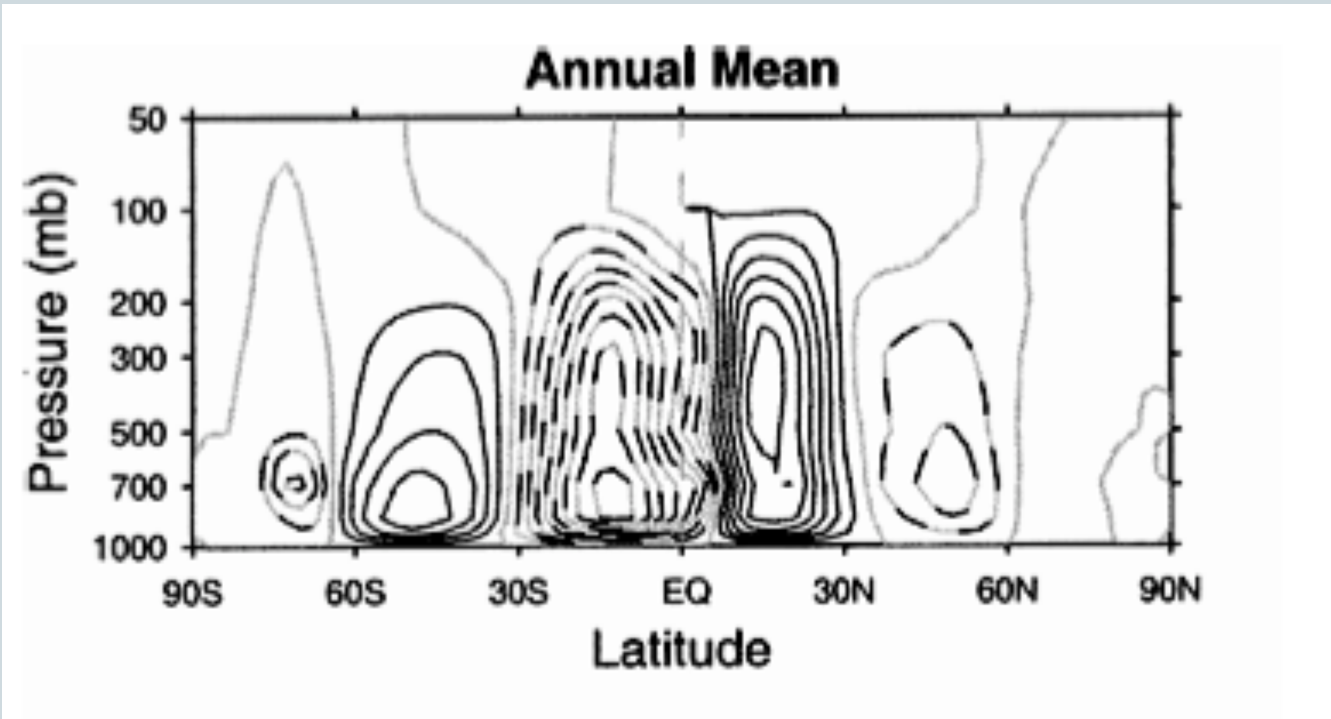
