools at One of the Adiabatic Lapse Rates

Air Around it Maintains Its Original Temperature Profile

Relative Density

1. Depends on Unsaturated or Saturated

DALP or SALP

2. Environmental Lapse Rate (ELP)

Three Types of Static Stability

1. Absolutely Unstable Air

2. Absolutely Stable Air

3. Conditionally Stable Air

Trading Height for Heat

There are two kinds of "static" energy in the parcel: potential energy (due to its height) and enthalpy (due to the motions of the molecules that make it up)

$$\Delta S = c_p \Delta T + g \Delta z$$

Change in static energy ***Change in enthalpy*** ***Change in gravitational potential energy***

Trading Height for Heat (cont'd)

- Suppose a parcel exchanges no energy with its surroundings … we call this state adiabatic, meaning, "not gaining or losing energy"

$$0 = c_p \Delta T + g \Delta z$$

$$c_p \Delta T = -g \Delta z$$

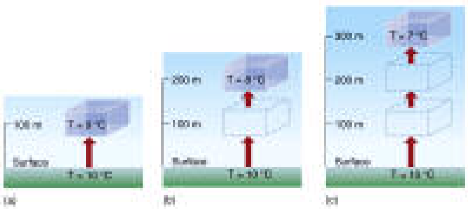
$$\frac{\Delta T}{\Delta z} = -\frac{g}{c_p}$$

"Dry adiabatic lapse rate"

Lapse Rates

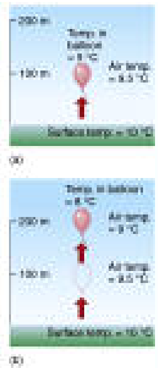
- Dry adiabatic lapse rate (DALR) –Rate at which rising parcel of unsaturated air cools. (1.0°C/100 m)
- Saturated adiabatic lapse rate (SALR) - Rate at which rising parcel of unsaturated air cools. (0.5°C/100 m)
- Dew point lapse rate – Rate at which dew point decreases with height. (0.2°C/100 m)
- Environmental lapse rate (ELR) – Vertical change in temperature profile through still air.

Lapse Rates

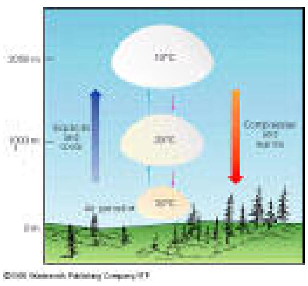


Lapse Rates

- Difference between ELR and DALR/SALR

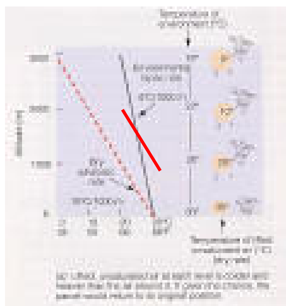


Reversible Process



Stability and the dry adiabatic lapse rate

- 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

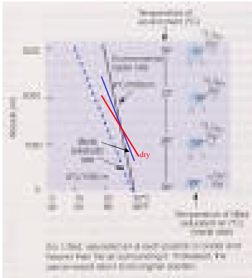


A saturated rising air parcel cools less than an unsaturated parcel

- If a rising air parcel becomes saturated condensation occurs
- Condensation warms the air parcel due to the release of latent heat
- So, a rising parcel cools less if it is saturated
- Define a moist adiabatic lapse rate
  - ~ 6 C/1000 m
  - Not constant (varies from ~ 3-9 C)
  - depends on T and P

Stability and the moist adiabatic lapse rate

- 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
  - What types of clouds do you expect to form if saturated air is forced to rise in an absolutely stable atmosphere?



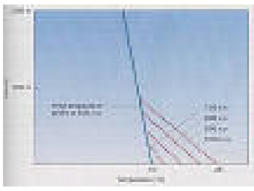
Factors Influencing the Environmental Lapse Rate

The Average Environmental Lapse Rate (ELR)
-0.65 °C / 100 meters (-6.5 °C / km)

Highly Variable in Space and Time
Both
Surface Air Temperature
Vertical Temperature Profile

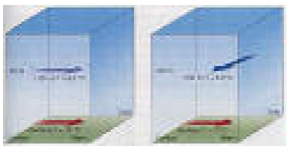
Influences
1. **Heating or Cooling of the Lower Atmosphere.**
2. **Advection of Cold or Warm Air at Different Levels.**
3. **Advection of a Different Air Mass with a Different ELR.**

Heating or Cooling of the Lower Atmosphere



Atmosphere Is Heated From the Surface
ELR Is Steeper (More Change in Temperature) at Mid-day
Greatest on Clear Days
Least at Night
Inversion - If Air at Surface Gets Colder Than Aloft
Positive ELR

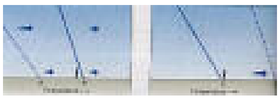
Advection of Cold or Warm Air at Different Levels



Advection or Wind Can Be Different at the Surface From That Aloft
ELR Can Be Different If Winds Are Different
Example Same Direction: -0.5°c/100m
Perpendicular : -1.0°c/100m

Idealized Example As Winds Gradually Change With Height
Seen by Cloud Movement

Advection of a Different Air Mass with a Different ELR

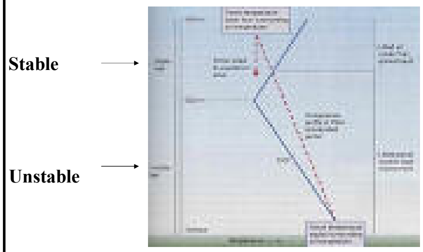


Air Mass
Large Area Distinguished From Its Neighbors by Differences in
1. **Temperature**
2. **Water Content (Humidity)**

Maintain Their Identity (1 & 2)

Air Masses Can Migrate Into Other Large Areas Changing ELR
(A takes the place of B)

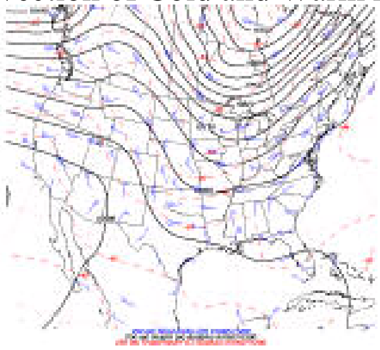
Limitations on Lifting Unstable Air



Unstable Air Can Not Lift Forever
Braking Mechanisms
1. Ascent Into Layer of Stable Air
2. Entrainment (Advection of Warmer Air)

Advection of Cold and Warm Air

Advection of Cold and Warm Air



Static Stability

Static Stability
Air's Susceptibility to Uplift.

