Hadley cell observations

- NCEP reanalysis (Dima and Wallace 2003):
Hadley cell observations

- ERA-40 reanalysis (Rei Ueyama):

\[ \sin(\text{latitude}) \]
Held-Hou theory for Hadley cell

- Zonal momentum budget:
  - Angular momentum conservation
  - Winds reach very strong speeds quickly: e.g., \( u = 95 \text{ m/s} \) at 25 deg

- Meridional momentum equation:
  - Geostrophic balance
    - One of the ignored terms was \( v \frac{dv}{dy} \): 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 diagram]
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
  - Would result in a stronger circulation
    - Cooling subtropics increases gradients within the Hadley cell

DJF eddy heat fluxes
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:

![Graph showing temperature variations in winter and summer](image_url)
Extensions to Held-Hou Model

  - Delta-function (or highly concentrated) forcing: “ITCZ”
  - Basic idea described in Vallis
Extensions to Held-Hou Model

  - 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

  - 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
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:

![Graph showing Evap and precip](image)

Evap and *precip*
NCEP Reanalysis 2
Satoh (1994) theory

- **Seasonal precip (July mean and December mean)**

  ![July precip](image1.png)
  ![December precip](image2.png)

- 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