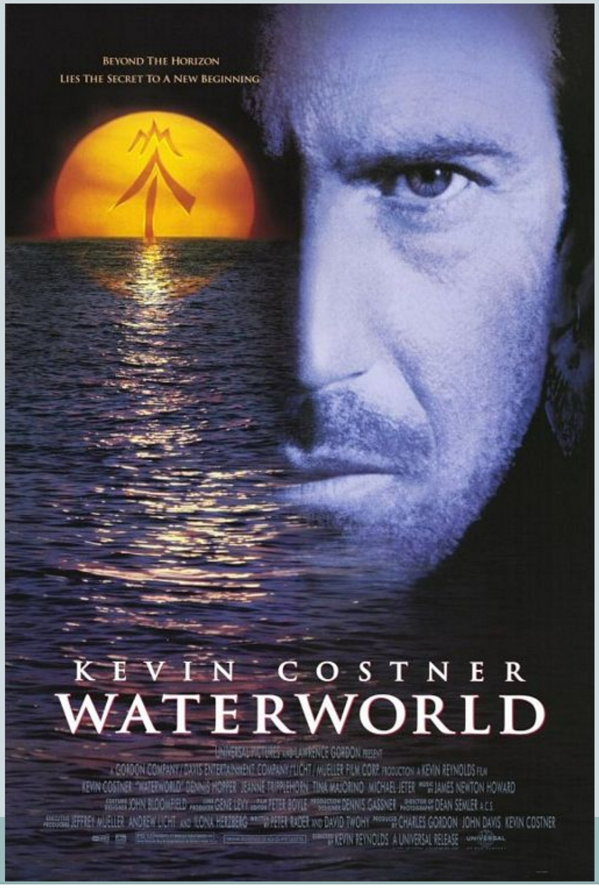
Simplified physics GCMs

- There is value in developing GCMs with simplified physics:
  - Easier to understand
  - Easier to reproduce results
  - Results more robust (less sensitive to parameters)
  - Less computational expense
  - Test ground for theories of the general circulation

Simplified GCM Experiments

- Nature has only provided us with one planet
- Computer models allow us to explore a range of imaginary planetary climates:
  - Ocean-covered planets
  - Planets with different rotation rates, radius, solar heating
  - Certain physical effects suppressed or enhanced



Simplified GCM Experiments

- See Held (2005, BAMS) for biological analogy:
  - In biology, hierarchy occurs naturally: bacteria, fruit flies, mice, etc
  - This has allowed rapid progress in understanding molecular biology, the genome, etc
- In atmospheric science, we have to create our own hierarchies
  - Have to additionally argue that the simplified models are worth studying though

An Idealized GCM

- Held-Suarez model (1994, BAMS)
- Radiation and convection parameterized as

$$Q = -k(T - T_{eq})$$

Warmer than T_{eq} => cooling

Cooler than T_{eq} => warming

That's it

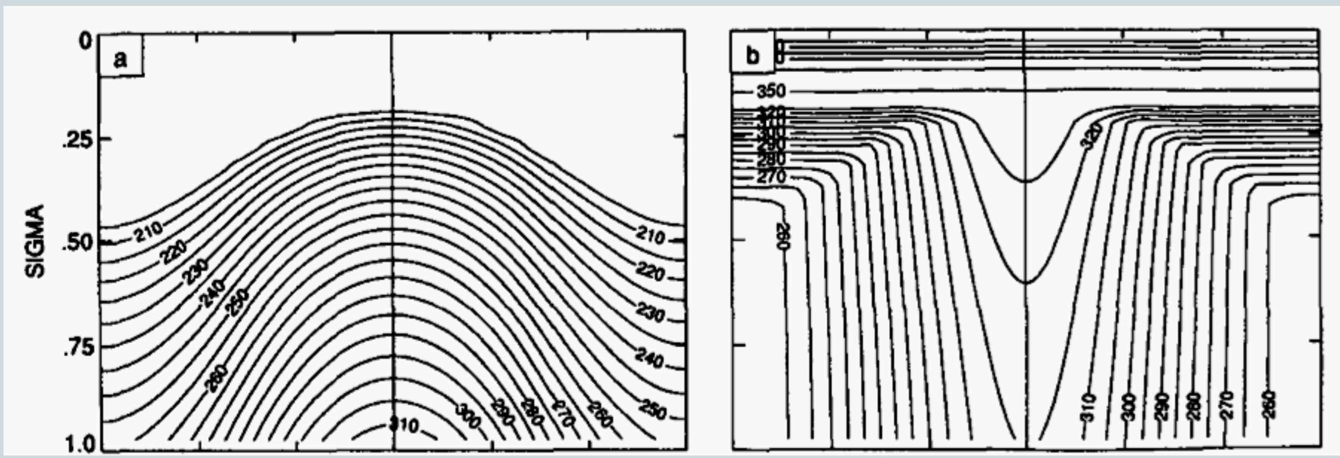
How to parameterize equilibrium temp?

- Equilibrium temperature = what would happen if dynamics didn't act
- Radiation and convection

The Held-Suarez Dry GCM

- Equilibrium distribution is what radiation and convection would produce without dynamics

Temperature	Potential Temperature



Latitude	Latitude

Equator is hotter than observed
Pole is colder than observed
Constant stratospheric temperature

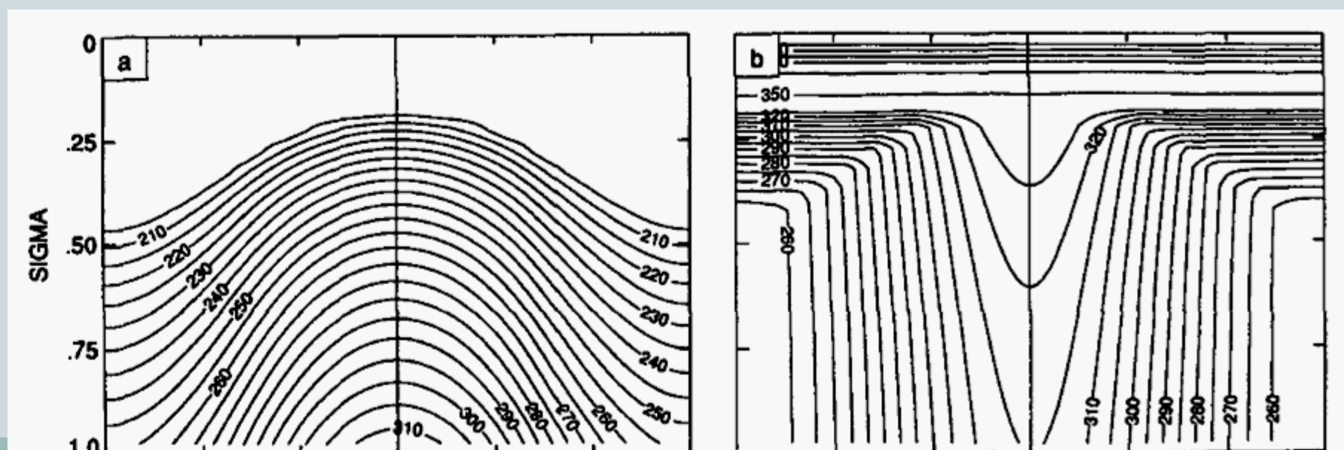
Roughly moist adiabatic vertical structure