Statically Unstable Air
Continues to Rise If Given an Initial Upward Push

Statically Stable Air
Resists Upward Displacement and Sinks Back to Original Level

Statically Neutral Air
Will not Rise or Sink After Its Initial Upward Push Comes to Rest Where It was Displaced

Stability

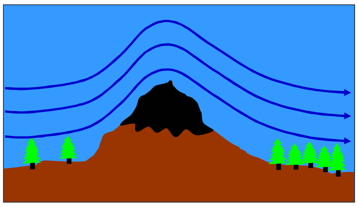
- Psychological Stability
- Meteorological Stability

Psychological Instability

- Results From Stress
  - Too many Exams
  - Too Much Homework
  - Poor Grades
  - Too Much Alcohol
- Example

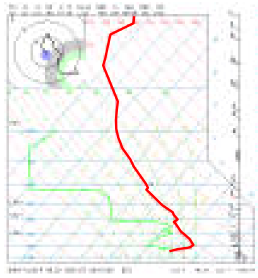
Meteorological Stability

- The ability of the air to return to its origin after displacement



Stability

- Depends on the thermal structure of the atmosphere

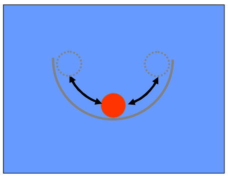


Stability

- Can be classified into 3 categories
  - Stable
  - Neutral
  - Unstable

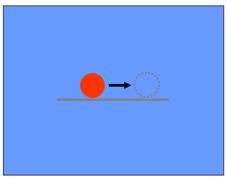
Stable

- Returns to original position after displacement



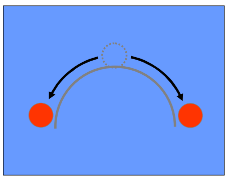
Neutral

- Remains in new position after being displaced



Unstable

- Moves farther away from its original position

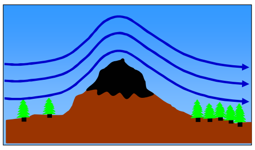


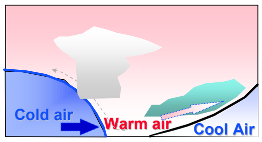
Stability

- How is air displaced?
  - Two methods
    - 1.) Forced Ascent
    - 2.) Auto-Convective Ascent

Forced Ascent

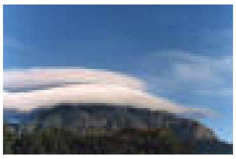
- Some mechanism forces air aloft
  - Usually synoptic scale feature



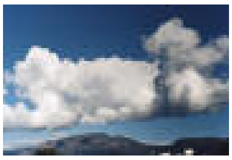


Forced Ascent

- Type of clouds
  - Depends on stability



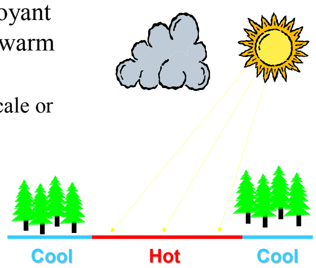
Stable - Stratus



Unstable - Cumulus

Auto-Convective Ascent

- Air becomes buoyant by contact with warm ground
  - Usually microscale or mesoscale

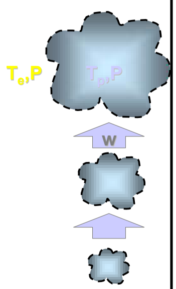


Auto-Convective Ascent

- Type of Clouds
  - Cumulus

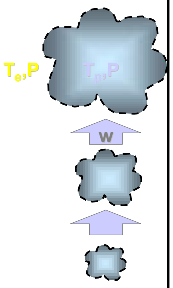
Parcel Theory

- Assumptions
  - Thermally insulated from its environment
  - Temperature changes adiabatically
  - Always at the same pressure as the environment at that level



Parcel Theory

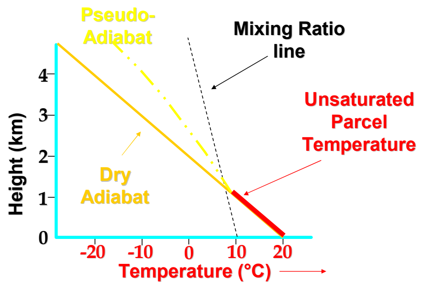
- Assumptions
  - Hydrostatic equilibrium
  - Moving slow enough that its kinetic energy is a negligible



Stability

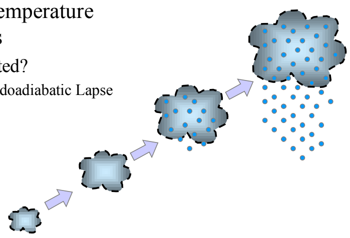
- As parcel rises
  1.) Parcel Temperature Changes
    - Unsaturated?
      - Dry Adiabatic Lapse Rate

Stability

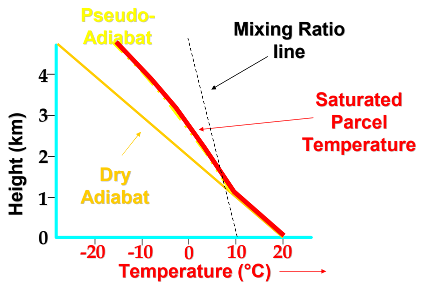


Stability

- As parcel rises
  1.) Parcel Temperature Changes
    - Saturated?
      - Pseudoadiabatic Lapse Rate

