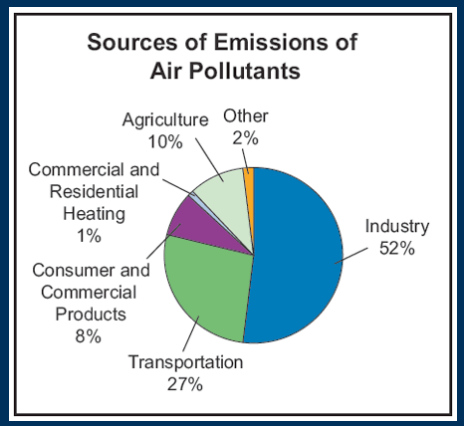
GGS 319
Part 1: Air Pollution Fundamentals

- ***The atmosphere and its components***
- How air pollutants are categorized
- The source of air pollutants
- How pollution affects health and welfare
- Clean air acts
- Air quality management & standards

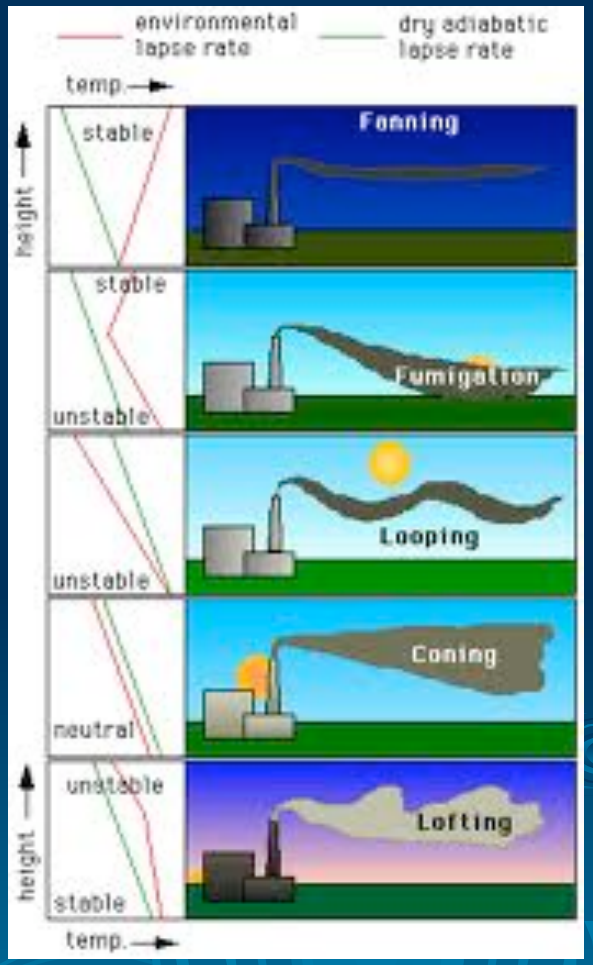






Atmospheric Stability & Dispersion

- Lapse Rates
  - Environmental Lapse rate
  - Dry adiabatic lapse rate
  - Wet (saturate) adiabatic lapse rate
  - Lifting condensation level
- Conditions
  - Inversion
- Stability
  - Adiabatic process
  - Stable air
  - Unstable air
  - Neutral air
- Upper Air Soundings



Stability Considerations (Temperature)

Archimedes Principle: Warm air rises, cold air sinks.

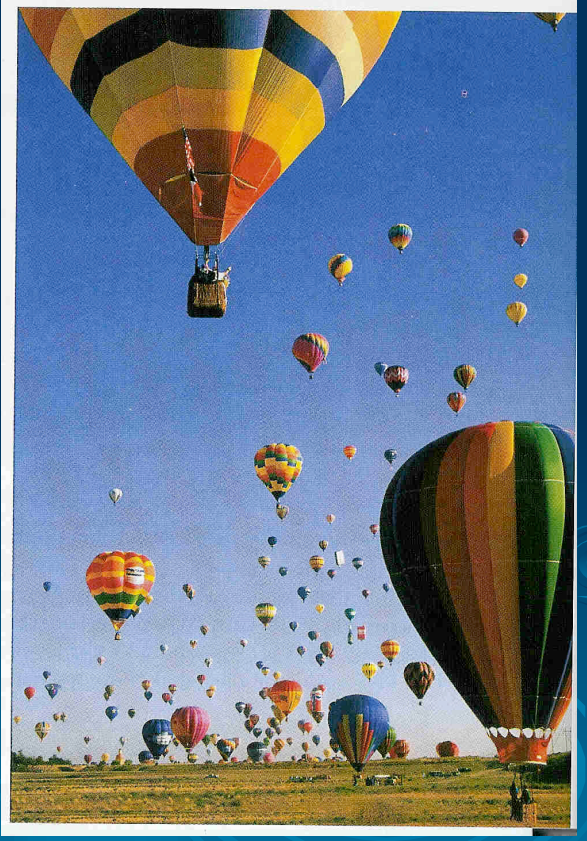
Balloons are used as analogs for parcels of air, and to illustrate buoyancy.

As long as air is warmer than its surroundings it will rise.

Is the same true for balloons? As long as the air inside a balloon is warmer than the surrounding air, will it continue to rise?

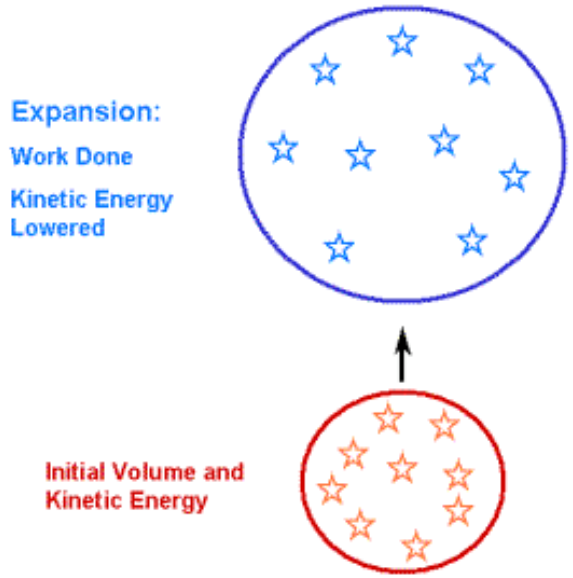
Buoyancy force = weight of displace air.

FIGURE 4-24 As long as air is warmer than its surroundings, it will rise. Hot-air balloons rise up through the atmosphere for this reason. *(Photo by Barbara Cushman Rowell/Mountain Light Photography, Inc.)*



Adiabatic Process - No Energy In/Out

Why do thermals expand and cool as they rise?



Adiabatic approximation -To a good approximation thermals rise without losing heat to the surrounding air.

Because atmospheric pressure decreases with height, the surrounding air pushes with less force on thermals as they rise. This causes them to **expand** as they rise.

Because they do work to increase their volume, they lose energy so they **cool.**

Familiar examples of **adiabatic expansion:**

Air escaping from an aerosol can or a tire

Analogs for Stability

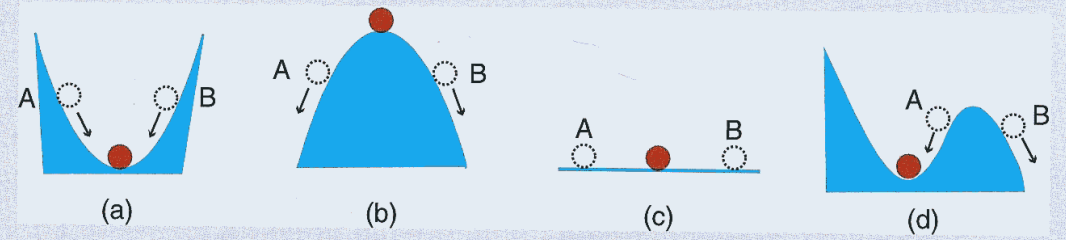


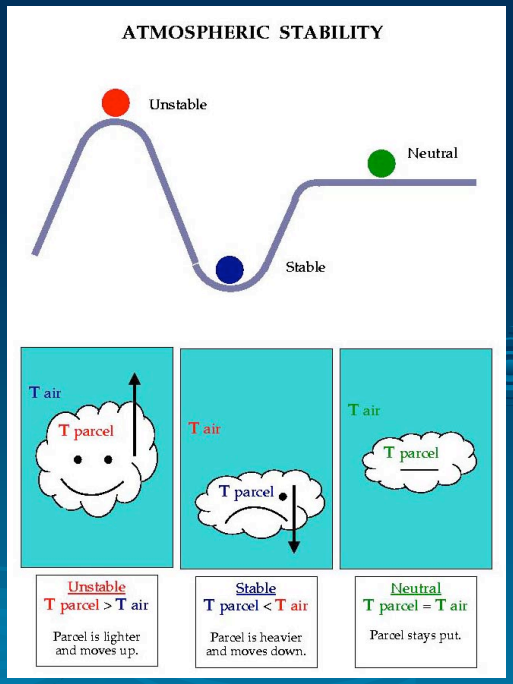
Fig. 3.17 Analogs for (a) stable, (b) unstable, (c) neutral, and (d) conditional instability. The red circle is the original position of the ball, and the white circles are displaced positions. Arrows indicate the direction the ball will move from a displaced position if the force that produced the displacement is removed.

Under **stable** atmospheric conditions, an air parcel that is displaced in the vertical direction will return to its original position.

Neutral stability occurs when the air parcel will remain at it's displaced position without any additional forces acting on it.

For **unstable** conditions, an air parcel that is displaced in the vertical will continue to move in the direction of the displacement.

Conditional instability occurs when a significant displacement of the air parcel must occur before instability can occur.



Stability Considerations (Key Players)

- ✓ Lifting mechanisms
- ✓ Air parcel temperature
- ✓ Air parcel moisture

Processes that Lift Air

When air rises, it expands and cools adiabatically. If air is lifted sufficiently high, it will eventually cool to its dew-point temperature (temperature at which air becomes saturated), and clouds will develop.

There are 5 mechanisms that cause air to rise are

(1) Localized convective lifting, where unequal surface heating causes localized pockets of air to rise because of their buoyancy.

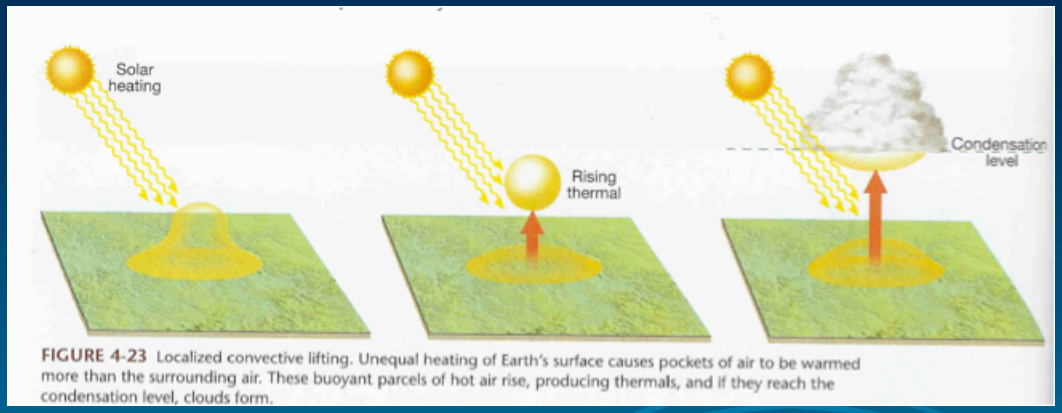


FIGURE 4-23 Localized convective lifting. Unequal heating of Earth's surface causes pockets of air to be warmed more than the surrounding air. These buoyant parcels of hot air rise, producing thermals, and if they reach the condensation level, clouds form.



Processes that Lift Air

When air rises, it expands and cools adiabatically. If air is lifted sufficiently high, it will eventually cool to its dew-point temperature, and clouds will develop.

There are 5 mechanisms that cause air to rise are

(2) Frontal wedging, where warmer, less dense air is forced over cooler, denser air along a front,

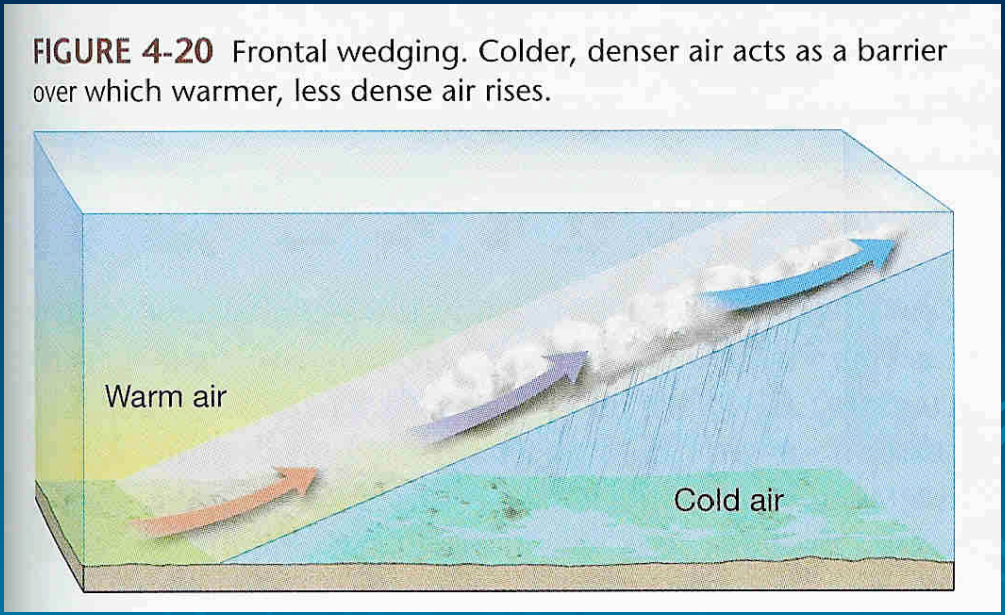


FIGURE 4-20 Frontal wedging. Colder, denser air acts as a barrier over which warmer, less dense air rises.

Processes that Lift Air

When air rises, it expands and cools adiabatically. If air is lifted sufficiently high, it will eventually cool to its dew-point temperature, and clouds will develop.

There are 5 mechanisms that cause air to rise are

(3) Orographic lifting, where air is forced to rise over a mountainous barrier,



Processes that Lift Air

When air rises, it expands and cools adiabatically. If air is lifted sufficiently high, it will eventually cool to its dew-point temperature, and clouds will develop.

There are 5 mechanisms that cause air to rise are

(4) Convergence, a pile-up of horizontal airflow resulting in an upward flow, and

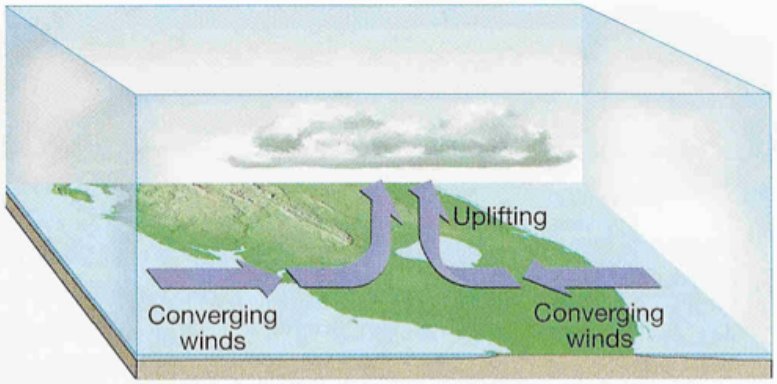


FIGURE 4-21 Convergence. When surface air converges, it increases in height to allow for the decreased area it occupies.



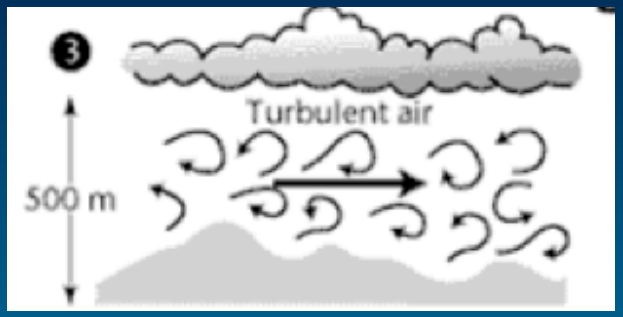
FIGURE 4-22 Southern Florida viewed from the space shuttle. On warm days, airflow from the Atlantic Ocean and Gulf of Mexico onto the Florida peninsula generates many mid-afternoon thunderstorms. *(Photo by NASA/Media Services)*

Processes that Lift Air

When air rises, it expands and cools adiabatically. If air is lifted sufficiently high, it will eventually cool to its dew-point temperature, and clouds will develop.

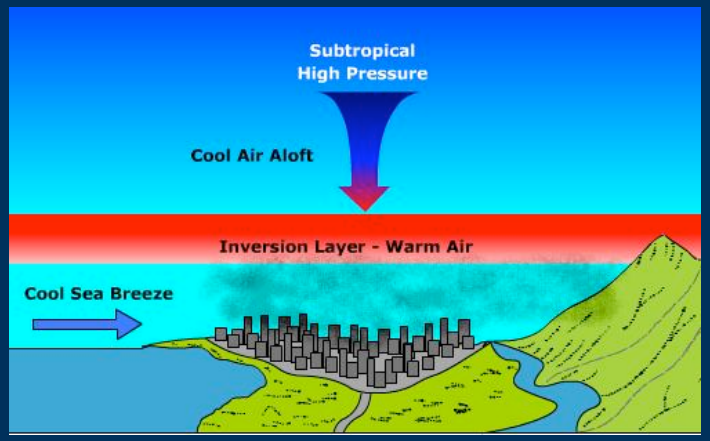
There are 5 mechanisms that cause air to rise are

(5) Turbulence can also lift air on very small scales, and can lead to small clouds.



Stability Considerations (Temperature)

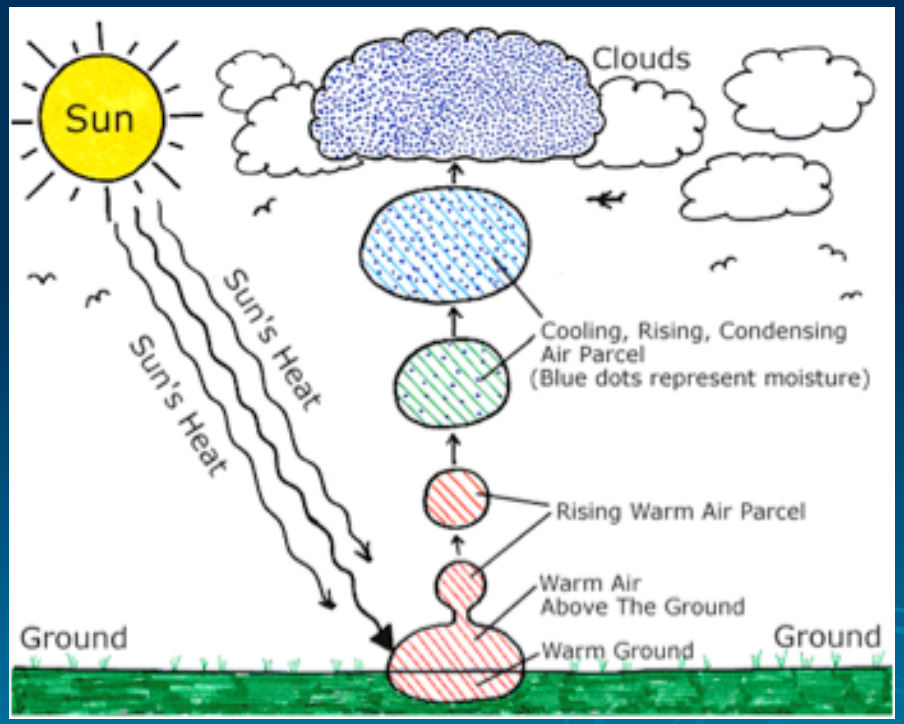
- ✓ Any factor that causes air near the surface to become warmed in relation to the air aloft increases the air's instability.
- ✓ The opposite is also true; any factor that causes the surface air to be chilled results in the air becoming more stable.
- ✓ Most processes that alter atmospheric stability result from temperature changes caused by horizontal or vertical air movements, although daily temperature changes are important too.
- ✓ Changes in stability occur as air moves horizontally over a surface having a markedly different temperature than the air.
- ✓ Furthermore, subsidence (a general downward airflow) generally stabilizes the air, while upward air movement enhances instability.