The Held-Suarez Dry GCM

- Radiation parameters:
  - Horizontal gradient of radiative equilibrium: 60 K
  - Vertical gradient of potential temperature at the equator: 10 K
  - Free tropospheric relaxation time: 40 days
  - Boundary layer relaxation time: 4 days at surface

Temperature

Potential Temperature



Latitude

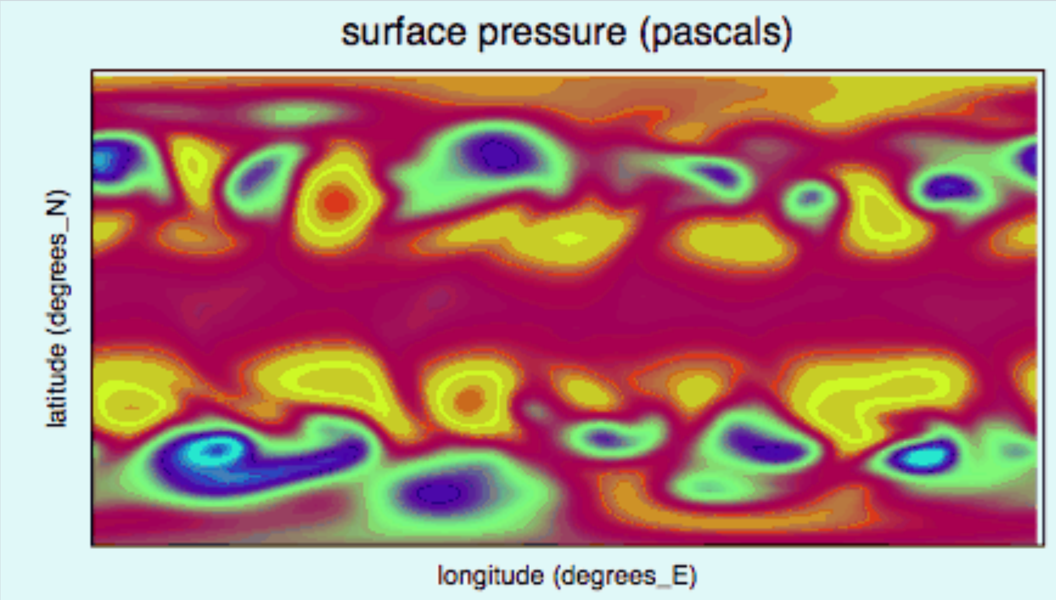
Latitude

The Held-Suarez Dry GCM

- Strong damping in the boundary layer is required to prevent a strong inversion from occurring
- Also friction within boundary layer:
  - Frictional damping time: 1 day at surface
  - Boundary layer depth: up to 700 hPa
- Other physical parameters:
  - Mean surface pressure = 1000 hPa, g = 9.8 m/s2
  - Dry air constants: R = 287.04 J/kg, cp = 1004 J/kg
  - a = 6.371 x 10^6 m
  - Omega = 7.292 x 10^-5 (s^-1)

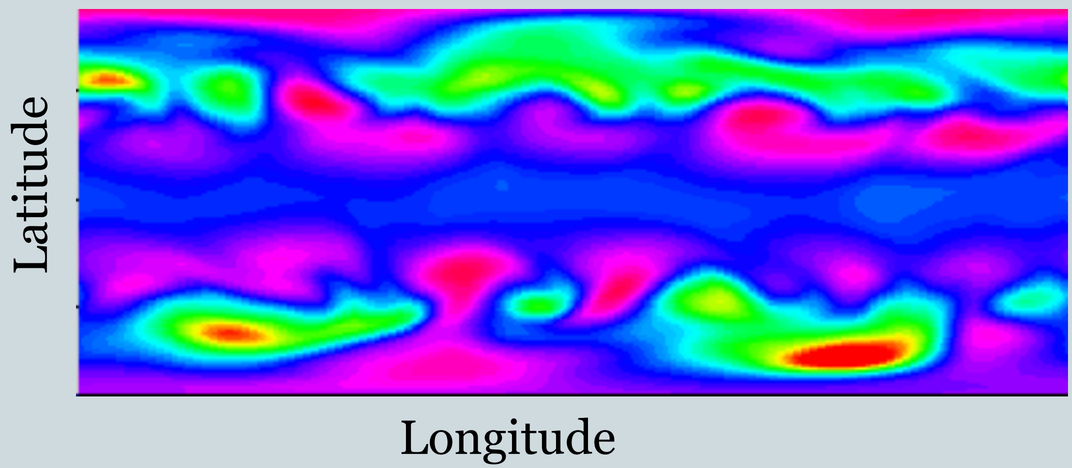
The Held-Suarez Dry GCM

- Instantaneous surface pressure:



The Held-Suarez Dry GCM

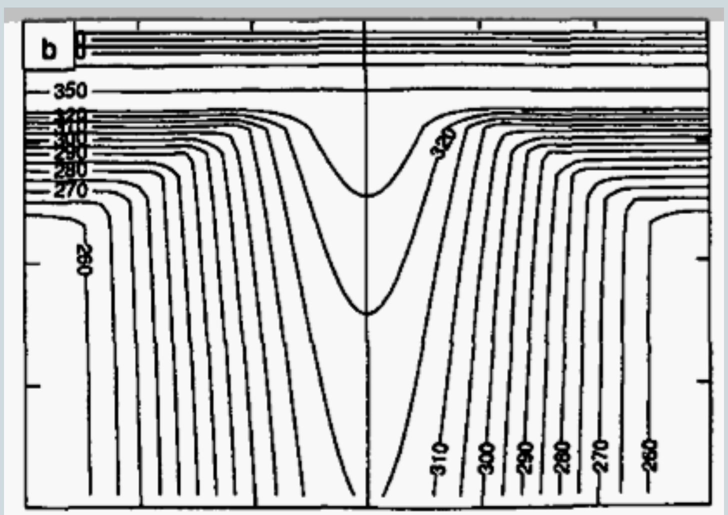
- Instantaneous surface pressure:

