Modeling the General Circulation of the Atmosphere. Topic 2: Tropical General Circulation

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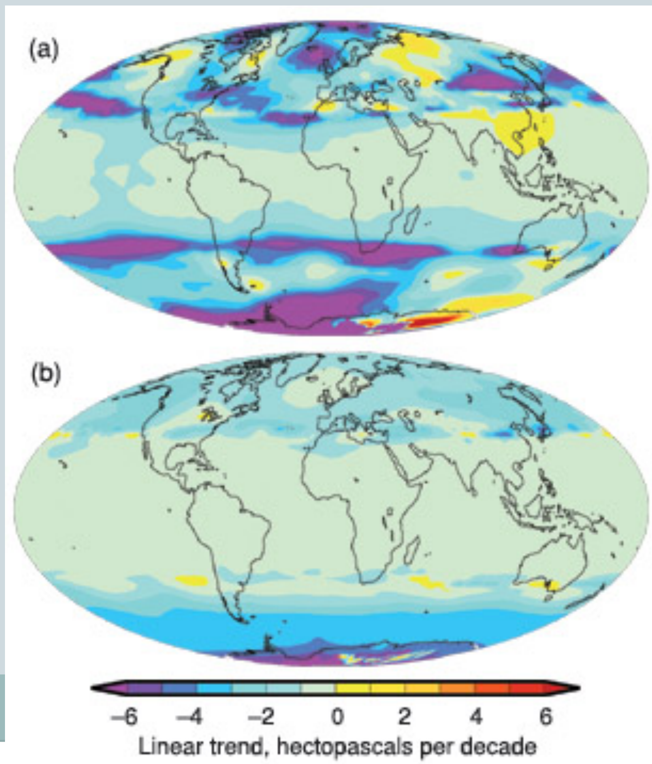
Today…

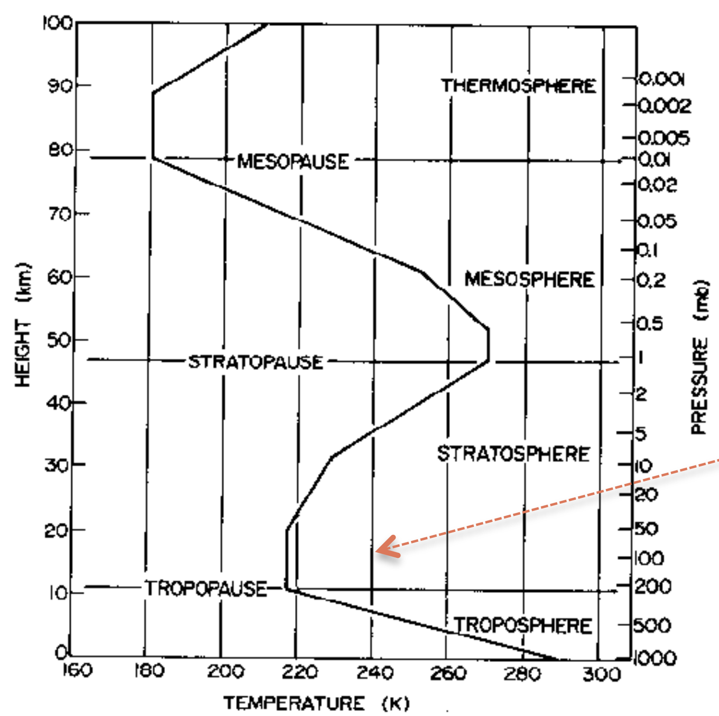
- What determines the tropopause height
- Why the tropopause will rise with global warming
  - Three separate effects cause a rise in tropopause height: result is the sum of all three!



Tropopause height rise in observations versus models.

Observed Temperature Structure

- Schematic of temperature structure with height:



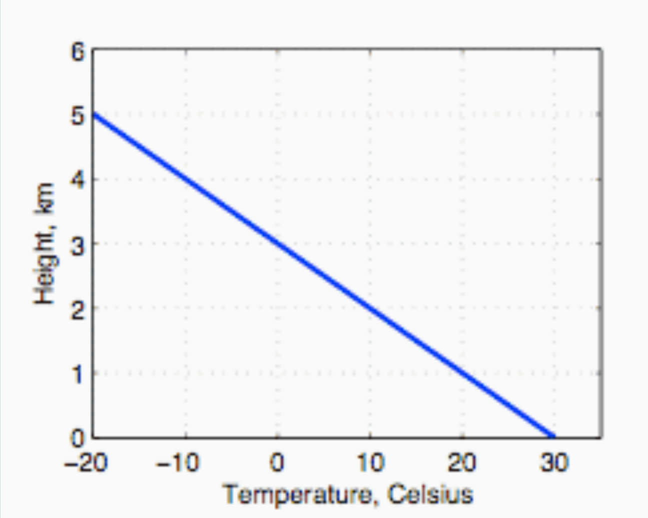
US Standard Atmosphere
Temperature Profile