Stability Considerations (Moisture)

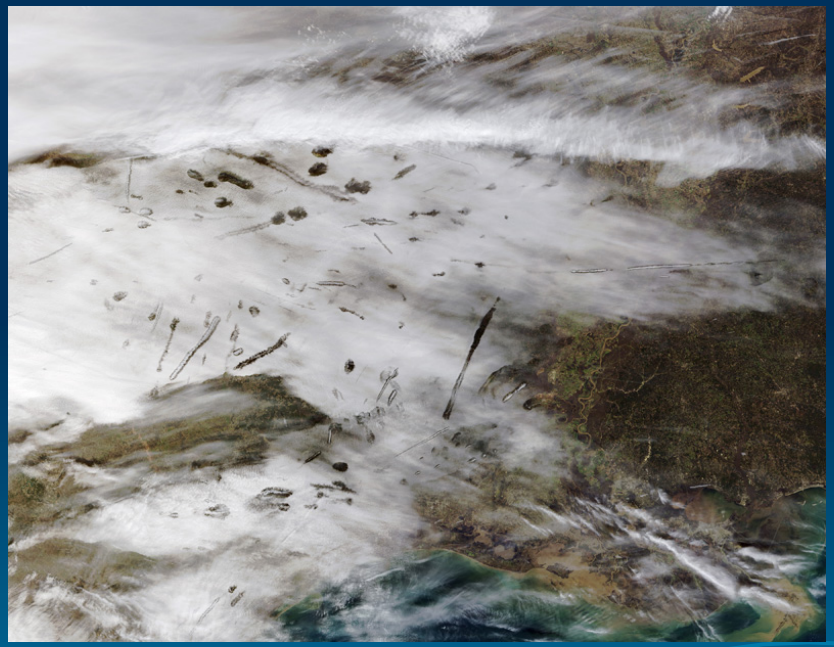
- Moisture affects Atmospheric stability
- Water vapor is less than air
- So, moist air will rise faster than dry air (more buoyant)





Stability Considerations (Moisture)

- Change of state of water also involves an exchange of heat and hence affecting atmospheric temperature and stability



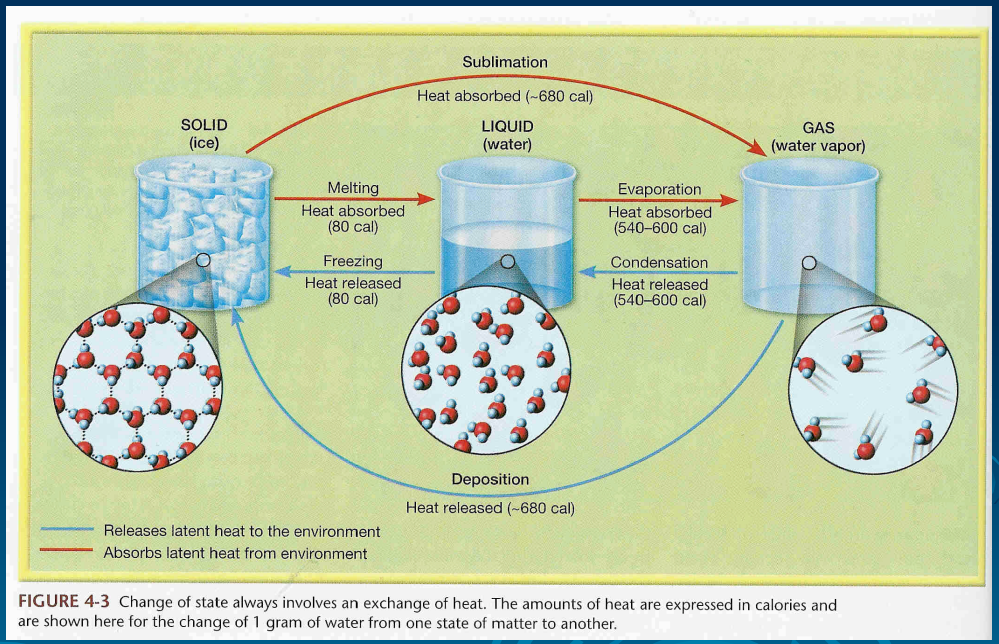
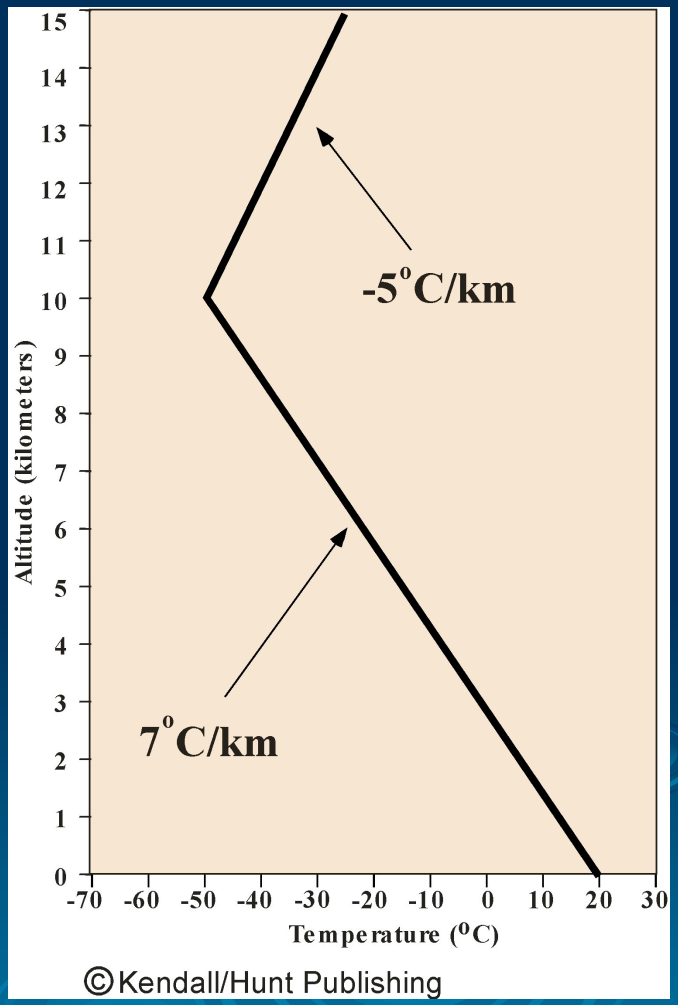


FIGURE 4-3 Change of state always involves an exchange of heat. The amounts of heat are expressed in calories and are shown here for the change of 1 gram of water from one state of matter to another.

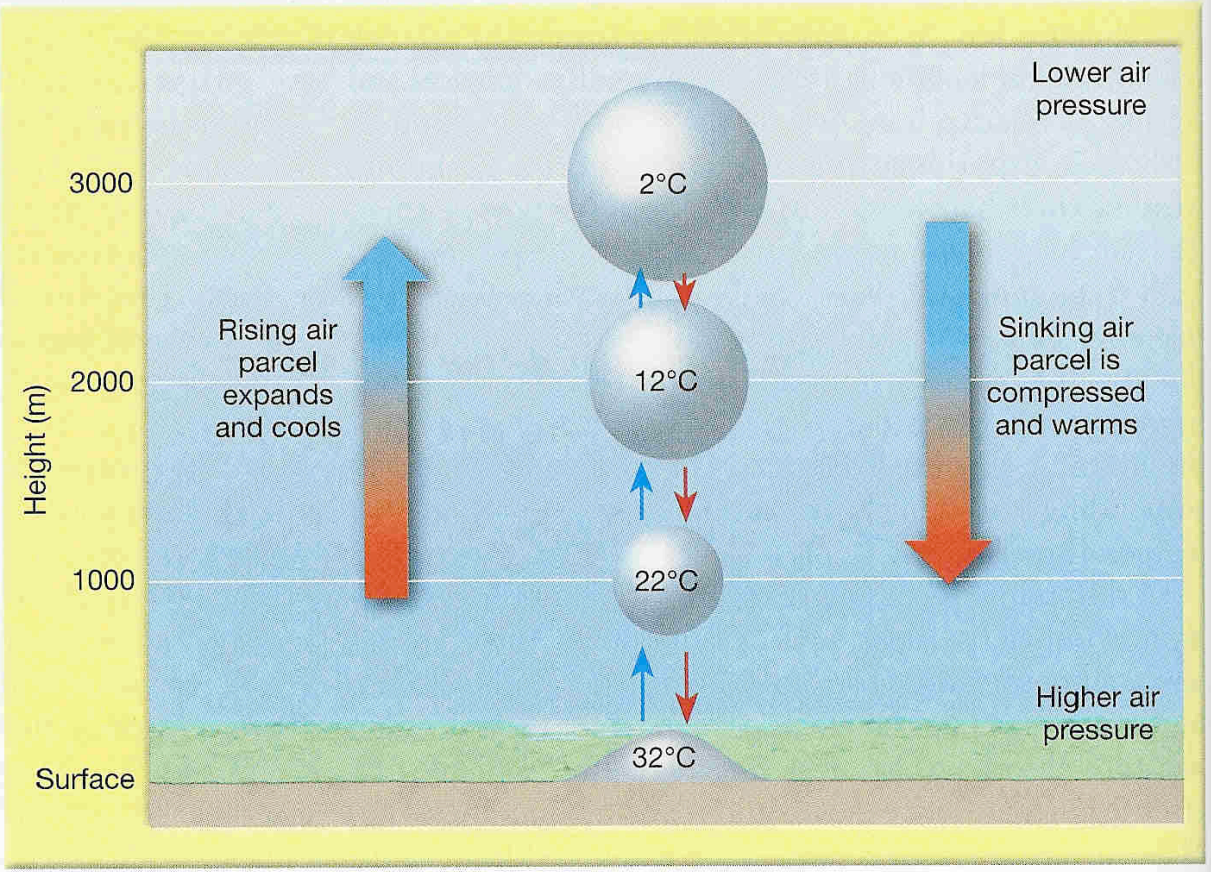
Lapse Rate vs. Inversion

- A lapse rate is the rate at which temperature decreases with increasing altitude.
- Inversion when the temperature of layer increases with height



What is the rate of temperature decrease for dry air? Dry Adiabatic Lapse Rate (DALR)

FIGURE 4-16 Whenever an unsaturated parcel of air is lifted it expands and cools at the *dry adiabatic rate* of 10°C per 1000 meters. Conversely, when air sinks, it is compressed and heats at the same rate.



DALR typically -10°C/kkm

Dry versus Wet (Saturated) Adiabatic Lapse Rate (SALR)

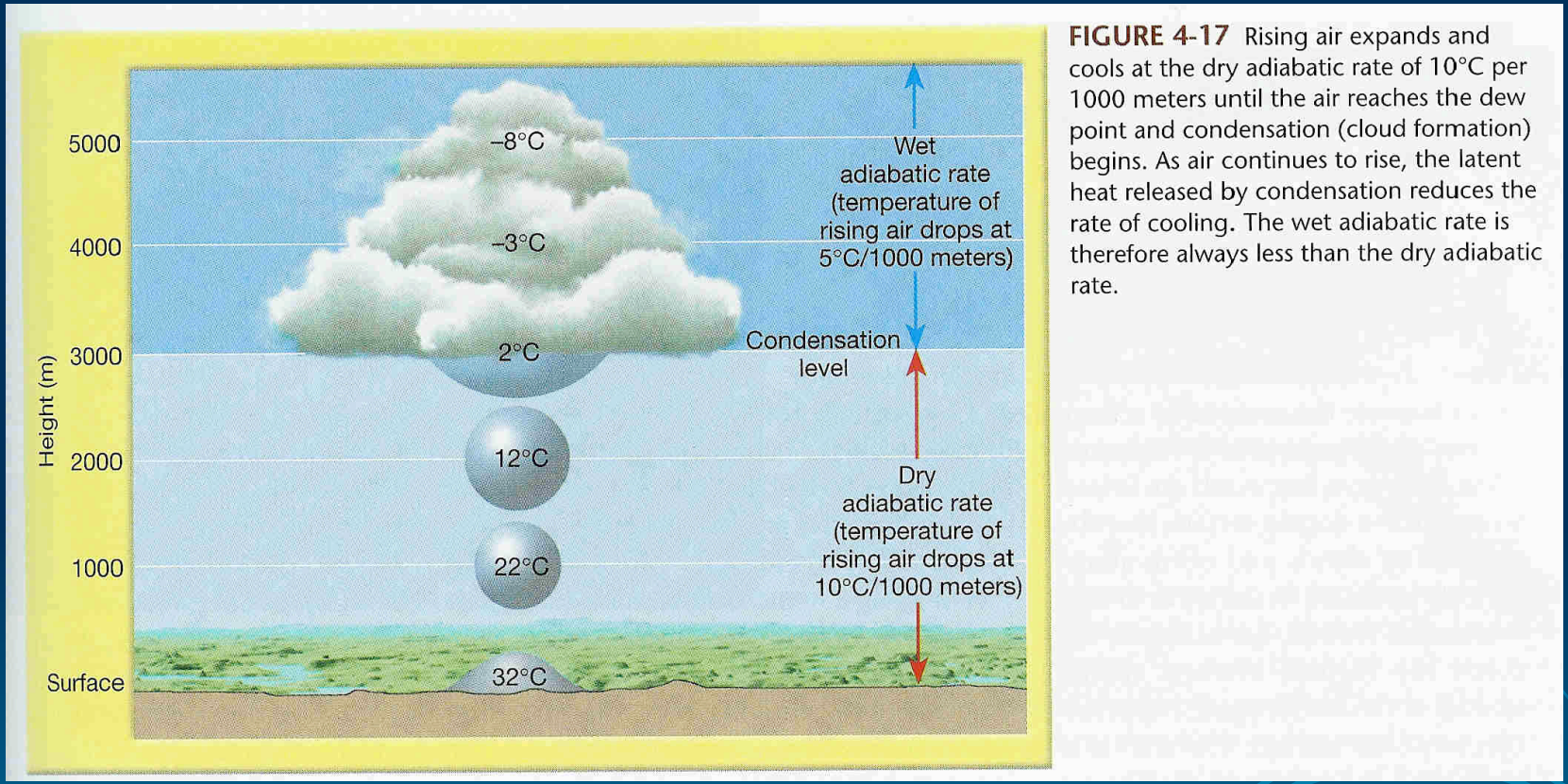


FIGURE 4-17 Rising air expands and cools at the dry adiabatic rate of 10°C per 1000 meters until the air reaches the dew point and condensation (cloud formation) begins. As air continues to rise, the latent heat released by condensation reduces the rate of cooling. The wet adiabatic rate is therefore always less than the dry adiabatic rate.

Atmospheric Stability

When air rises, it cools and can eventually produce clouds. Stable air resists vertical movement, whereas unstable air rises because of its buoyancy.

The stability of air is determined by the environmental lapse rate, i.e., the temperature of the atmosphere at various heights.

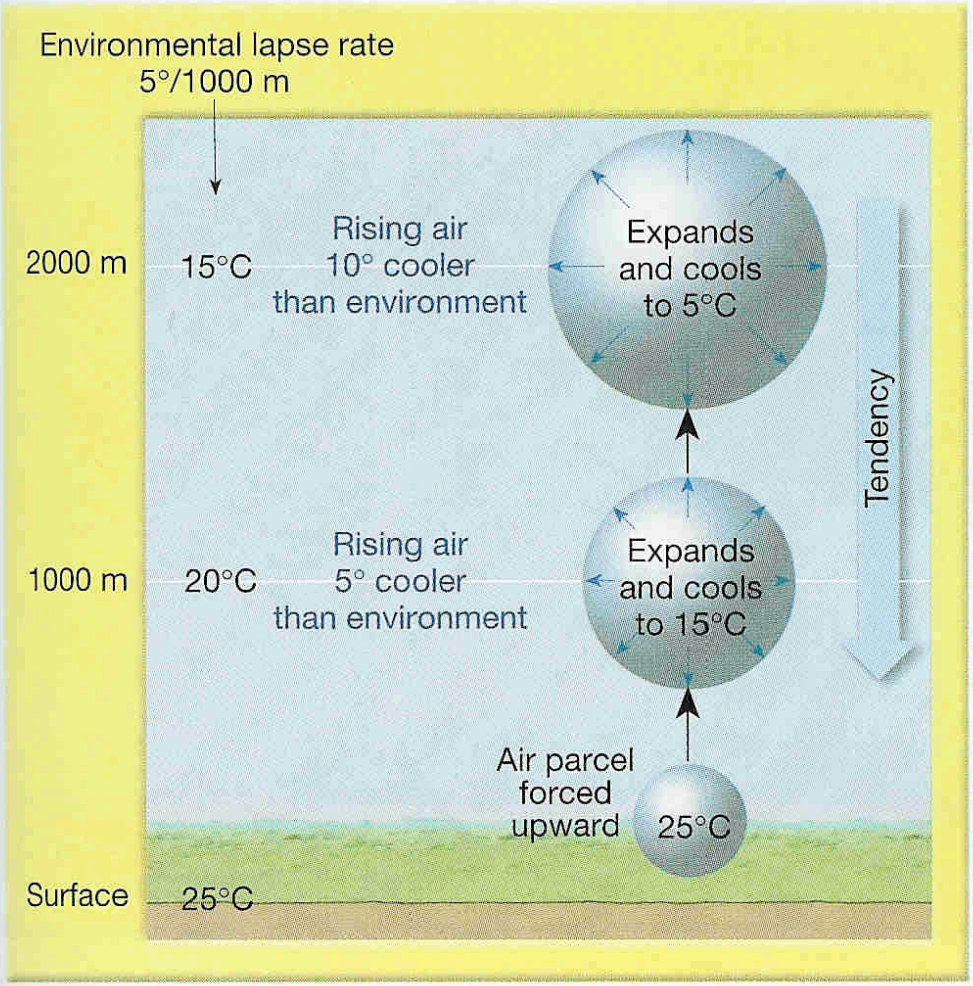
The three fundamental stability conditions of the atmosphere are

(1) absolute stability, when the environmental lapse rate is less than the wet adiabatic rate,
(2) absolute instability, when the environmental lapse rate is greater than the dry adiabatic rate, and
(3) conditional instability, when moist air has an environmental lapse rate between the dry and wet adiabatic rates.

In general, when stable air is forced aloft, the associated clouds have little vertical thickness, and precipitation, if any, is light. In contrast, clouds associated with unstable air are towering and frequently accompanied by heavy rain.

Stable Conditions

FIGURE 4-25 In a stable atmosphere, as an unsaturated parcel of air is lifted, it expands and cools at the dry adiabatic rate of 10°C per 1000 meters. Because the temperature of the rising parcel of air is lower than that of the surrounding environment, it will be heavier and, if allowed to do so, will sink to its original position.



Absolute Stability: Parcel of air is always heavier than surrounding air.

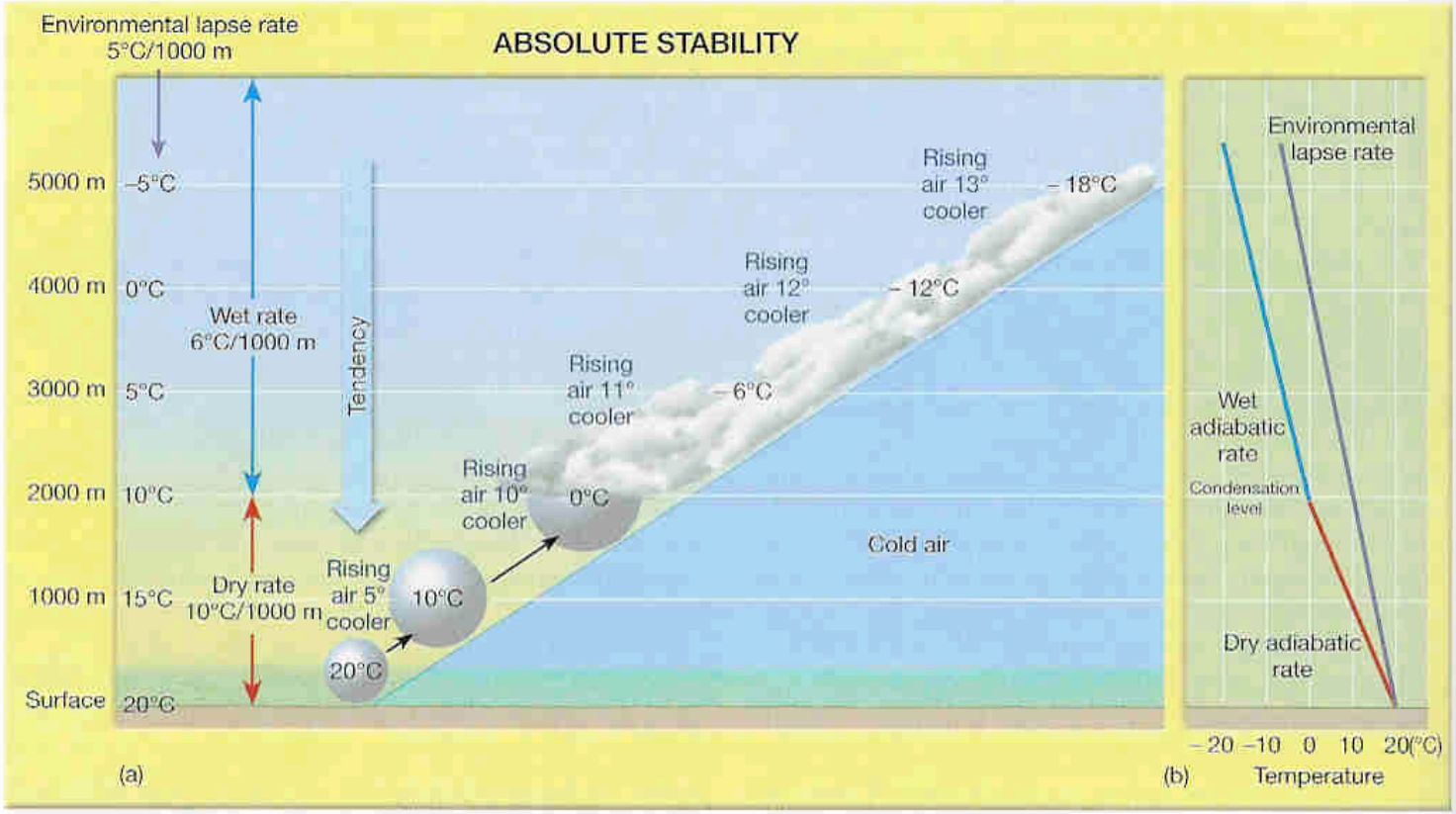


FIGURE 4-26 *Absolute stability* prevails when the environmental lapse rate is less than the wet adiabatic rate. (a) The rising parcel of air is always cooler and heavier than the surrounding air, producing stability. (b) Graphic representation of the conditions shown in part (a).

Absolute Instability: Parcel is always lighter than surrounding air.

