V. Composition and structure of the atmosphere

(and some related feedbacks)

review

- we described Earth's radiative balance
- we established the magnitude and origin of the natural greenhouse effect
- we looked at the role of gases that selectively absorb radiation within the atmosphere
- what did we learn?

clicker question

Earth's surface temperature is warmer than its calculated radiative equilibrium temperature because

a) **Earth's true albedo is smaller than 0.30**

b) **the solar radiation at the top of the atmosphere is actually greater than ~1365 W/m^2**

c) **the Stefan Boltzmann constant is not very well established**

d) **the atmosphere traps infrared radiation that is being transmitted from Earth back toward space**

e) **the Earth is not in thermal or radiative balance**

clicker question

If Earth's true albedo were 0.10 instead of 0.30

a) **Earth's surface temperature would be higher**

b) **Earth's surface temperature would be lower**

c) **Earth's surface temperature would be unchanged**

d) **the flux of outgoing infrared radiation would increase**

e) **both a) and d)**

learning goals

- know the major atmospheric gases
- describe the major greenhouse gas trends and explain the relative “strength” of some GHGs
- explain the density, pressure and temperature structure of the atmosphere
- describe the relationship between the vapor pressure of water and temperature
- explain climate feedbacks involving temperature and water vapor and clouds
- explain the concepts of climate forcing, response and sensitivity

major gases in the atmosphere

Components in Dry Air	Volume Ratio compared to Dry Air
Oxygen	20.95%
Nitrogen	78.09%
Argon	0.933%

these are the "permanent" gases in Earth's atmosphere, making up 99.9+% by volume there are other permanent gases but they occur in just trace amounts

these gases do not absorb infrared radiation!

greenhouse gases

gas (formula)	current conc. by volume	pre-industrial conc. by volume
water vapor (H_20)	0 – 4% (S. Pole v. tropics)	~same
carbon dioxide (CO_2)	380 ppm	270 ppm
methane (CH_4)	1700 ppb	700 ppb
nitrous oxide (N_2O)	315 ppb	275 ppb
ozone (0_3)	~40 ppb (but variable)	?
freon-11 (a CFC)	0.26 ppb (declining)	0
freon-12 (a CFC)	0.54 ppb (declining)	0

note vertically decreasing units from per cent, to parts per million, then per billion

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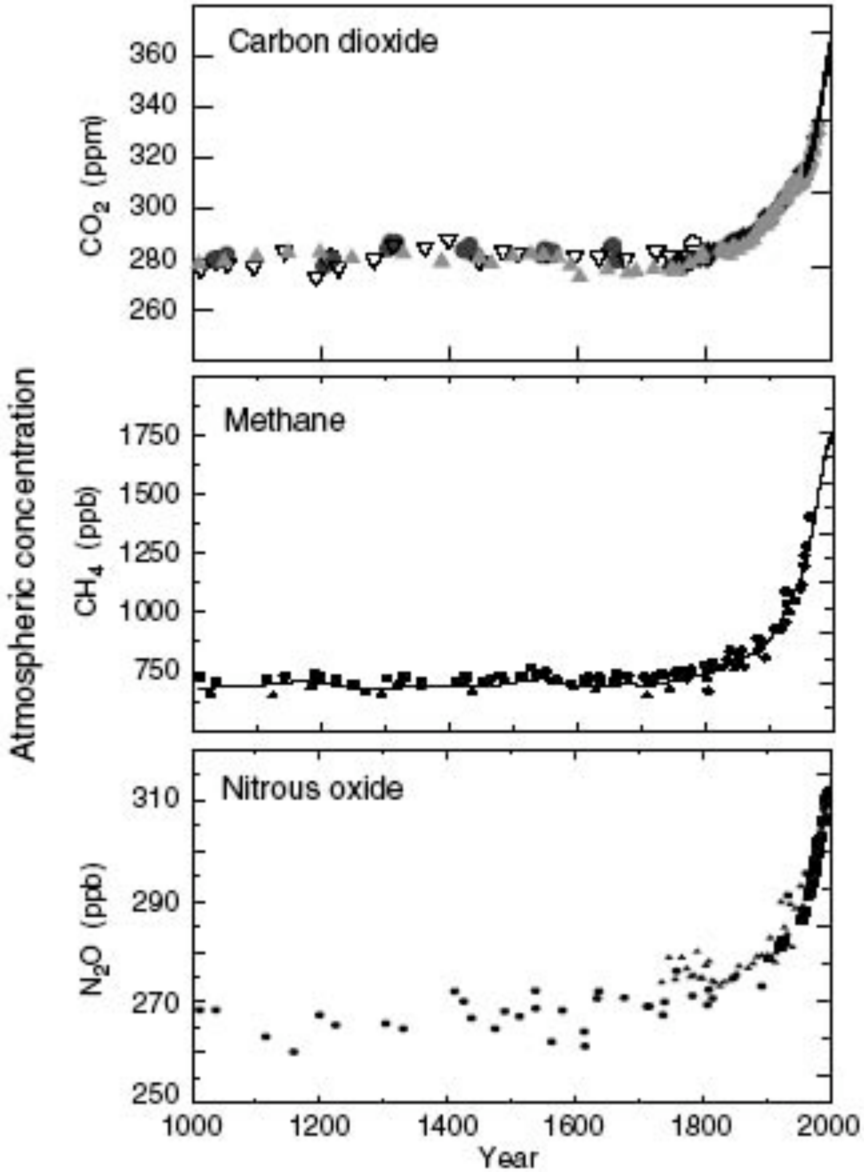
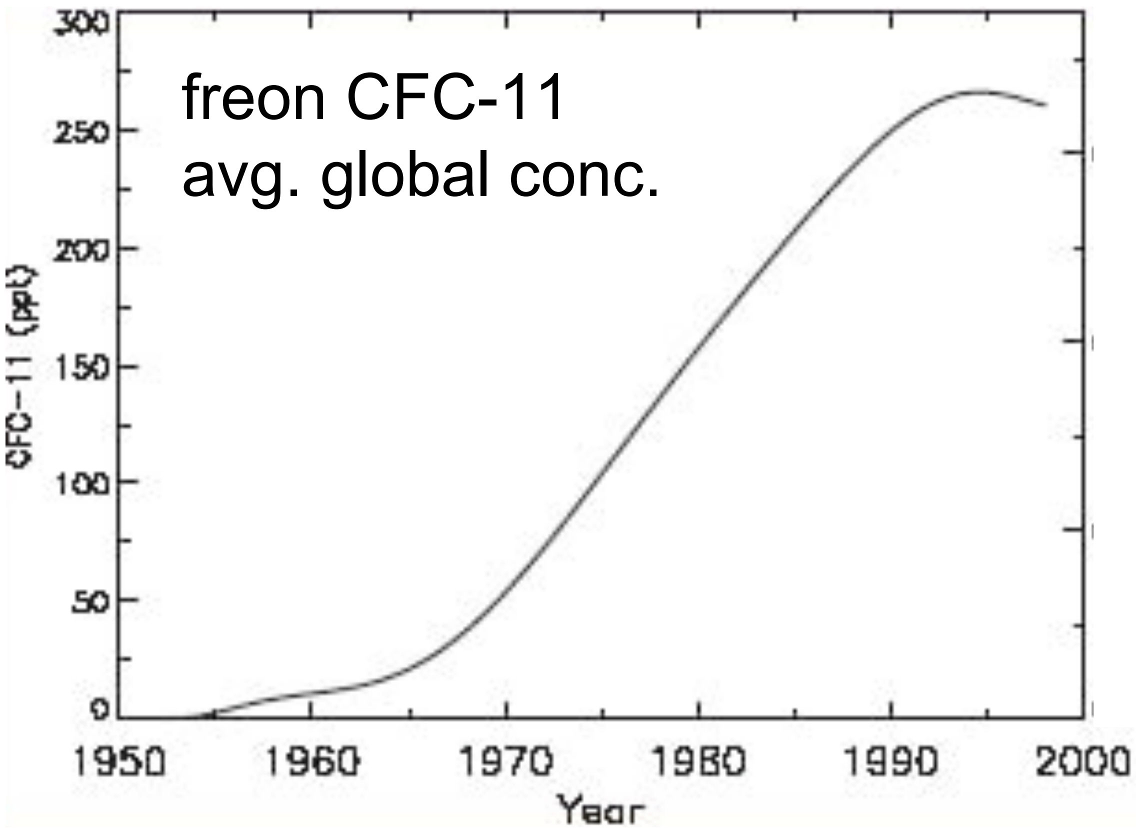
pre-industrial concentrations are uniformly lower

the human influence
during industrial era



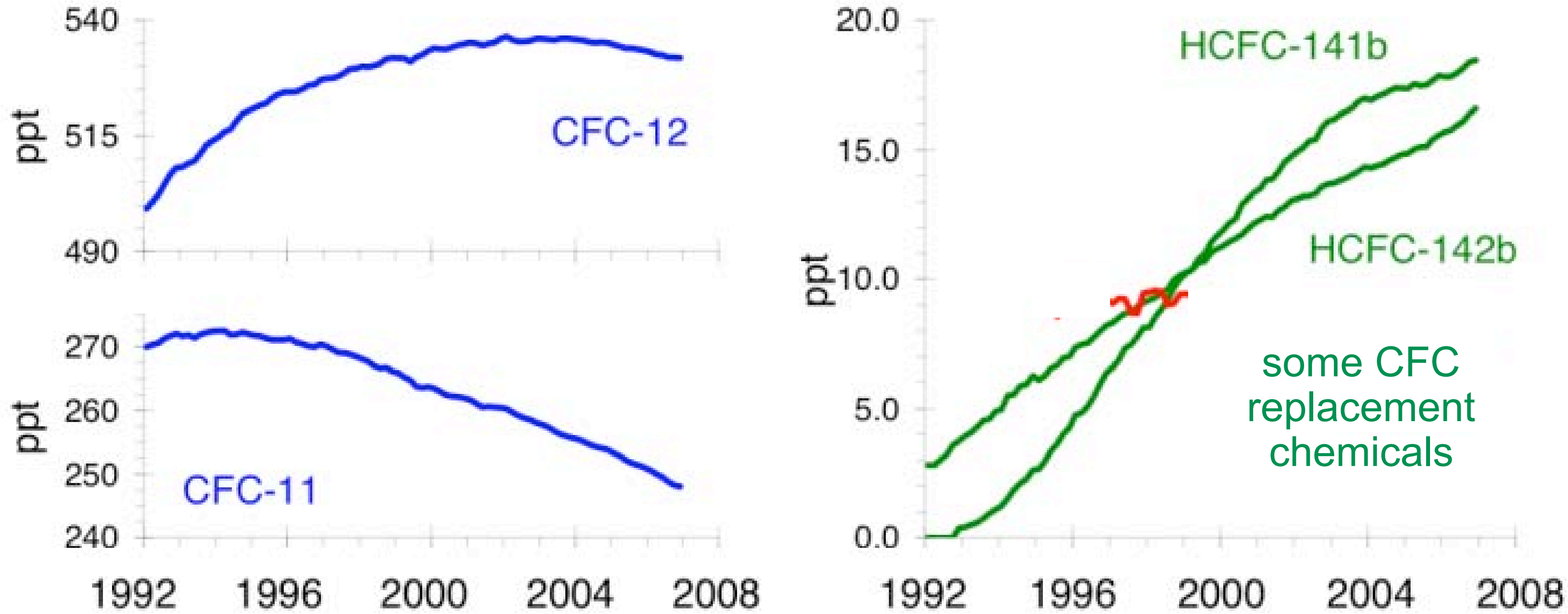
measurements of globally-well mixed GHGs from ice cores and global air sampling networks

the human influence
during industrial era



although banned CFC's are declining, their replacement chemicals (HCFC's etc.) are increasing and are potent GHG's........

the human influence
during industrial era



global concentration of some anthropogenic halocarbons
(measured by NOAA here in Boulder)

greenhouse gases

gas (formula)	current conc. by volume %	lifespan in atmosphere	greenhouse potential (v. CO_2)
water vapor (H_20)	0 – 4% (S. Pole v. tropics)	weeks	(important feedback)
carbon dioxide (CO_2)	380 ppm	>250 yr	1
methane (CH_4)	1700 ppb	~ 15 yr	~21
nitrous oxide (N_2O)	315 ppb	~ 100 yr	~200
ozone (0_3)	~40 ppb (but variable)	var.	var.
freon–11 (a CFC)	0.26 ppb		
freon–12 (a CFC)	0.54 ppb	~ 100 yr	~15,000

atmospheric lifespan or "residence time" of different GHGs varies greatly due to differing processes of formation and destruction

greenhouse gases

gas (formula)	current conc. by volume %	lifespan in atmosphere	greenhouse potential (v. CO_2)
water vapor (H_20)	0 – 4% (S. Pole v. tropics)	weeks	(important feedback)
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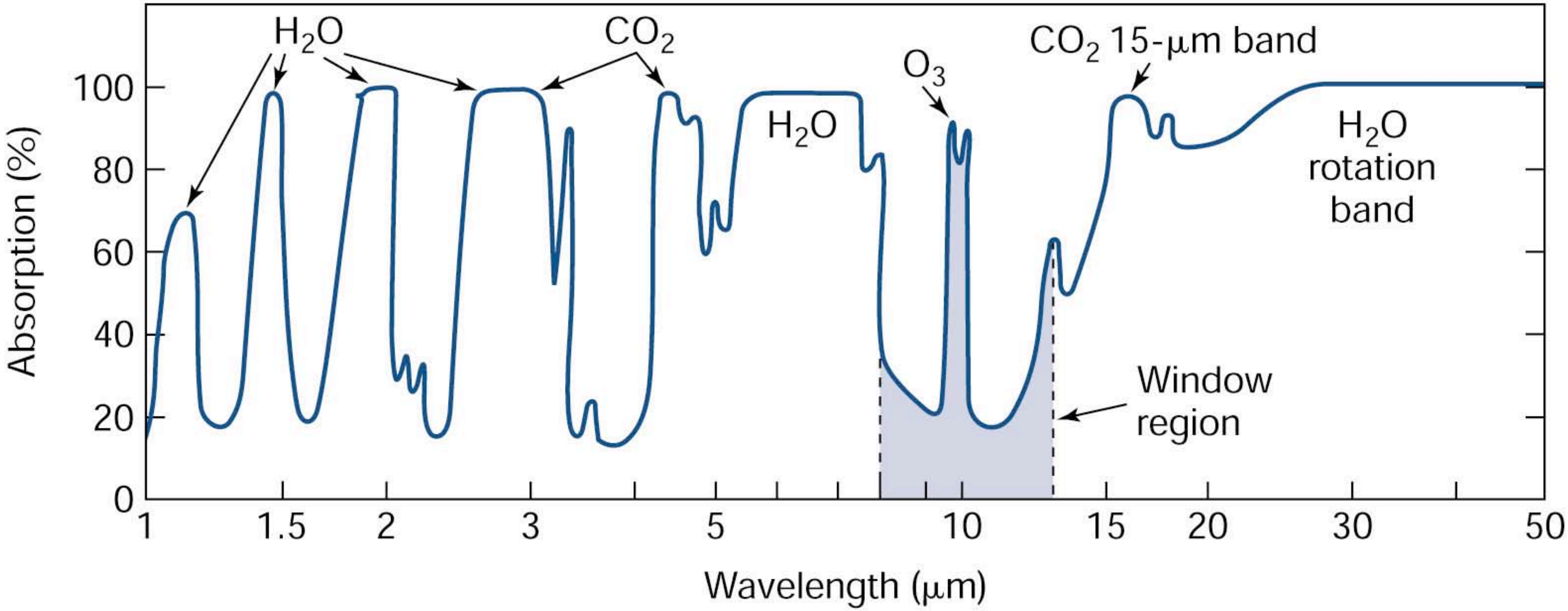
freon–11 (a CFC)	0.26 ppb		
freon–12 (a CFC)	0.54 ppb	~ 100 yr	~15,000

