Climate Dynamics (PCC 587): Water Vapor

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Water...

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

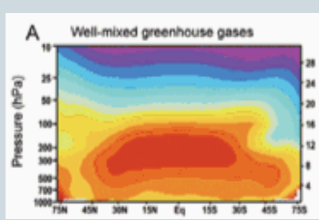
- Today:
  - **Phase changes** of water (e.g., condensation, evaporation...) are equally fundamental for climate dynamics
    - Phase change → heat released or lost (*"latent heating"*)

Today…

- 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…

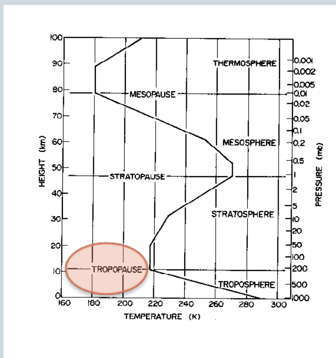
- The controversy about whether the upper troposphere has warmed in recent decades
  - Why global warming would be a lot worse if it didn't warm up there…

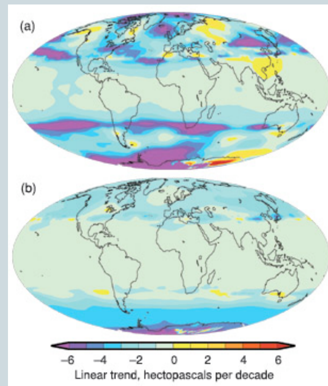


Modeled temperature trends due to greenhouse gases

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!

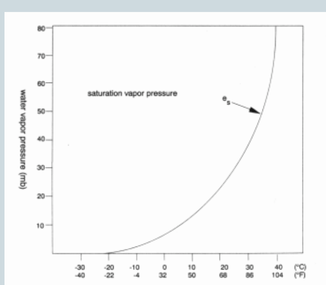




Tropopause height rise in observations versus models

Introduction to Moisture in the Atmosphere

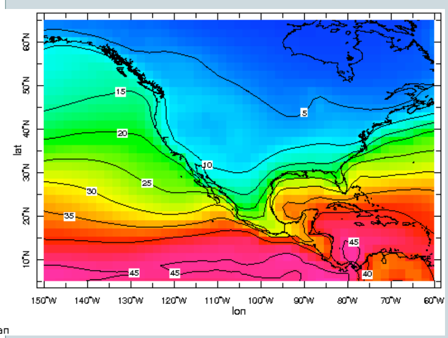
- Saturation vapor pressure:
  - Tells how much water vapor can exist in air before condensation occurs

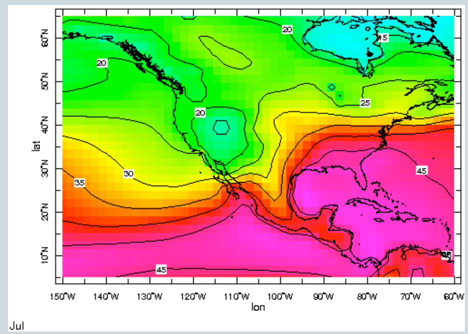


- Roughly exponential for temperatures on Earth
  - Warmer air can hold *much* more moisture

Saturation Vapor Pressure

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

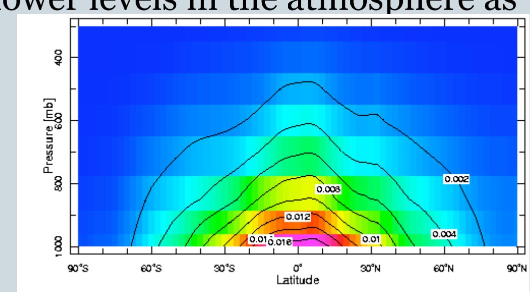




January average surface humidity (in C)   July average surface humidity (in C)

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

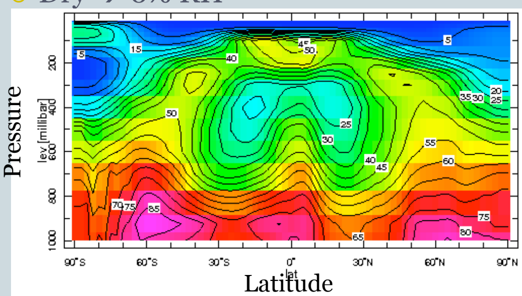


Annual and zonal mean humidity content (in kg/kg)

