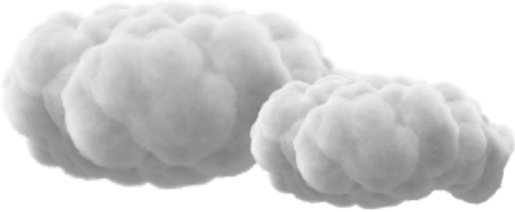
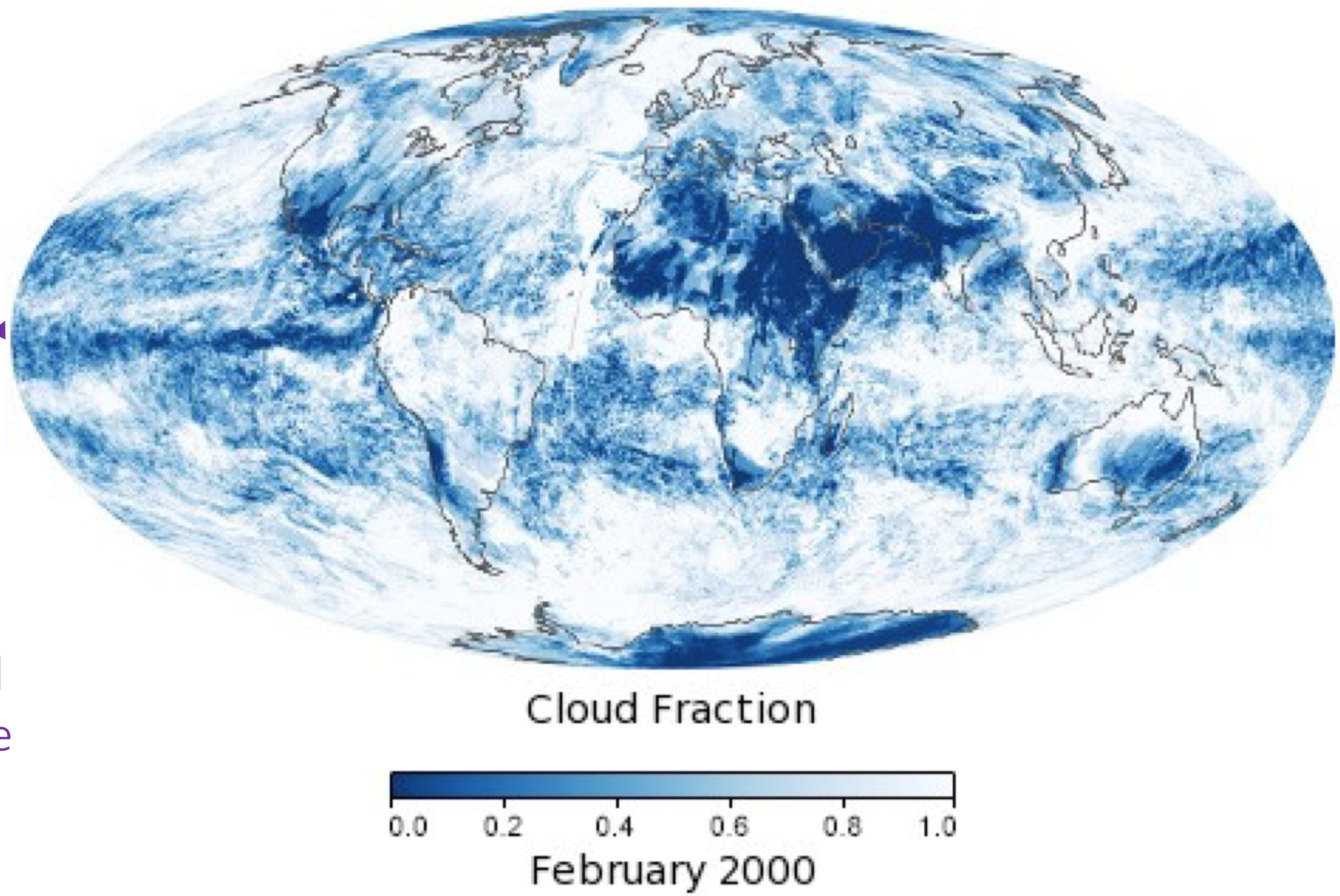
Lecture 5



Clouds

*"visible aggregation of very small water droplets, or ice crystals, in air, which forms when water vapour **condenses** in the atmosphere due to **adiabatic cooling**."*

Cloud fraction



intertropical convergence zone

NASA Terra satellite observations of what fraction of an area was cloudy on average each month. Blue indicates no clouds, while white is totally cloudy.

https://earthobservatory.nasa.gov/global-maps/MODAL2_M_CLD_FR

Cloud types

Cumulus

Cumulo means 'heap'

Many varieties! Generally form in unstable air.

Stratus

Strato means 'layer'

Low-lying blanket.
Fog-like: if any precipitation it's a misty drizzle.

Cirrus

Cirro means 'curl of hair'

Made of ice crystals.
Highest levels of the troposphere.
Advance of frontal systems so indicate weather about to change.