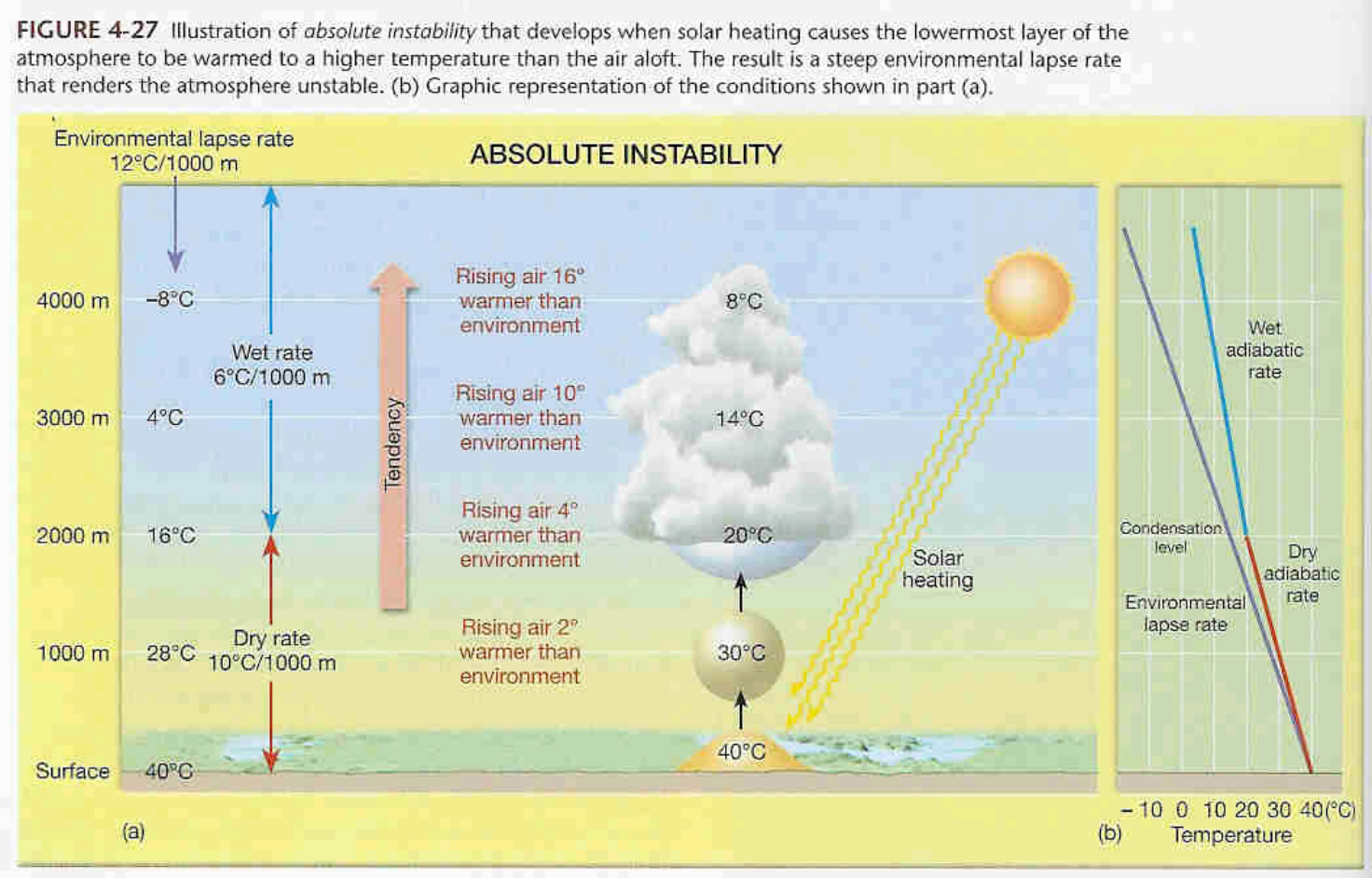
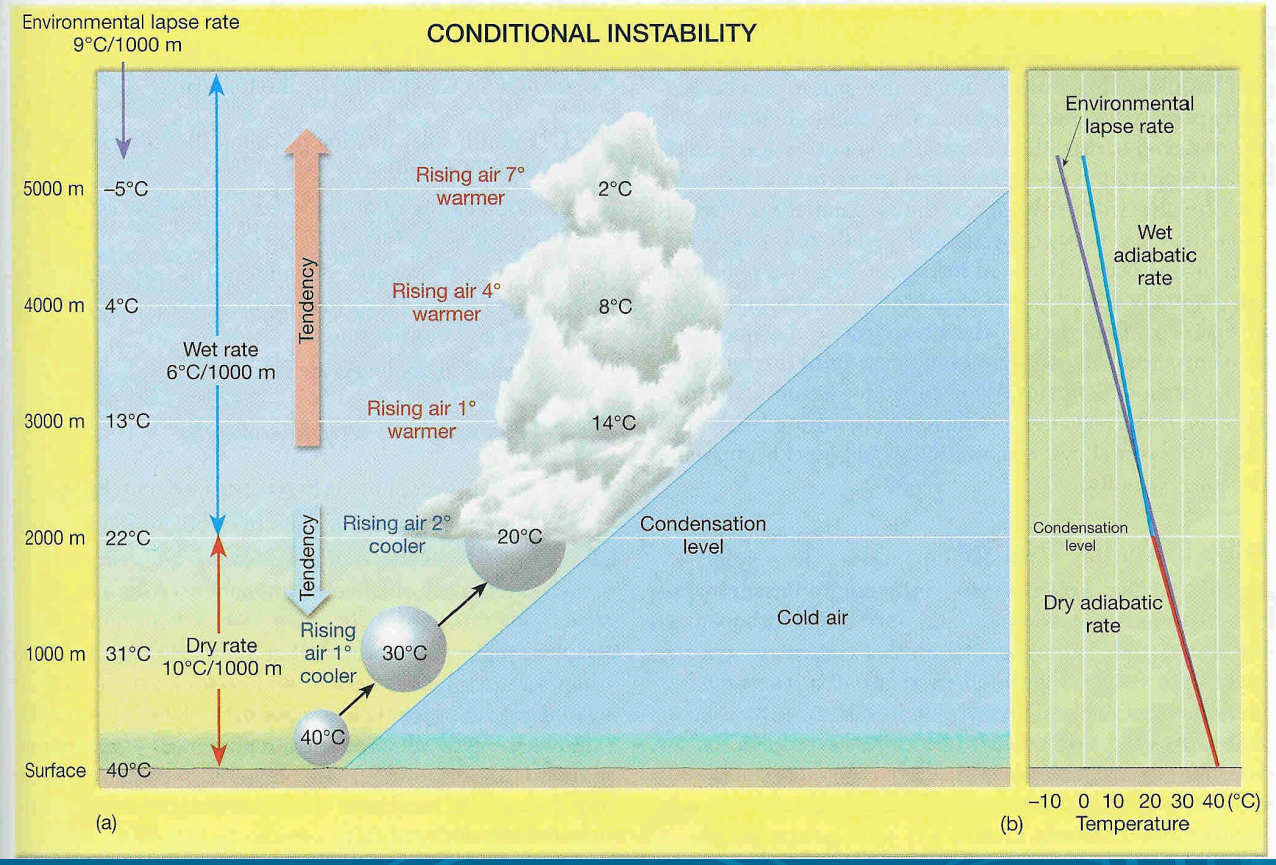


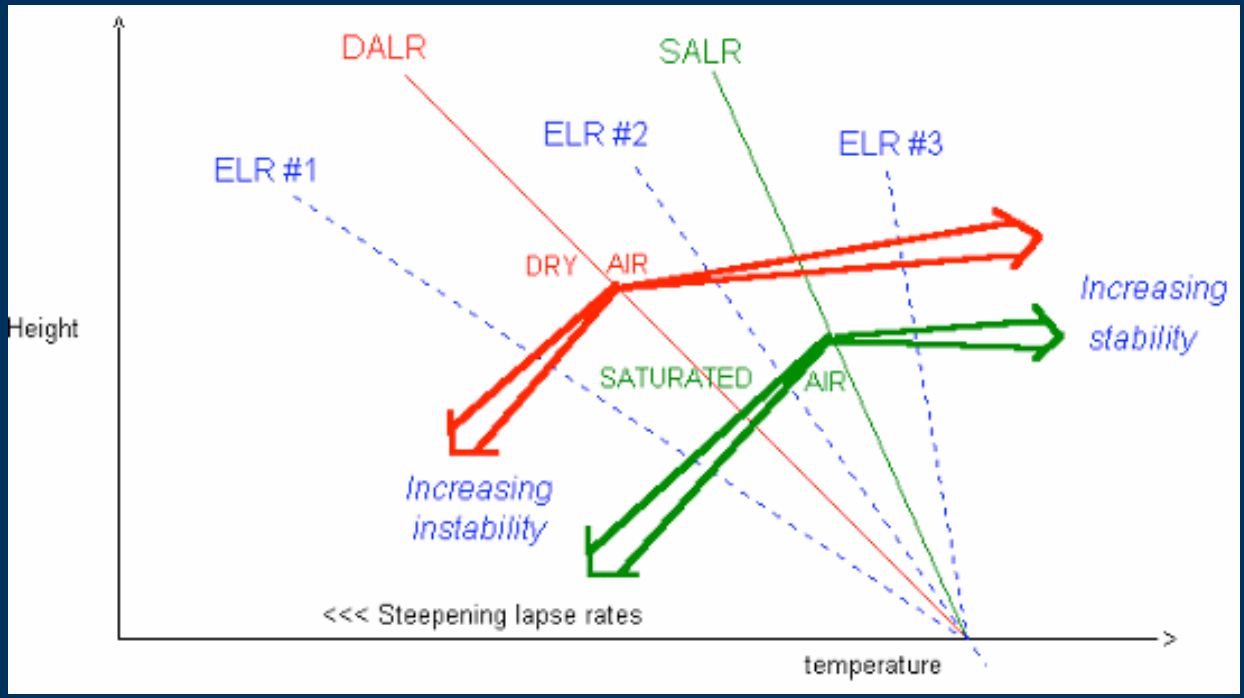
FIGURE 4-27 Illustration of *absolute instability* that develops when solar heating causes the lowermost layer of the atmosphere to be warmed to a higher temperature than the air aloft. The result is a steep environmental lapse rate that renders the atmosphere unstable. (b) Graphic representation of the conditions shown in part (a).

Conditional Instability: Depends on the surrounding air.

FIGURE 4-28 Illustration of *conditional instability,* where warm air is forced to rise along a frontal boundary. Note that the environmental lapse rate of 9°C per 1000 meters lies between the dry and wet adiabatic rates. (a) The parcel of air is cooler than the surrounding air up to nearly 3000 meters, where its tendency is to sink toward the surface (stable). Above this level, however, the parcel is warmer than its environment and will rise because of its own buoyancy (unstable). Thus, when conditionally unstable air is forced to rise, the result can be towering cumulus clouds. (b) Graphic representation of the conditions shown in part (a).



Atmospheric Stability



- Absolute stability: when environmental lapse rate is less than the saturated (wet) adiabatic lapse rate (SALR)
- Absolute instability: when environmental lapse rate is greater than the dry adiabatic lapse rate (DALR)
- Conditional stability: when environmental lapse rate is between DALR and SALR

Temperature Inversions

- ✓ Temperature inversions represent a situation in which the atmosphere is very stable and the mixing depth is significantly restricted.
- ✓ When an inversion exists and winds are light, diffusion is inhibited and high pollution concentrations are to be expected in areas where pollution sources exist.
- ✓ Surface-temperature inversions form because the ground is a more effective radiator than the air above.
- ✓ Inversions aloft are associated with sinking air that characterizes centers of high air pressure.

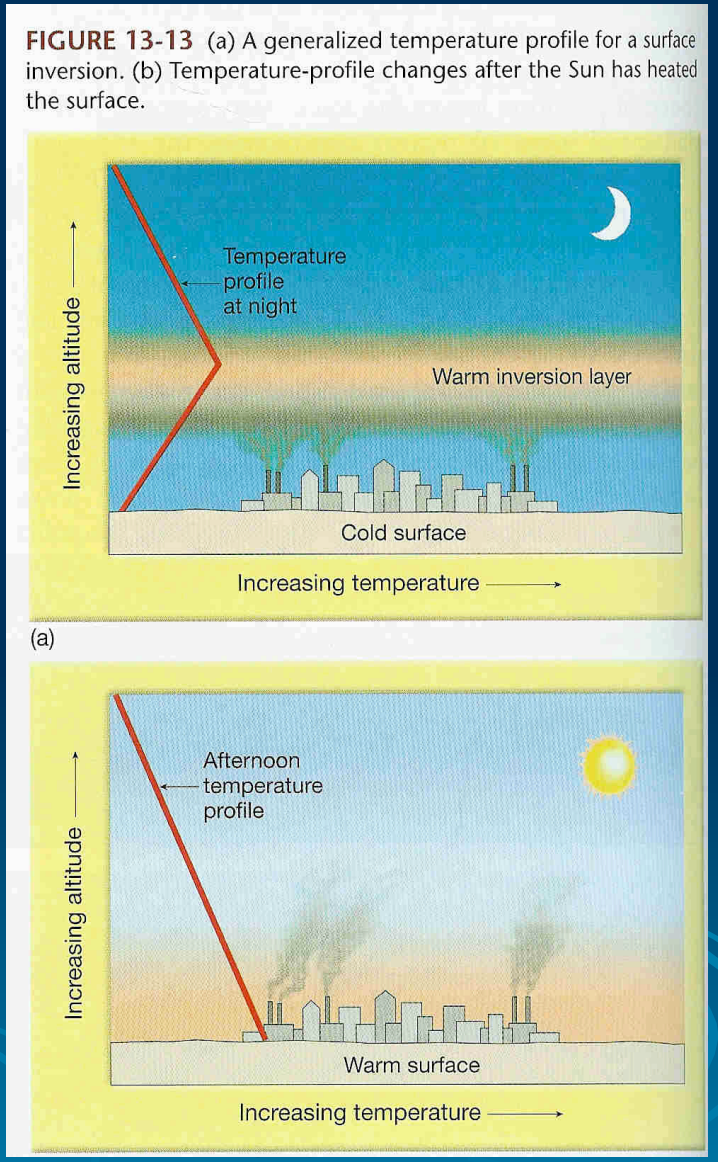


FIGURE 13-13 (a) A generalized temperature profile for a surface inversion. (b) Temperature-profile changes after the Sun has heated the surface.

Upper Air Observation

- Because the atmosphere is 3D, upper-air observations are essential.
- Worldwide nearly 900 balloon-borne instrument packages, called radiosondes, are launched twice daily at 0000 and 1200 Greenwich Mean Time (GMT).



Upper Air Observation

- Radiosondes measure
  - Temperature
  - Relative Humidity
  - Wind Direction and Speed
  - Pressure
  - Height



Skew-T/Log-P Diagram

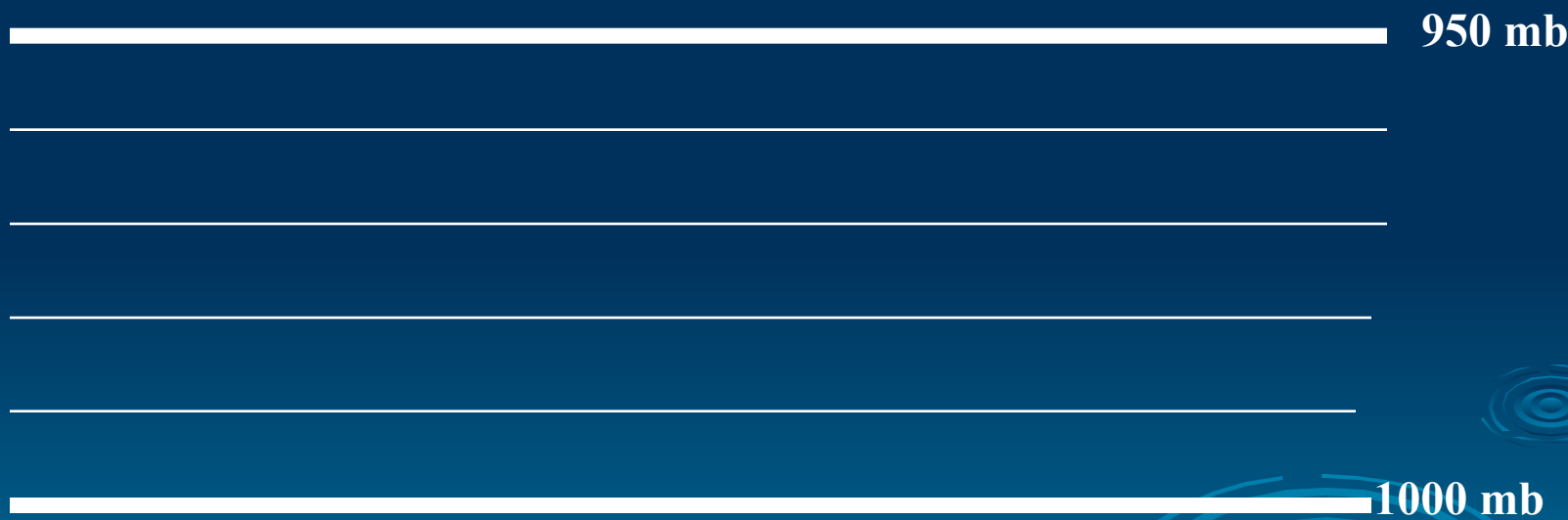
- The most common diagram used to plot rawinsonde soundings and to analyze stability is called the Skew-T/Log-P diagram
- Coordinates
  - Pressure decreases logarithmically
  - Temperature skewed at 45° angle
    - Easier to identify stable layers

Skew-T/Log-P Diagram

- Five different variables are plotted on the basic Skew-T/Log-P
  - Isobars (equal lines of pressure)
  - Isotherms (equal lines of temperature)
  - Dry adiabats (DALR)
  - Pseudoadiabats (SALR)
  - Mixing ratios (amount of water vapor in the air)

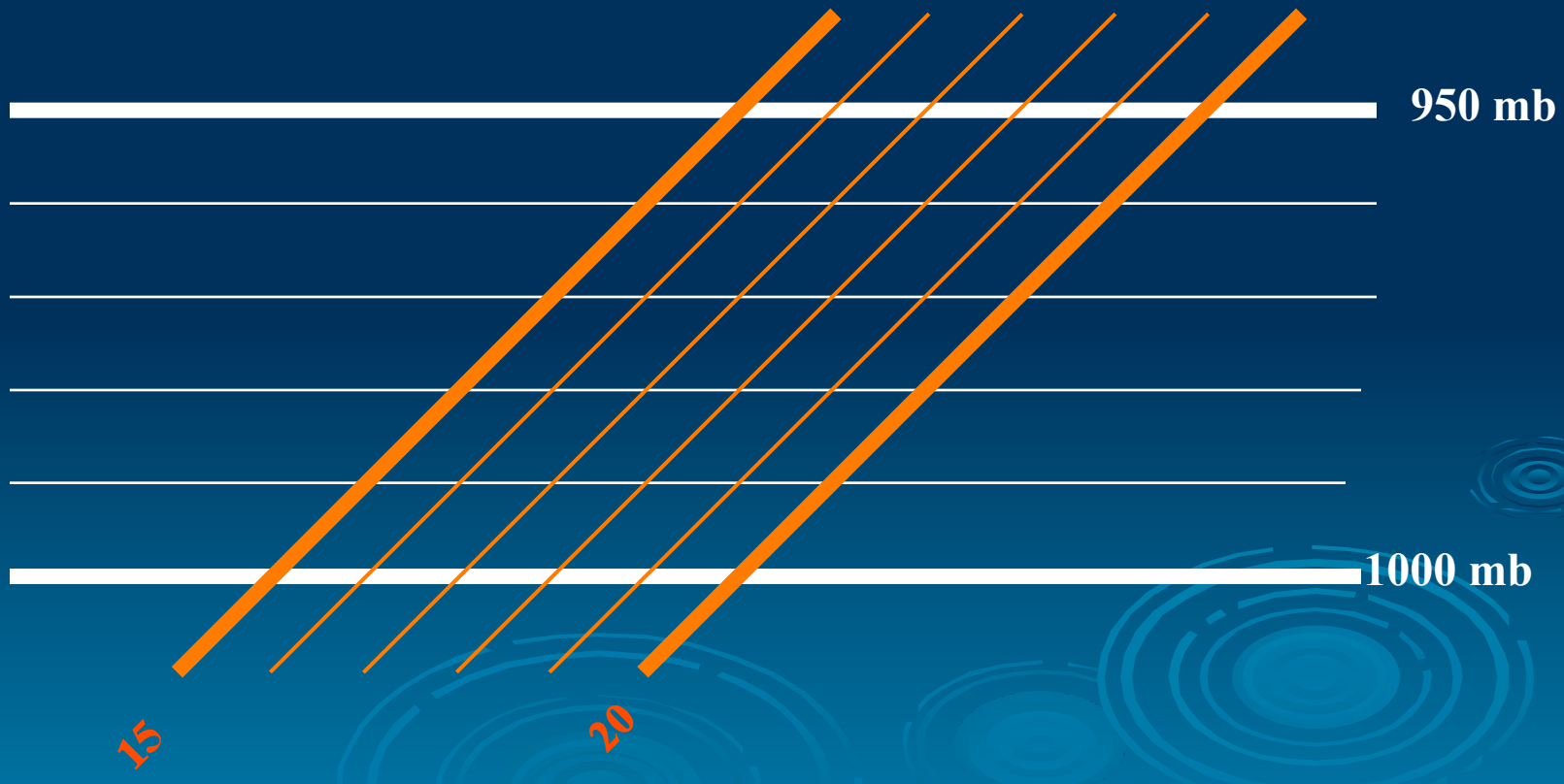
Skew-T/Log-P Diagram

1. Isobars are roughly horizontal lines that represent the pressures on the Skew-T/Log-P. They are plotted every 10 mb and are labeled every 50-100 mb



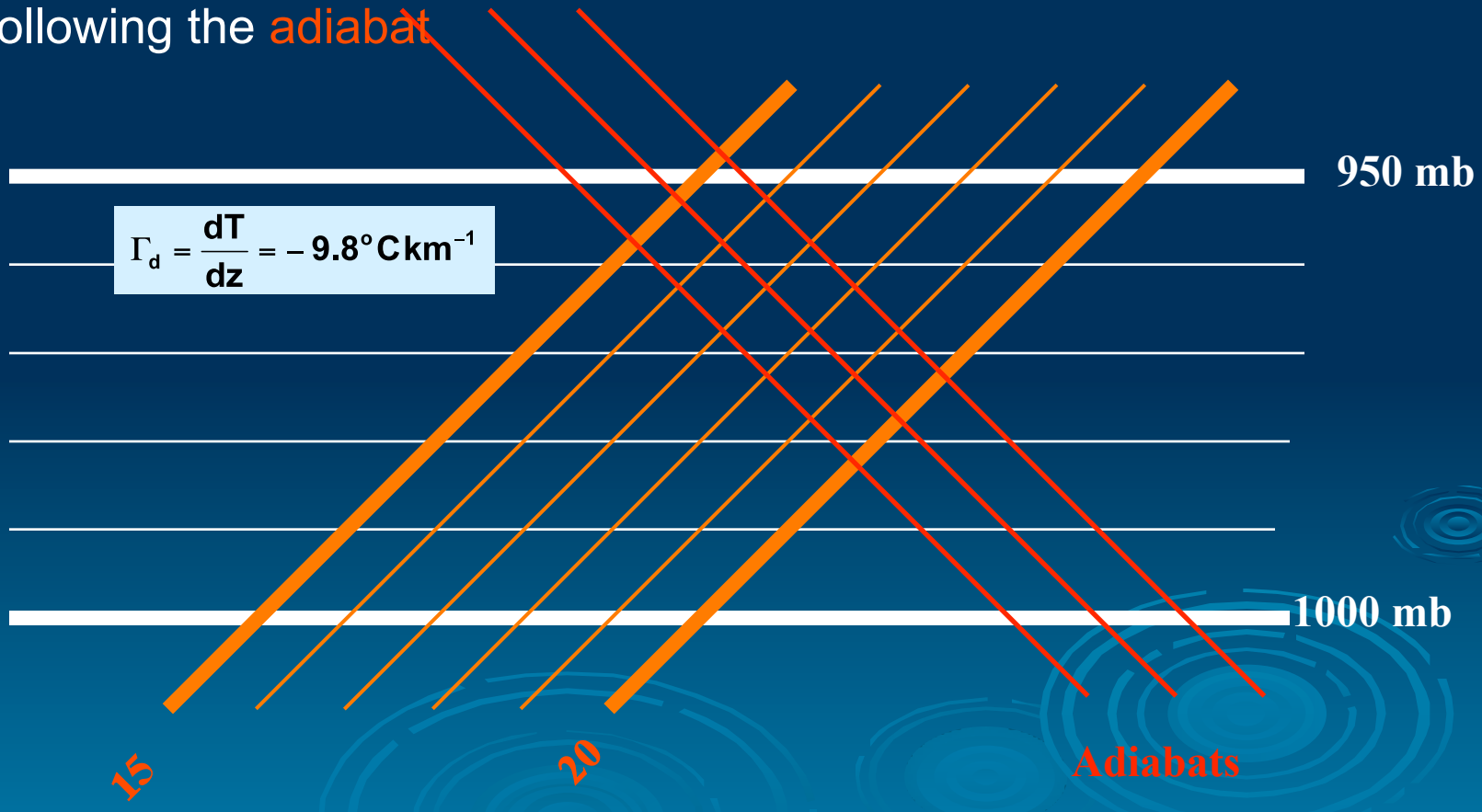
Skew-T/Log-P Diagram

2. Isotherms are nearly straight lines running from the lower left to the upper right that represent the temperatures. Both temperatures and dew point temperatures are plotted using the isotherms. Isotherms are plotted every 1°C and are labeled every 5°C.