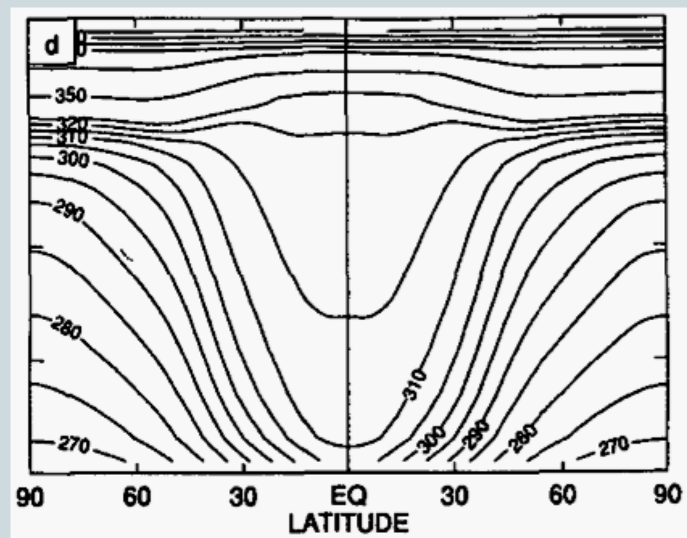


The Held-Suarez Dry GCM

- Potential temperature climatology

θ_{eq} θ



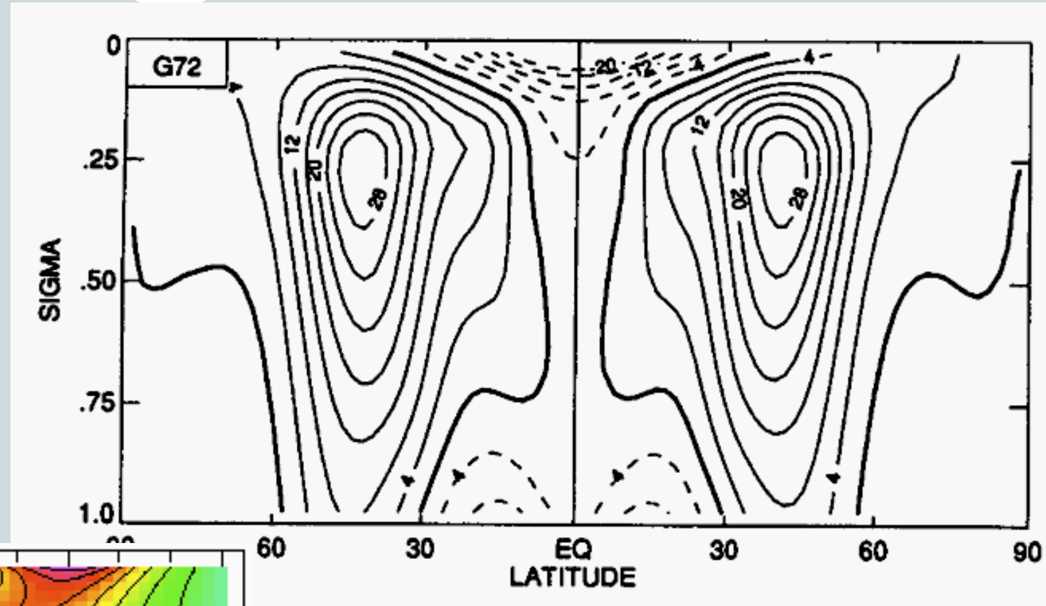


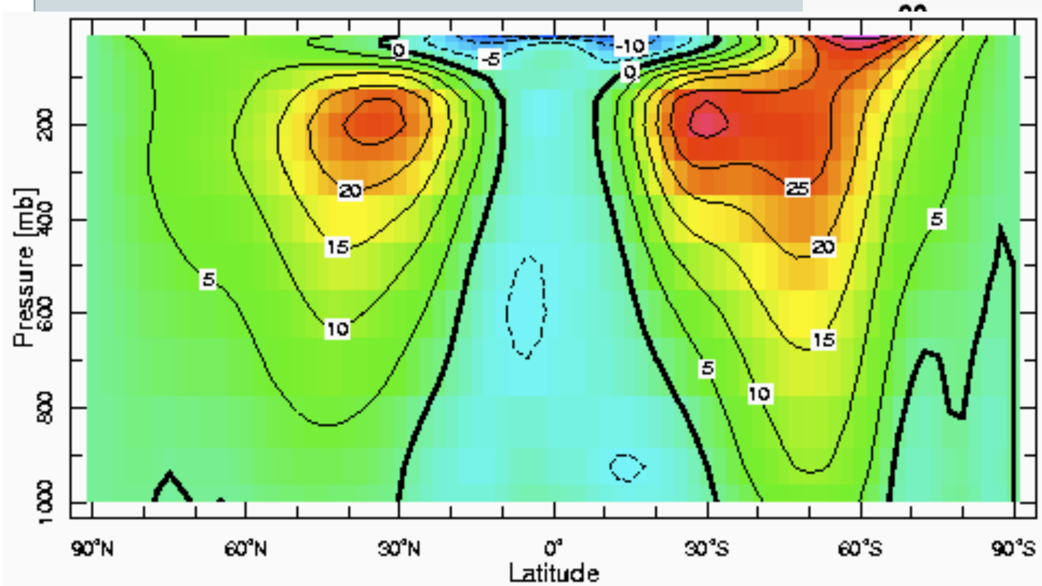
Circulation transports heat poleward and upward

From Held and Suarez (1994)

The Held-Suarez Dry GCM

- Zonal winds versus observations:





The Held-Suarez Dry GCM

- Held-Suarez model has been used to study:
  - Annular modes of extratropical variability (Gerber and Vallis)
  - Sensitivity of extratropical circulation to tropopause height (Williams; Lorenz and DeWeaver)
  - Winds in equatorial troposphere (Kraucunas and Hartmann)
  - Stratosphere-troposphere coupling (Reichler, Kushner and Polvani)