Cloud types

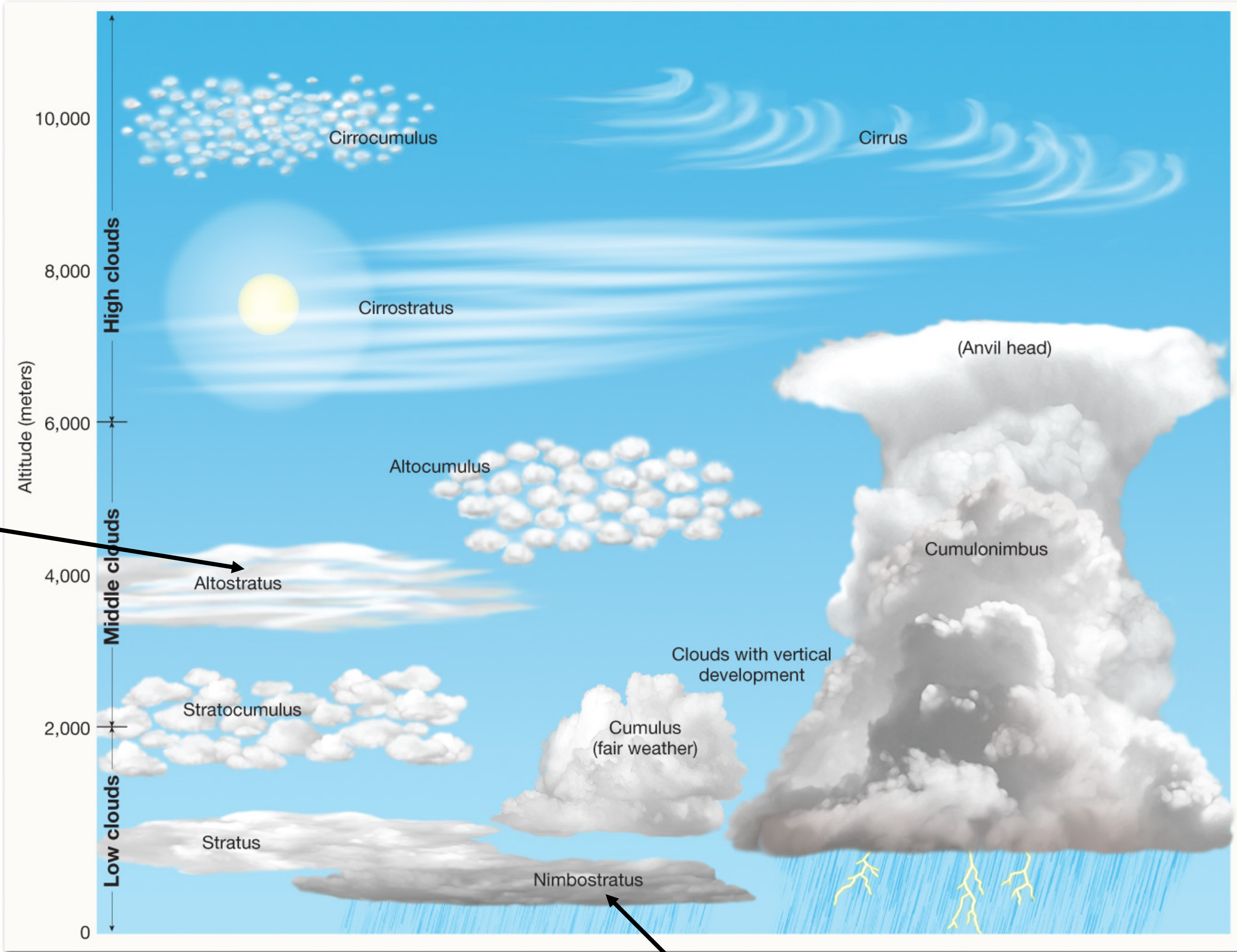
TABLE 5-1 Basic Cloud Types

Cloud Family and Height	Cloud Type	Characteristics
High clouds—above 6000 m (20,000 ft)	Cirrus (Ci)	Thin, delicate, fibrous, ice-crystal clouds. Sometimes appear as hooked filaments called "mares' tails" or cirrus uncinus (Figure 5-3a).
	Cirrostratus (Cs)	Thin sheet of white, ice-crystal clouds that may give the sky a milky look. Sometimes produce halos around the Sun and Moon (Figure 5-3b).
	Cirrocumulus (Cc)	Thin, white, ice-crystal clouds. In the form of ripples or waves, or globular masses all in a row. May produce a "mackerel sky." Least common of high clouds (Figure 5-3c).
Middle clouds—2000–6000 m (6500–20,000 ft)	Altocumulus (Ac)	White to gray clouds, often made up of separate globules; "sheepback" clouds (Figure 5-4a).
	Altostratus (As)	Stratified veil of clouds that is generally thin and may produce very light precipitation. When thin, the Sun or Moon may be visible as a "bright spot," but no halos are produced (Figure 5-4b).
Low clouds—below 2000 m (6500 ft)	Stratus (St)	Low uniform layer resembling fog but not resting on the ground. May produce drizzle.
	Stratocumulus (Sc)	Soft, gray clouds in globular patches or rolls. Rolls may join together to make a continuous cloud.
	Nimbostratus (Ns)	Amorphous layer of dark gray clouds. One of the primary precipitation-producing clouds (Figure 5-5).
Clouds of vertical development	Cumulus (Cu)	Dense, billowy clouds often characterized by flat bases. May occur as isolated clouds or closely packed (Figure 5-6).
	Cumulonimbus (Cb)	Towering cloud, sometimes spreading out on top to form an "anvil head." Associated with heavy rainfall, thunder, lightning, hail, and tornadoes (Figure 5-7).

© 2013 Pearson Education, Inc.

Cloud types

alto
- middle

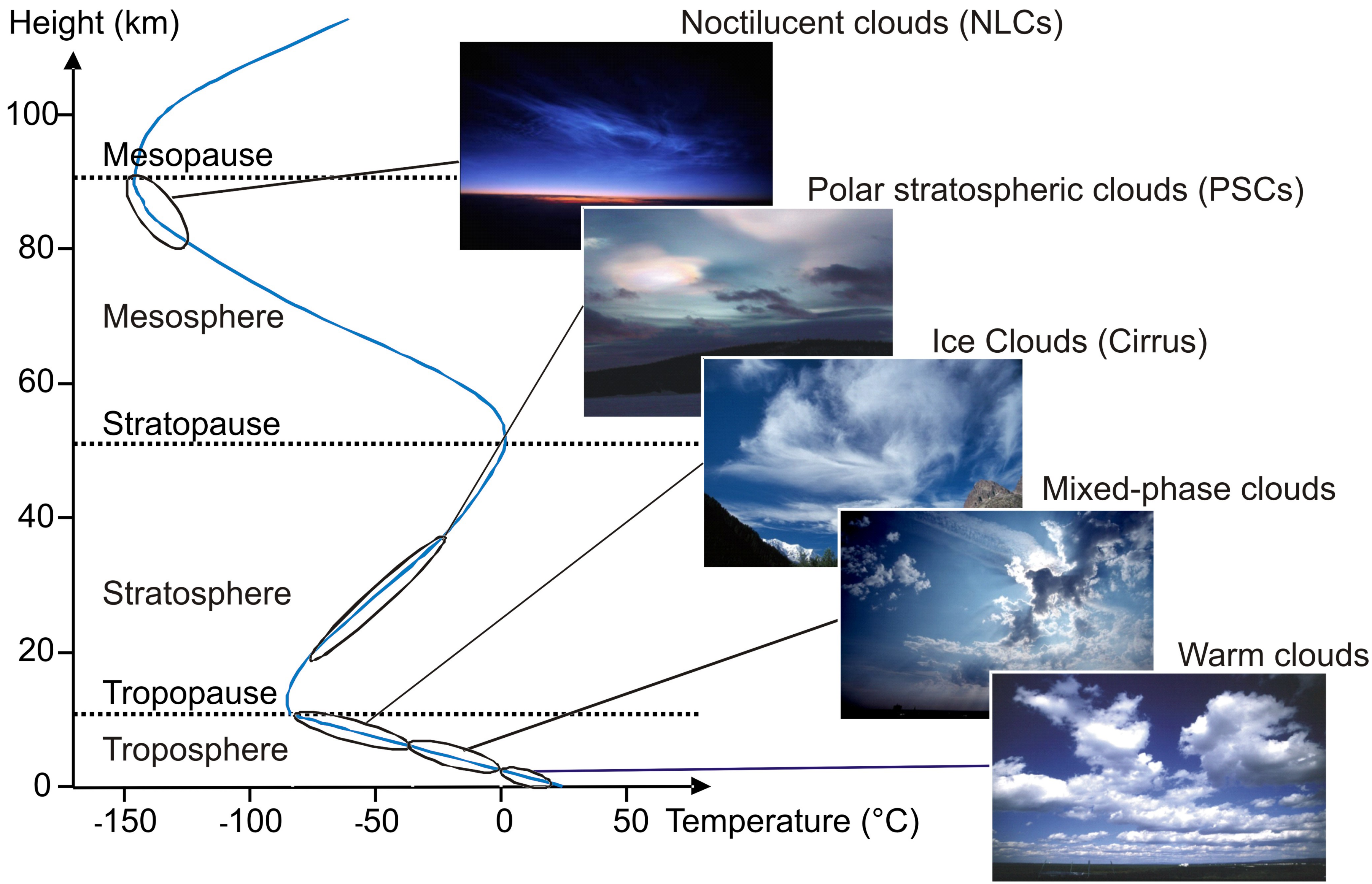


© 2013 Pearson Education, Inc.

nimbus - precipitation

Higher up

Altitude of cloud tells us how much it warms the planet



Ice clouds

- The situation for freezing is similar to that for condensation, and **homogeneous condensation** is only realistic below a certain threshold temperature (≈ -36°C). **Heterogeneous condensation** can occur at much higher temperatures if an appropriate freezing nucleus is available.

- As water saturation pressure is lower over ice than over water, ice particles will grow at the expense of super-cooled water droplets (**Findeisen Effect**).

TABLE 5-2 Relative Humidity with Respect to Ice When Relative Humidity with Respect to Water Is 100 Percent

Temperature (°C)	Relative Humidity with Respect To: Water	Ice
0	100%	100%
–5	100%	105%
–10	100%	110%
–15	100%	115%
–20	100%	121%

© 2013 Pearson Education, Inc.

