Energy Transports in an Idealized Moist General Circulation Model

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Introduction to Moisture in the Atmosphere

- Saturation vapor pressure: tells how much water vapor can exist in air before condensation occurs
- Sat. vapor pressure is a function of temperature:

$$e_s = A\, exp\,(-B/T)$$

(Increases rapidly with temperature)

- Water vapor releases latent heat when it condenses
- Typical tropical lower tropospheric moisture values: $40K$ of latent energy

Effect of Moisture on Large Scale Dynamics

- With global warming, atmospheric moisture content will increase
- What effects will the increased moisture have on the Earth's climate?
  - Poleward fluxes of energy
  - North-south temperature gradients
  - Intensity of storms
  - Precipitation changes

Outline

- Intro: static stability, eddy scale, energy fluxes
- Description of model: simplified moist GCM
  - Primitive equations
  - Aquaplanet mixed layer surface
  - Gray radiative transfer
  - Moisture/convection
- Results
  - Extratropical static stability
  - Eddy length scales
  - Jet latitude
  - Energy fluxes
    - Energy balance models

Theories for Midlatitude Static Stability

- Static stability $= \frac{\partial T}{\partial z} + \frac{g}{c_p} = \frac{1}{c_p}\frac{\partial s}{\partial z}$
  where $s = c_p T + gz$ (dry static energy)
- In tropics, moist adiabat determines stability
- Dry baroclinic eddy flux theories for midlatitudes:
  - Held 1982, Schneider 2004, baroclinic adjustment theories (Stone, etc)
  - Isentrope from subtropical boundary layer goes to tropopause at the pole
- Juckes (2000): moisture/convection is important

Theories for Midlatitude Eddy Scales/Energy Fluxes

- Most unstable mode of linear baroclinic instability problems
  - Rossby radius of deformation: $L_D \sim \frac{NH}{f}$
- Turbulent inverse cascade:
  - Rhines scale: $L_\beta \sim \sqrt{\frac{|v'|}{\beta}}$
- Energy fluxes: $\int \overline{v(c_pT + gz + Lq)}dp$
  - Moisture provides extra energy source to storms: stronger eddies?
  - Stronger moisture fluxes means weaker eddies to compensate?

Primitive equations

$$
\begin{aligned}
\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} &= fv + \frac{uvtan(\theta)}{a} - \frac{1}{acos\theta} \frac{\partial \Phi}{\partial \lambda} + S_{u,B} \\
\frac{\partial v}{\partial t} + \mathbf{v} \cdot \nabla v + \omega \frac{\partial v}{\partial p} &= -fu - \frac{u^2 tan(\theta)}{a} - \frac{1}{a} \frac{\partial \Phi}{\partial \theta} + S_{v,B} \\
\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + \omega \frac{\partial T}{\partial p} &= \frac{\kappa T \omega}{p} + Q_R + Q_C + Q_B \\
\frac{\partial \Phi}{\partial lnp} &= -R_d T_v \\
\nabla \cdot \mathbf{v} + \frac{\partial \omega}{\partial p} &= 0
\end{aligned}
$$

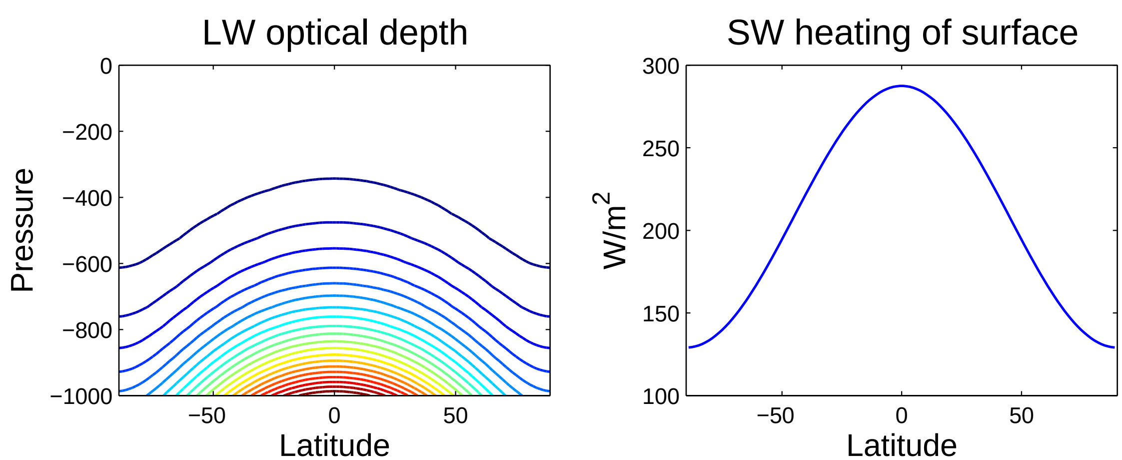
- Spectral method, T170 resolution (0.7° or 80 km), 25 levels

