Fundamentals of Climate Change (PCC 587): Water Vapor

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DAY 2: 9/30/13

Water…

- Water is a remarkable molecule
  - Water vapor
    - Most important greenhouse gas
  - Clouds
    - Albedo effect **&** greenhouse effect
  - Ice
    - Albedo in polar latitudes
    - Ice sheets affect sea level
  - Ocean
    - Circulation, heat capacity, etc

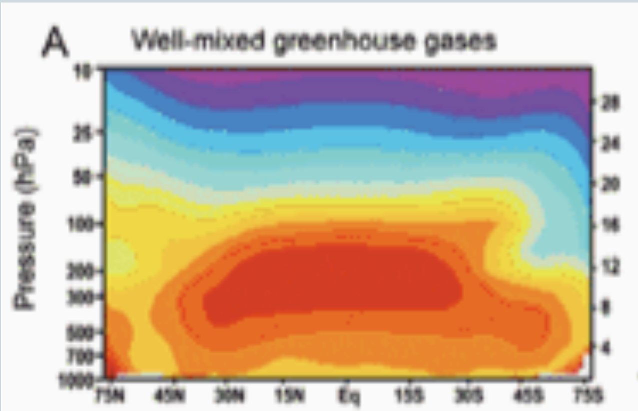
- Next topic:
  - **Phase changes** of water (e.g., condensation, evaporation…) are equally fundamental for climate dynamics
    - Phase change → heat released or lost (*"latent heating"*)

Outline…

- Why water vapor content will increase with global warming
  - *Feedback* on warming, not a *forcing*
- Effect of water vapor on current climate:
  - Vertical temperature structure
  - Horizontal temperature structure

Along the way…

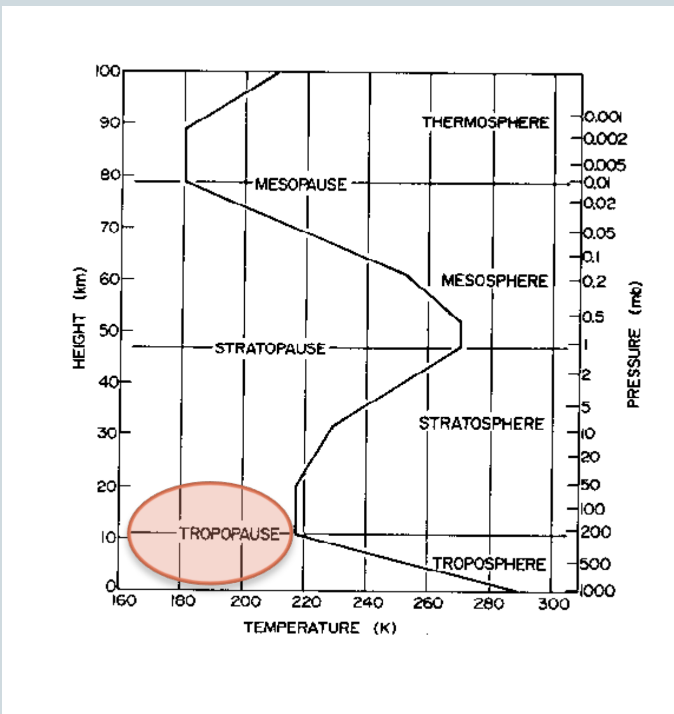
- The controversy about whether the upper troposphere has warmed in recent decades
  - And why global warming would be a lot worse if it didn't warm up there…

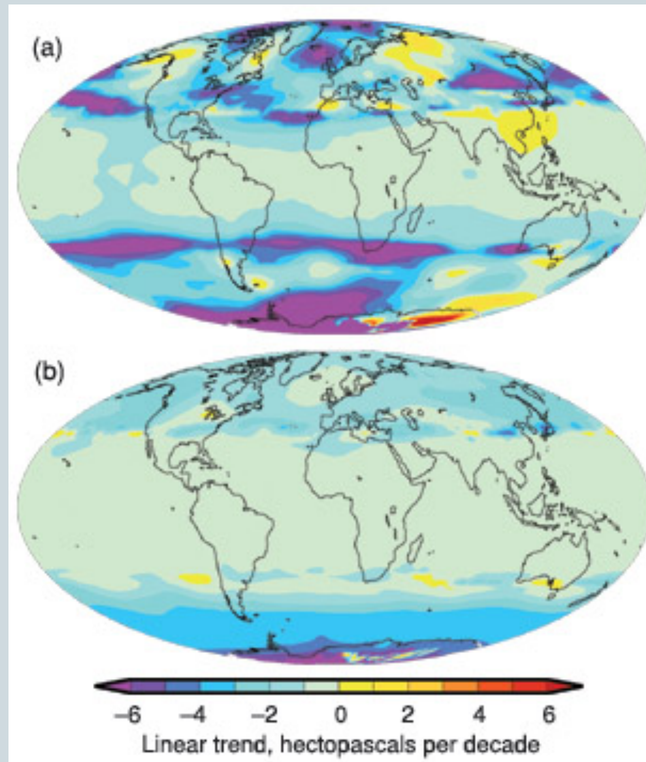


Modeled temperature trends due to greenhouse gases

Along the way…

- Why the tropopause will rise with global warming
  - Three separate effects cause a rise in tropopause height: result is the sum of all three!

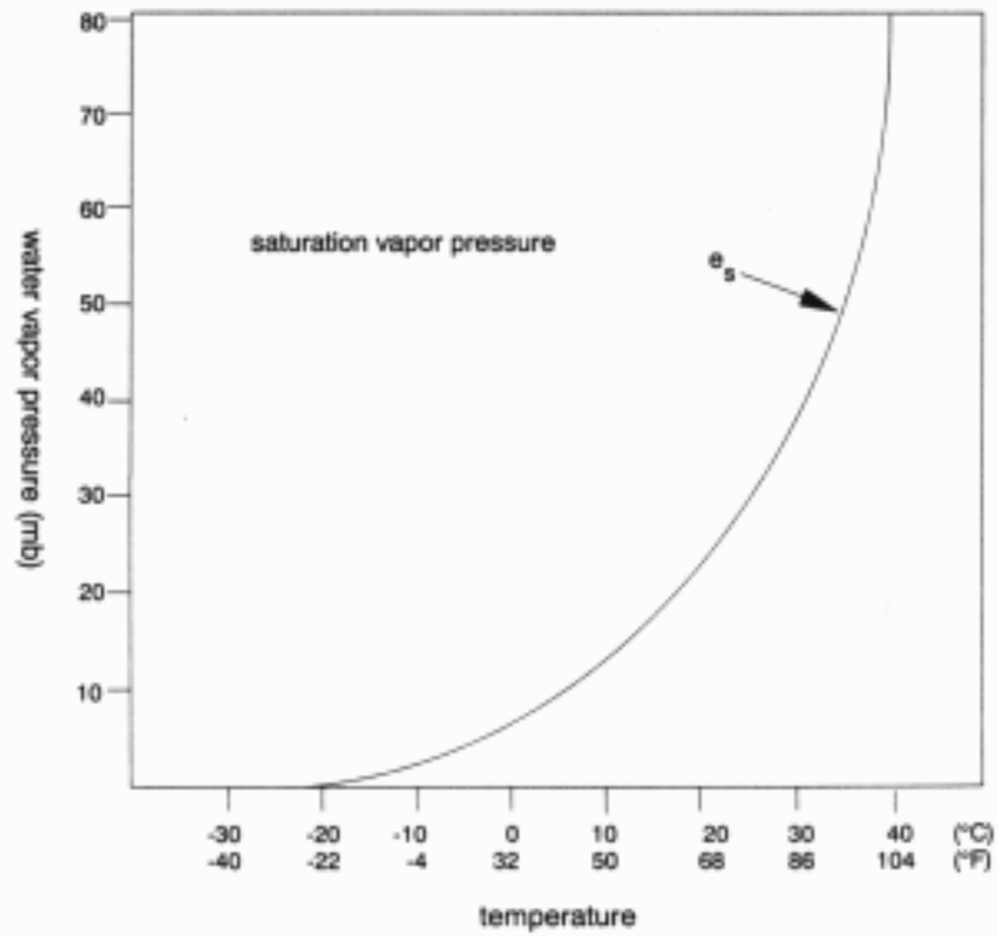




Tropopause height rise in observations versus models

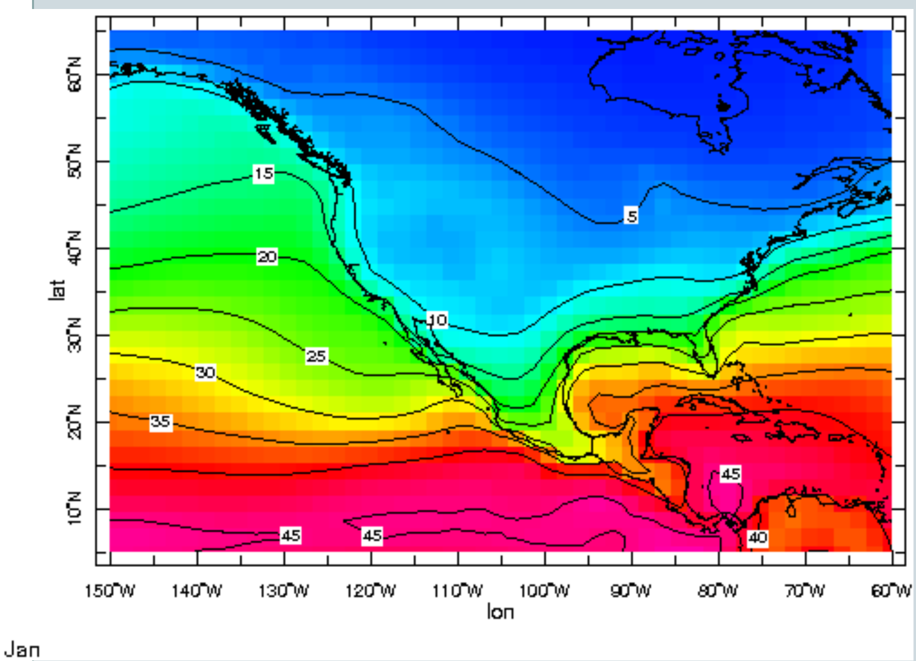
Introduction to Moisture in the Atmosphere