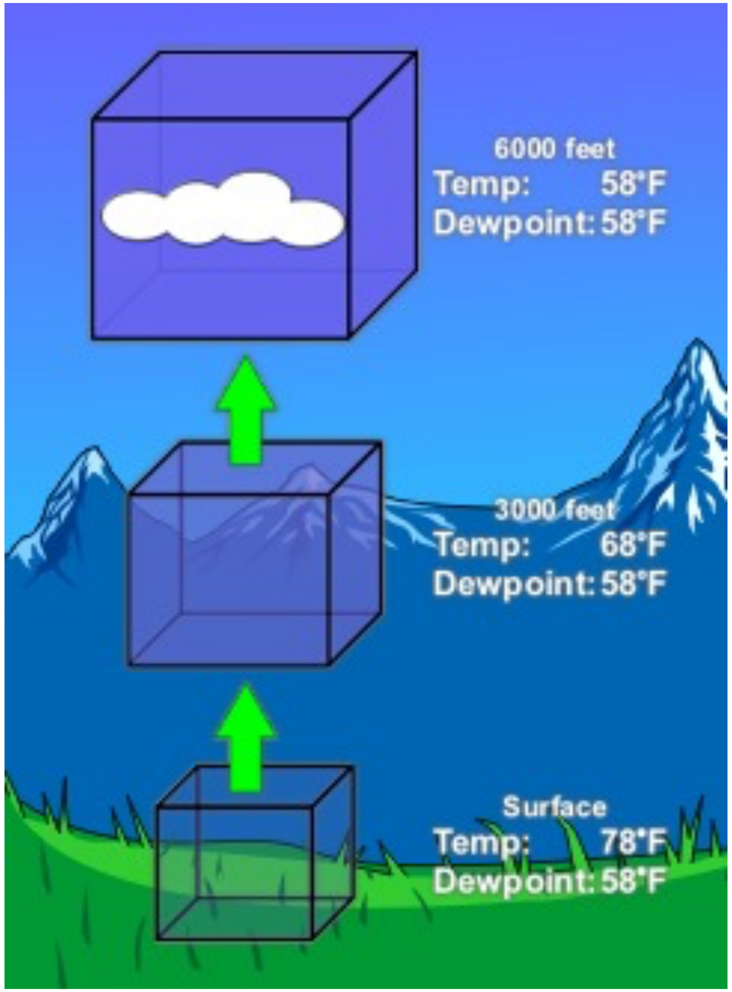
Adiabatic cooling and cloud formation

- Heat exchange can take place between the Earth surface and air near the surface. As the ground loses heat by radiation after sunset, dew may form in the grass and fog may form in the air near the ground.

- However, clouds can form in the hottest part of the day and far above ground level. →Need another cooling mechanism to form clouds!

- Clouds are formed via adiabatic cooling when an air parcel rises.

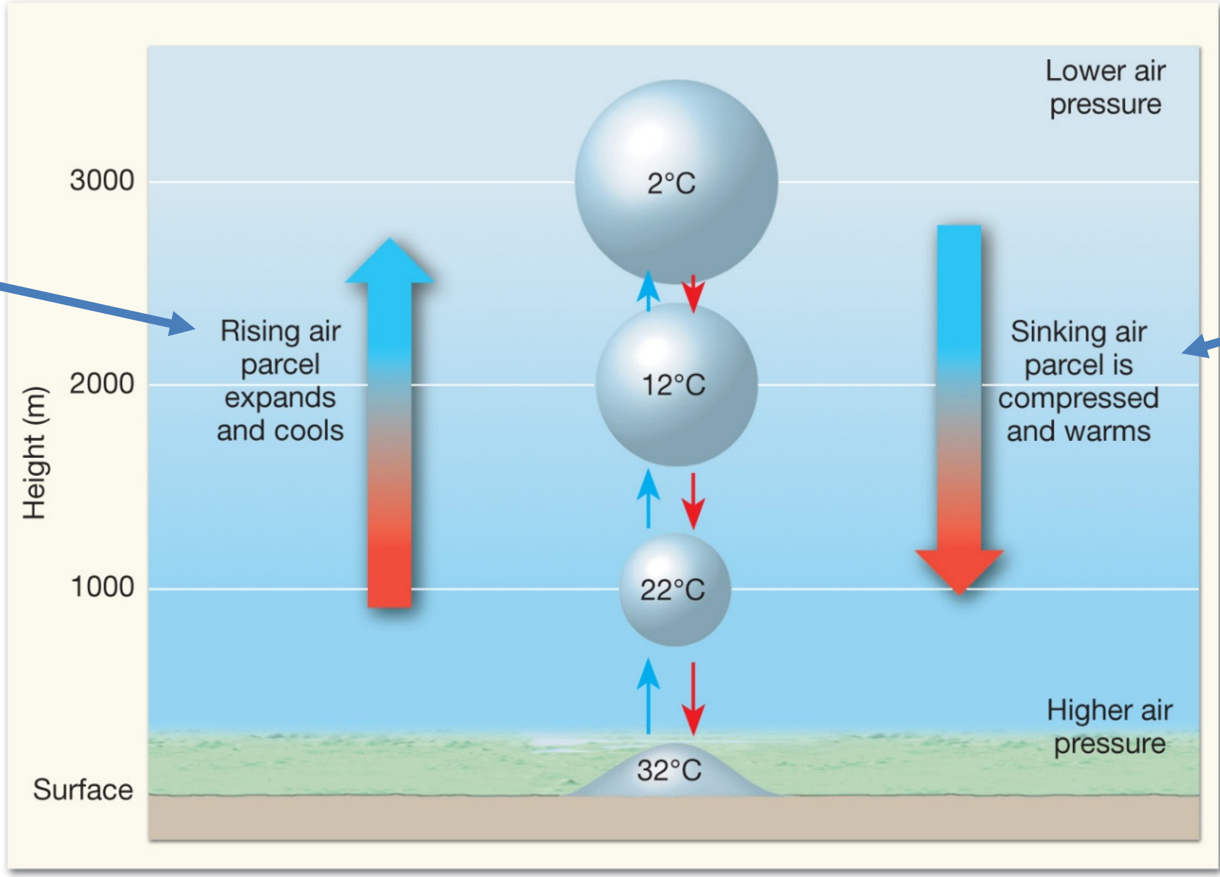
- Air parcel: large volume of air (several hundred cubic meter) which is at the same pressure as the surrounding air but without mixing or heat transfer.



Adiabatic cooling and cloud formation

adiabatic cooling

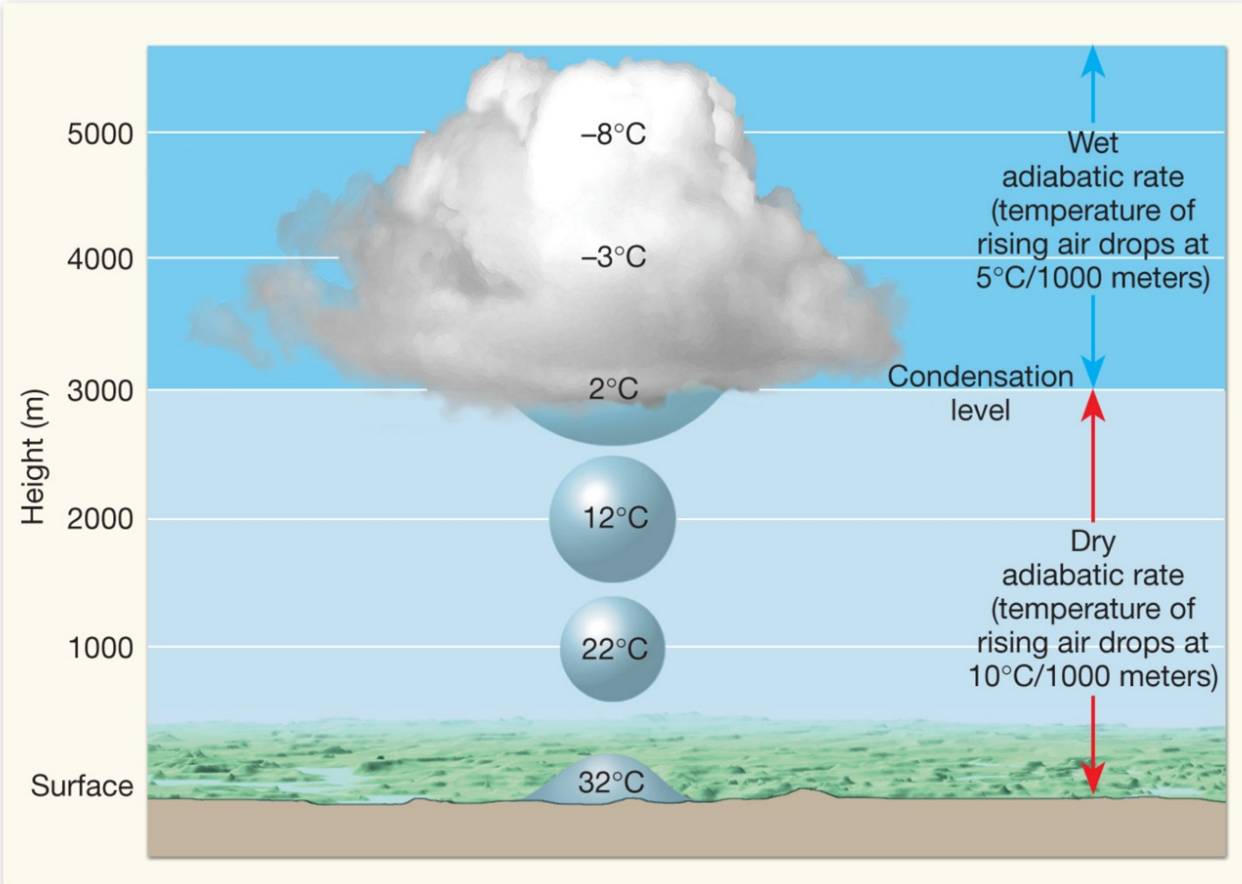
adiabatic warming



© 2013 Pearson Education, Inc.