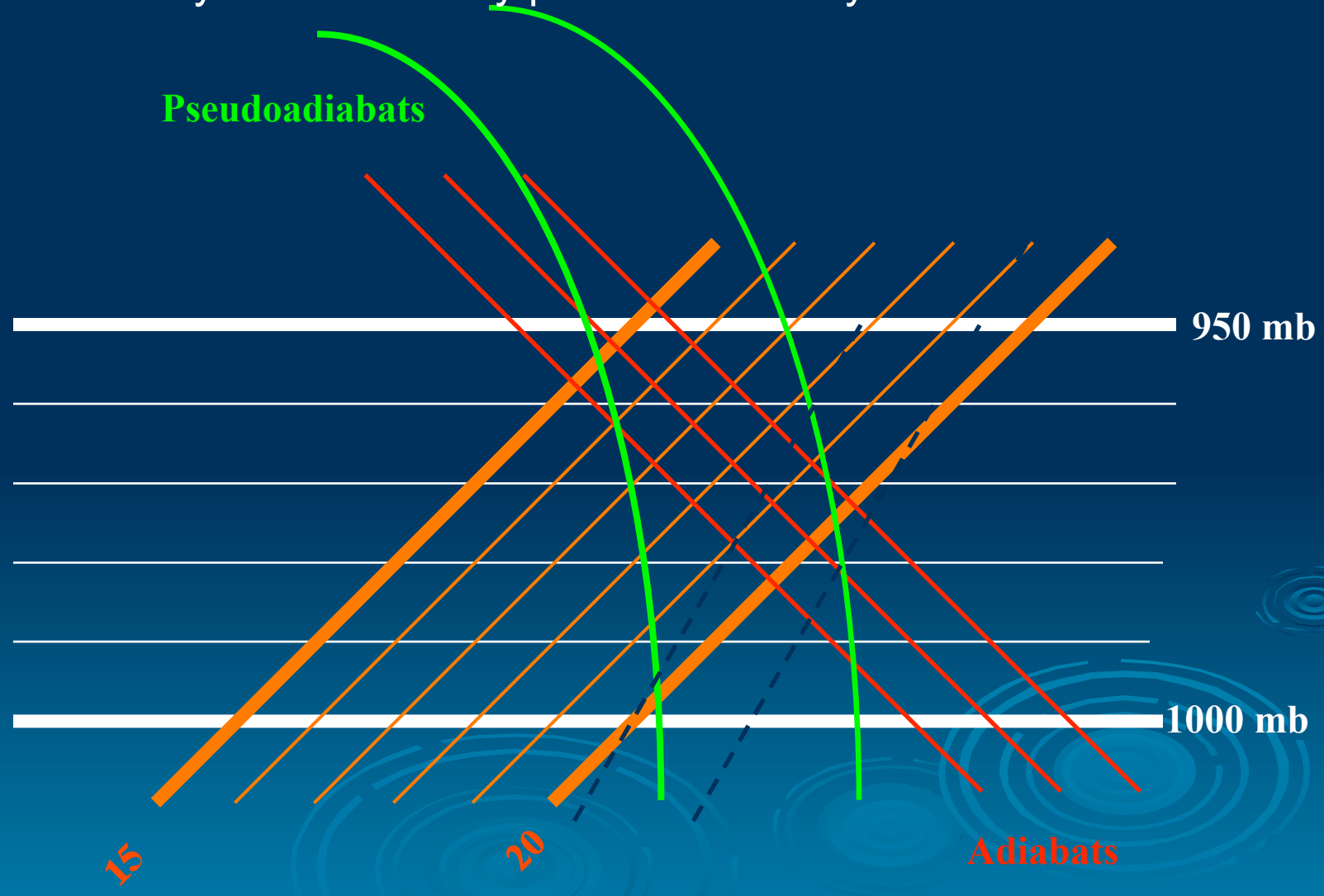
Skew-T/Log-P Diagram

3. Dry adiabats are nearly straight curves running from the lower right to the upper left that represent the Dry Adiabatic Lapse Rate. Unsaturated air parcels move vertical along the adiabats as they are lifted or sink. The temperature of an unsaturated air parcel moving vertically during and adiabatic process can be determined by following the adiabat



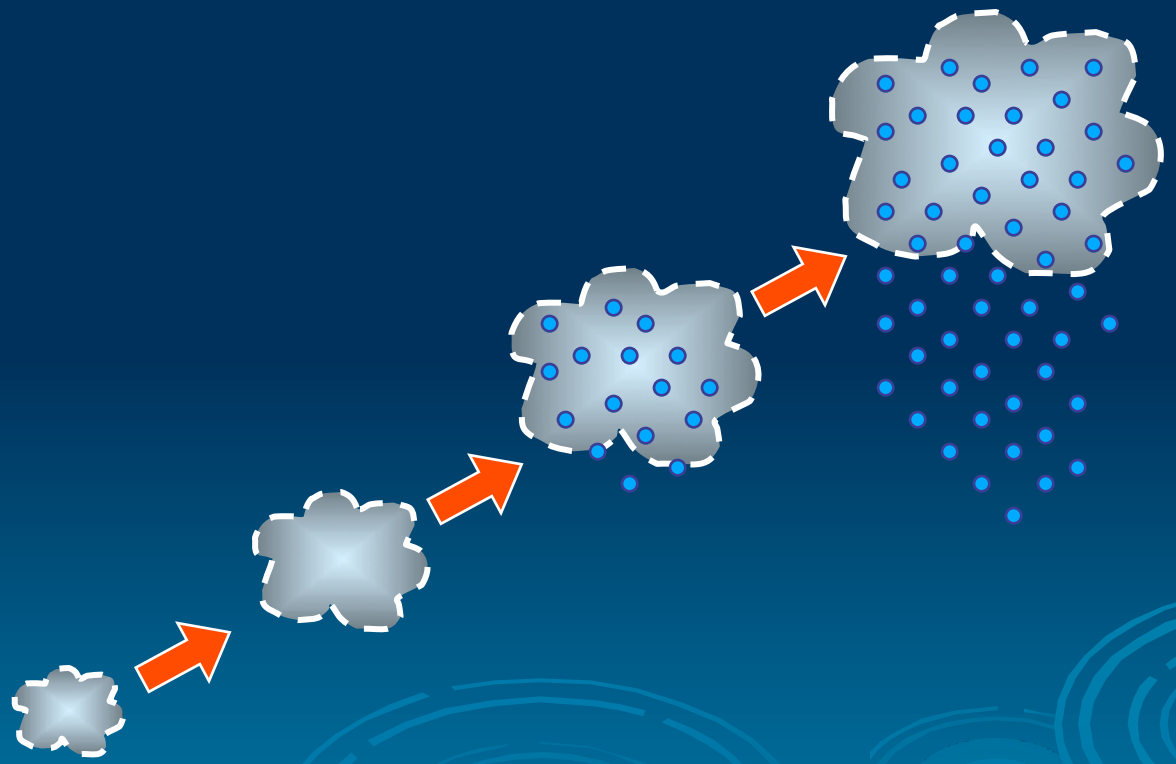
Skew-T/Log-P Diagram

4. Pseudoadiabats are curves running from the bottom of the diagram and gradually curving toward the upper left that ultimately become nearly parallel to the dry adiabats.



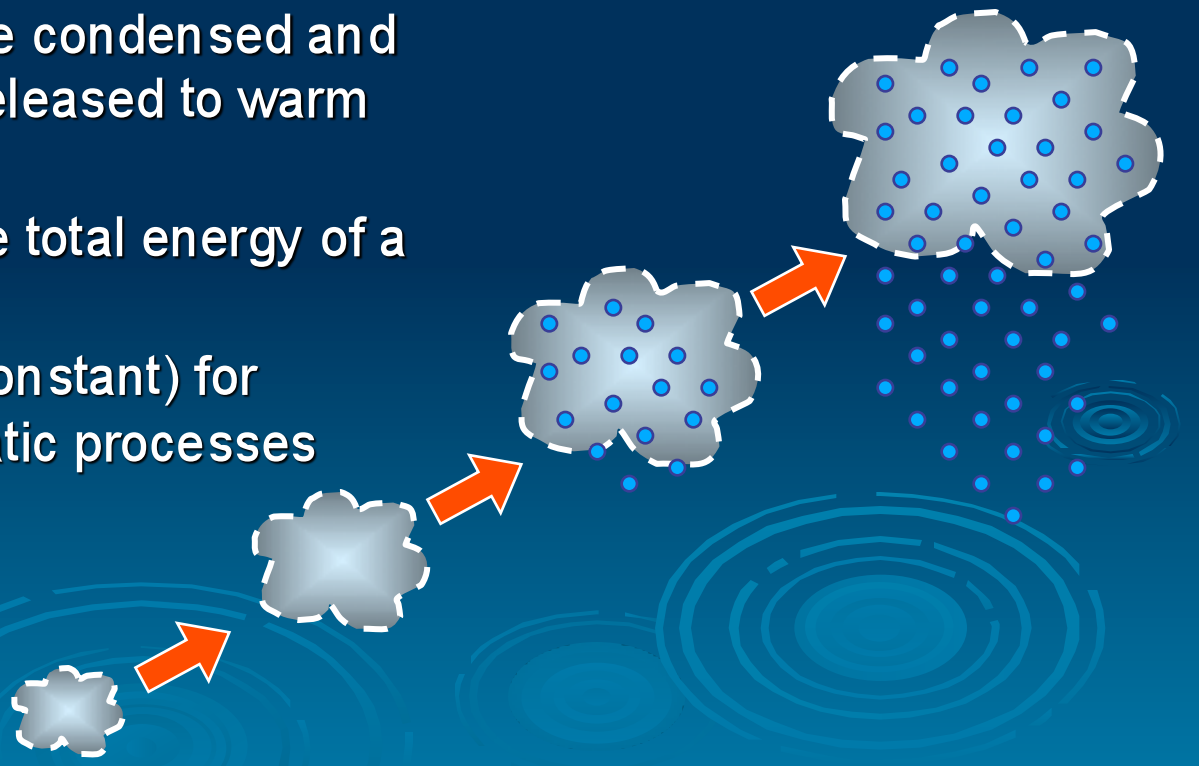
Skew-T/Log-P Diagram

- Pseudoadiabats represent the Saturated Adiabatic Lapse Rate (lines of constant saturated adiabatic lapse rate).
- The change in temperature of saturated air parcels moving vertically occurs along the pseudoadiabats.



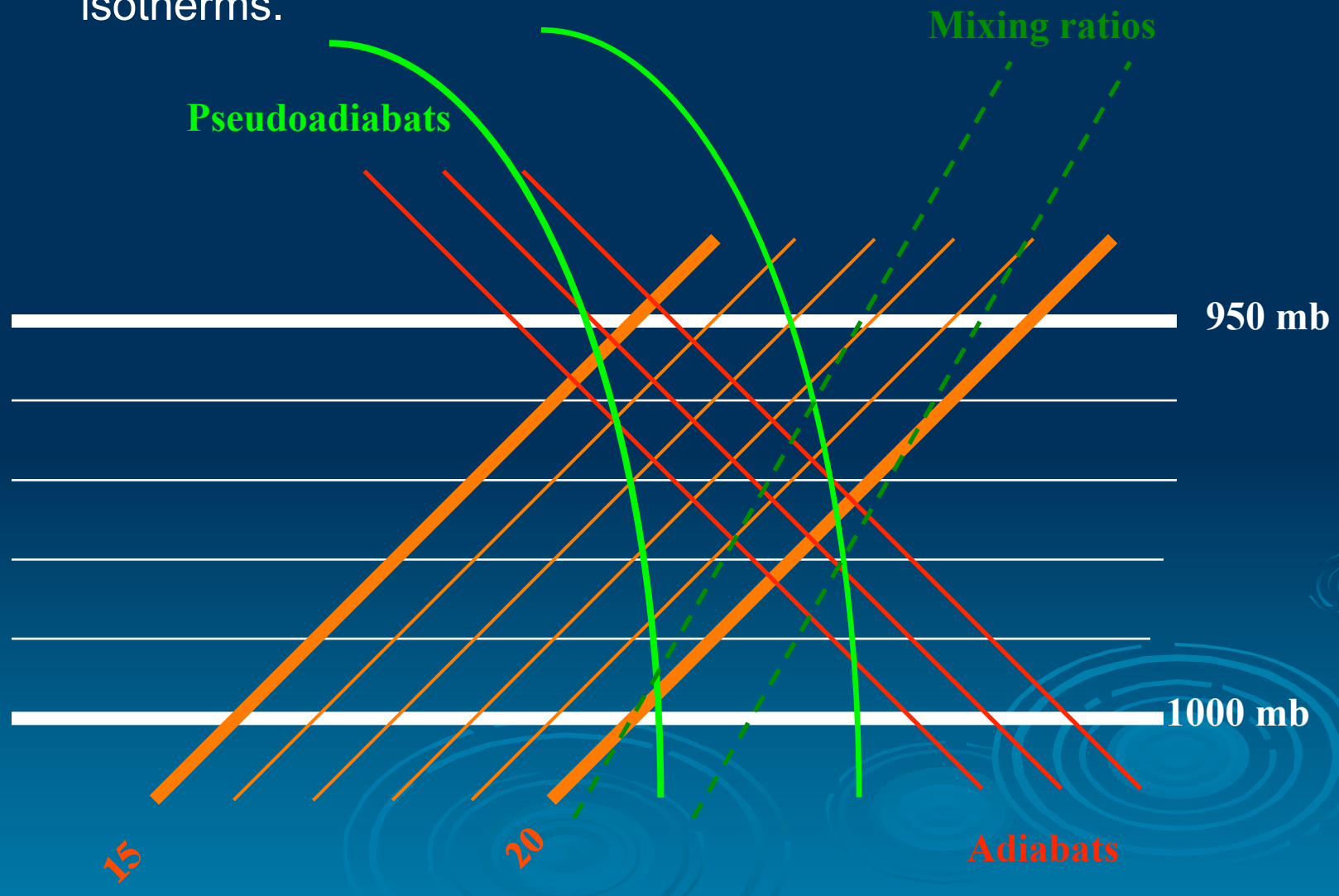
Skew-T/Log-P Diagram

- Pseudoadiabats are also lines of constant Equivalent Potential Temperature (θ_e)
- Equivalent Potential temperature
  - The potential temperature of a parcel of air would have if all of its water vapor were condensed and the latent heat released to warm only the dry air
  - A measure of the total energy of a parcel of air
  - Conserved (or constant) for saturated adiabatic processes



Skew-T/Log-P Diagram

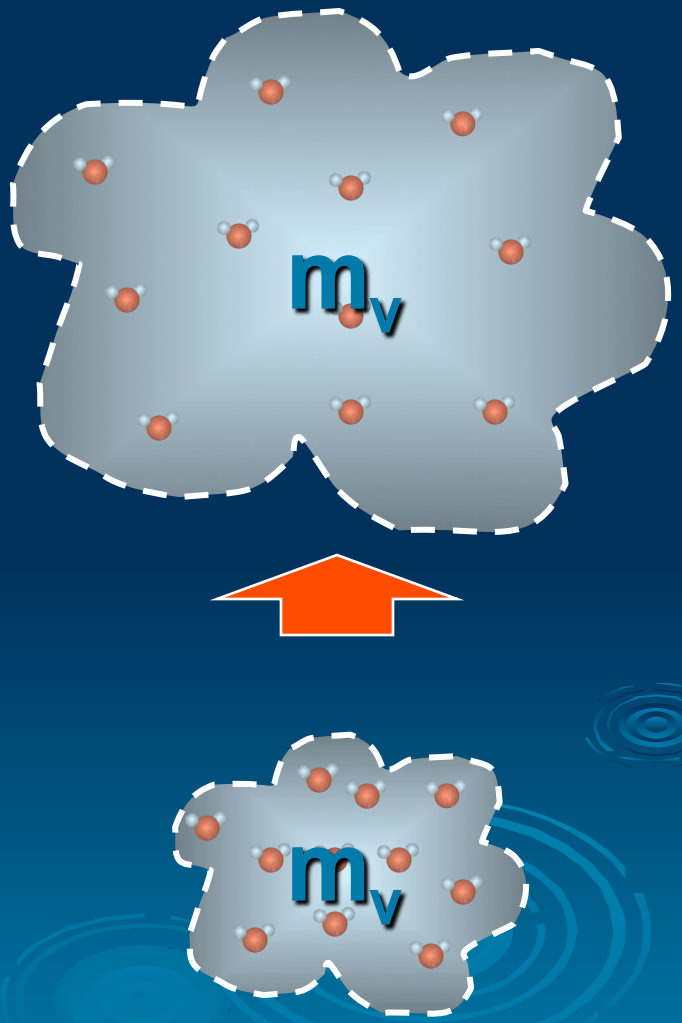
5. The mixing ratios are also plotted as straight dashed lines running from the lower left to upper right more steeply than the isotherms.



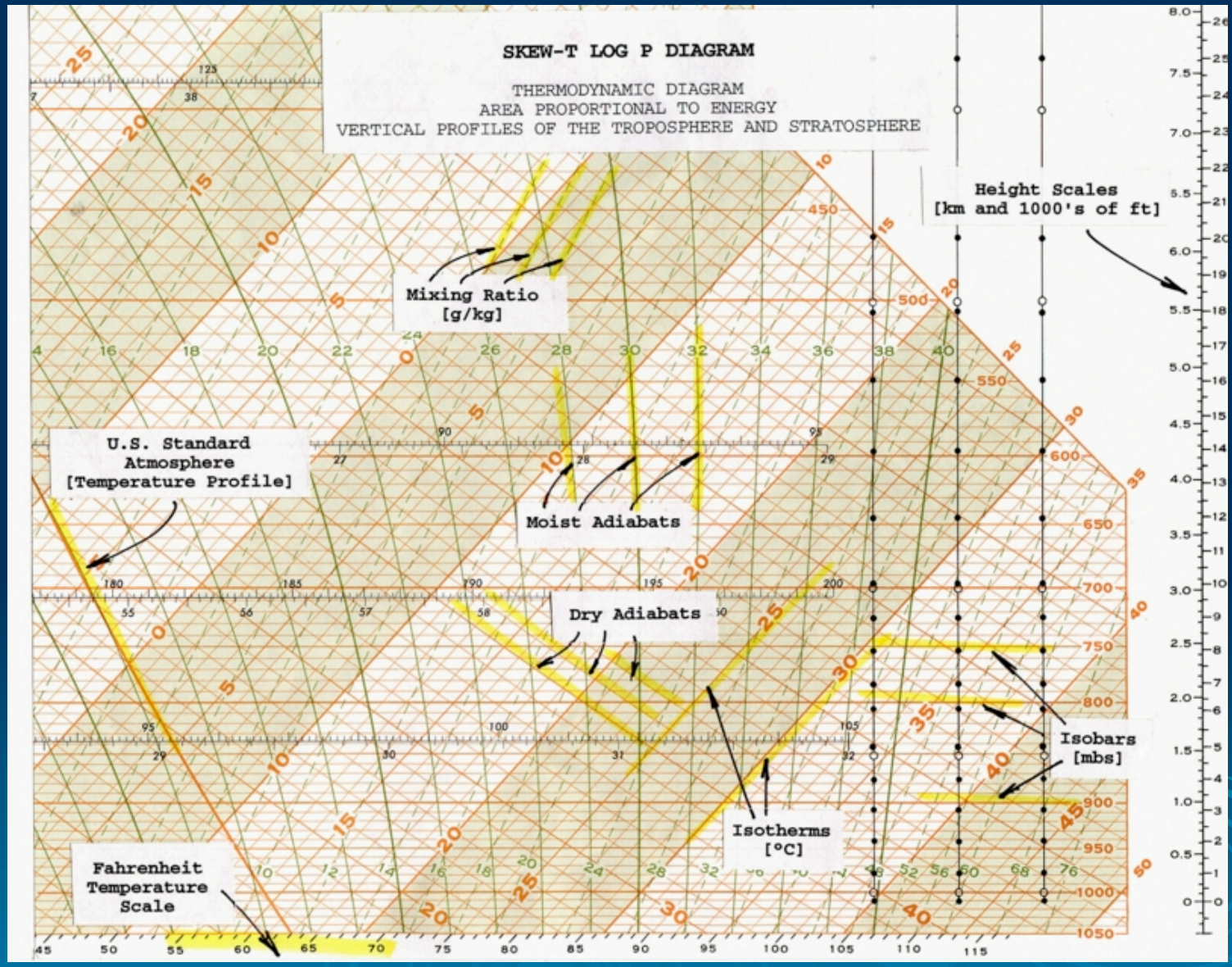
Skew-T/Log-P Diagram

- The mixing ratios (w) can be used to find the height at which condensation would occur under various conditions if unsaturated parcels rise.