Model Description

- Aquaplanet slab mixed layer ocean
  - Ocean-covered Earth, shallow mixed layer
  - Sea surface temperatures adjust to conserve energy in the time mean
  - Means atmosphere performs all the energy transports
  - Facilitates variation over wide parameter range
- Simplified Monin-Obukhov surface flux scheme
- K-profile boundary layer scheme
  - Diffusion up to a calculated boundary layer depth

Radiation Scheme

- Gray radiation: simplest scheme other than Newtonian cooling. Water vapor, clouds, other tracers have no effect on radiation.
- All solar heating goes directly into surface
- Parameters: longwave optical depths, shortwave heating



- Strongly unstable radiative equilibrium profile

Moisture/Convection

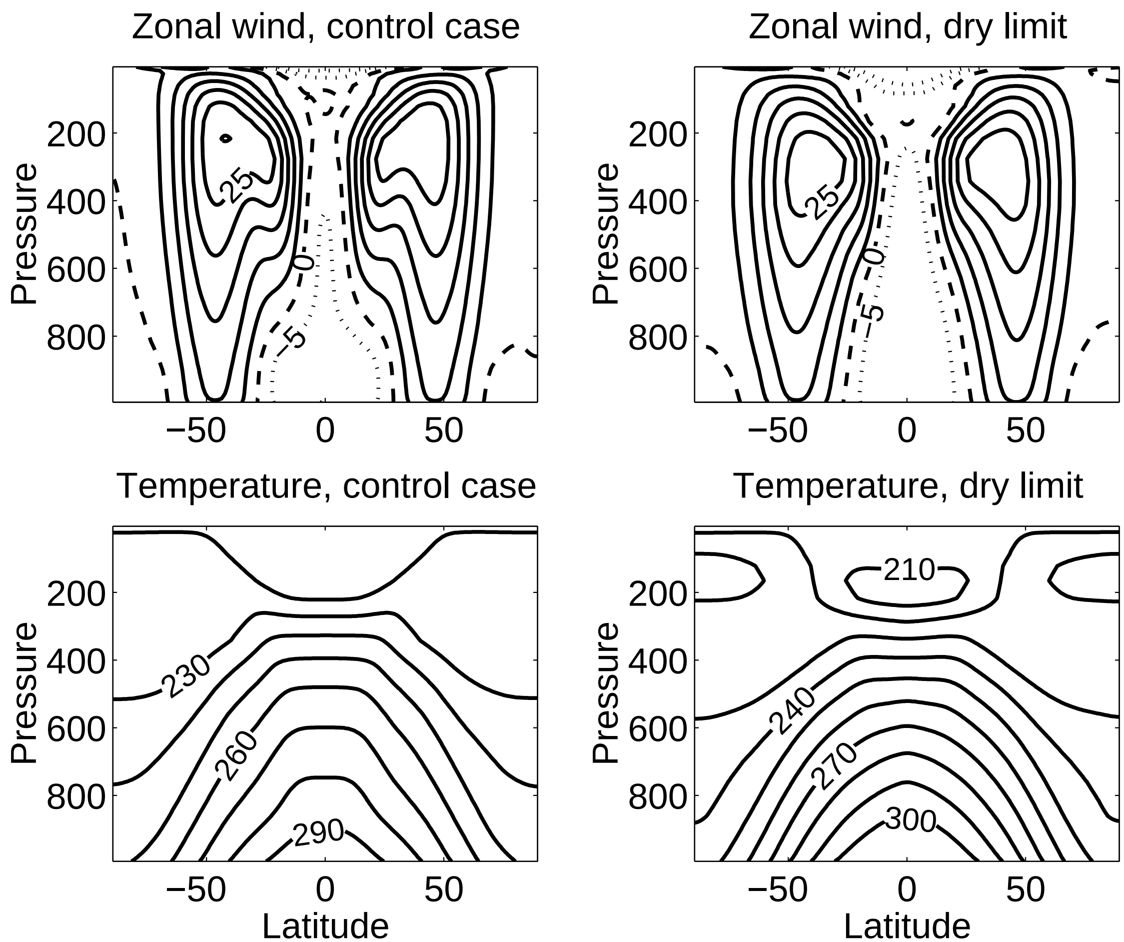
- Analytic Clausius-Clapeyron relation:

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

- e_{s0} is **key parameter** which we vary
  - Control: $e_{s0} = 610.78\ Pa$
  - Dry limit: $e_{s0} = 0$
  - Up to: $e_{s0} = 6107.8\ Pa$ (10 times moisture)
- Simplest convection scheme: **no convection scheme**! (large scale condensation only)
  - Revaporate precipitation into unsaturated areas
  - Similar in practice to moist convective adjustment