- Also concentrated in tropics…

Relative Humidity

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



Zonally and annually averaged relative humidty

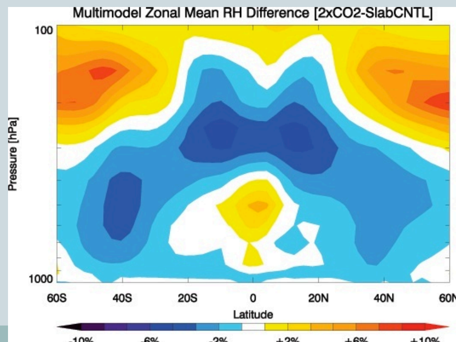
  - Generally higher in rainier regions, and lower in drier regions

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

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

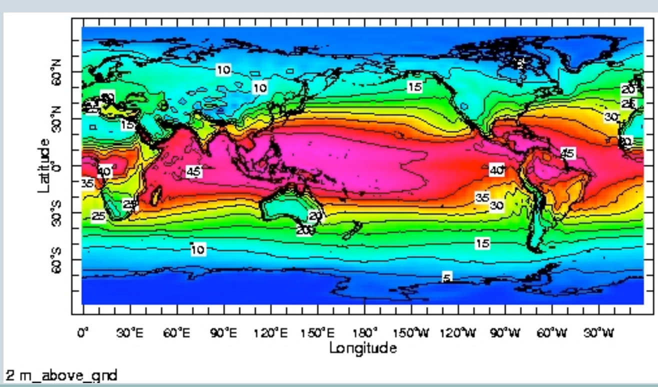
- We're all familiar with the idea that evaporation causes cooling
  - Evaporation of sweat cools you off
  - Getting out of a pool on a windy day → cold!
- Similarly, **condensation** -> **heating** of the atmosphere
  - Condensation of water vapor is associated with a release of latent heat
  - Huge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



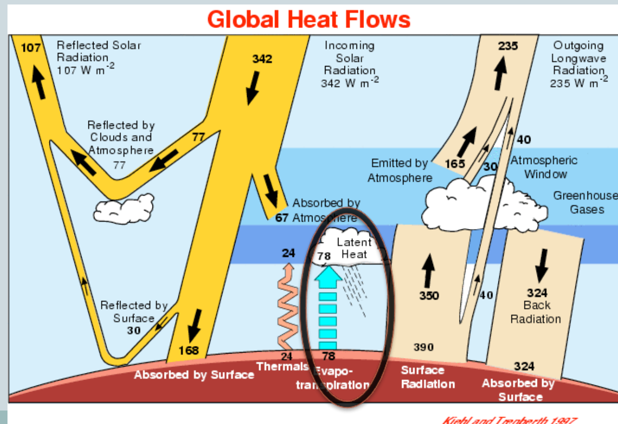
Latent heating is huge potential heat source!

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:

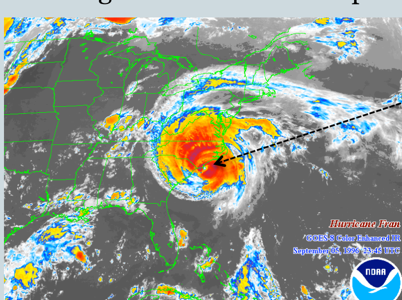


Latent heat flux = 78
Sensible (thermal) heat flux = 24
Net radiative flux from surface to atmos = 350-324 = 26

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



Wilmington, NC
(my home town)

Hurricane Fran (1996)

Water Vapor and Global Warming

- With global warming, atmospheric moisture content will increase
  - Over 20% increase in humidity with 3° C global temperature increase
    - Tropics will have 55° C of latent heating potential instead of 45° 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

Hurricanes and Global Warming

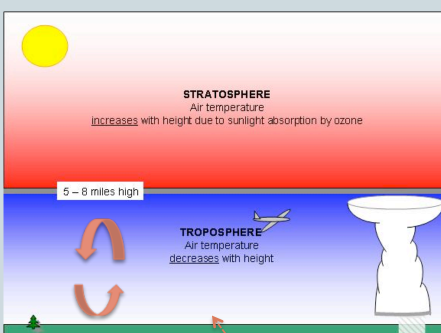
- Strongest hurricanes are expected to increase in strength
  - More moisture content → more fuel for the strongest storms
- Hurricanes are sensitive to many other factors though
  - E.g., El Nino → weaker Atlantic storms
  - More wind shear → storms get broken apart
- Models can't resolve hurricanes yet
  - Hard to estimate what will happen until models get higher res
    - May be that hurricanes will decrease in the Atlantic while increasing in other basins, for instance

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!

