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:

\[ e_s = A \exp\left(-\frac{B}{T}\right) \]

(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: \( L_\beta \sim \sqrt{|v'|/\beta} \)

- Energy fluxes: \( \int v(c_pT + gz + Lq)dp \)
  - Moisture provides extra energy source to storms: stronger eddies?
  - Stronger moisture fluxes means weaker eddies to compensate?
Primitive equations

\[
\begin{align*}
\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} &= fv + \frac{uv \tan(\theta)}{a} - \frac{1}{a \cos \theta} \frac{\partial \Phi}{\partial \lambda} + S_{u,B} \\
\frac{\partial v}{\partial t} + \mathbf{v} \cdot \nabla v + \omega \frac{\partial v}{\partial p} &= -fu - \frac{u^2 \tan(\theta)}{a} - \frac{1}{a} \frac{\partial \Phi}{\partial \theta} + S_{v,B} \\
\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + \omega \frac{\partial T}{\partial p} &= \frac{\kappa T \omega}{p} + Q_R + Q_C + Q_B \\
\frac{\partial \Phi}{\partial \ln p} &= -R_d T_v \\
\nabla \cdot \mathbf{v} + \frac{\partial \omega}{\partial p} &= 0
\end{align*}
\]

- 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 $T$:

![Graphs showing zonal wind, temperature, and pressure distributions for control case and dry limit.](image)
Climatologies

- Instantaneous precip

- Control case dry static energy
**Static stability**

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

  ![Graphs showing dry static energy](image)

  - 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 $\bar{L} = \frac{2\pi \cos(\theta)}{k}$ with $\bar{k} = \frac{\int k E(k) dk}{\int E(k) dk}$

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 $\beta$ to change.

![Vertical mean EKE graph](image-url)
Moist Static Energy Fluxes

Moist static energy fluxes

Flux, PW

Latitude
Moist Static Energy Fluxes

- MSE, DSE, and moisture fluxes:

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<thead>
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<th>Flux, PW</th>
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<tbody>
<tr>
<td>-5</td>
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<tr>
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Latitude

Moist static energy fluxes

Dry static energy fluxes

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:

$$\frac{\partial m}{\partial t} = Q_{SW} - \sigma T_E^4 + D\nabla^2 m$$

$$= Q_{SW} - \sigma \left(\frac{m - gz_E}{c_p}\right)^4 + D\nabla^2 m$$

- 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):

  [Graph showing diffusivity against latitude]

- Mean extratropical diffusivities: $1.9 \times 10^6 \text{m}^2 \text{s}^{-1}$ (control), $2.1 \times 10^6 \text{m}^2 \text{s}^{-1}$ (dry), $1.3 \times 10^6 \text{m}^2 \text{s}^{-1}$ (10X)

- EBM with the mean diffusivities above gives correct compensation
Theory for diffusivity

- Mixing length theory:

\[ \frac{v'm'}{k |v'| |m'|} = k |v'| L \frac{\partial m}{\partial y} \]

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)

![Vertical mean EKE](image)

- 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