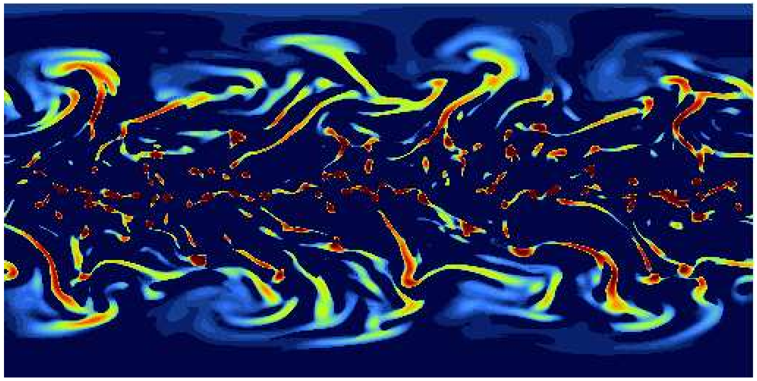
Climatologies

- Control case and dry limit u and T:

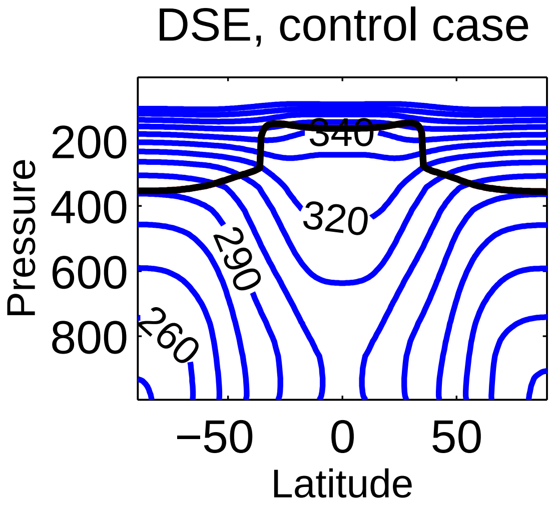


Climatologies

- Instantaneous precip

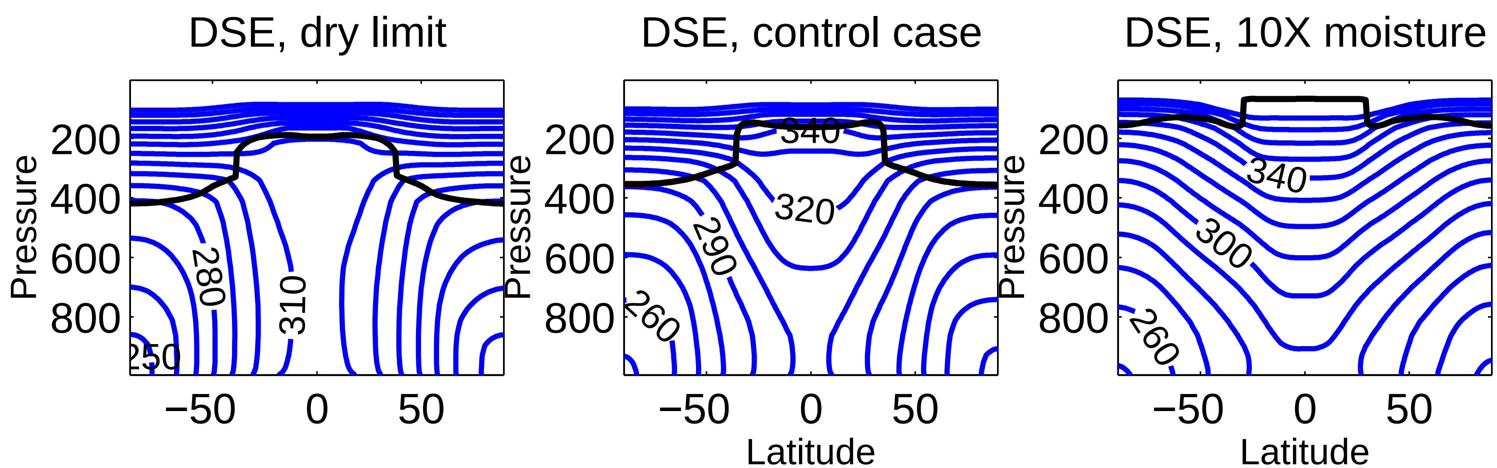


- Control case dry static energy



Static stability

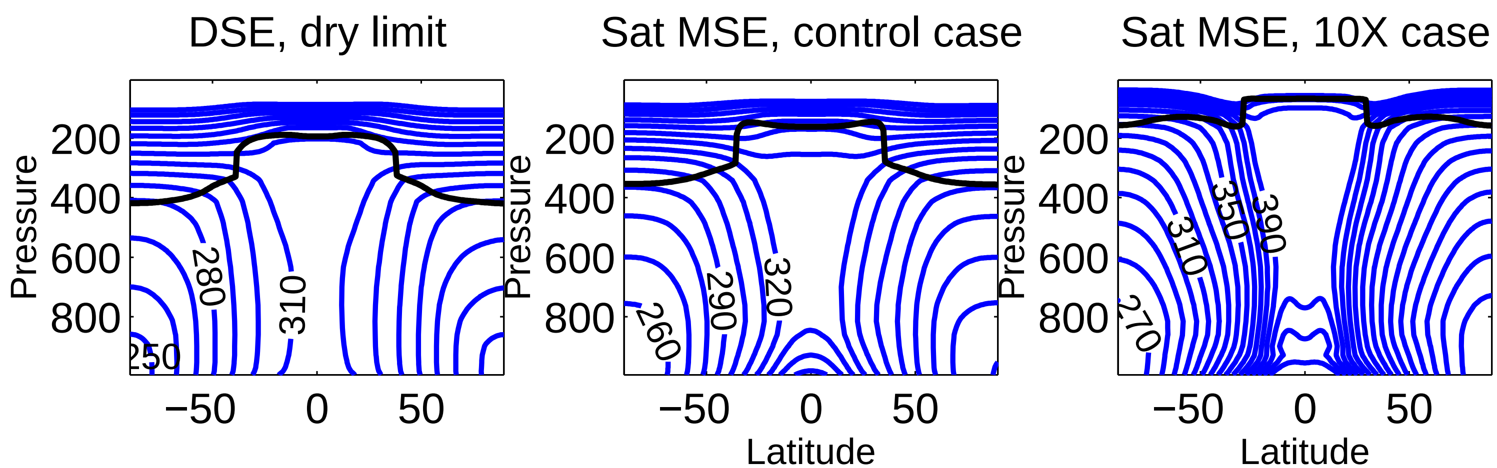
- **Dry static energy** for dry limit, control, and 10X moisture case:



- Isentropic slope clearly changes with moisture content
