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

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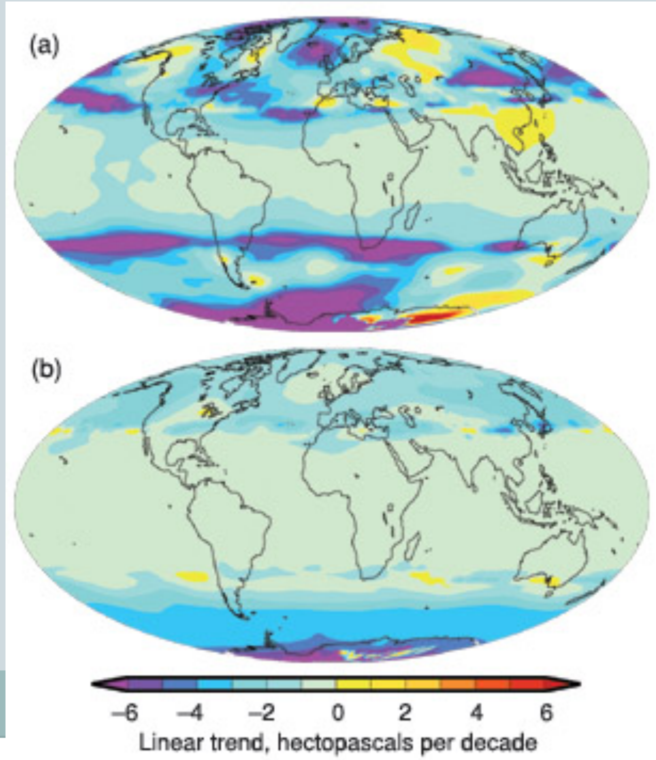
Today…

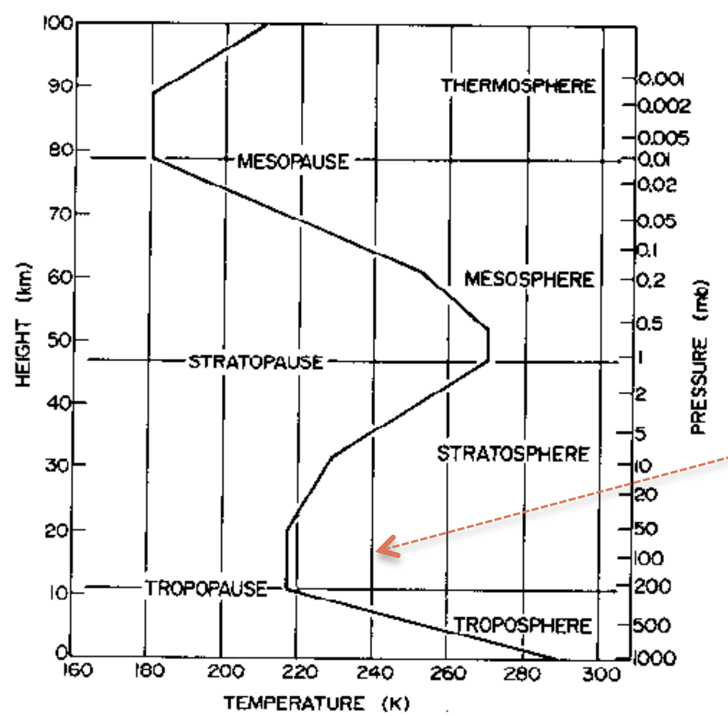
- What determines the tropopause height
- Why the tropopause will rise with global warming
  - Three separate effects cause a rise in tropopause height: result is the sum of all three!



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 is constant in this atmosphere,

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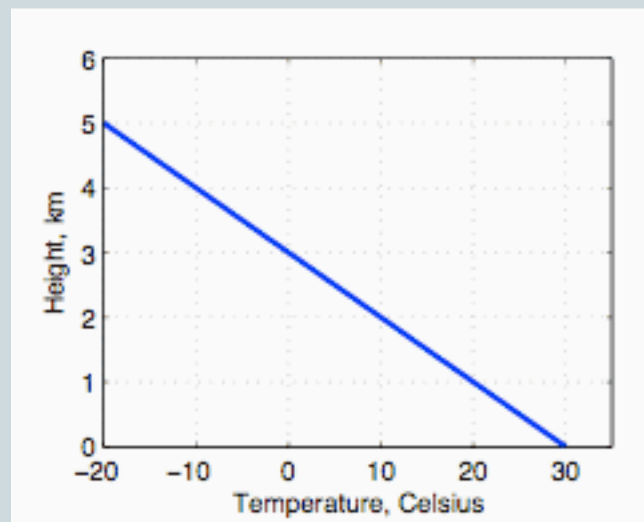
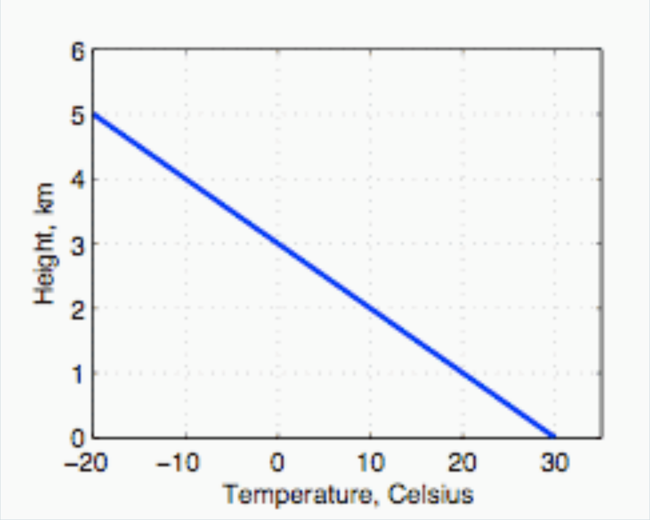


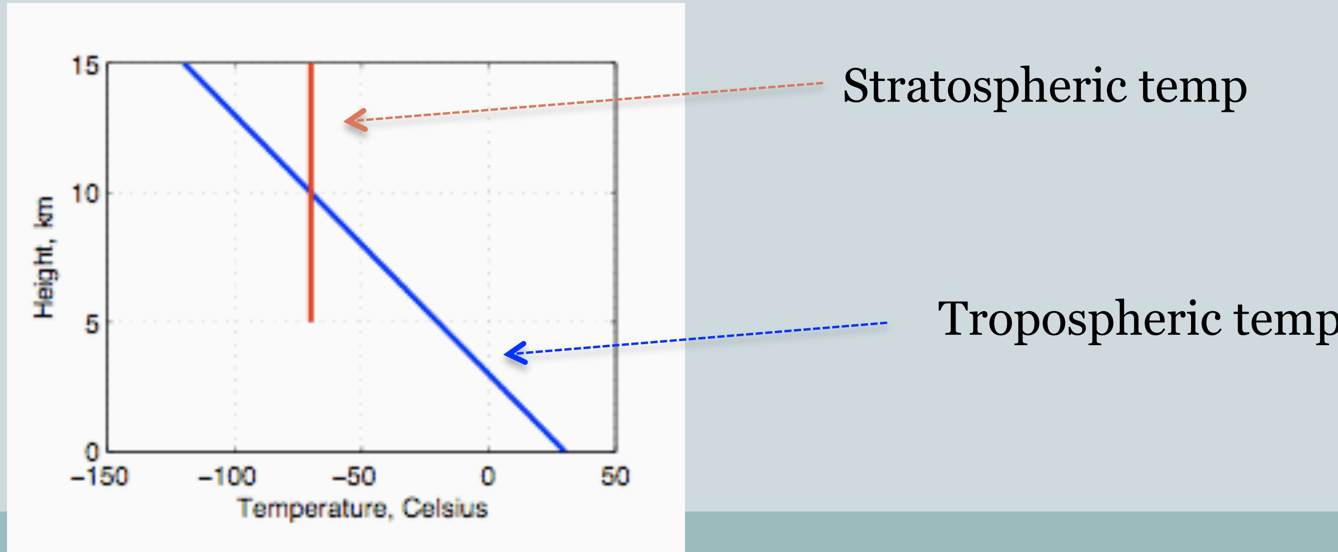
Tropopause Height

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



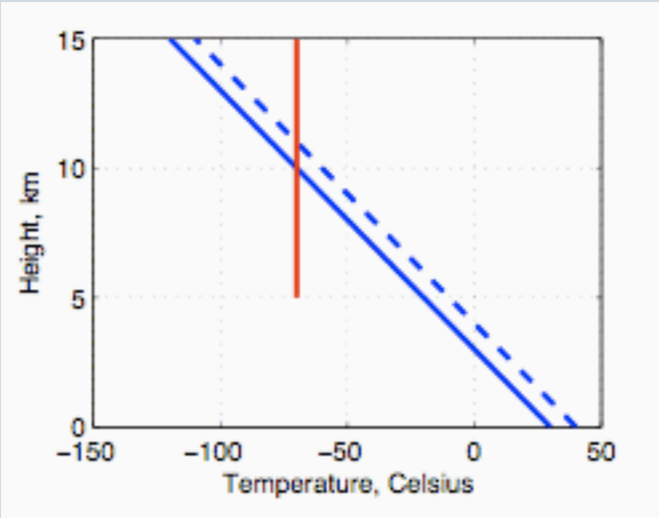
Tropopause Height

- 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!



Changes with Global Warming

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



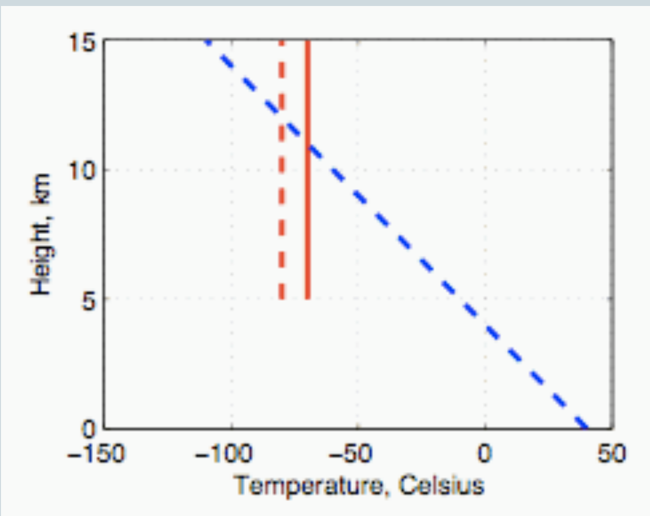
Increased tropospheric temperature => Convection penetrates more deeply

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

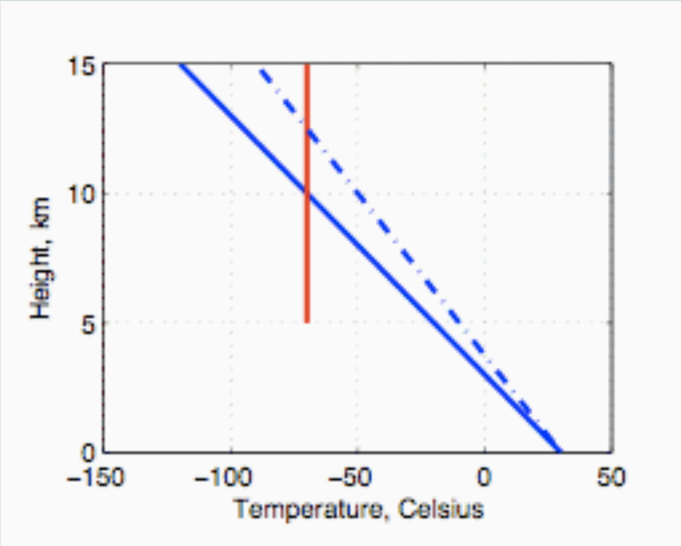
Dashed lines = warmed tropospheric temperatures, cooled stratospheric temps

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

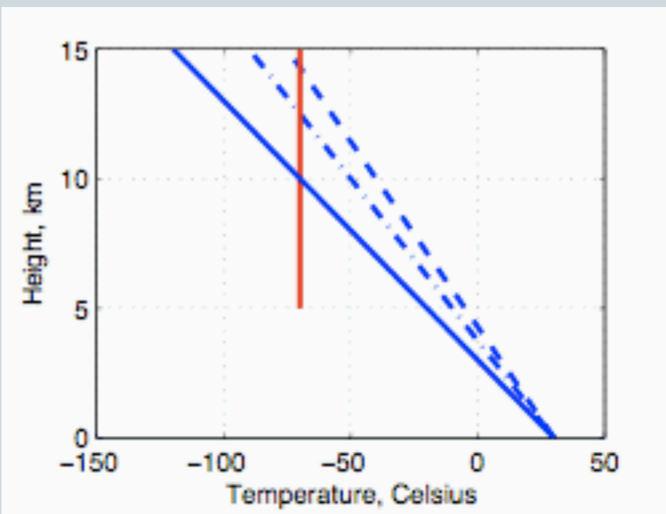


Solid = dry
Dash-dot = with moisture

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

Moisture Effect on Temperature Structure

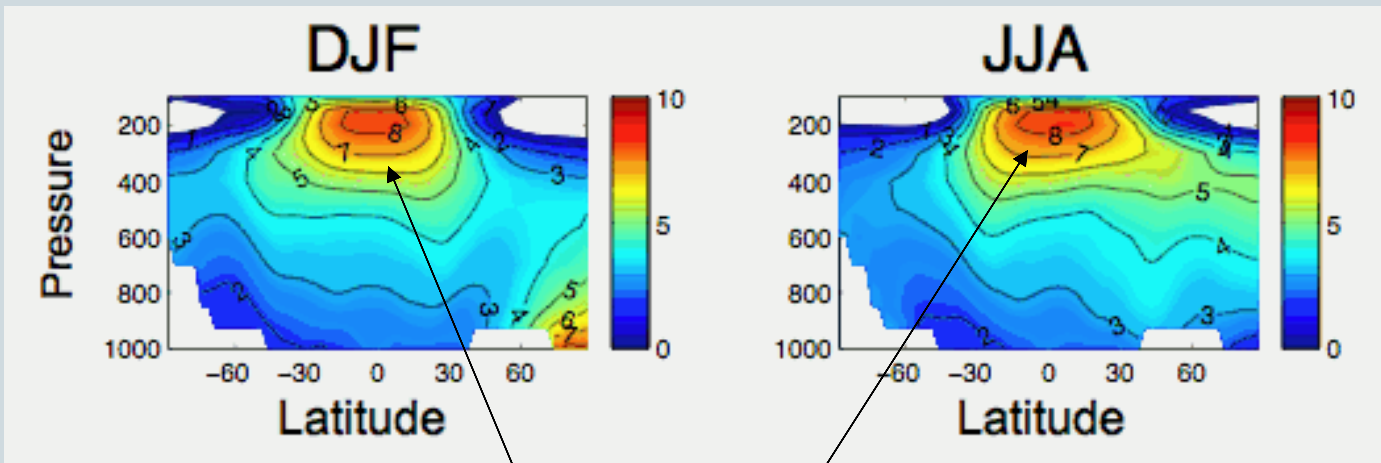
- With global warming, moisture content increases, so lapse rate decreases as well
  - Should imply more heating aloft



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

Global Warming Temperature Change

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

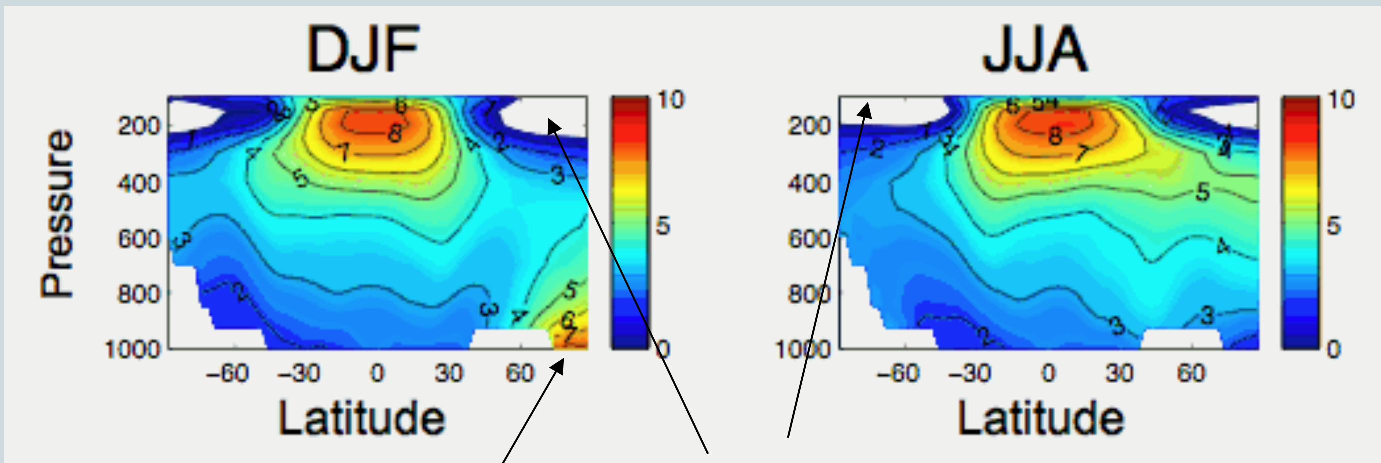


Tropical upper tropospheric warming (due to moisture)

From Frierson (2006)

Temperature Changes: IPCC Models

- Global warming simulations *change* in potential temp:



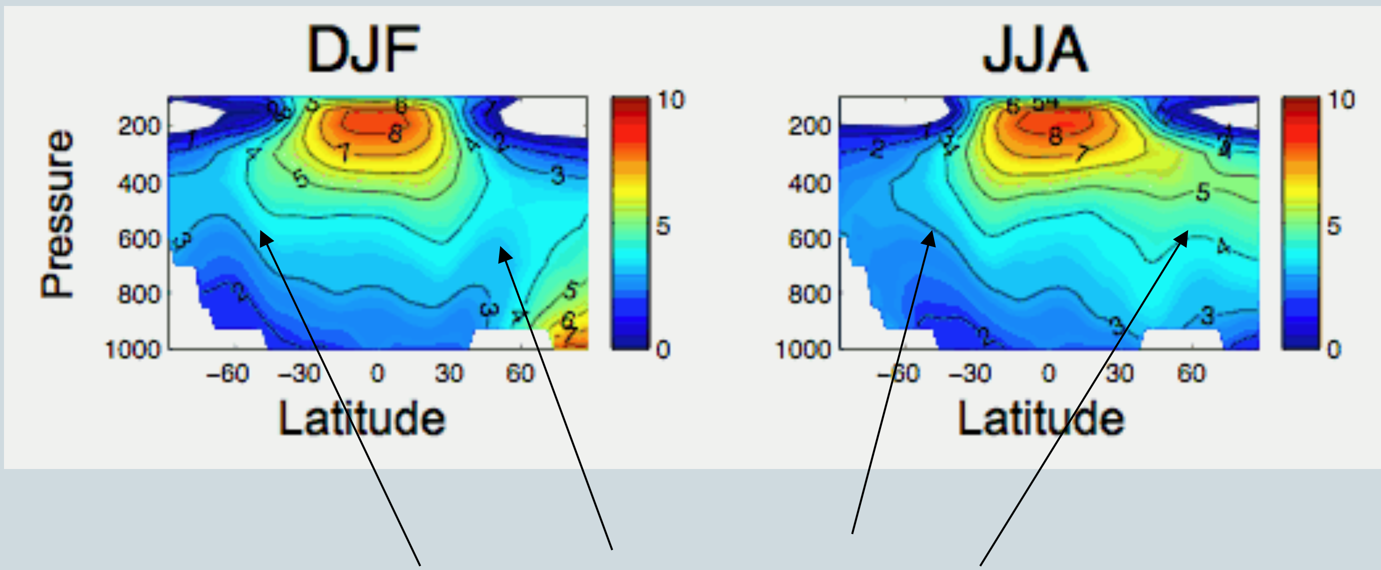
Stratospheric cooling

Polar amplification

From Frierson (2006)

Temperature Changes: IPCC Models

- Global warming simulations *change* in potential temp:



Midlatitude static stability increases as well

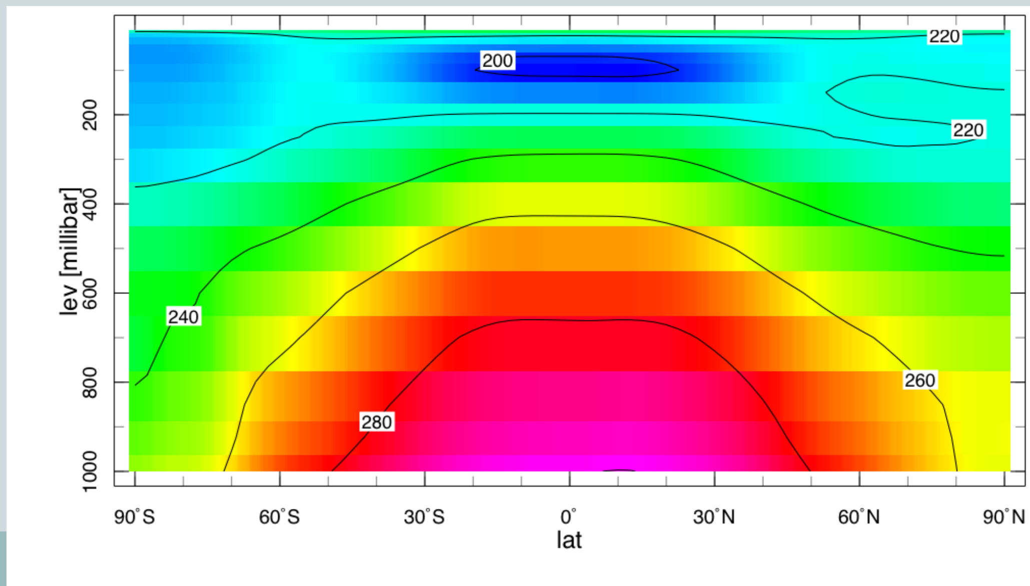
From Frierson (2006)