Review: Layers of the Atmosphere

- Troposphere: layer where all weather occurs



Troposphere

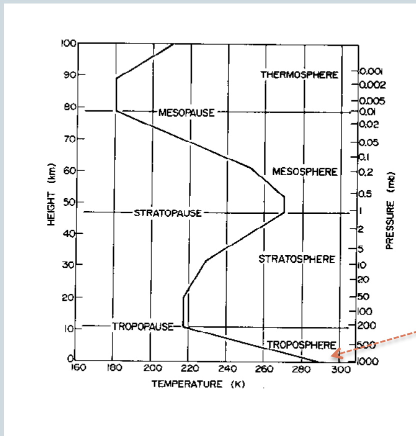
• The Sun heats the atmosphere strongly from below

• 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:



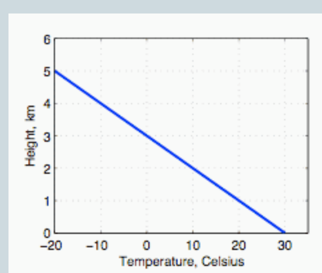
In the troposphere, there are rapid decreases of temperature with height (6.5° C/km)

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,

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

"dry adiabatic lapse rate"



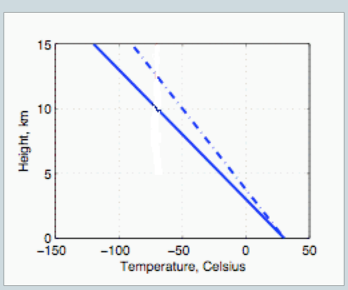
Note this is much larger than the observed lapse rate of 6.5° C/km

Lapse Rate and Static Stability

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

Missing Ingredient from our Model: Moisture

- Observed lapse rate of 6.5º 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)

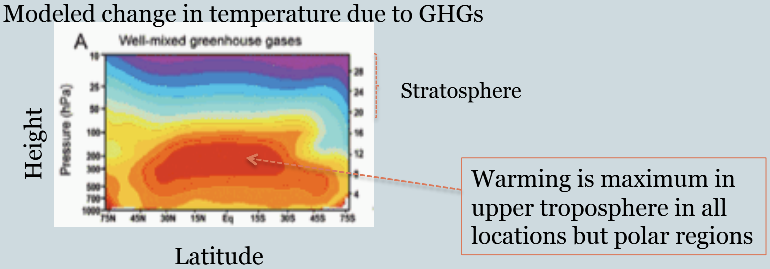
Moisture and Lapse Rate

- Moisture makes the lapse rate less
  - Around 6.5º C/km instead of 9.8º 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

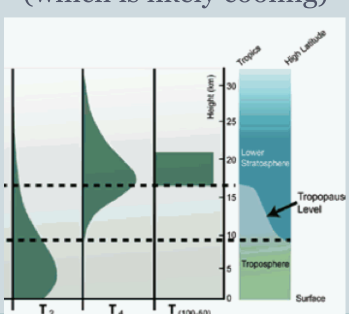


Lapse Rate Feedback

- 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
  - Less water vapor → 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)



Part of the controversy has been resolved (see Fu and Johanson)

Better reconstructions, and finding a bug in some code led to changes

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…

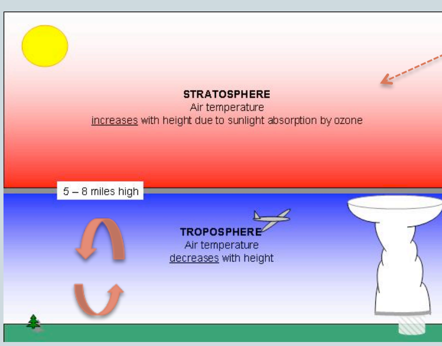
- Upper tropospheric warming is significantly outpaced by lower tropospheric warming, and that this continues
- Claim: Global warming would be much more severe
  - First, lapse rate feedback is main negative feedback to global warming
    - So surface warming would be expected to be more intense without 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