In the stratosphere, the temperature is roughly constant, then increases with height

A Dry Atmosphere

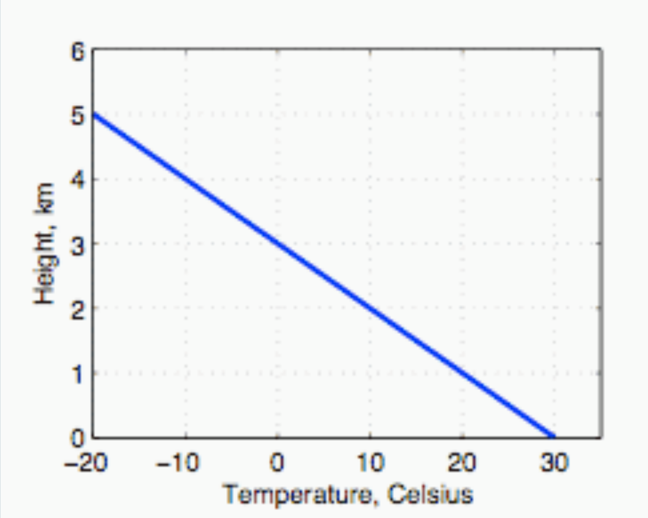
- In a dry atmosphere forced from below, convection occurs to make the dry static energy constant, up to the tropopause
- Lapse rate $\frac{dT}{dz}$ is constant in this atmosphere,

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



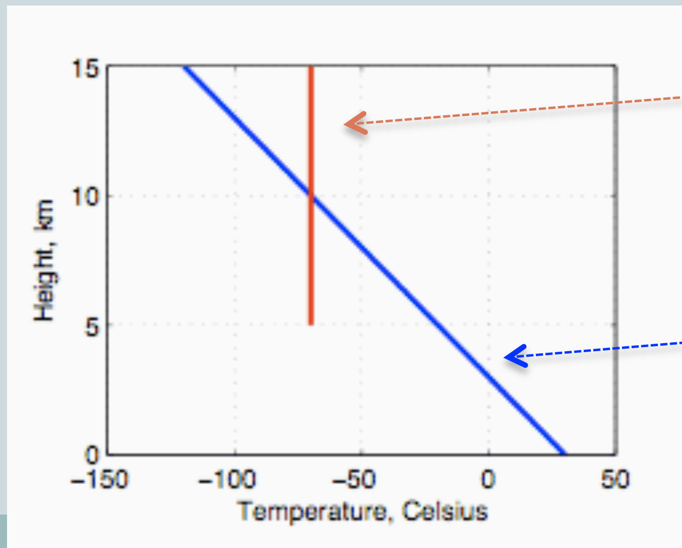
Tropopause Height

- Can we calculate the tropopause height in this dry atmosphere?
- Need one more constraint…



Tropopause Height

- Decent approximation of lower stratospheric temperature: *constant* temperature
  - Determined by ozone content, solar forcing, CO2 content, etc
- Stratosphere puts a lid on convection
- Temperature must be constant => tropopause height!