- As an air parcel move upwards it moves through regions of decreasing pressure, expands adiabatically and cools.
- While the air remains unsaturated it cools at a rate of 10°C per 1000 m – this is called the **dry adiabatic rate**.
- Conversely the temperature of descending air will rise at the same rate.

Adiabatic cooling and cloud formation



© 2013 Pearson Education, Inc.

- A parcel of air may rise high enough so it is cooled to the dew point temperature. The altitude where saturation is reached is called the **lifting condensation level**.
- If the air parcel continues to rise above the condensation level latent heat will be released as water vapour condenses. The cooling rate is reduced, giving the **wet adiabatic rate**. The amount of latent heat released depends on the moisture content, thus the wet adiabatic rate varies between 5°C and 9°C per 1000 m.

Calculating the adiabatic rate

Start by assuming that when air parcel moves vertically there is no heat exchange with surroundings – adiabatic process.

Use first law: $\Delta U = Q - W$

For an incremental change: $dU = dQ - dW$

But $dU = C_V\, dT$, $dQ = 0$ and $dW = P\, dV$

Thus, $$C_V\, dT = -P\, dV$$

---- Equation 1

The ideal gas law for 1 mole (i.e., n=1): $PV = RT$

Differentiate: $V\, dP + P\, dV = R\, dT$

Substitute for PdV from Equation 1:

$$C_V\, dT = V\, dP - R\, dT$$

$$(C_V + R) dT = V\, dP$$

$$C_P\, dT = V\, dP = RT\, \frac{dP}{P}$$

$$\frac{dT}{T} = \frac{R\, dP}{C_P\, P}$$

---- Equation 2

Calculating the adiabatic rate

When deriving the hydrostatic equation in Lecture 2 we had:

$$dP = -P\frac{Mg}{RT}dz \quad \text{or} \quad \frac{dP}{P} = -\frac{Mg}{RT}dz$$

--- Equation 3

For an adiabatic process (Equation 2): $\frac{dT}{T} = \frac{R\,dP}{C_P P}$ or $\frac{dP}{P} = \frac{C_P}{RT}dT$

Substitute for $\frac{dP}{P}$ in Equation 3: $\frac{C_P}{RT}dT = -\frac{Mg}{RT}dz$

Then the **dry adiabatic rate** is: $\boxed{\Gamma_d = \frac{dT}{dz} = -\frac{Mg}{C_P}}$

(sometimes call the dry adiabatic lapse rate)

And : $\Gamma_d = \frac{dT}{dz} = -\frac{28.8\times10^{-3}\times9.8}{29} = -9.7\times10^{-3}\ {}^\circ\text{C per m}$

...or approximately 10°C per 1km

For a diatomic gas,
C_P = 3.5 R = 29 J mol^{-1} K^{-1}

Calculating the adiabatic rate

We can integrate Equation 2 to yield:

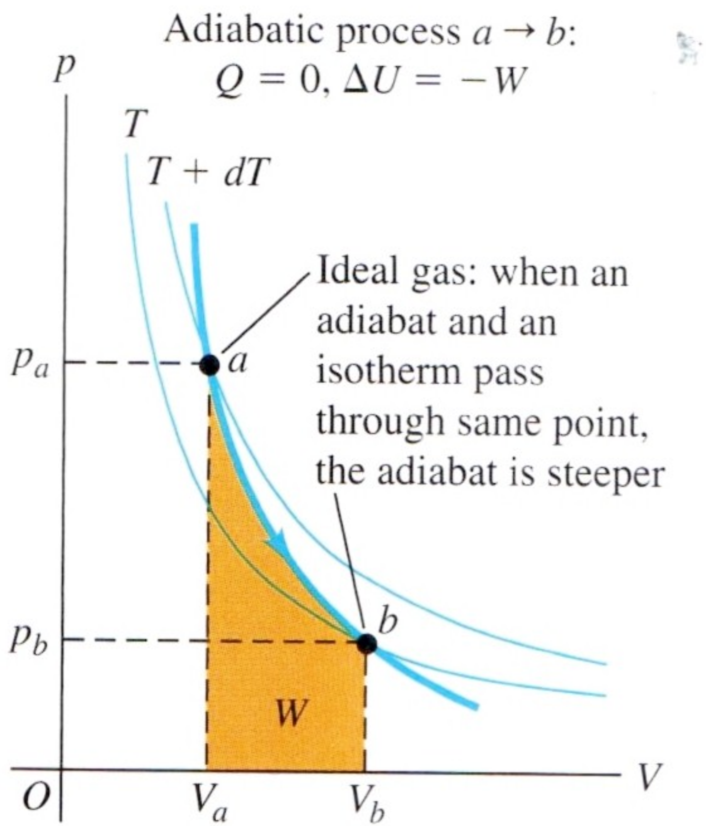
$$\frac{T^{\gamma}}{P^{\gamma-1}} = \text{const.}$$

Where $\gamma = \frac{C_P}{C_V}$

We can then use $PV = RT$ to find other equations for the adiabatic process:

$$PV^{\gamma} = \text{const}$$

$$TV^{\gamma-1} = \text{const.}$$



19.19 A pV-diagram of an adiabatic ($Q = 0$) process for an ideal gas. As the gas expands from V_a to V_b, it does positive work W on its environment, its internal energy decreases ($\Delta U = -W < 0$), and its temperature drops from $T + dT$ to T.

Potential temperature

In an adiabatic process,

$$\frac{T^{\gamma}}{P^{\gamma-1}} = \frac{T_0{}^{\gamma}}{P_0{}^{\gamma-1}}$$

Thus if air at T, P is brought adiabatically to another pressure $P_{0,}$ its temperature T_o (the **potential temperature**) will be given by:

$$T_o = T\left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}}$$

The potential temperature is a measure of the sum of potential and internal energy and is a conserved quantity in an adiabatic process.

Air is composed of diatomic gas, thus $\gamma = 7/5$ and $\frac{\gamma-1}{\gamma} = 0.286$

The wet adiabatic rate

If an air parcel rises high enough it will cool to the dew point and condensation begins. Latent heat, which was absorbed when the water was evaporated, is now released.