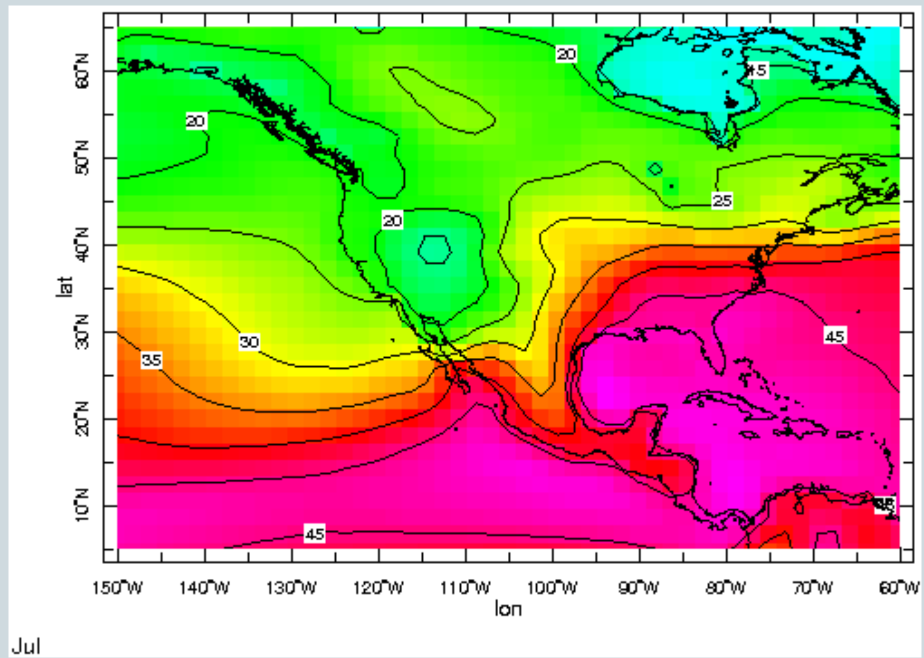
- Saturation vapor pressure:
  - Tells how much water vapor can exist in air before condensation occurs
- **Exponential** function of temperature
  - Warmer air can hold *much* more moisture



Saturation Vapor Pressure

- Winters are much drier than summers
  - Simply because cold temperatures means small water vapor content



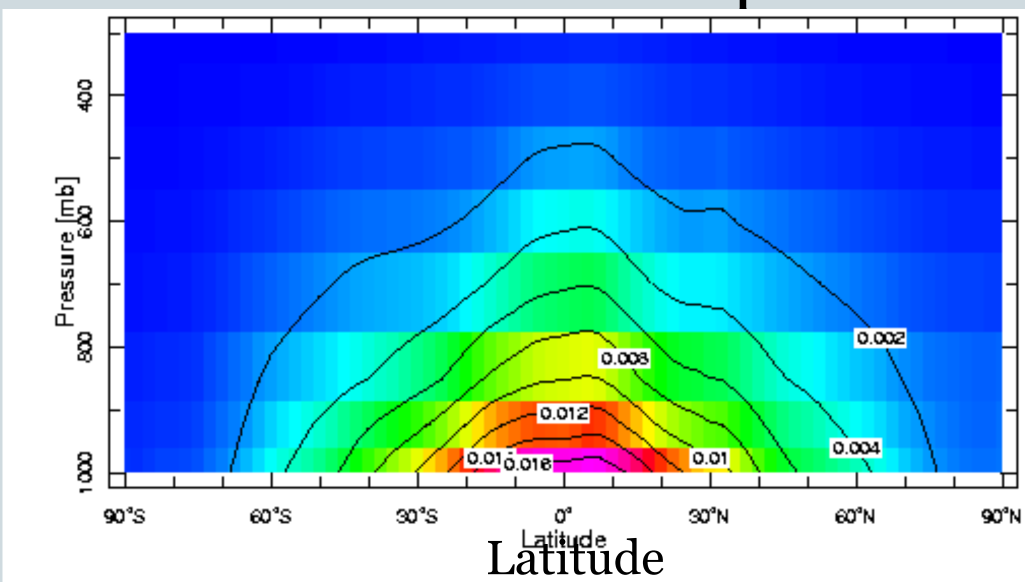


January average surface humidity (in C) July average surface humidity (in C)

Saturation Vapor Pressure

- Temperatures decrease with height in the troposphere
- This means most water vapor is confined in the lower levels in the atmosphere as well

Pressure

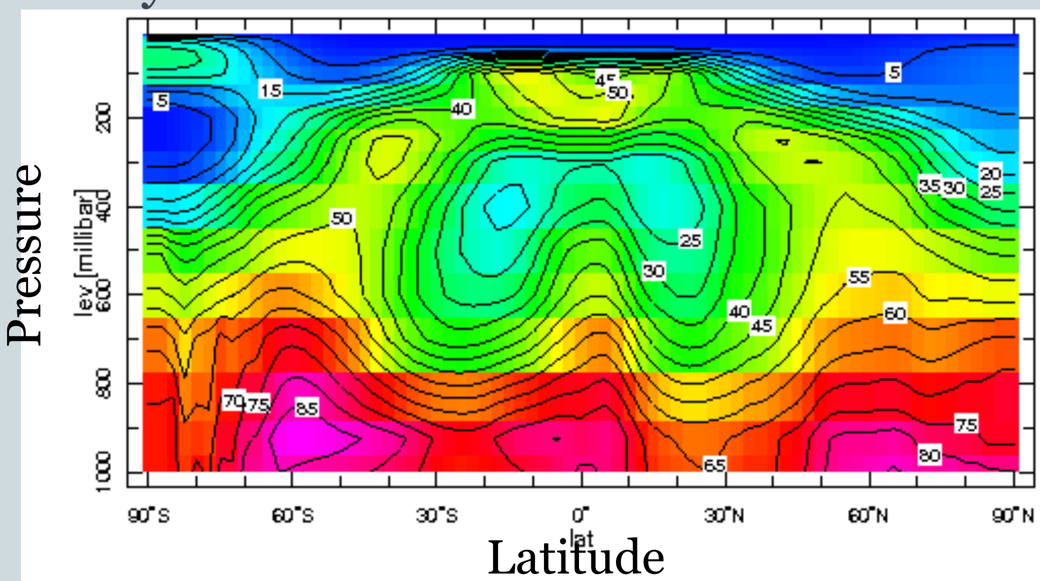


Annual and zonal mean **humidity content** (in kg/kg)

- Also concentrated in the warmer tropics…

Relative Humidity

- Relative humidity = vapor pressure/saturation vapor pressure
  - Saturation at 100% RH
  - Dry → 0% RH



Zonally and annually averaged relative humidty

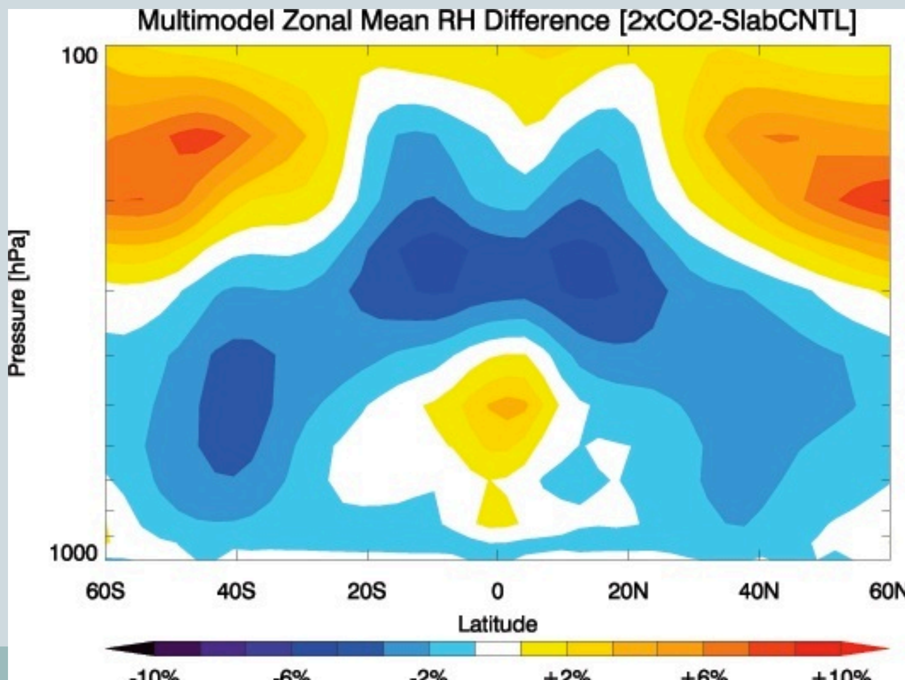
  - Generally higher in rainier regions, and lower in drier regions