- Tropopause height additionally increases with moisture (as in radiative constraint of Held (1982))

Moist static stability

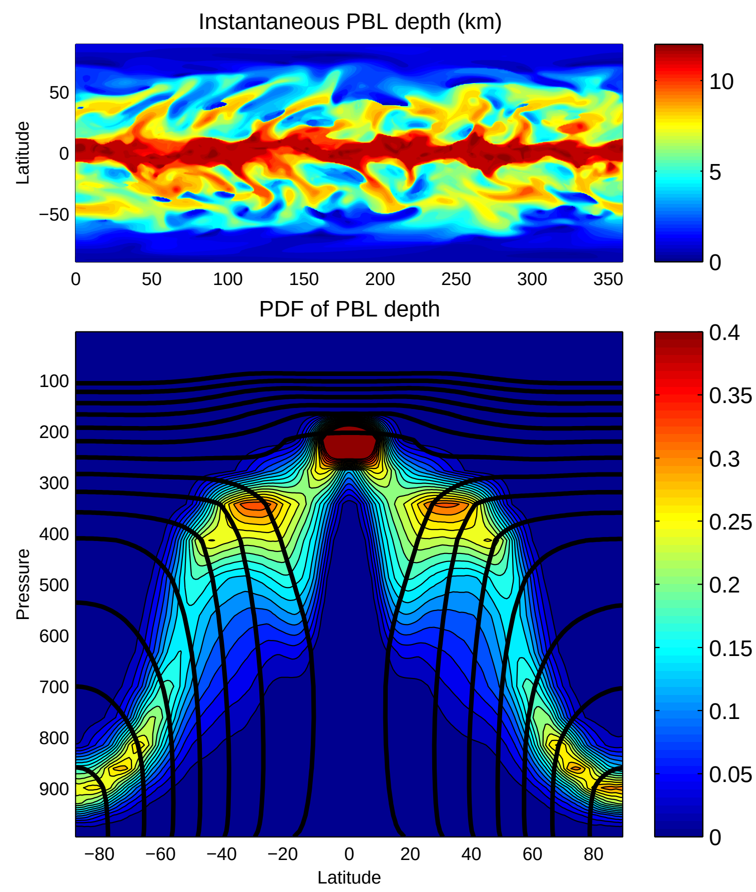
- Dry limit DSE, and saturated MSE for control case and 10X case (indication of moist stability):



- Theory of Juckes (2000): **moist convection** is key
  - Moist convection always occurs in warm areas of baroclinic eddies
  - Moist stability is set by surface variance of moist static energy