Held-Suarez Extensions

- More realistic stratospheric winds (Polvani and Kushner)
- Statically unstable reference profile + convection scheme (Schneider)
- Perpetual austral winter (Ring and Plumb)

Held-Suarez Model

- Strengths:
  - Remarkably simple formulation
  - Gives realistic circulation in many aspects
- Weaknesses:
  - No surface fluxes, no possibility of land-sea contrast
  - Says nothing about precipitation, clouds, ice, etc
  - Not heated from below like real atmosphere
  - Tropics are very quiet
  - Diabatic processes are weak
  - Baroclinic eddies tend to do everything

Introduction to Moisture in the Atmosphere

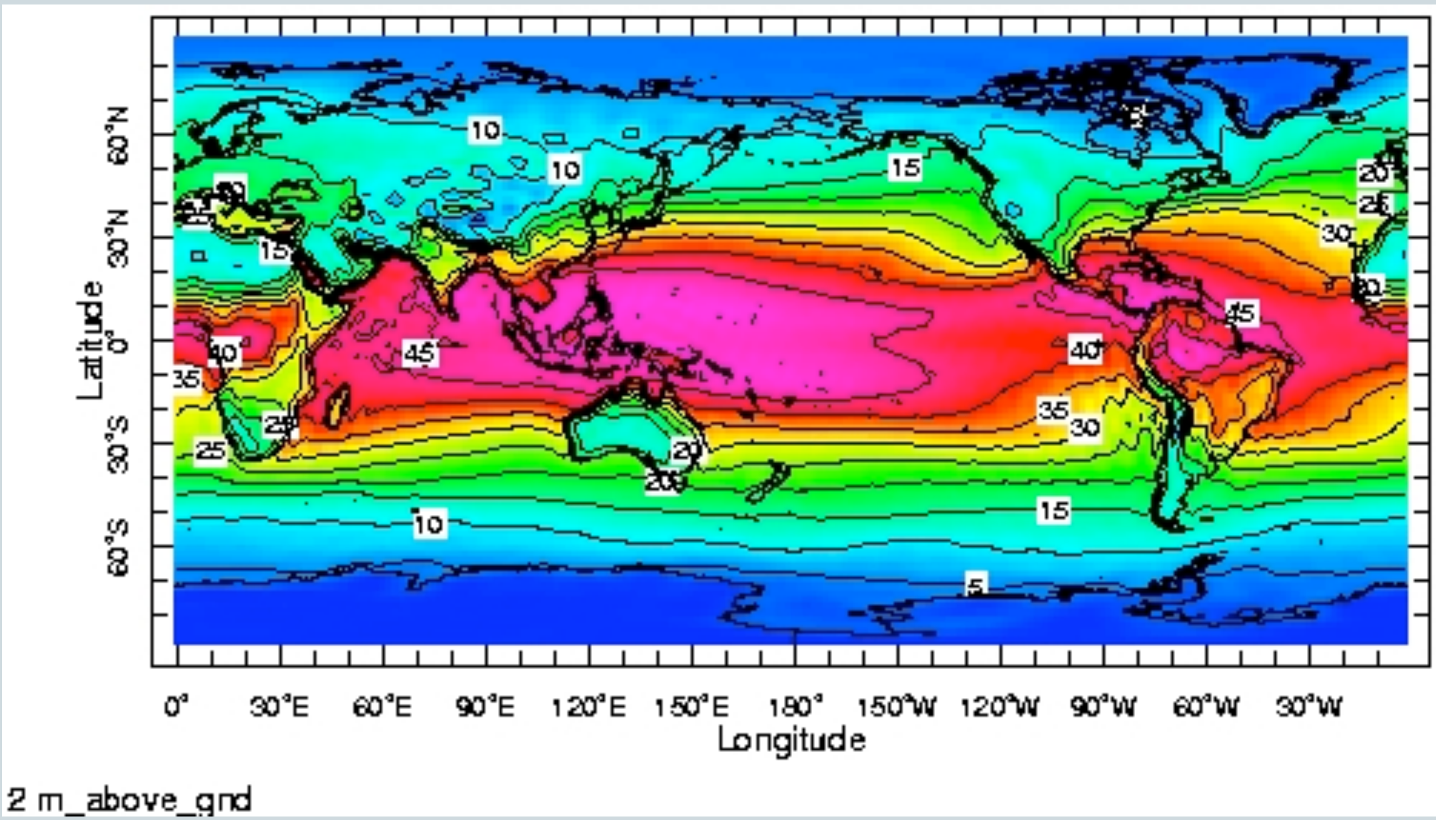
- Saturation vapor pressure e_s is a function of temperature T in the Clausius-Clapeyron equation:

$$e_s = e_{s0}\ exp\left(-\frac{L}{R_V}\left(T^{-1} - T_0^{-1}\right)\right)$$

- Roughly exponential for temperatures on Earth
  - Warmer air can hold much more moisture
  - 7% per K increase in temperature
- Condensation of water vapor can be huge heat source on Earth
  - Typical tropical lower tropospheric moisture content: 45 K

Introduction to Moisture in the Atmosphere

- Surface specific humidity, measured in Kelvin:

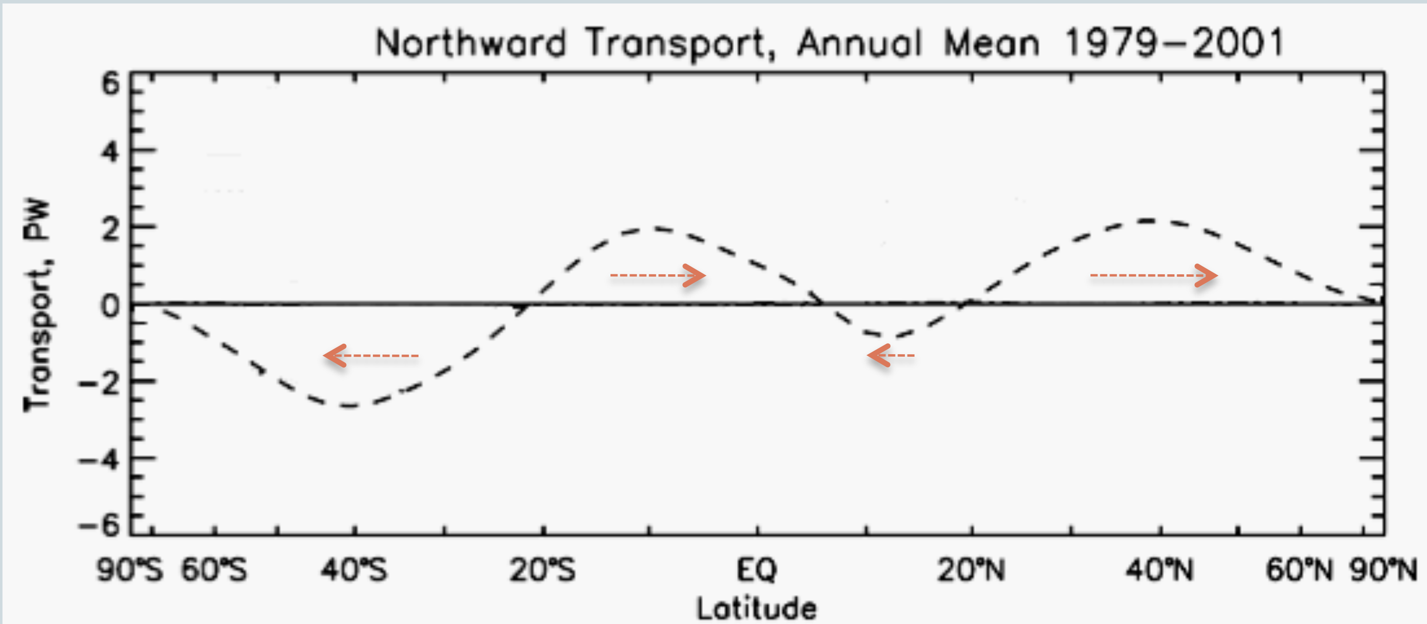


$$\frac{Lq}{c_p}$$

Source: NCEP Reanalysis

Introduction to Moisture in the Atmosphere

- Moisture flux in the atmosphere:

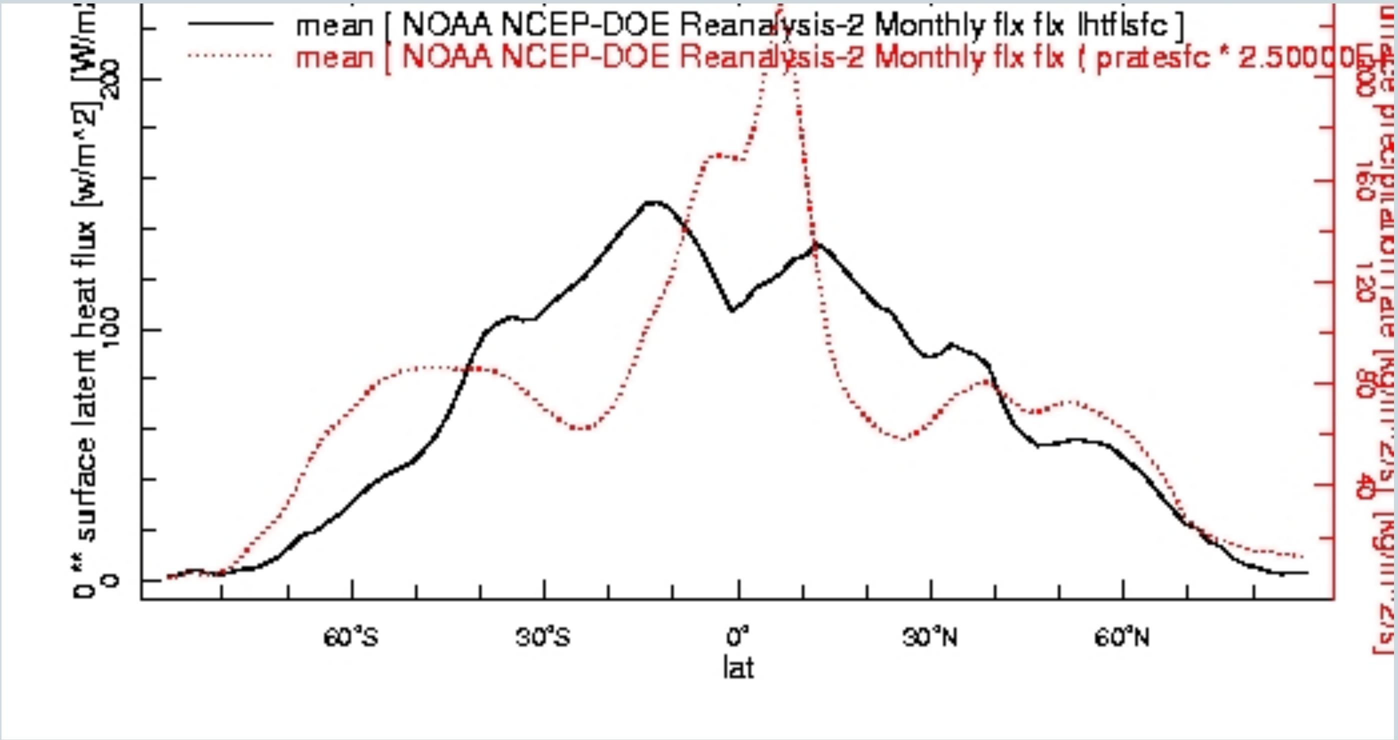


  - Equatorward moisture flux in tropics
  - Poleward moisture flux in midlatitudes

Source: Trenberth and Stepaniak (2003)