Water Cycle

- Evaporation occurs from ocean surfaces or wet land surfaces
  - Proportional to 1-RH (drier air evaporates more)
- Saturation occurs within the atmosphere
  - Condensation & precipitation is formed
- Evaporation and precipitation balances in steady state
  - This also determines the relative humidity of the atmosphere

Relative Humidity

- Relative humidity expected to stay roughly the same with climate changes
  - If it didn't, there would be more evaporation, which would humidify the atmosphere



Simulated changes in relative humidity with global warming
(note there are only small changes)

Water Vapor Content and Global Warming

- Constant relative humidity → warmer climates have much more moisture!
  - 7% increase per degree of warming
- More water vapor → more water vapor greenhouse effect
  - Primary positive feedback to global warming
- Water vapor is a *feedback* to climate change, not a *forcing* of climate change
  - Can't change water vapor content directly: it responds to the global mean temperature

Tropical Water Vapor Content

- Water vapor content has been increasing (tropics only shown here)
  - Big peaks are El Niño events
  - Climate models can simulate water vapor content well given sea surface temperatures

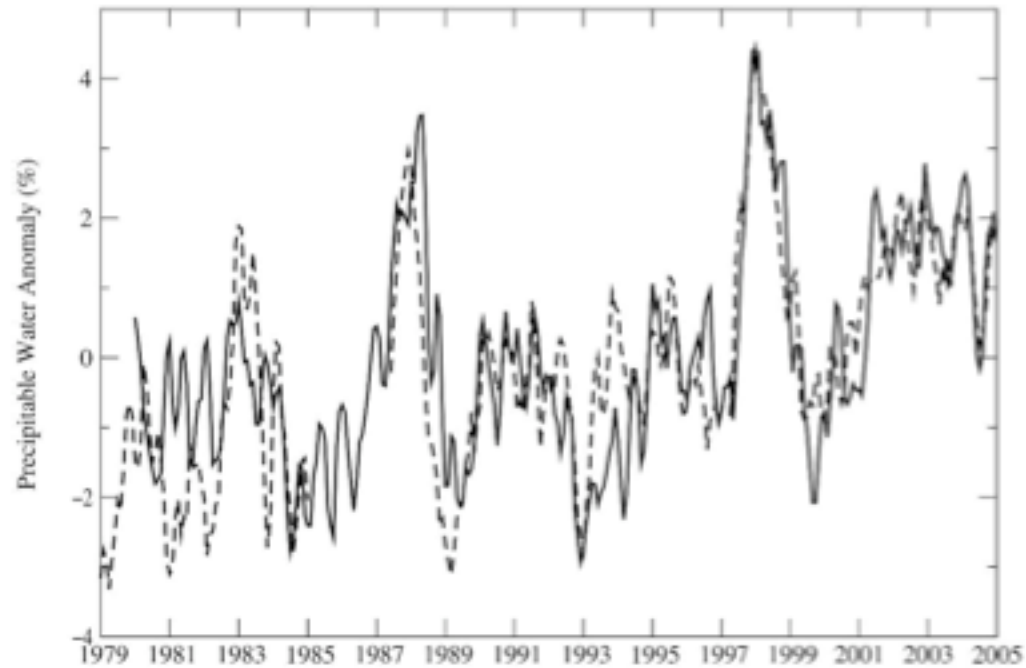


FIG. 1. A time series of the tropical-mean (30°N–30°S), ocean-only column-integrated water vapor from satellite observations (dashed) and GFDL GCM simulations with prescribed SST (solid). The satellite observations for 1979–84 are from the SMMR (Wentz and Francis 1992) and for 1987–2004 are from the SMM/I (Wentz 1997). The mean seasonal cycle is removed from both the observations and model simulations, and the SMMR anomalies are adjusted such that their mean equals that of the model for their overlapping time period (1980–84). All time series are smoothed using a 3-month running mean.

Summary so far…

- **Warmer temperatures → more moisture can exist in air**

- Next: the effects on *energetics*
  - **Phase changes** are associated with **heating/cooling**

Condensation and Latent Heating

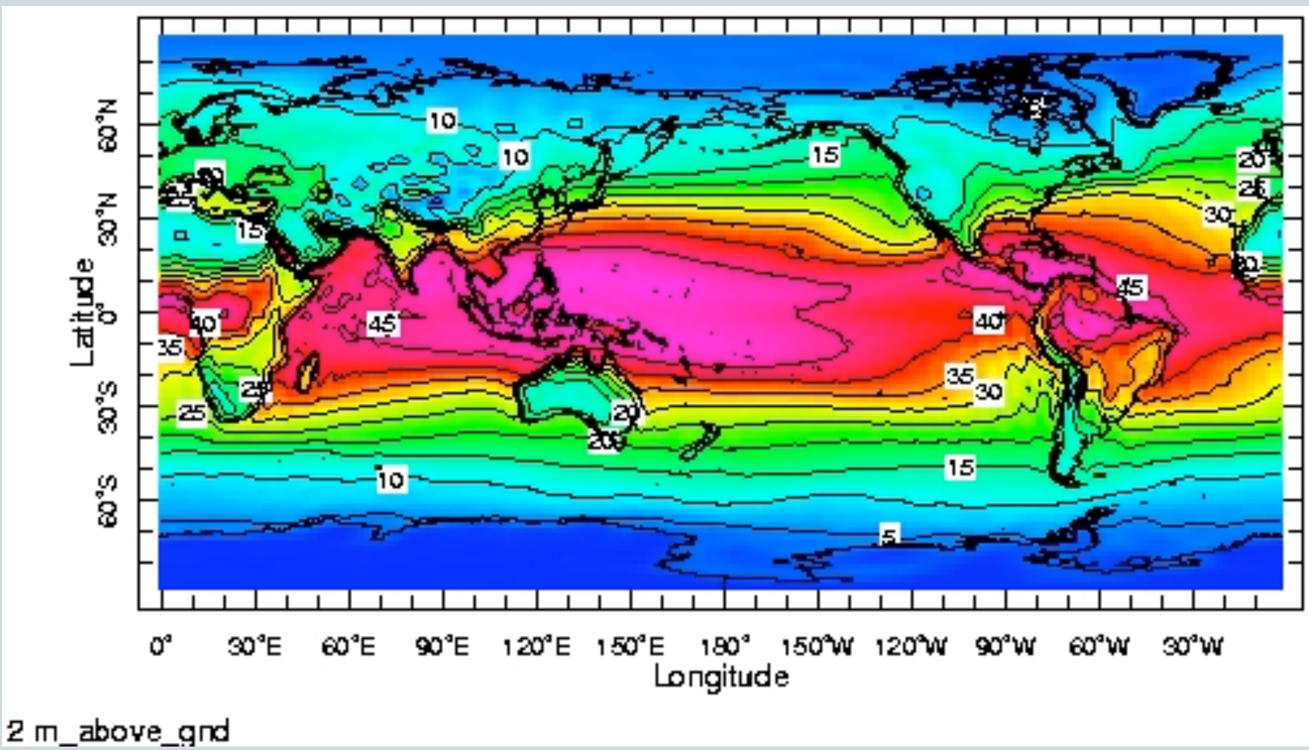
- We're all familiar with the idea that evaporation causes cooling
  - Evaporation of sweat cools you off
  - Getting out of a pool on a windy day → cold!
- Similarly, **condensation** -> **heating** of the atmosphere
  - Condensation of water vapor is associated with a release of latent heat
  - Huge heat source:
    - Average tropical lower tropospheric moisture values: 45° C of heating potential!

Freezing as a Latent Heat Source

- Freezing is also associated with latent heat release
  - It's a significantly smaller heat source though
  - Latent heat of vaporization: 2.5 x 10^6 J/kg
  - Latent heat of fusion: 3.3 x 10^5 J/kg

Moisture Content of Atmosphere

- Observed surface water vapor content
  - Measured in degrees (Celsius) of warming that would occur if all the moisture was condensed out at once