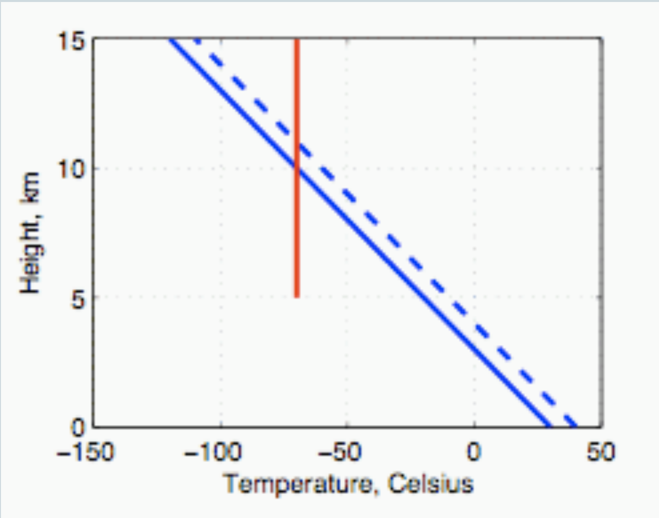


Stratospheric temp

Tropospheric temp

Changes with Global Warming

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



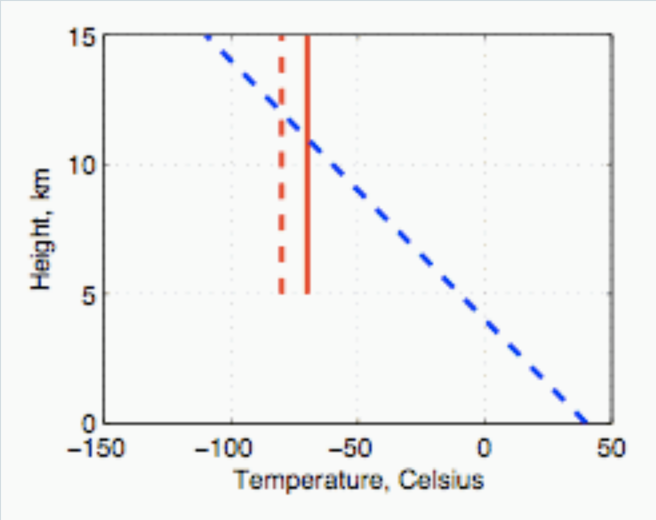
Increased tropospheric temperature => Convection penetrates more deeply

Solid line = pre-global warming temperature

Dashed line = warmed tropospheric temperature

Tropopause Changes with Global Warming

- With global warming, the stratosphere cools
  - More CO_2 cools the stratosphere



Leads to additional tropopause height rise!

Solid line = pre-global warming temperature

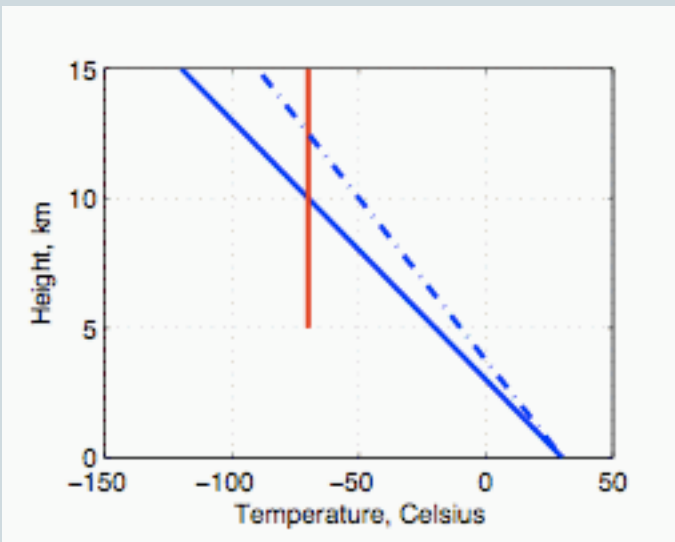
Dashed lines = warmed tropospheric temperatures, cooled stratospheric temps

Tropopause Height

- This was just a dry model though
- Moisture plays a fundamental role in determining the tropopause height

Moisture Effect on Temperature Structure

- Instead of 9.8 K/km lapse rate, moisture condensation causes warmer temperatures aloft
  - Condensational heating as parcels rise

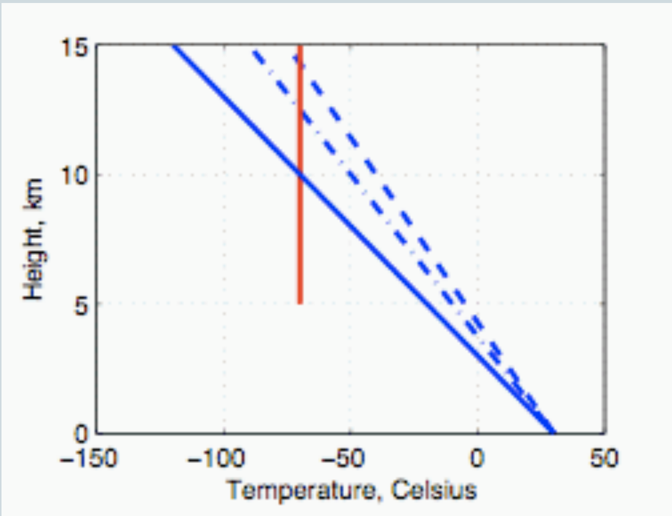


Solid = dry
Dash-dot = with moisture

Causes the temperature structure to be nonlinear too
(Figure to the left is just a schematic)