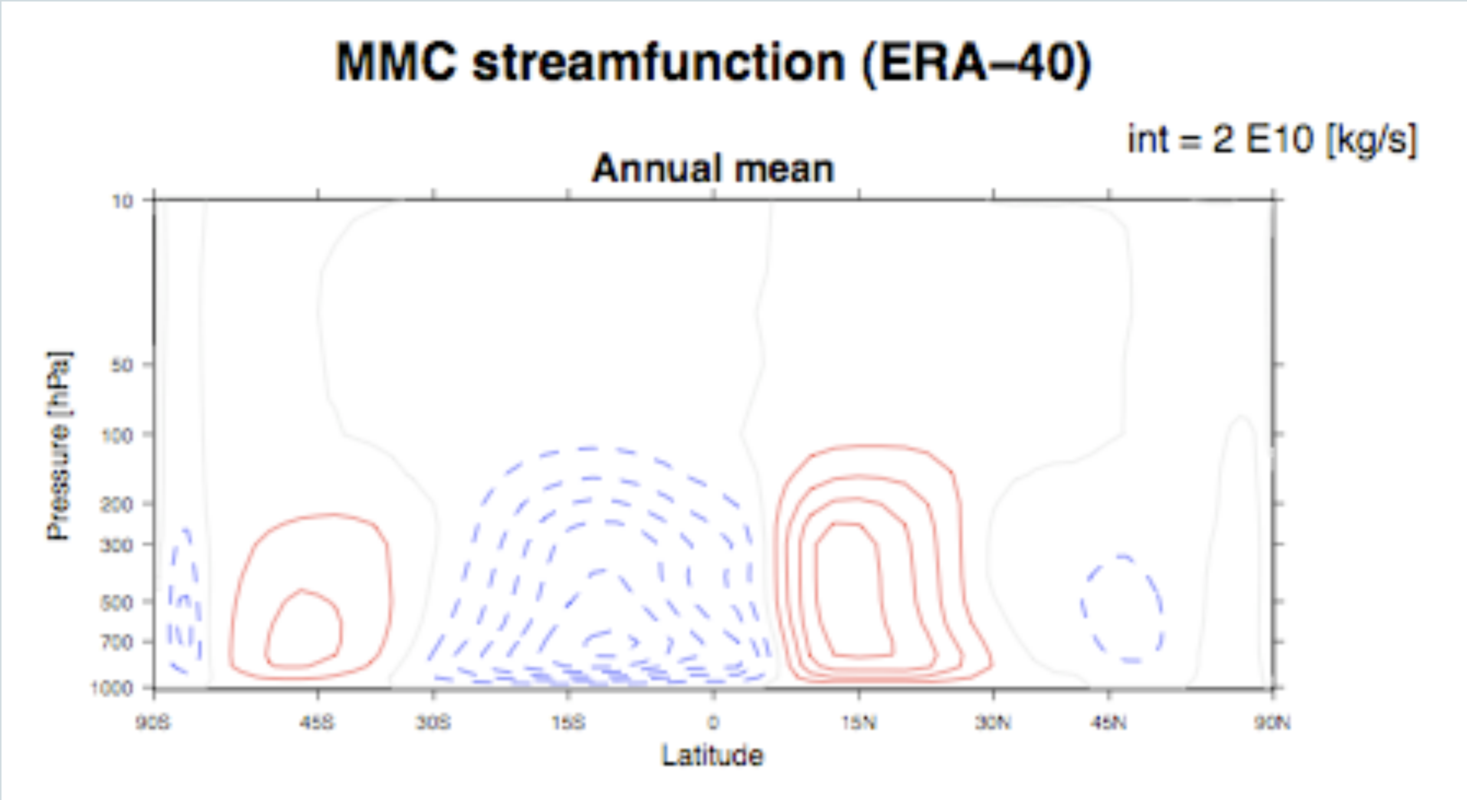
Hadley cell observations