Dry limit static stability

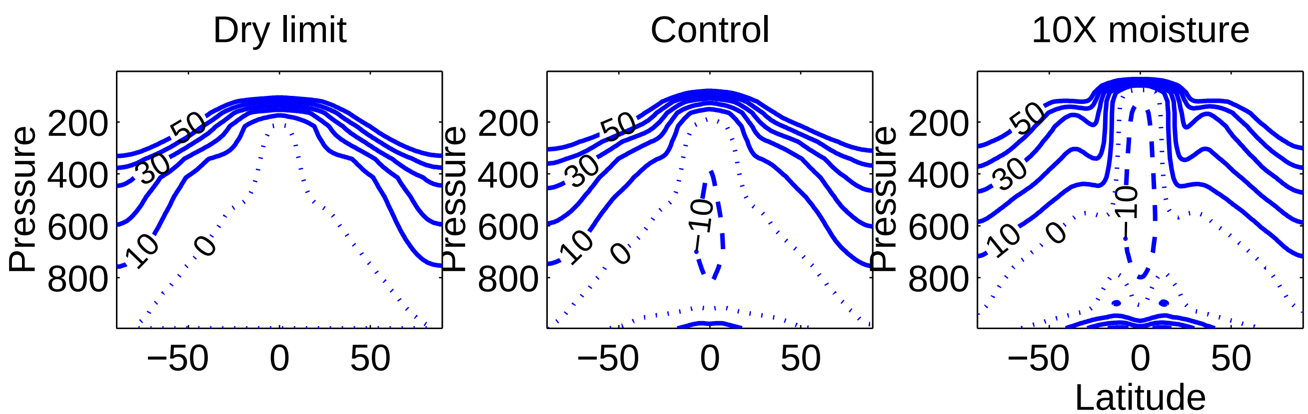
- Dry limit: only convection is boundary layer (BL) scheme
- Instantaneous BL depth and PDF of BL depth



Stability with moisture

- Clearly dry stability increases significantly as moisture content increases: what about **moist stability?**

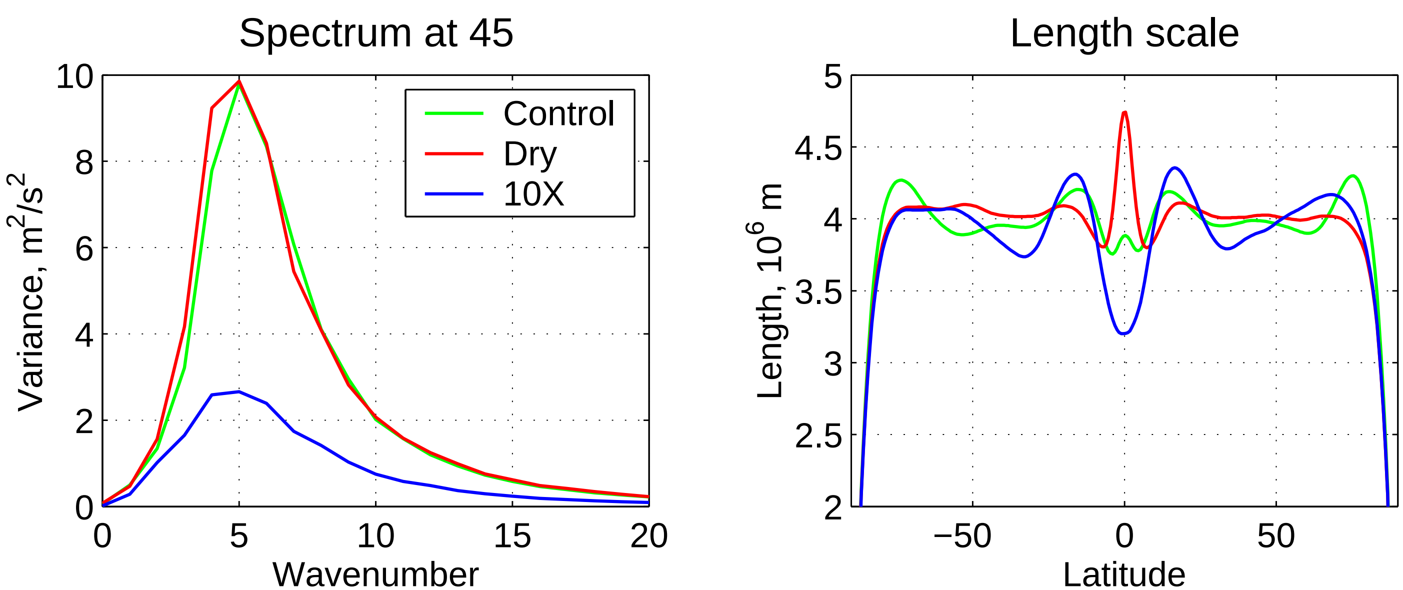
  Saturated MSE - surface MSE:



- Moist stability increases as well, due to increased variance of surface MSE. **What's the effect on length scales?**