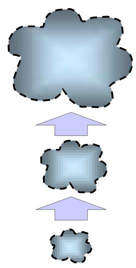


Stability

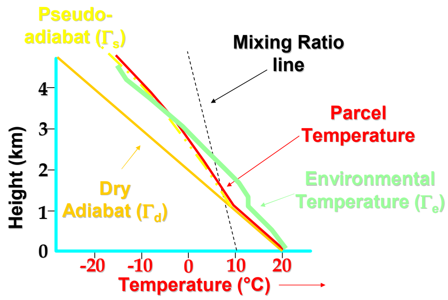


Stability

- As parcel rises
  2.) Environmental Temperature Changes
    - Environmental Lapse Rate (Γ_e)

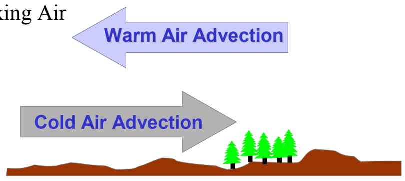


Stability



Stability

- Environmental temperature profile depends on many factors
  - Advection
  - Sinking Air

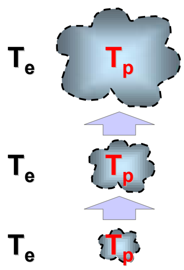


Stability

- Environmental Temperature
  - Measured by rawinsonde

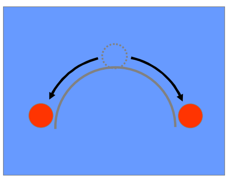
Stability

- Stability depends on
  - Temperature
    - Environment
    - Parcel
  - Condition of Parcel
    - Unsaturated

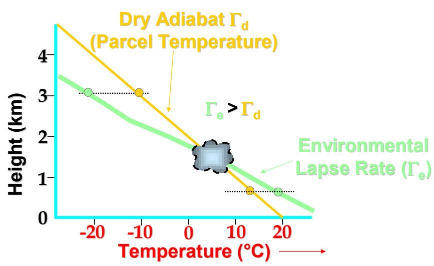


Unsaturated

- Unstable
  - Once displaced, continues

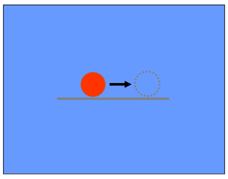


Unsaturated-Unstable

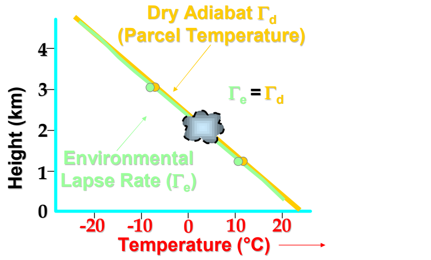


Unsaturated

- Neutral
  - Once displaced, stays

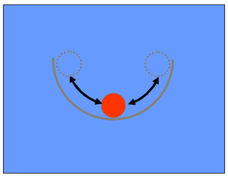


Unsaturated-Neutral

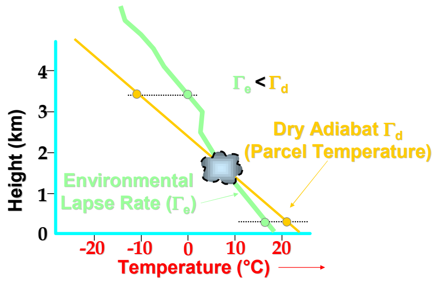


Unsaturated

- Stable
  - Once displaced, returns

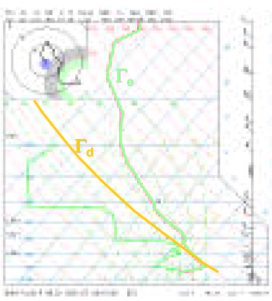


Unsaturated-Stable



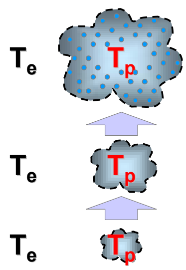
Stability

- A real environmental sounding sometimes combines all three
- Evaluate each layer

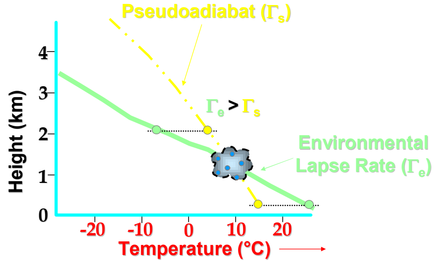


Stability

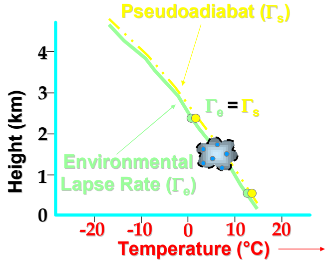
- Stability depends on
  - Condition of Parcel
    - Saturated



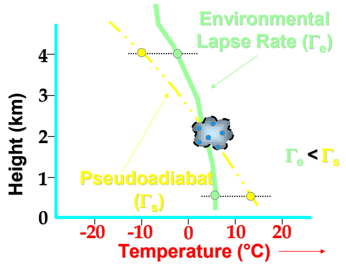
Saturated-Unstable



Saturated-Neutral

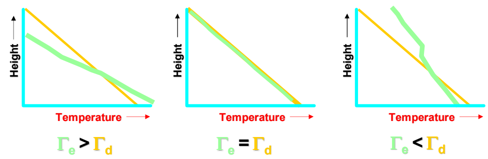


Saturated-Stable



Stability

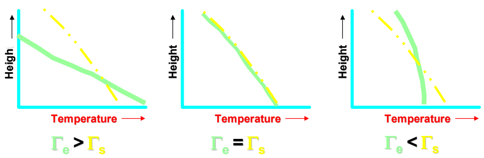
- Dry (or Unsaturated)