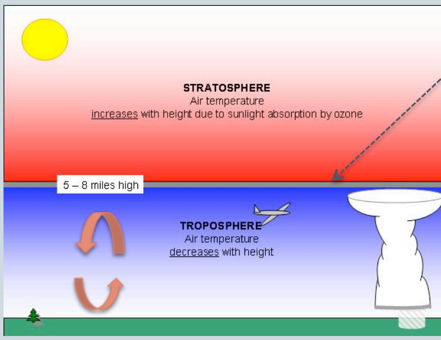


Stratosphere

• 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

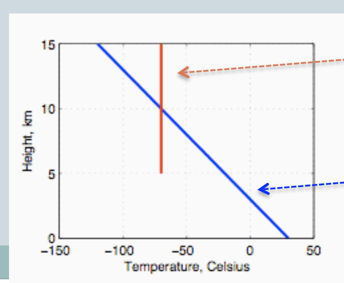


Tropopause

- 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!

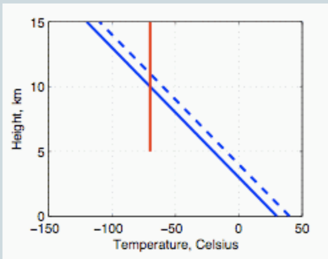


Stratospheric temp

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

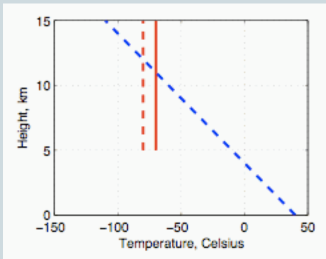
Dashed line = warmed tropospheric temperature

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



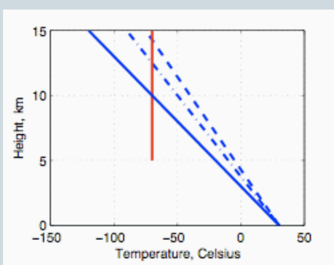
Leads to additional tropopause height rise!

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:
  - Tropospheric warming
  - Stratospheric cooling
  - Changes in lapse rate
- Tropopause height increases likely influences
  - The position of the jet stream
  - Strength & scale of storms in extratropics and tropics

Vertical Temperature Change with Height

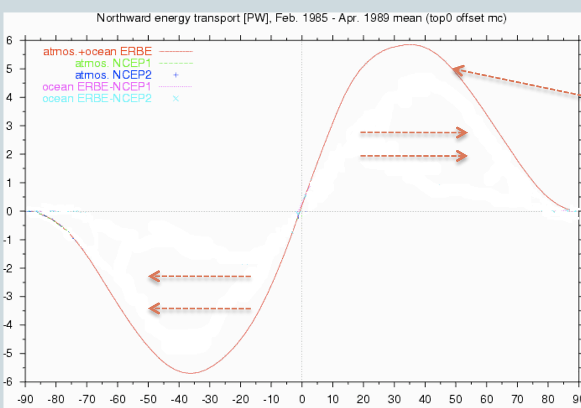
- Important for determining tropopause height
  - We showed in a 1-D picture how more warming aloft causes tropopause height increases
- Important for climate sensitivity
  - Lapse rate feedback is negative feedback on global warming
- Determines "static stability" of the atmosphere
  - Get potential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

Moisture and Horizontal Temperature Gradients

- Next: moisture also strongly influences pole-to-equator temperature gradients
- If moisture evaporates at low latitudes, but condenses at higher latitudes, this is exactly like a poleward transport of heat

Energy Transports

- Climate system transports energy polewards (from hot to cold)