Even though the air parcel continues to cool adiabatically as it rises, the release of latent heat reduces the height variation of temperature, giving the wet adiabatic rate Γ_{WA} (also called the pseudo adiabatic lapse rate):

mixing ratio

$$\Gamma_{\mathrm{w}} = g\,\frac{\left(1 + \dfrac{H_{\mathrm{v}}\,r}{R_{\mathrm{sd}}\,T}\right)}{\left(c_{\mathrm{pd}} + \dfrac{H_{\mathrm{v}}^2\,r}{R_{\mathrm{sw}}\,T^2}\right)} = g\,\frac{R_{\mathrm{sd}}\,T^2 + H_{\mathrm{v}}\,r\,T}{c_{\mathrm{pd}}\,R_{\mathrm{sd}}\,T^2 + H_{\mathrm{v}}^2\,r\,\epsilon}$$

water vapour pressure of saturated air

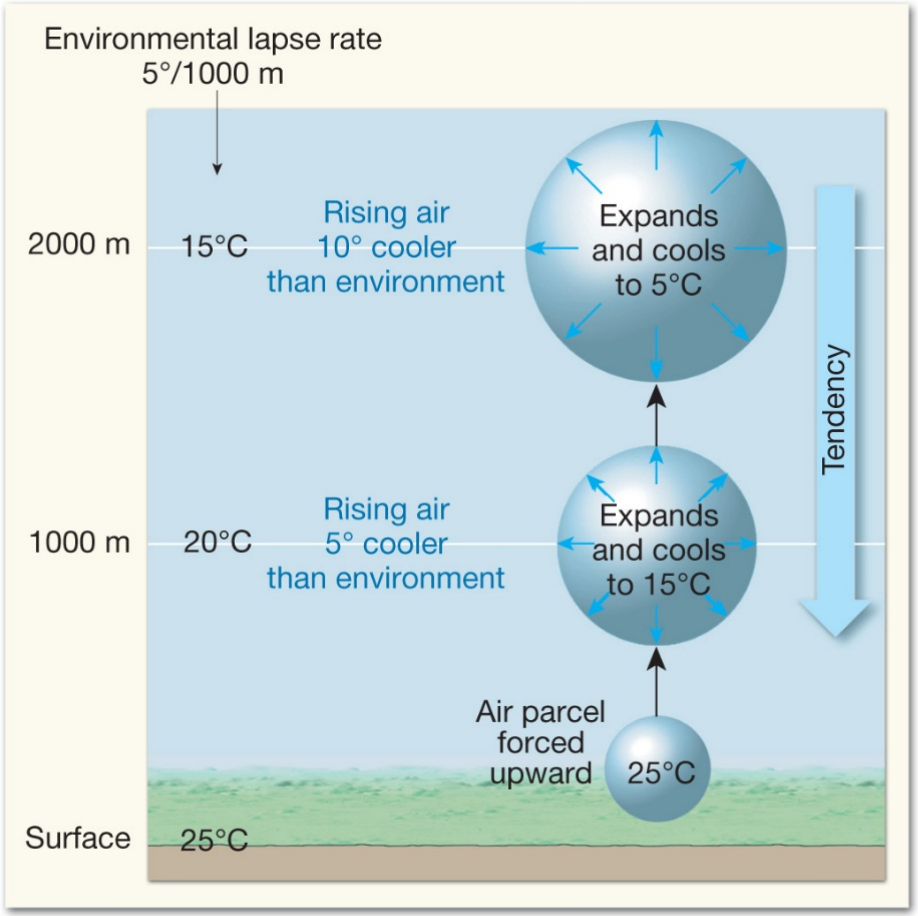
The wet adiabatic rate is always smaller the dry rate. The difference between the two rates is bigger at higher temperature due to the exponential dependence of P_{ws} on temperature.

Wet rate varies from 5 °C per 1000 m for air with high absolute humidity to 9.5 °C per 1000 m for low moisture content (0.5 °C)

Atmospheric stability

Compare the temperature of a rising air parcel with the temperature of the surrounding air

If the air parcel rises and becomes cooler than its surroundings, it will also be denser and will tend to sink. This is **stable air**; vertical motion is inhibited.

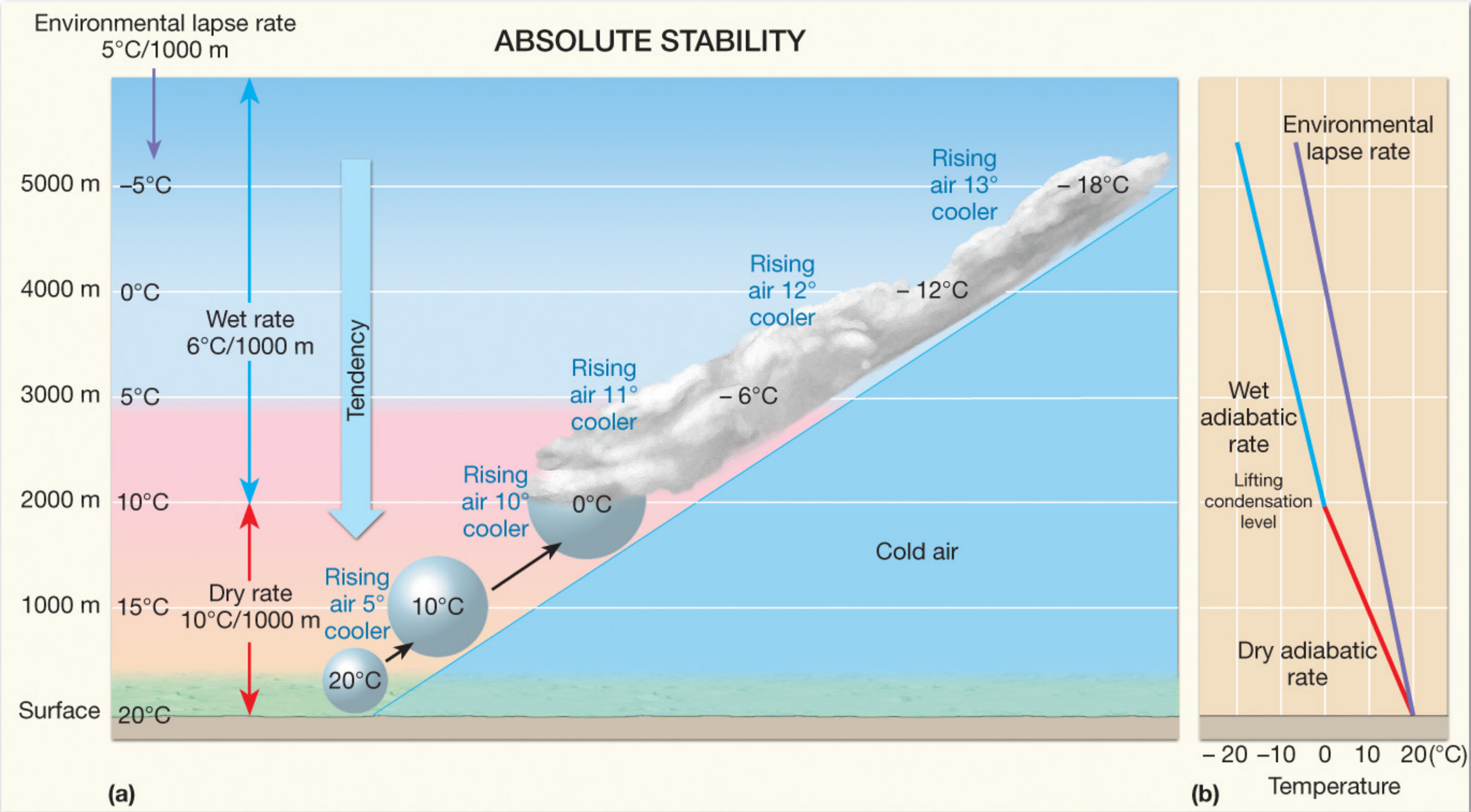


© 2013 Pearson Education, Inc.

If the rising parcel becomes warmer and less dense than surroundings it will continue to rise until it reaches a region where it has the same temperature at its environment. This is **unstable air**, where vertical motion occurs.

To determine the stability of the atmosphere, measure the temperature at various heights to find the environmental lapse rate, $\Gamma_{E,}$ typically 5 °C per 1000 m.