Dry Unstable **Dry Neutral** **Dry Stable**

Stability

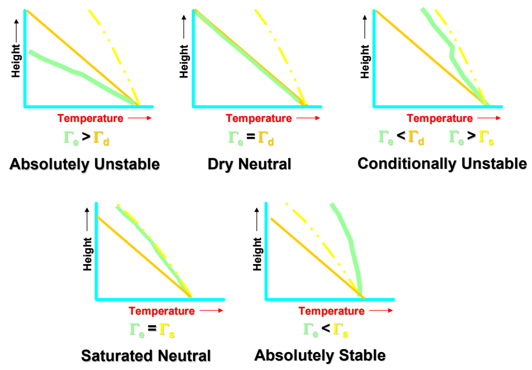
- Saturated



Saturated Unstable **Saturated Neutral** **Saturated Stable**

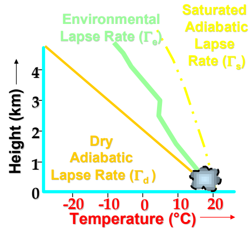
Stability

- Combine to simplify
  - Absolutely Unstable
  - Dry Neutral
  - Conditionally Unstable
  - Saturated Neutral
  - Absolutely Stable



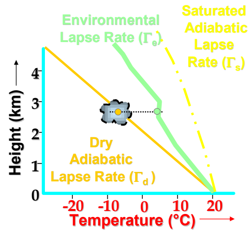
Stability

- Conditional Instability
  - Depends upon whether the parcel is dry or saturated



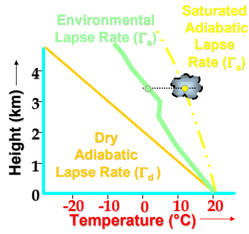
Stability

- Conditional Instability
  - Unsaturated Parcel
    - Stable



Stability

- Conditional Instability
  - Saturated Parcel
    - Unstable



Other Types of Stability

- Static Stability
- Potential (or Convective) Instability

Stability

- Static Stability
  - The change of potential temperature with height

$$\frac{\partial \theta}{\partial z}$$

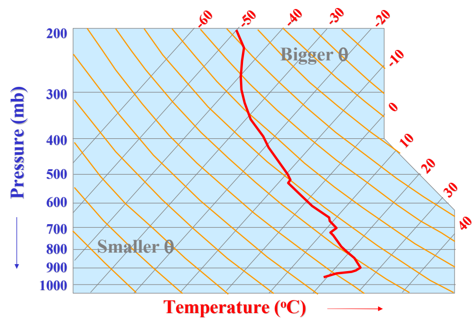
Static Stability

- Atmosphere is said to be statically stable if potential temperature increases with height

$$\frac{\partial \theta}{\partial z} > 0$$

  - Typical of atmosphere

Static Stability

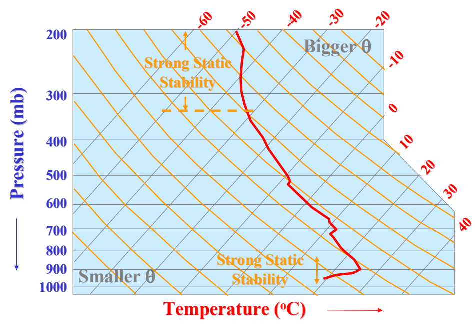


Static Stability

- Large
  - Tropopause
  - Stratosphere

$$\frac{\partial \theta}{\partial z} > 0$$

Static Stability



Potential Instability

- The state of an unsaturated *layer (or column)* of air in the atmosphere
- Either
  - Wet bulb potential temperature (θ_w) or
  - Equivalent potential temperature (θ_e)
- Decreases with elevation

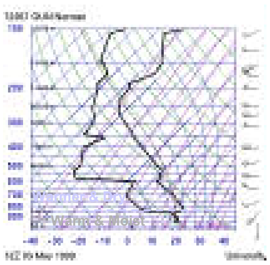
Potential Instability

- Also Called Convective Instability

$$\frac{\partial \theta_w}{\partial z} < 0 \qquad \frac{\partial \theta_e}{\partial z} < 0$$

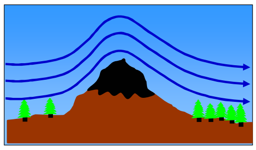
Potential Instability

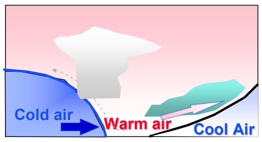
- Common when dry layer tops a warm, humid layer
  - Low level southerly flow
  - Upper level southwesterly flow



Potential Instability

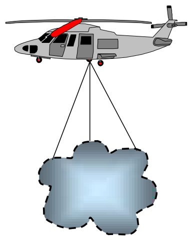
- Lifting Destabilizes Layer





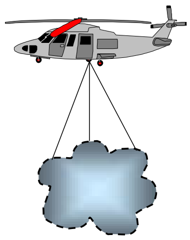
Stability

- Now the math!
  - Let's lift a parcel



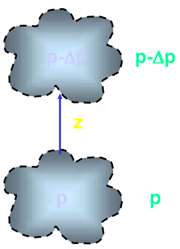
Stability

- During displacement
  - Changes of state of parcel
  - Changes of state of environment



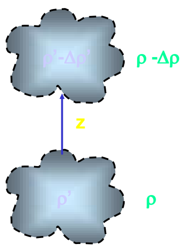
Stability

- During displacement
  - Pressure of parcel is the same as pressure of environemnt
    - Parcel Theory Assumption



Stability

- During displacement
  - Density of parcel is different than density of environment
    - Why?
      - Cools at a different rate



Stability

- What is the equation for momentum balance of the environment?

$$\text{Vertical Acceleration} = \text{PGF} + g$$

Vertical Equation of Motion

$$\frac{d^2z}{dt^2} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + g$$

Stability

- The atmosphere on average is balanced

$$\frac{d^2z}{dt^2} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + g$$

No Acceleration

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} + g$$

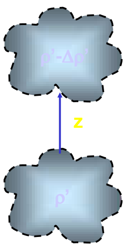
Hydrostatic Balance

Stability

- The equation of motion of the parcel

$$\frac{d^2z}{dt^2} = -\frac{1}{\rho'}\frac{\partial p}{\partial z} + g$$

Parcel is accelerating



Stability

- Equations of motion for parcel & environment

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} + g \qquad \frac{d^2z}{dt^2} = -\frac{1}{\rho'}\frac{\partial p}{\partial z} + g$$

Hydrostatic Balance

Absolutely Unstable Air

- **Dry Adiabatic Lapse Rate - DALR**
- **DALR = 10º C/1000 m**
- **ELR > DALR**
- **$T_{environment} < T_{parcel}$**
- **Parcel will rise away from original position**