greenhouse potential compares the warming potential of one molecule of a given GHG to that of one molecule of CO_2

clicker question

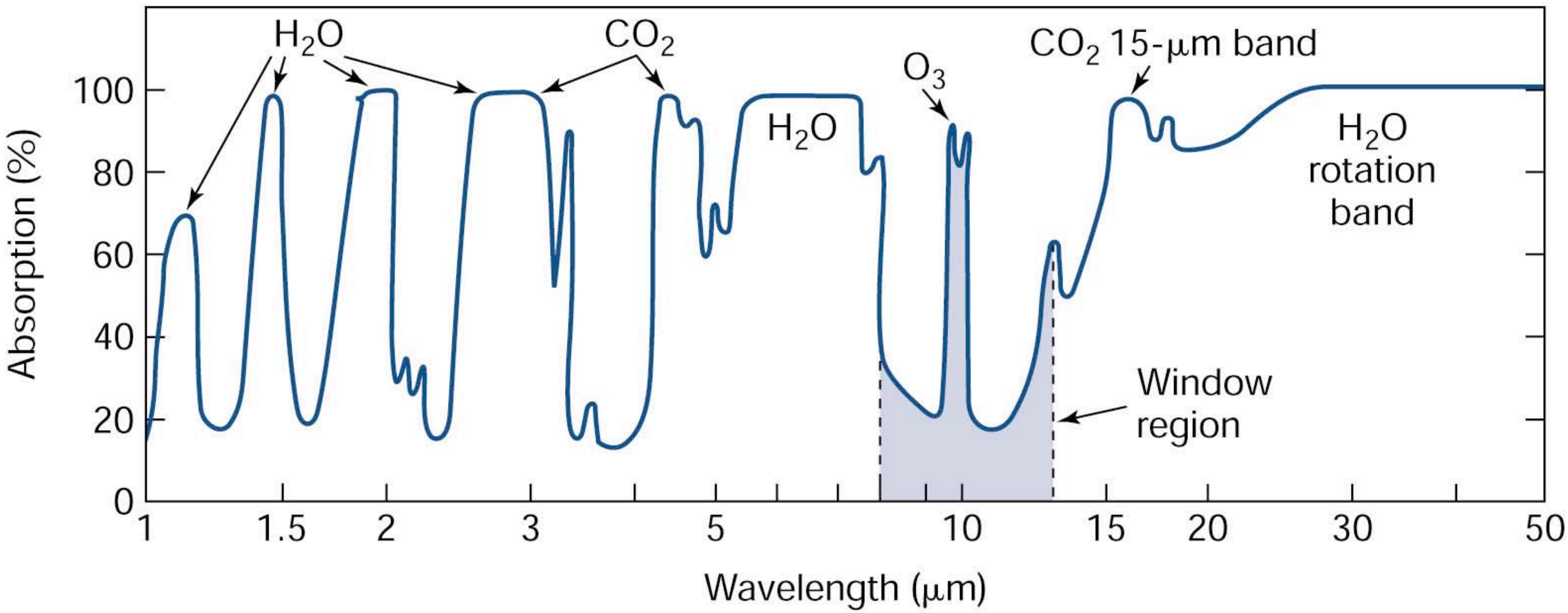
recall the absorption spectra of the major GHGs:



Some entirely man-made greenhouse gases like freon-11 or -12 might be especially "potent" because: <u>a) they selectively absorb within the atmospheric window</u>, b) they selectively absorb at the same wavelength as other more abundant GHGs, c) they destroy ozone, d) they exhibit black body behavior, e) none of the above

why are some GHGs more effective

recall the absorption spectra of the major GHGs:



freons -11 and -12 absorb at 8-12 μm

many of the man-made GHG's absorb w/in the "atmospheric window"

GHG overview

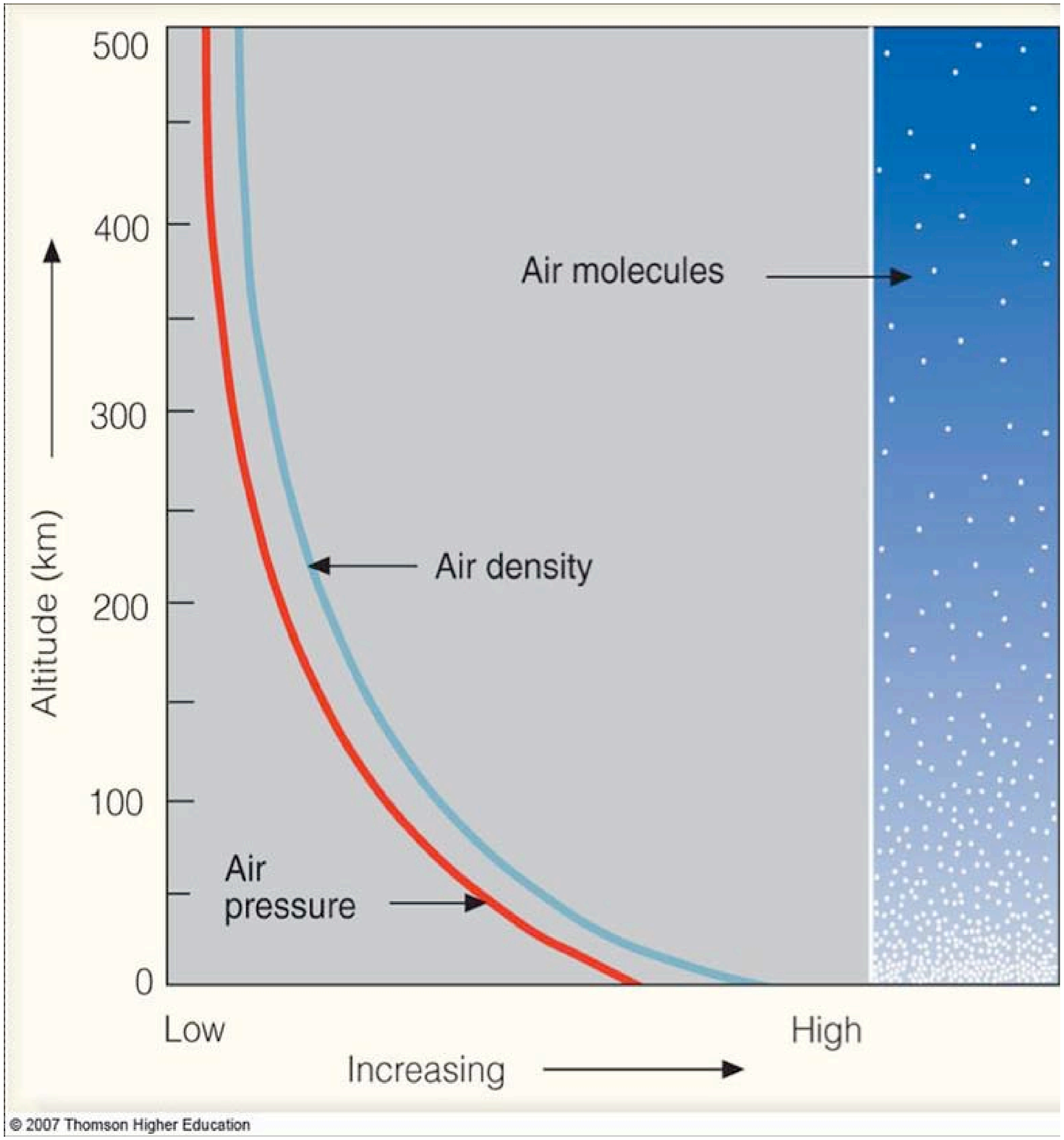
- GHGs selectively absorb and emit infrared radiation
- GHG abundances have increased markedly (or production began) since the beginning of the industrial revolution
- atmospheric lifetimes differ due to differing processes of formation and destruction
- longer-lived gases are more difficult to control since they accumulate in the atmosphere more effectively over time
- "greenhouse potentials" of individual gases vary widely and is high for gases absorbing in the "atmospheric window" (or, like methane, where the absorption is not yet near saturation for a given range of wavelengths)

We will come back to these GHGs repeatedly…

For now, lets proceed to the basics of the density, pressure and temperature structure of the atmosphere.

This will help us understand some important system feedbacks (and, according to the "layer model" in your book, the magnitude of the GH effect at the surface).

<u>density</u> and pressure structure of atmos.



***density* = mass/volume (grams/m^3)**

so the density of air is computed by determining the mass of air in a given volume

the mass is related to number of air molecules

why does the density go up rapidly with decreasing altitude?

clicker question:

discuss with your neighbors

why does the density of air increase rapidly as altitude decreases?

a) because the lower atmosphere is warmer

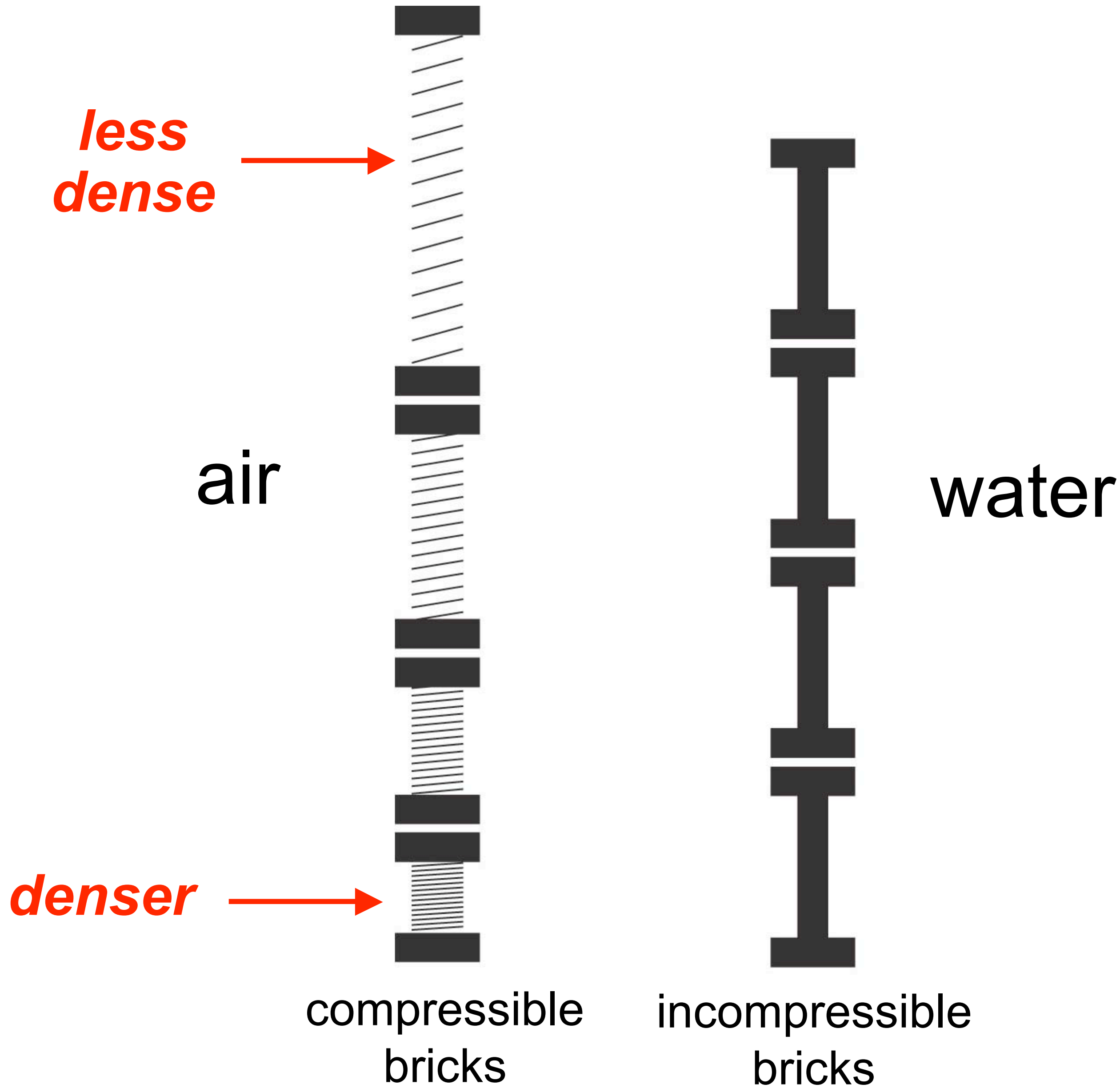
b) because the chemical composition of the lower atmosphere is different

c) <u>because Earth's gravity pulls air molecules toward the bottom of the atmosphere</u>

d) because the atmospheric pressure is greater

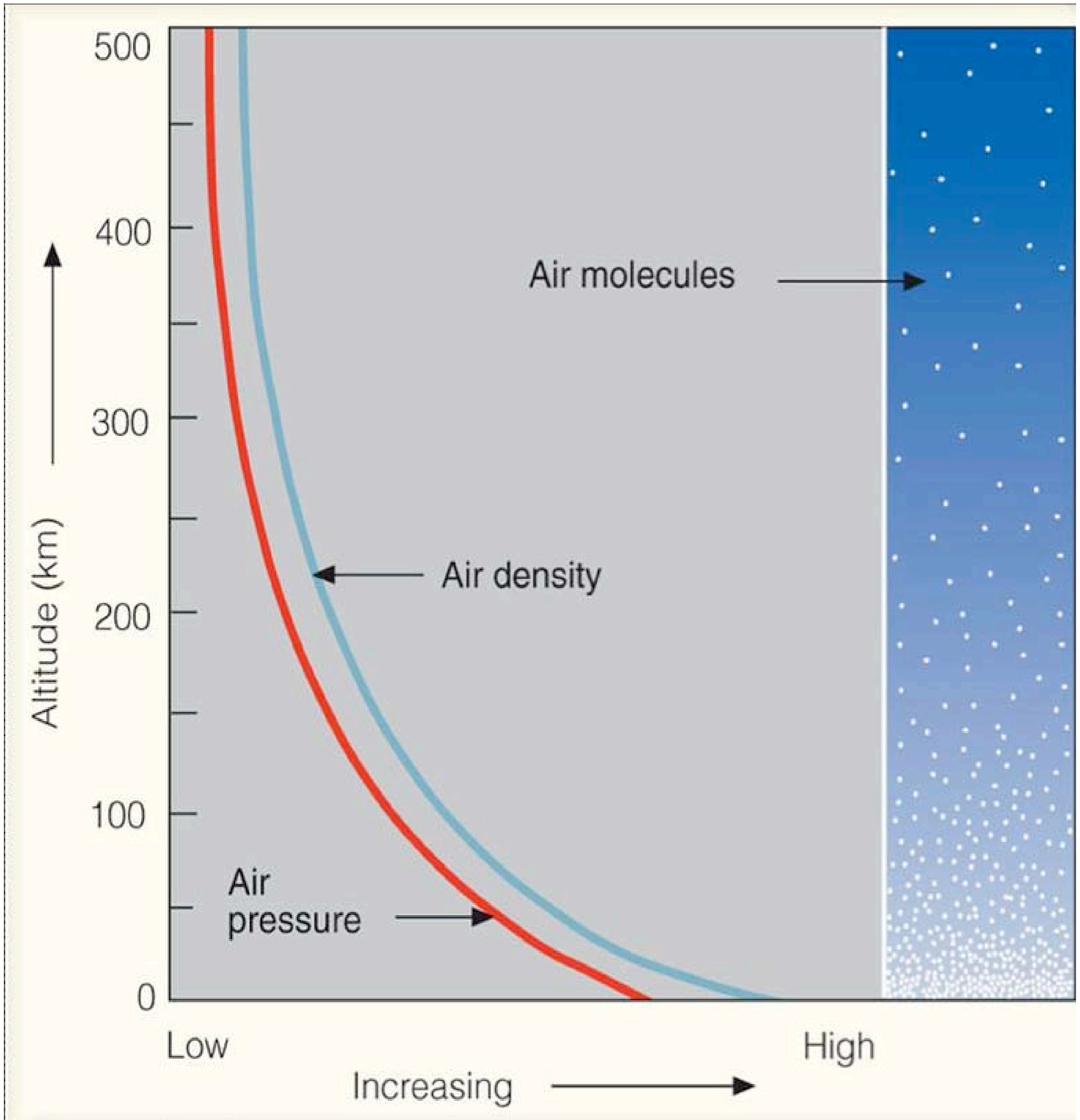
e) all of the above

compressibility of air (vs. water)



air compresses under its own weight, water does not (much)

density and <u>pressure</u> structure of atmos.