Atmospheric stability

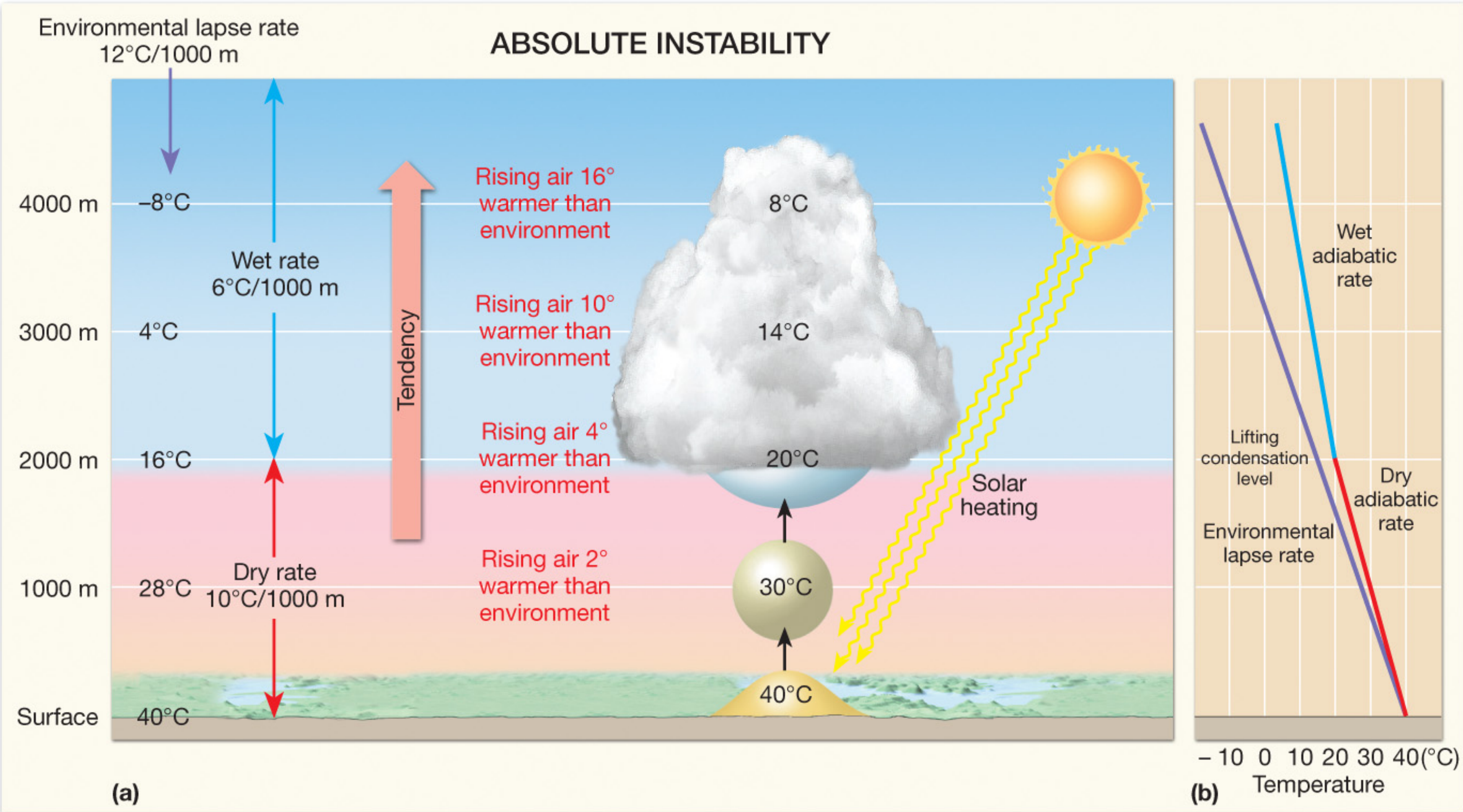


© 2013 Pearson Education, Inc.

Absolute stability when $\Gamma_d > \Gamma_w > \Gamma_E$.

Most stable situation occurs when air temperature rises with height (**temperature inversion)**. May occur on clear night due to radiation cooling of the Earth's surface.

Atmospheric stability

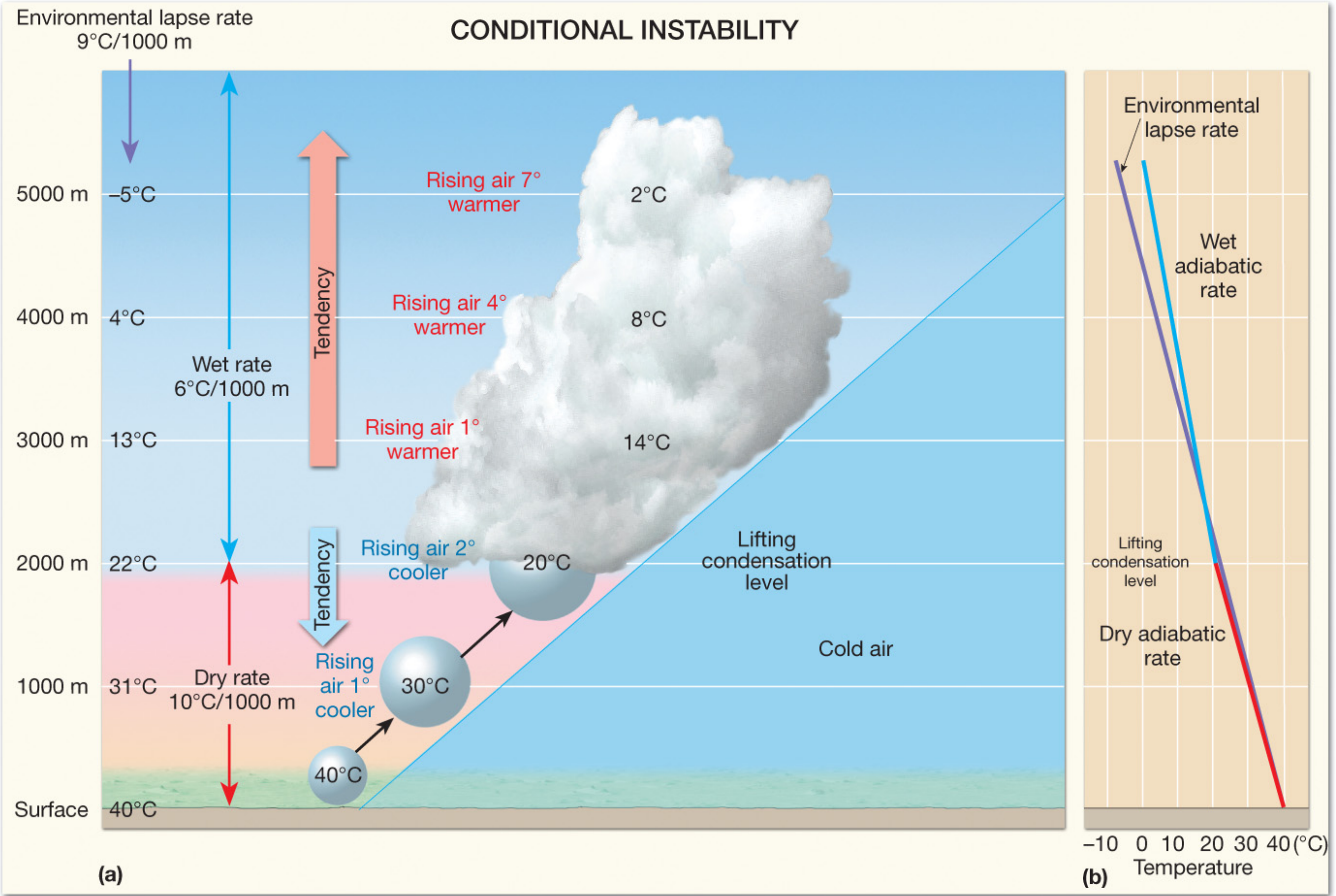


© 2013 Pearson Education, Inc.

Absolute instability when $\Gamma_w < \Gamma_d < \Gamma_E$.

Here ascending air will be warmer and less dense than its environment and will continue to rise. Most likely to occur in the warmest months on clear days when solar heating of the surface is intense; the lowest layers are heated more than higher layers leading to steep Γ_E.

Atmospheric stability



© 2013 Pearson Education, Inc.

Conditional instability when $\Gamma_d > \Gamma_E > \Gamma_w$.

Atmosphere conditionally unstable if it is stable wrt unsaturated parcel of air, but unstable wrt saturated parcel of air. With the release of latent heat above the lifting condensation level the air parcel becomes warmer than the surrounding air and will continue to rise. The air parcel has to be forced upward to where it becomes unstable and rises on its own.

Atmospheric stability

In an **absolutely stable environment**, no clouds will likely form.