- NCEP reanalysis (Dima and Wallace 2003):



Hadley cell observations

- ERA-40 reanalysis (Rei Ueyama):



Sin(latitude)

Momentum Equation Derivations…

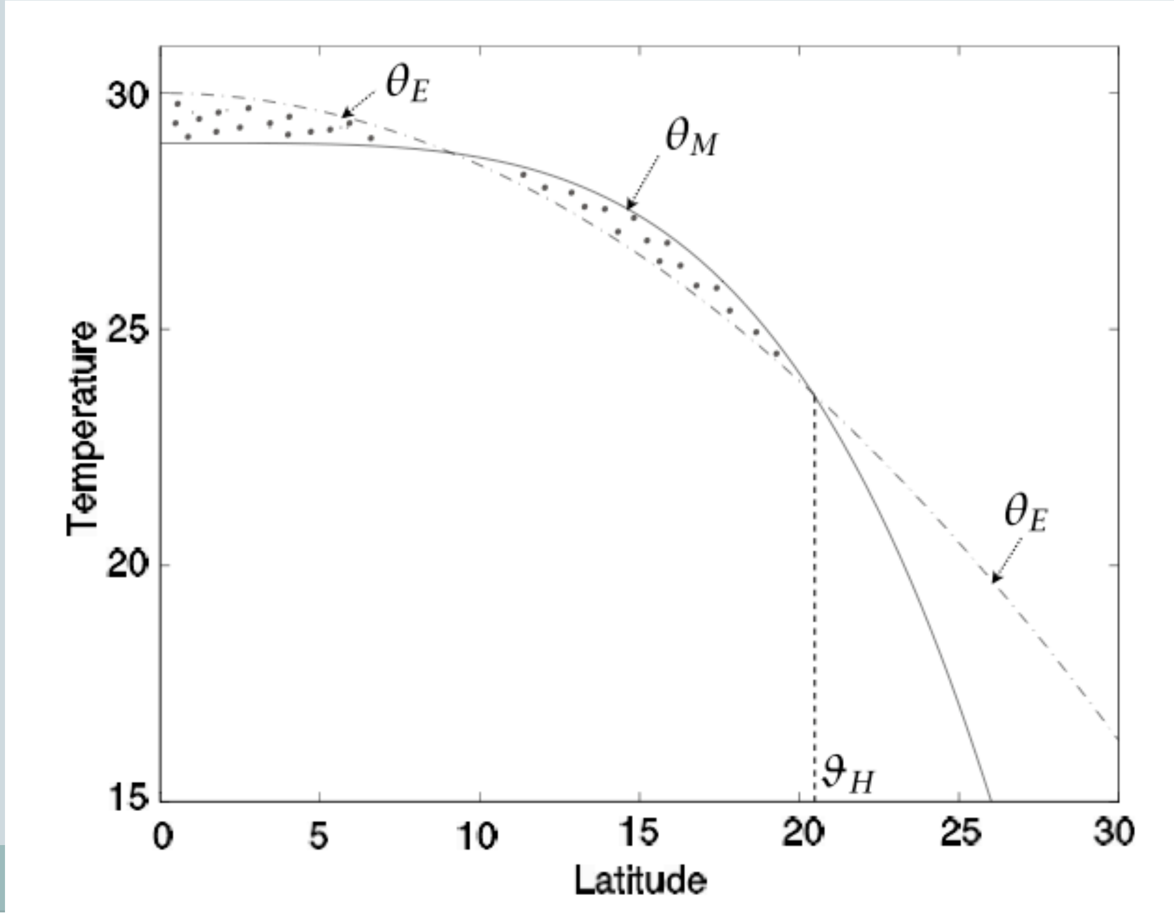
- Held-Hou theory for Hadley cell
  - Zonal momentum budget:
    - Angular momentum conservation
    - Winds reach very strong speeds quickly: e.g., u=95 m/s at 25 deg
  - Meridional momentum equation:
    - Geostrophic balance
      - One of the ignored terms was v dv/dy: assumed small relative to f 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:

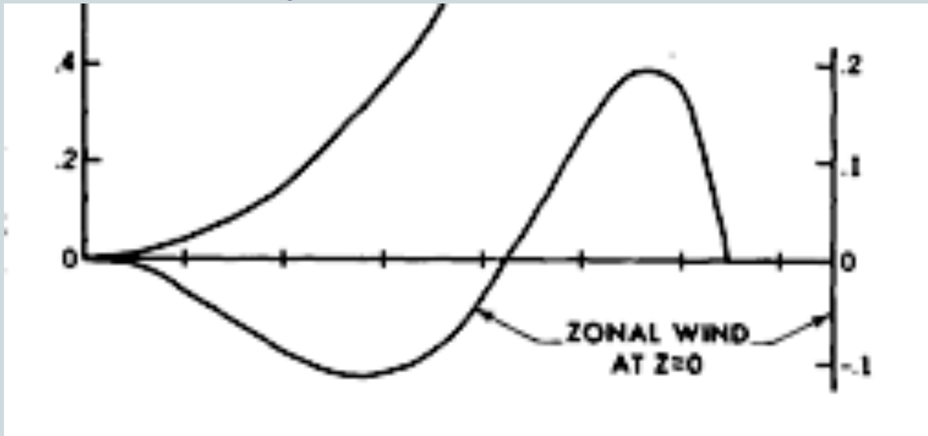


Held-Hou Results

- 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



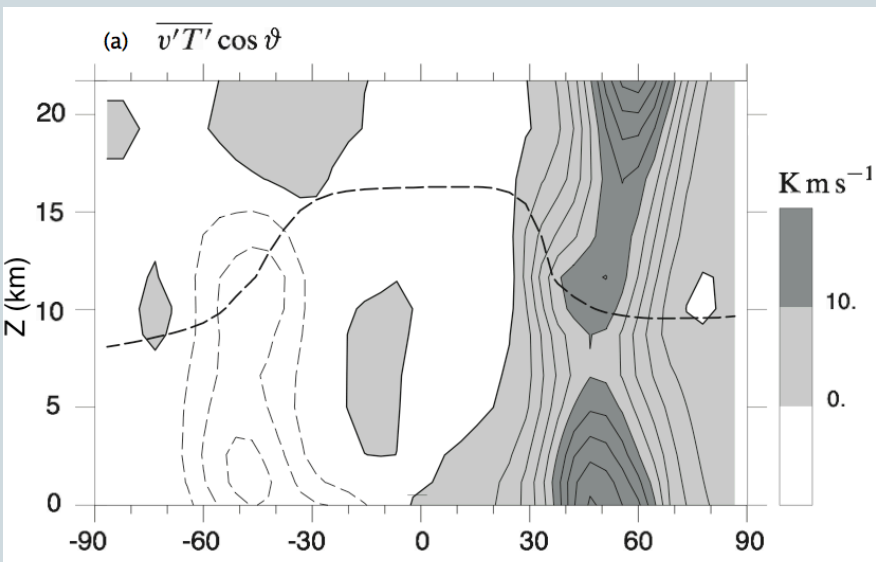
Surface winds

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

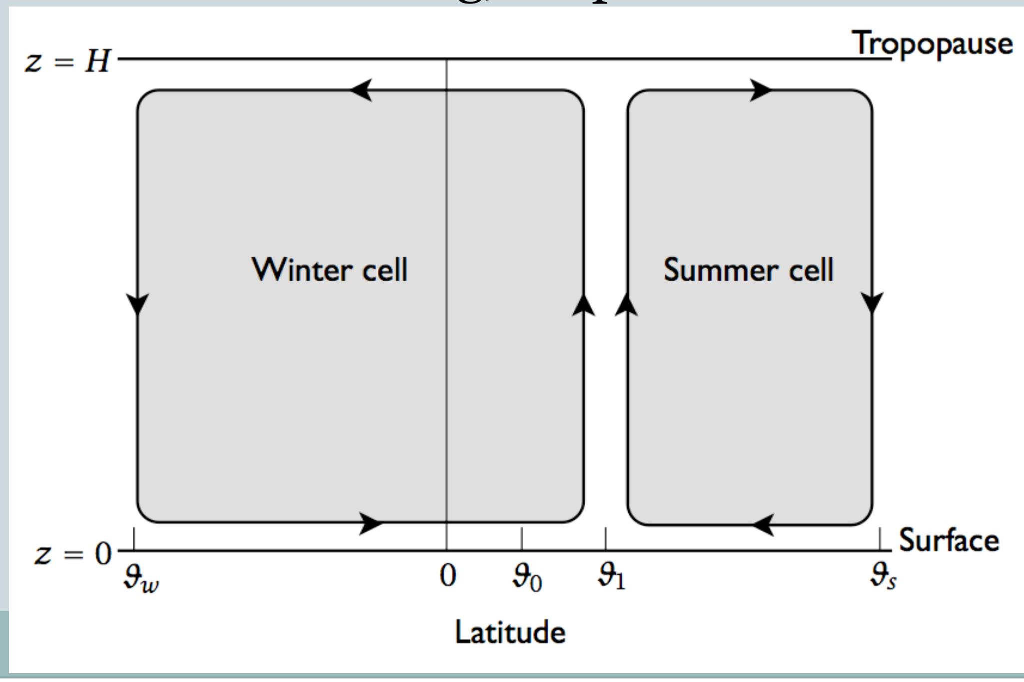


DJF eddy heat fluxes

  - 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"