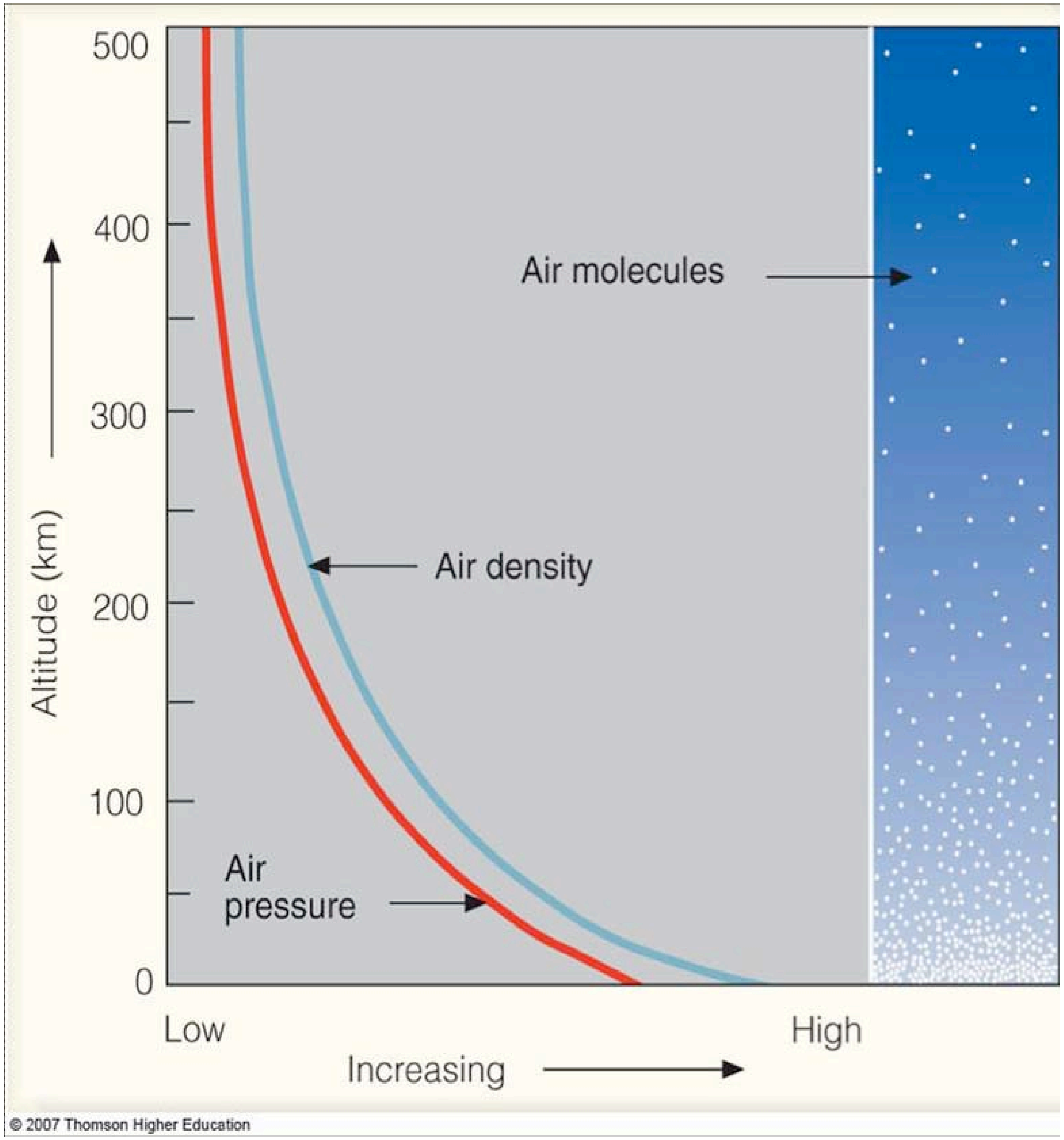
pressure* = *force/area

force is push or pull of one object on another

consider that your weight is your mass as pulled by gravity into the bathroom scale

so weight is force
ergo
pressure = weight/area

density and pressure structure of atmos.



the increasing air pressure is due to weight of the column of atmosphere above

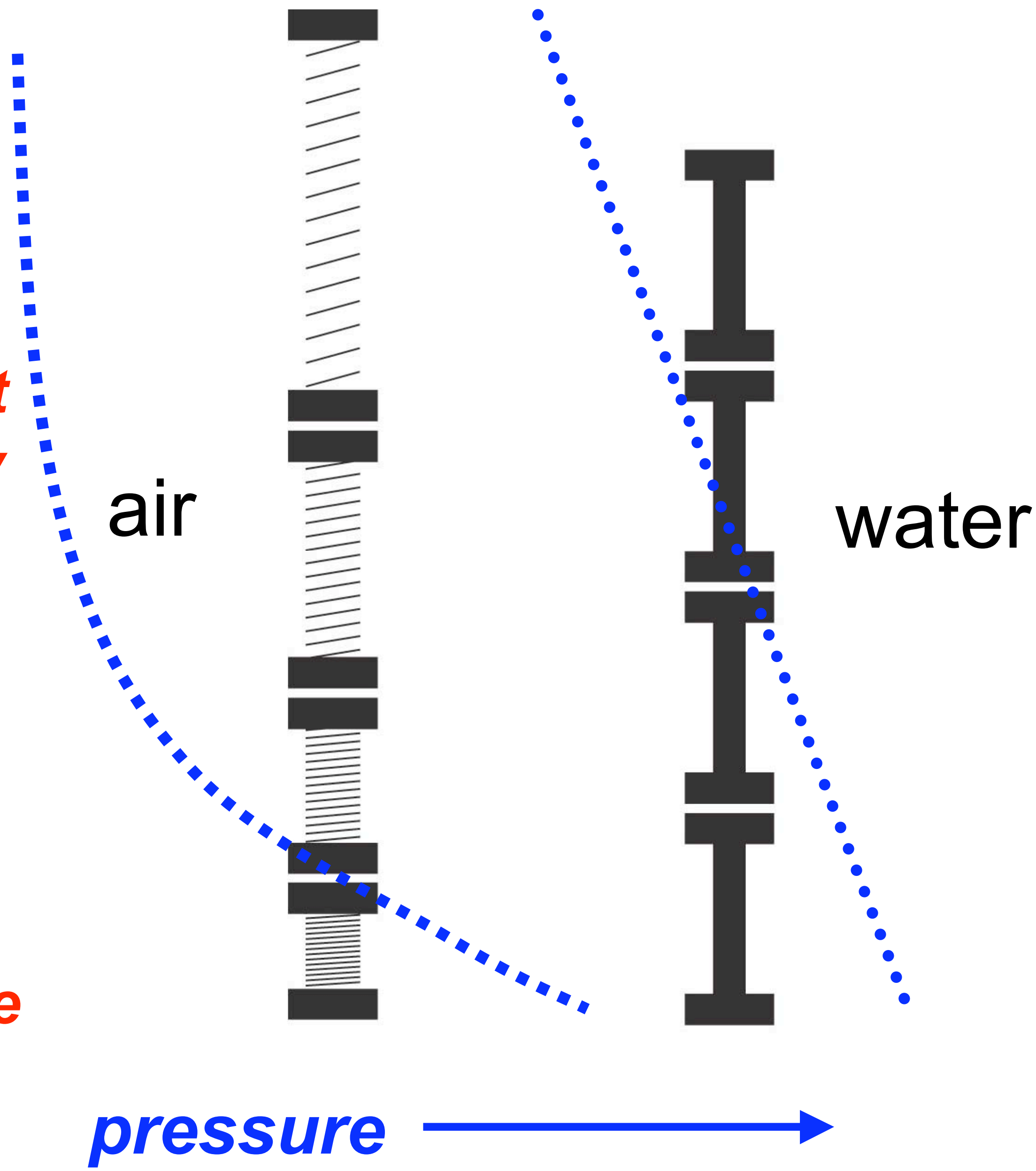
why does pressure decrease exponentially with height?

recall compressibility

think about this:

each brick has the same mass or weight (no. of molecules), but due to compressibility the lower bricks are shorter and the upper bricks are taller

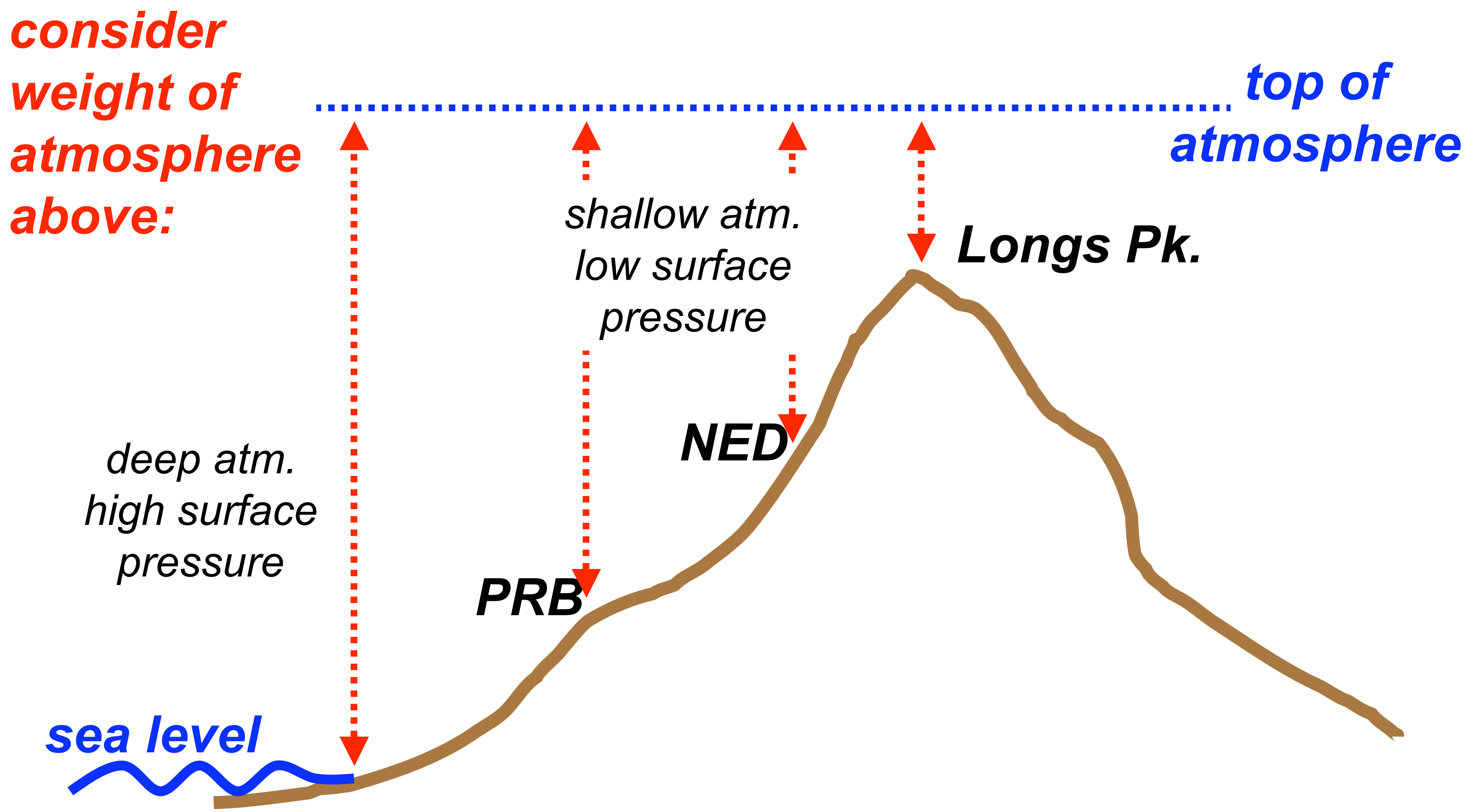
with each brick we add, we add the same mass (pressure) but gain increasingly more height



atmospheric pressure

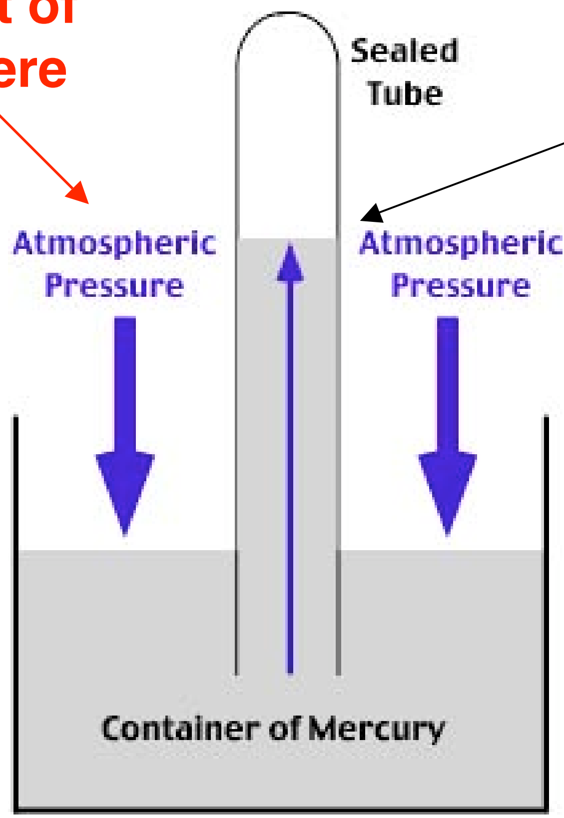
pressure is force or weight per unit area

(i.e. pounds per square inch, but prefer other units in climate science)



consider a mercury barometer

i.e. weight of atmosphere



say height of Hg is 29.92 in. (76 cm)

this is typical value at sea-level (Paris?) and defined as value of one standard atmosphere (or 1 atm)

29.92 in. (76 cm) Hg = 1 atm = ~1 bar (1000 mbar) = ~1000 hPa

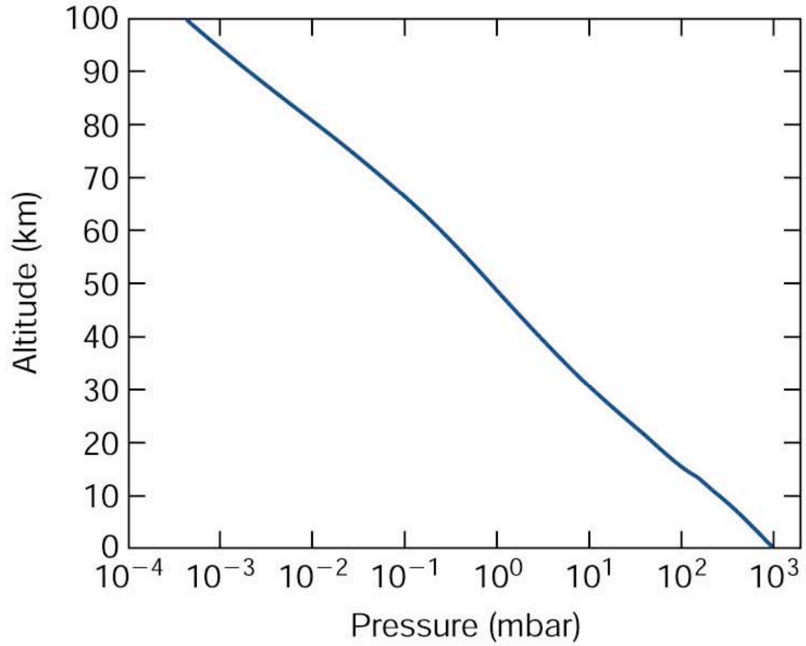
preferred by oceanographers!