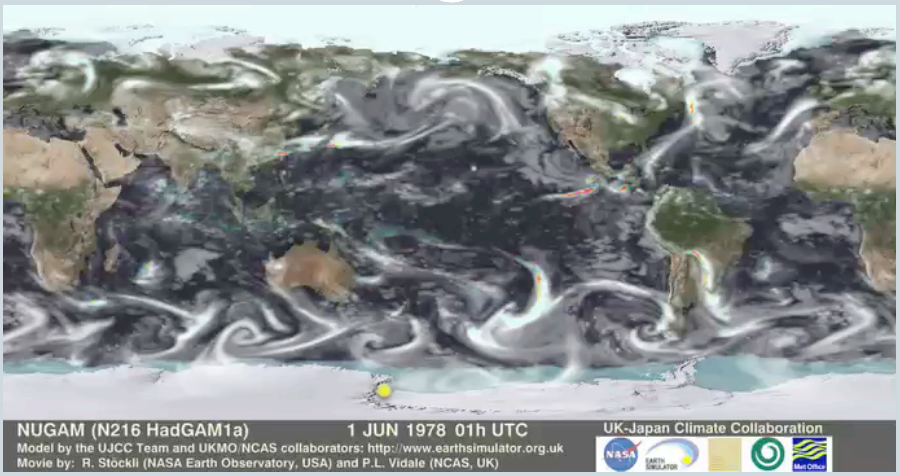


Latitude

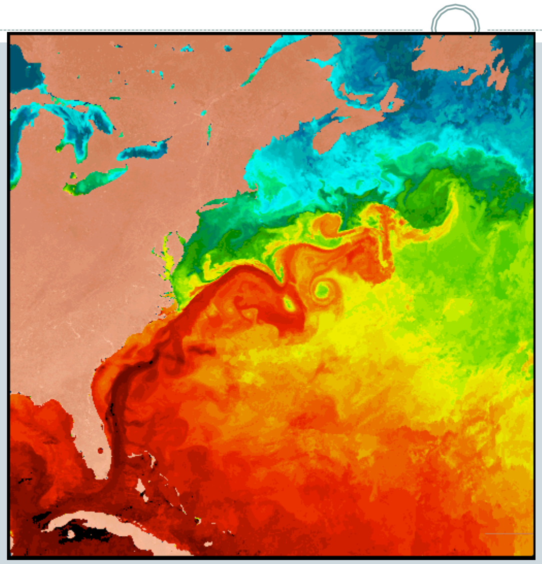
Total (atmosphere plus ocean) flux

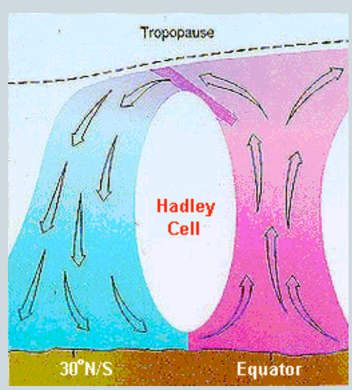
Northward flux in NH, Southward flux in SH

Atmospheric and Oceanic Energy Transports



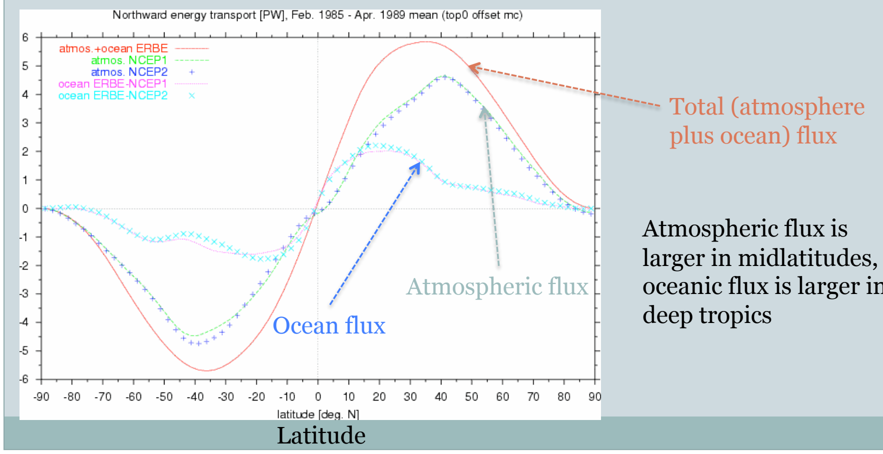
Atmospheric and Oceanic Energy Transports