Moisture Effect on Temperature Structure

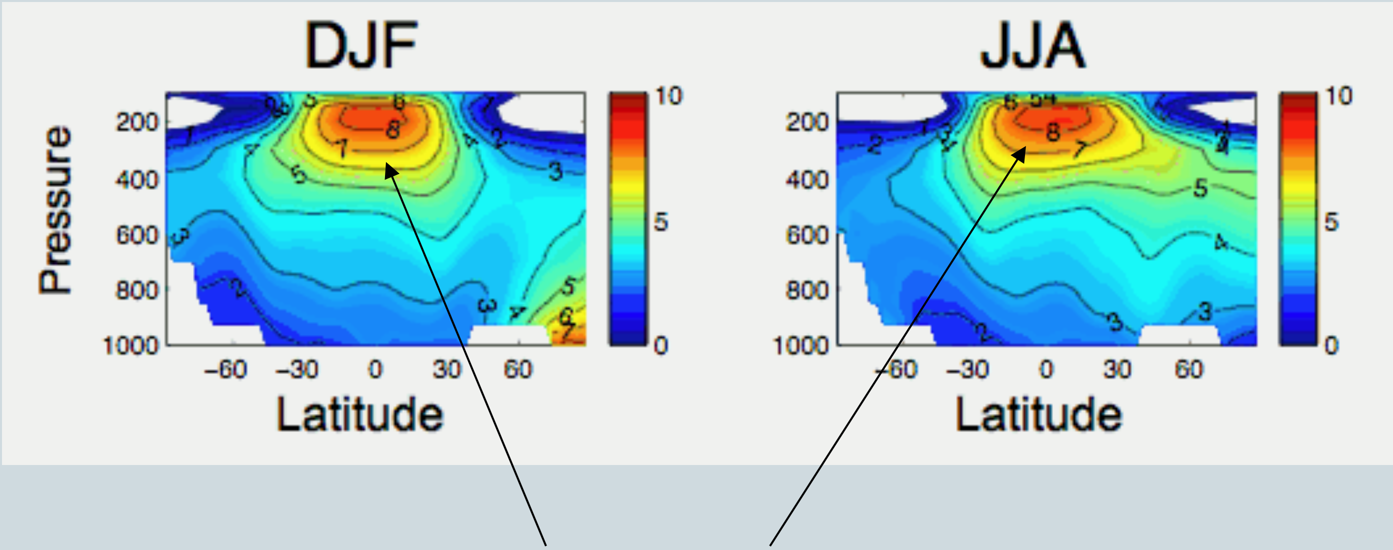
- With global warming, moisture content increases, so lapse rate decreases as well
  - Should imply more heating aloft



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

Global Warming Temperature Change

- Temperature change in AR4 global warming simulations (21 models)