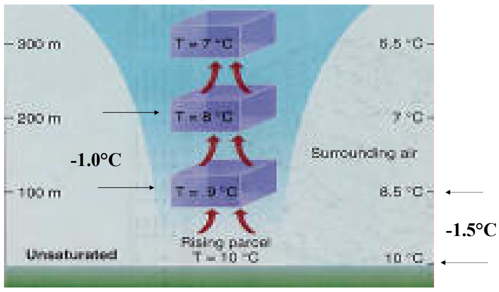
Absolute instability

- 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
- Mixing results in a dry adiabatic lapse rate in the mixed layer, unless condensation (cloud formation) occurs (in which case it is moist adiabatic)

Absolutely Unstable Air

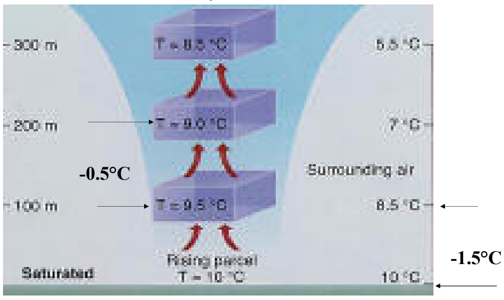
- Once a parcel is lifted it continues to move upward regardless of saturation.
- Whenever the ELR exceeds the DALR (1°C/100 m) the air is absolutely unstable.

Absolutely Unstable Air



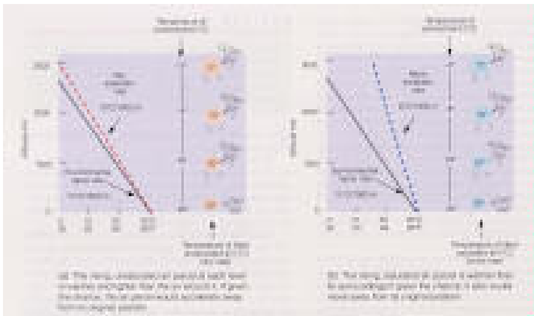
ELR = -1.5°C / 100 m Unsaturated DALR = -1.0°C / 100 m
Will Keep Rising - Cooling Slower than Surrounding Air

Absolutely Unstable Air

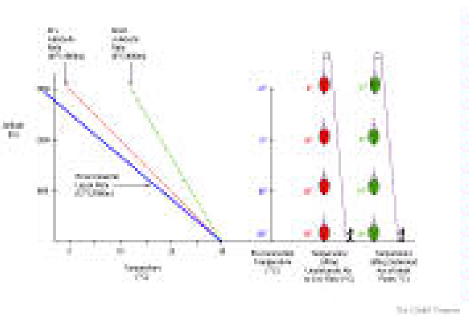


ELR = -1.5°C / 100 m Saturated SALR = -0.5°C / 100 m
Will Keep Rising - Cooling More Slowly than Surrounding Air

Absolute instability (examples)



Absolutely Unstable



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Absolutely Unstable Air

For Absolutely Unstable Air

ELR Exceeds the DALR

ELR Exceeds the SALR

Parcel of Air will continue to Rise
Faster IF the Temperature Difference Increases
Slower IF the Temperature Difference Decreases

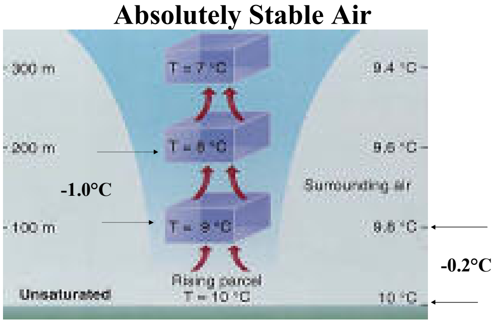
Absolutely Stable Air

- Saturated Adiabatic Lapse Rate - SALR
- ELR < SALR
- $T_{environment} > T_{parcel}$
- Parcel will sink back to original position

Absolutely Stable Air

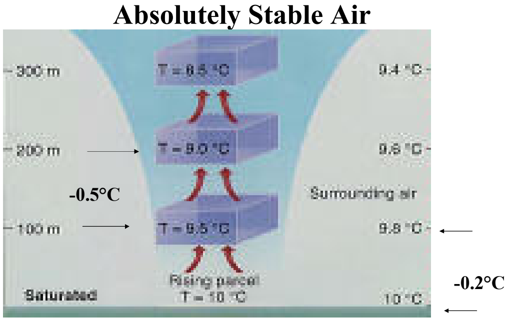
- Air parcel returns to its original location after being displaced.
- When ever the ELR is less than the SALR (0.5°C/100 m), the air is absolutely stable.

Absolutely Stable Air



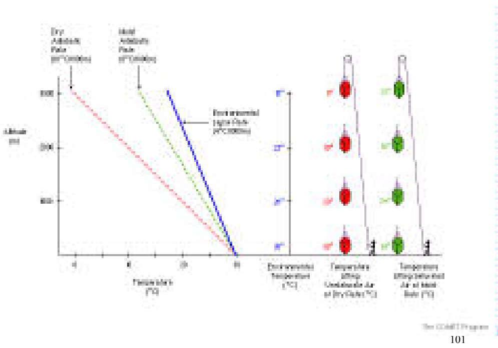
ELR = -0.2°C / 100 m Unsaturated DALR = -1.0°C / 100 m
Will Not Rise - Cooling Faster than Surrounding Air

Absolutely Stable Air



ELR = -0.2°C / 100 m Saturated SALR = -0.5°C / 100 m
Will Not Rise - Cooling Faster than Surrounding Air

Absolutely Stable



Absolutely Stable Air

For Absolutely Stable Air

ELR Does NOT Exceed the DALR

ELR Does NOT Exceed the SALR

Parcel of Air will NOT Rise

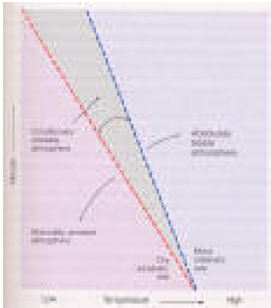
The Larger Temperature Difference the MORE Stable