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

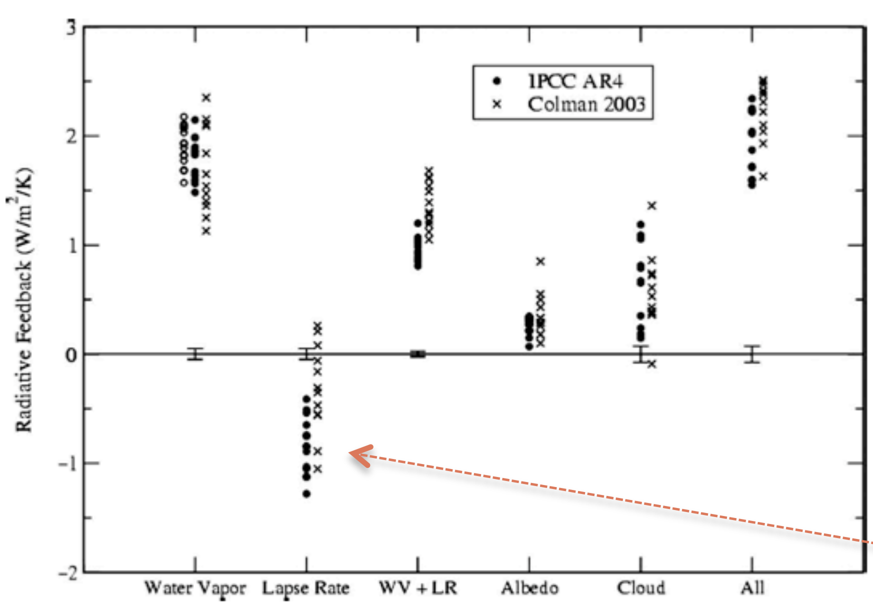


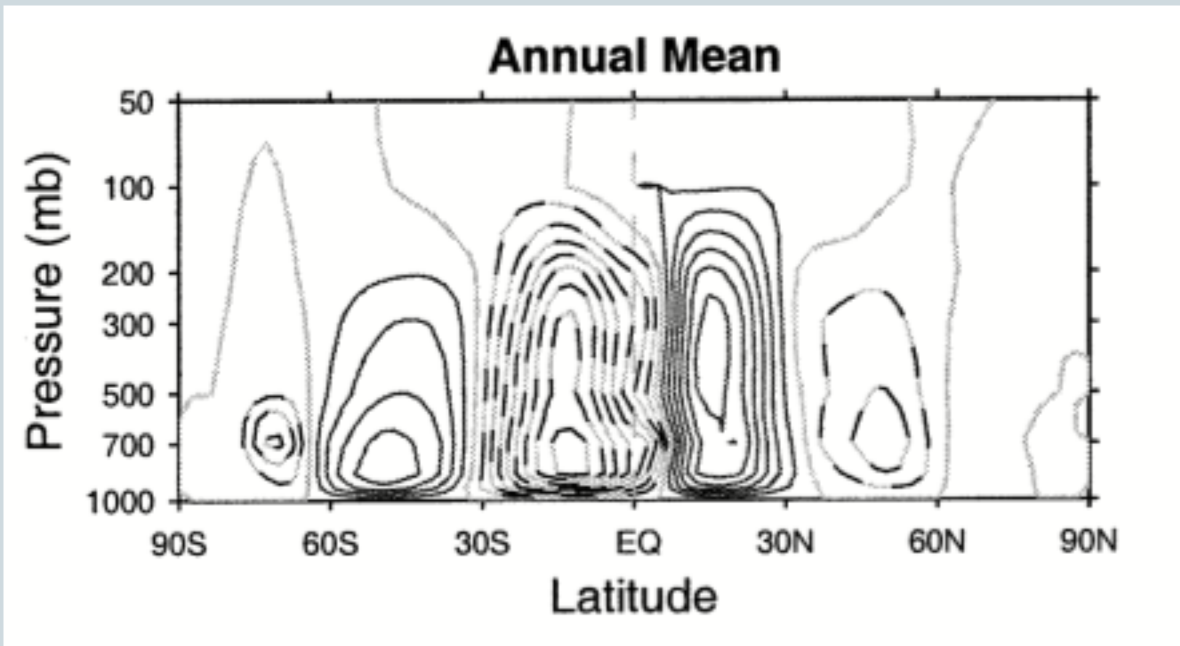
FIG. 1

Soden and Held 2005

Lapse rate is primary negative feedback

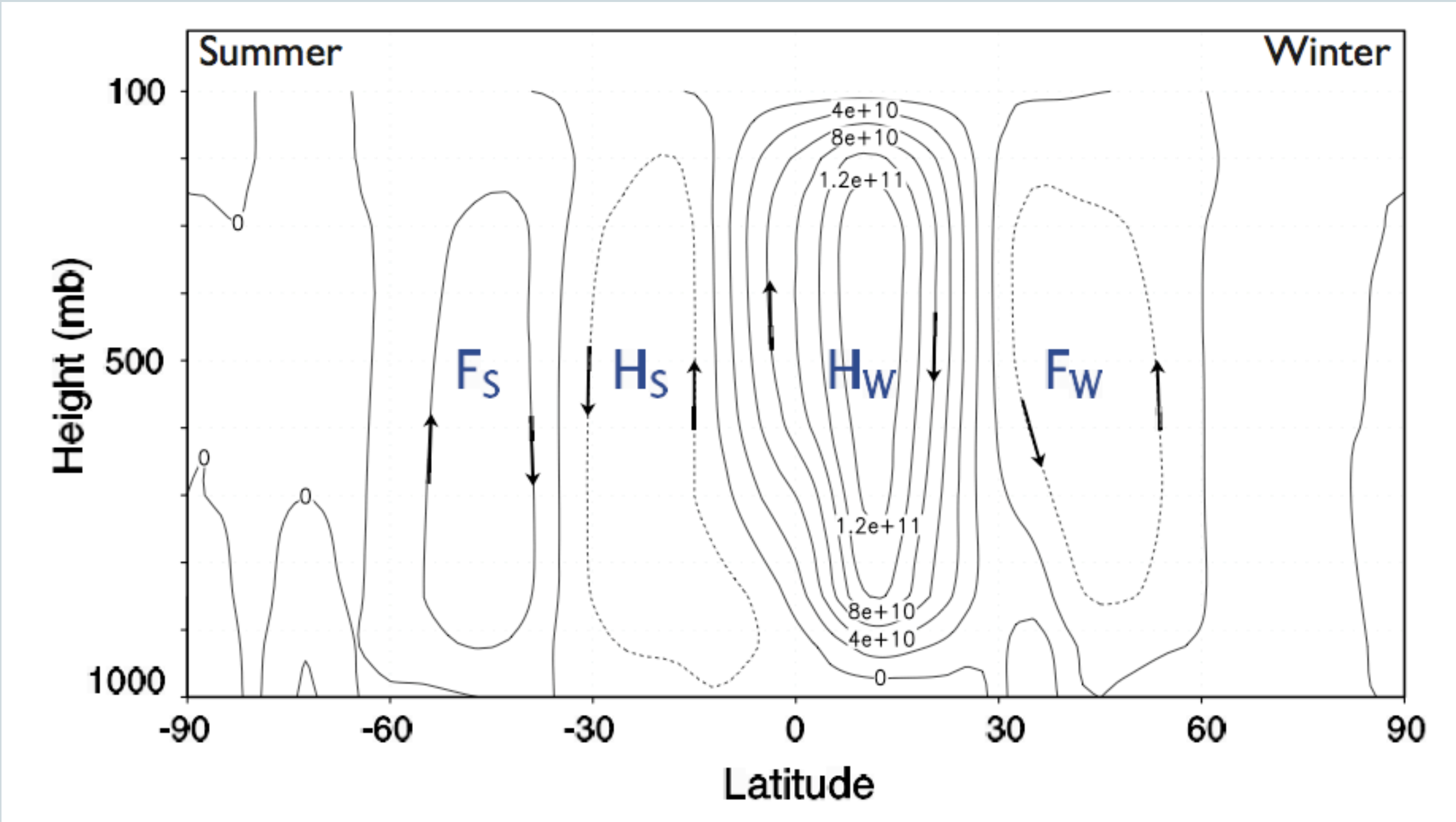
Hadley Circulation

- Dominant feature of zonally averaged circulation



Hadley Circulation

- 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?

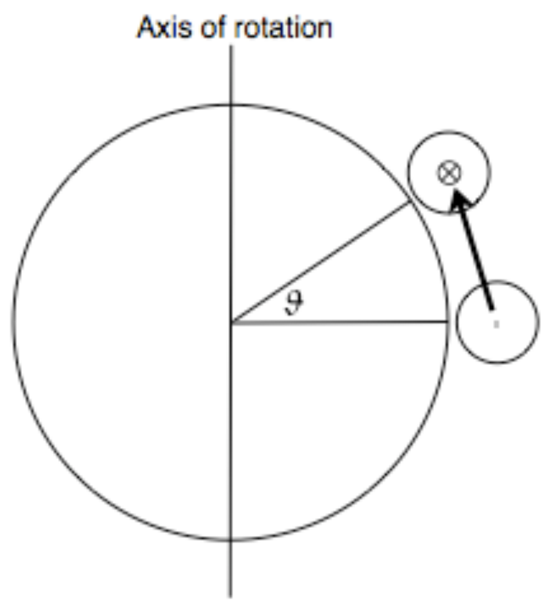


Fig. 11.5 If a ring of air at the equator moves polewards it moves closer to the axis of rotation. If the parcels in the ring conserve their angular momentum their zonal velocity must increase; thus, if $m = (\overline{u} + \Omega a \cos\vartheta) a \cos\vartheta$ is preserved and $\overline{u} = 0$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

Hadley Circulation Extent

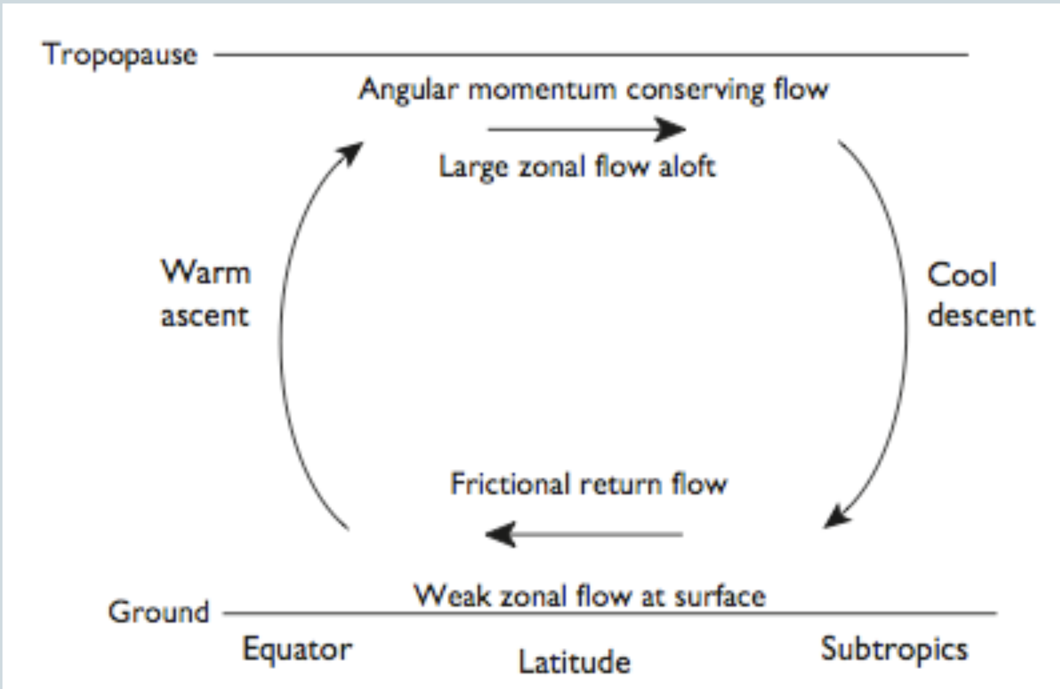
- Traditional view:
  - Hadley cell extends out until the latitude where baroclinic instability sets in
  - Winds accelerate rapidly due to Coriolis
  - Associated shear becomes baroclinically unstable (higher Coriolis parameter helps with this too)
  - Induces Ferrel cell type behavior, ending Hadley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

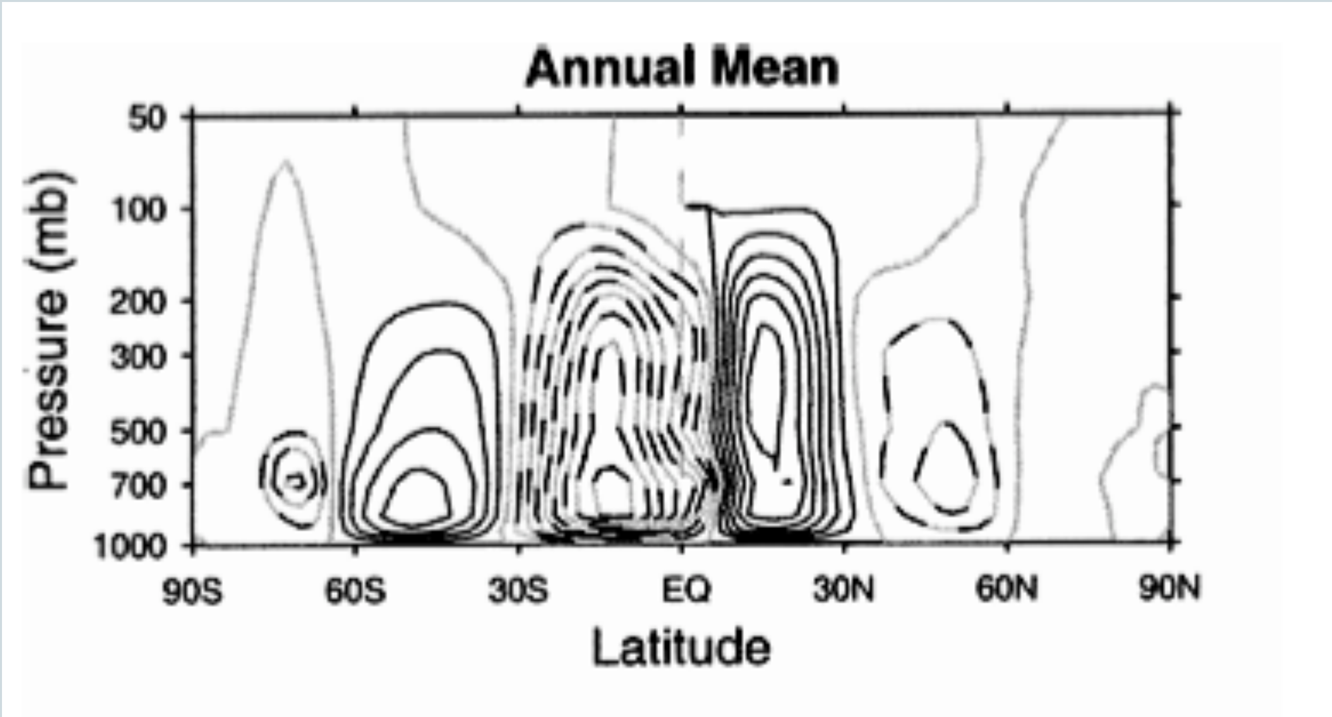


Held-Hou Theory

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

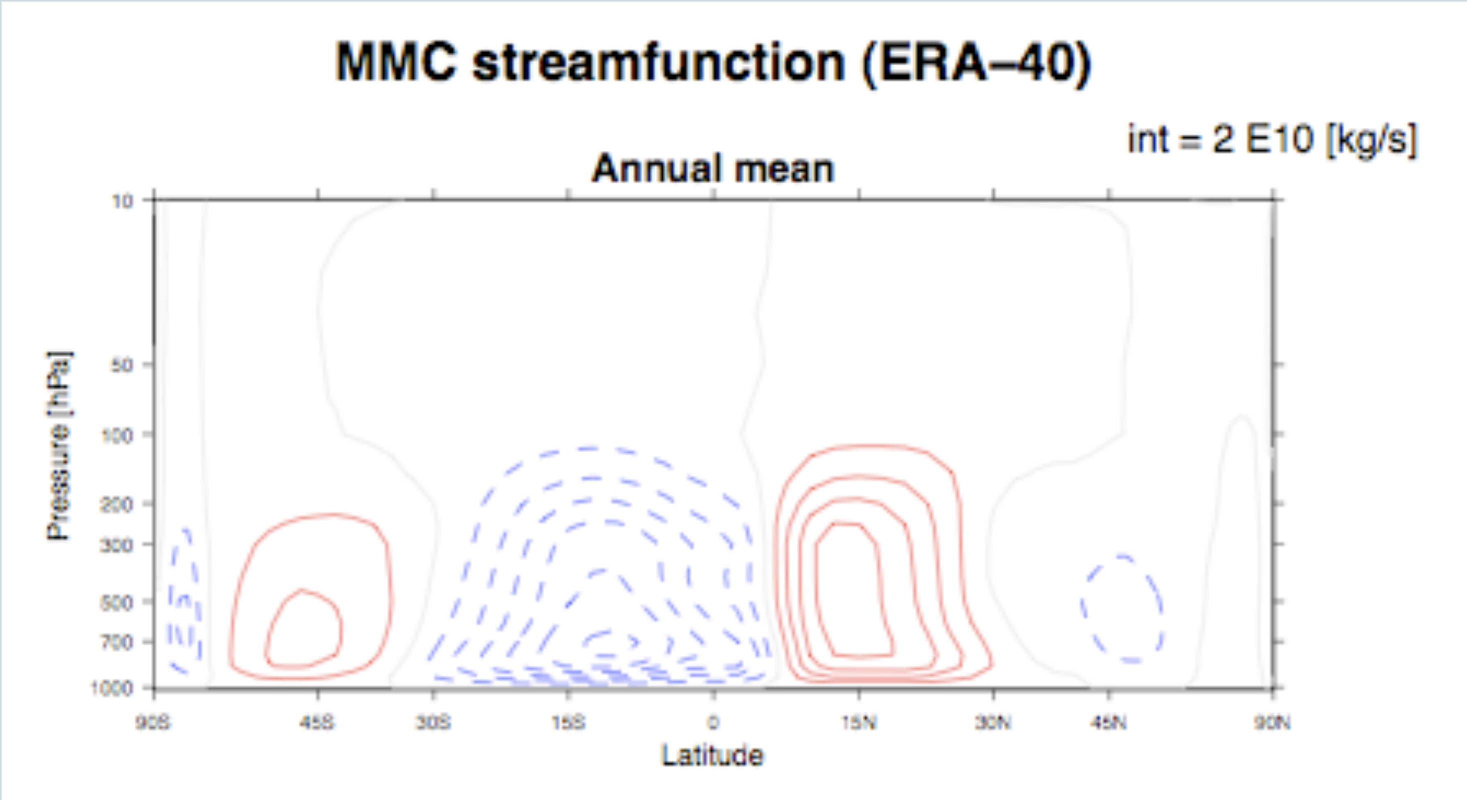
Hadley cell observations

- NCEP reanalysis (Dima and Wallace 2003):



Hadley cell observations

- ERA-40 reanalysis (Rei Ueyama):



Sin(latitude)

Momentum Equation Derivations…

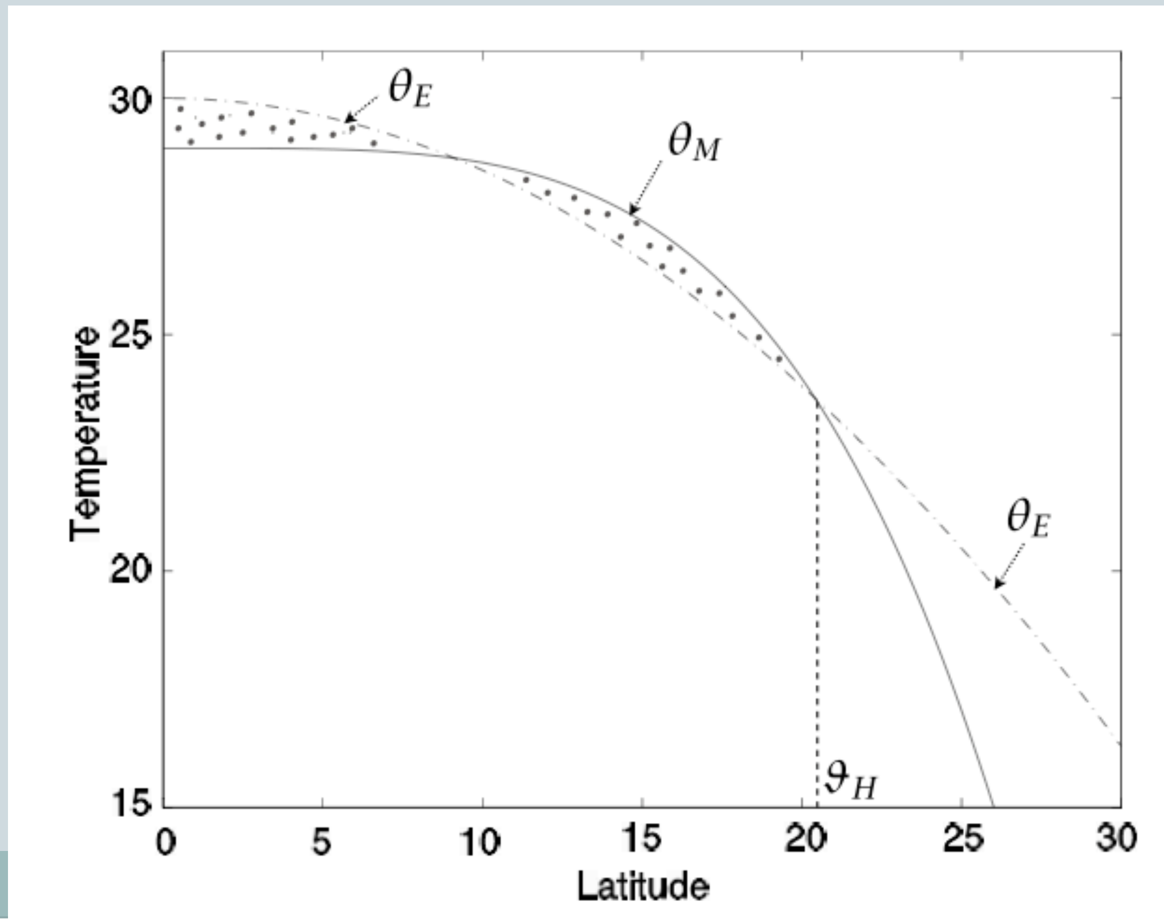
- Held-Hou theory for Hadley cell
  - Zonal momentum budget:
    - Angular momentum conservation
    - Winds reach very strong speeds quickly: e.g., u=95 m/s at 25 deg
  - Meridional momentum equation:
    - Geostrophic balance
      - One of the ignored terms was v dv/dy: assumed small relative to f u because v << u
    - Thermal wind in meridional direction then gives you temperatures
      - Reeelly small temperature gradients
      - 0.6 K at 12 deg, 3.2 K at 18 deg