The most stable conditions occur in temperature inversion, which usually happens at night due to radiative cooling of the Earth surface and may give rise to fog. The cooler air near the surface is heavier, and there is little vertical mixing. Pollutants, which are added near the surface tend to accumulate.

When stable air is forced upwards the clouds formed have relatively small vertical thickness, and give rise to little precipitation. On an overcast day with drizzle the atmosphere is likely to be stable.

-> shallow, layered **stratus**

Atmospheric stability

In a shallow conditionally **unstable** or absolutely unstable environment clouds may develop, but their vertical growth will be limited

- **cumulus** humilis (shallow cumulus) stratocumulus

In a deep conditionally unstable or absolutely unstable environment clouds may develop with significant vertical development

- cumulus congestus cumulonimbus

© 2013 Pearson Education, Inc.

Towering clouds are formed in unstable air, giving rise to heavy precipitation. Cauliflower-shaped clouds suggest bubbles of warm air surging upwards

Mechanisms that lift the air

Why does the air parcel rise?

1. **Orographic lifting**
   Air is forced to rise as it is blown towards a mountain.

Obstructions (e.g., hills, buildings) disrupt air flow -> turbulence.

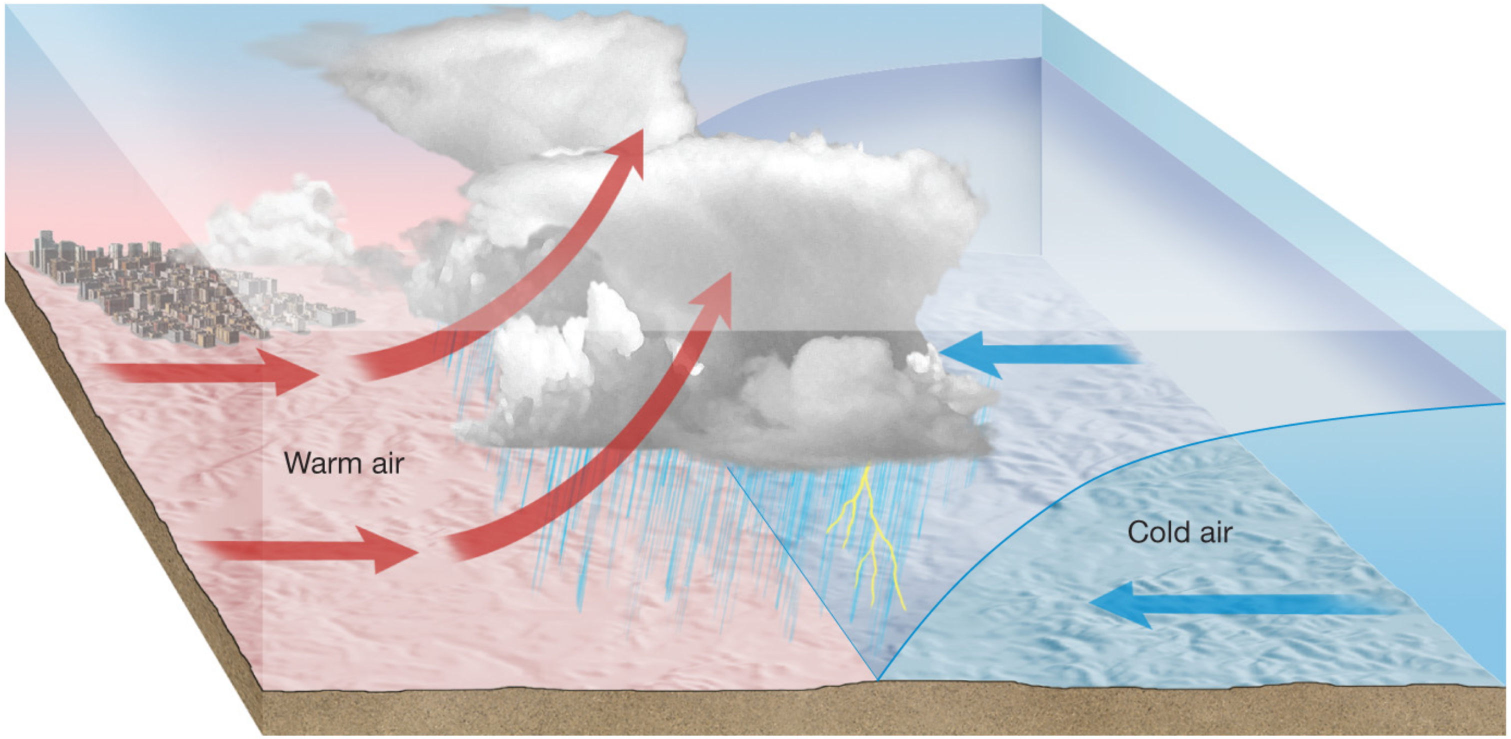
When moist stable air flows over these ‘eddies’, large-scale standing waves form. If temperature below dew point, moisture in the air can form these clouds.

Lenticular cloud, Harold’s Cross, Dublin

Mechanisms that lift the air

2. Frontal lifting

When cool air meets warm air - the warmer, less dense air is forced to rise over cooler, denser air.

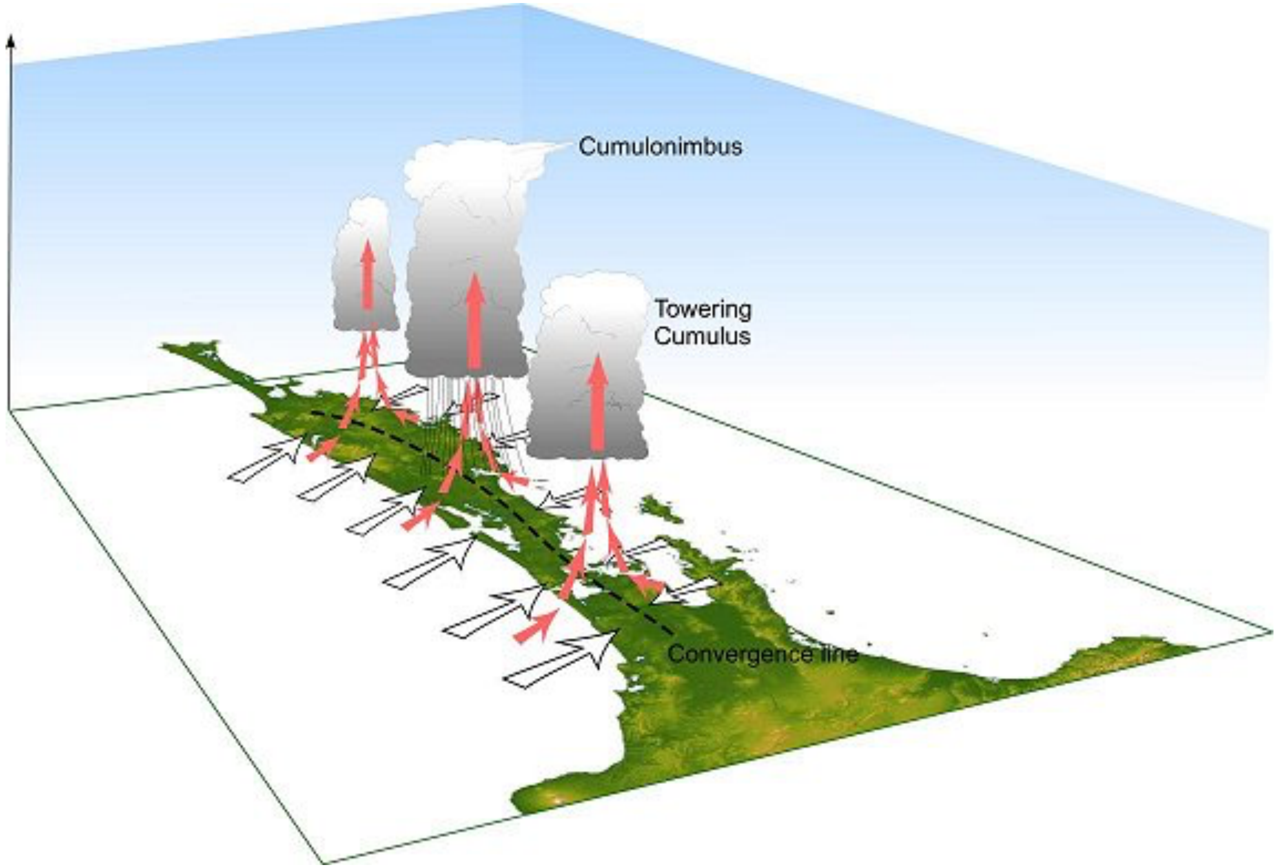


© 2013 Pearson Education, Inc.