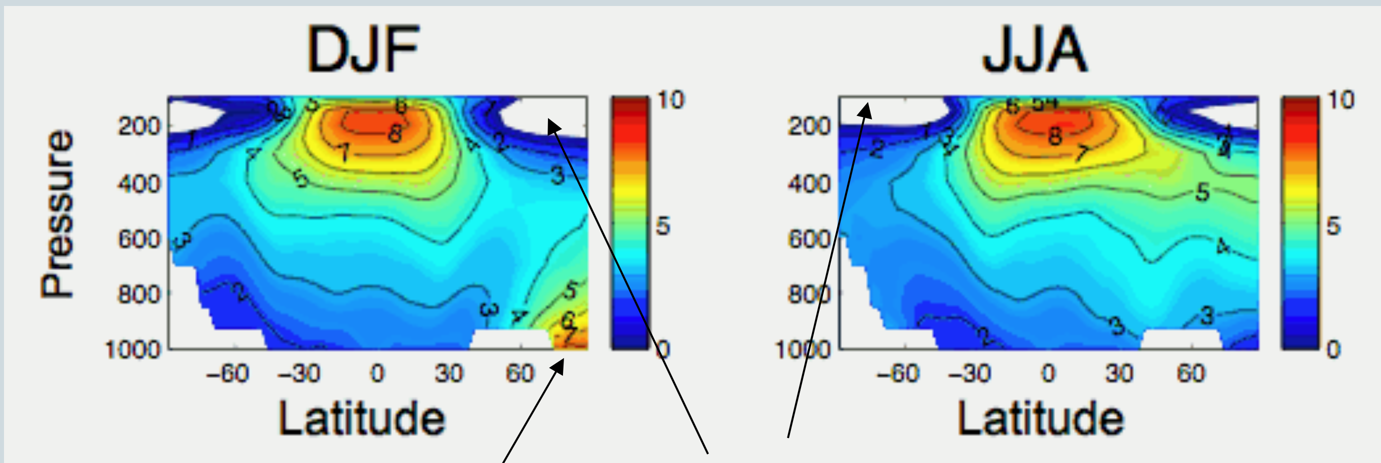


Tropical upper tropospheric warming (due to moisture)

From Frierson (2006)

Temperature Changes: IPCC Models

- Global warming simulations *change* in potential temp:



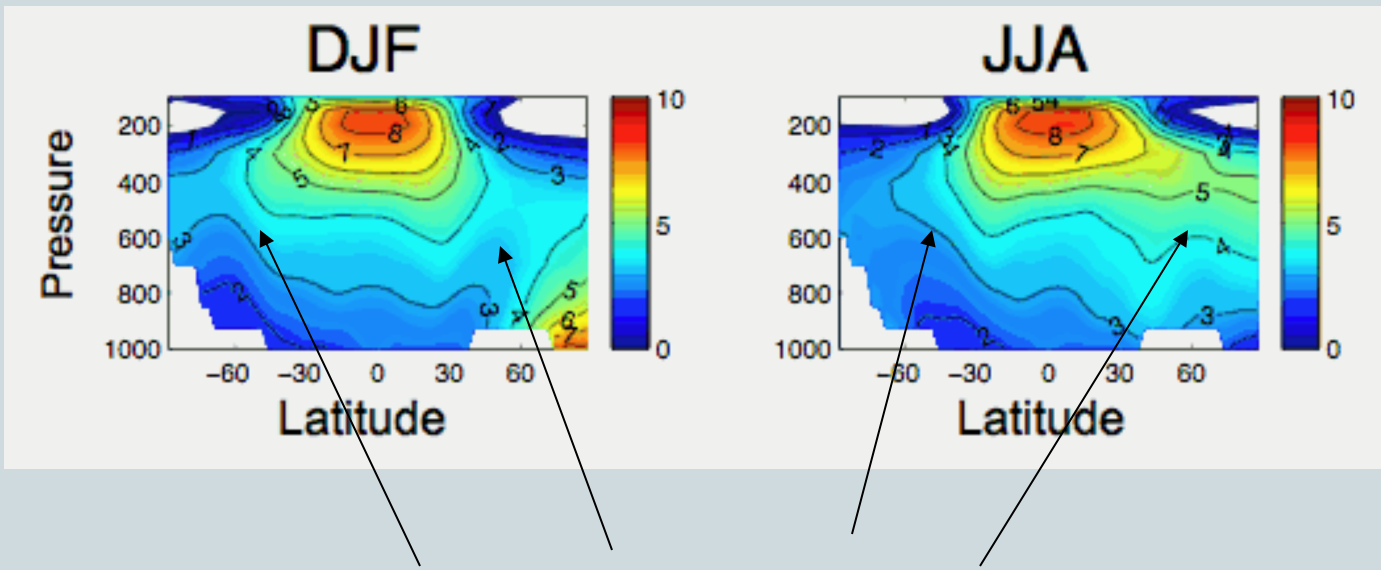
Stratospheric cooling

Polar amplification

From Frierson (2006)

Temperature Changes: IPCC Models

- Global warming simulations *change* in potential temp:



Midlatitude static stability increases as well

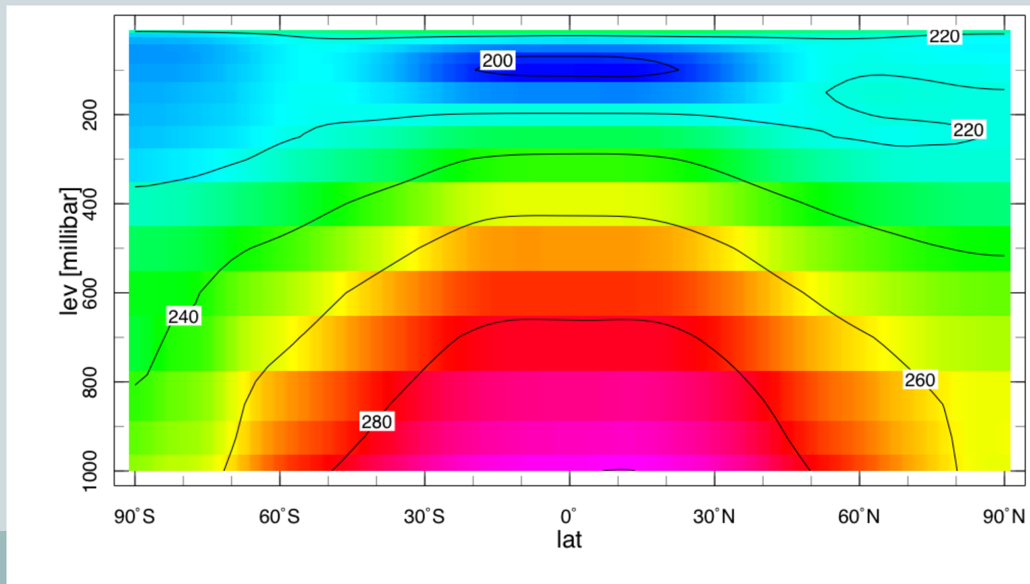
From Frierson (2006)

Tropopause Rises with Global Warming

- In this simple picture, there are three reasons the tropopause rises with global warming:
  - Tropospheric warming
  - Stratospheric cooling
  - Changes in lapse rate $\frac{dT}{dz}$
- Increase in tropopause height and tropospheric static stability will come up again and again in this class

More accurate picture…

- Changes in troposphere affect the radiative equilibrium temperature of the stratosphere
  - Can solve this with a radiative transfer model
- Stratosphere is not in radiative equilibrium
  - Brewer-Dobson circulation, etc affect energy transports



Zonally averaged temperature profile from reanalysis

Importance of Temperature Change with Height

- Determines tropopause height
- Determines static stability of the atmosphere
- Important for climate sensitivity
  - Lapse rate feedback is negative feedback on global warming