Length scales

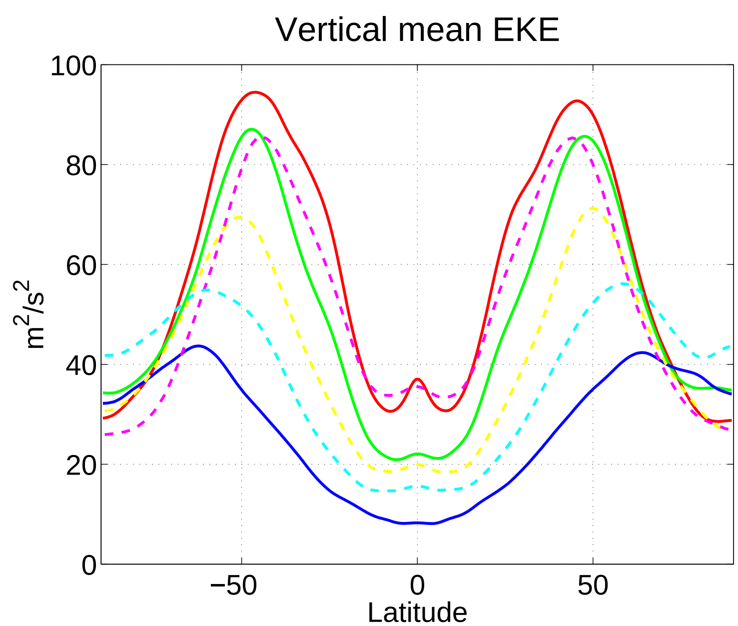
- Left: Spectrum for $\frac{1}{\delta p}\int |v|dp$ at 45 degrees
- Right: Mean length scale $\bar{L} = \frac{2\pi a cos(\theta)}{\bar{k}}$ with $\bar{k} = \frac{\int kE(k)dk}{\int E(k)dk}$



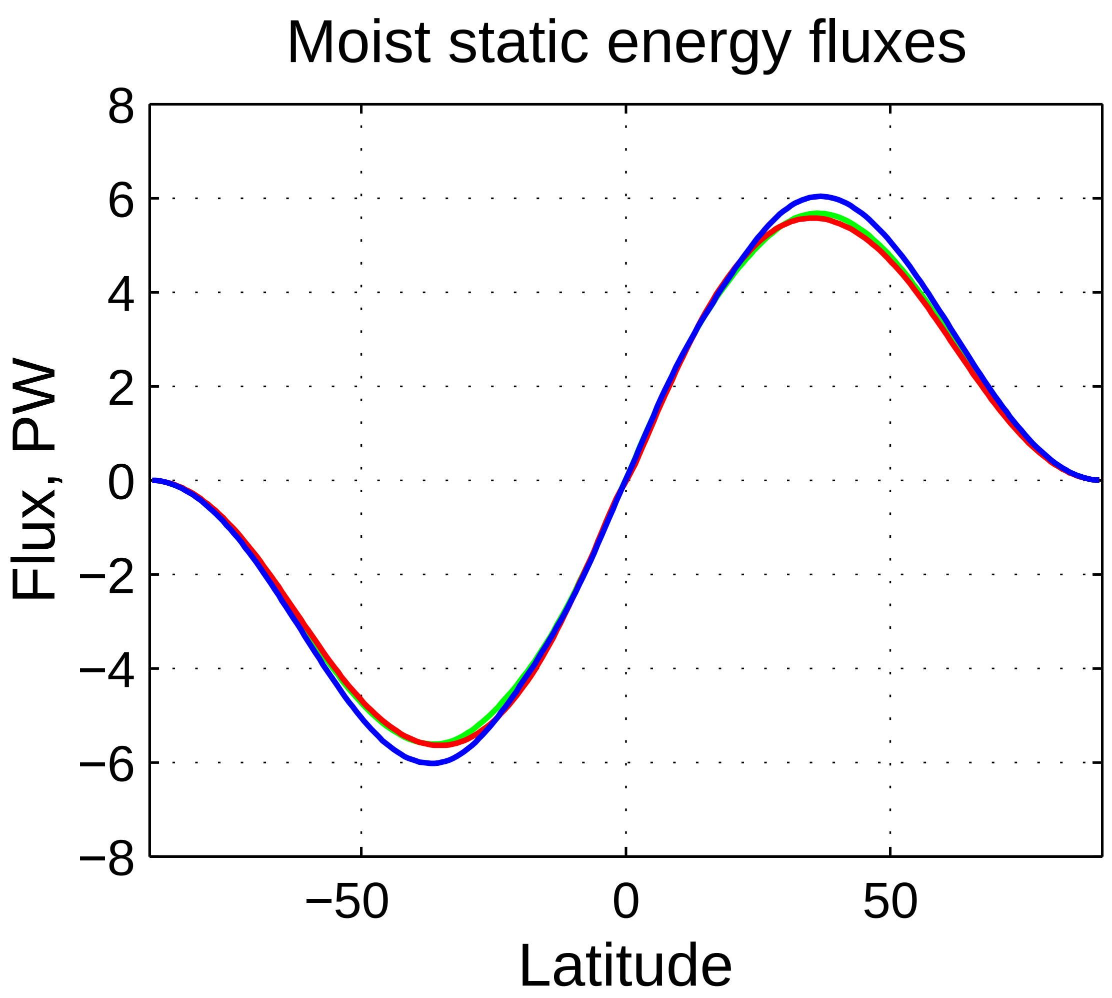
Green = control, Red = dry limit, Blue = 10X moisture