Next…

- Thermodynamics:
  - To close the problem & solve for width, strength, etc
- First assume Newtonian cooling, as in Held-Suarez model

“Equal-area” argument

- Conservation of energy:

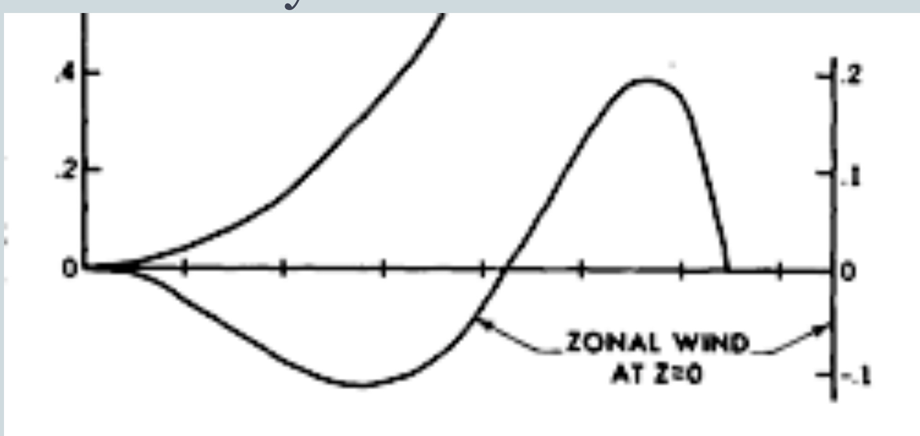


Held-Hou Results

- Width is proportional to:
  - Square root of equilibrium temperature gradient
  - Square root of height of tropopause
- Inversely proportional to:
  - Rotation rate

Held-Hou Results

- Strength proportional to:
  - “Area” in equal area argument (distance from equilibrium profile)
- Strength inversely proportional to:
  - Radiative relaxation time
  - Static stability



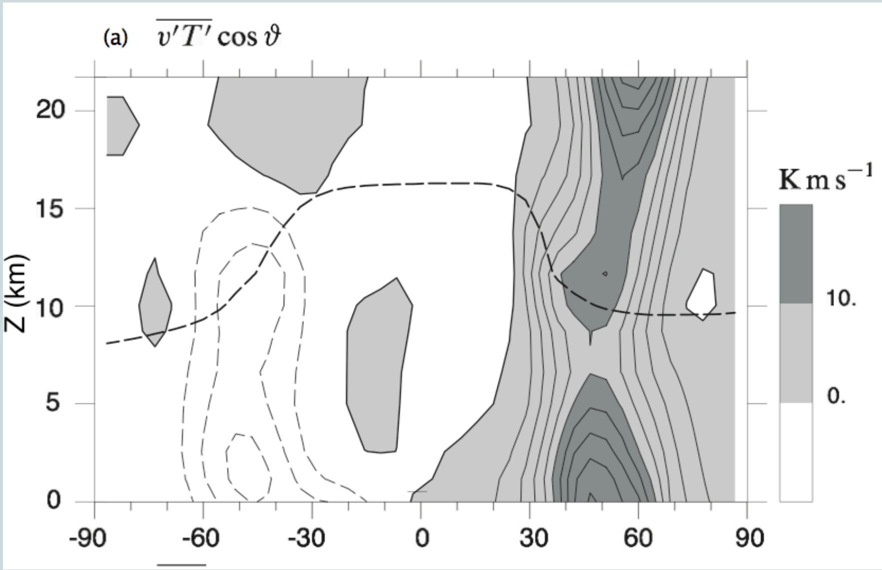
Surface winds

Held-Hou Criticism

- Rough comparison with observations:
  - Good:
    - Right width
    - Surface winds right sign in right places
  - Bad:
    - Upper tropospheric winds way too strong
    - Circulation too weak
  - Ugly:
    - Radiative equilibrium outside the cell
    - Impossible to get surface winds outside the cell

Ways to Fix Problems?

- Can use a radiative-convective-***eddy*** equilibrium temperature profile:
  - Eddies cool the subtropics, warm the higher latitudes

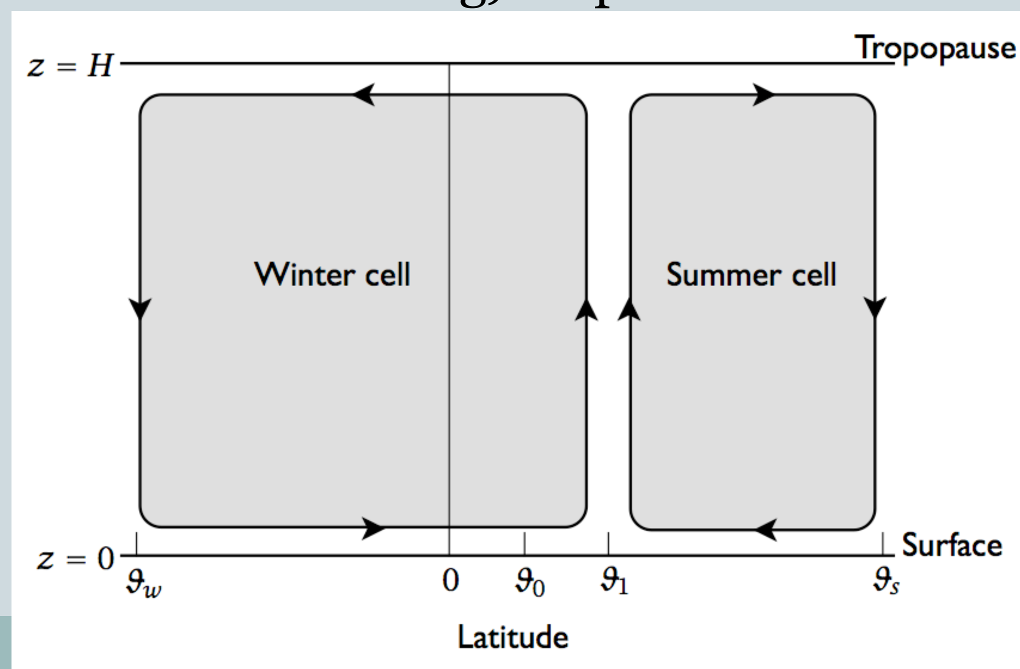


DJF eddy heat fluxes

  - Would result in a stronger circulation
    - Cooling subtropics increases gradients within the Hadley cell

Extensions to Held-Hou Model

- Lindzen & Hou (1988): forcing asymmetric about the equator
  - Can predict boundary between cells, cell widths, & cell strengths
    - ITCZ location (location of maximum heating) is specified in this problem
    - Boundary b/w cells is poleward of "ITCZ"

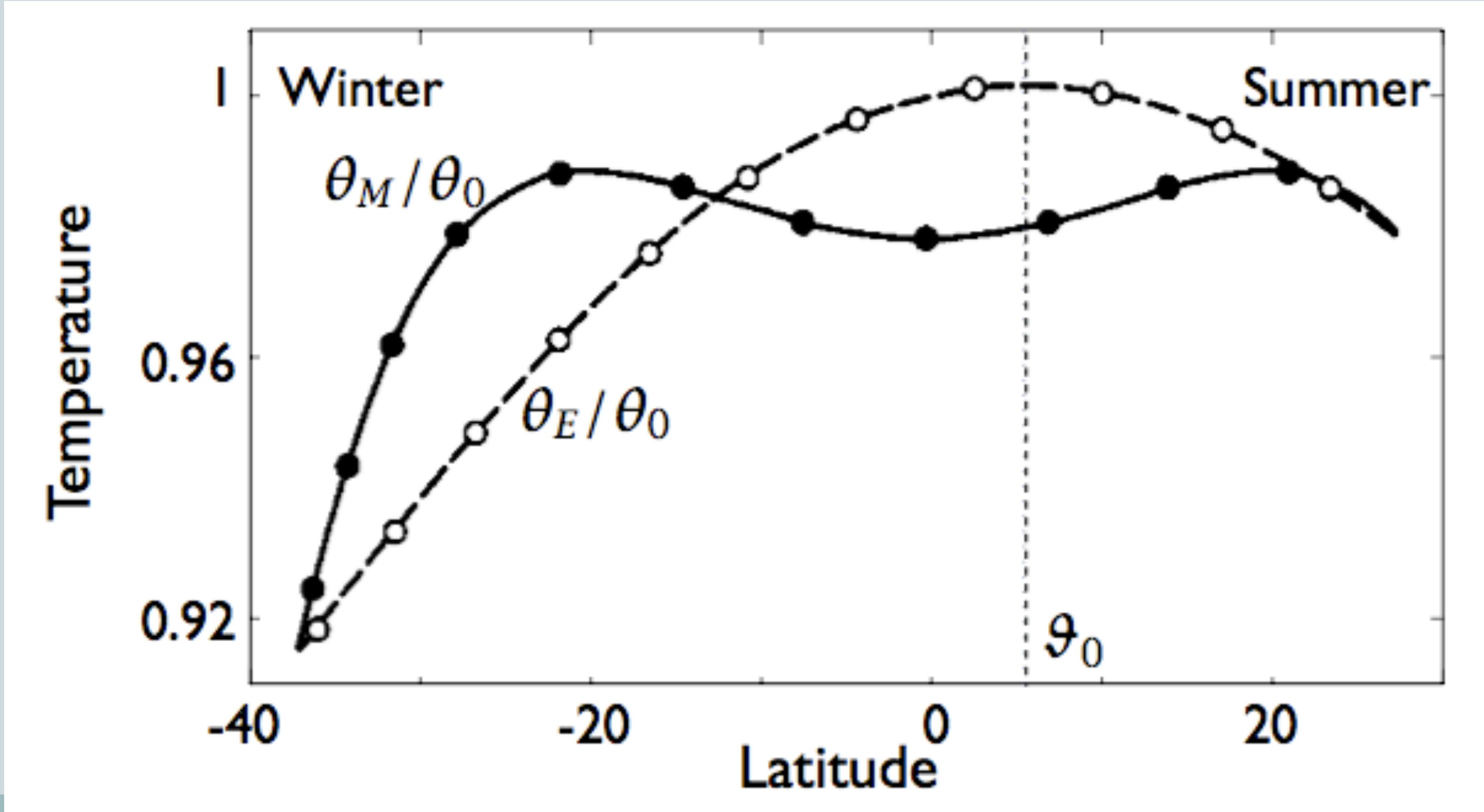


Extensions to Held-Hou Model

- Lindzen & Hou (1988): forcing asymmetric about the equator
  - Asymmetry is very large between summer and winter hemispheres
    - As in observations
  - Derivation: wind and temperature structure when forcing is off-equator (on the board)

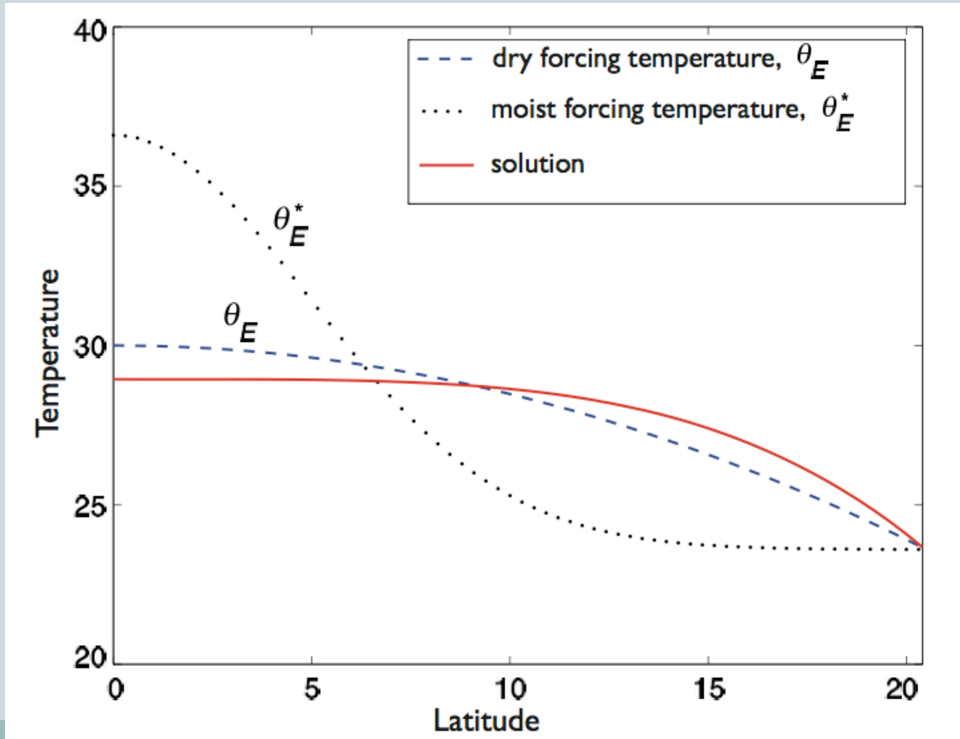
Asymmetric Hadley cell

- Temperatures:



Extensions to Held-Hou Model

- Hou & Lindzen (1992): localized forcing
  - Delta-function (or highly concentrated) forcing: “ITCZ”
  - Basic idea described in Vallis



Extensions to Held-Hou Model

- Hou & Lindzen (1992): localized forcing
  - Gives stronger circulation (obviously)
  - Dangerous way to put in moisture
    - Might expect stronger circulation with more moisture/heating
    - However, one of the main things moisture does is change static stability: actually can get significantly weaker circulation with higher moisture contents with this effect
  - Models with active moisture budgets are preferable

Extensions to Held-Hou Model

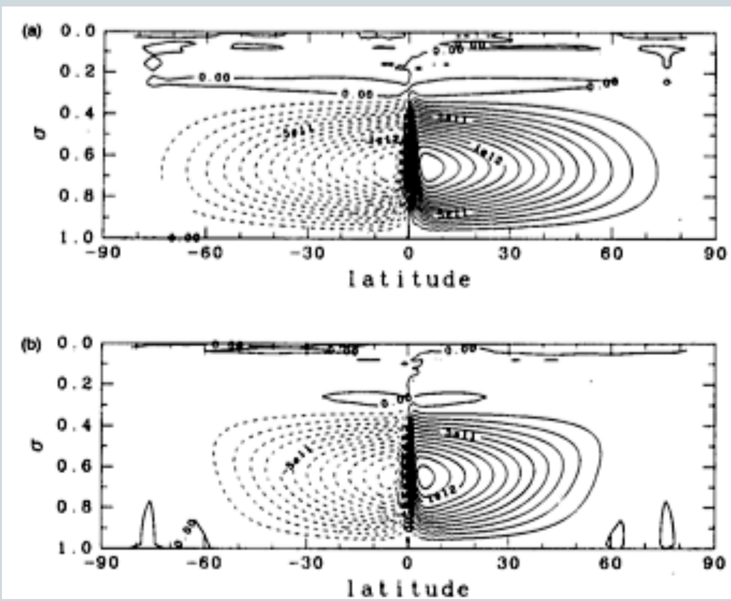
- Fang and Tung (1996, 1997, 1999):
  - Analytic solutions w/ viscosity, vertical structure, etc
  - Changes with thermal relaxation time
  - Time dependent circulations

Adding moisture

- Satoh (1994): moisture
  - Ran simulations with a moist axisymmetric model (gray radiation, etc)
  - Developed theory for this

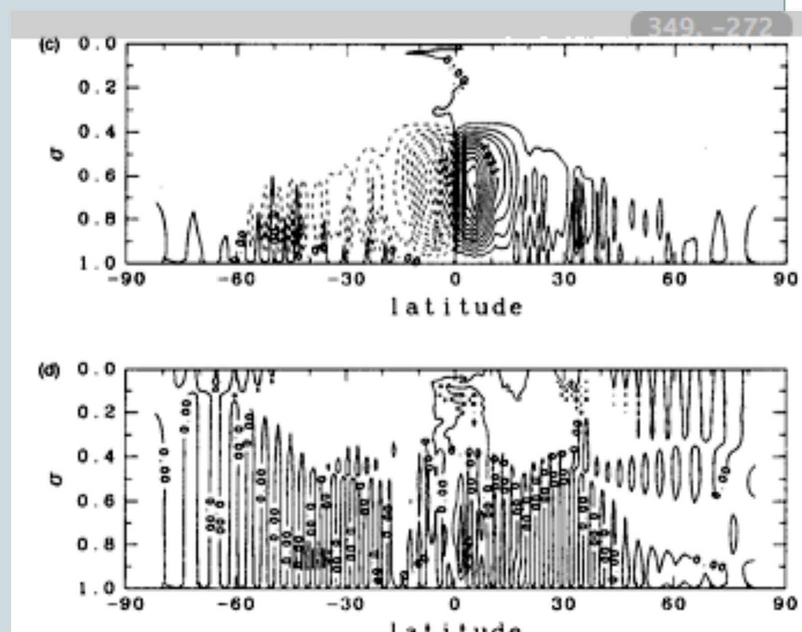
Omega = 0

Omega = 0.1*OE



Omega = OE

Omega = 10*OE

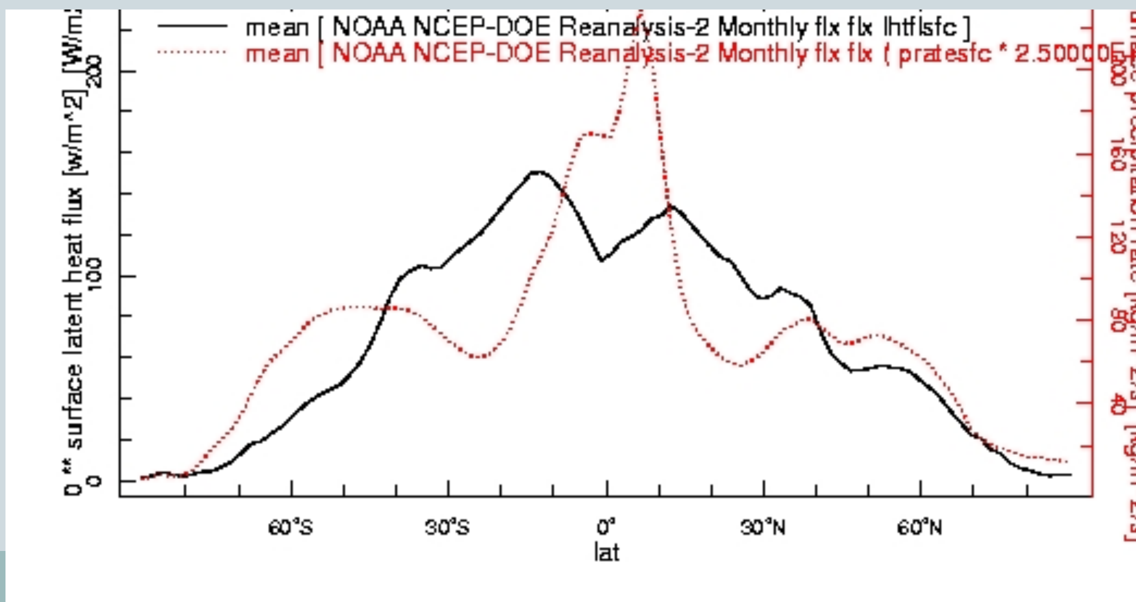


A first moist Hadley cell

- Satoh (1994): moisture
  - All simulations show very concentrated upward motion
  - Developed simple theory based on the axisymmetric simulations:
    - Assume localized ITCZ, dry subtropics
    - Static stability determined by moist adiabat (humidity at equator)
    - Balance between radiative cooling and subsidence in dry subtropics determines strength
    - Angular momentum conserving winds
    - Width determined by thermodynamics (as in Held-Hou)