Mechanisms that lift the air

3. Convergence lifting

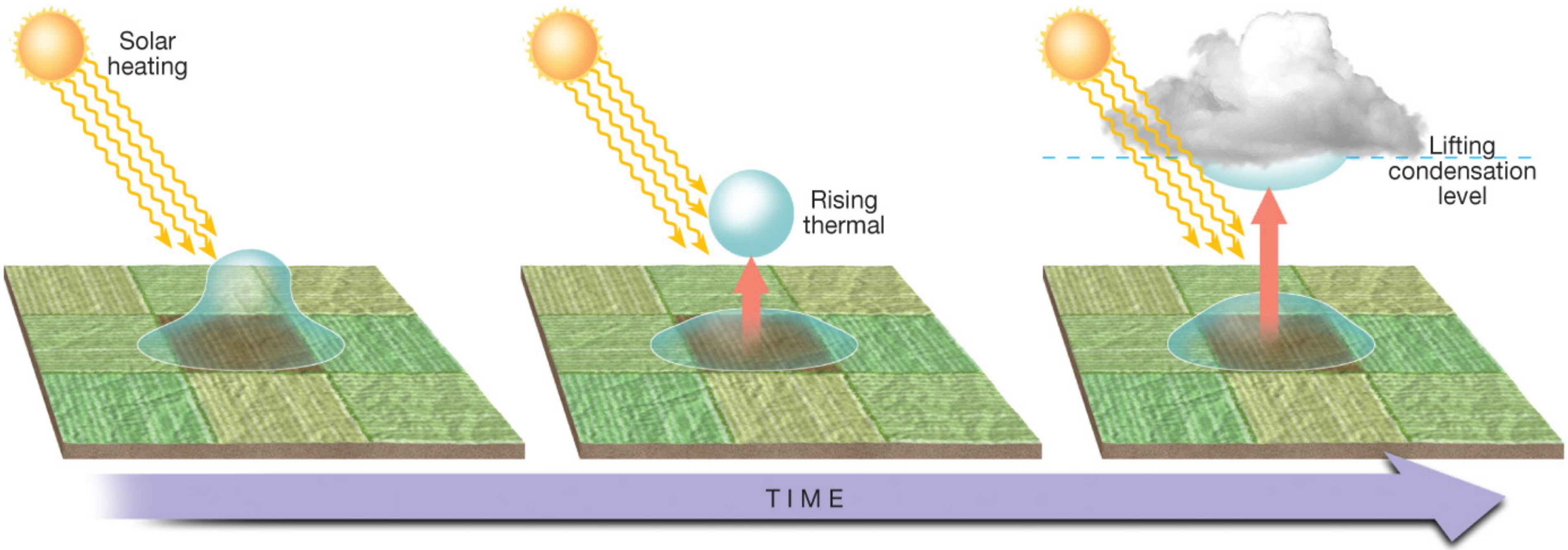
The collision of two air masses moving horizontally towards each other leads to a pile-up and generates an upward movement.



Mechanisms that lift the air

4. Convective lifting

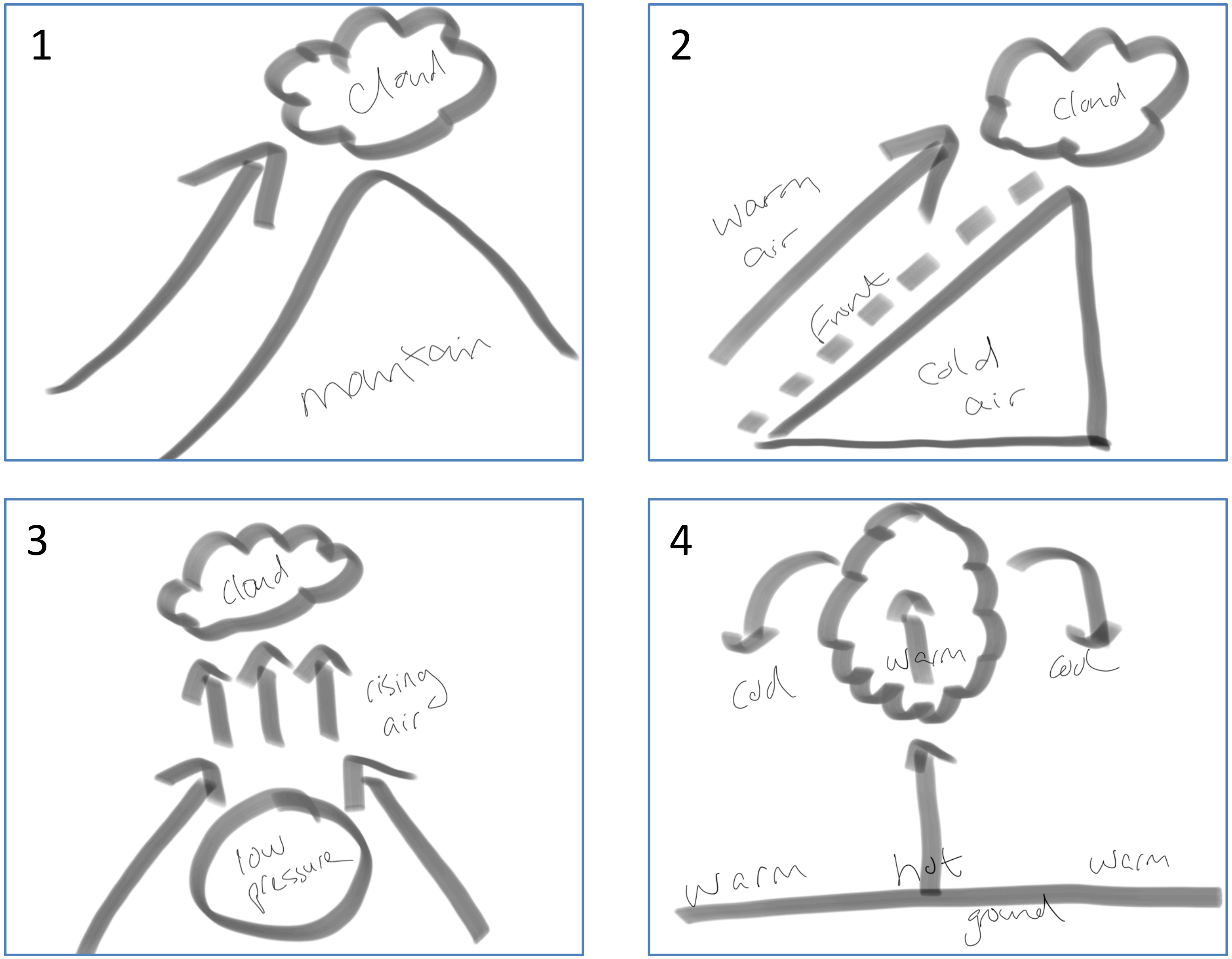
Unequal surface heating generates parcels of warmer less dense air which rise due to buoyancy. It is localised, e.g., air above a paved car park will be warmed more than air above a wooded area. These rising parcels of air are call thermals.



© 2013 Pearson Education, Inc.

Mechanisms that lift the air

The rising air in all lifting mechanisms causes an updraft, which keeps cloud particles suspended regardless of gravity.



Summary

- Cloud types
- Formation via adiabatic cooling
  - Lapse rates indicating decrease of temperature with altitude
- Atmospheric stability and environmental lapse rate
- Four mechanisms that lift the air
  - Orographic
  - Frontal
  - Convergence
  - Convective

Homework assignment #3 due Wednesday 31st October at 2pm lecture with SM

Cloud demo

https://www.youtube.com/watch?v=E8AvfXar9zs