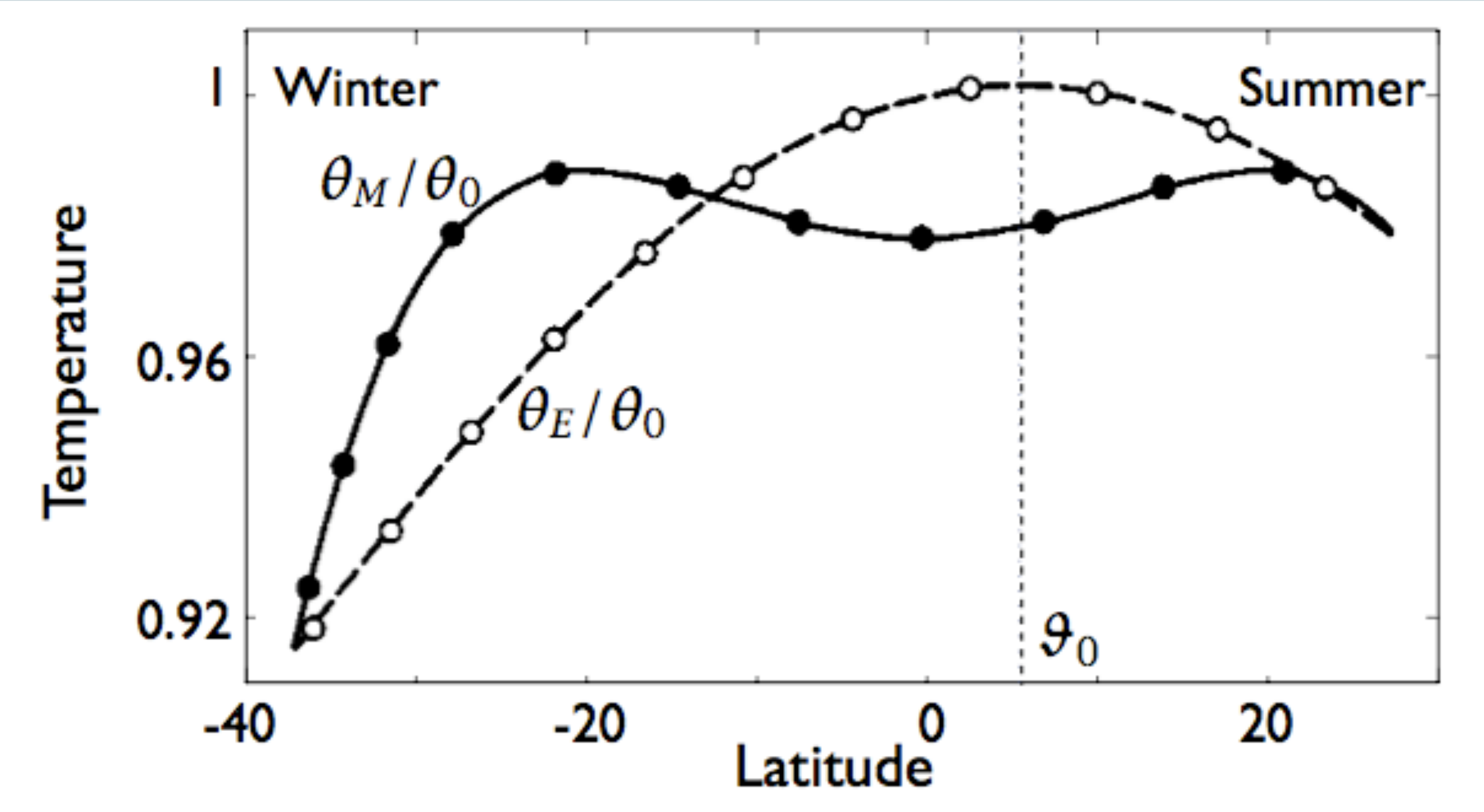


Extensions to Held-Hou Model

- 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)