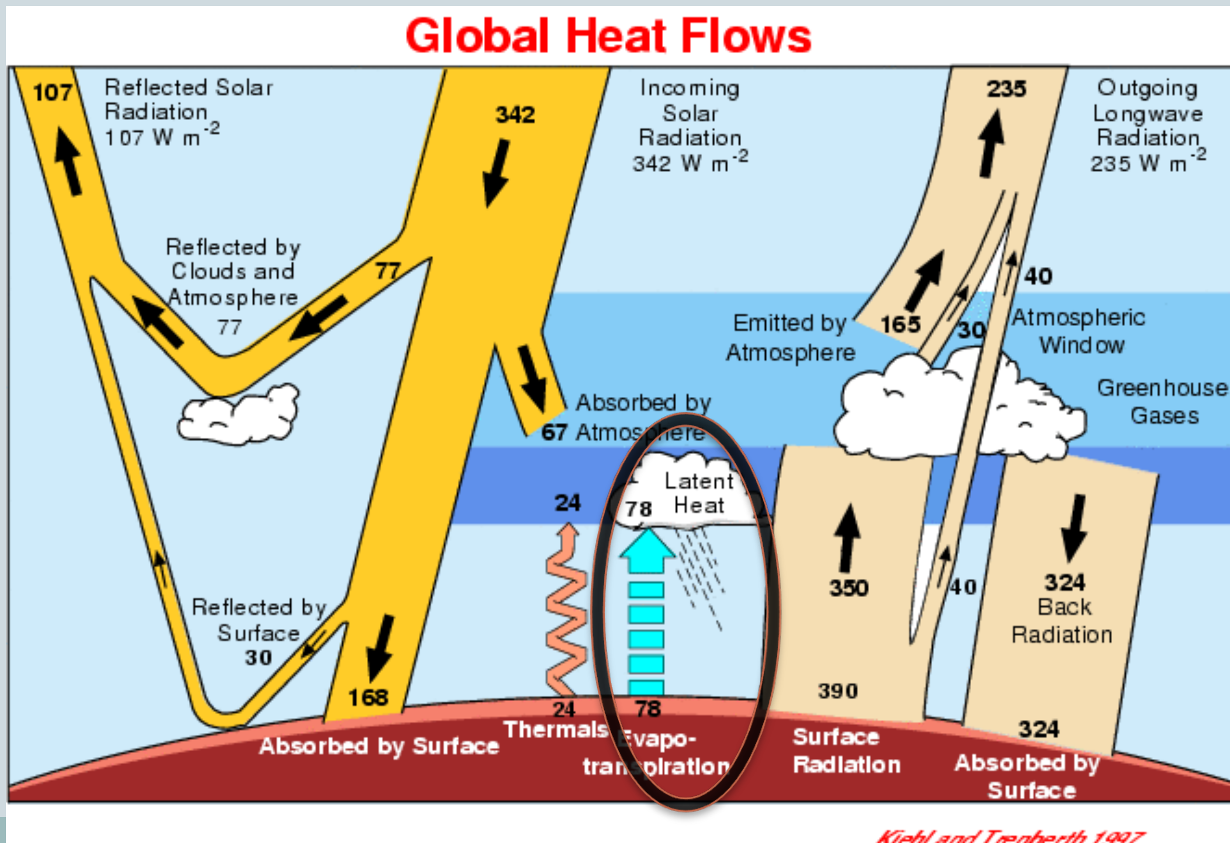
Latent heating is huge potential heat source!

All of this moisture is condensed out in storms or large scale circulations

Source: NCEP Reanalysis

Latent Heating in Energy Budget

- Evaporation/condensation is primary way that energy is transferred from surface to atmosphere:

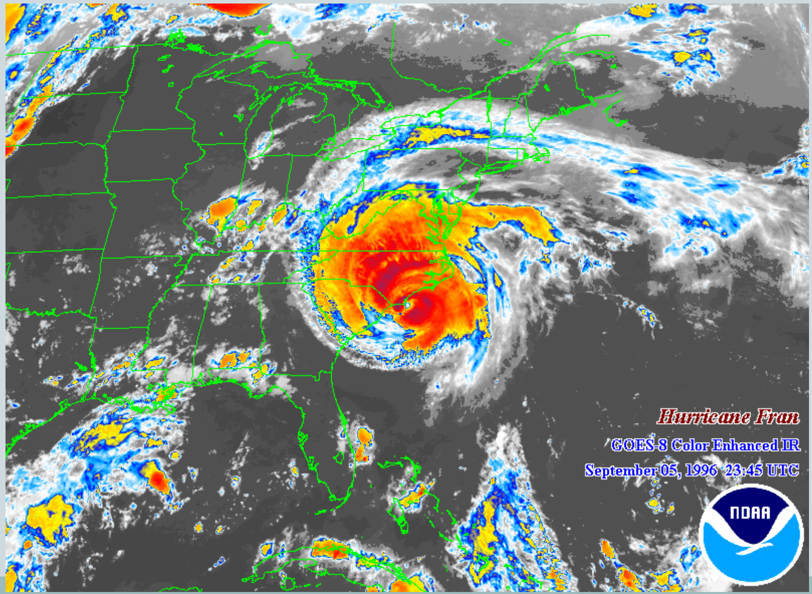


Latent heat flux = 78
Sensible (thermal) heat flux = 24
Net radiative flux from surface to atmos = 350-324 = 26

Over 60% of heat is transferred off of surface by moisture!

Latent Heating in Hurricanes

- Hurricanes
  - Evaporation from ocean surface is fuel
    - Why hurricanes dissipate over land
  - Condensation is like the combustion of that fuel!
    - Huge latent heat release powers winds, etc



Hurricane Fran (1996)

Water Vapor and Global Warming

- With global warming, atmospheric moisture content will increase
  - Over 20% increase in humidity with 3^o C global temperature increase
    - Tropics will have 55^o C of latent heating potential instead of 45^o C
- What effects will the increased moisture content have on the Earth's climate?
  - More fuel for hurricanes & extratropical storms
    - Don't panic yet though…
  - Also affects temperature gradients, vertical temperature profile
    - We'll show these are both negative feedbacks

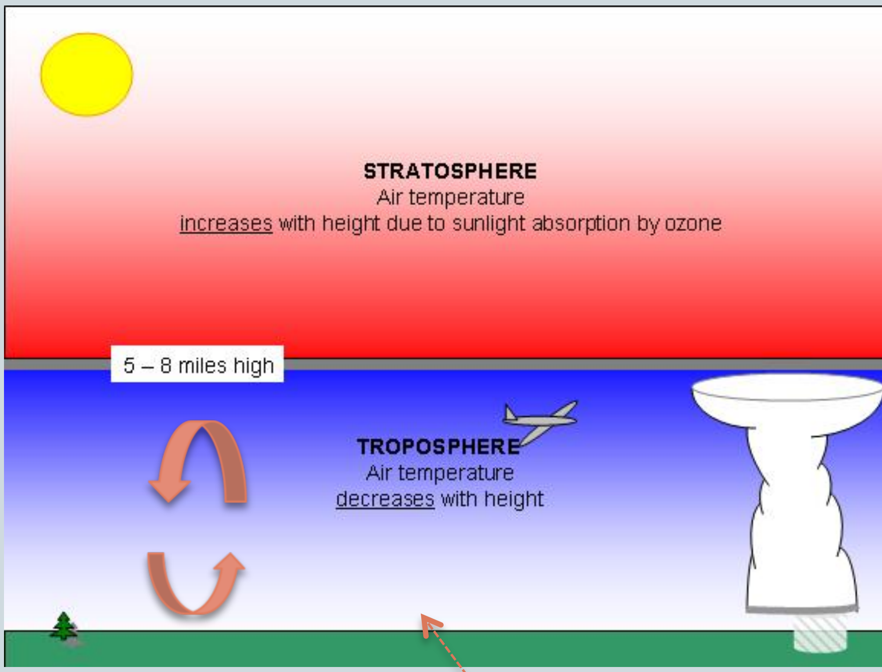
Summary so far…

- Warmer temperature → more moisture can exist in air
- **Condensation of water vapor causes a huge amount of heating**

- Next:
  - How this impacts the vertical temperature profile of the atmosphere
    - "Lapse rate": rate of temperature decrease with height
      - Primary negative feedback to global warming!

Layers of the Atmosphere

- Troposphere: layer where all weather occurs



Troposphere

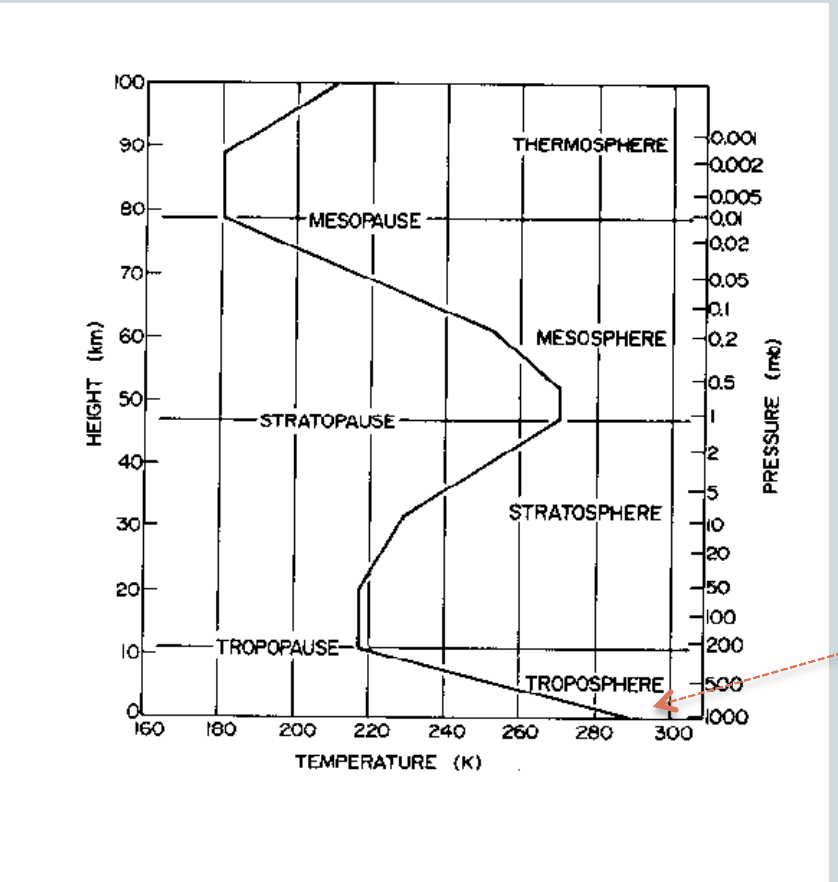
- The Sun heats the atmosphere strongly from below