proper SI units (i.e. $1 N/m^2$)

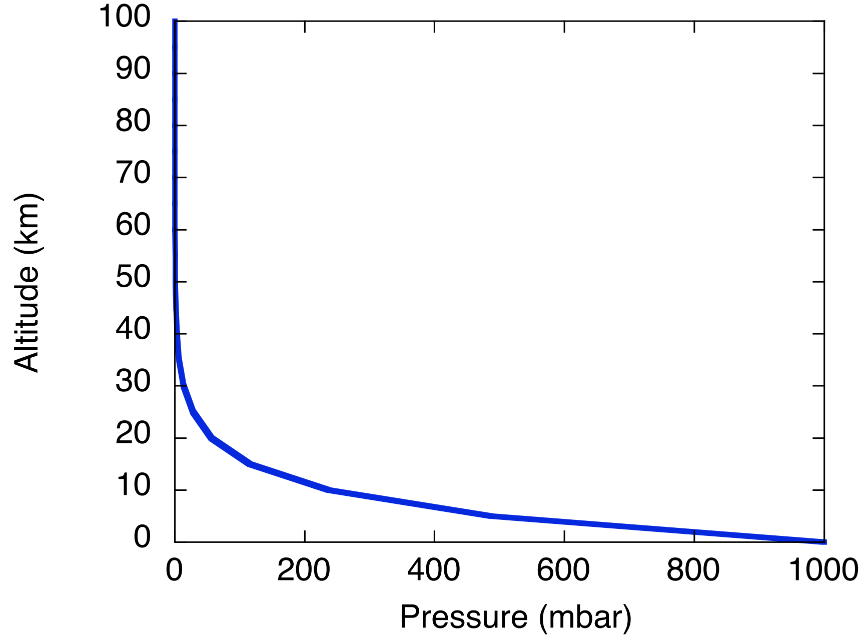
surface pressure

• sea level (0 m)	1000 mb
• Boulder (1650 m)	820 mb
• Longs Peak (4300 m)	600 mb
• Chomolongma (8850 m)	320 mb
• *tropopause* (16 km)	100 mb

pressure v. altitude



logarithmic scale

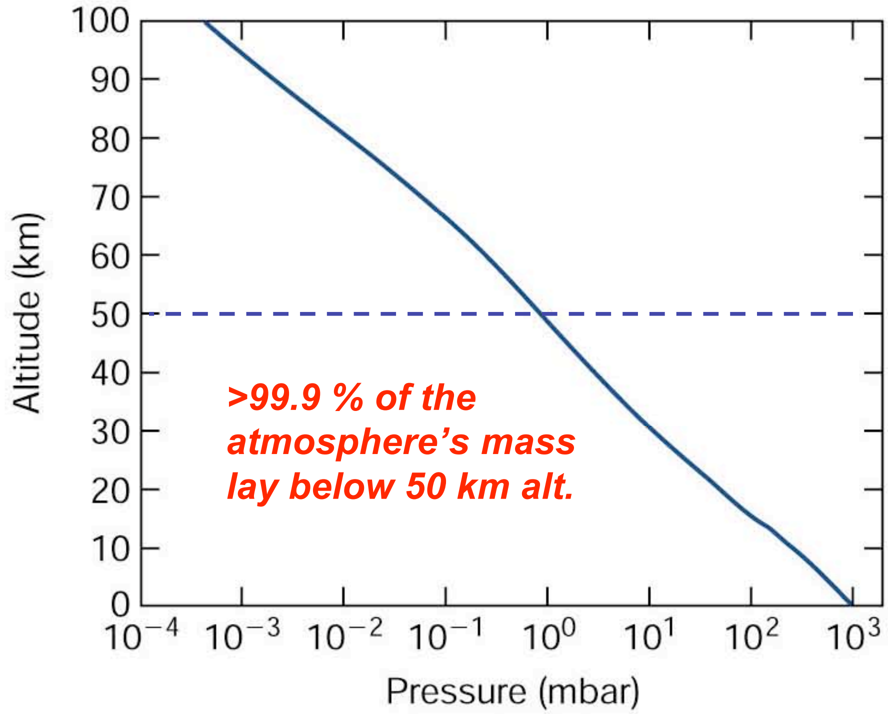


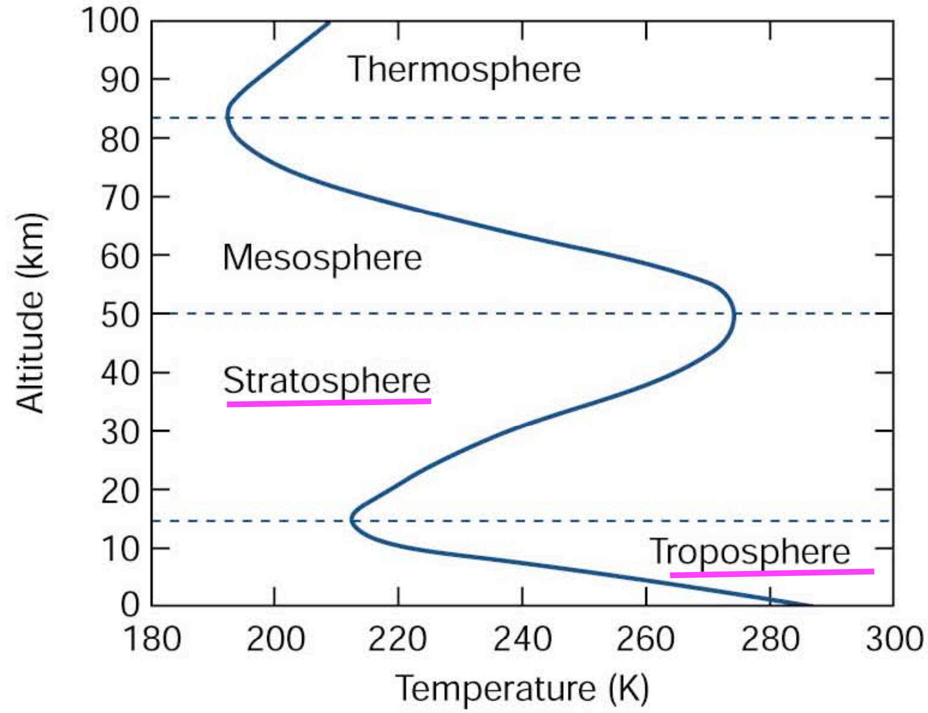
linear scale

rule of thumb:
pressure drops by a factor 10 for every 16 km alt.

(given the relationship above, can we use pressure as a measure of altitude?)

temperature structure of the atmosphere

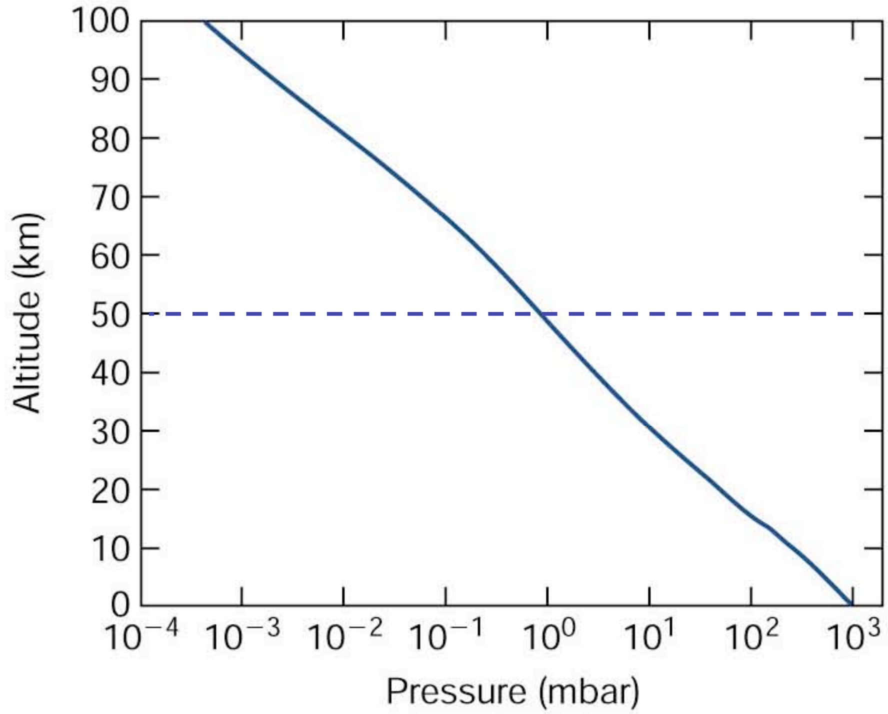


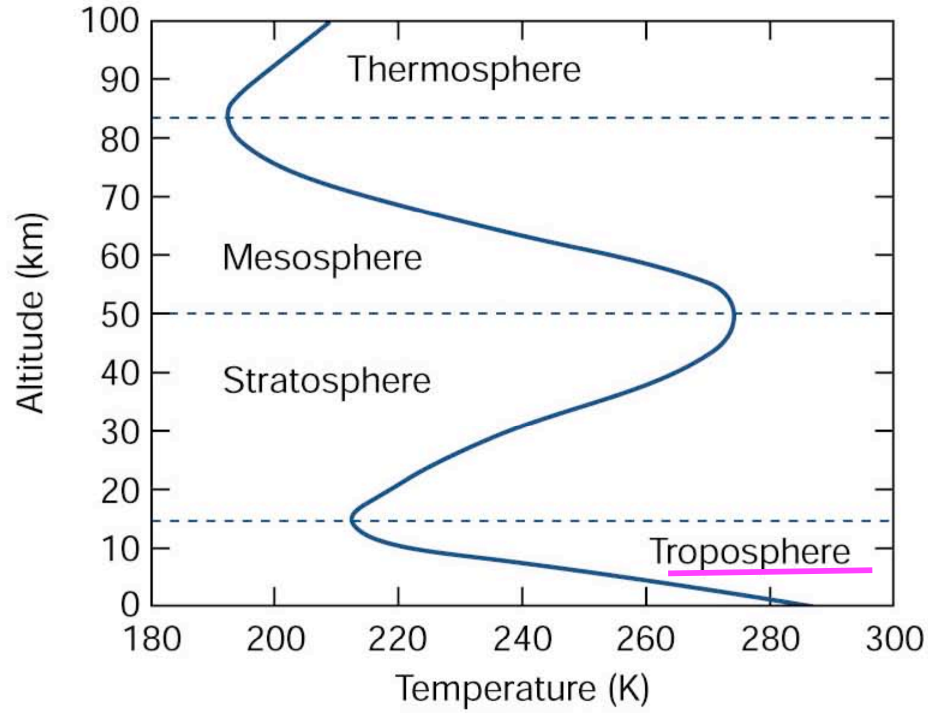


focus on the TROPOSPHERE and STRATOSPHERE

contains nearly all the mass, and all the weather

temperature structure of the atmosphere





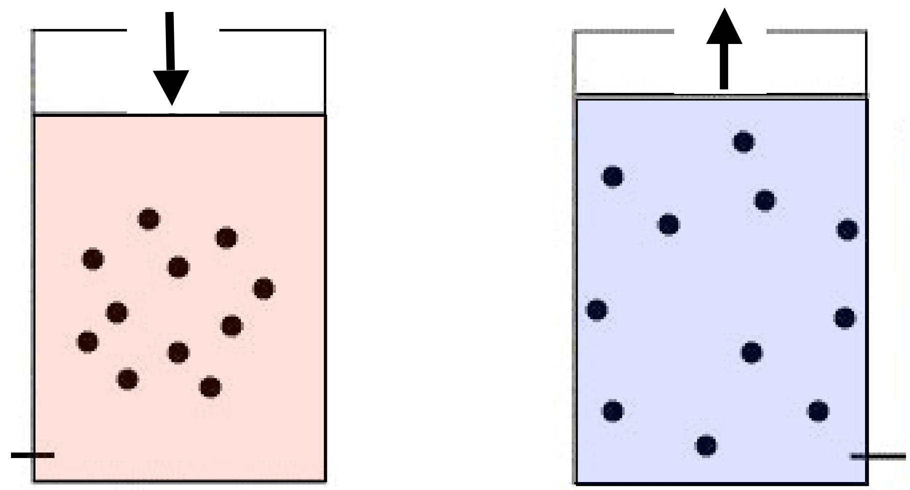
notice familiar cooling w/ altitude in the lower ~16 km, called the TROPOSPHERE

why does air cool w/ height?

Let's now consider two things about air…

compression and heating

(or expansion and cooling)



if we take a volume of air and compress it, it heats up (w/out any addition of heat)

if we take a volume of air and expand it, it cools (like the air racing out of a tire)

in this way, when a volume of air is raised from sea level to low pressures above, it cools

this cooling is called adiabatic cooling, this is the cooling (or heating…) that occurs in an idealized, "closed system" to which we neither add nor take away heat

latent or "hidden" heat

- water exists in three states (solid, liquid and gas) and energy is taken up or released during changes from one state to another
- this is latent or "hidden" heat

water ⟷ vapor

- energy is required to free molecules from liquid water to produce water vapor (i.e. evaporation)
- when water vapor molecules recombine (i.e. condensation) the "hidden" energy is released as heat
- when moist air is cooled, condensation occurs….

physical thinking exercise:

Adiabatic or expansion cooling of dry air would be expected to produce a vertical temperature profile of -10 K (°C) per km. However, air usually contains moisture in the form of water vapor. How would you expect the amount of water vapor to change as air rises and cools, and what impact might that have on the vertical temperature profile (vs. that for dry air)?