$$w = \frac{m_v}{m_d}$$



Skew-T/Log-P Diagram



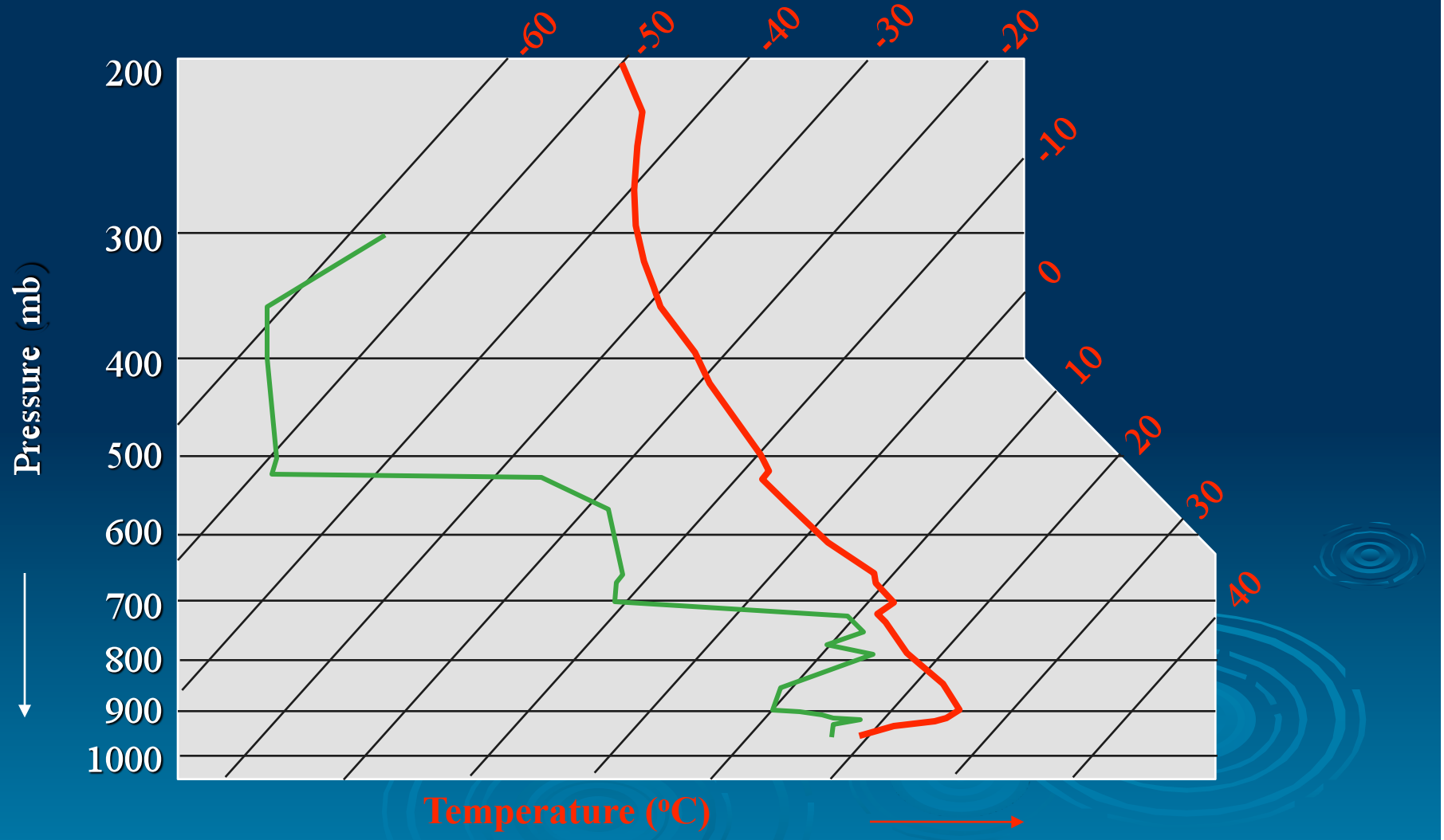
Skew-T/Log-P Diagram

- Skew-T/Log-P advantages for air pollution applications
  - Determine stability, instability, weather elements at every layer (such as severe weather).
  - Used in numerical models

- Skew-T/Log-P disadvantages
  - Temporal resolution (only available twice a day (00Z & 12Z), i.e., weather can change dramatically between soundings
  - Sounding does not give a true vertical dimension & instantaneous measurements

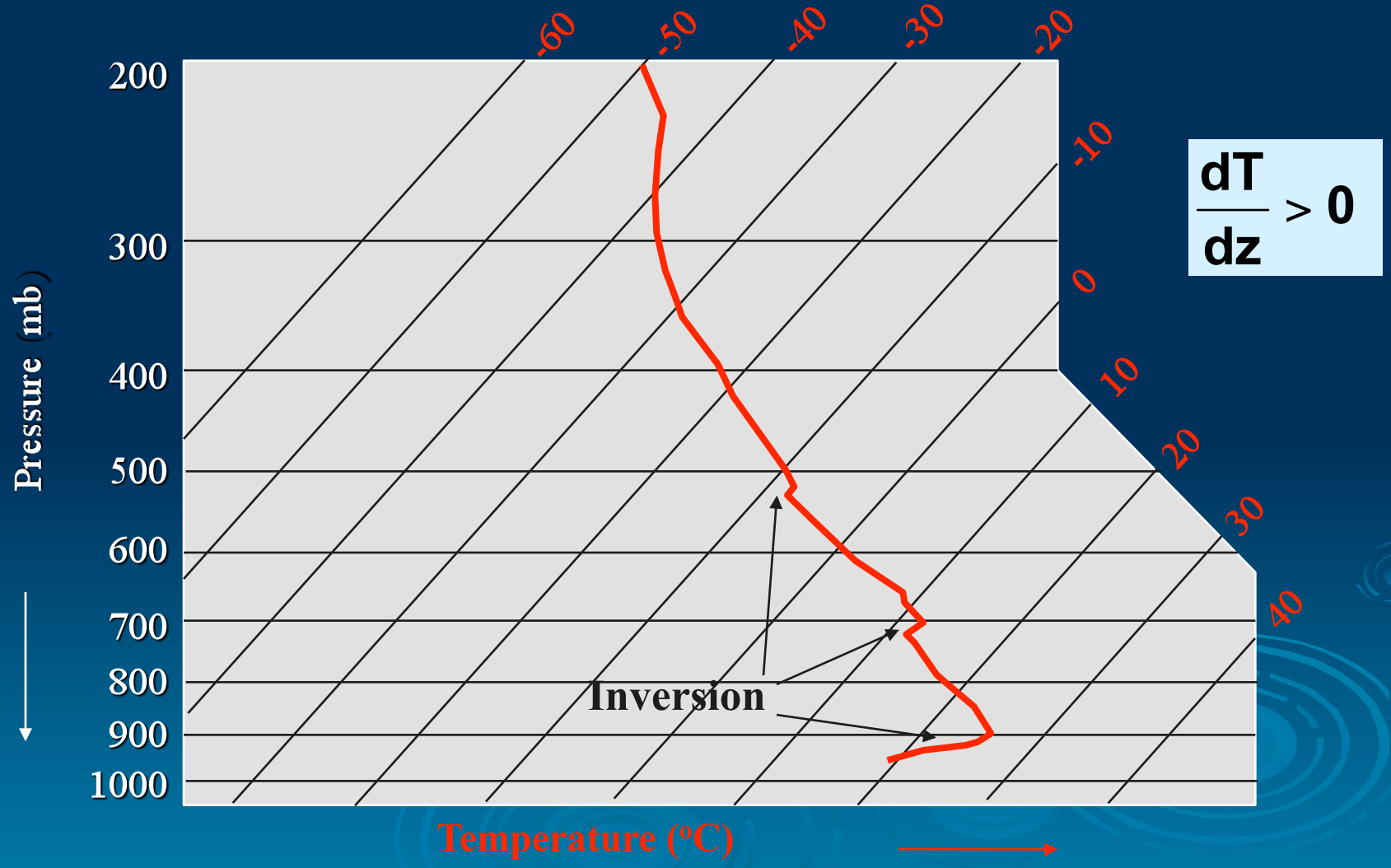
Soundings on Skew-T/Log-P Diagram

- One of the most basic uses of a SKEWT diagram is to plot temperatures and dew point temperatures observed by radiosondes in order to display and analyze the vertical structure of the atmosphere.



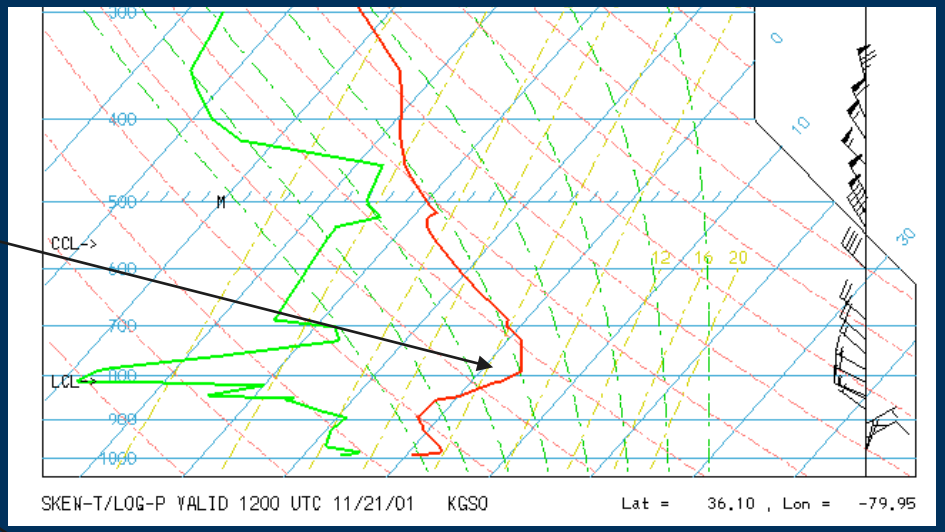
Skew-T/Log-P Diagram
Temperature Inversion