Satoh (1994) theory

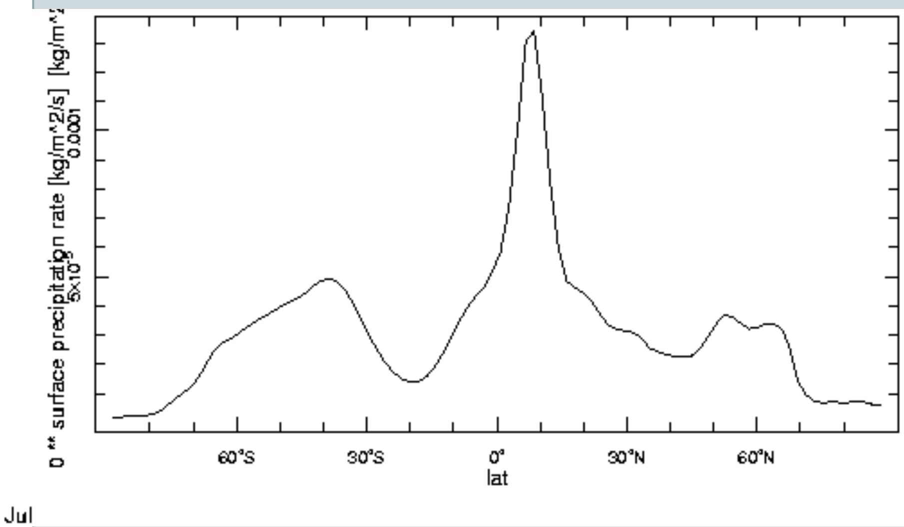
- Satoh (1994): moisture
  - Interesting way to consider the effect of moisture without an active moisture budget
    - Dry region controls everything
  - Limited applicability though? Subtropics are clearly not dry:



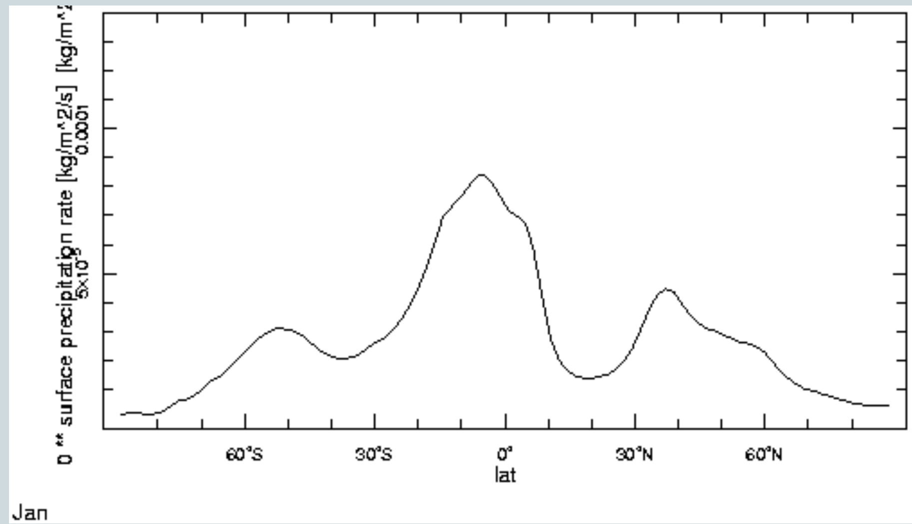
Evap and precip
NCEP Reanalysis 2

Satoh (1994) theory

- Seasonal precip (July mean and December mean)



July precip



December precip

- We'll discuss models with active moisture shortly
  - These predict the width of the precipitating regions as well

Next: effect of eddies on the Hadley circulation

- We talked about ways to incorporate eddy heat fluxes into an axisymmetric model
- How about effect of eddy momentum fluxes?
  - Ferrel cell derivation
  - An eddy-driven Hadley cell model

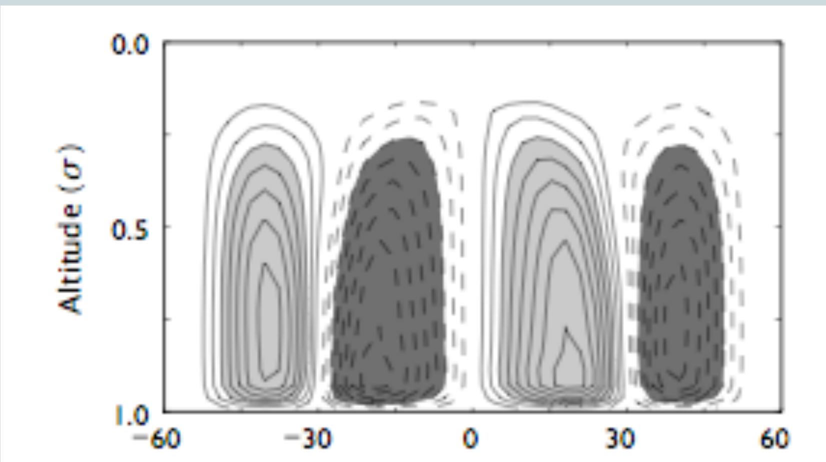
Effect of eddy fluxes

- Compare the dry dynamical core model run axisymmetrically versus with eddies
  - Hadley cell is significantly stronger with eddies
  - Suggests eddies are a major driver in this model!
  - Heat fluxes or momentum fluxes?
- Not true in moist model!
  - Axisymmetric cell is stronger in moist GCM
  - Comparing axisymmetric and full Hadley cells in different models could be nice project

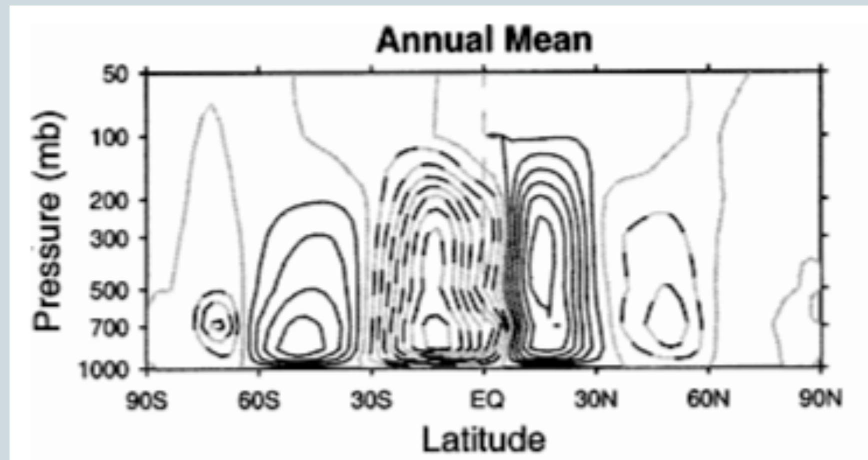
Dry GCM Results

- Hadley cell strengths:

Model

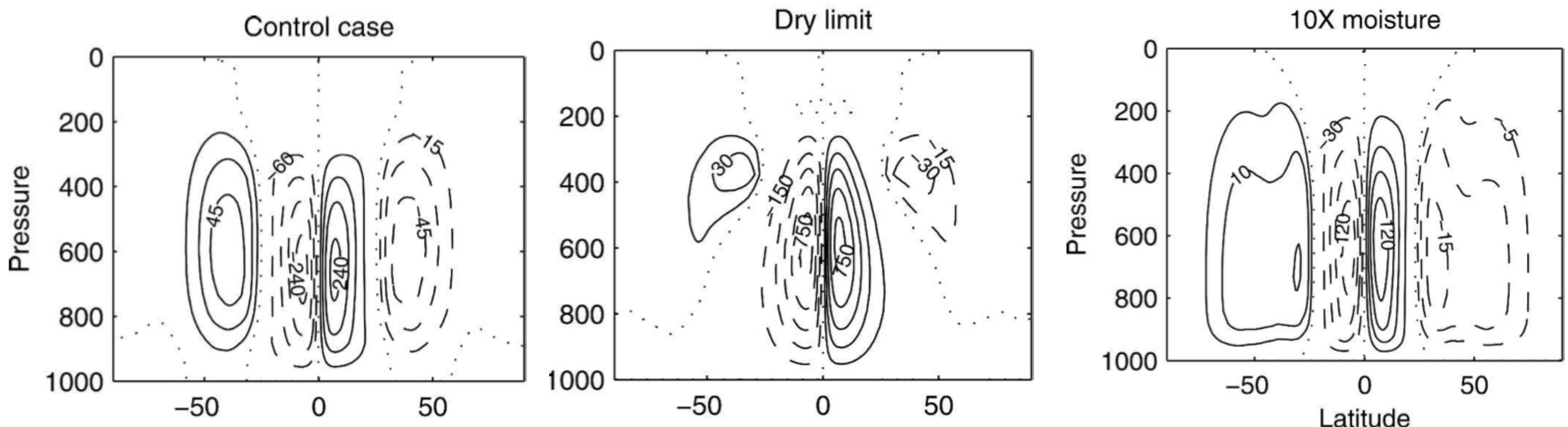


Obs



Hadley Circulation in GrAM

Remember those simulations varying moisture content?
(control, dry, and 10x Clausius-Clapeyron constant)



Max contour = 240 Sv

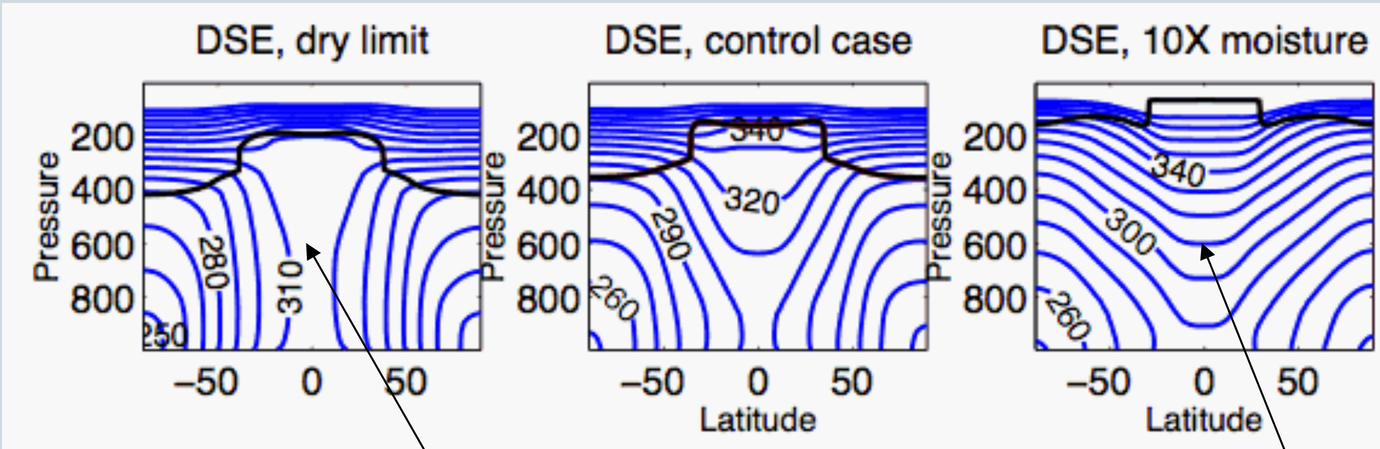
Max contour = **750** Sv

Max contour = **120** Sv

Hadley circulation is **much stronger** in **dry** case!

Temperature Structure Changes

- Dry static energy, idealized GCM simulations:



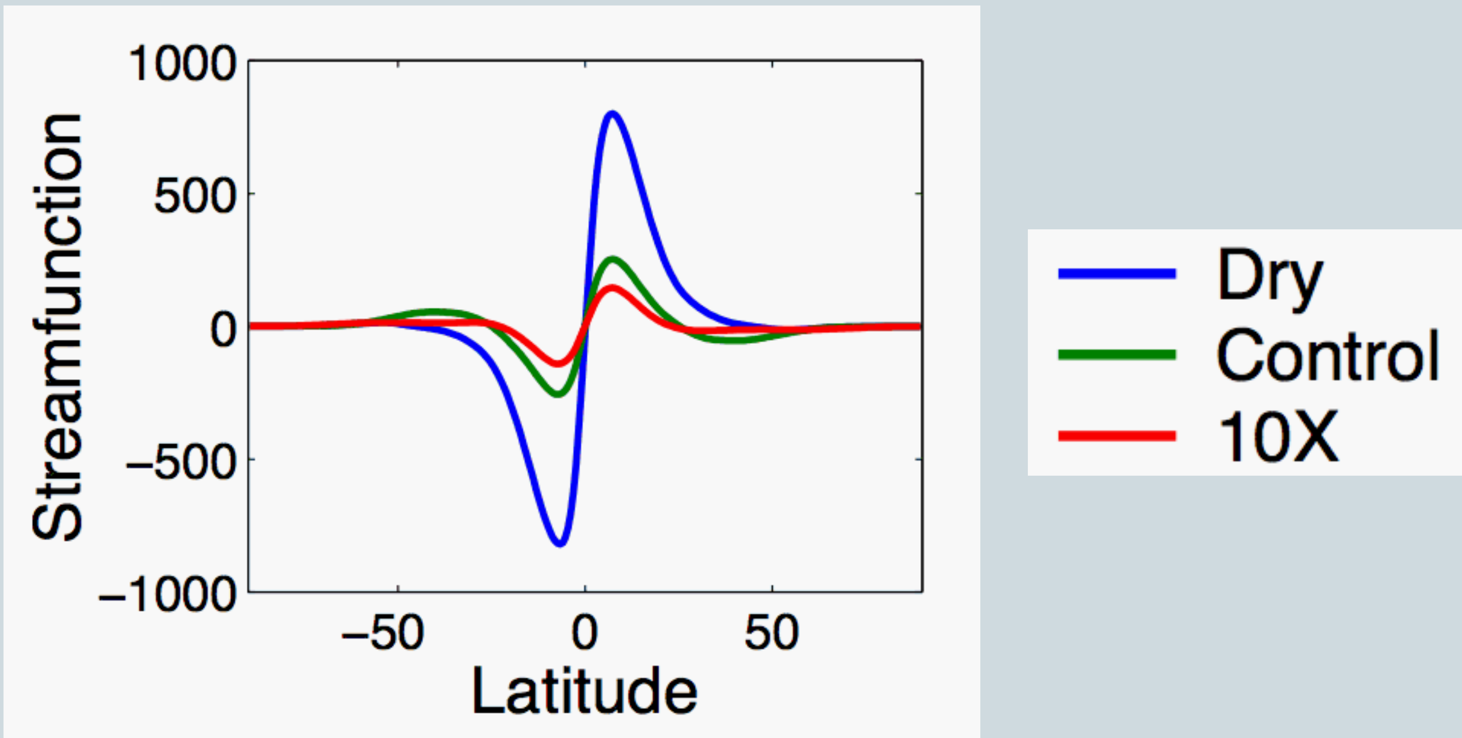
~Zero stability

Large stability

- Static stability ($\frac{d\theta}{dz}$) increases in tropics (as expected)

From Frierson, Held and Zurita-Gotor (2006)

Hadley Circulation in GrAM

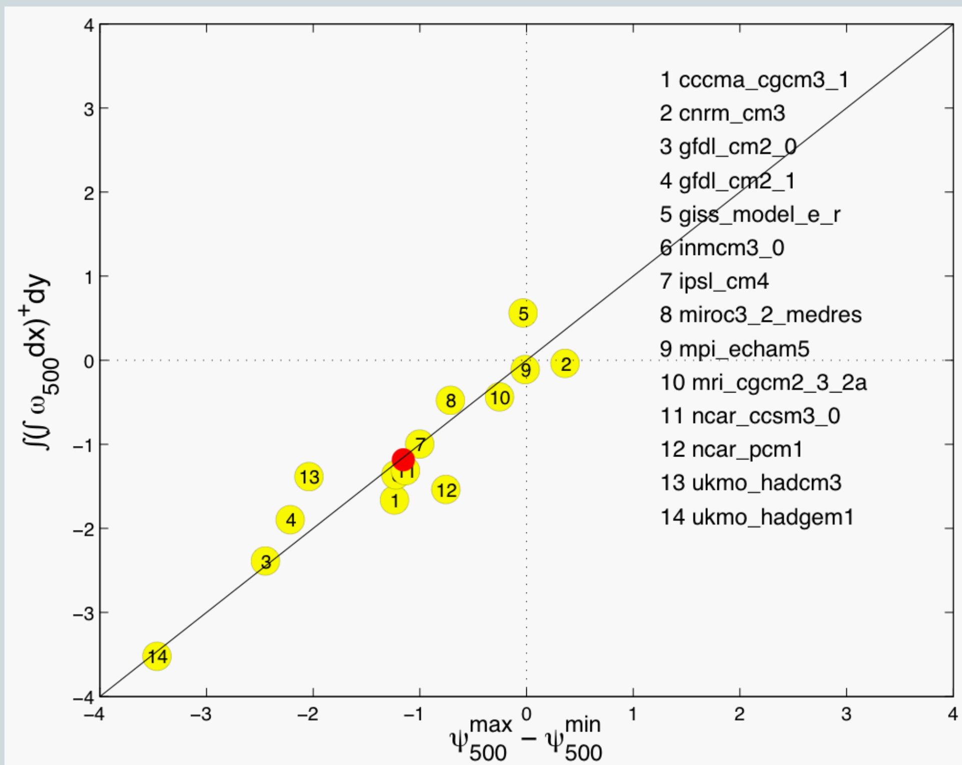


Hadley circulation is **much stronger** in **dry** case!

Hadley Circulation Changes

- Changes w/ global warming in CMIP3:

Vertical velocity measure



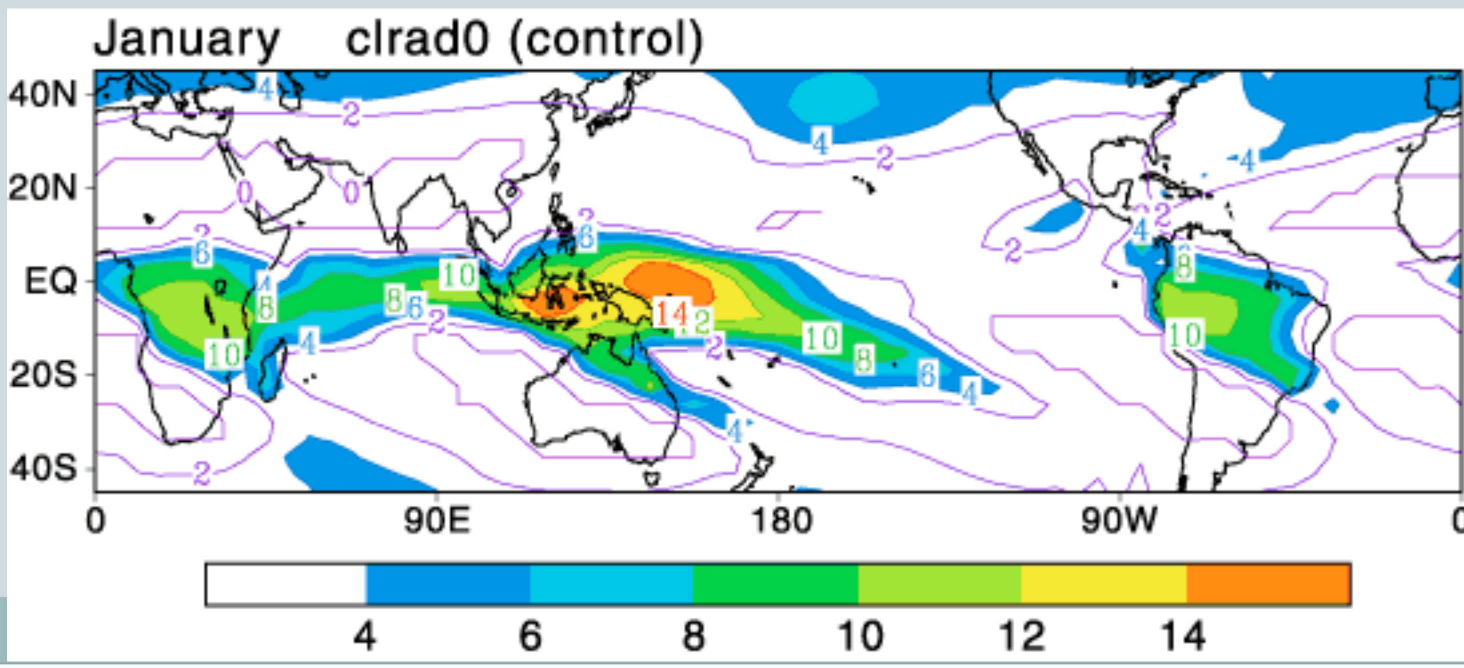
Streamfunction measure

Decreases 0-3.5% per K warming

From Lu, Vecchi, and Reichler (2006)

Next…

- We'll return to Hadley cell later when discussing extratropical-tropical interactions
- Next: theories with an active moisture budget and the "gross moist stability" (GMS)