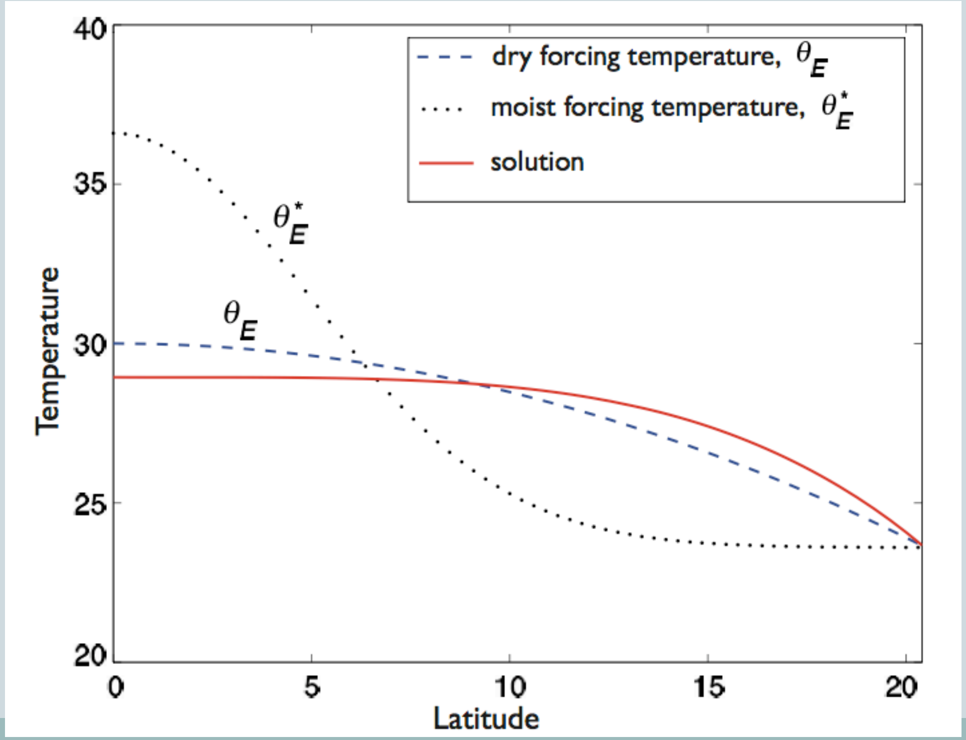
Asymmetric Hadley cell

- 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

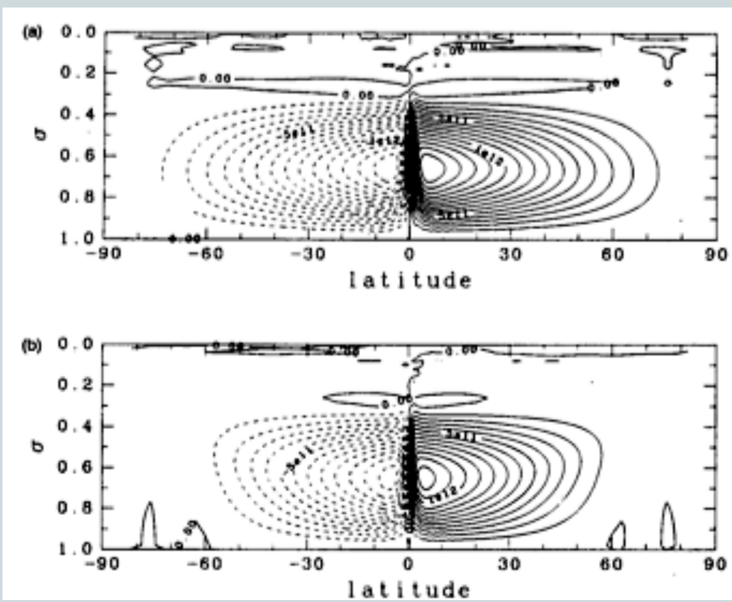
- Fang and Tung (1996, 1997, 1999):
  - Analytic solutions w/ viscosity, vertical structure, etc
  - Changes with thermal relaxation time
  - Time dependent circulations