Length scales

- Clearly dry Rossby radius is not appropriate! Not moist Rossby radius either
- Rhines scale has too much change as well (in the other direction).
- Rhines at latitude of maximum EKE works very well: allows β to change

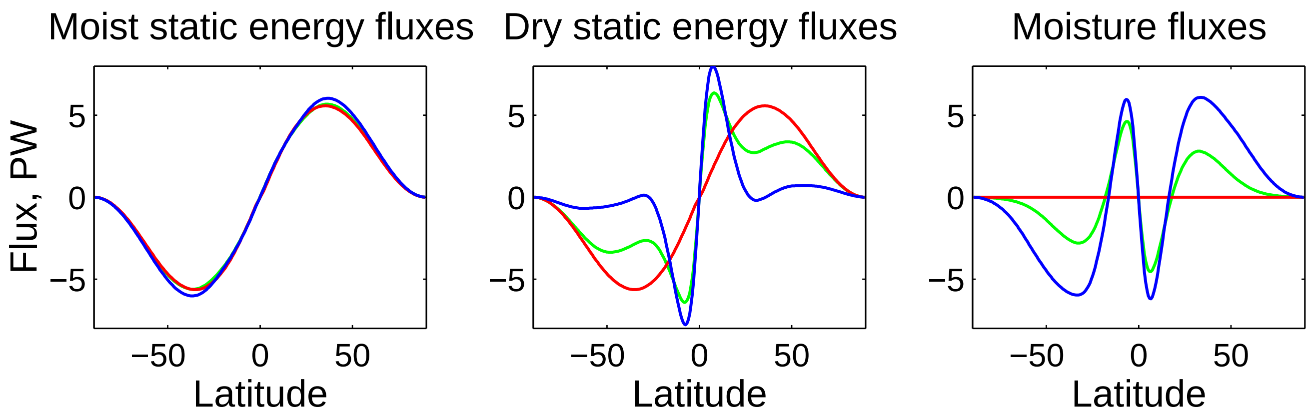


Moist Static Energy Fluxes



Moist Static Energy Fluxes

- MSE, DSE, and moisture fluxes:



Green = control, Red = dry limit, Blue = 10X moisture

- Increase of moisture fluxes compensated nearly perfectly by decrease of DSE flux. "Compensation" = 99% for dry to control, and 93% for dry to 10X

Interpreting the MSE fluxes

- Stone (1978) gives reason for **shape of profile** not varying much:
  - Flat OLR implies profile that's nearly identical to this
  - Same as in observations (Trenberth and Stepaniak 2003)
  - Flux from flat OLR = $7.8\ PW$ (much larger than here)
- Energy balance model:

$$\frac{\partial m}{\partial t} = Q_{SW} - Q_{LW} + D\nabla^2 m$$

  - Diffusing surface moist static energy m
  - Radiation forcing (Q_{SW} = shortwave heating, $Q_{LW} = \sigma T_E^4$ = longwave cooling)
  - Only energy flux is diffusive, with some diffusivity D

EBM with exact compensation

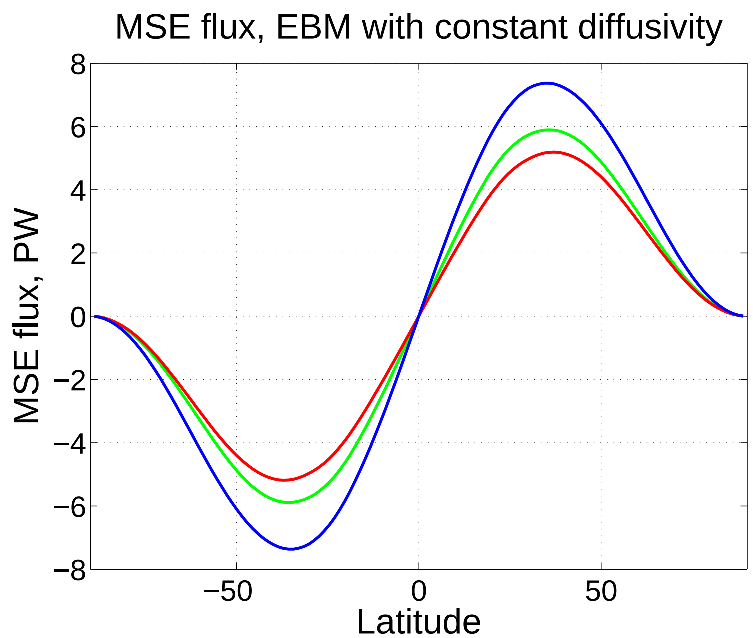
- The following assumptions give exact compensation:
  - Fixed diffusivity
  - Fixed level of emission z_E
  - All water condensed out by emission level ($q(z_E) = 0$)
  - Neutral stability to emission level ($m(z_E) = m$)
- Equation becomes:

$$\begin{aligned}\frac{\partial m}{\partial t} &= Q_{SW} - \sigma T_E^4 + D\nabla^2 m \\ &= Q_{SW} - \sigma(\frac{m - gz_E}{c_p})^4 + D\nabla^2 m\end{aligned}$$