Conditionally Unstable Air

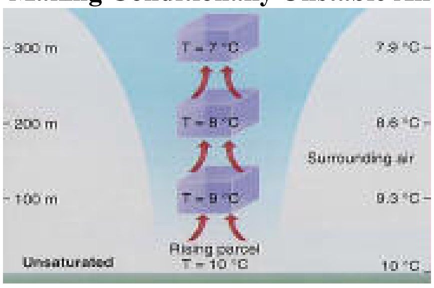
- **Conditionally Unstable Air**
  - **SALR < ELR < DALR**
  - **depends on whether or not the rising air parcel is saturated**

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



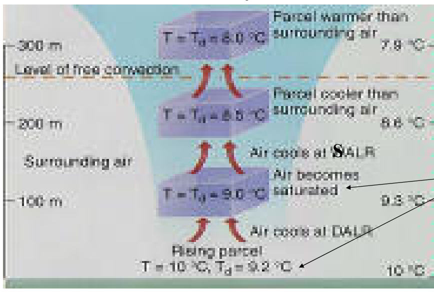
Making Conditionally Unstable Air



ELR = -0.7°C / 100 m   Unsaturated DALR = -1.0°C / 100 m
Will Keep Rising - Cooling Faster than Surrounding Air
UNSTABLE

Conditionally Unstable Air

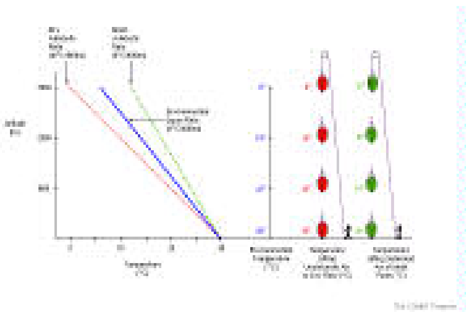
Air is Warmer Rises Freely



Dew Point

ELR = -0.7°C / 100 m   **Unsaturated: DALR = -1.0°C / 100 m**
Saturated: SALR = -0.5°C / 100 m

Conditionally Unstable



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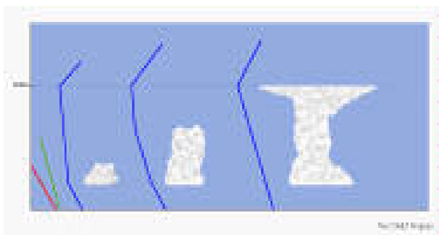
Growth of a thunderstorm



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Stability Rules #1,#2, & #3

1. Absolutely Unstable Air
Whenever the ELR Exceeds the DALR or SALR
(Positive Buoyancy)

2. Absolutely Stable Air
Whenever the ELR Is Less Than the DALR or SALR
(Negative Buoyancy)

3. Conditionally Unstable Air
Whenever the ELR Is Between the DALR and SALR

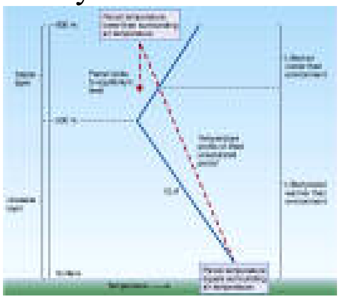
Limitations on Lifting

- What causes air to quit rising?
  - Stable air
    - Inversions
  - Entrainment (mixing)

Inversions

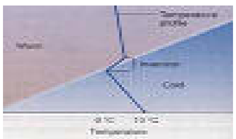
- **Layer of the atmosphere where temperature of the air increases with altitude**
  - **Makes the air extremely stable**
- **Types of Inversions**
  - **Radiation inversion**
  - **Frontal inversion**
  - **Subsidence inversion**

Layer of Stable Air



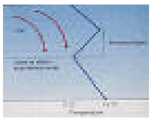
Inversions: Extremely Stable Air

1. Radiation Inversion
Cooling of Surface
Develops at Ground Level
Radiation Fog If Cools to Dew Point
Crop Damage If Cold enough - Frost



2. Frontal Inversion
100s km long
Cold Enough - Sleet or Freezing Rain

Inversions: Extremely Stable Air



3. Subsidence (Sinking) Inversion
Compressed Gas
Warms
Top Sinks and Warms Most
Develops Well Above Surface

Hawaiian High
Caps Air Above Los Angeles
Heavy Pollution

Entrainment

- When air rises considerable turbulence is generated. This entrainment draws in environmental air into the parcel and suppresses further growth.

Level of Free Convection

A Conditionally Unstable Air Mass
Rises Above the Level of Free Convection
Must be Lifted
Then Can Rise on Its Own

LFC
Clouds Increase in Depth (Thickness)
Yield Precipitation

Factors Influencing the ELR

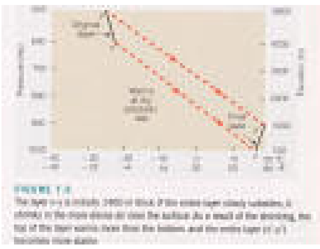
- **Heating or cooling of the lower atmosphere**
- **Advection of cold and warm air at different levels**
- **Advection of an air mass with a different ERL**

Limitations on the Lifting of Unstable Air

- **A layer of stable air above the unstable layer**
- **Entrainment**
  - **Mixing with surrounding unsaturated air, causing evaporation and cooling of the borders of the cloud**

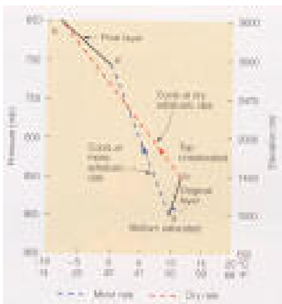
What conditions contribute to a stable atmosphere?

- 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)



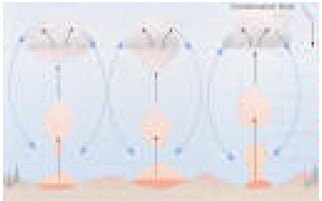
What conditions enhance atmospheric instability?