- Troposphere is the layer where convective overturning and vertical mixing occurs

Key difference between atmosphere and ocean:
atmosphere heated from below,
ocean heated from above

Observed Temperature Structure

- Schematic of temperature structure with height:



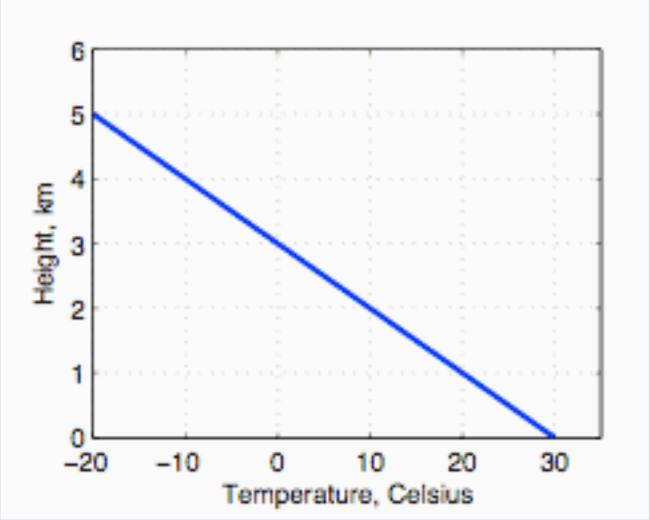
In the troposphere, there are rapid decreases of temperature with height (6.5° C/km)

A Dry Atmosphere

- In a dry atmosphere forced from below, convection (vertical overturning) occurs, and temperatures decrease as air goes to lower pressure
- Lapse rate - $\frac{dT}{dz}$ is constant in this atmosphere,

$$\frac{dT}{dz} = -\frac{g}{c_p} = -9.8^{\circ}C/km$$

"dry adiabatic lapse rate"



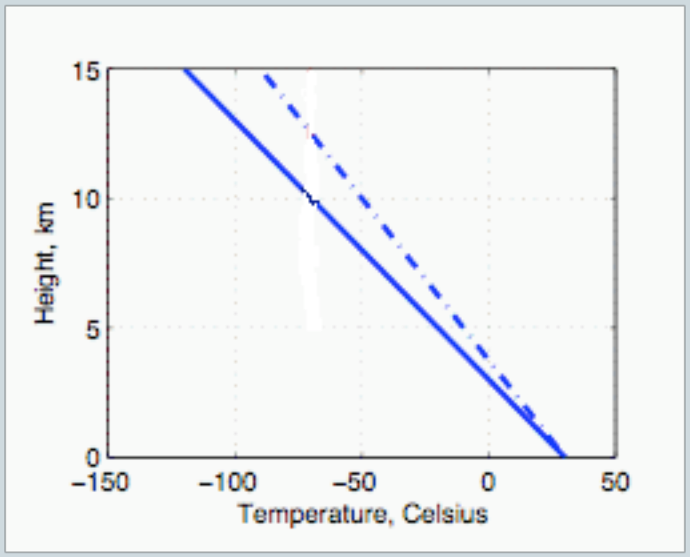
Note this is much larger than the observed lapse rate of 6.5° C/km

Lapse Rate and Static Stability

- Lapse rate compared with dry adiabatic lapse rate (9.8^{o} C/km) tells you atmospheric stability to dry convection
  - Determines "buoyancy frequency" (springiness) of atmosphere
  - Observed lapse rate of 6.5^{o} C/km means atmosphere is stable to dry convection

Missing Ingredient from our Model: Moisture

- Observed lapse rate of 6.5° C/km is due to moisture condensation
  - Moisture condenses as it rises, releasing heat



Solid: dry
Dashed: with moisture

Dashed curve is just a schematic:
Moisture make the lapse rate not
constant with height (*moist adiabatic* profile)

Moisture and Lapse Rate

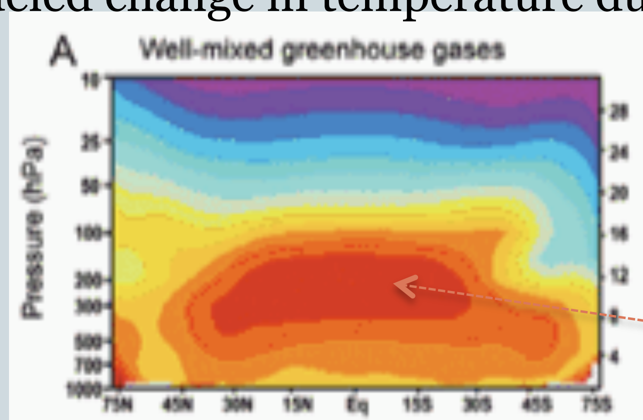
- Moisture makes the lapse rate less
  - Around 6.5° C/km instead of 9.8° C/km
- How accurate is a *moist adiabatic* temperature profile?
  - It's essentially **exact in the tropics** where there's lots of moist convection
    - And remember the tropics are a large percentage of the globe…
  - In **extratropics**: combination of moist convection and eddies
    - Observed lapse rate is smaller than moist adiabat on average (but relatively close to it)
  - In **polar regions in winter**, there's no sunlight so atmosphere get much more stable
    - Moist adiabat is bad approximation there

Temperature Changes with Global Warming

- Temperature change is predicted to be larger in upper troposphere than lower troposphere
  - Due to increased moisture content: more condensation → more moisture condensed out as air rises

Modeled change in temperature due to GHGs

Height



Stratosphere

Latitude

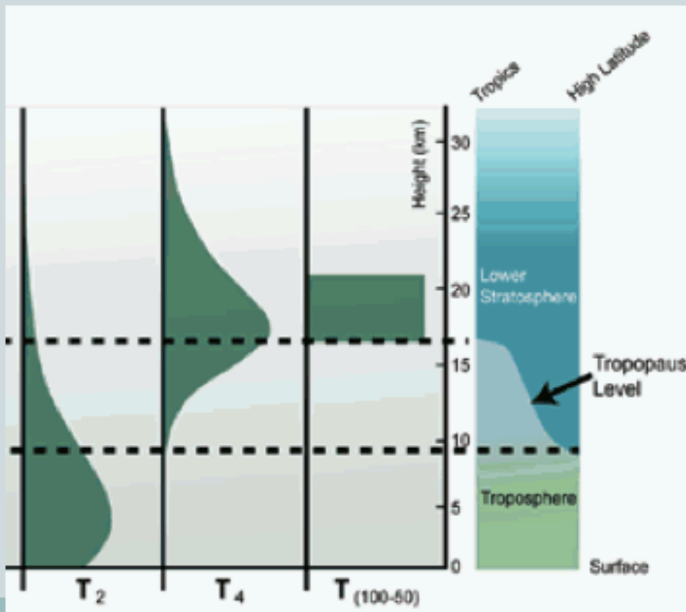
Warming is maximum in upper troposphere in all locations but polar regions

Lapse Rate Feedback

- Due to the greenhouse effect, outgoing longwave radiation on Earth comes from high levels in the troposphere
- Moisture causes the highest levels to warm the fastest
  - This means OLR can increase faster: negative feedback to warming!
  - Primary negative feedback to global warming
- Highly correlated with water vapor radiative feedback in models
  - Models that increase water vapor less have less positive radiative feedback, but also less negative lapse rate feedback
  - Sum of the two feedbacks is positive

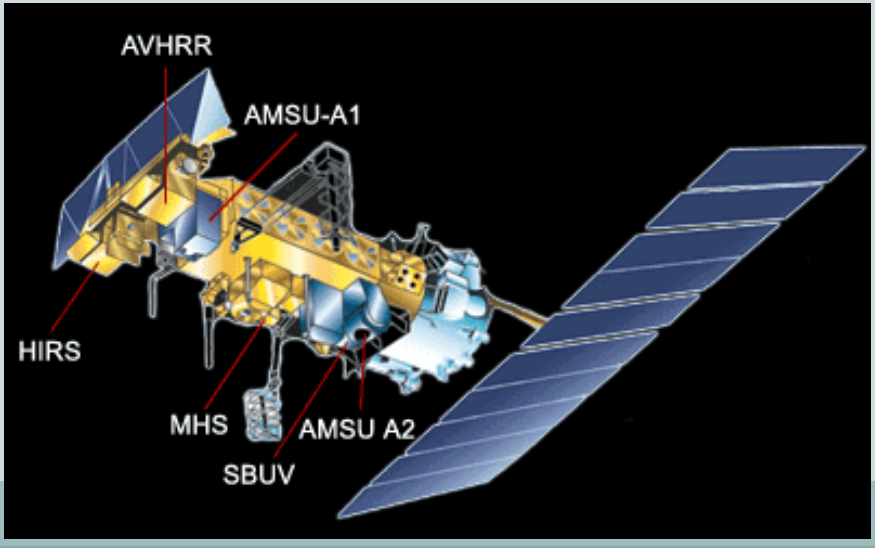
Observations of Upper Tropospheric Temps