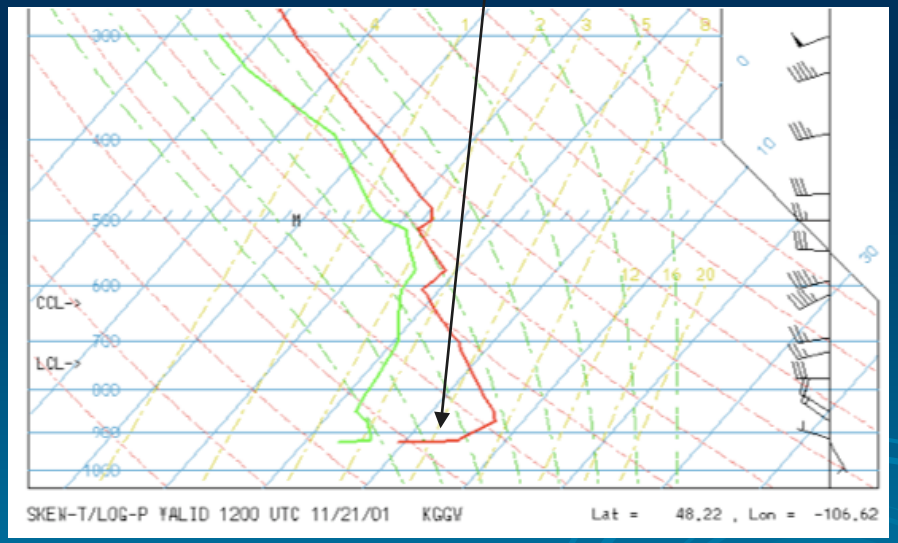
- Increase in temperature with height

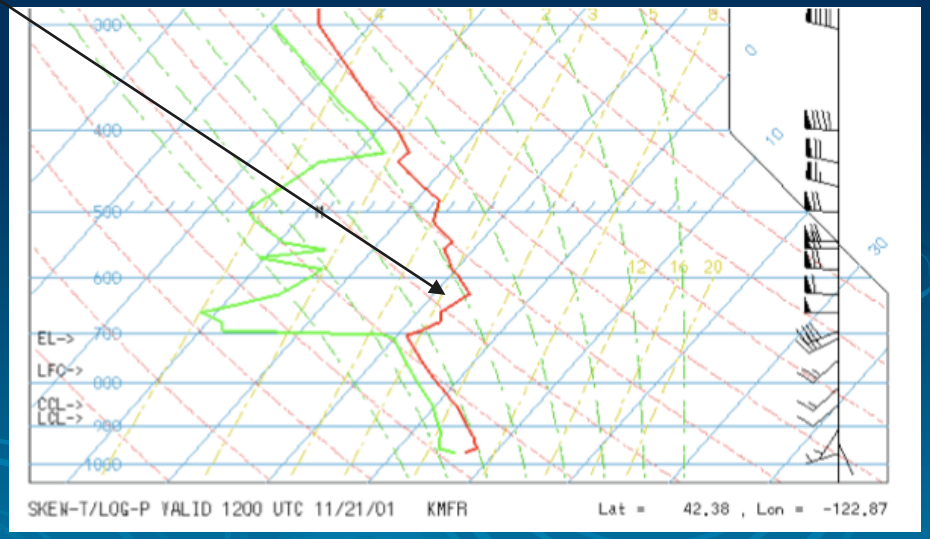


Skew-T/Log-P Diagram
Temperature Inversion

- Types
  - Subsidence
  - Frontal
  - Radiation

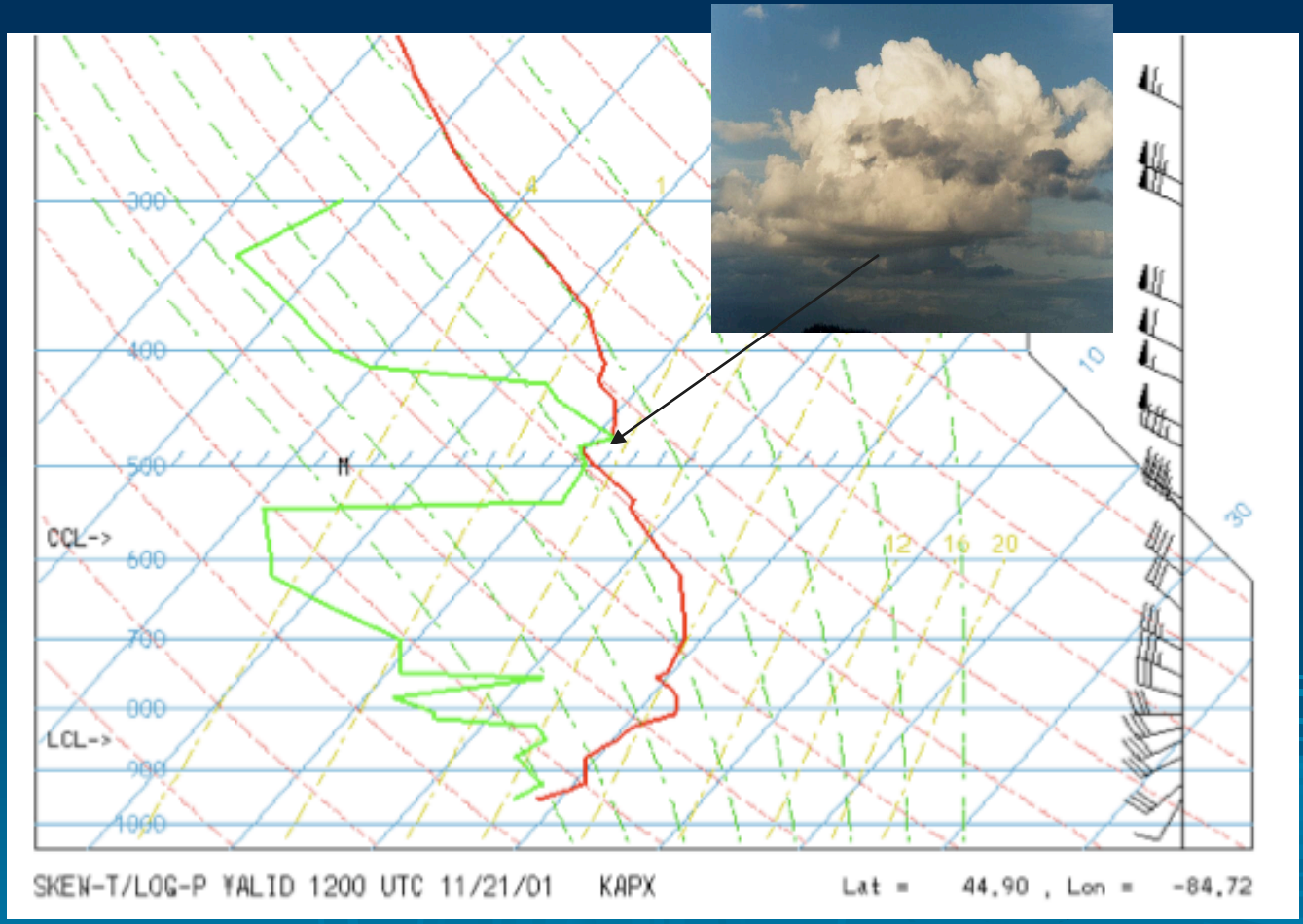






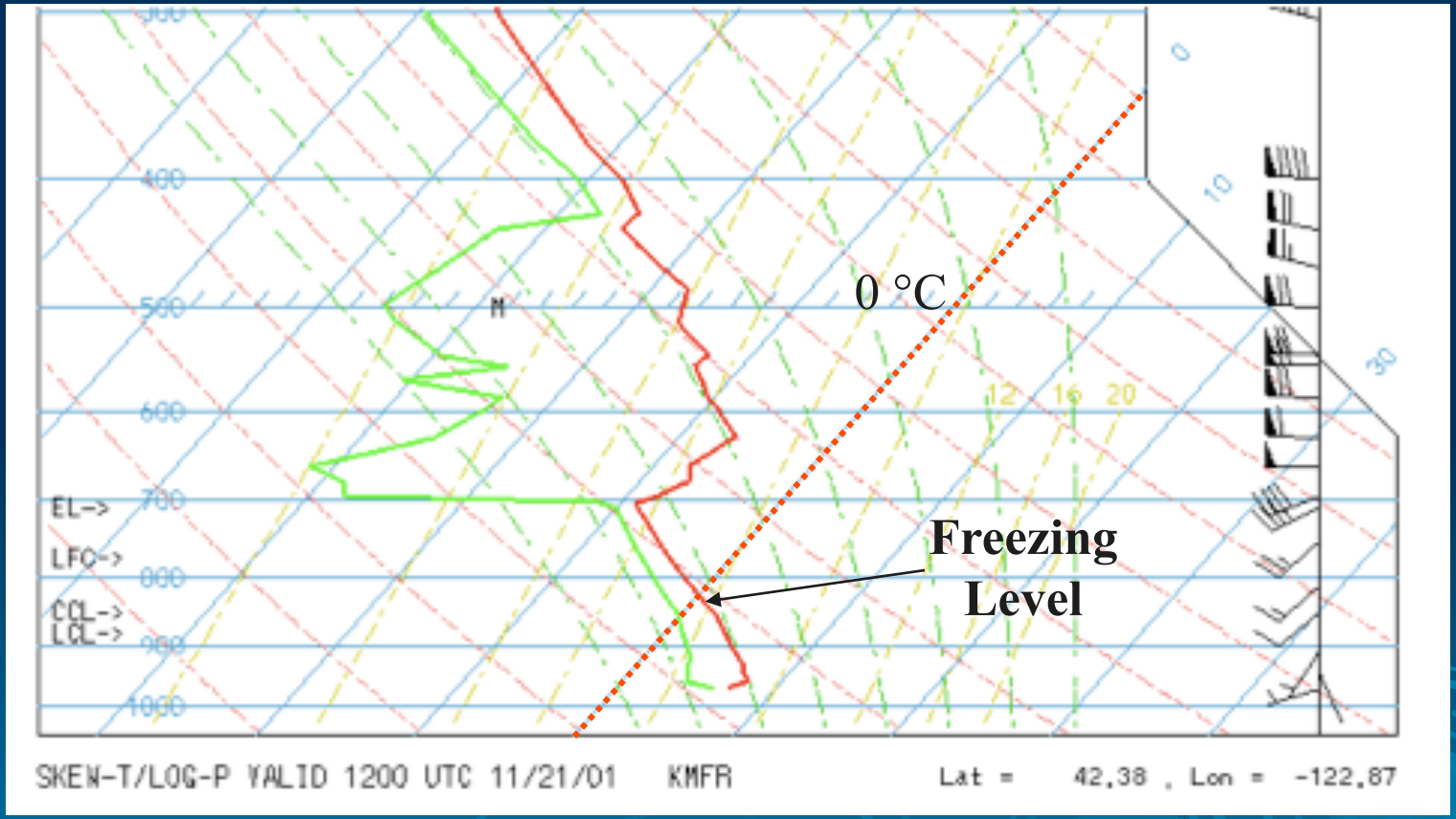
Skew-T/Log-P Diagram
Clouds

- Temperature – Dew Point Temperature
  - Less than 5 °C



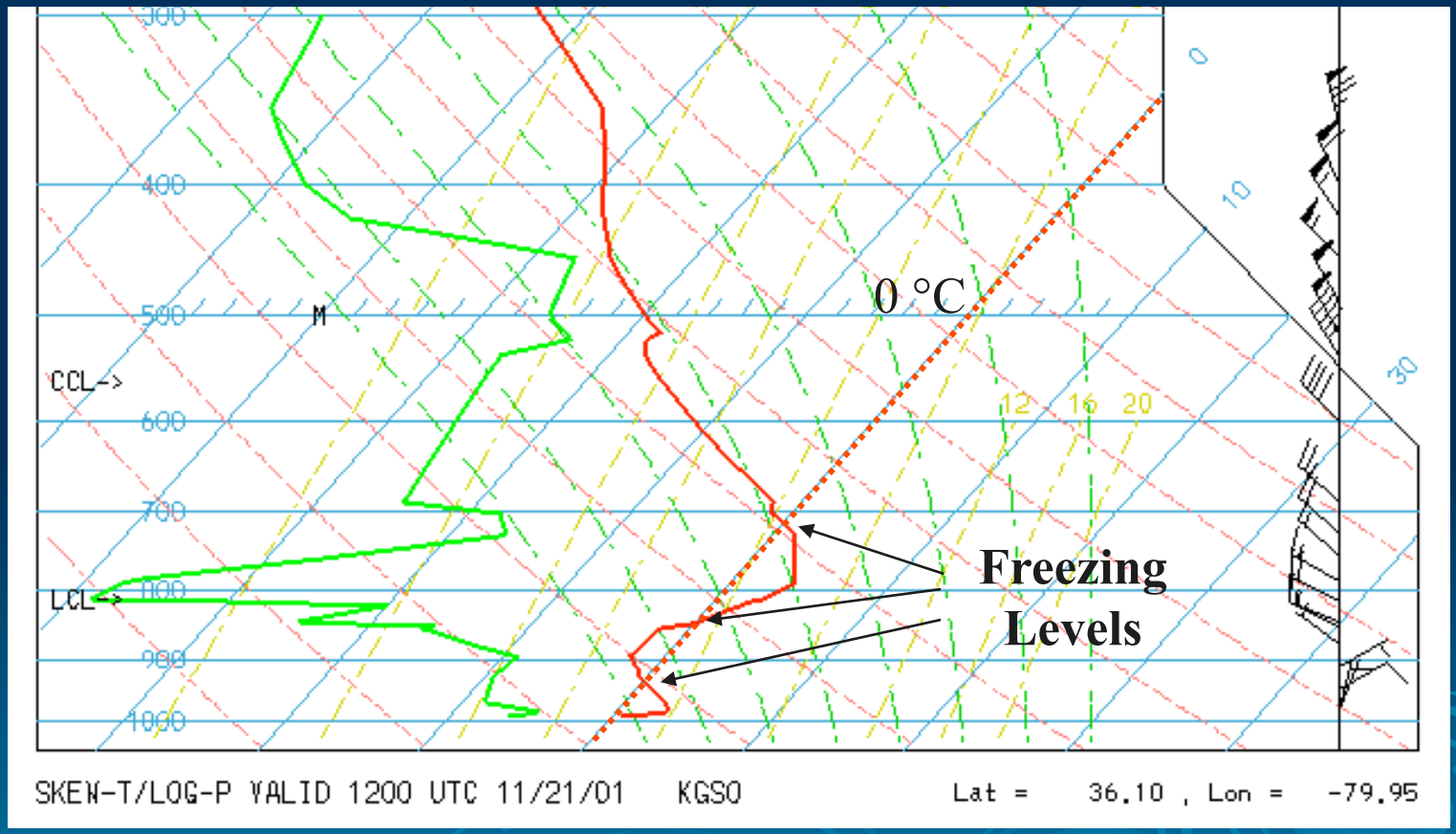
Skew-T/Log-P Diagram
Freezing Level

- Freezing level is the height at which 0 °C occurs in the atmosphere



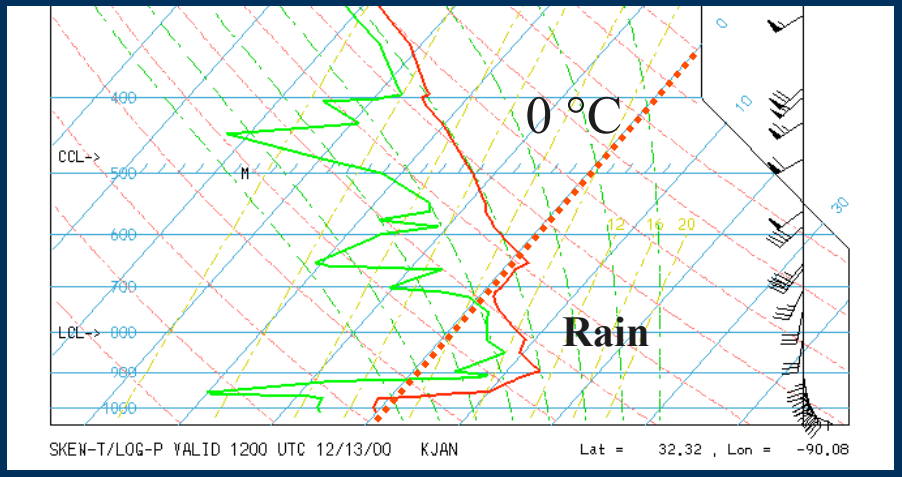
Skew-T/Log-P Diagram
Freezing Level

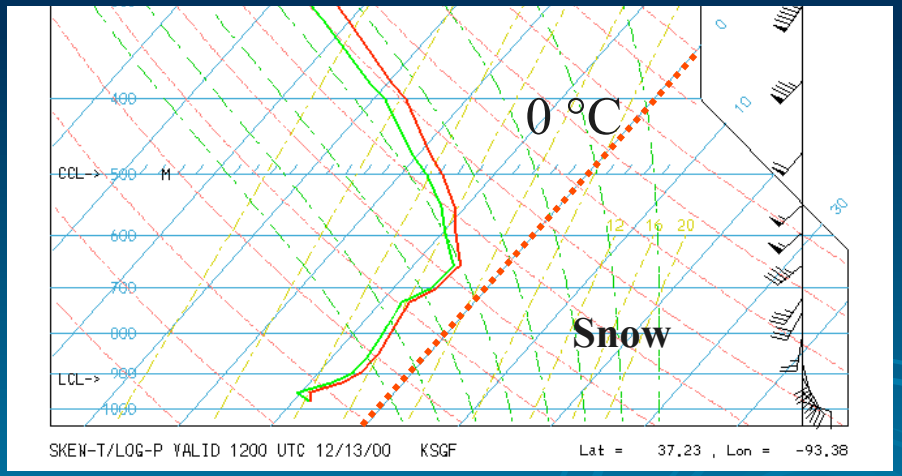
- Multiple freezing levels
- Important in forecasting type of precipitation

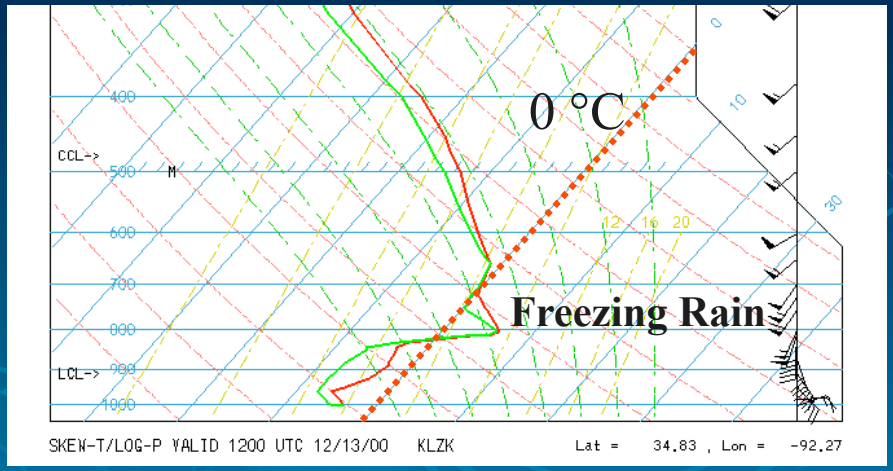


Skew-T/Log-P Diagram
Freezing Level

- Important in forecasting type of precipitation

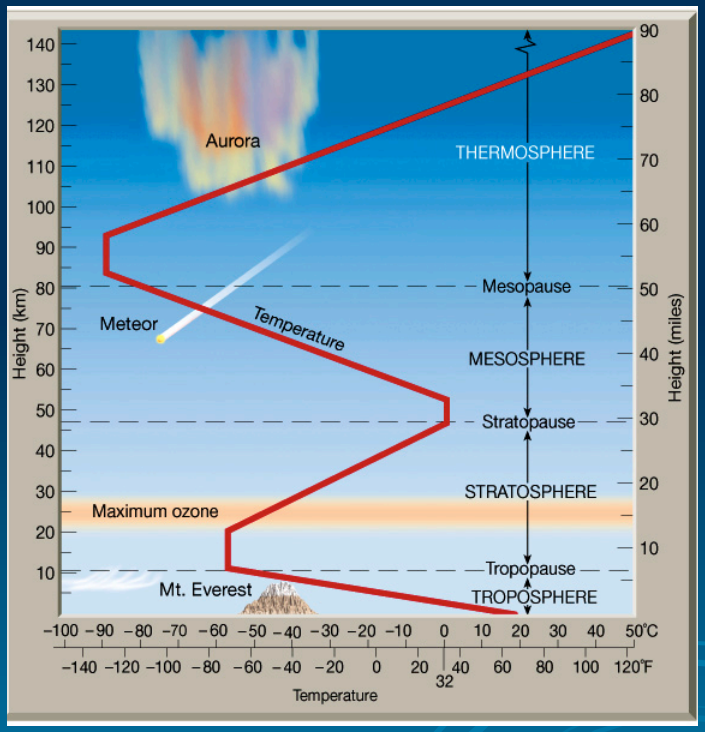


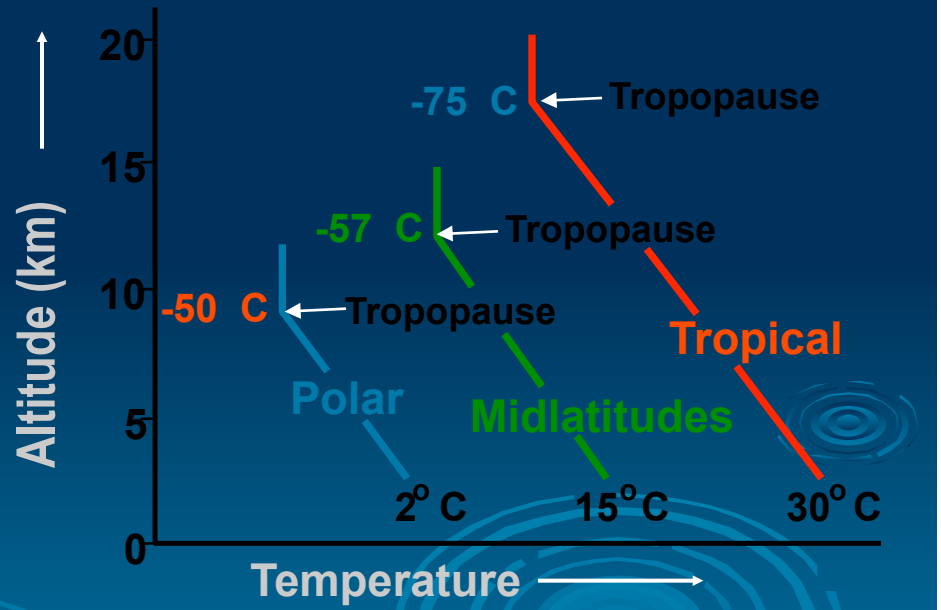




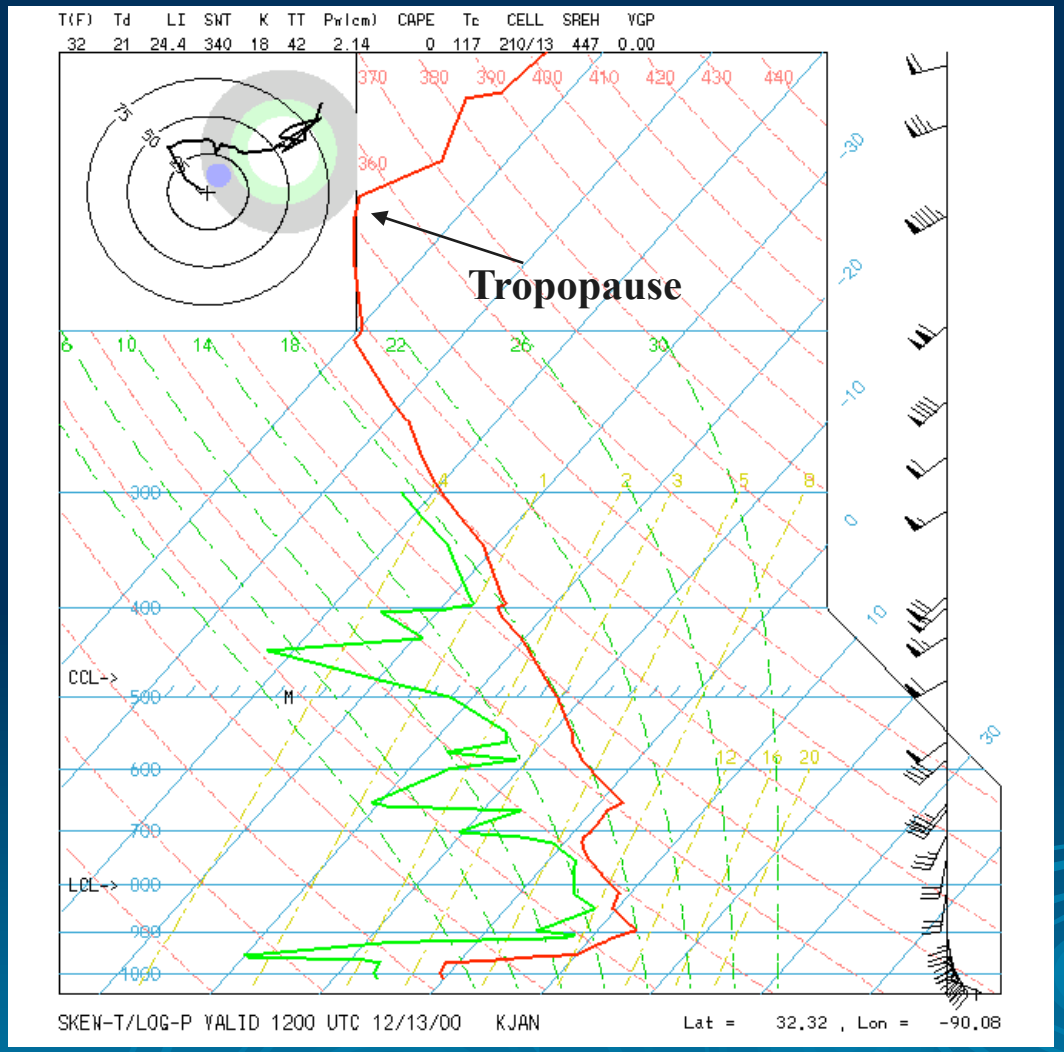
Skew-T/Log-P Diagram
Tropopause

- Top of Troposphere depends on latitude
  - Warmer at Poles
  - Colder at Equator





Skew-T/Log-P Diagram
Tropopause

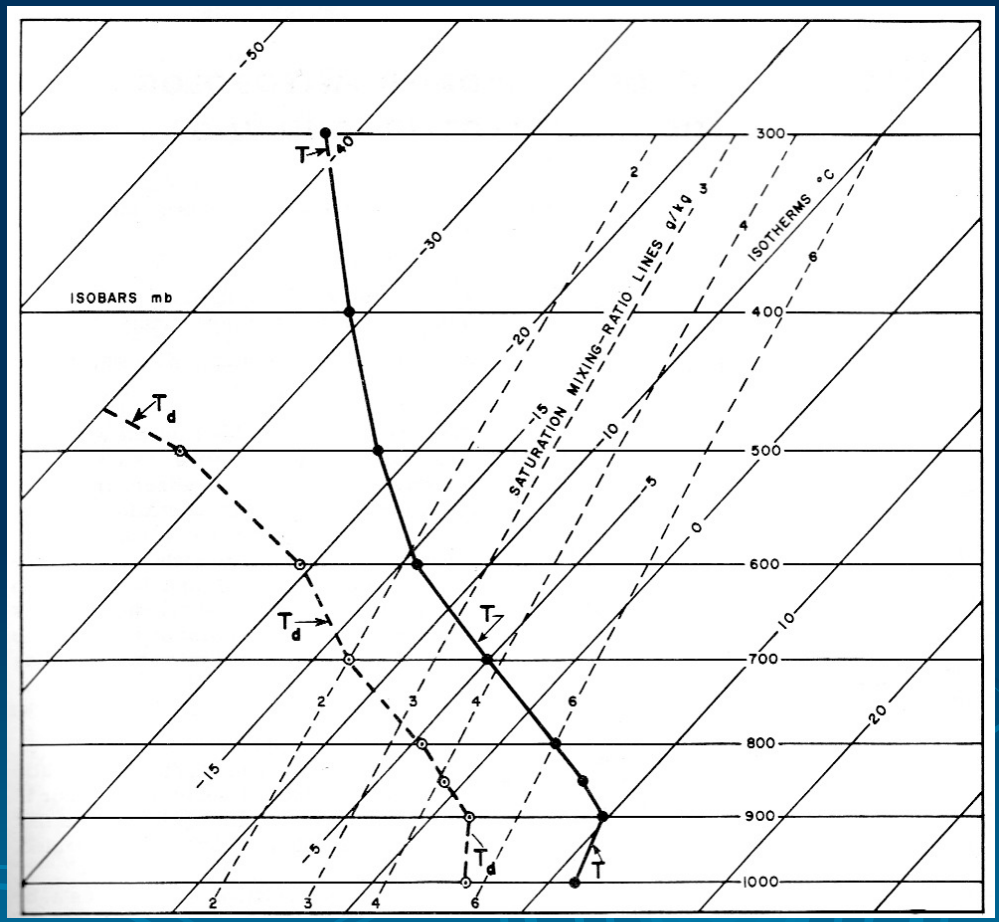


Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Mixing ratio
  - Mixing ratio (w) is the ratio of the mases of water vapor (m_v) to mass of dry air (m_d)

$$w = \frac{m_v}{m_d} \text{ (gm/kg)}$$

- Read the value, either directly or interpolation, of the saturated mixing-ratio line that crosses the T_d curve at an given pressure.
- E.g., mixing ratio of the air at the 700-mb level and -13 °C is 2 gm/kg

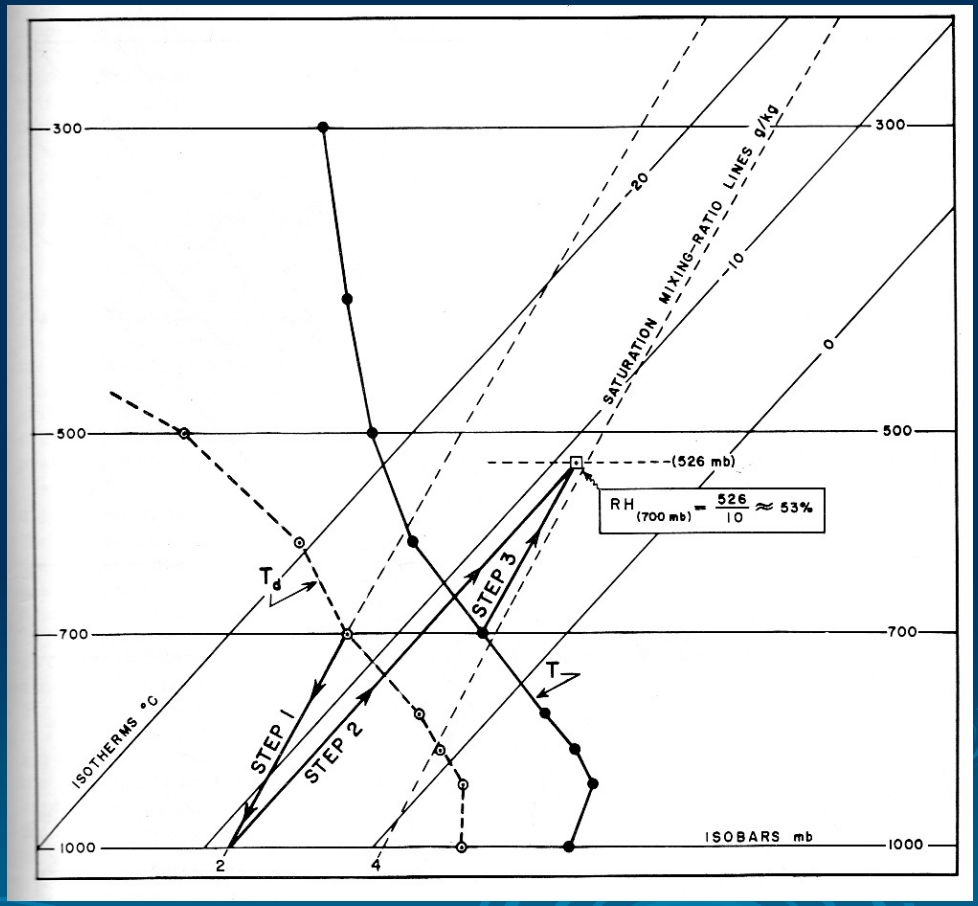


Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Relative humidity
  - Relative humidity (*RH*) is the ratio (in percent) of the amount of water vapor in a given volume of air to the amount that volume would hold if the air were saturated
- Use equation

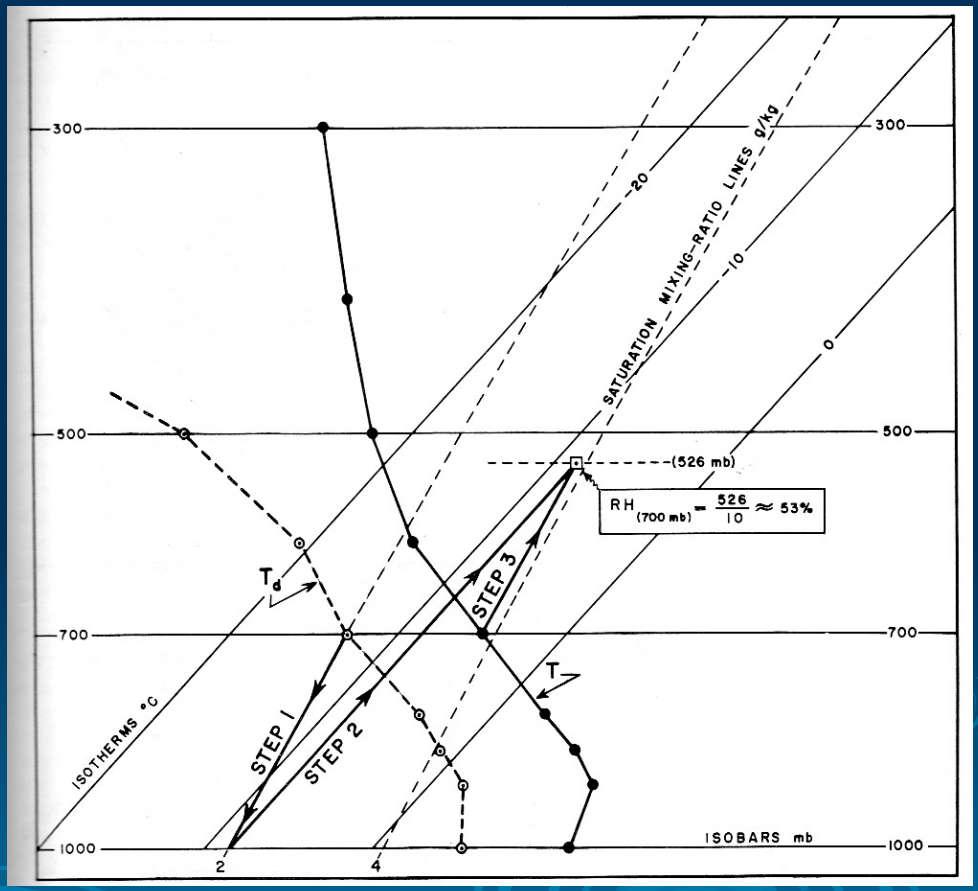
$$RH = 100 \times \left(\frac{w}{w_s} \right)$$

  - E.g., in previous example RH = 100 (2.0/3.8) = 53%



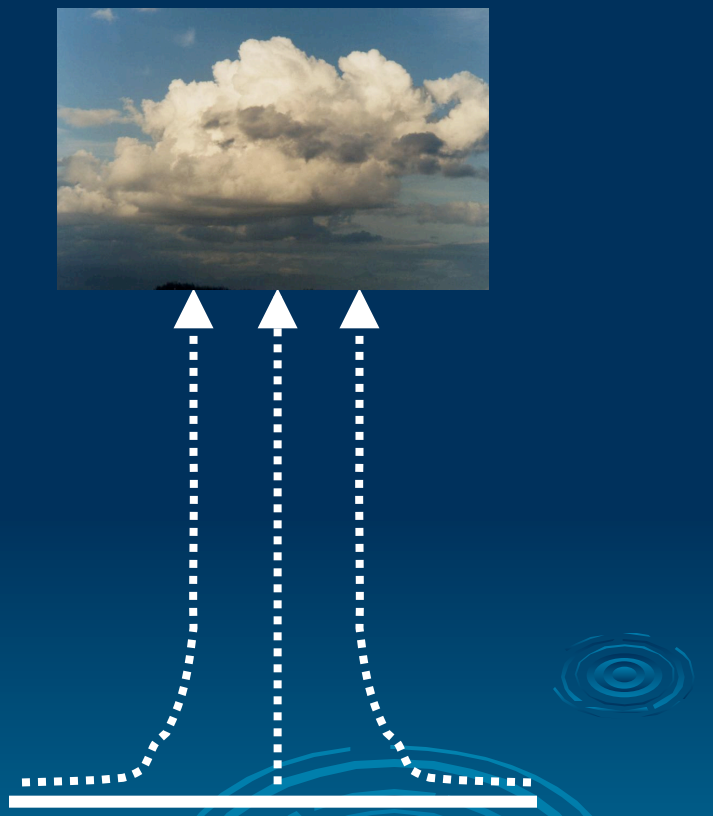
Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Relative humidity
- Alternative procedure
  - From the T_d curve at the given pressure, follow the saturation mixing-ratio line to the 1000-mb isobar
  - From this intersection, draw a line parallel to the isotherms
  - From the T curve at the given pressure, follow the saturation mixing-ratio lines to the intersection with the line drawn in Step 2
  - The numerical value of the isobar through this last intersection point is then divided by ten.