Draw the vertical T profile for adiabatic cooling of dry air and show how it might change for the case with water vapor. Discuss and explain your reasoning with your neighbor (*and get ready for a clicker question*)

clicker question

The vertical temperature profile for dry and moist air differ in the following way(s) and for the following reason(s):

a) T changes more rapidly with height in the moist case

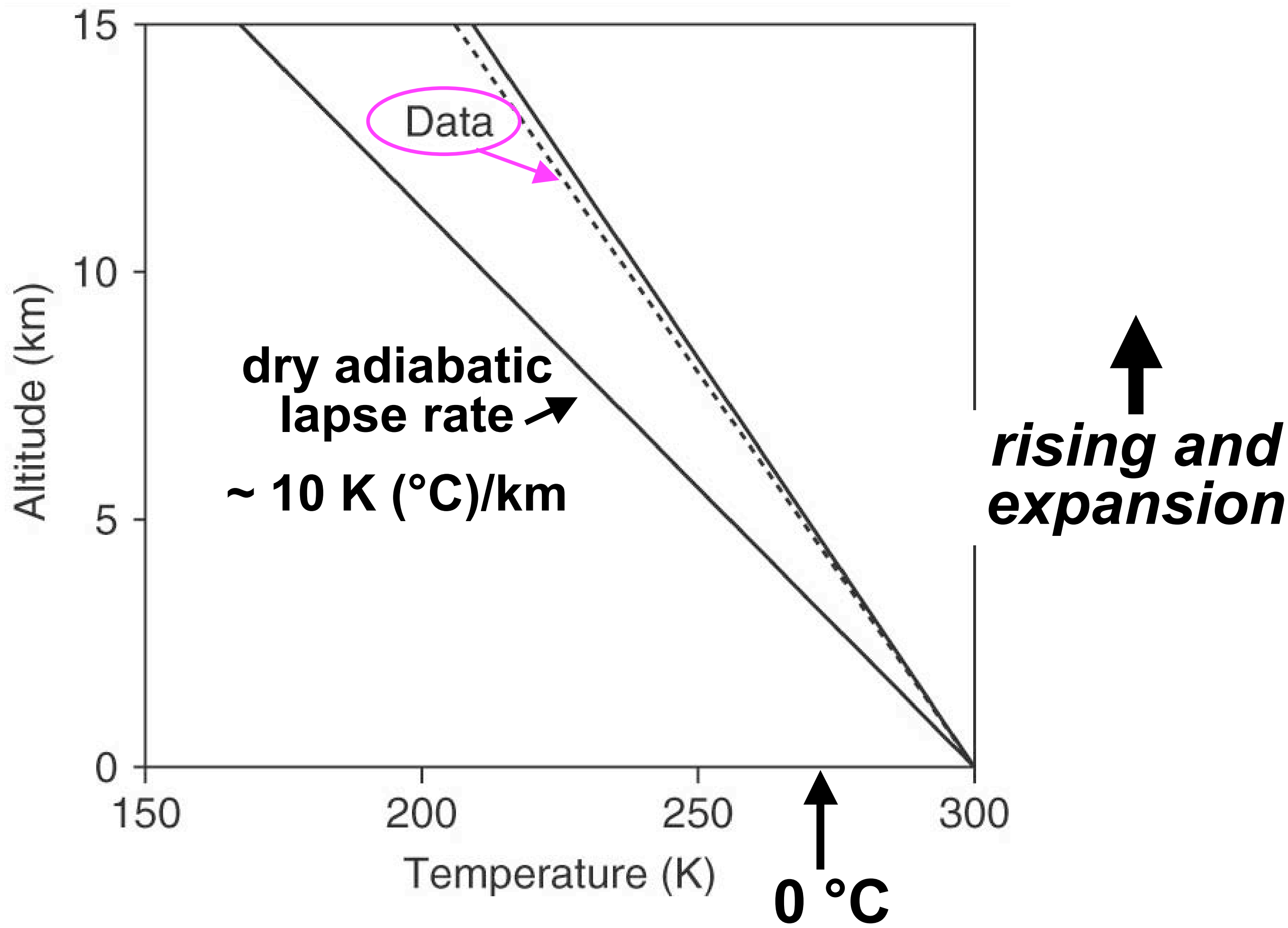
b) T changes less rapidly with height in the moist case

c) the condensation of moisture effectively adds heat to the profile as height increases

<u>d) both b) and c)</u>

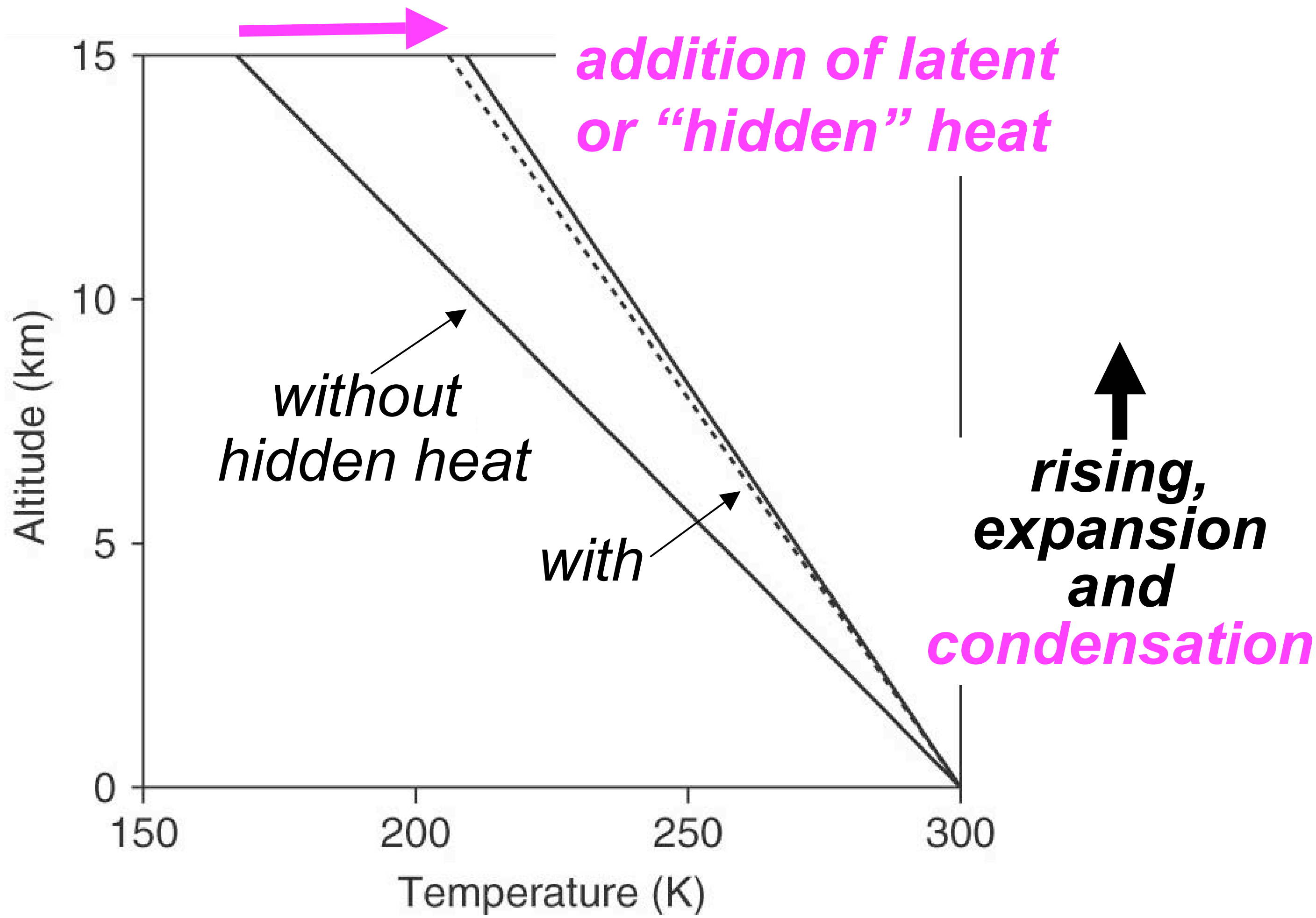
e) one can’t guess from an understanding of the process alone (a complicated model is needed)

lapse rate
(the change in temperature w/ height)



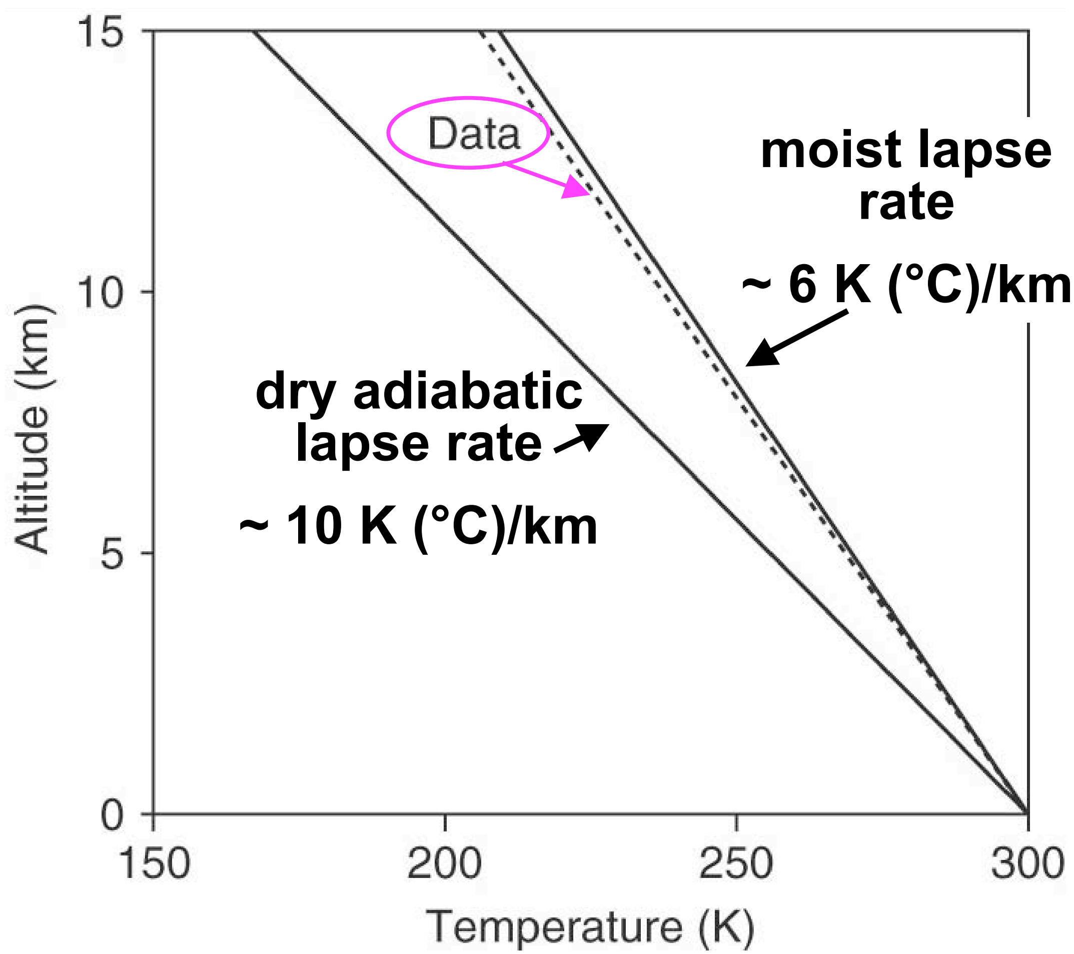
the observed decrease in temperature with height is actually less than expected for adiabatic expansion of dry air

lapse rate
(the change in temperature w/ height)



the energy needed to evaporate water is released upon condensation, heating the surrounding air

lapse rate
(the change in temperature w/ height)



the lapse rate of moist air dominates the observations, especially in the tropics

lapse rate

(the change in temperature w/ height)

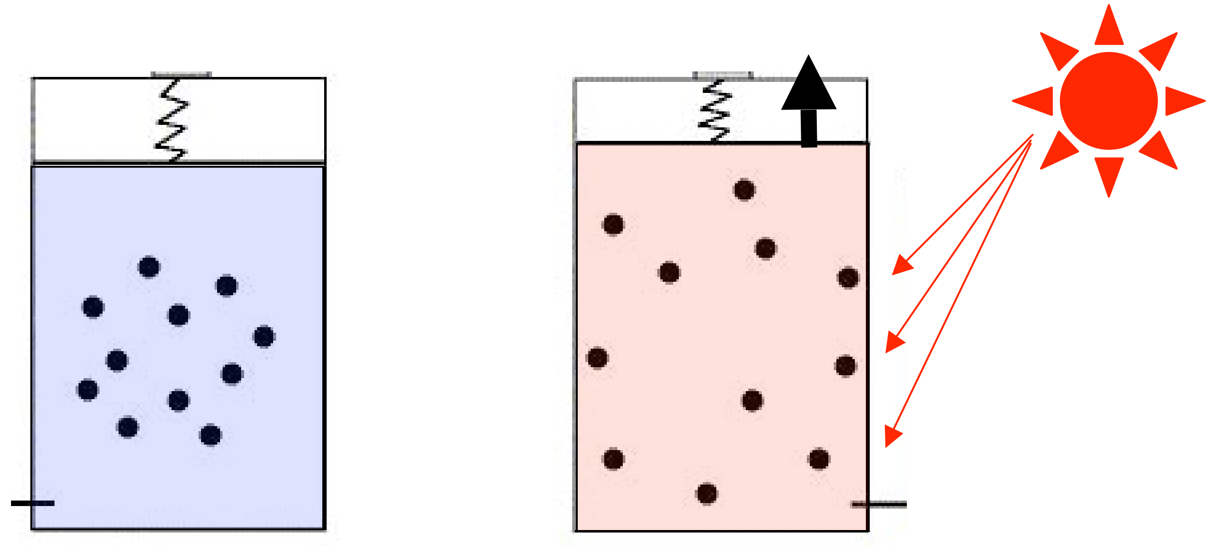
In the case just studied, we mentioned that air cools and moisture condenses as air rises…

Why does it rise?

<u>convection</u> due to heating from below

fluid becomes less dense when heated and therefore rises, while cooler, denser fluid sinks

heating drives expansion



What happens when we <u>add</u> heat to the system? Molecules move faster and take up more volume. The number of molecules has not changed, so the mass has not changed. This must mean the larger volume of air has become less dense. In the manner of a hot air balloon, the less dense air will rise….

(note that in the earlier slide on <u>adiabatic</u> expansion cooling, we considered what would happen if no heat were added or taken away)

physical thinking exercise:

Adiabiatic or expansion cooling of dry air would be expected to produce a vertical temperature profile of -10 K (°C) per km. In fact, this is rarely observed… When the sun is up the troposphere is "heated from the bottom" causing convection or vertical mixing of the atmosphere. Draw the vertical temperature profile expected for adiabatic cooling of dry air. Now, use that to help determine how the profile might change due to convection when the sun is up.

Discuss and explain your reasoning with your neighbor (*and get ready for a clicker question*).

clicker question

Heating from below and convection would influence the profile expected from expansion cooling alone in the following way(s):

a) vertical mixing increases the rate of T change with height

b) <u>vertical mixing decreases the rate of T change with height</u>

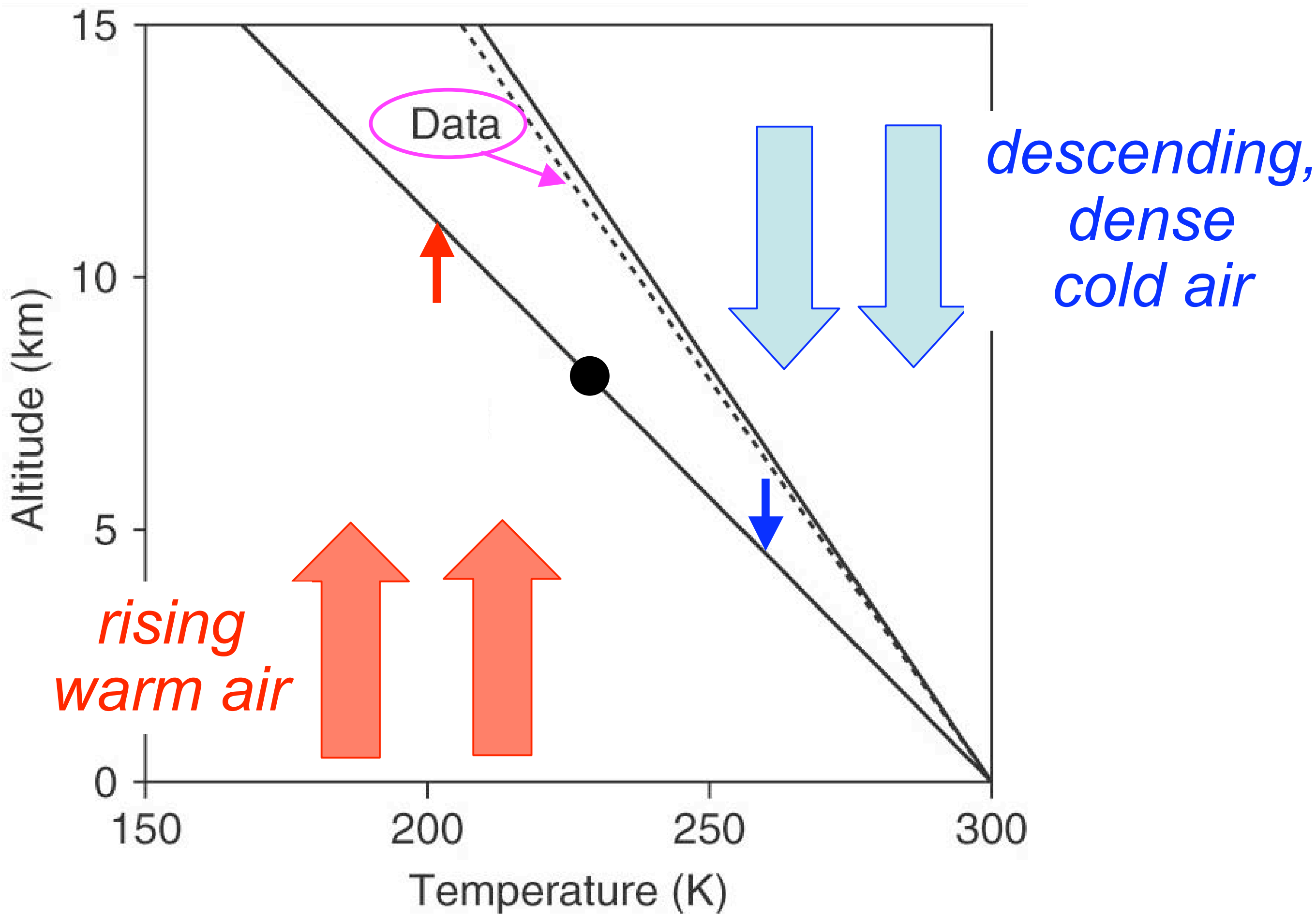
c) hot air rises, cooling the upper part of the vertical profile

d) *both* b) and c)

e) one can’t tell from an understanding of the process alone (a complicated model is needed)

lapse rate

(the change in temperature w/ height)



the change in temperature w/ height is also suppressed by the <u>convection</u> driven by solar heating

what controls the lapse rate in the troposphere?