Adding moisture

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

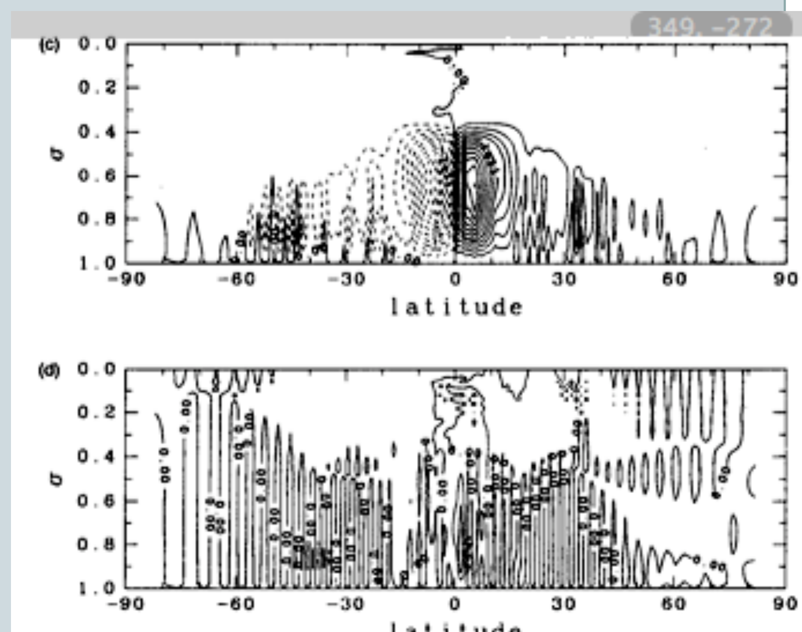
Omega = 0

Omega = 0.1*OE



Omega = OE

Omega = 10*OE

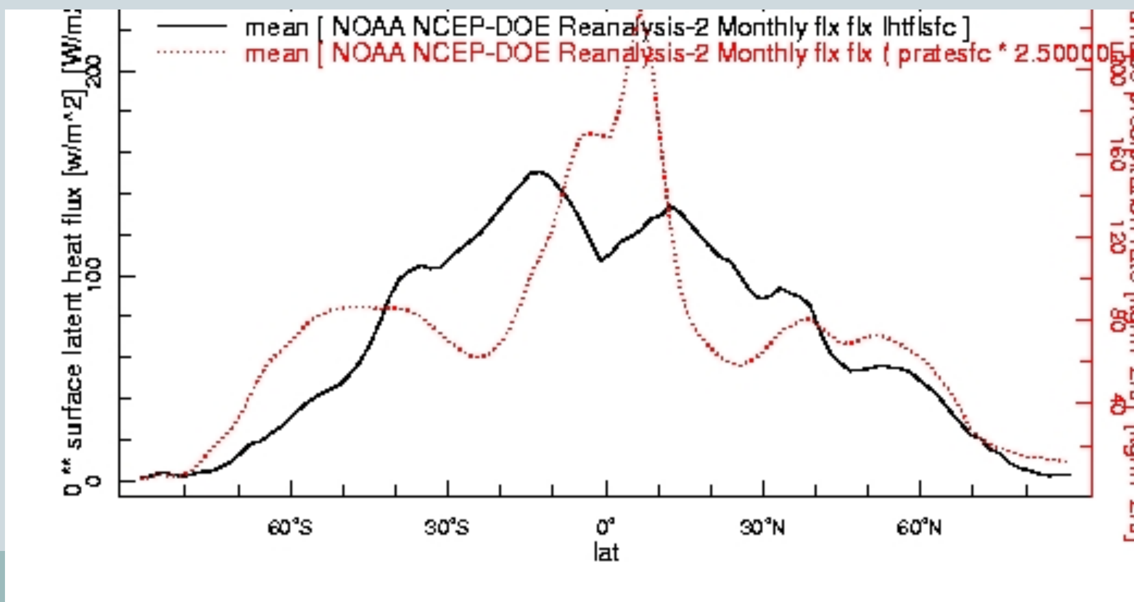


A first moist Hadley cell

- 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

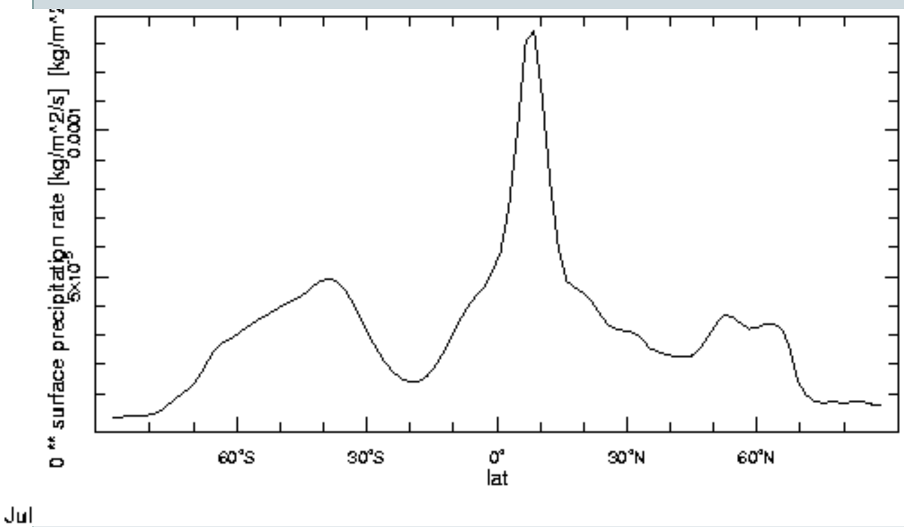
- Satoh (1994): moisture