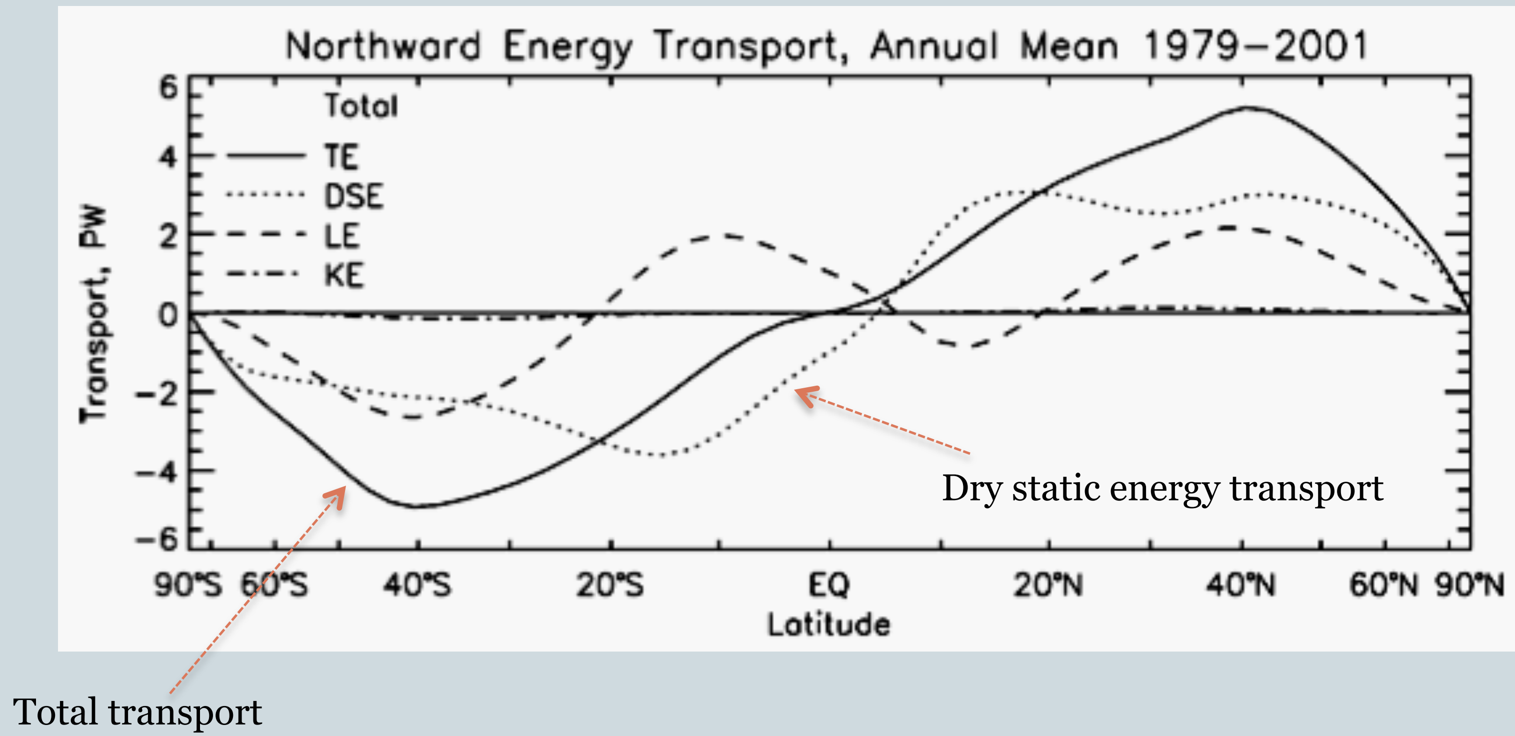
Introduction to Moisture in the Atmosphere

- Precipitation and evaporation:



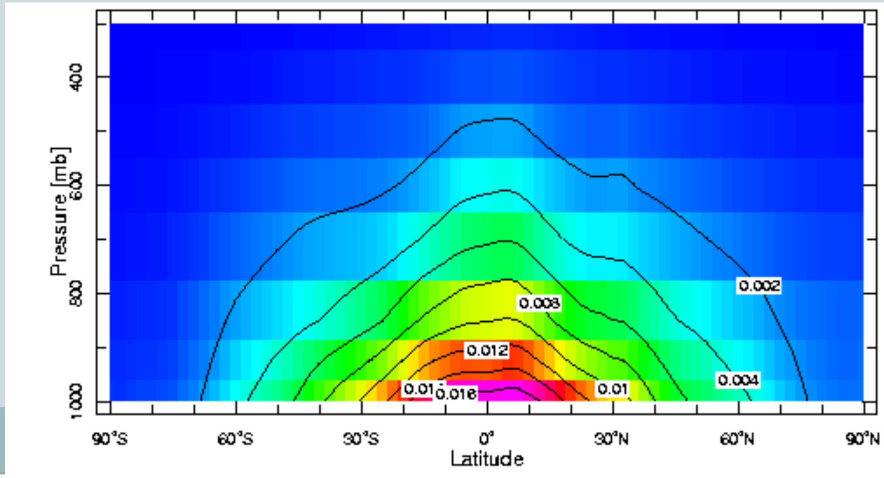
Introduction to Moisture in the Atmosphere

- Effect of moisture on energy transports:
  - Comparison with dry flux:



Introduction to Moisture in the Atmosphere

- Moisture is concentrated in the lower levels of the atmosphere
  - Upper atmosphere is too cold to hold much water vapor
- 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



Zonal mean moisture content

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 general circulation of the atmosphere?
  - Motivation for developing a simplified moist GCM