- 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 an air layer and associated vertical "stretching"
  - Especially if bottom of layer is moist and top is dry



Fair weather cumulus cloud development

- Air rises due to surface heating
- RH rises as rising parcel cools
- Cloud forms at RH ~ 100%
- Rising is strongly suppressed at base of subsidence inversion produced from sinking motion associated with high pressure system
- Sinking air is found between cloud elements
  - Why?



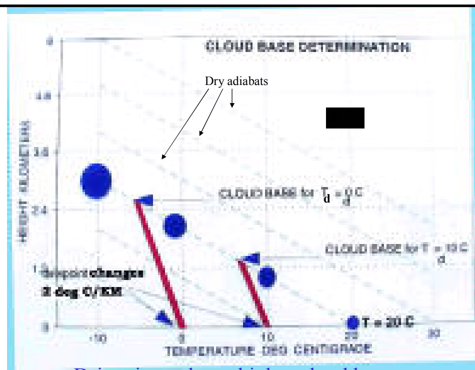
Fair weather cumulus cloud development schematic

What conditions support taller cumulus development ?

- 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

Determining Convective Cloud Bases

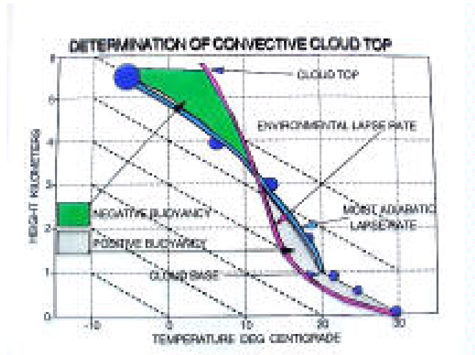
- Dry air parcels cool at the dry adiabatic rate (about 10°C/km)
- Dew point decreases at a rate of ~ 2°C/km
- This means that the dew point approaches the air parcel temperature at a rate of about 8°C/km
- If the dew point depression were 4°C at the surface, a cloud base would appear at a height of 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



Drier air produces higher cloud bases; moist air produces lower cloud bases

Determining convective cloud top

- **Cloud top is defined by the upper limit to air parcel rise**
- **The area between the dry/moist adiabatic lapse rate, showing an air parcel's temperature during ascent, and the environmental lapse rate, can be divided into two parts**
  - A positive acceleration part where the parcel is warmer than the environment
  - A negative acceleration part where the parcel is colder than the environment
- **The approximate cloud top height will be that altitude where the negative acceleration area is equal to the positive acceleration area**



Dry Adiabatic Processes

It is also possible for a parcel of air to change temperature without a change in the overall level of energy. This is referred to as an *adiabatic process*.

Think back to basic chemistry with Charles Law and Boyles Law. Temperature is related to pressure and volume through the ideal gas law.

Dry air can undergo an adiabatic change in temperature. For the temperature to change, however, we require the parcel of air to change its volume and/or pressure.

Dry Adiabatic Processes

The strength of the change in temperature is related to the change in volume according to the relation:

$$p \cdot \Delta\alpha = -c_v \cdot \Delta T$$

p	- pressure
$\Delta\alpha$	- the change in volume
c_v	- the specific heat of air (assuming constant volume)
ΔT	- the change in temperature

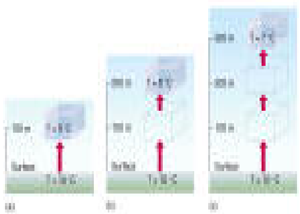
This is a form of the first law of thermodynamics.

Dry Adiabatic Processes

The rate at which the temperature decreases is called the *dry adiabatic lapse rate* (DALR.)

The DALR (Γ_d) is approximately 1 degree for every 100 meters.

$$\Delta T / \Delta z = \Gamma_d$$



Dry Adiabatic Processes

The DALR (Γ_d) is constant throughout the atmosphere.

The DALR (Γ_d), by itself, does not tell us the temperature of the air at a given height.

Consider lifting a parcel of air.

The temperature of the parcel of air will drop according to the DALR.

The surrounding air will normally be equal to or greater than that prescribed by the DALR.

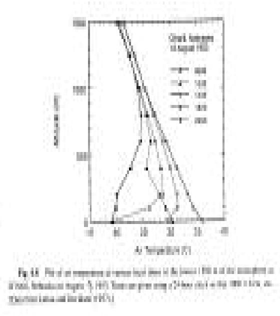
This is a stable situation.

Dry Adiabatic Processes

The atmosphere is almost always stable to dry adiabatic processes.

The only time that one can find the atmosphere to be unstable is at the surface on hot days.

Convection happens in such instances to quickly make the atmosphere stable again.



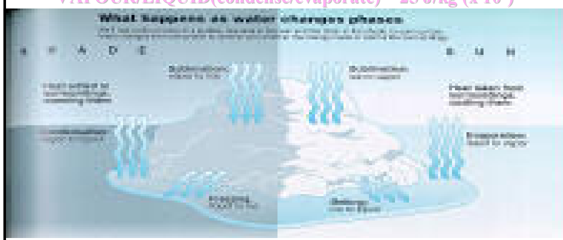
Moist Adiabatic Processes

A parcel of air may experience an adiabatic change in temperature through moist processes.

Consider water undergoing a phase change, ie when water vapour condenses in a parcel of air. The air warms, but this didn't require any exchange in solar or terrestrial radiation. The net energy is conserved.

Phase changes of water

ICE/LIQUID (freezing/melting) 3.3 J/kg (x 10^5)
ICE/VAPOUR (sublimation) 28.3 J/kg (x 10^5)
VAPOUR/LIQUID(condense/evaporate) ~25 J/kg (x 10^5)



Moist Adiabatic Processes

Consider lifting a parcel of air even further. It will continue to cool according to the DALR. At some height, the parcel will cool enough so that the air will reach its saturation point.

This height is called the *lifting condensation level* (*LCL*). Typically this is the height of the base of convective clouds.

Moist Adiabatic Processes

If we were to raise the air above this height, then the excess vapour would condense.

Energy is released when the water vapour condenses.

The parcel of air will now cool at a different rate than the DALR.