Back to Observed Energy Transports

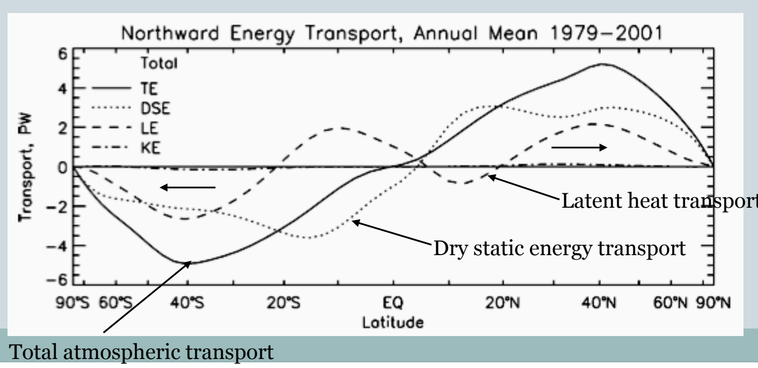
- Separated into atmospheric and oceanic components:



Atmospheric flux is larger in midlatitudes, oceanic flux is larger in deep tropics

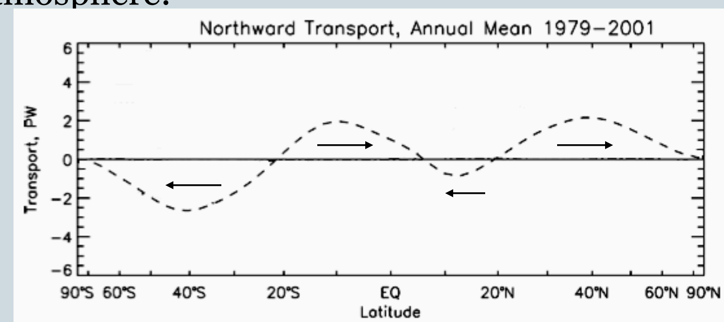
Atmospheric Energy Fluxes

- Let's take a closer look at the **atmospheric** energy fluxes in the extratropics
  - Dry static energy flux = internal + potential energy flux
  - Latent heat transport = moisture flux



Moisture flux

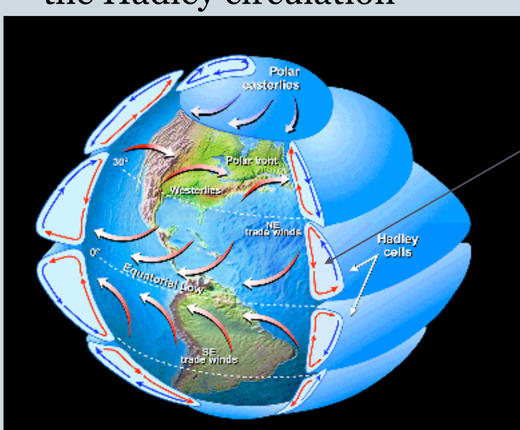
- Annual and zonal mean moisture flux in the atmosphere:



Equatorward moisture flux in the tropics
Poleward moisture flux in the extratropics

Moisture flux

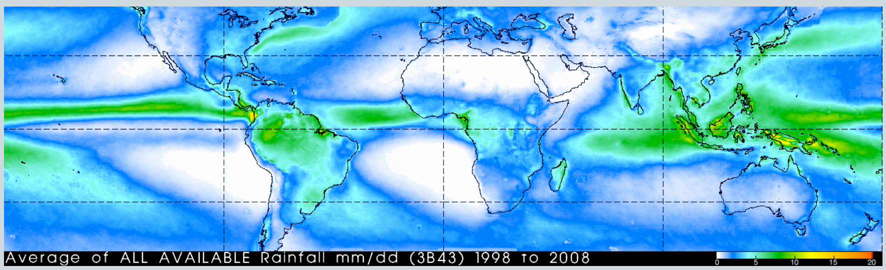
- Equatorward moisture flux in the tropics is due to the Hadley circulation