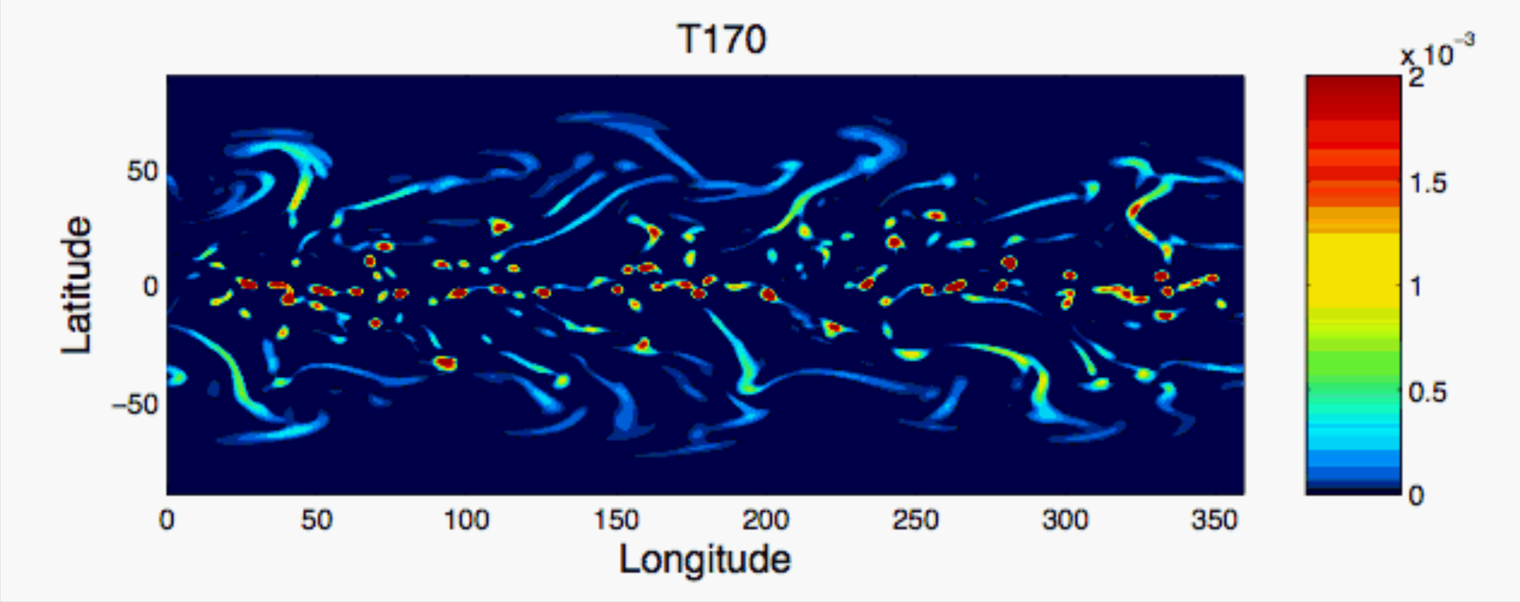
GRaM: An Idealized Moist GCM

- **G**ray **Ra**diation **M**oist GCM
  - If most GCMs have a metric ton of physics, use a model with a GRAM!
- Primitive equations
- Gray radiative transfer
  - Water vapor, cloud, & other radiative feedbacks suppressed
  - Radiative fluxes only a function of temperature
- Aquaplanet surface (ocean-covered Earth)
  - Slab mixed layer
  - Zonally symmetric
- Simplified Monin-Obukhov surface fluxes
- K-profile boundary layer scheme
- Simple convection schemes
  - Grid-scale condensation or simplified Betts-Miller scheme