- adiabatic (expansion) cooling as air rises
- release of latent ("hidden") heat as moist air rises and vapor condenses
- and, vertical mixing by convection when the sun is up

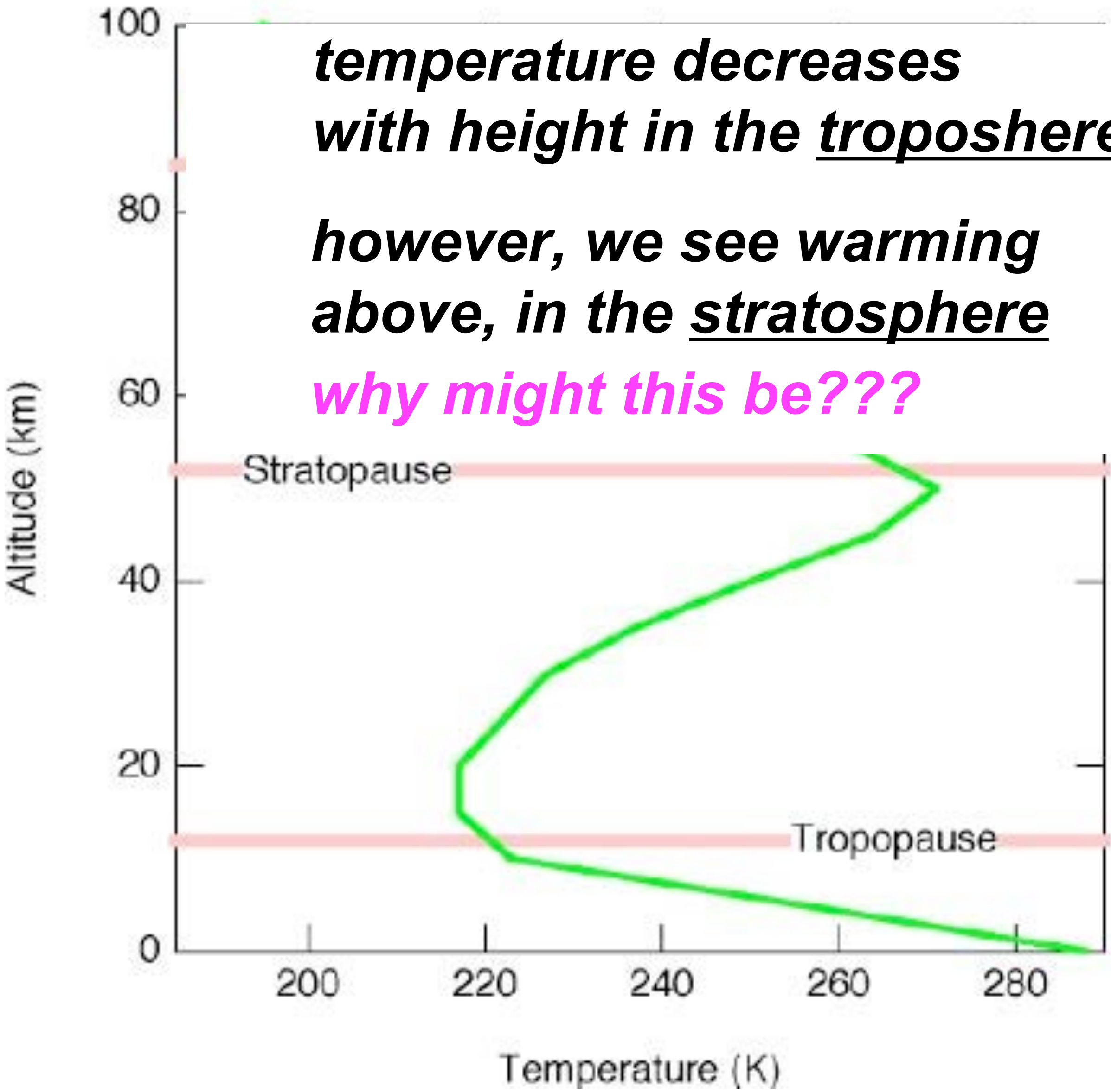
(more on latent heat and convection in your text and upcoming lectures)

temperature structure of the atmosphere

temperature decreases with height in the <u>troposhere</u>

however, we see warming above, in the <u>stratosphere</u>

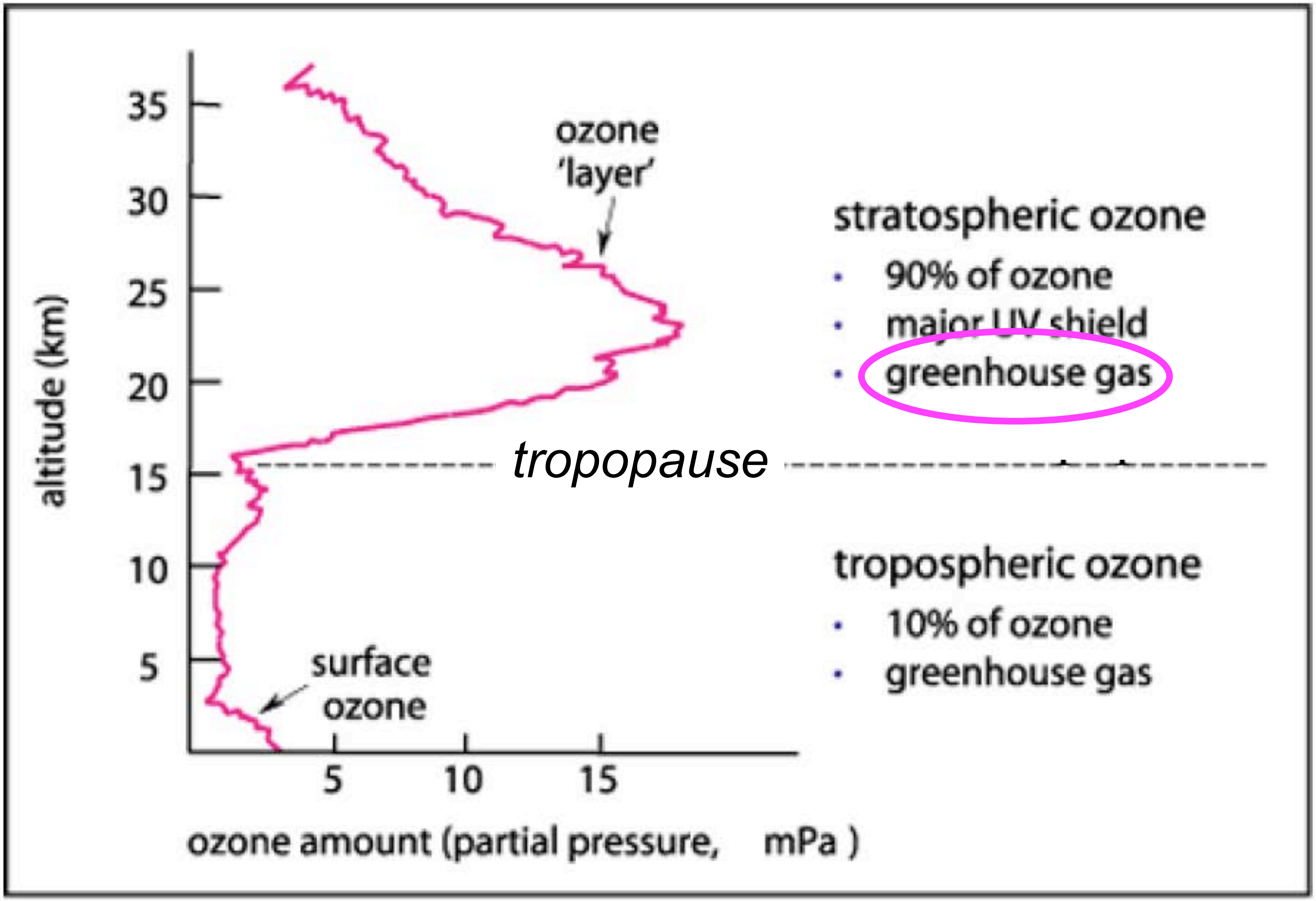
why might this be???



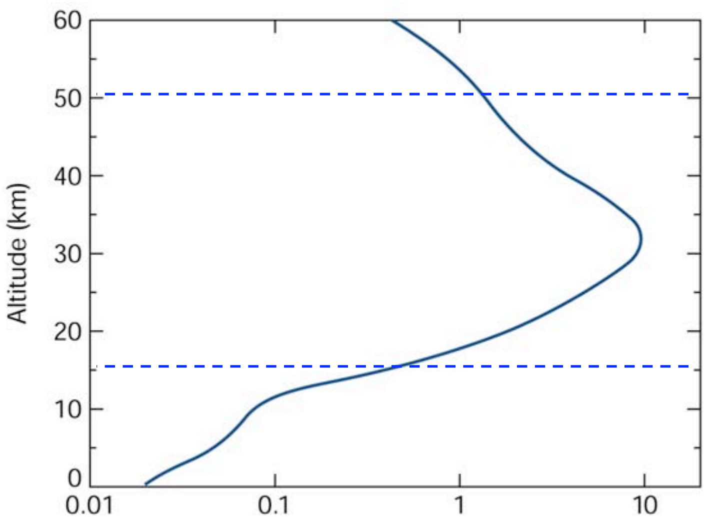
stratosphere

<u>Tropopause</u>: top of troposhere, ie. height at which temperature stops falling rapidly

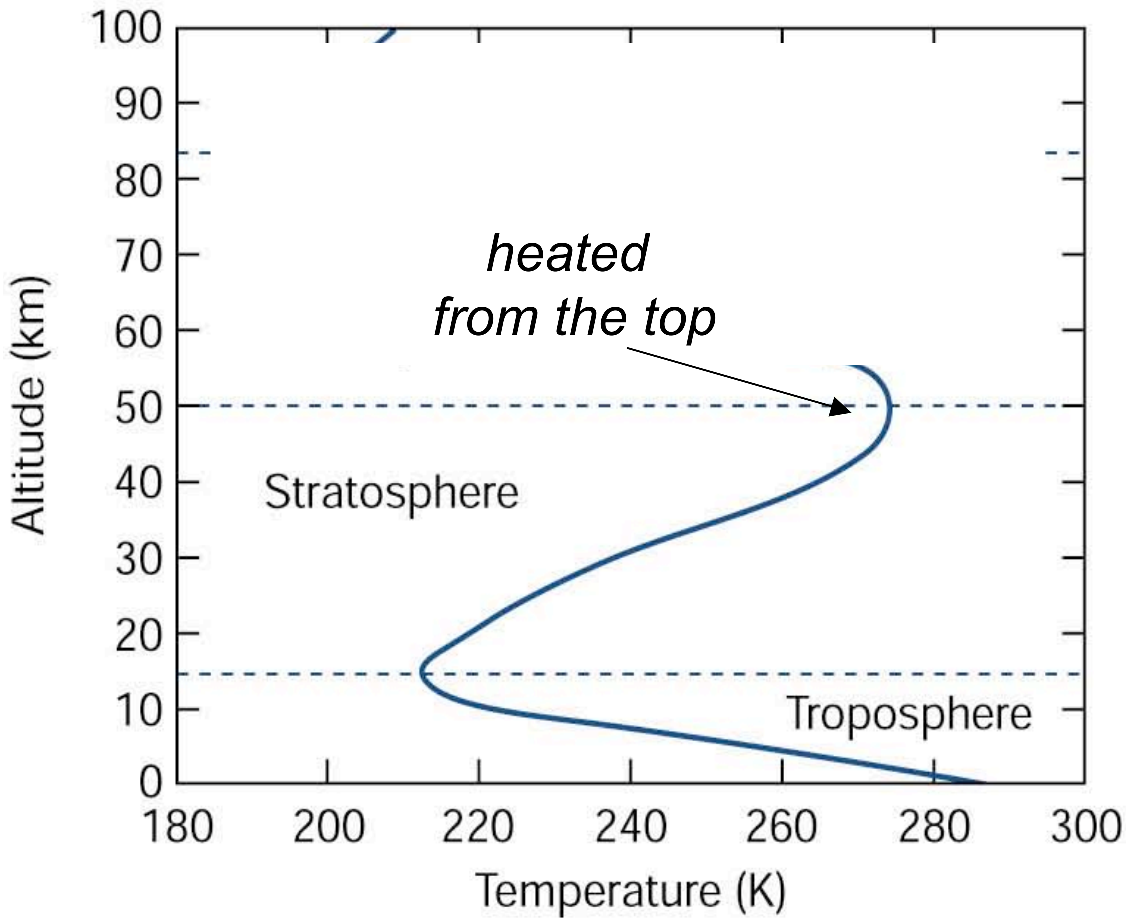
what about ozone?



ozone peaks in the stratosphere

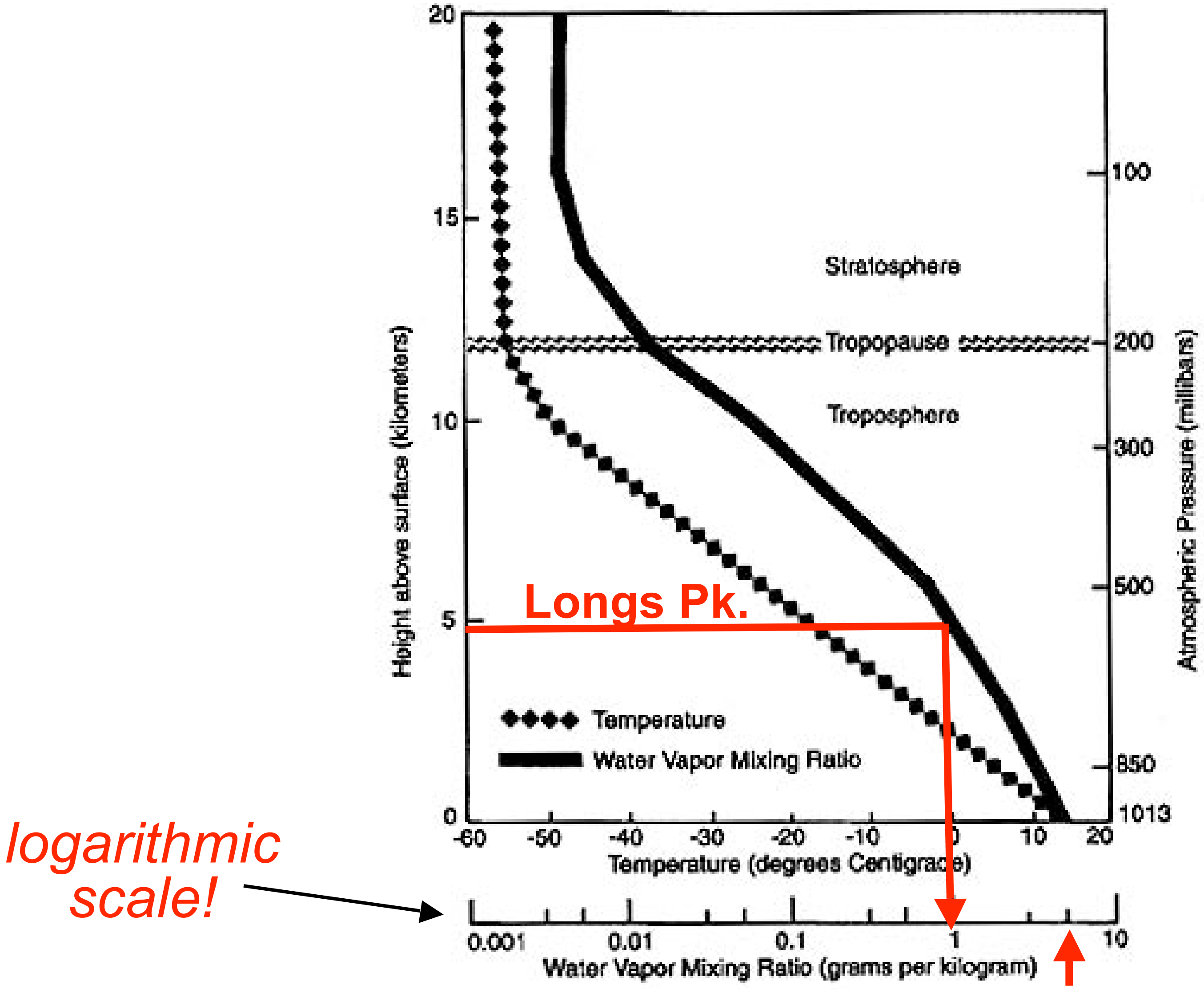


ozone concentration (ppm)



absorption of UV radiation by ozone warms the stratosphere

water vapor in the atmosphere



consider Longs Peak vs. sea level!
(less water vapor by a factor of 5!)