Models with a Moisture Budget

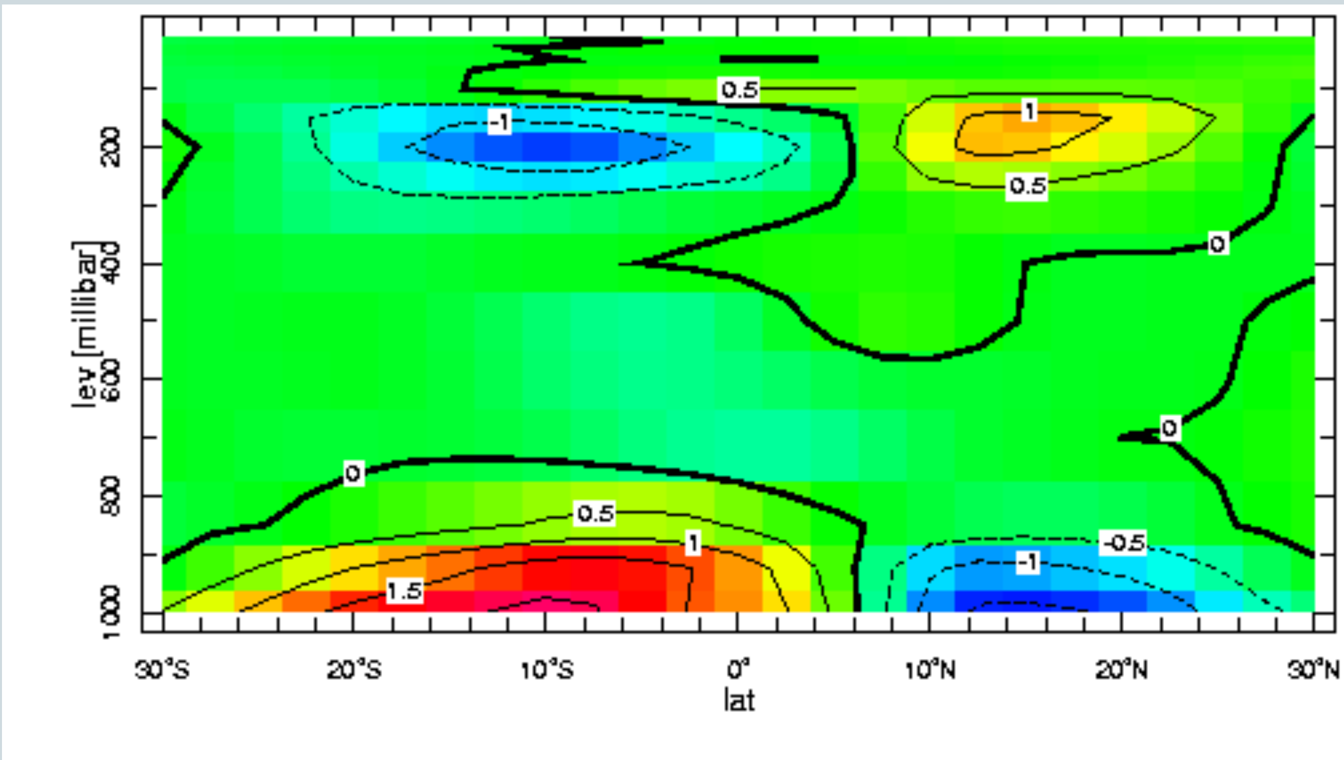
- Complications with adding moisture:
  - It’s an active tracer
    - Advected by the flow and influences the flow (through latent heat release)
  - Evaporation
    - Everything that precipitates has to evaporate from somewhere (where and how much evap?)
  - Convective closure
    - When does it precipitate and how much, as a function of the atmospheric state

Models with a Moisture Budget

- Common approximation for toy models of the tropics is *simplified vertical structure*
- We'll introduce the GMS in a 2-mode model with moisture
  - The Quasi-equilibrium Tropical Circulation Model (QTCM) of David Neelin and Ning Zeng is one example of this
  - Other users/contributors to QTCM include Chris Bretherton, Adam Sobel, Bjorn Stevens, Daehyun Kim, etc
- The derivation here will be slightly more based on Frierson, Majda and Pauluis (2004)

Justification for Two-Layer Approach

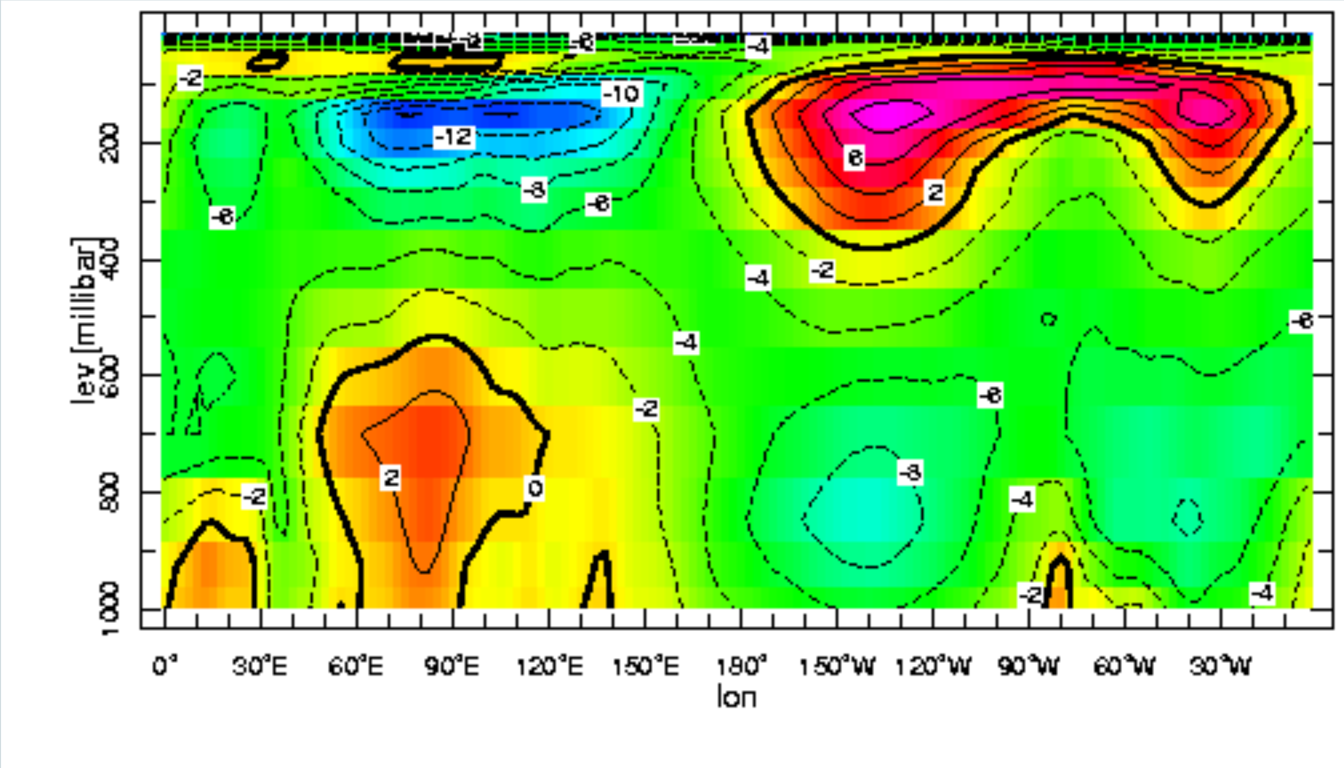
- Simple structure of winds in Hadley cell:



Zonal mean meridional velocity, NCEP Reanalysis 2

Justification for Two-Layer Approach

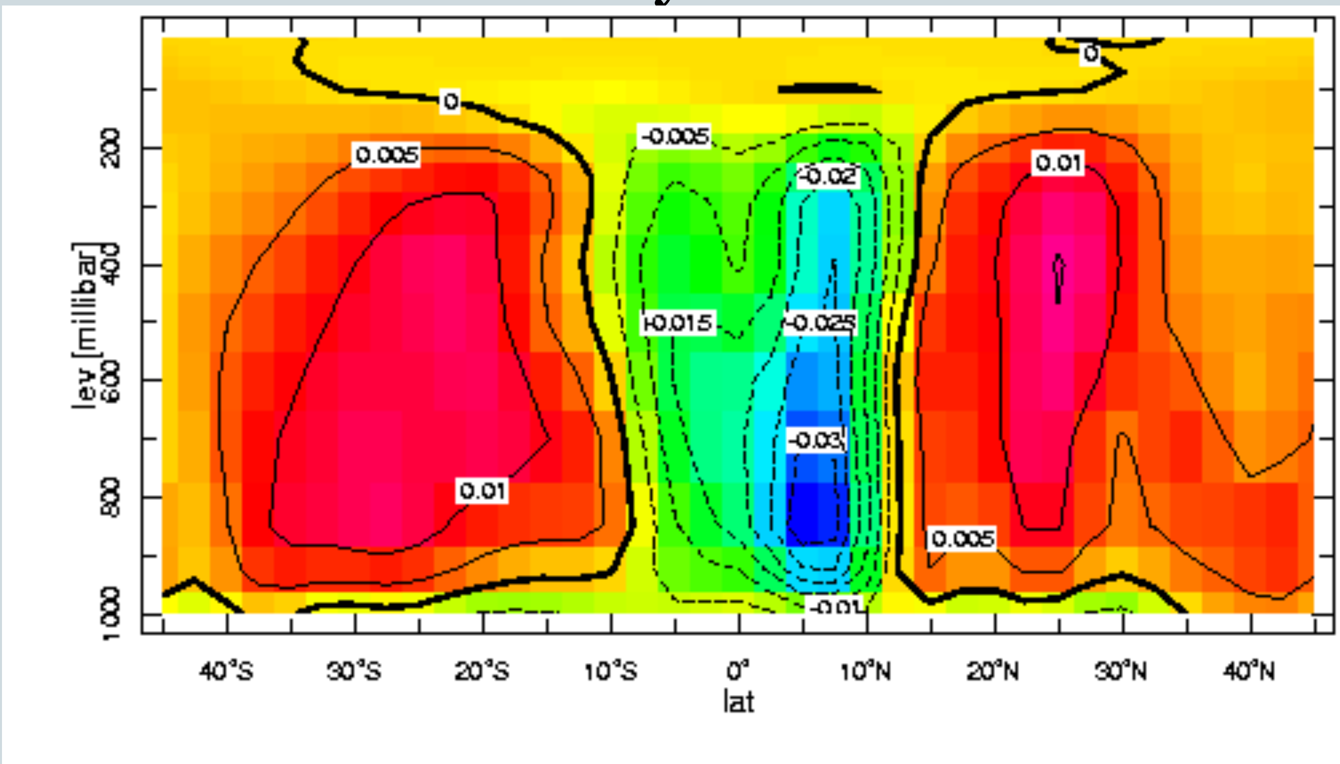
- Simple structure of winds in Walker cell:



Zonal winds averaged b/w 5N and 5S, NCEP Reanalysis 2

Justification for 2-Layer Approach

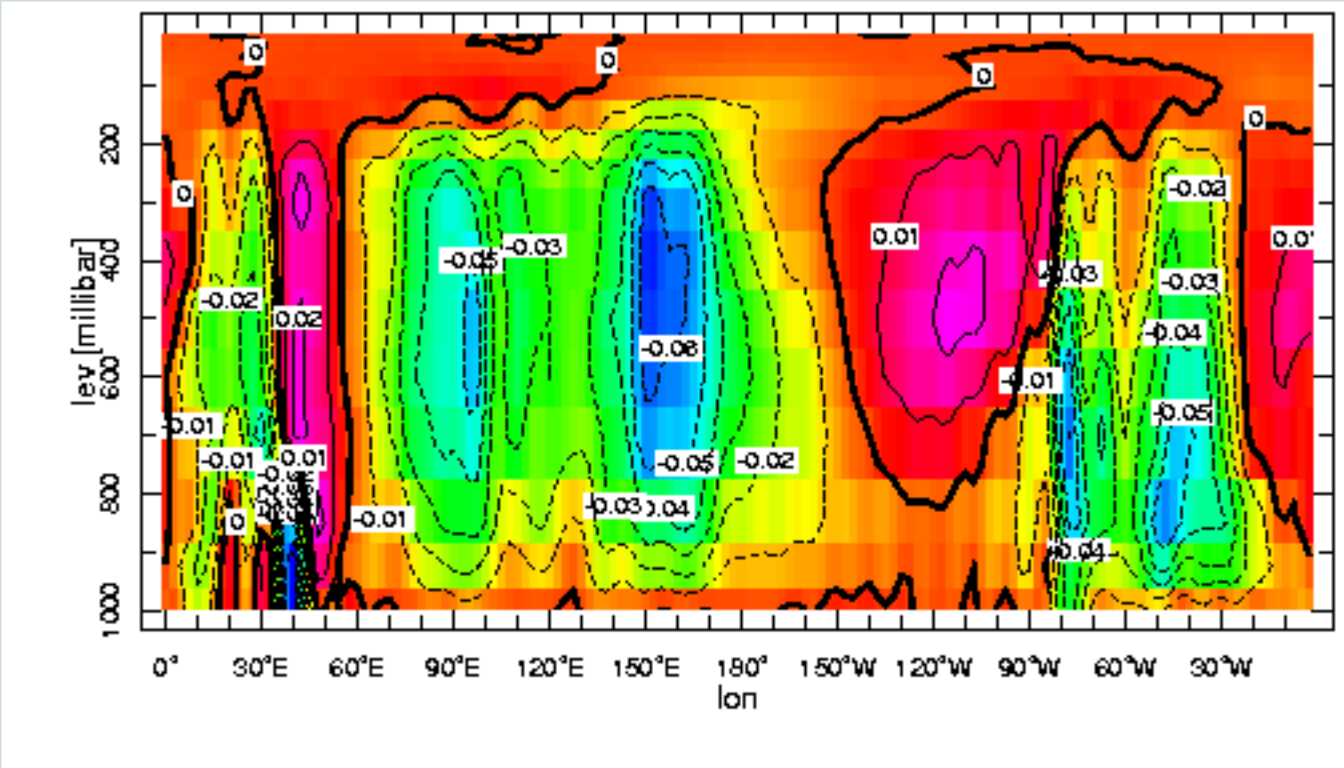
- Vertical motion in Hadley cell:



Zonal mean pressure velocity, NCEP Reanalysis 2

Justification for 2-Layer Approach

- Vertical motion in Walker cell:



Pressure velocity avg'd b/w 5N and 5S, NCEP Reanalysis 2

Gill Model

- Steady response to heating:

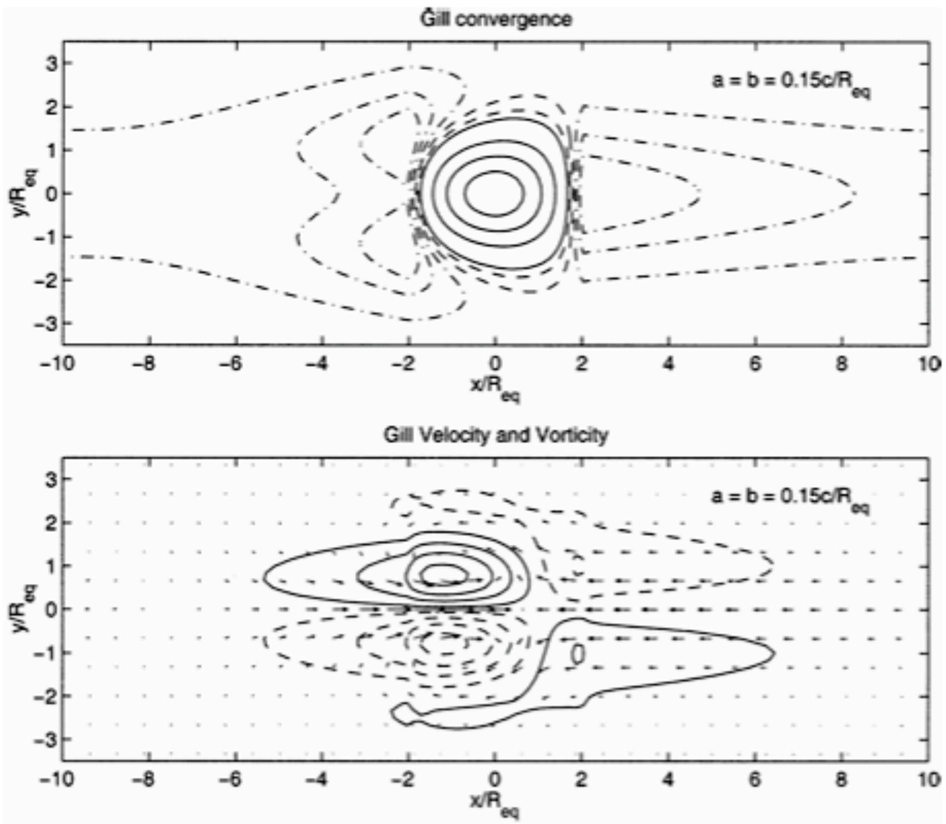


FIG. 1. Exact solution to the Gill model (no zonal compensation of mass sink) with zonally periodic boundary conditions. (top) Horizontal divergence (solid contours 0.1 to 0.9 by 0.2; dashed 0.02 and 0.06; and chain-dashed −0.1 to −0.02, by 0.04; all in units of D_0). (bottom) Velocity vectors and contours of vorticity (contour interval is $0.6D_0$, negative contours dashed). Full computational domain extends up to $|y/R_{eq}| = 10$.

Gaussian heat source in center of domain.

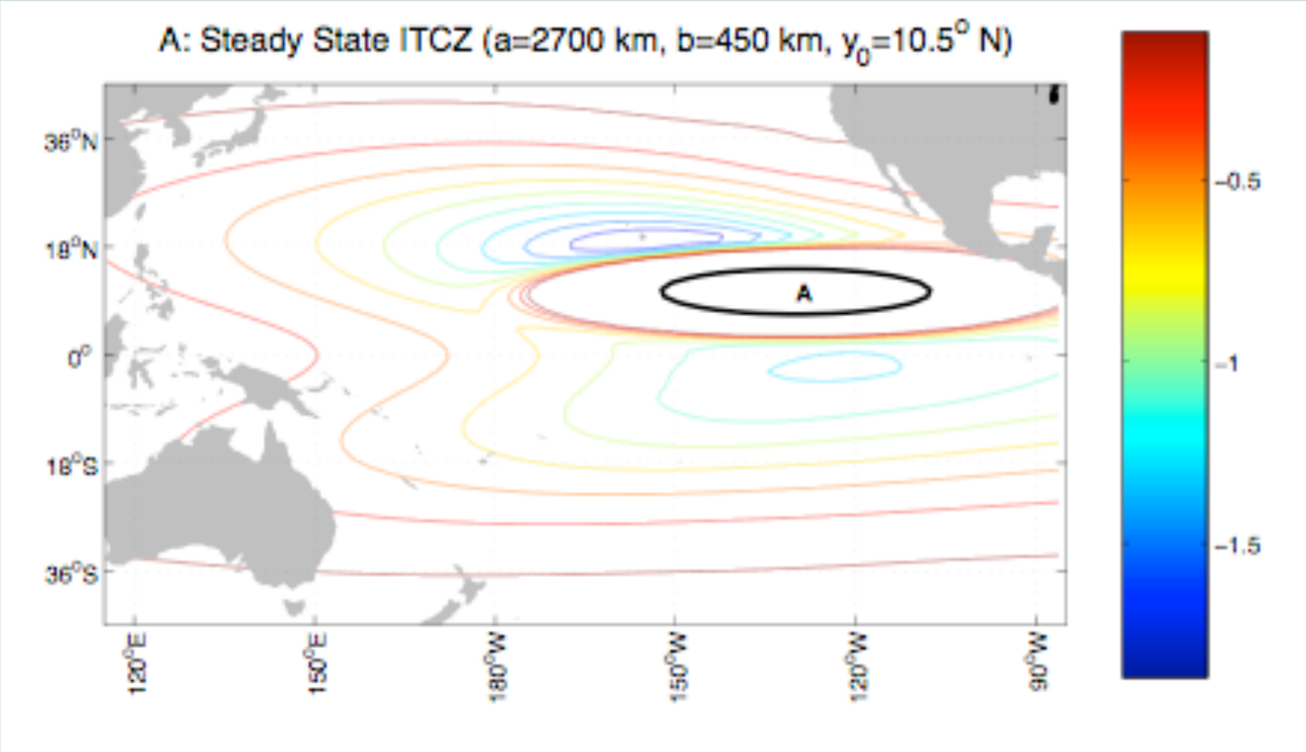
Boundary conditions are infinite in y, periodic in x

Top panel: convergence
Bottom panel: velocity vectors and vorticity

From Bretherton and Sobel 2003

Gill Model

- Also get asymmetric (about the equator) things:



Heating applied in region A.

Only subsidence contours are drawn (there is upward motion elsewhere).