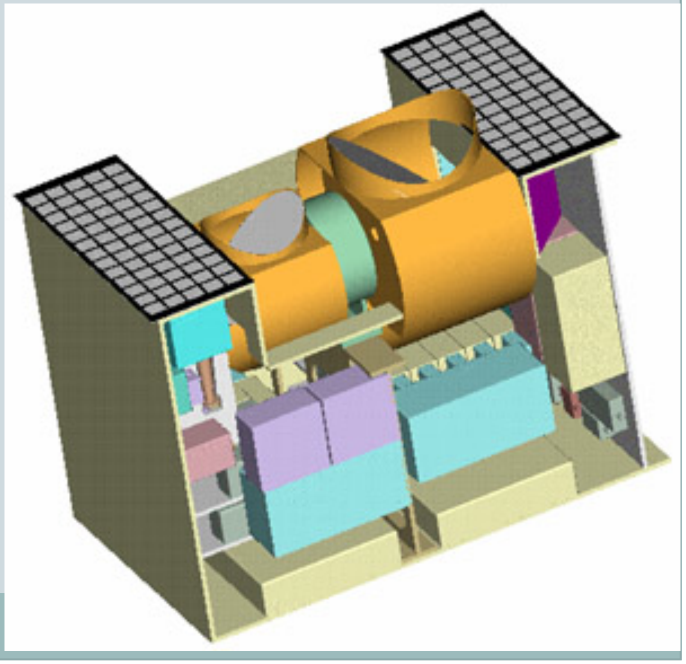
- Major controversy about whether upper tropospheric *satellite data* has shown warming
  - It's difficult to measure b/c measurement combines upper tropospheric (which is likely warming) with lower stratosphere (which is likely cooling)

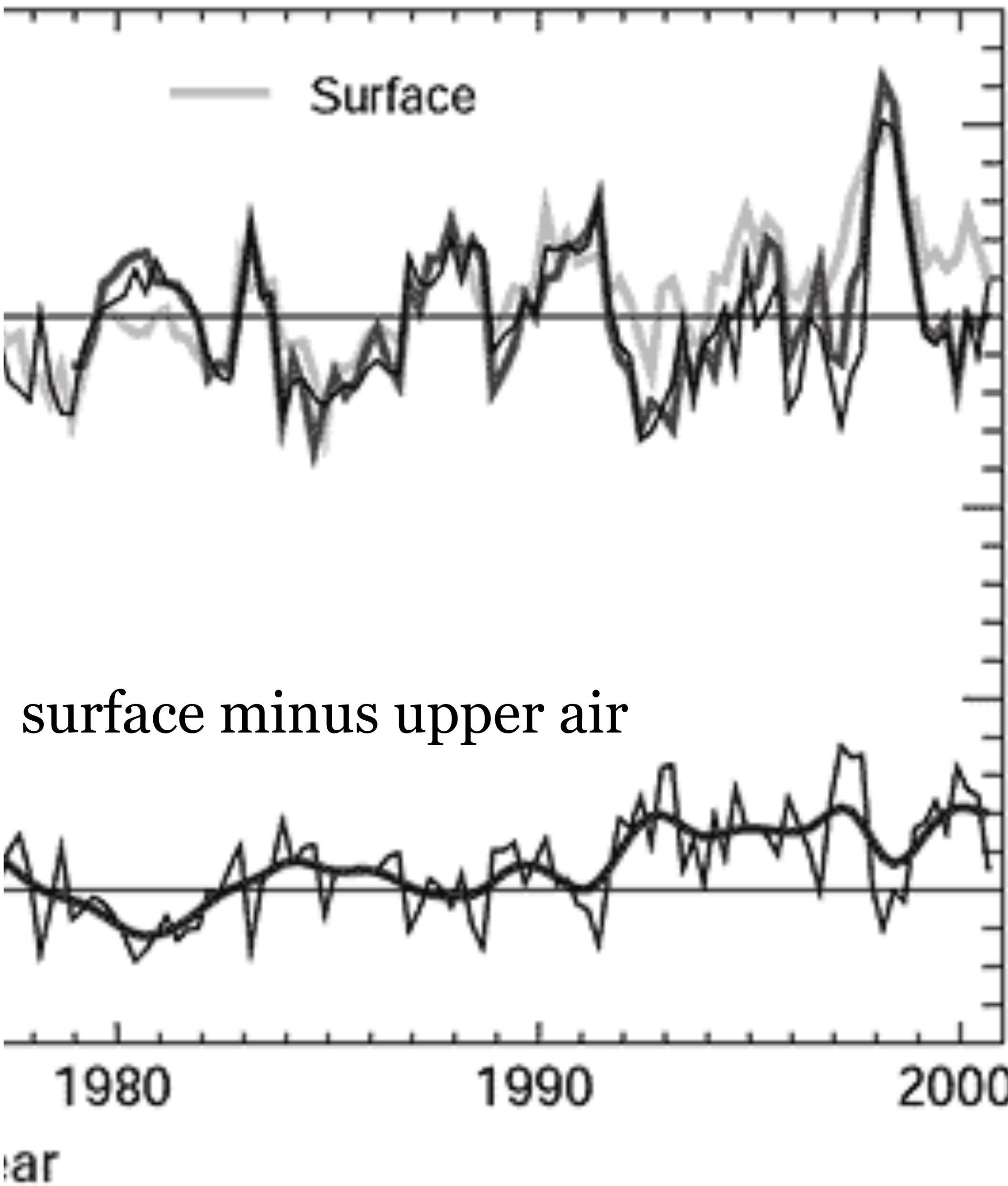


“Via Satellite” Temperatures

- Remote temperature sensing
  - The microwave sounding unit (MSU): since 1979
  - Works like infrared thermometer
  - Multiple wavelength channels give temperatures at different heights
  - Global coverage twice daily



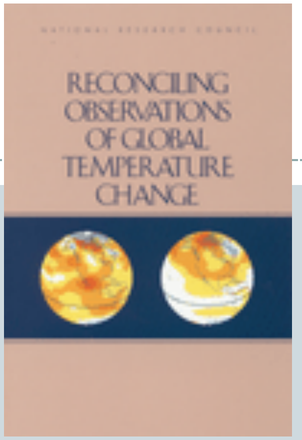




Plots from the 2001 IPCC Report

At this time (2001), **we thought** the **surface warmed faster** than the upper atmosphere (black lines are balloons and MSU)

Yet: Both are supposed to heat up together.

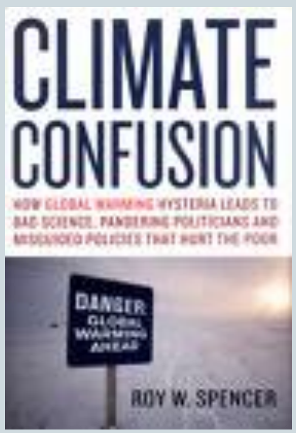


In 2000 a panel convened by the National Academy of Sciences said:

"Major advances in the ability to interpret and model the subtle variations in the vertical temperature profile of the lower atmosphere" are needed…

Panel chair J. M. Wallace
(UW Atmos Sci)

Prior to 2001, global warming skeptics Spencer and Christy and the UAH team were the sole producers of the MSU satellite estimates



Roy Spencer, NASA

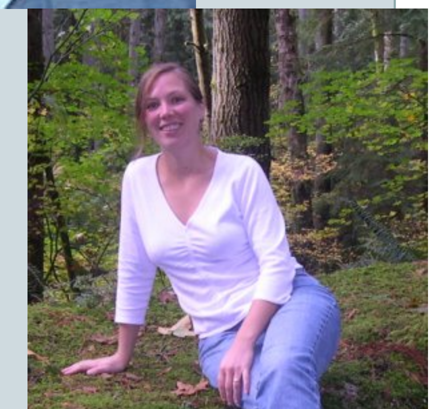
John Christy, UAH

Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends

Qiang Fu[1], Celeste M. Johanson[1], Stephen G. Warren[1] & Dian J. Seidel[2]

[1]*Department of Atmospheric Sciences, University of Washington, Seattle, Washington 98195, USA*
[2]*NOAA Air Resources Laboratory, Silver Spring, Maryland 20910, USA*