Moisture near the surface is converged equatorward by Hadley cells

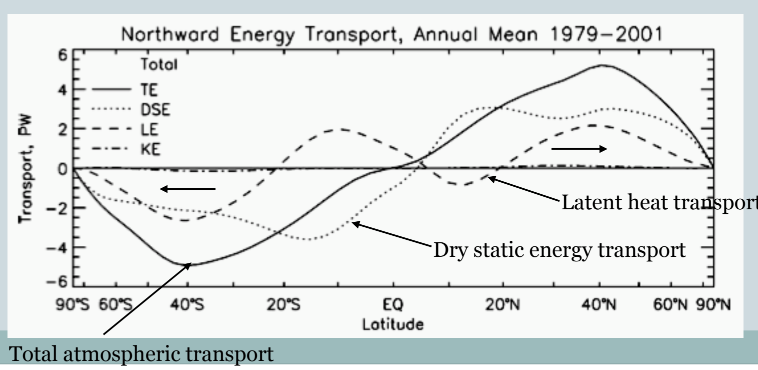
Hadley Circulation

- Hadley circulation brings moisture equatorward
  - Much condenses out in the "Inter-tropical Convergence Zone": line of convection in deep tropics
  - Latent heating is concentrated there



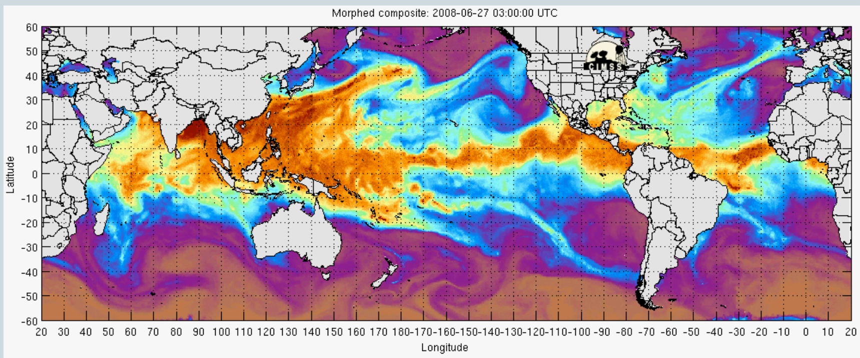
Hadley Cell Energy Transports

- Large dry static energy fluxes within Hadley cell ensure that total transport is poleward
  - High potential energy air being moved poleward



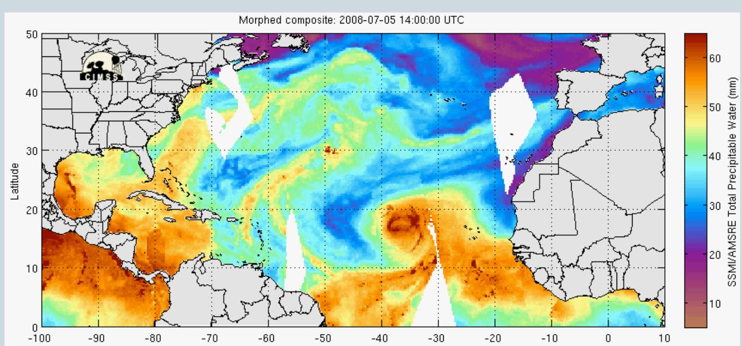
Midlatitude Moisture Flux

- Poleward moisture flux occurs in midlatitudes
  - Primarily accomplished by eddies



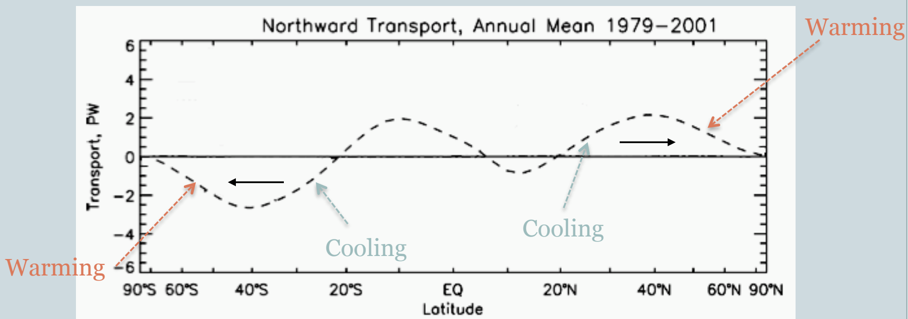
Moisture Flux in Midlatitudes

- Poleward moisture flux occurs in midlatitudes
  - Primarily accomplished by eddies