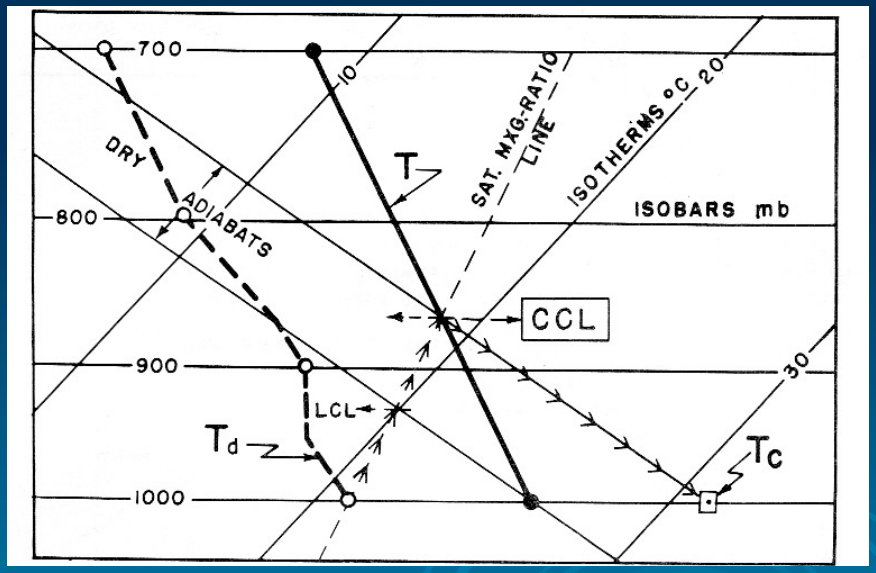
Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

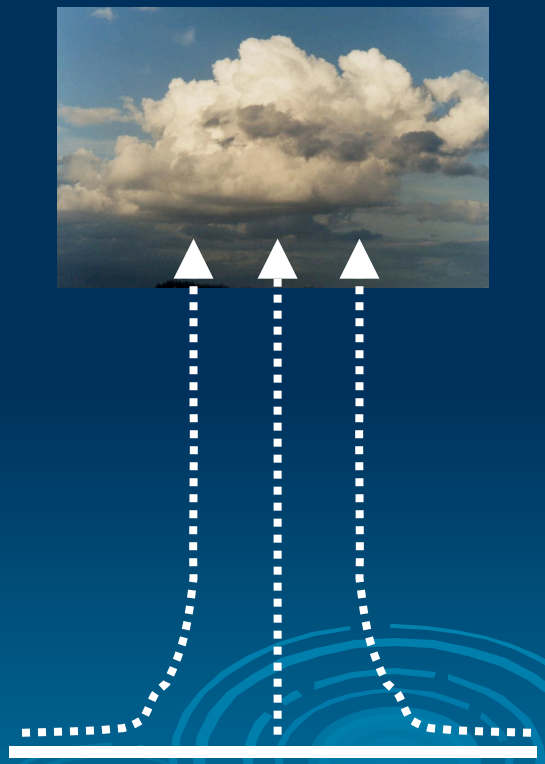
- Convective Ascent (Updraft)
  - Air becomes buoyant by contact with warm ground
  - Usually microscale or mesoscale



Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

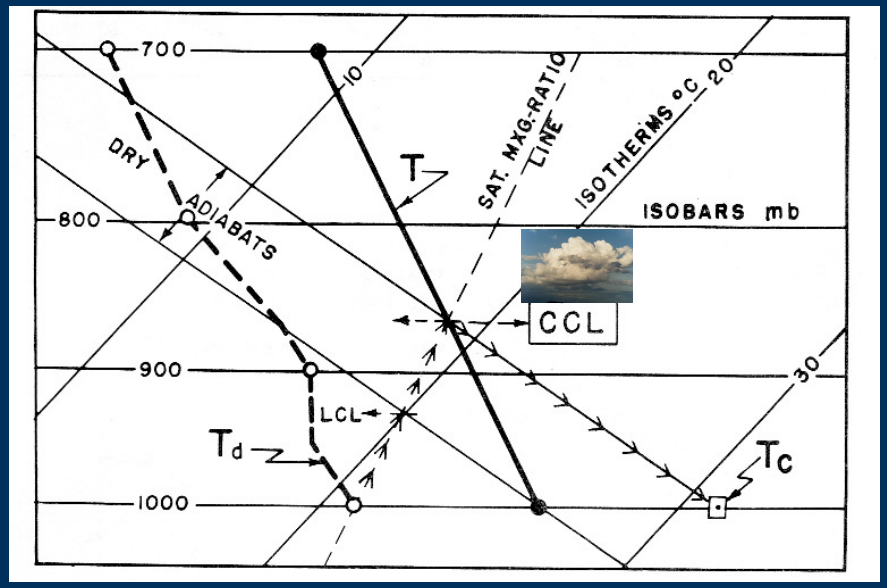
- Convection Condensation Level (CCL)
  - The CCL is the height to which a parcel of air, if heated sufficiently from below, will rise adiabatically until it is just saturated (condensation starts)

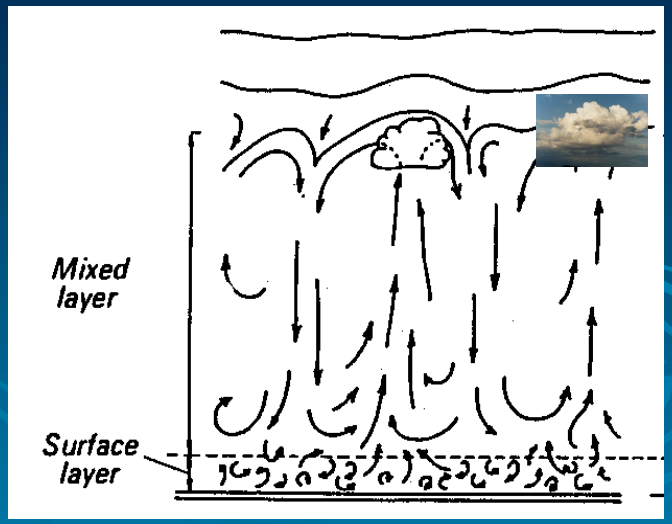




Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

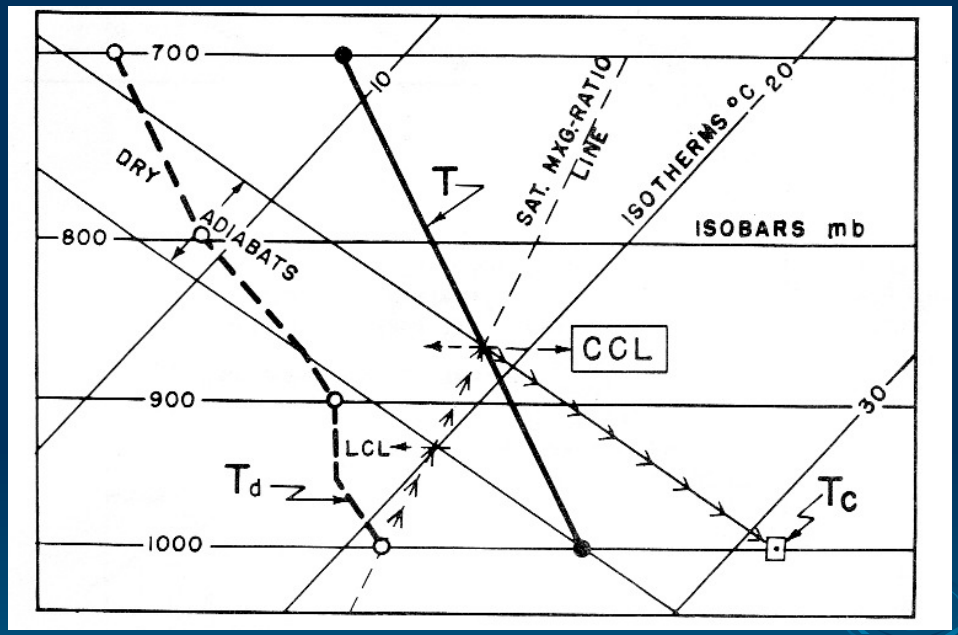
- Convection Condensation Level (CCL)
- Procedure
  - It is the height of the base of cumuliform clouds which are produced by thermal convection solely from surface heating
  - Proceed upward along the saturation mixing-ratio line through the surface dew-point temperature until this line intersects the *T* curve on the sounding





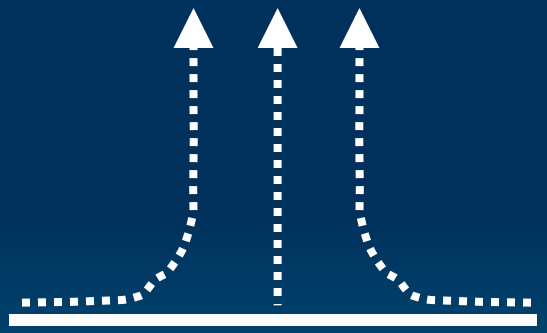
Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Convection Temperature
  - The convection temperature (T_c) is the surface temperature that must be reached to start the formation of convective clouds by solar heating of the surface layer
- Procedure
  - From the CCL point on the T curve of the sounding, proceed downward along the dry adiabat to the surface-pressure isobar.
  - The temperature read at this intersection is the convection temperature (T_c)



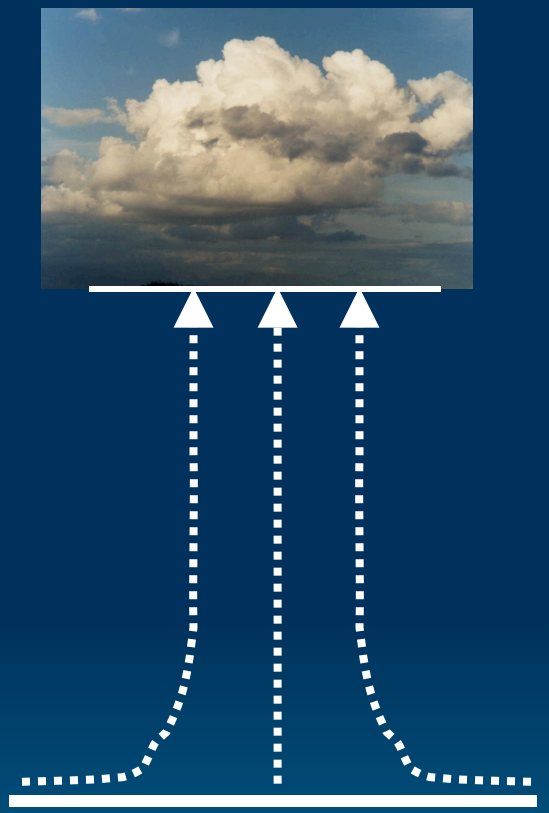
Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Convection Temperature
  - Forecasting thunderstorms (will the afternoon thunderstorms develop?)



$T<T_c$

– Thermals will form, but will not rise high enough to condense, NO THUNDERSTORMS WILL DEVELOP.



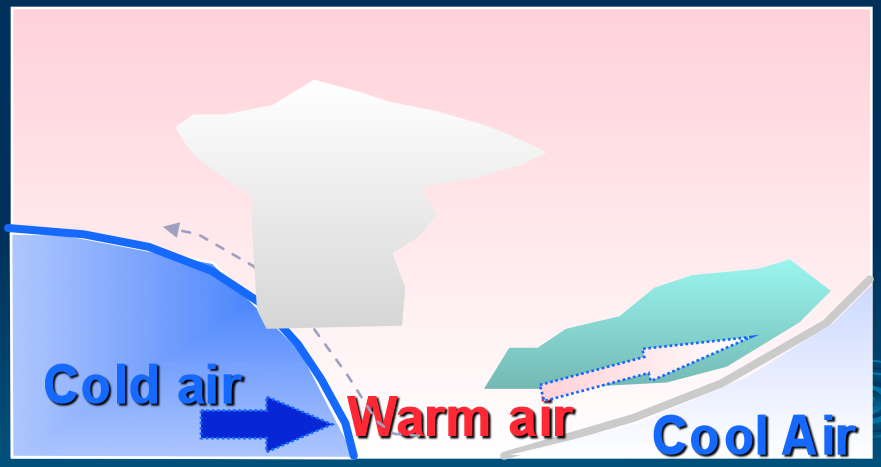
$T>T_c$

– Thermals will rise high enough to condense, YES POSSIBLY THUNDERSTORMS WILL DEVELOP.

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Mechanically Forced Ascent (Upward)
  - Some mechanism forces air aloft
  - Usually mesoscale - synoptic scale features





Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

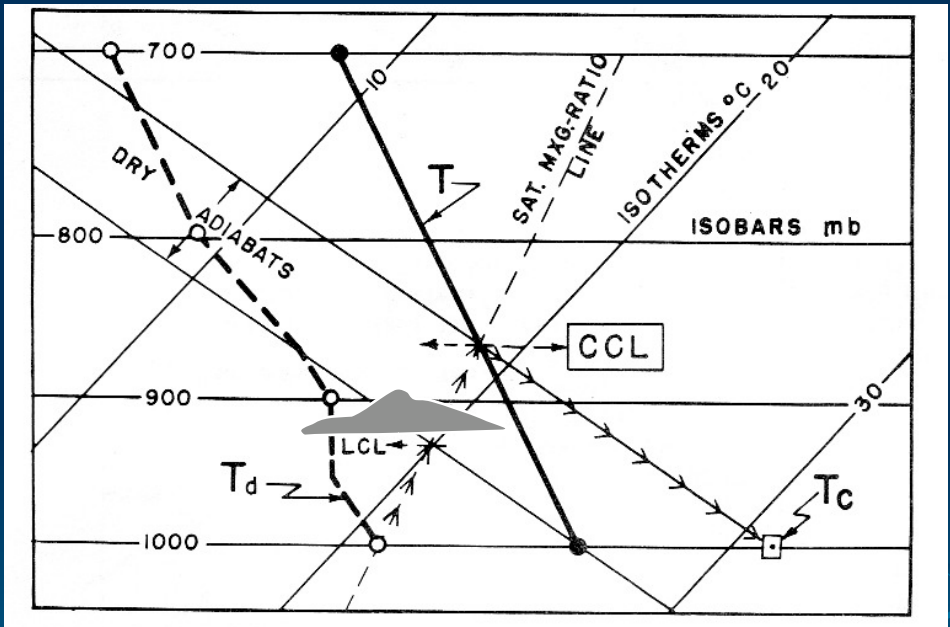
- Mechanically Forced Ascent (Upward)
  - Type of clouds depends on stability
  - Lifting Condensation Level (LCL)
  - Level of Free Convection (LFC)
  - Equilibrium Level (EL)


Stable – Stratus


Unstable - Cumulus

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Lifting Condensation Level (LCL)
  - The LCL is the height at which a parcel of air becomes saturated when it is lifted dry adiabatically
  - The LCL for a surface parcel is always found at or below the CCL
- Procedure
  - The LCL is located at the intersection of the saturation mixing-ratio line through the surface dew point temperature with the dry adiabat through the surface temperature

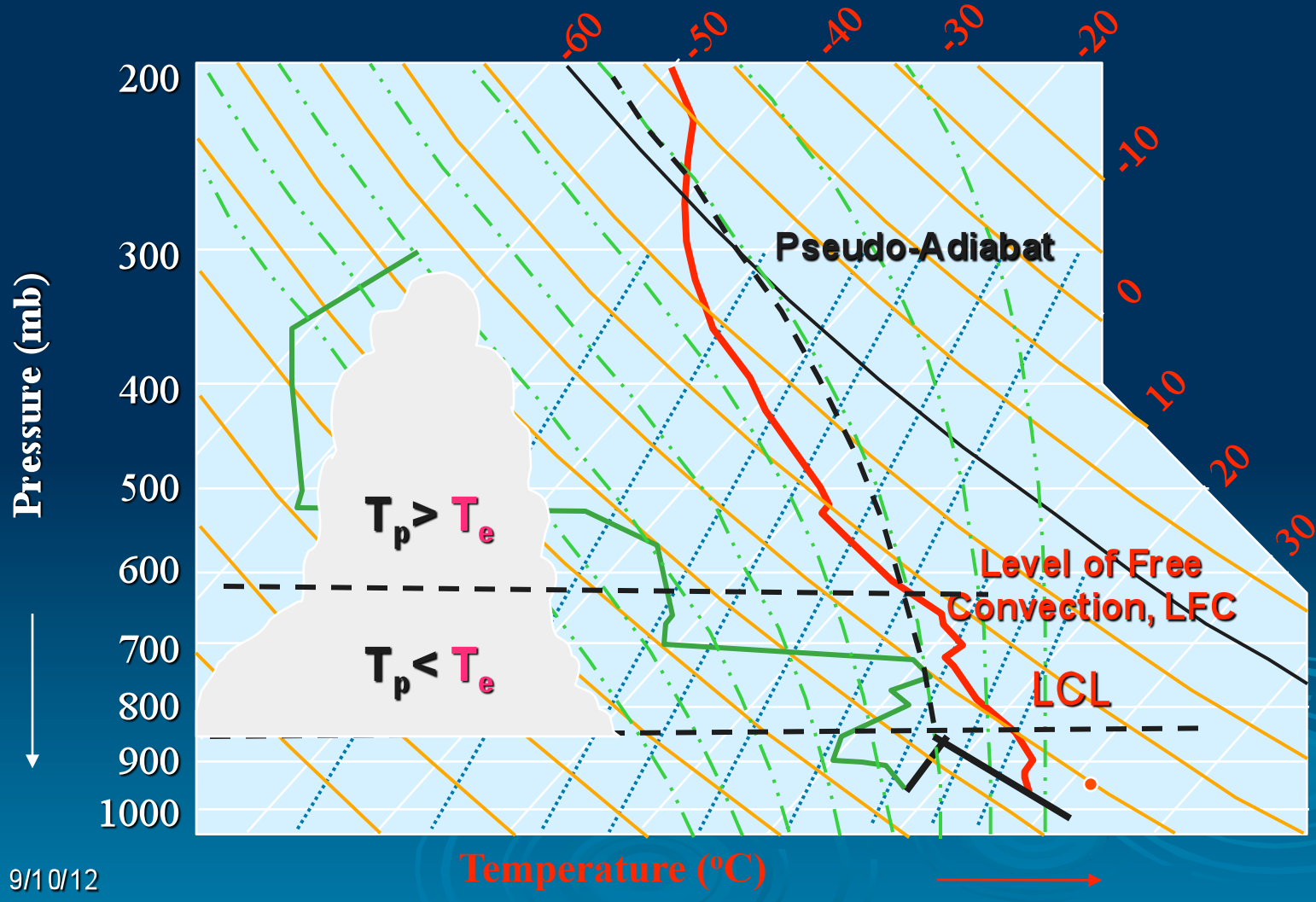


Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Level of Free Convection (LFC)
  - The height at which a parcel of air lifted dry adiabatically until saturated and pseudoadiabatically thereafter would first become warmer (less dense) that the surrounding air
  - The parcel will then continue to rise freely above this level until it becomes colder (more dense) than the surrounding air.