Prof. Q. Fu



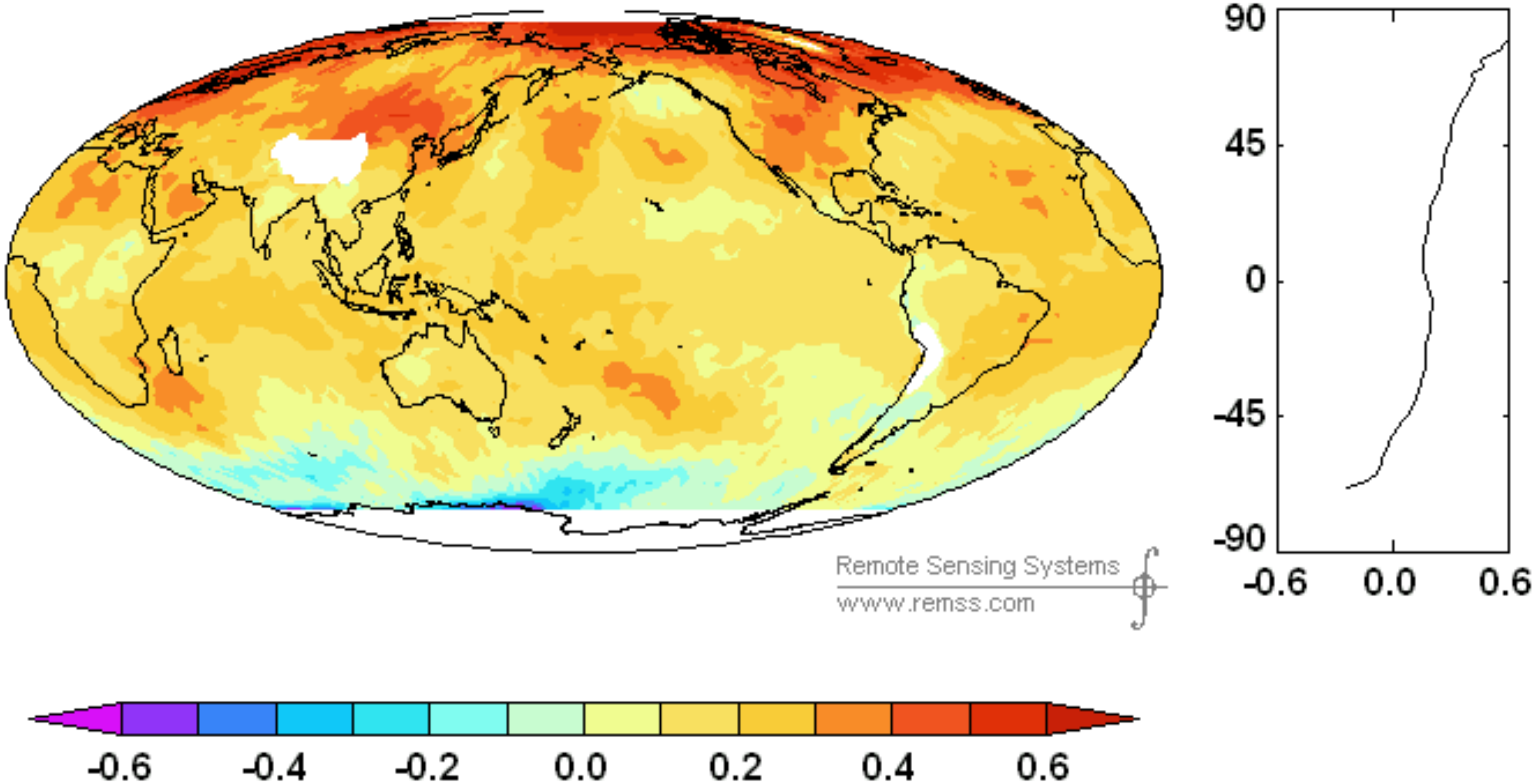
Dr. Celeste Johanson

Celeste Johanson identified an **error in the algorithm** used by Spencer and Christy, who have acknowledged & corrected the error

The RSS team now offers an independent estimates of trends and shows much more significant warming.

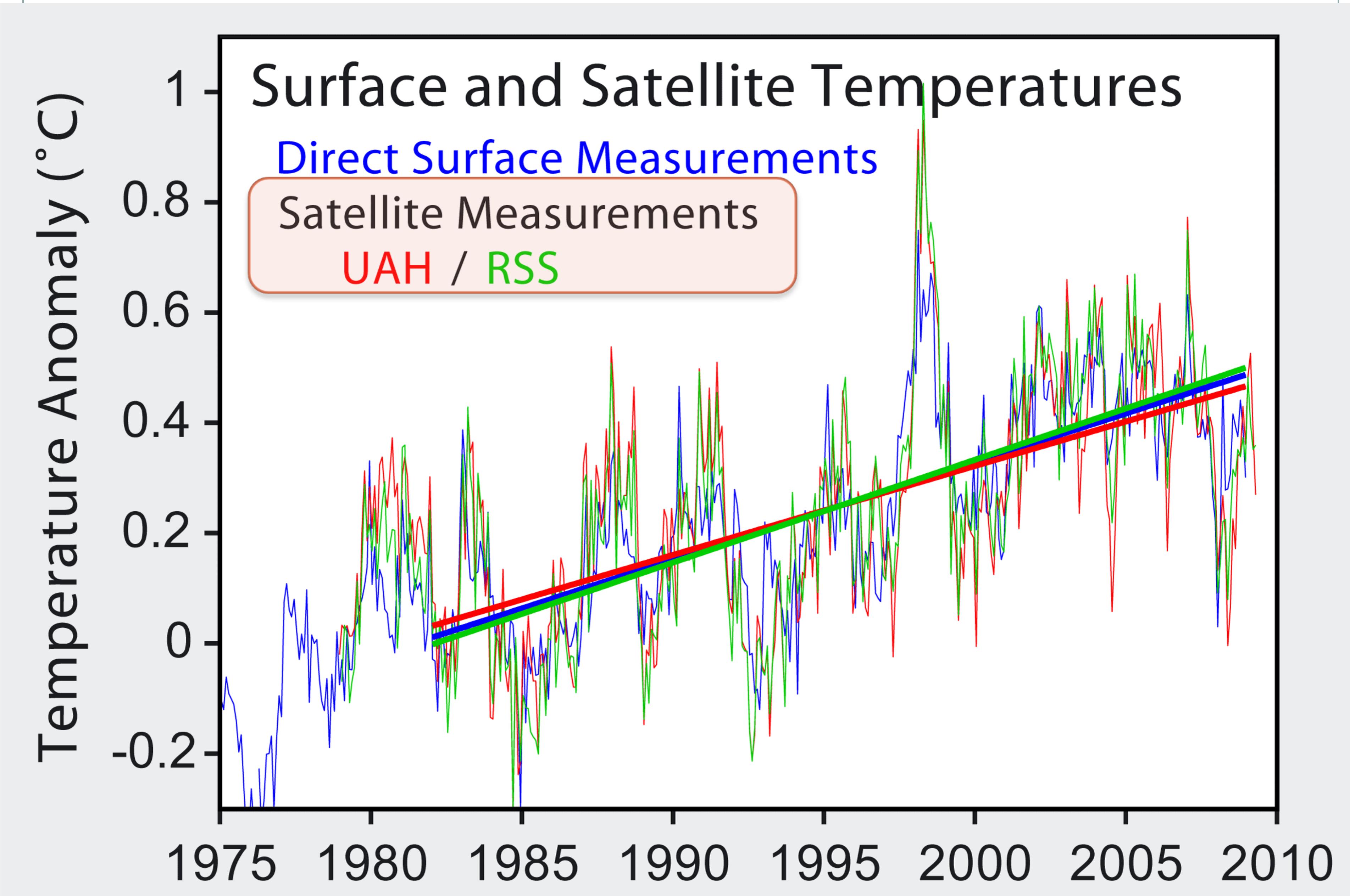
The RSS team in fact show substantial upper air warming

1979-2007 trend



deg C in 29 years

Heat at a Height



Observations of Upper Tropospheric Temps

- Consensus (see U.S. Climate Change Program Synthesis and Assessment Product 1.1, for instance):
  - Upper troposphere has likely warmed about the same as the lower troposphere
  - Observational uncertainty is large in upper troposphere though (could be larger or smaller)
  - Surface warming is known with much more certainty

What if…

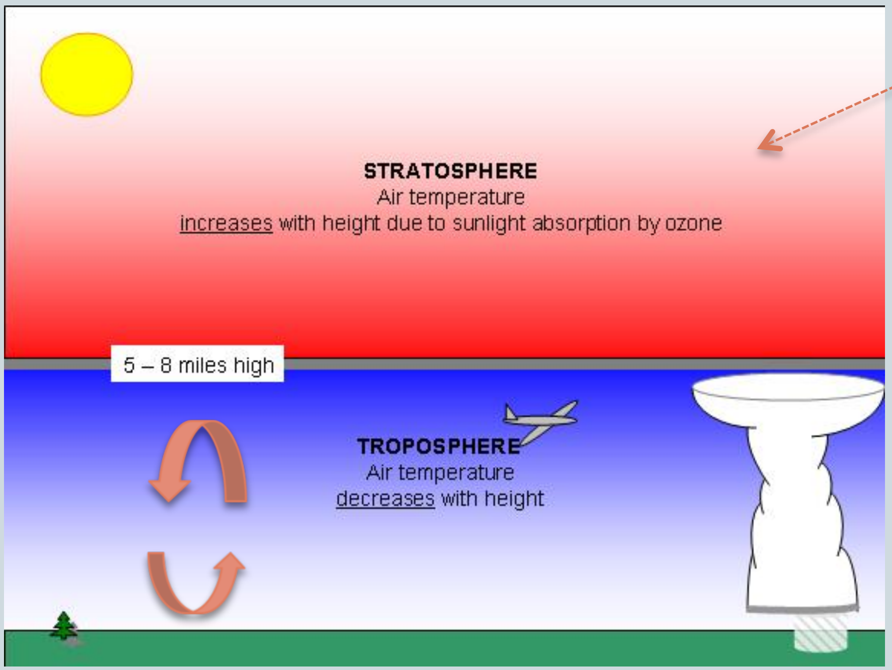
- Upper tropospheric warming is significantly outpaced by lower tropospheric warming, and that this continues
- Claim: Global warming would be much more severe
  - First, lapse rate feedback is main negative feedback to global warming
    - So surface warming would be expected to be more intense without this
  - Second, convective instability would be greater in the warmed atmosphere
    - Would expect much more severe storms, hurricanes, etc.
- Lapse rate feedback is a safety valve for climate!