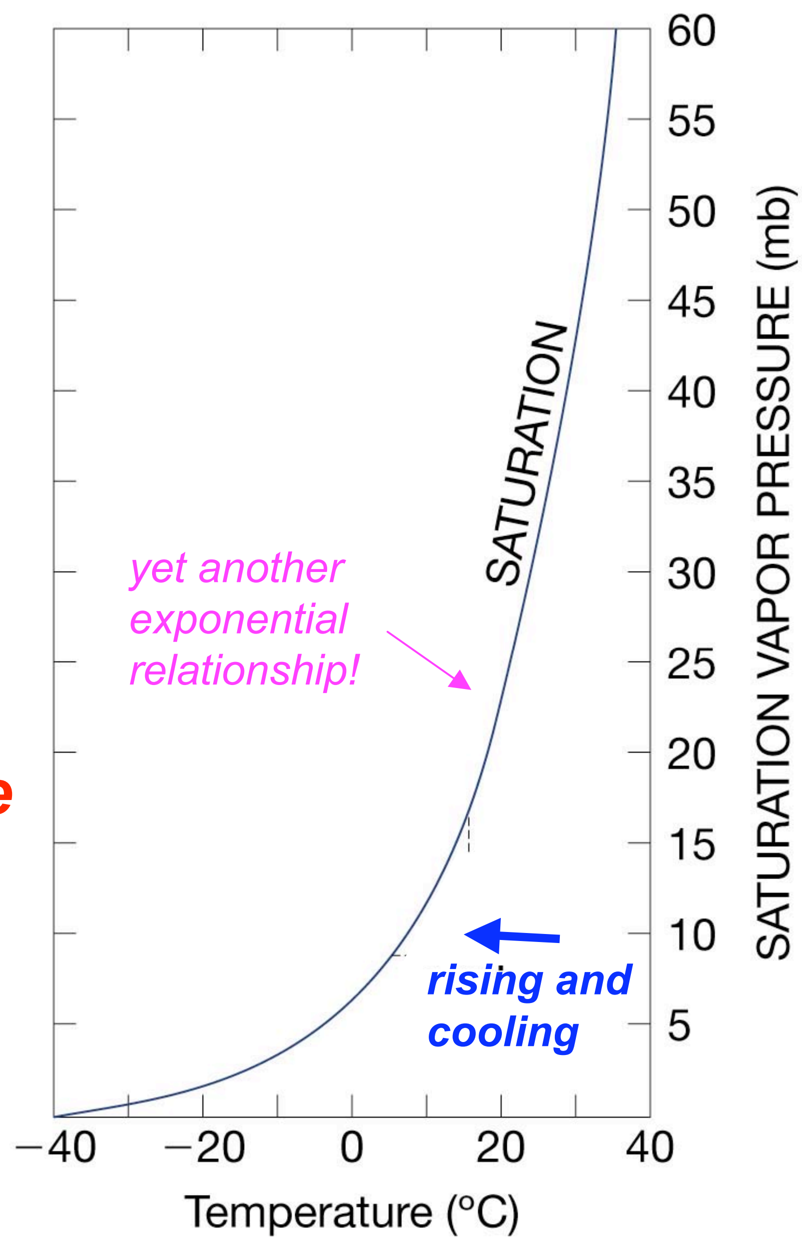
water vapor pressure v. temperature

warm air holds more water, increasingly so at high temperatures......

because air is generally colder at high altitude, it is also drier

rule of thumb:

the saturation vapor pressure (equiv. to amount of water that can be held by a volume of air) goes up ~5% per °C

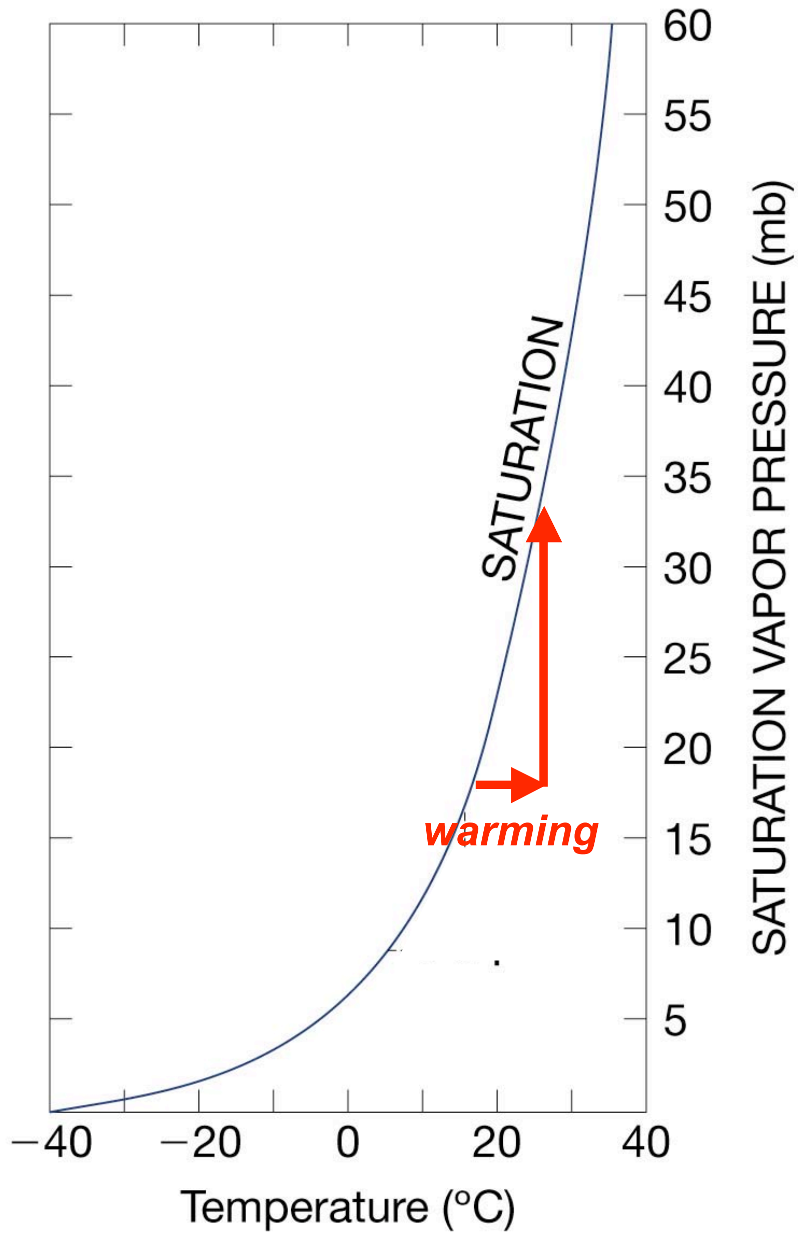


water vapor pressure v. temperature

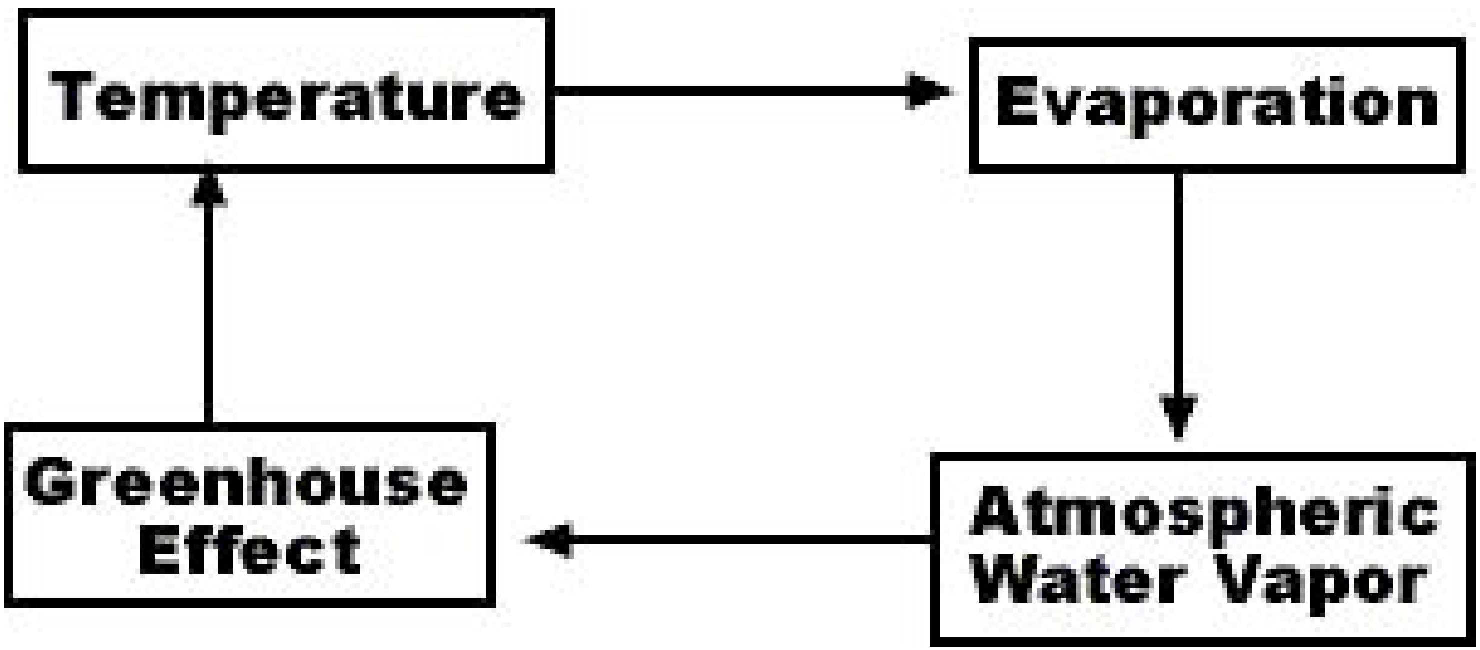
warm air holds more water, increasingly so at high temperatures......

this also means water vapor increases rapidly in a warming atmosphere

(recall water vapor is a GHG)



clicker question:
talk w/ your neighbor



the feedback shown, which includes water vapor and the greenhouse effect (trapping of long wave radiation) is
***a*) negative, *b*) positive, *c*) tending to restore equilibrium, *d*) tending to promote warming, *e*) both b) and d)**

estimated contributions to present greenhouse effect

gas or entity	**percent contribution** (low-high range)
water vapo r	36-66
water vapor plus cloud s	66-85
CO_2	9-26
other GHGs	7-8

only about 1/3 of warming is due directly to CO_2 and other GHGs

does this mean the CO_2 and the other GHGs are not so important?

estimated contributions to present greenhouse effect

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water vapo r	36-66
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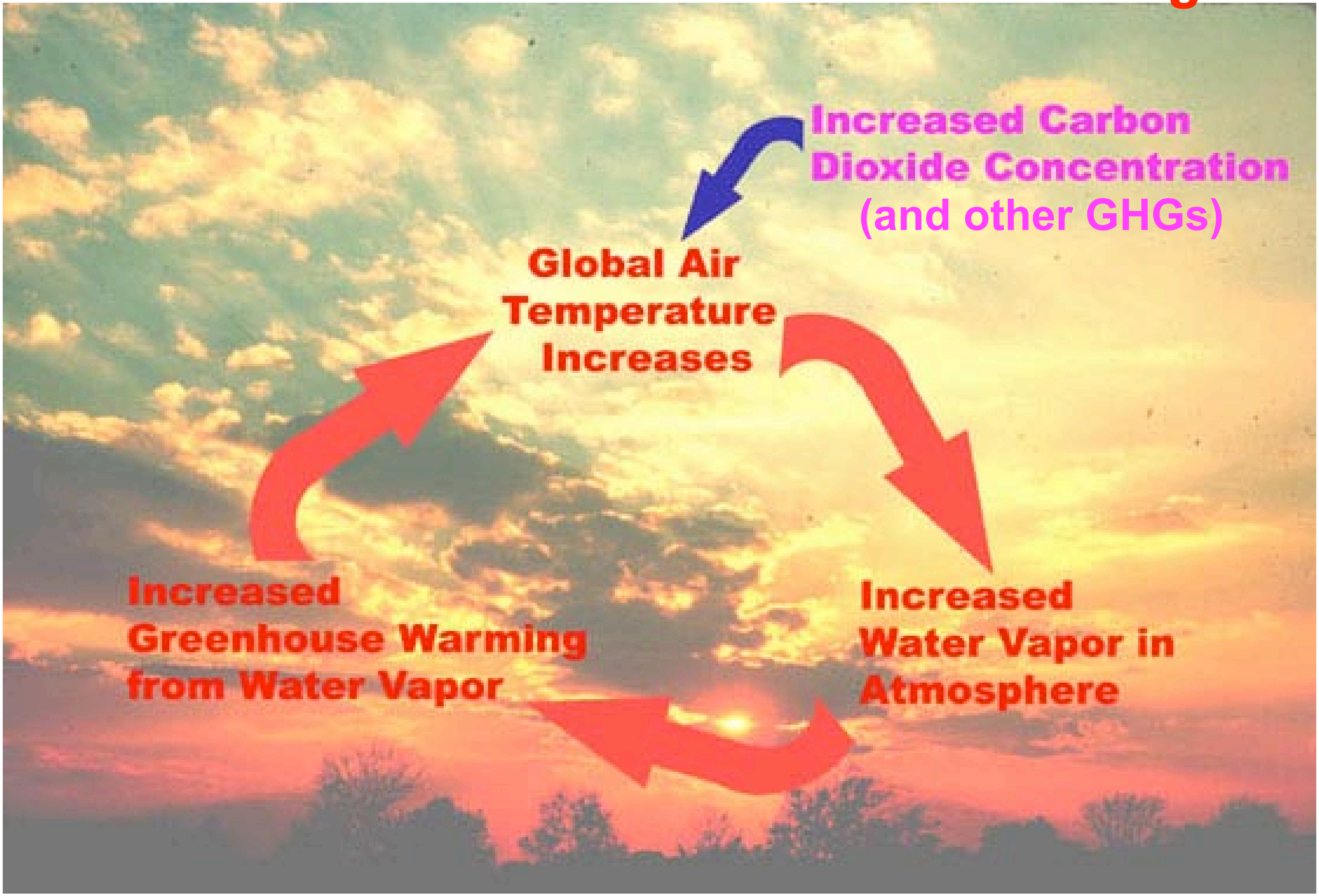
NO! as we have already seen, it reflects the role of water vapor (and clouds) as important <u>feedbacks</u> on the natural (and now enhanced) greenhouse effect

what kind of feedback? what is the forcing?