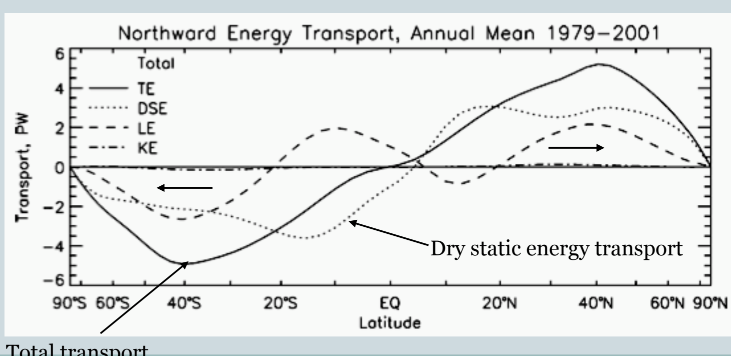
Moisture Flux as an Energy Flux

- Poleward moisture flux acts to flatten temperature gradients just like heat fluxes:
  - When the moisture condenses at higher latitudes, it warms those latitudes



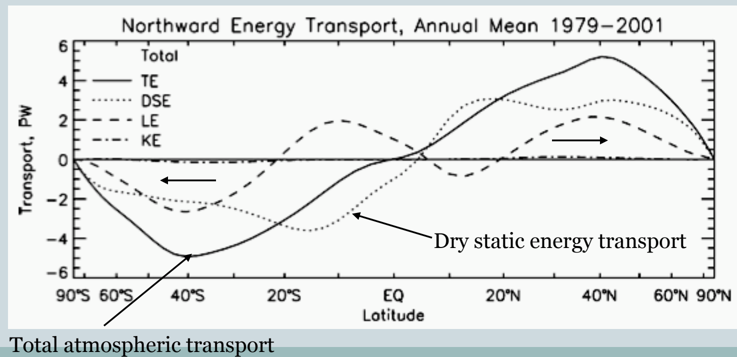
Extratropical Energy Fluxes

- Comparison with dry and total flux:
  - Dry static energy flux = $v(c_pT + gz)$
    = flux of internal energy + potential energy



Extratropical Energy Fluxes

- Comparison with dry and total flux:
  - Moisture flux is roughly 50% of the total transport in midlatitudes

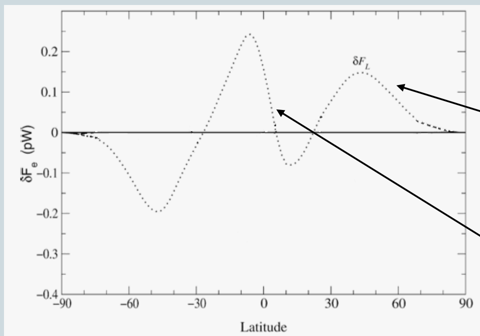


Water Vapor and Global Warming

- With global warming, atmospheric moisture content will increase
  - 20% increase with 3 K global temperature increase
- What effects will the increased moisture content have on the Earth's climate?
  - More moisture flux => flatter temperature gradients in midlatitudes
  - This should weaken dry static energy transports

Energy Fluxes in IPCC Simulations

- Change in moisture flux in slab ocean global warming simulations:

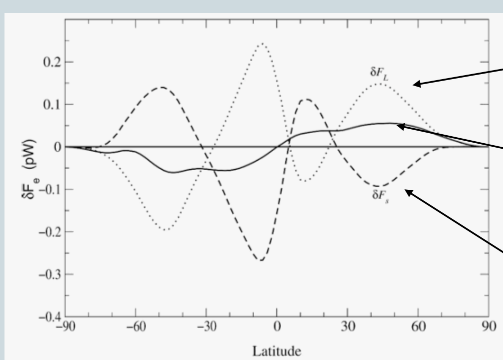


- Increase in poleward flux in extratropics
- Increase in equatorward flux in tropics

From Held and Soden (2006)

Energy Fluxes in IPCC Simulations

- Energy fluxes in slab ocean global warming simulations:



Change in moisture flux

Change in total flux

Change in dry static energy flux

~70% compensation

From Held and Soden (2006)

Moisture and Horizontal Temperature Gradients

- Moisture plays major role in determining midlatitude temperature gradients
  - Roughly 50% of flattening of temperatures is by moisture
- Moisture fluxes are expected to increase with global warming
  - Due to increased moisture content
  - Will lead to decreased temperature gradients

Next class…

- A summary of feedbacks
  - Water vapor, lapse rate, ice-albedo
  - Cloud feedbacks: can be positive or negative
- How to estimate climate sensitivity given different feedbacks