Summary so far…

- Warmer temperature → more moisture can exist in air
- Condensation of water vapor causes a huge amount of heating
- **Moisture causes lapse rate to be smaller**
  - **In other words: latent heating causes temperatures to cool less quickly with height**
- Next: What determines the height of the tropopause
  - And why it will rise with global warming

Review: Layers of the Atmosphere

- Stratosphere: layer just above troposphere

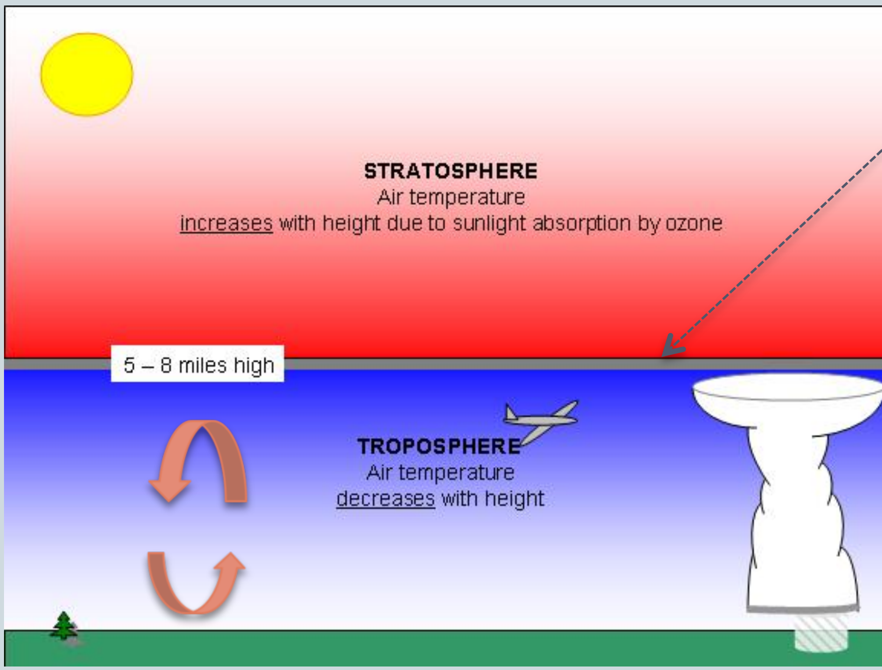


Stratosphere

- In the stratosphere, there's heating from above due to absorption of UV radiation by ozone

Review: Layers of the Atmosphere

- Tropopause: boundary between layers

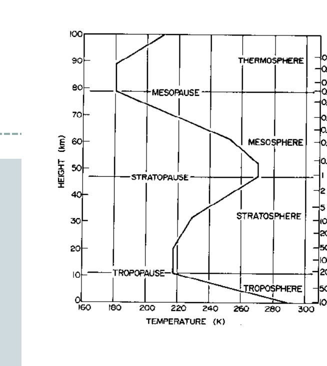


Tropopause

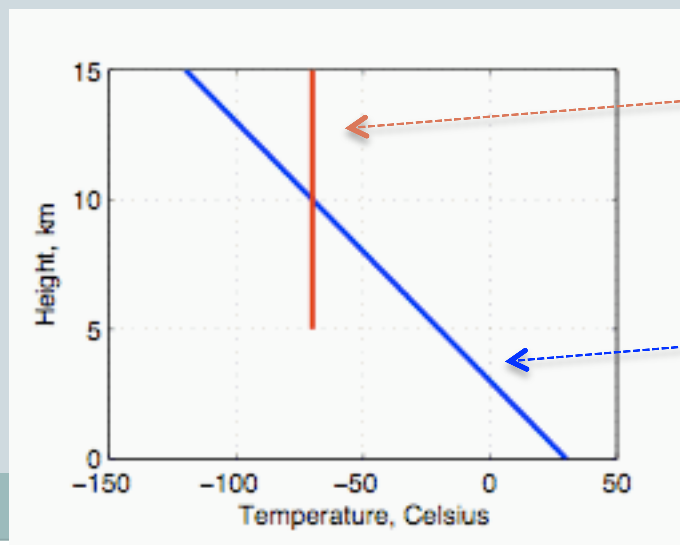
• Tropopause is rising with global warming

• We'll discuss what determines the tropopause height and why this rise occurs

Tropopause Height



- Good approximation of lower stratospheric temperature: *constant* temperature
  - Determined by ozone content, solar forcing, CO2 content, etc
- Stratosphere puts a lid on convection
  - Connect the dots: Surface temp + lapse rate + stratospheric temp => tropopause height!

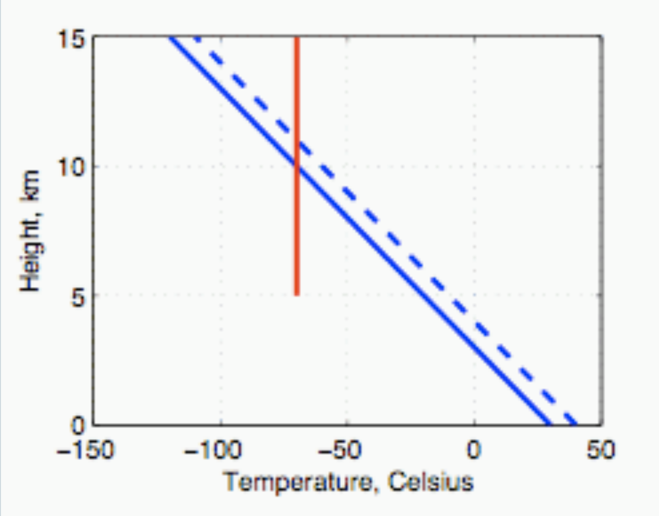


Stratospheric temp

Tropospheric temp

Changes with Global Warming

- Easy to see why global warming would cause an increase in tropopause height:



Increased tropospheric temperature =>
Convection penetrates more deeply

Solid line = pre-global warming temperature

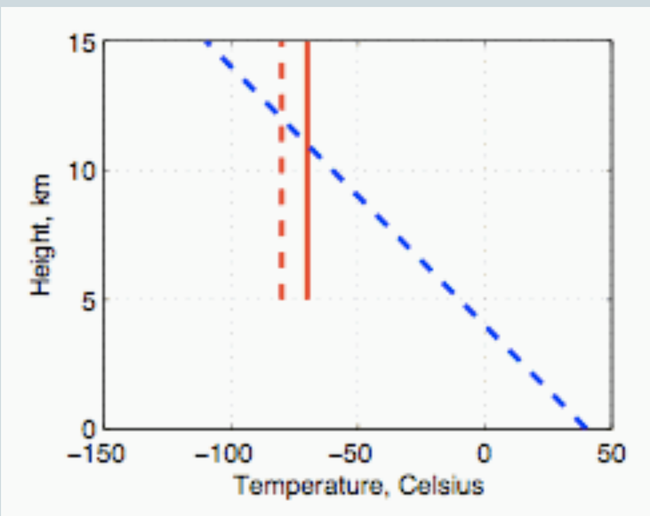
Dashed line = warmed tropospheric temperature

Changes with Global Warming

- How about changes to the stratosphere temperature?
  - Stratospheric warming could offset the tropospheric warming effect…
- With increased CO_2, the stratosphere cools though!
  - Primary cooling mechanism in stratosphere: CO_2 cooling

Tropopause Changes with Global Warming

- With global warming, the stratosphere cools
  - Due to increased thermal emission by CO_2 there



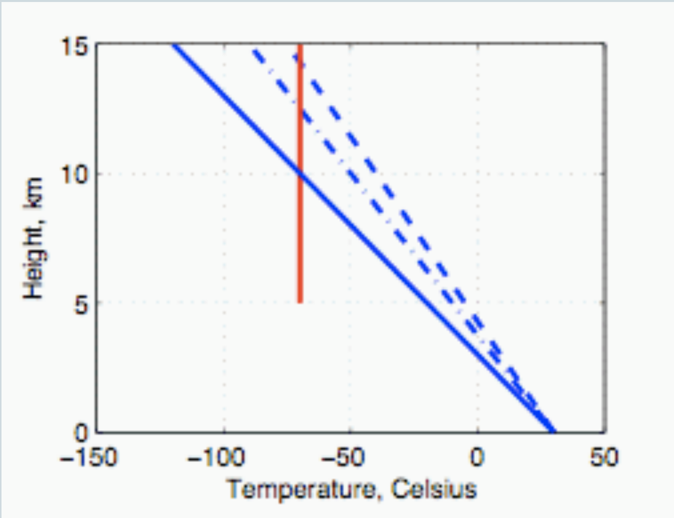
Leads to additional tropopause height rise! (this is a smaller effect though)

Solid line = pre-global warming temperature

Dashed lines = warmed tropospheric temperatures, cooled stratospheric temps

Moisture Effect on Temperature Structure

- With global warming, moisture content increases, so lapse rate changes as well
  - Should imply more heating aloft



Solid = dry
Dash-dot = with moisture
Dashed = with more moisture

Tropopause Rises with Global Warming

- In summary, there are three reasons the tropopause rises with global warming (listed in order of importance, most to least):
  - Changes in lapse rate
  - Tropospheric warming
  - Stratospheric cooling

- Tropopause height increases likely influences
  - The position of the jet stream
  - Strength & scale of storms in extratropics and tropics

Vertical Temperature Change with Height

- Important for determining tropopause height
  - We showed in a 1-D picture how more warming aloft causes tropopause height increases
- Important for climate sensitivity
  - Lapse rate feedback is negative feedback on global warming
- Determines "static stability" of the atmosphere
  - Get potential temperature with pressure (or dry static energy with height) from temperature profile