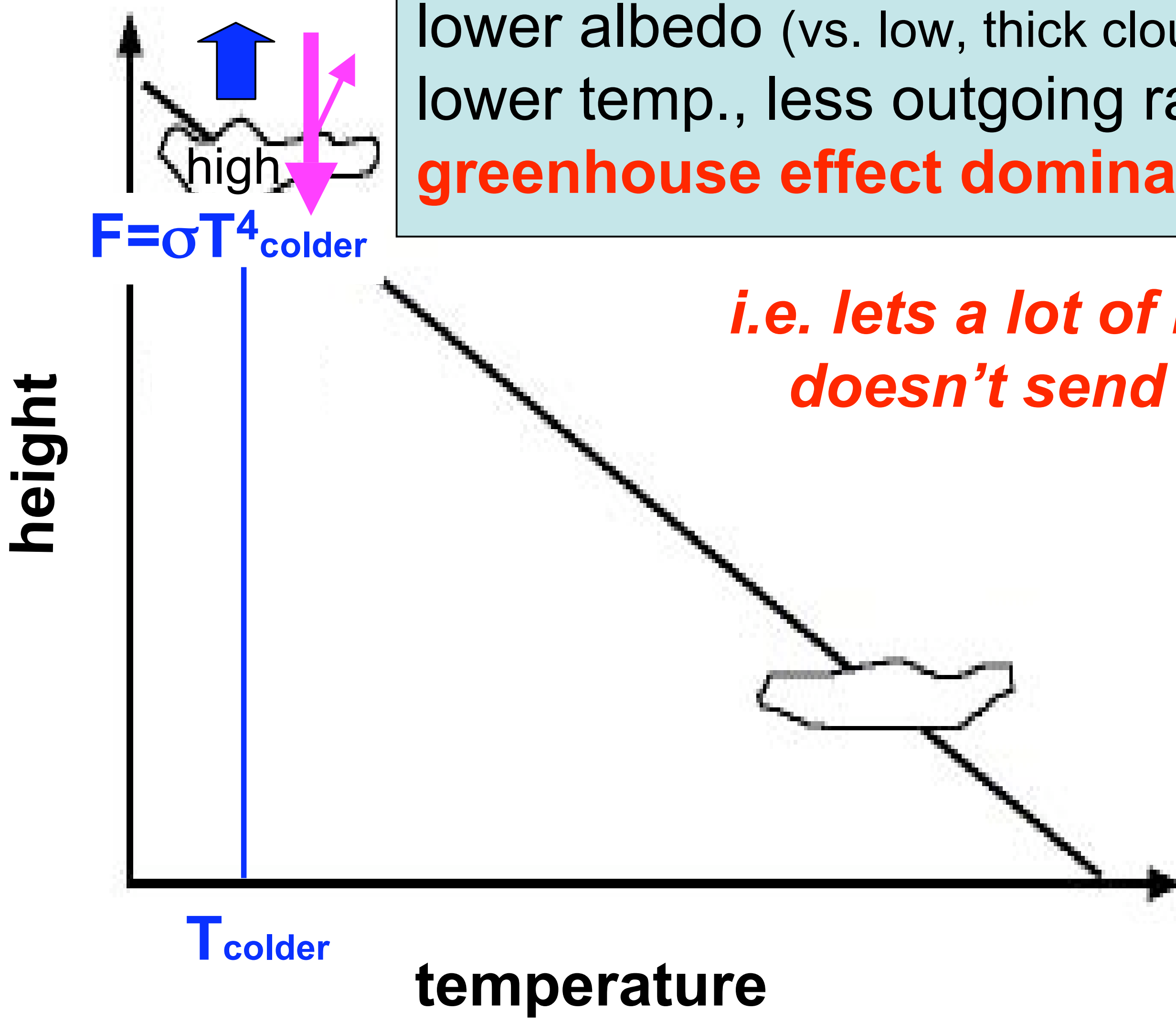
clouds

- clouds are complex in form and distribution and their physical interactions within the climate system are poorly understood
- for purposes of beginning to understand this complexity we can simplify our treatment of clouds by distinguishing between high, thin clouds and low, thick ones…

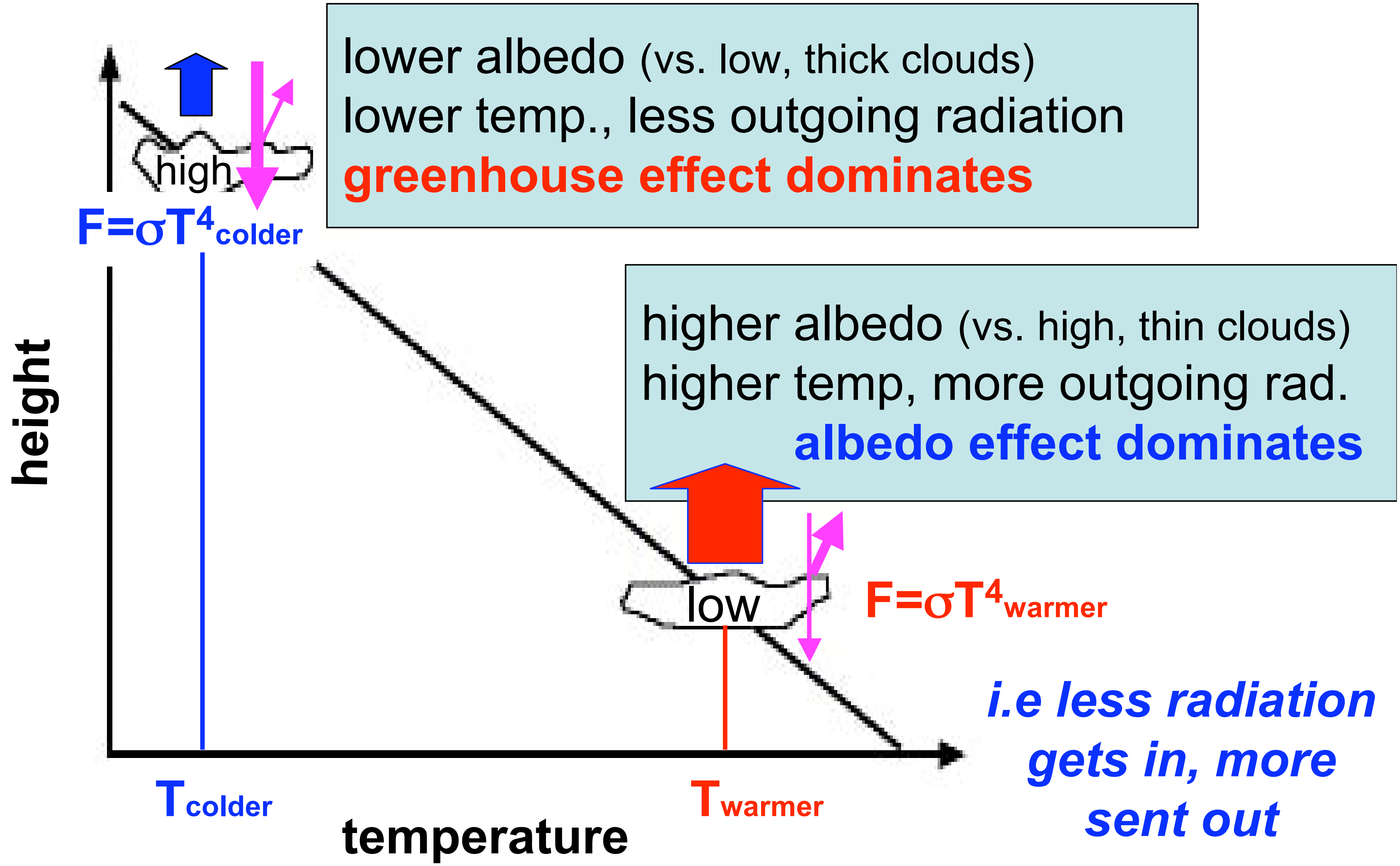
clouds simplified

lower albedo (vs. low, thick clouds)
lower temp., less outgoing radiation
greenhouse effect dominates

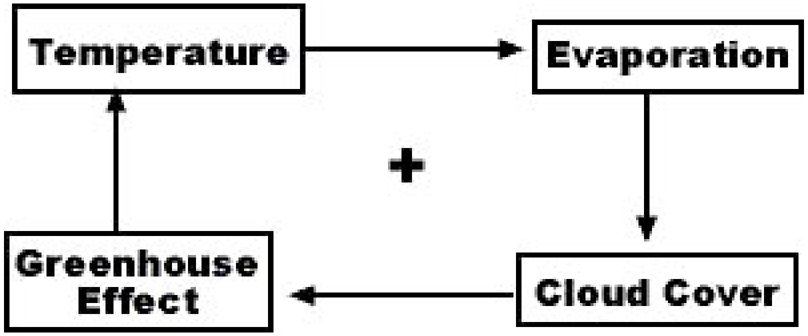
i.e. lets a lot of radiation in, doesn't send much out



clouds simplified

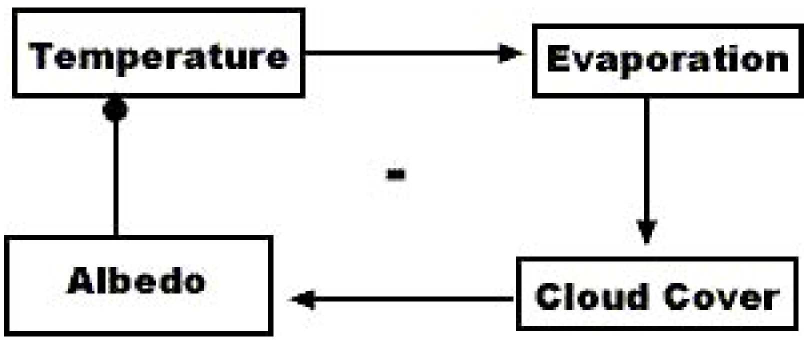


2 opposing cloud effects



the positive feedback associated with "net greenhouse" clouds?

vs.



the negative feedback associated with "net albedo" clouds?

which effect dominates now (and in future?) hard to say.....

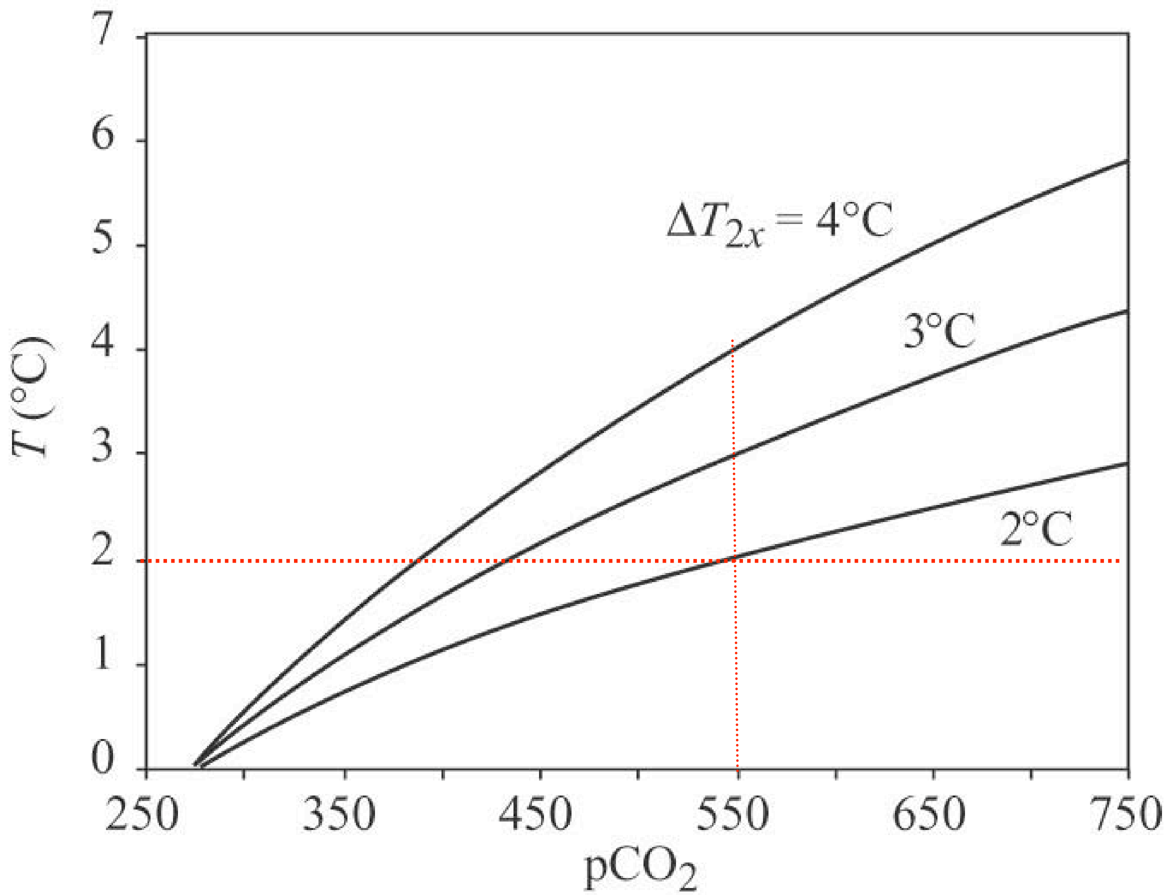
forcing and response

- **climate forcing** - any mechanism that influences the amount of energy received or retained by the climate system (often expressed in W/m^2)
- **climate response** - the response of the climate system to a particular forcing (or forcings), *where the response may include climate feedback processes* (often expressed in terms of a *global average temperature response*)

and climate sensitivity

- **climate forcing** - any mechanism that influences the amount of energy received or retained by the climate system (often expressed in W/m^2)
- **climate response** - the response of the climate system to a particular forcing (or forcings), *where the response may include climate feedback processes* (often expressed in terms of a *global average temperature response*)
- **climate sensitivity - **the ratio of response to forcing, at equilibrium (often therefore expressed as temperature change per W/m^2 or per “CO_2 doubling”)

climate sensitivity



in each case the CO_2 forcing is the same… which case includes the larger pos. feedbacks?

A simple approximation of the global temperature response for different estimates of the climate sensitivity (expressed in terms of ΔT per CO_2 doubling). The uncertainty in sensitivity is due to inadequate understanding of the feedbacks. It now looks like the feedbacks and sensitivity may be larger than previously surmised…

key terms and concepts

GHGs (name and formula)

GHG concentration trends (increasing or decreasing)

density of air vs. height (compressibility)

atmospheric pressure vs. height

millibar

temperature change vs. height

adiabatic or expansion cooling of dry air

lapse rate, moisture and convection

troposphere, stratosphere

saturation vapor pressure (air's water "holding power")

water vapor - temperature feedback

energy balance of high and low clouds

climate forcing, response (incl. feedback), and sensitivity

summing up

- so far, we have considered the Earth as a whole
- in order to begin to understand changes at smaller scales, we will need to think about how winds and currents move heat from one place to another
- this we will begin next class
- reading: Ch. 6