  - Interesting way to consider the effect of moisture without an active moisture budget
    - Dry region controls everything
  - Limited applicability though? Subtropics are clearly not dry:



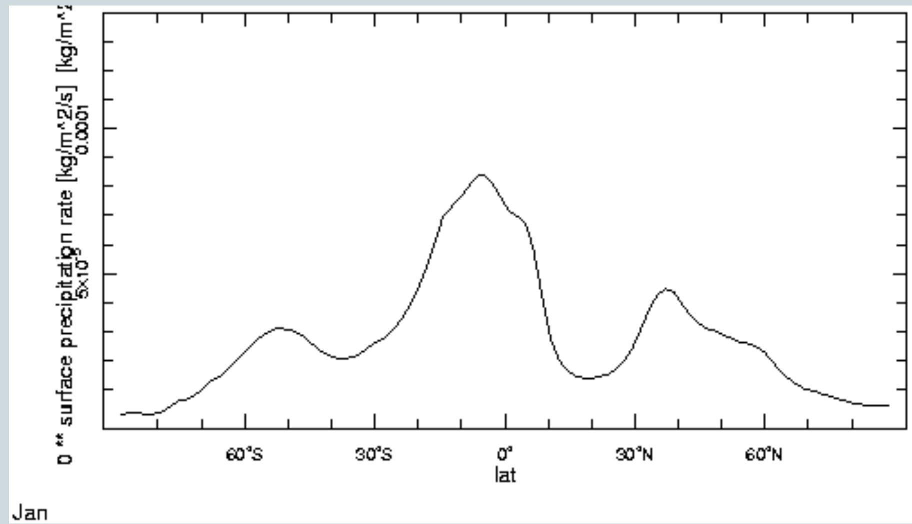
Evap and precip
NCEP Reanalysis 2

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

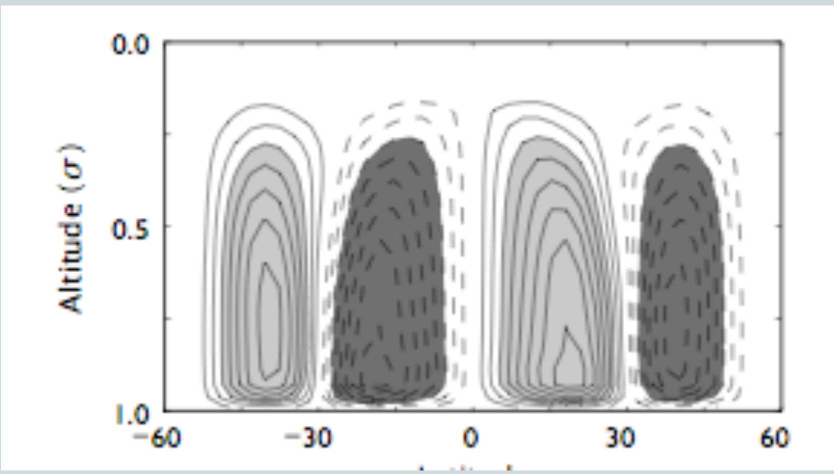
Effect of eddy fluxes

- 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