The air cools at the *saturated* (or *wet*) *adiabatic lapse rate* (*SALR* or Γ_w).

Moist Adiabatic Processes

Γ_w is not constant throughout the atmosphere. It can vary considerably with temperature and pressure.

A typical value may be roughly 6 K per kilometer. This will always be less than the dry adiabatic lapse rate of 10 K per kilometer.

$$\Gamma_w < \Gamma_d$$

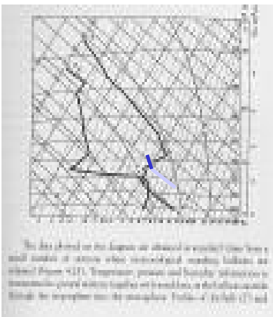
Air cools LESS quickly when rising along Γ_w instead of Γ_d because it is receiving latent energy from the condensation.

Moist Adiabatic Processes

Let's review this diagram considering the DALR (Γ_d) and the SALR (Γ_w).

In the lowest 100 hPa, the dry air roughly follows a dry adiabat. This suggests the air is well mixed.

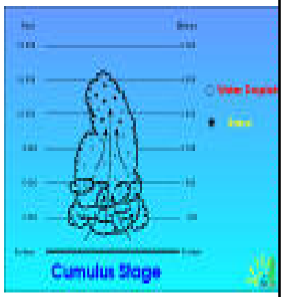
Above this region, the air roughly follows a saturated adiabat for suggesting the air is saturated in this layer.



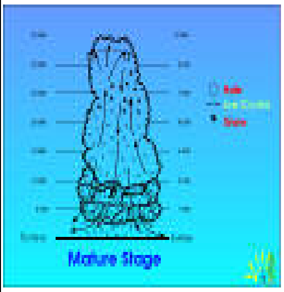
Convection - part 2

As the air rises, we know that it will eventually reach the lifting condensation level.

If the cloud air is pushed up higher, it will cool along a saturated adiabat.



Convection - part 2

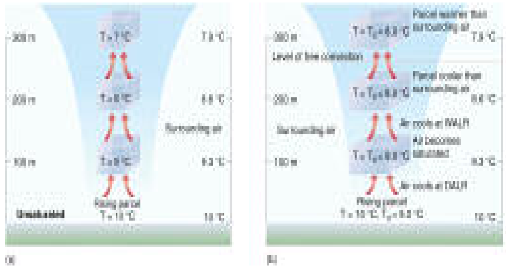


The air is no longer cooling as quickly as along a dry adiabat.

It is possible that the cloud air will actually be warmer than the air surrounding it.

This situation is unstable.

Convection - part 2



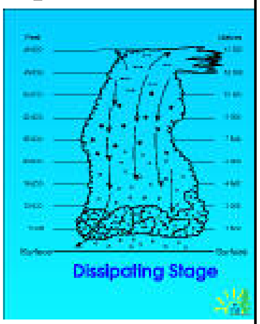
Stable to dry adiabatic lifting

Unstable to moist adiabatic lifting

Convection - part 2

The warm cloudy air will want to continue to rise, and deep convection is likely to occur.

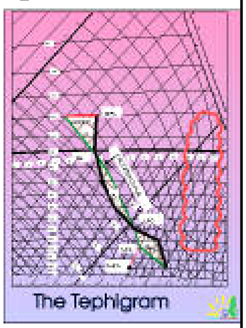
The air will continue to rise until it reaches a level where the surrounding air is once again warmer than the cloudy air.



Convection - part 2

Deep convection is critical process in the atmospheric circulation as it mixes vapour, energy and momentum throughout the troposphere.

Representing convection in numerical models is still a challenging research topic.



Summary

Conditions for a Stable Atmosphere

1. Environmental lapse rate is small - i.e. the difference in temperature between the surface air and the air aloft is relatively small.

   Air aloft warms - how? Warm Air Advection
   or surface air cools - how? Radiational Cooling
   Cold Air Advection
   Air moving over a cold surface

2. Another way the atmosphere becomes more stable is when an entire layer of air sinks (subsides)

Example: Large layer of air 1000 m thick subsides, the entire layer will warm due to compression. As the layer subsides, it is compressed by the atmospheric pressure and shrinks vertically. Actually, the upper portion sinks farther and warms more than the lower portion. The upper portion will become warmer than the bottom forming an inversion. This type of inversion is known as a Subsidence Inversion

Summary

Conditions for an Unstable Atmosphere

Unstable atmosphere is characterized when the air temperature drops rapidly with height

Air aloft cools how? **Cold Advection**
Radiational cooling from clouds

Surface air warms how? **Daytime solar Heating**
Warm surface advection
Air moving over a warm surface

And now...

Summary

1. Instability implies that if a parcel is given an initial boost upward, it will become buoyant and continue to rise. On the other hand, if the air is stable, a parcel displaced vertically will tend to return to its original position.
2. Static stability or instability is determined by the air column's rate of temperature decrease with altitude. When the temperature lapse rate is less than the saturated adiabatic rate, the air is statically stable; when it exceeds the dry adiabatic lapse rate, it is unstable. Conditional instability arises when the lapse rate is between the two adiabatic rates. When the air is conditionally unstable, a lifted parcel will rise on its own accord only if it is lifted above a certain critical point called the level of free convection.
3. Three processes modify the lapse rate: the inflow of warm and cold air at different altitudes, the advection of a different air mass, and heating or cooling of the surface.

Summary

5. Environmental lapse rates vary not only through time, but also with elevation. Thus, a column of atmosphere might be unstable at one level but stable aloft.

6. No matter what the condition of the troposphere, the stratosphere is always statically stable and thereby limits the maximum height of updrafts.

7. Inversions are a special case in which the temperature increases with altitude. Because of their strong static stability, inversions suppress the vertical motions necessary for cloud formation and for the dispersion of air pollution. Inversions are formed by subsidence (sinking air), the emission of longwave radiation from the surface, and the presence of fronts.

Review Questions

After lifting a parcel of air to a new level, if the parcel's temperature equals that of the surrounding environment, what type of stability is characterized?

Reading

- Hess
  - Chapter 7
    - pp 92 - 106
    - pp 110- 112