See Frierson, Held & Zurita-Gotor 2006 for details

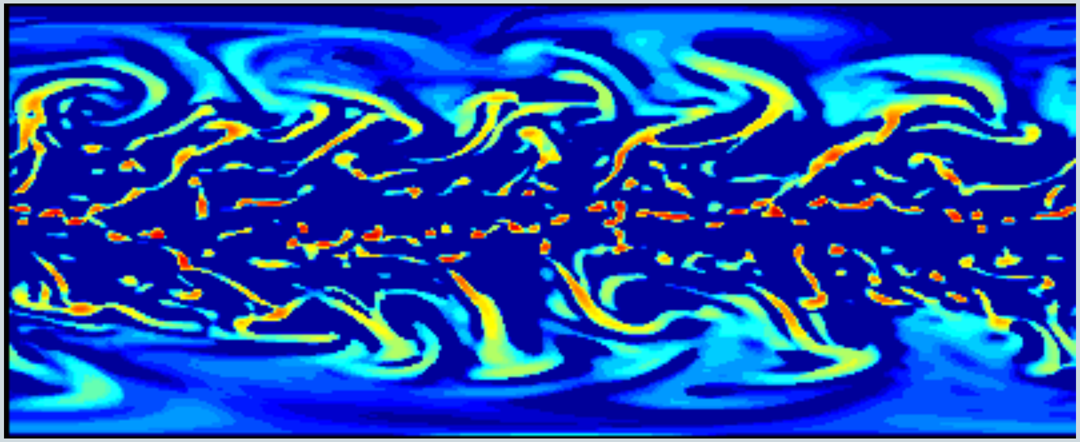
Model Climatology

- Instantaneous precipitation



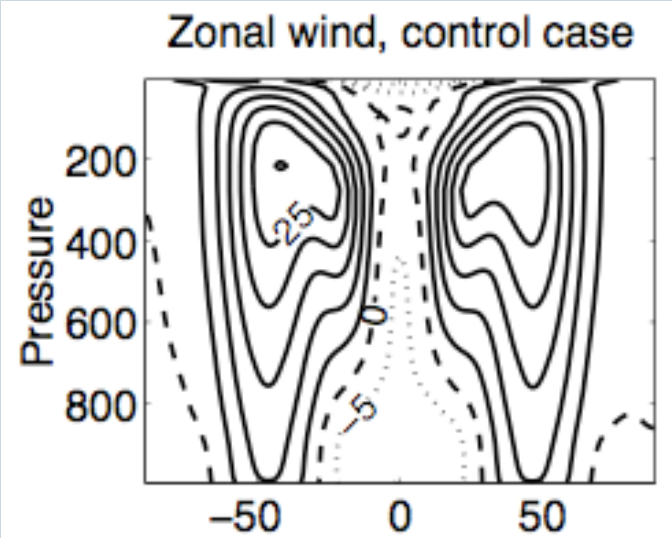
Model Climatology

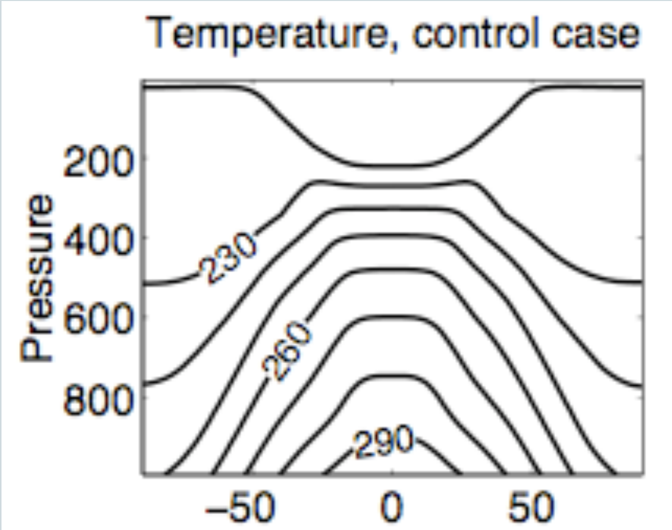
- Instantaneous precipitation



Model climatology

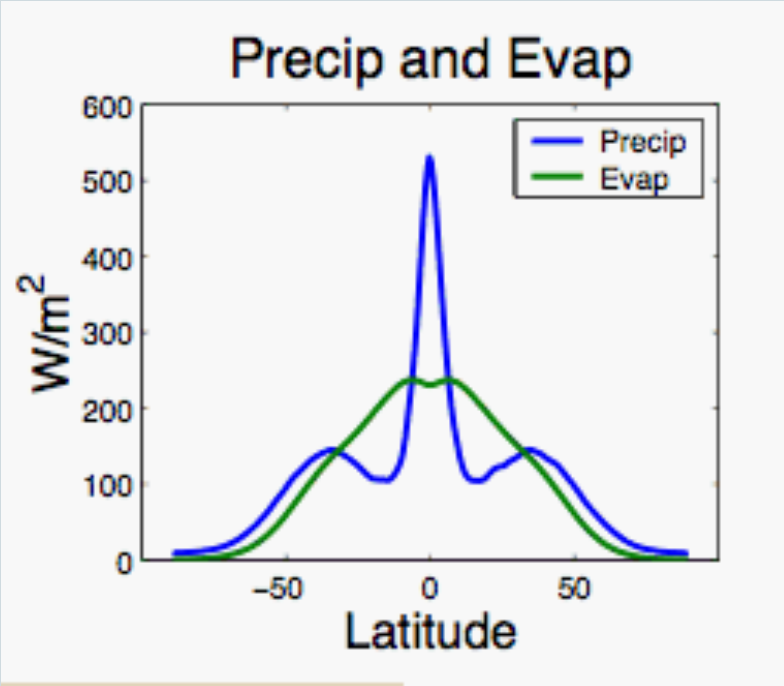
- Zonal wind and temperature





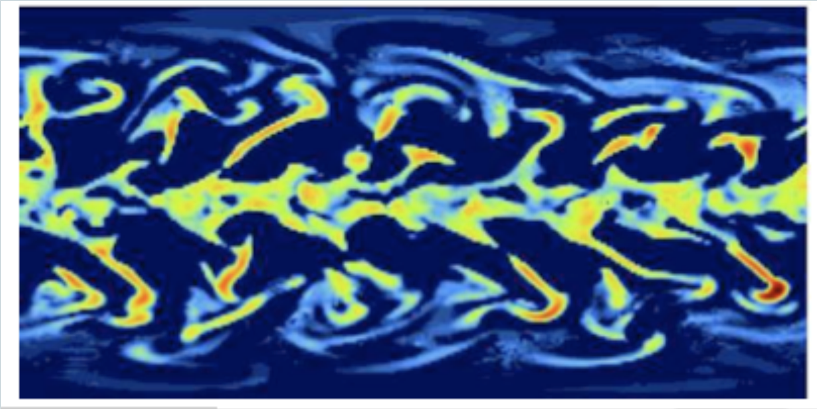
Model Climatology

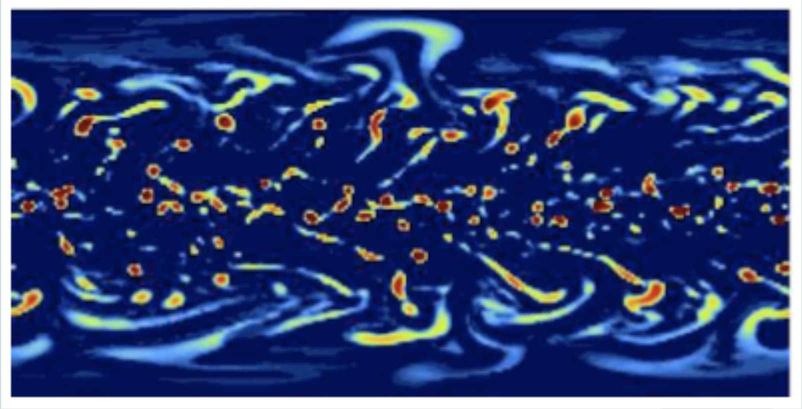
- Precipitation and evaporation



Effect of convection scheme

- Instantaneous precipitation





Simplified Betts-Miller convection scheme

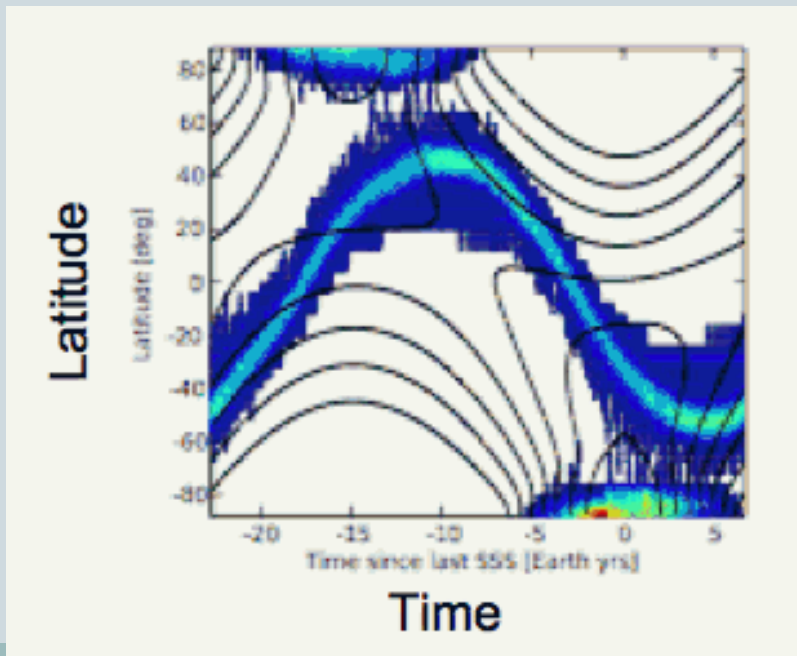
Grid scale condensation only

Strengths/Weaknesses of Idealized Moist GCM

- Strengths:
  - Simple consideration of condensation
  - Closed energy budget, active surface
  - Not tuned to current climate parameters
  - Allows large parameter variations
  - Expandable into a full GCM
- Weaknesses:
  - Too awesome?
  - Much more complex than Held-Suarez
  - Stratosphere
  - Lack of water vapor/clouds in radiative transfer

GRaM GCM

- Model is very adaptable to different physical regimes
  - Nothing is tuned to current climate parameters
  - Allows large parameter variations
  - Applicable to other climates as well



Simulation of seasonal cycle of convection on Titan (Mitchell et al 2006)

End of Topic 1: Model Hierarchies

- We have running on pynchon:
  - Held-Suarez dry dynamical core model
    - With spectral, finite volume, or B-grid dynamical core
  - Idealized moist GCM (GRaM)
  - GFDL's AM2 model
    - Full GCM over realistic geography
  - Aquaplanet version of AM2
  - Models with simplified vertical structure:
    - Barotropic vorticity equation model on the sphere
    - Shallow water model on the sphere