From Gerber, Ito and Schubert (2001)

Summary of Derivations

- Barotropic and first baroclinic modes
- No barotropic mode => dynamics are linear!
  - No barotropic mode + Newtonian cooling + Rayleigh friction + prescribed latent heating => "Matsuno-Gill model"
- Moisture equation for precipitation term
  - Can make condensation the only nonlinearity

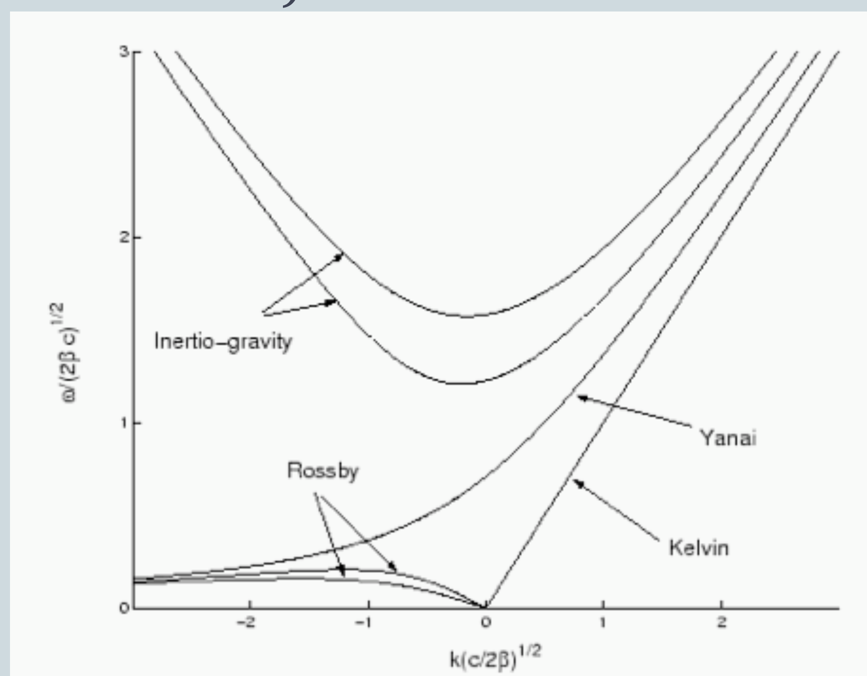
The Transients

- Equatorial waves:
  - Dry and with moisture
  - Observations and models
- Start with derivations:
  - 1-D, non-rotating baroclinic modes
  - Equatorial Kelvin wave derivation

Dispersion Relations for Equatorial Waves

- System has the following: (see Majda 2003 or Gill for more details)
  - Kelvin waves (nondispersive eastward propagating waves)
  - Mixed Rossby-gravity wave (Yanai mode)
  - Equatorial Rossby waves
  - Inertia-gravity waves

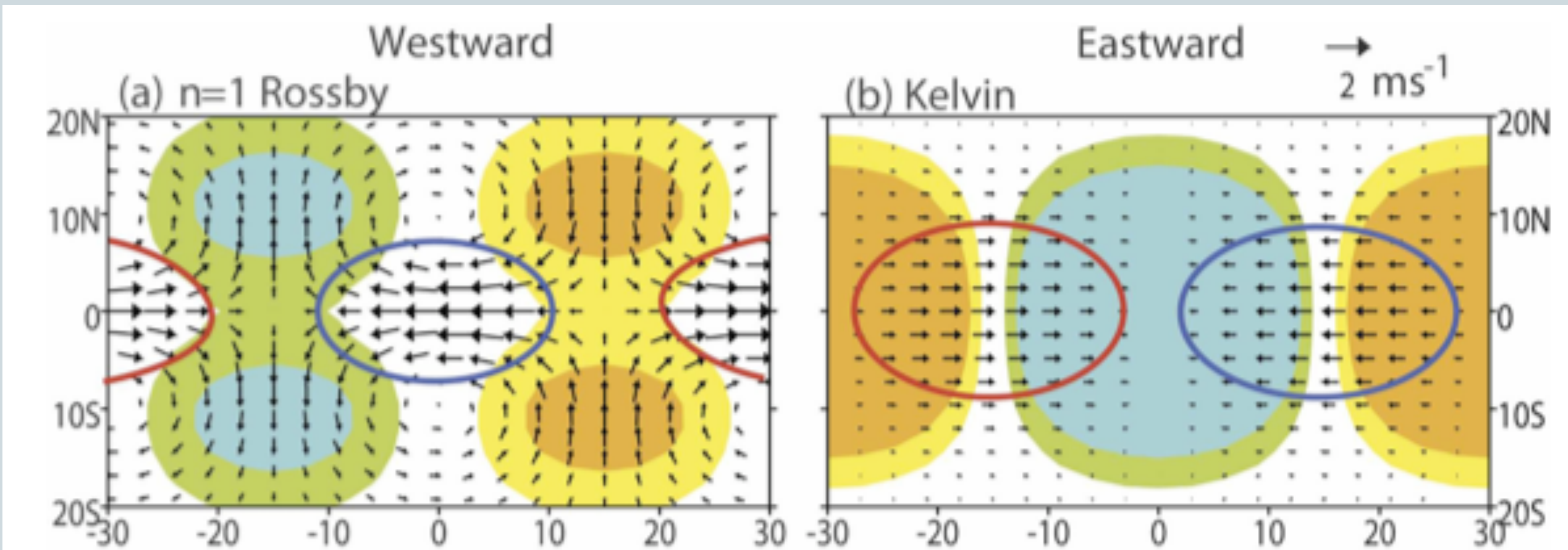
Frequency



Wavenumber

Structure of Equatorial Waves

- Structures (Rossby and Kelvin):

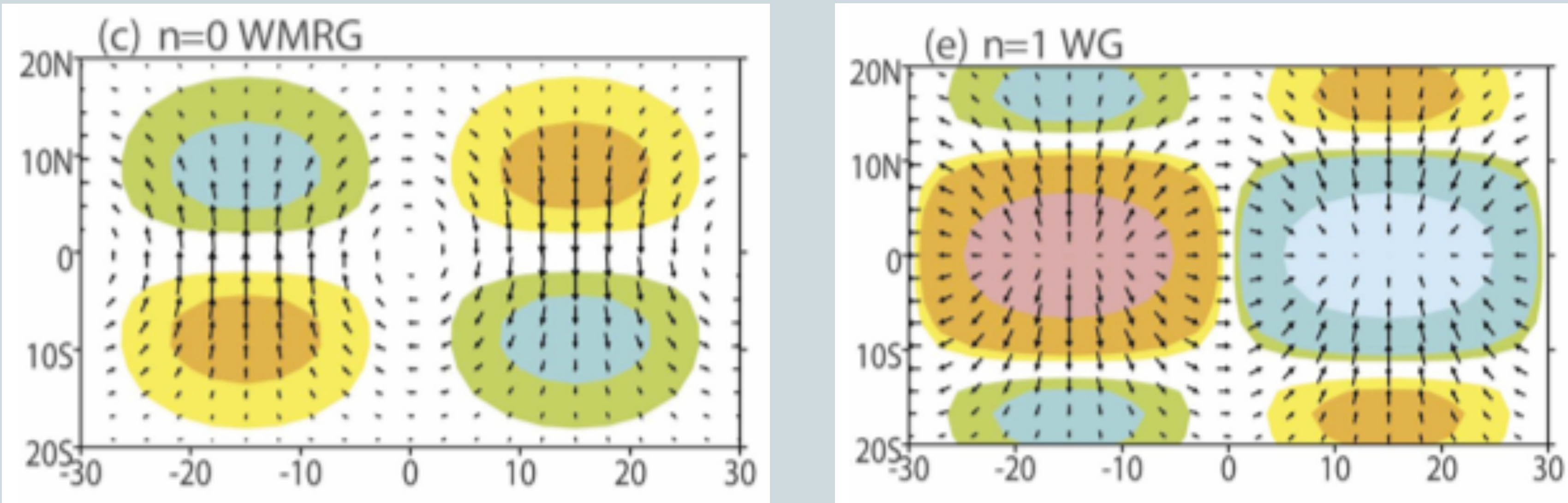


Vectors = winds
Colors = divergence contours
(ignore the ovals)

From Yang et al 2007

Structure of Equatorial Waves

- More structures (mixed Rossby gravity and WIG):



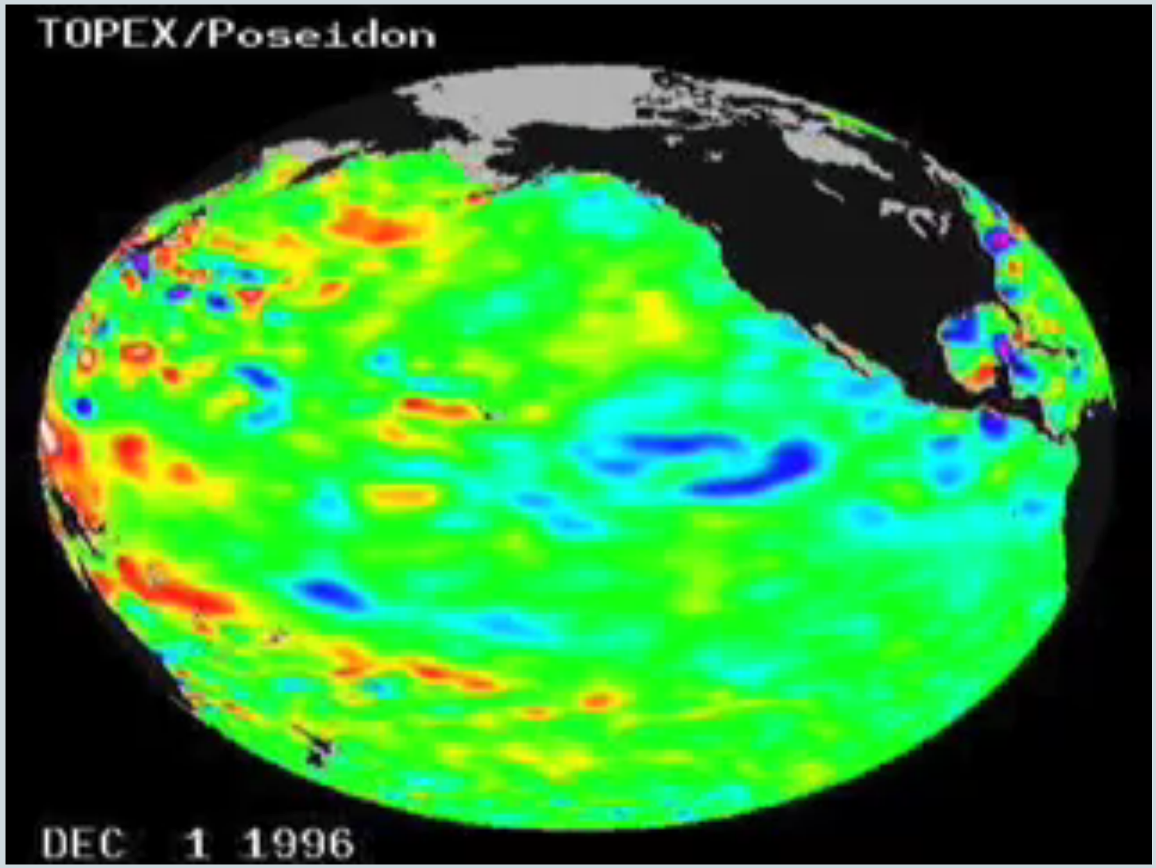
Vectors = winds
Colors = divergence contours
(ignore the ovals)

From Yang et al 2007

Equatorial Kelvin Waves in the Ocean

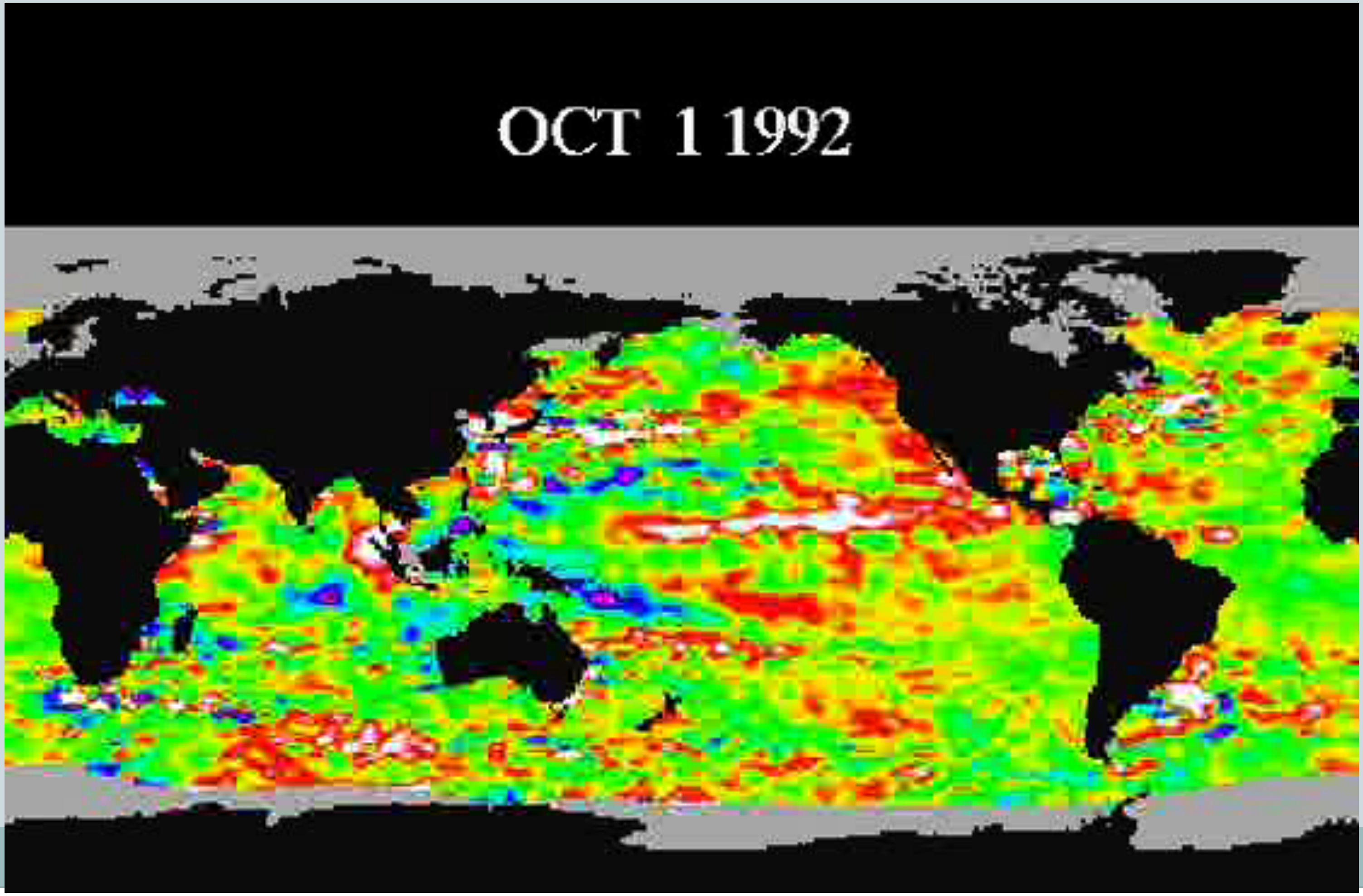
- These are seen in the ocean, and are key to El Nino dynamics

Sea surface height anomalies



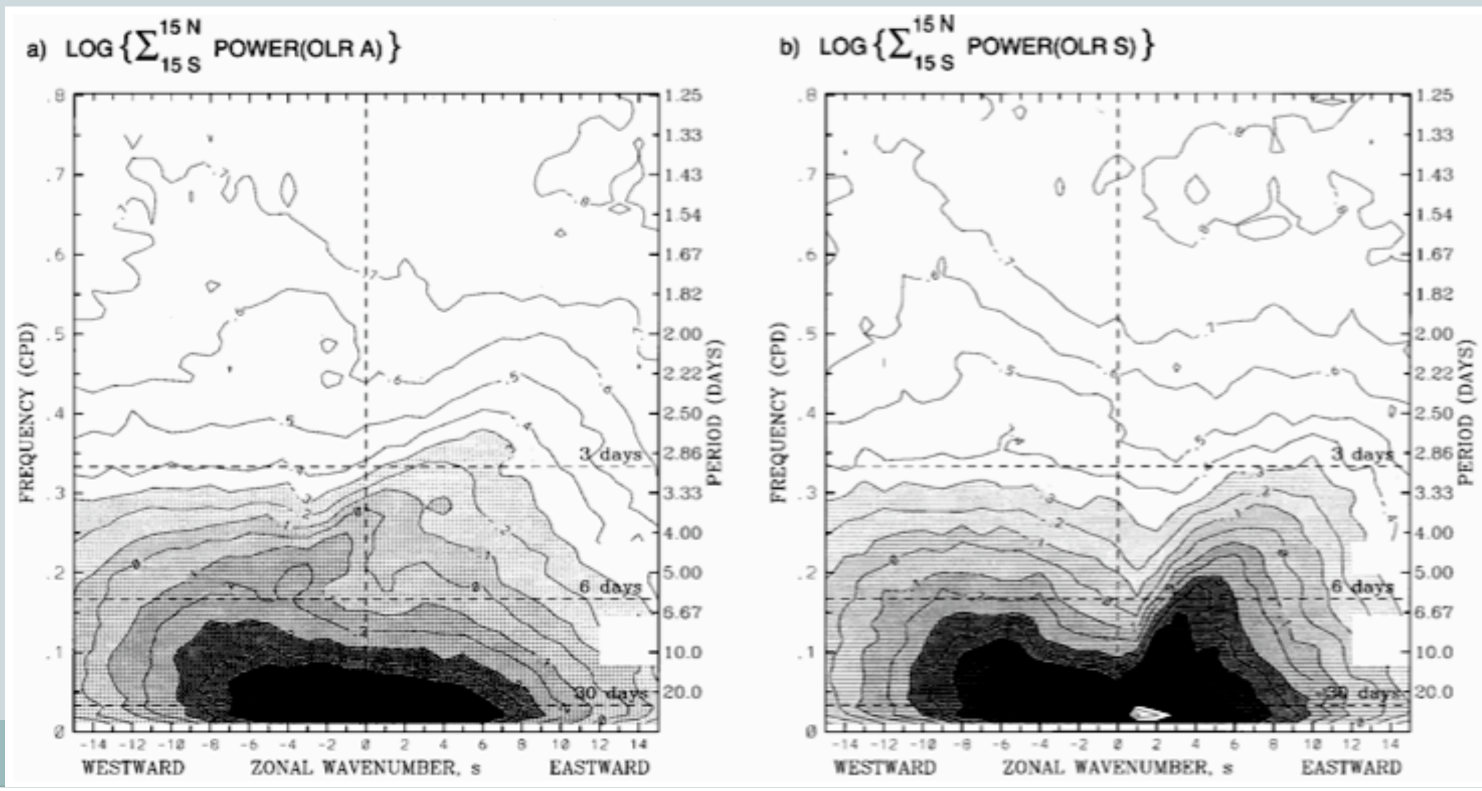
Equatorial Kelvin Waves in the Ocean

- A global picture:



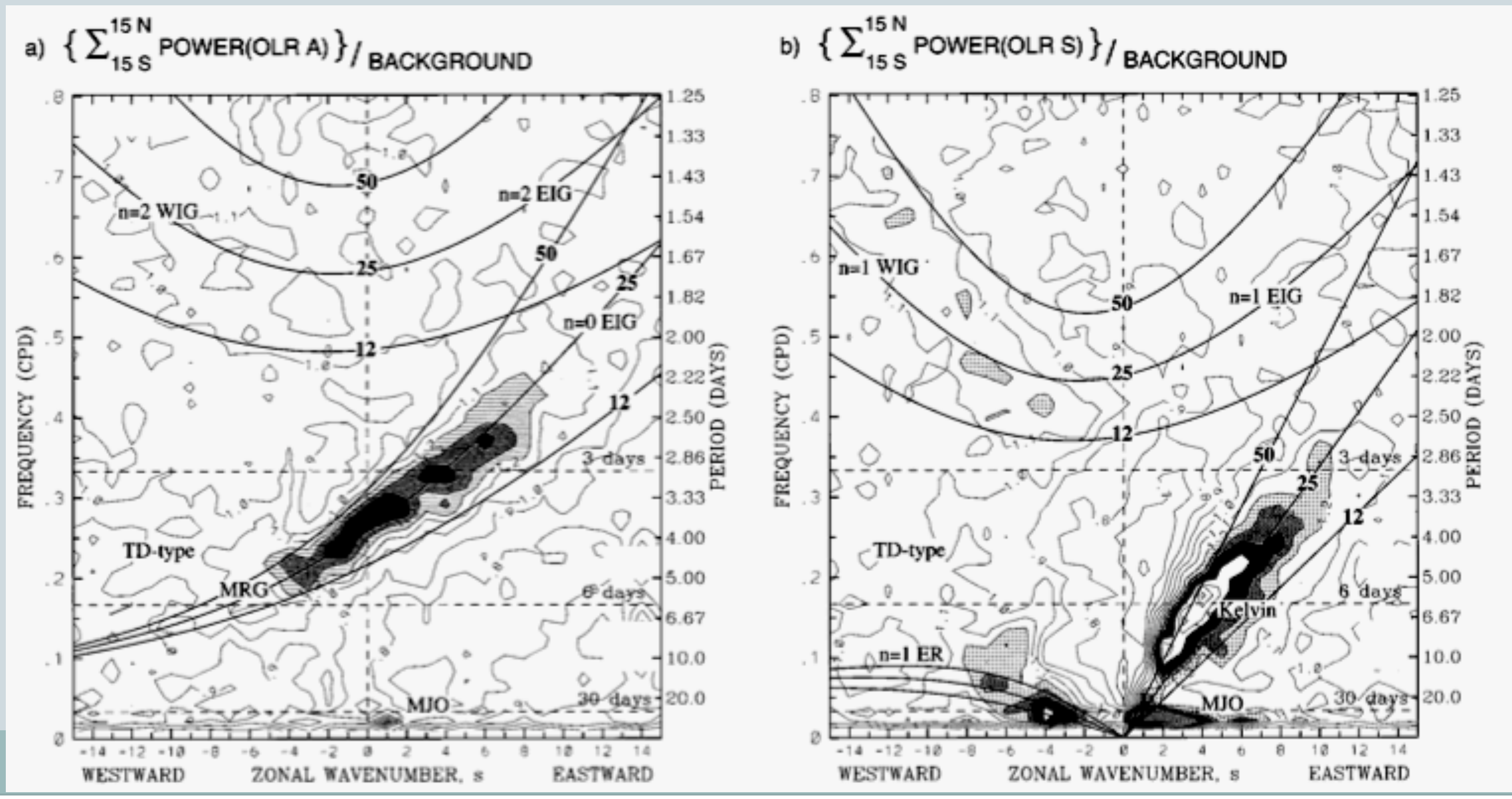
Atmospheric Obs. of Equatorial Waves

- Wheeler and Kiladis (1999) examined spectra of OLR data in the tropics:



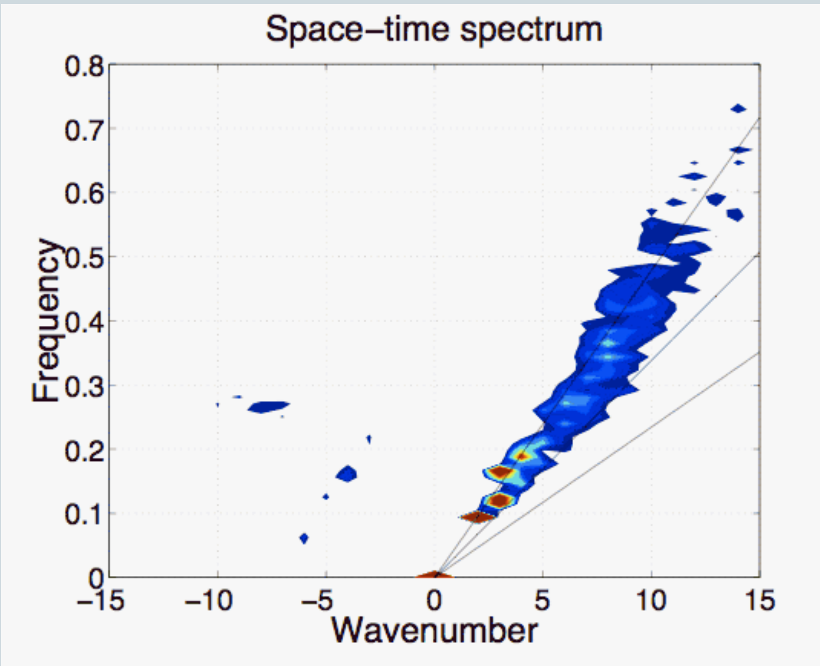
Atmospheric Obs. of Equatorial Waves

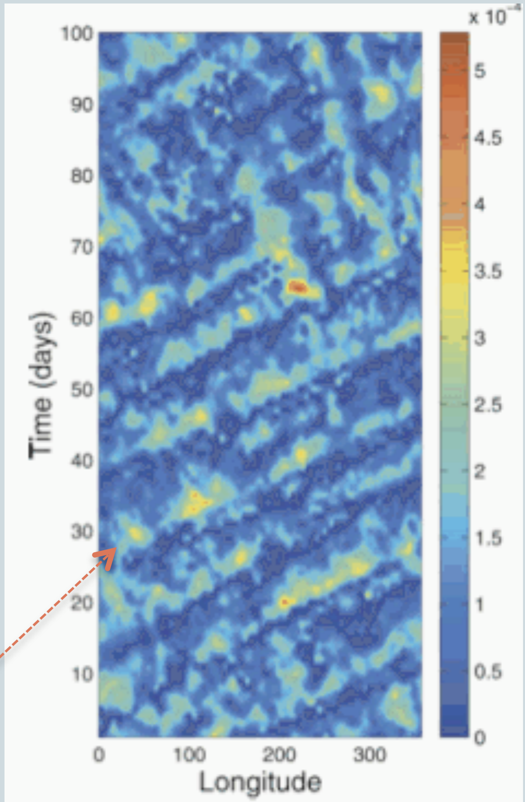
- Filter out "background spectrum":
  - Can see all different wave types! Especially Kelvin, MRG, and ER. Also, the mysterious MJO…



Equatorial Waves in Idealized GCM

- In simplified moist GCM, Kelvin waves dominate the spectrum

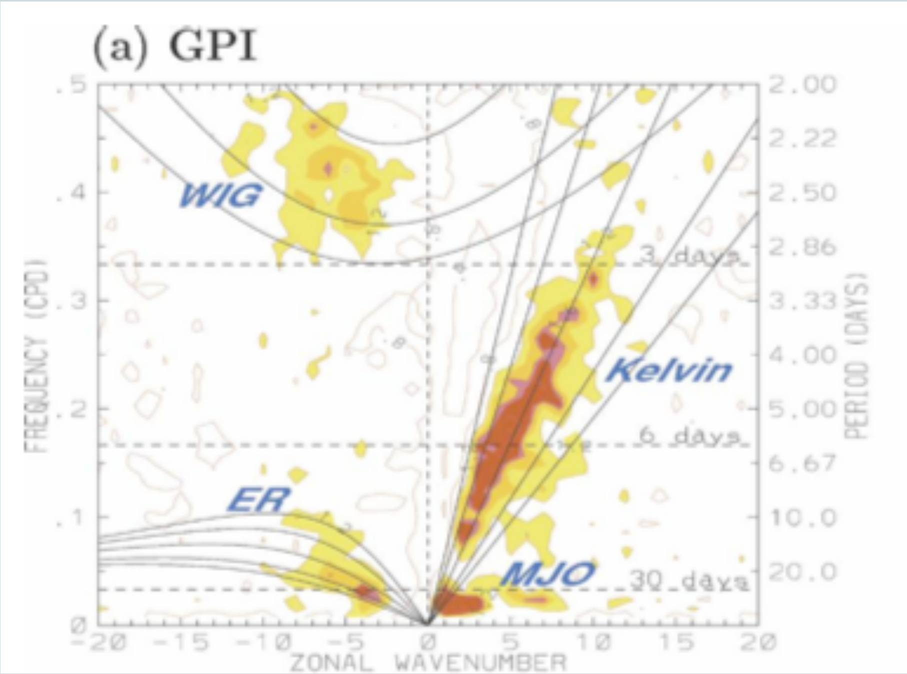




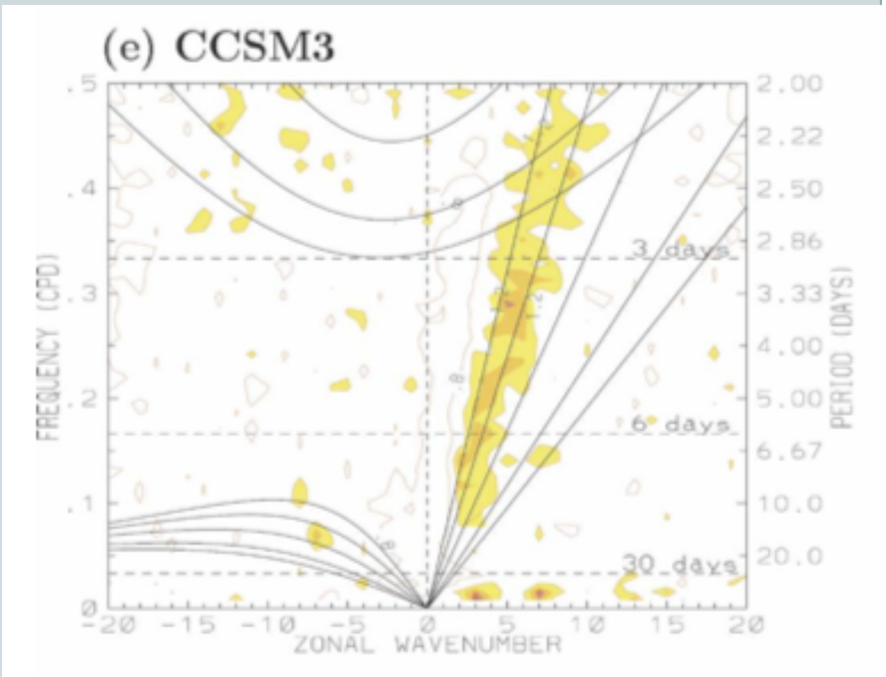
They can propagate around and around the equator multiple times!

Full GCM Waves

- Observations versus models:



Obs

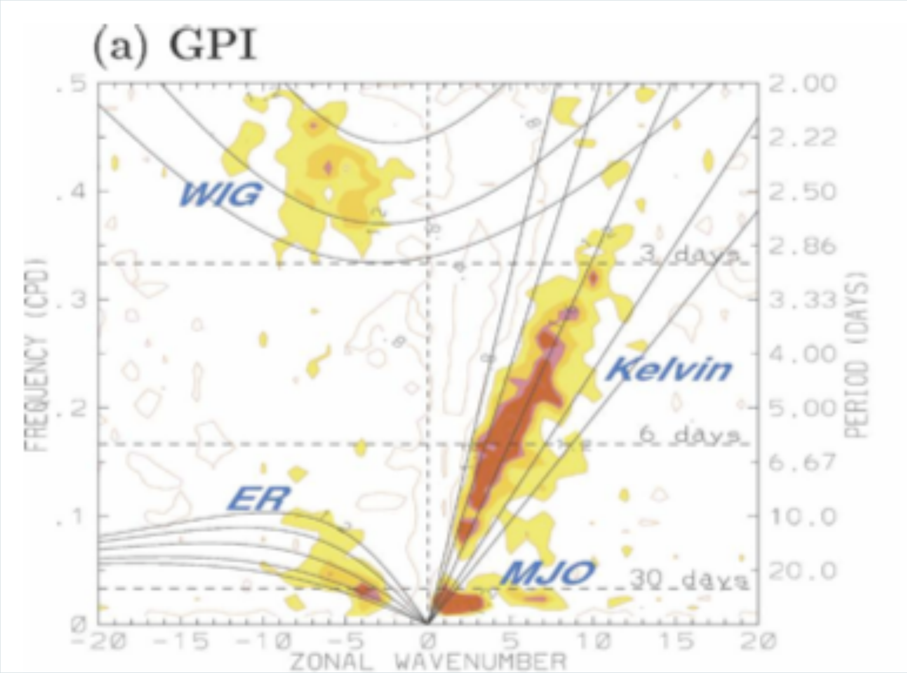


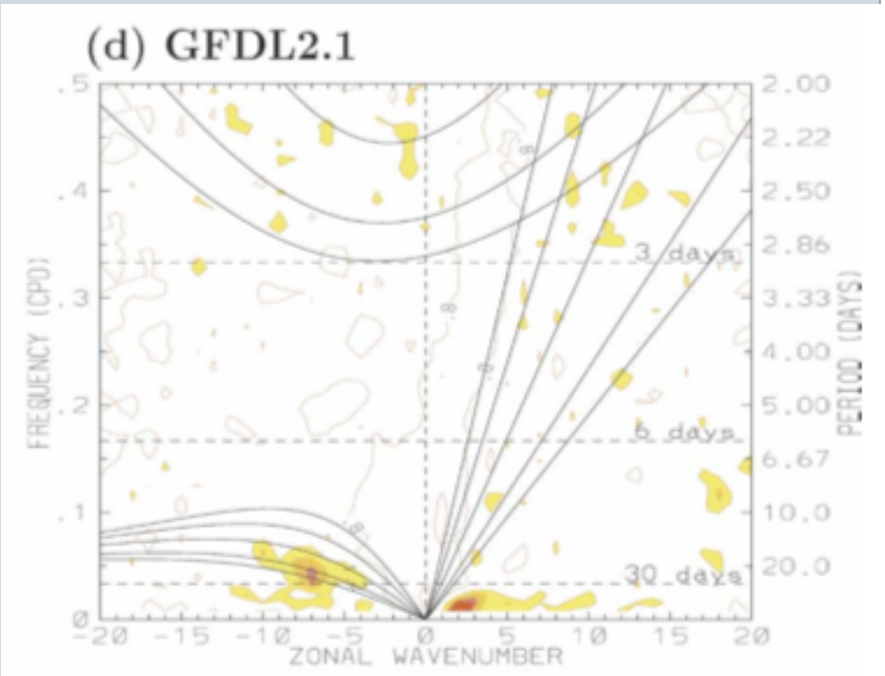
AM2

From Lin et al (2006)

Full GCM Waves

- Models are too weak, too fast





Obs

NCAR CCSM

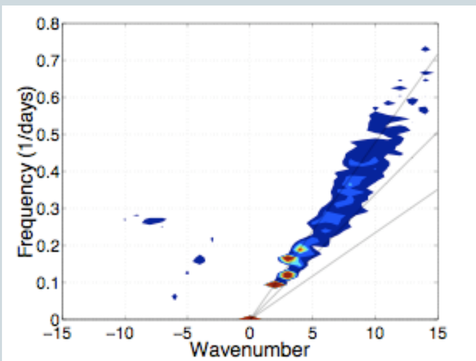
From Lin et al (2006)

Equatorial Waves

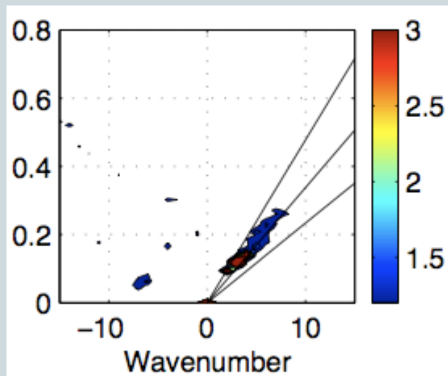
- In observations, speeds are significantly slower than predicted by the dry theory
  - Kelvin wave travels at ~15-20 m/s in obs
- Also true in simplified GCM/full GCMs:
  - Speeds are still significantly slower than predicted by the dry theory
  - Even in fastest model, only get ~30 m/s speed
- There's a simple theory for speed reduction that involves condensation
  - Gross moist stability setting a reduced static stability

Convectively coupled Kelvin waves

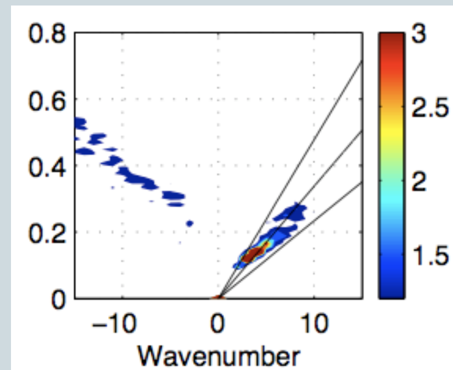
- In simplified moist GCM, GMS reduction leads to slower convectively coupled waves:



GMS = 7 K



GMS = 4.5 K



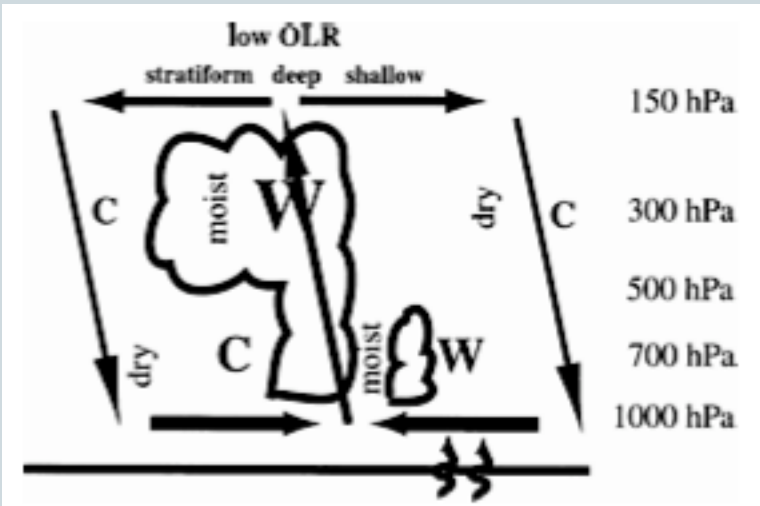
GMS = 2.5 K

Wavespeed can be tuned to essentially any value in this model

See Frierson (2007b) for more detail

Equatorial Waves

- Alternative theory for wave speed:
  - Higher vertical mode structure causes phase speed reduction



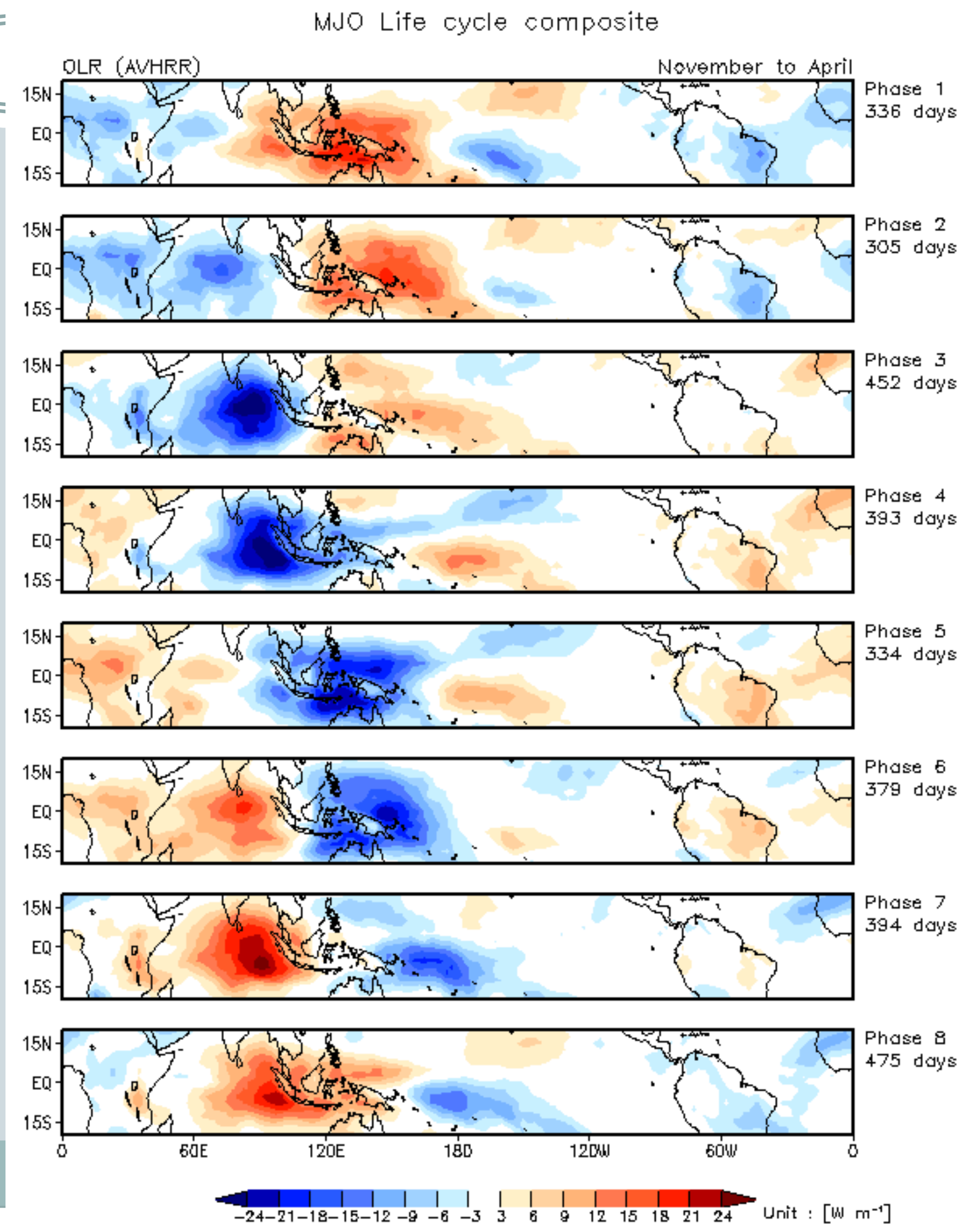
Schematic of Kelvin wave structure from Straub and Kiladis (2003)