  - Equation is only a function of m
  - Independent of partition into dry and moist

Refinements to EBM

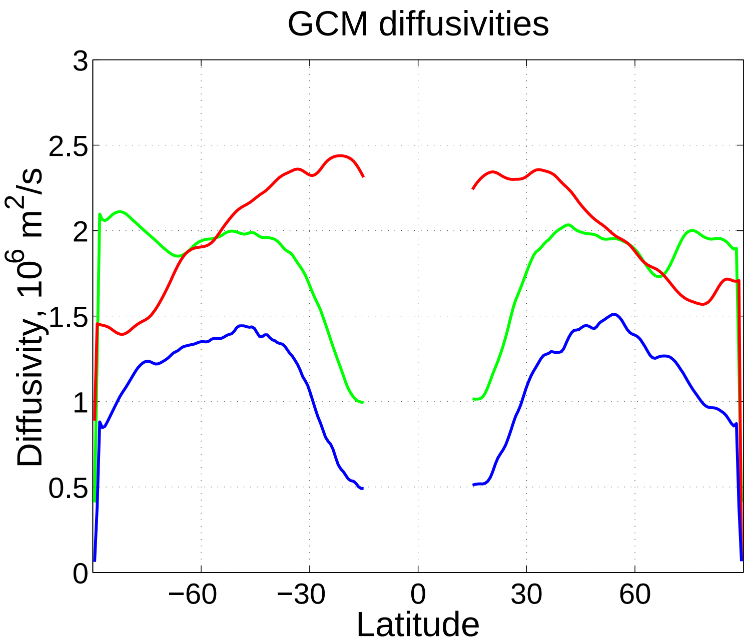
- Actually calculating moist adiabats gives less perfect compensation (especially on moist side)



- Some change in diffusivity is necessary

Diffusivity

- GCM diffusivity (average flux divided by surface gradient):



- Mean extratropical diffusivities: $1.9 \times 10^6 m^2 s^{-1}$ (control), $2.1 \times 10^6 m^2 s^{-1}$ (dry), $1.3 \times 10^6 m^2 s^{-1}$ (10X)
- EBM with the mean diffusivities above gives correct compensation

Theory for diffusivity

- Mixing length theory:

$$\begin{aligned}\overline{v'm'} &= k\,|v'|\,|m'| \\ &= k\,|v'|\,L\,\frac{\partial m}{\partial y}\end{aligned}$$

  with k = correlation coefficient, $|v'|$ = rms velocity, and L = mixing length

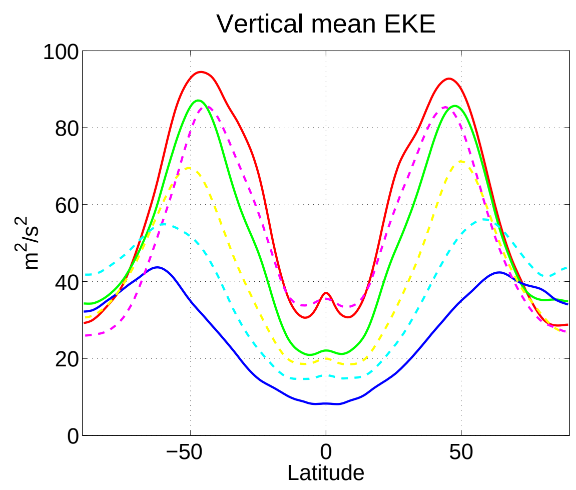
- Diffusivity proportional to **velocity scale times length scale** ($D = k\,|v'|\,L$)

- Length scale as before: Rhines scale at latitude of maximum EKE

- All that remains for full EBM is theory for jet latitude and velocity scale

Jet Latitude

- Jet latitude: **poleward shift** robustly seen in global warming forecasts (Yin 2005)



- Theory for jet latitude: latitude of maximum midtropospheric temperature gradient
- Determined purely thermodynamically in our model (moist adiabats from surface)
- Shift is present in EBM with exact compensation

Theory for Velocity Scale

- v from equipartition of EKE and mean available potential energy: $v \sim \frac{1}{f}\frac{\partial T}{\partial y}$
- Not dependent on static stability or moisture content
- Full EBM with all these converges, and predicts qualitatively:
  - Poleward shift of eddies with increased moisture
  - Reduction of diffusivity
  - Near-equality of fluxes

Conclusions

- Static Stability
  - Dry static stability is dominated by moist adiabat
  - Moist cases are more stable in terms of moist stability (and much more stable in terms of dry stability)
- Eddy scales
  - Varies little with moisture (not standard Rossby radius)
  - Rhines scale at latitude of maximum EKE works well
- Energy fluxes
  - High degree of compensation of moisture fluxes by dry static energy fluxes
  - Seen in simple EBM's with fixed diffusivity
  - Diffusivity reduction with moisture aids compensation