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Level of Free Convection (LFC)

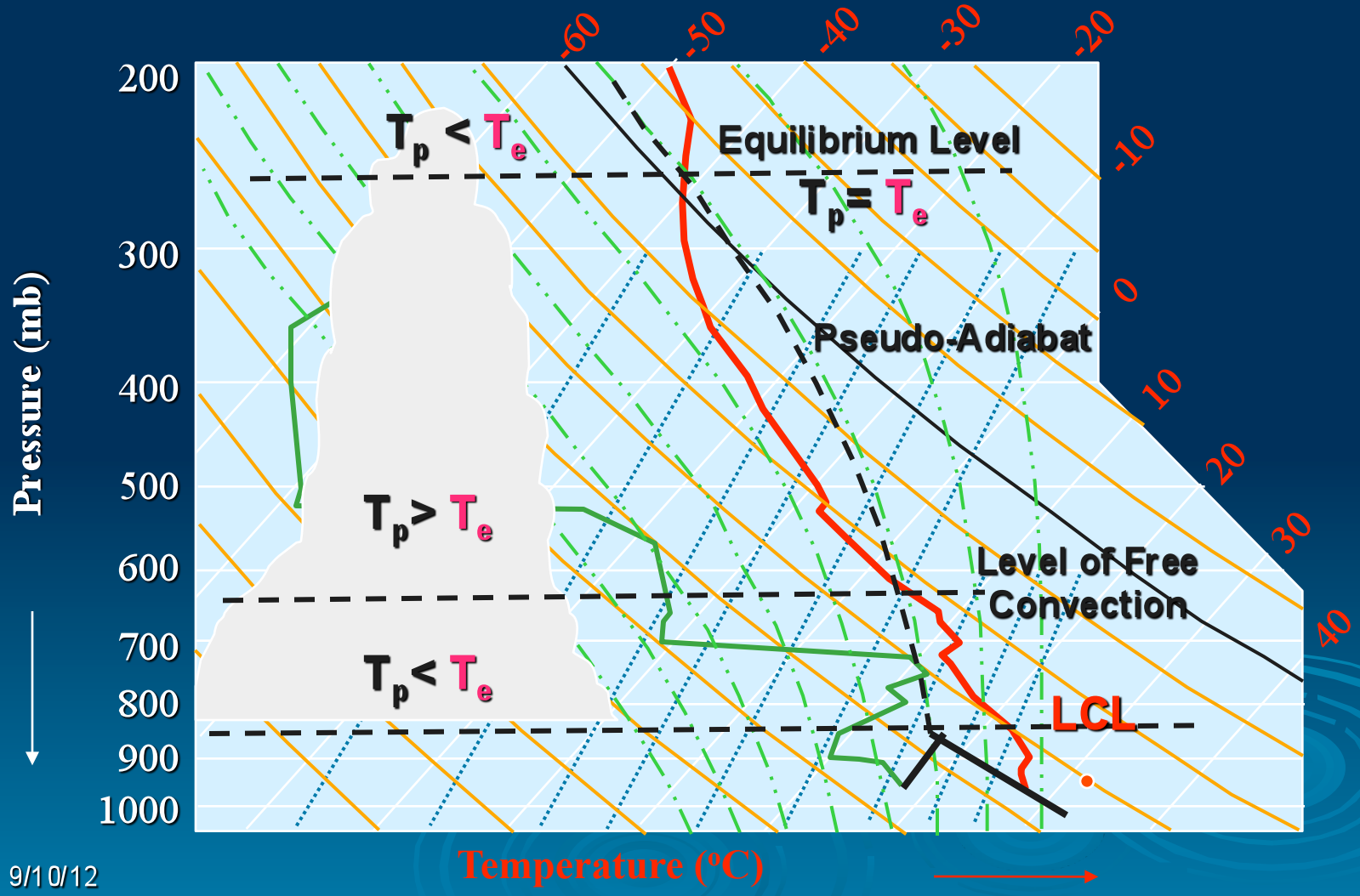


Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Equilibrium Level (EL)
  - The height where the temperature of a buoyantly rising parcel again becomes equal to the temperature of the environment

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Equilibrium Level (EL)



Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Stability Indices
  - Based on "parcel" method, single number that characterizes the stability (or instability of the atmosphere
  - Indices must be used with other forecasting methods
  - Disadvantage
    - Details of atmospheric profile may be ignored
  - Advantages
    - Ease of computation
    - Easily used in forecasting

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Lifted Index (LI)
  - Temperature difference between
    - The environmental air at 500 mb and the temperature of an air parcel at 500 mb
      - first lifted dry adiabatically until saturated and then pseudoadiabatically from that level upward

$$LI = T_{500_e} - T_{500_p}$$

LI only provides information about the possible stability/instability of a parcel that is lifted to 500 mb.

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

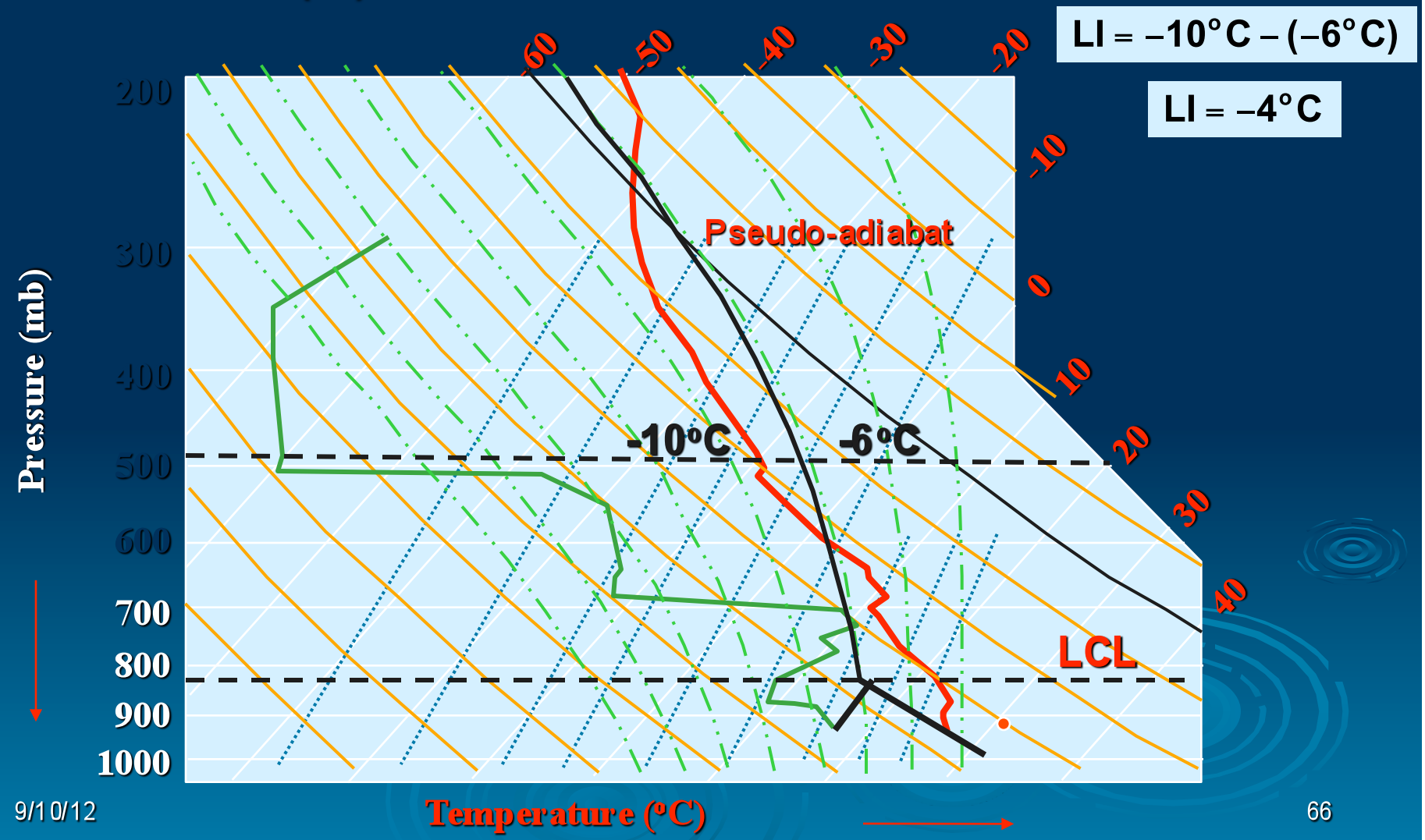
- Lifted Index (LI)
  - Positive – Stable
  - Negative – Unstable

$$LI = T_{500_e} - T_{500_p}$$

  - 0 to -2 Thunderstorms possible
  - -3 to -5 Unstable – Thunderstorms Probably
  - Less than -5 Very unstable – Heavy to strong thunderstorm potential

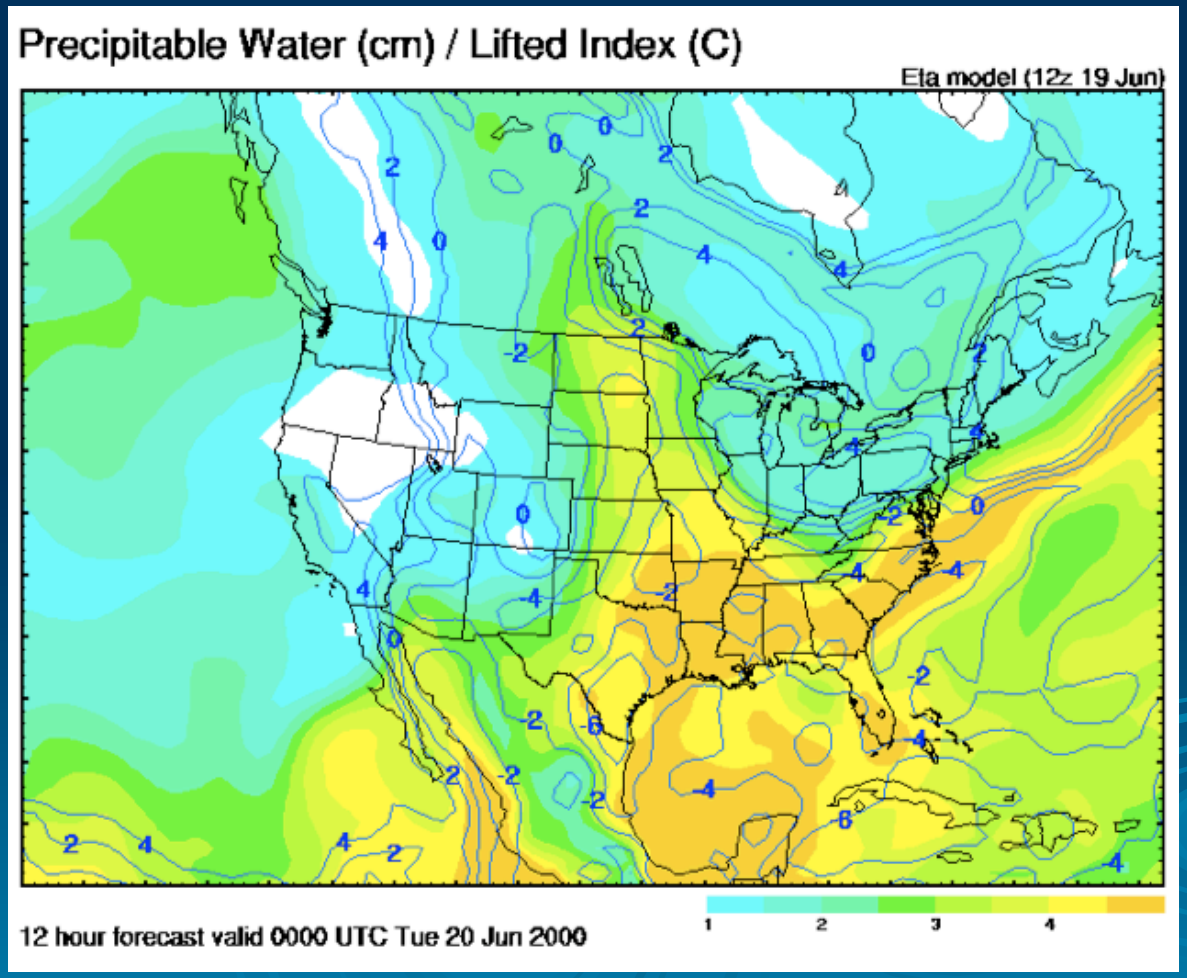
Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Lifted Index (LI)



Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- Lifted Index (LI)



Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- K Index (KI)
- Measure of thunderstorm potential based on
  - Vertical temperature lapse rate
  - Moisture content of the lower atmosphere
  - Vertical extent of the moist layer
- Does not require a plotted sounding
- Biased towards ‘air mass’ type thunderstorms
- Works best for non-severe thunderstorms
- K only provides information about the environment at 850, 700 and 500 mb.

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

K Index (KI)

$$KI = (T_{850} - T_{500}) + T_{d850} - (T - T_d)_{700}$$

Vertical Temperature Lapse Rate	Moisture Content of Lower Atmosphere	Vertical Extent of Moist Layer

T_{850} = 850 mb Temperature

T_{500} = 500 mb Temperature

T_{d850} = 850 mb Dew Point Temperature

$(T\text{-}T_d)_{700}$ = 700 mb Dew Point Depression

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

K Index (KI)

Index	Probability of Thunderstorms
K < 15	0%
15 to 20	20%
21 to 25	20 – 40%
26 to 30	40 – 60%
31 to 35	60 – 80%
36 to 40	80 – 90%
K > 40	Near 100%

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

Total Totals (TT)

- Used in identifying areas of potential thunderstorm development
- Sum of two other indices
  - Vertical Totals (VT)
  - Cross Totals (CT)

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

Vertical Totals (VT)

$$VT = (T_{850} - T_{500})$$

T_{850} = 850 mb Temperature

T_{500} = 500 mb Temperature

- Lapse rate between 850 & 500 mb
- VT > 26 for thunderstorm development
- Good for air mass thunderstorms
- Requires evaluation of moisture

28	Isolated Thunderstorms
29 to 32	Few Thunderstorms
32	Scattered Thunderstorm

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

Cross Totals (CT)

$$CT = (T_{d850} - T_{500})$$

T_{d850} = 850 mb Dew Point Temperature

T_{500} = 500 mb Temperature

- Indicators of thunderstorm development
  - High low level moisture
  - Cold temperatures aloft
- CT > 18 for thunderstorm development

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

Total Totals (TT)

$$TT = VT + CT$$

Total Totals	Vertical Totals	Cross Totals

$$TT = (T_{850} + T_{d850}) - 2T_{500}$$

T_{850} = 850 mb Temperature

T_{500} = 500 mb Temperature

T_{d850} = 850 mb Dew Point Temperature

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

Total Totals (TT)

- More reliable predictor of severe thunderstorm activity

< 44	No Thunderstorm Activity
45 - 50	Weak Potential for Heavy Thunderstorms
50 - 55	Moderate Potential for Heavy Thunderstorms
> 55	Strong Potential for Heavy Thunderstorms

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

Convective Available Potential Energy (CAPE)

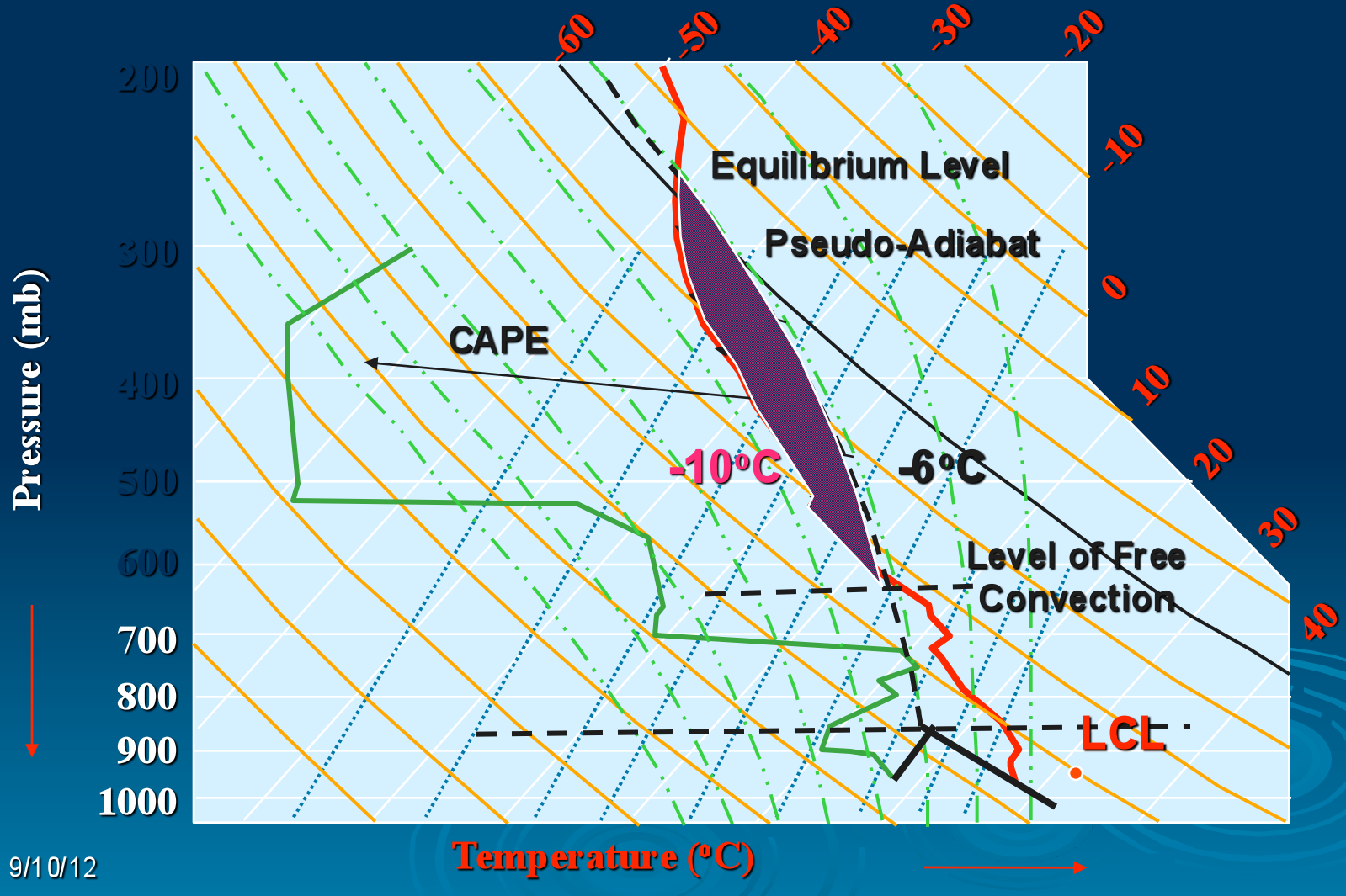
- Buoyantly energy, CAPE is measure of the amount of energy available for convection
- The area (above the LFC) between the environmental sounding and the pseudoadiabat

$$CAPE = \int_{z_{LFC}}^{z_{EL}} g\left(\frac{T_p - T_e}{T_e}\right) dz$$

(courtesy F. Remer)

Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

- CAPE

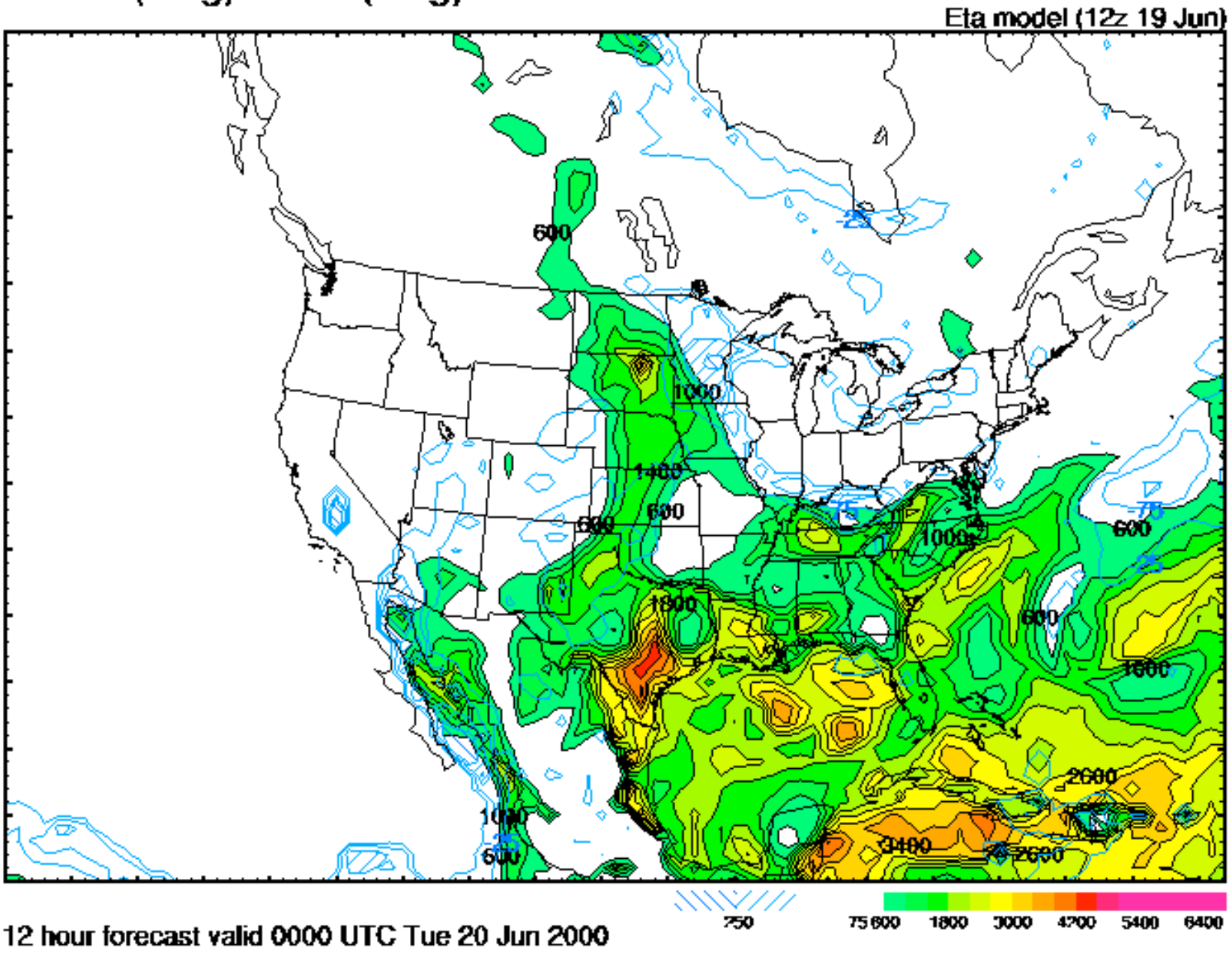


Skew-T/Log-P Diagram
Determination of Unreported Meteorological Quantities

Convective Available Potential Energy (CAPE)

- Unlikely Development of Strong Convection
  - <1000 J kg^{-1}
- Strong or Severe Thunderstorms
  - 2000 J kg^{-1}

CAPE (J/kg) / CIN (J/kg)



12 hour forecast valid 0000 UTC Tue 20 Jun 2000