- What powers the waves?
  - Evaporation-wind feedback derivation

Madden-Julian Oscillation

- 30-60 day eastward propagating envelope of enhanced/suppressed precip

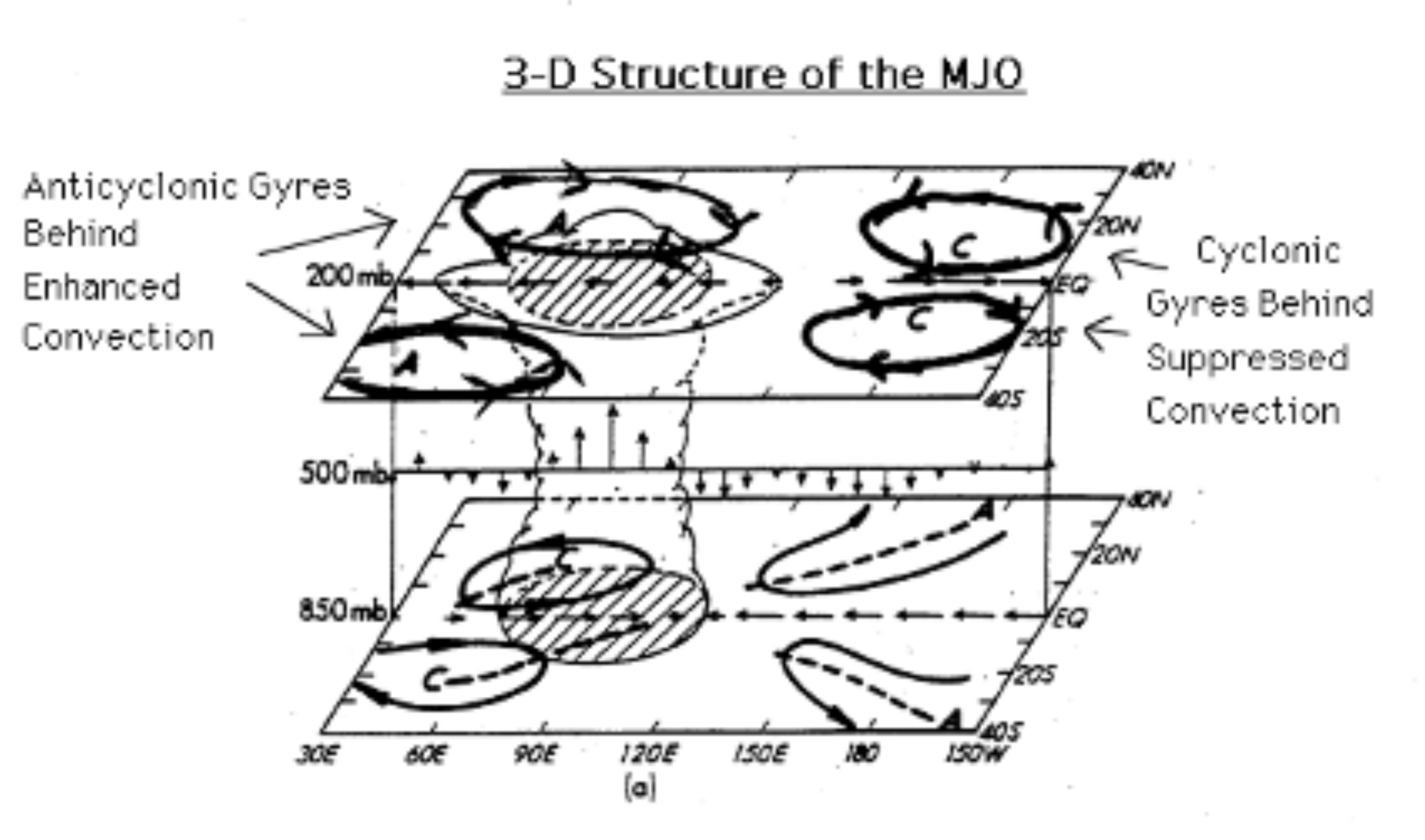
Figure is boreal winter OLR composite



From MJO diagnostics webpage

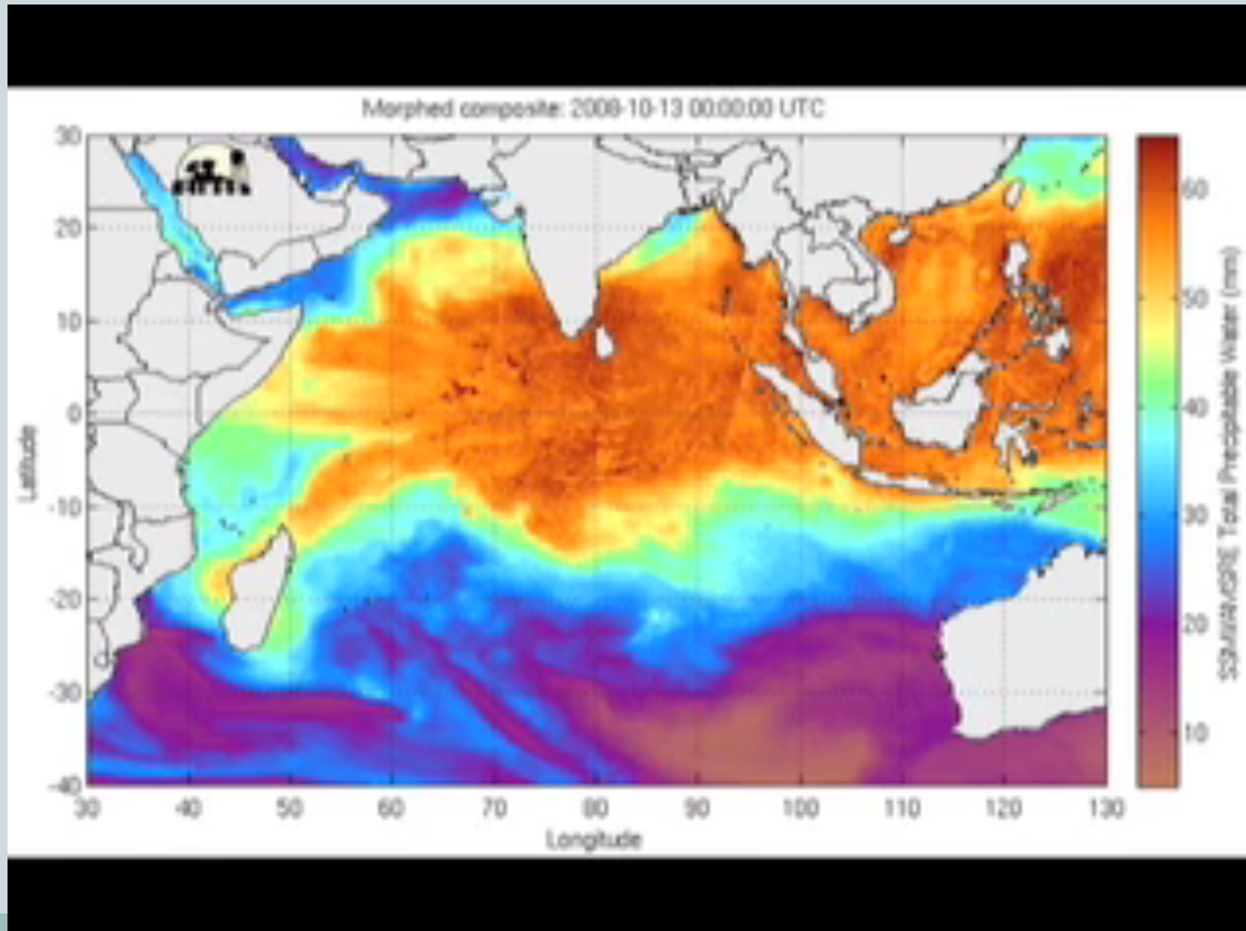
MJO Structure

- Has characteristics of Kelvin wave and Rossby wave



Movie of Indian Ocean Twin Cyclones

- Precipitable water satellite images:



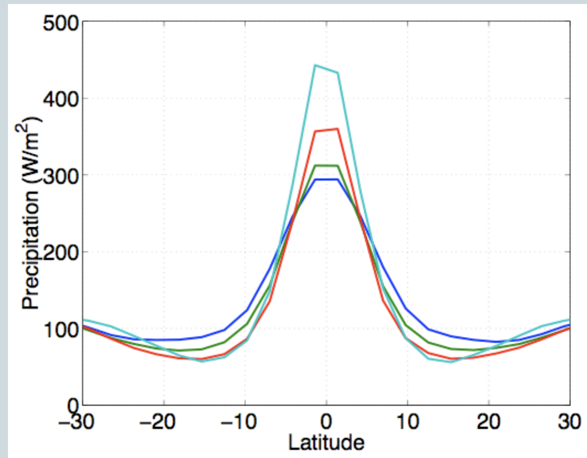
Next: Moisture Effects on Mean Circulation

- Non-rotating Walker cell derivation
  - “Weak temperature gradient” aside
  - Precipitation change with global warming aside
- Application to Hadley cell derivation
- Testing in simplified moist GCM

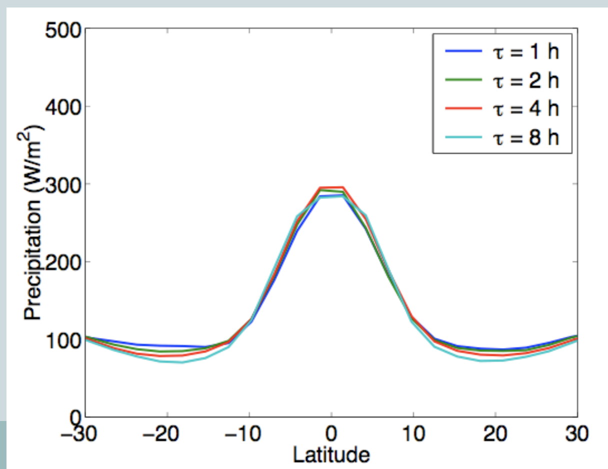
Hadley Circulation in Moist GCM

- Hadley circulation is sensitive to some conv. scheme parameter changes:

Tropical precipitation distribution with identical forcing, moisture content, etc.



- Not sensitive to others:



Changing convective relaxation time by a factor of 8

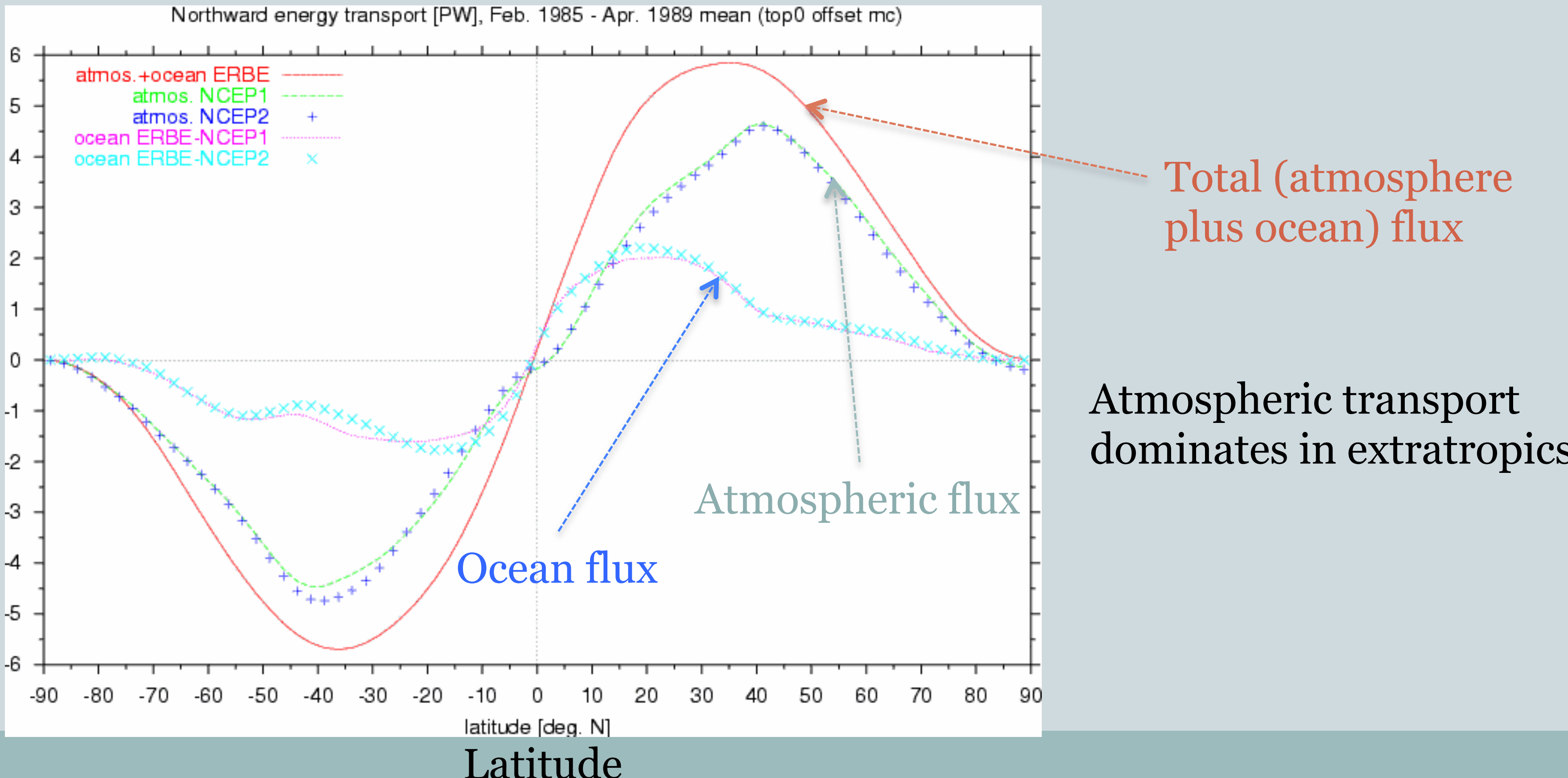
See Frierson (2007a) for more detail

Effect of Gross Moist Stability

- Parameters that don’t change GMS don’t affect Hadley cell
- GMS can change cell strength though
  - Different than Satoh b/c dry region is never completely dry (precipitation in subtropics changes)

Tropical Energy Fluxes

- Oceanic flux is actually larger than atmospheric flux in the deep tropics!



Atmospheric transport dominates in extratropics

Tropical Oceanic Fluxes

- What determines oceanic flux larger?
- Relation to Hadley circulation flux?
- Held (2001) derivations:
  - Ekman transports
  - Oceanic upwelling mass flux
  - Oceanic and atmospheric energy fluxes

Tropical upwelling

- Tropical upwelling forces thermocline up, drives SSTs down

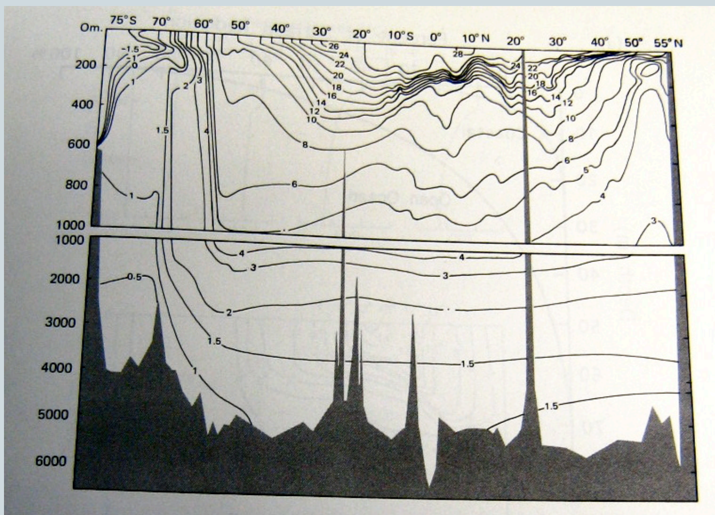
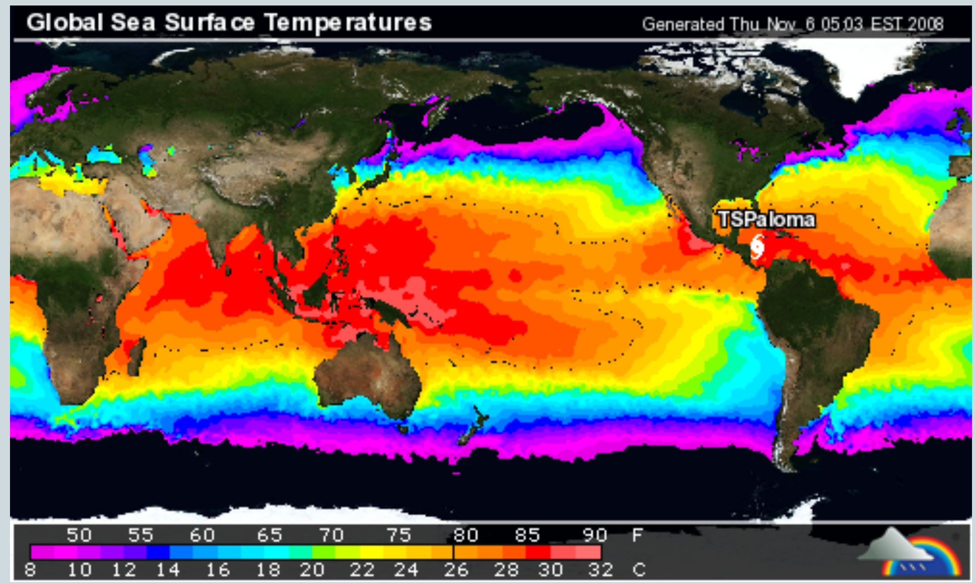


Figure 1.3 Temperature along approximately 160° W in the Pacific from the Antarctic to Alaska. Vertical exaggeration is 5.5×10^3 in the upper 1000 m and 1.11×10^3 below 1000 m. (After Reid, *Intermediate Waters of the Pacific Ocean,* The John Hopkins Oceanography Studies, The John Hopkins Press, 1965.)



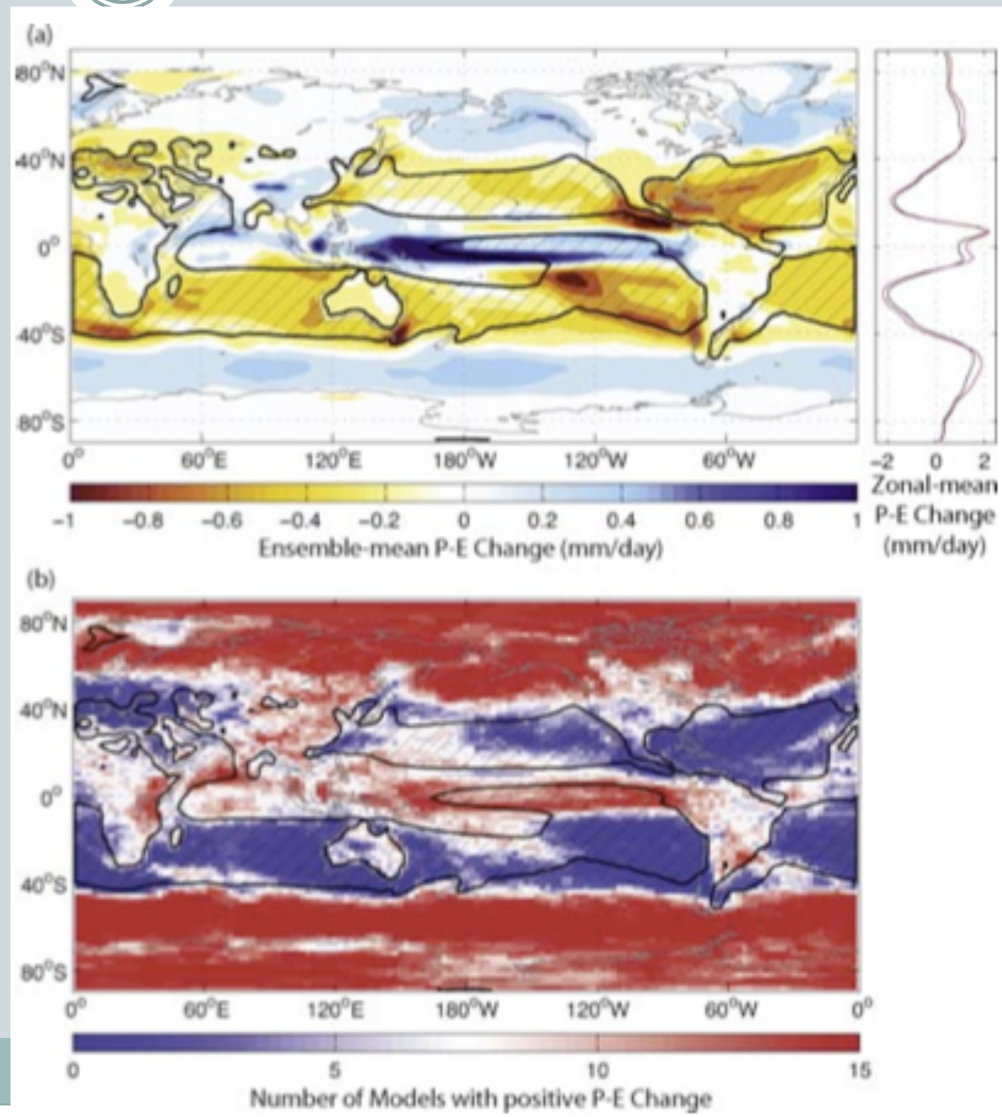
Width of Hadley Circulation

- Hydrologic cycle changes in AR4 models:

Top panel: change in P-E (blue = moistening, red = drying)

Black line is where P=E in climatology (separates "deserts" from "rain belt").

Bottom panel: number of models that show moistening at any location (red = moistening, blue = drying)



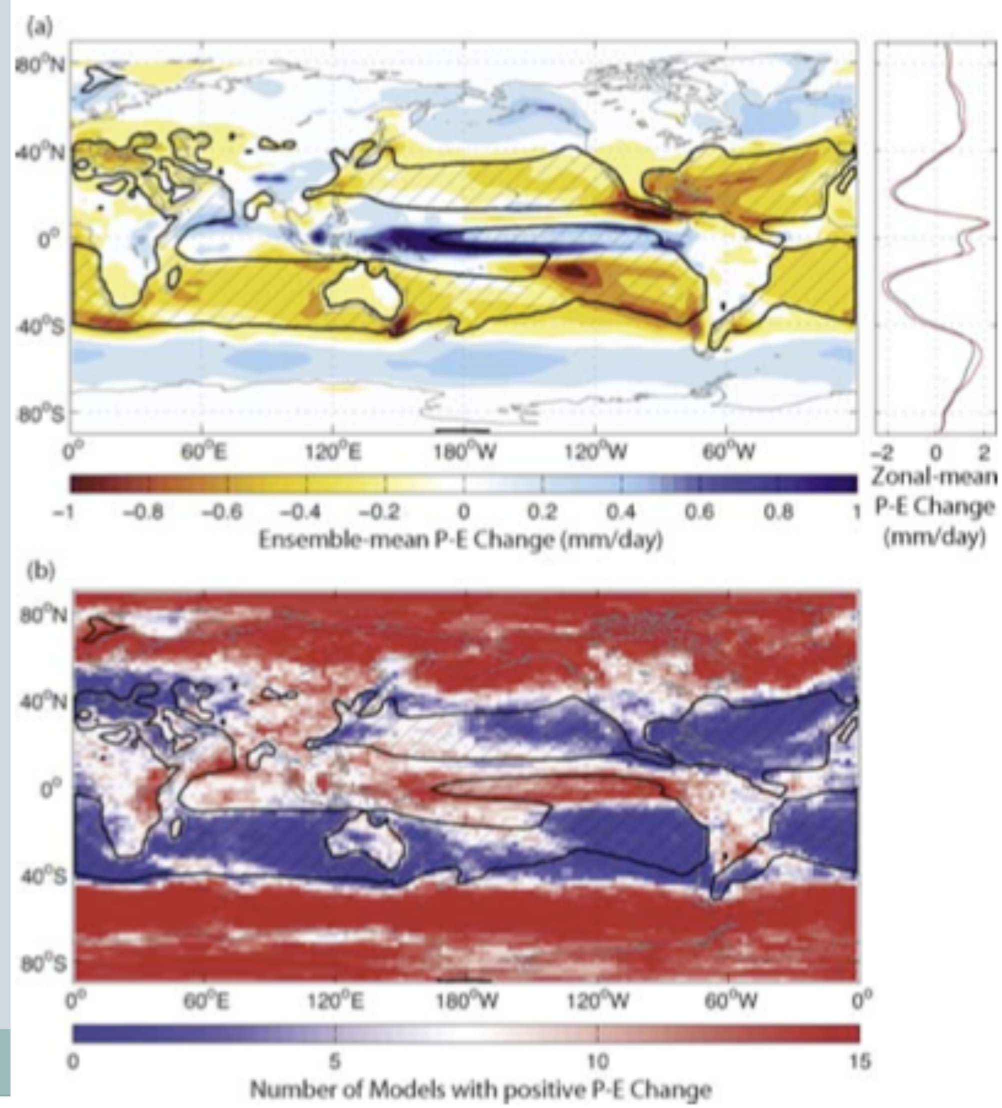
From Lu et al 2007

Width of Hadley Circulation

- Dry regions get drier, wet regions get wetter
- Also, deserts shift poleward

Top panel: change in P-E
(blue = moistening, red = drying)
Black line is where P=E in climatology (separates "deserts" from "rain belt").

Bottom panel: number of models that show moistening at any location
(red = moistening, blue = drying)



From Lu et al 2007

Width of Hadley Cell

- What causes the expansion?
  - Predictions from Held-Hou theory
  - Alternative theory for widening: Held (2000) derivation
    - Using Phillips' criterion
    - Using Eady growth rate