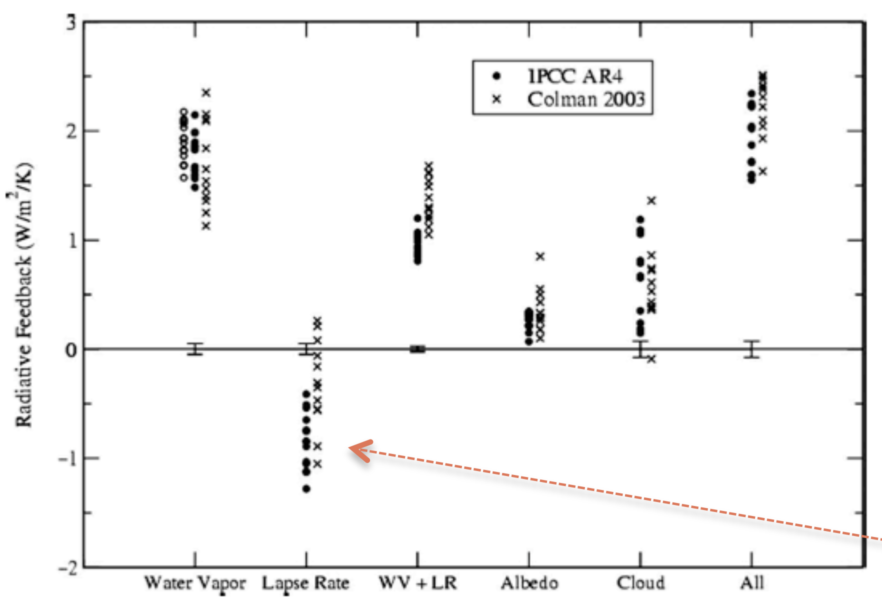


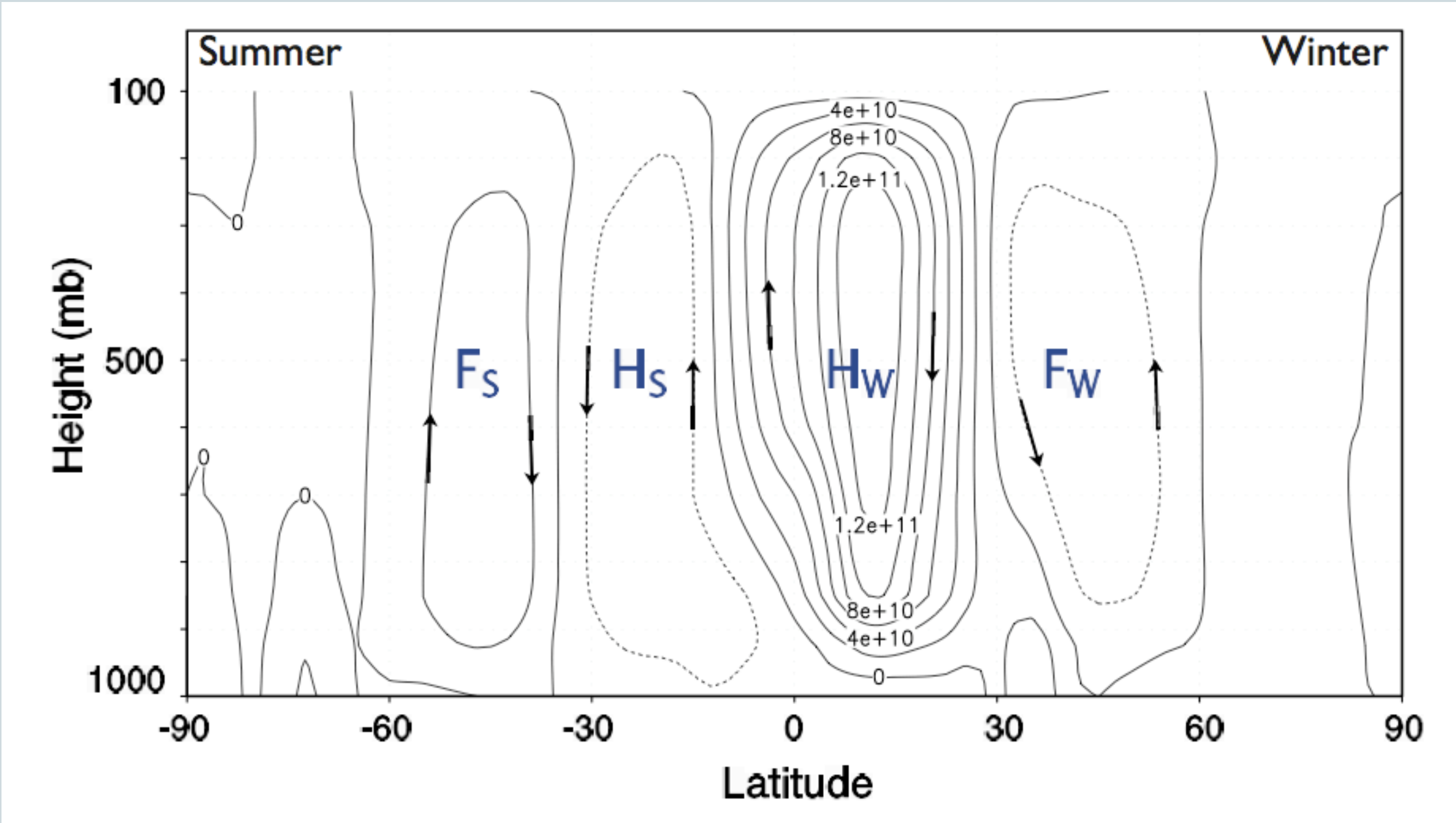
FIG. 1

Soden and Held 2005

Lapse rate is primary negative feedback

Hadley Circulation

- Dominant feature of zonally averaged circulation



Hadley Circulation

- If the planet were non-rotating, air would rise at the equator and descend at the pole
- Rotation causes finite extent: but how?

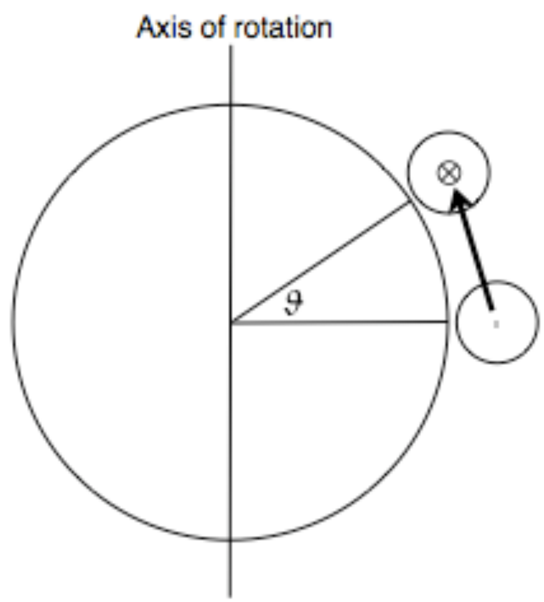


Fig. 11.5 If a ring of air at the equator moves polewards it moves closer to the axis of rotation. If the parcels in the ring conserve their angular momentum their zonal velocity must increase; thus, if $m = (\overline{u} + \Omega a \cos\vartheta) a \cos\vartheta$ is preserved and $\overline{u} = 0$ at $\vartheta = 0$ we recover (11.7).

Hadley Circulation Extent

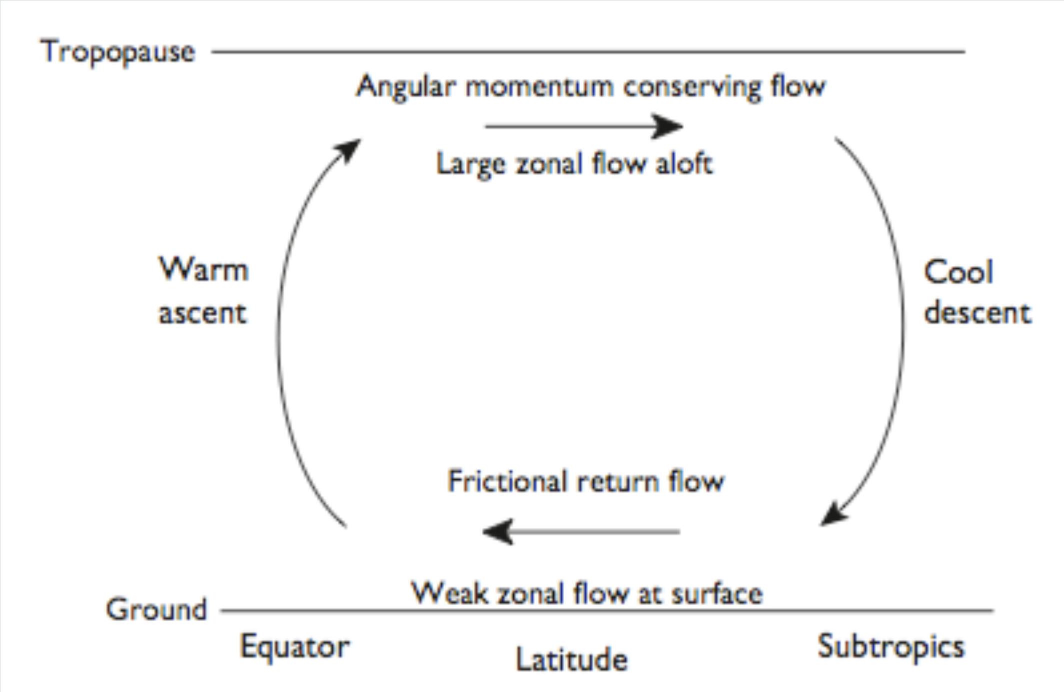
- Traditional view:
  - Hadley cell extends out until the latitude where baroclinic instability sets in
  - Winds accelerate rapidly due to Coriolis
  - Associated shear becomes baroclinically unstable (higher Coriolis parameter helps with this too)
  - Induces Ferrel cell type behavior, ending Hadley cell

Hadley Circulation Extent

- Held and Hou 1980: showed Hadley cell has finite extent even when baroclinic eddies are not allowed to occur
  - Inhibit baroclinic eddies by assuming zonal symmetry: axisymmetric model
  - Dry model! (even though latent heating is a dominant heat source in the cell)
  - Many aspects will apply to moist situations though (although this dry model actually doesn't give such a bad estimate of the intensity)

Held-Hou Theory

- Basic physical setup:



Held-Hou Theory

- We’ll assume:
  - Angular momentum concentration in upper branch
  - Thermal wind balance
  - Weak winds (due to friction) at the surface
  - This will essentially be a vertically averaged theory