Modeling the General Circulation of the Atmosphere. Topic 3: Midlatitude General Circulation

DARGAN M. W. FRIERSON
UNIVERSITY OF WASHINGTON, DEPARTMENT OF ATMOSPHERIC SCIENCES

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Precip Changes with Global Warming

- Multi-model mean precip change
  - With stippling based on a weak significance criteria

*Figure SPM.7. Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. (Figure 10.9)*
Why Wet Get Wetter

- More moisture in the atmosphere → more moisture flux → wet get wetter, dry get drier

\[ P = E - \nabla \cdot (vq) \]

Actual (solid) and thermodynamic prediction (dashed) of P-E change with global warming

Held & Soden 2006, Allen & Ingram 2002, etc
Poleward Expansion of Deserts

- Results of Jack Scheff
  - Robust drying is mostly due to **poleward shift** of midlatitude systems

Storm track shifts are the primary cause of significant drying

- Drying on equatorward side
- Moistening on poleward side

Scheff & Frierson (2012; GRL)
Poleward Shifts of Midlatitude Storm Tracks

- **Feature-relative** precipitation changes

  - Most drying occurs b/w midlat max and subtrop min
  - We confidently project high latitude moistening
  - From Scheff and Frierson (2012, J. Climate)

  Each dot = 1 model
  Blue/Red = fraction of points w/ significant moistening/drying
Poleward Shifts of Eddies w/ Global Warming

- Eddy kinetic energy changes from Yin 2005
  - Black contours are current mean, colors are predicted change

- Poleward (and upward) shift with global warming

See also Kushner et al, Miller et al, Lorenz & DeWeaver, Previdi & Liepert, etc
Poleward Shift of Eddies

- DJF zonal wind changes from Lu, Chen & Frierson 2007
  - Black contours are current mean, colors are predicted change

- Poleward (and upward) shift with global warming

See also Kushner et al, Miller et al, Lorenz & DeWeaver, Previdi & Liepert, etc
Idealized Model Changes with Moisture

- Zonal winds in a simplified physics aquaplanet GCM:
  - Poleward and upward shift with increased moisture
    - Similar to global warming simulations

From Frierson, Held and Zurita-Gotor (2006)
Poleward shifts with warming (and equatorward shifts with cooling) are very robust in many types of models over large range of climates. From Frierson, Lu, & Chen 2007.
Poleward Shifts in Dry Models

- Happens in dry models due to rises in the tropopause height

Lorenz & DeWeaver 2007
Not due to El Niño...

- People often talk about “El Niño-like” responses to global warming...

- But El Niño causes an **equatorward contraction**
  - Although zonal asymmetries are clearly important in ENSO...

Lu, Chen & Frierson 2008
SH Poleward Shift due to Ozone Depletion

- The **ozone hole** has clearly induced changes in winds as well – only in DJF though

Observations

Model

Thompson et al 2012
Width of Hadley Cell Predictions

- Can we use our tropical intuition to understand the shift?
  - Predictions from Held-Hou theory
    - Using Phillips’ criterion
    - Using Eady growth rate
Where do eddies grow?

- Eddies grow due to **baroclinic instability**
- Faster eddy growth where there’s...
  - Large **temperature gradient**, or equivalently, large **wind shear**
  - Also **small stratification** helps and **higher latitudes** are better due to Coriolis
A Baroclinic Mechanism

- These theories focus on the **generation** of baroclinic instability
- Related argument: stratification increases preferentially on **equatorward side** of storm tracks
  - Causes shift of baroclinic instability away from stabilization?

Frierson 2006
Midlatitude Dynamics

- Zonal winds:

Surface winds are frictionally damped: require momentum flux to support

Zonally averaged zonal winds from NCEP reanalysis
Atmospheric and oceanic heat transports make temperature gradients significantly weaker.

- Atmospheric transport dominates in extratropics.
- Total (atmosphere plus ocean) flux.
Extratropical Energy Fluxes

- Comparison with dry and total flux:
  - Moisture flux is roughly 50% of the total transport in midlatitudes

![Graph showing Northward Energy Transport, Annual Mean 1979-2001]

- Total atmospheric transport
- Dry static energy transport
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 Earth’s climate?
  - More moisture flux => flatter temperature gradients => weaker eddies?
  - On the other hand, more moisture => more latent energy available => stronger eddies?
Eddy moist static energy fluxes

- Would like a way to consider moisture fluxes as well as dry static energy fluxes
- Framework: diffusive transport of moist static energy
- Derivations: justification for diffusive transport of a conserved tracer under “mixing length theory”
Mixing Length Theory

- Let’s consider transport of a conserved scalar $\xi$ by eddies: $\overline{v'\xi'}$
  - Overbar: time mean
  - Prime: deviation from time mean

- First, write the flux as the product of the standard deviations of the quantities, and a correlation coefficient
  \[ \overline{v'\xi'} = k |v'| \overline{\xi'} \]
  - This can be considered to be the definition of the correlation coefficient
Next, consider fluctuations of the scalar occurring within a mean gradient:

- Low $\xi$
- High $\xi$

If $\xi$ is conserved over its displacement, this generates fluctuations in $\xi' \approx -L \frac{\partial \xi}{\partial y}$
Mixing Length Theory

- Combining, we have
  \[ v' \xi' = k |v'| |\xi'| \]
  \[ = -kL |v'| \frac{\partial \xi}{\partial y} \]

- Or,
  \[ v' \xi' = -D \frac{\partial \xi}{\partial y} \]
  with \( D = kL |v'| \)

- Diffusivity is proportional to length scale times velocity scale (eddy intensity)
Usefulness of Mixing Length Theory

- Good for conserved tracers only:
  - Not for dry static energy or PV in the presence of condensation, for instance
  - Works for moist static energy \( m = c_p T + g z + Lq \)
- Quantities like mixing length and eddy intensity may not be constant over parameter regimes
- Can’t capture phenomena such as wave breaking at critical latitude influencing shears
- Still a useful framework for thinking about energy fluxes though
Theories for Diffusivity

- Stone (1972): $L \sim$ Rossby radius, $V \sim$ mean jet strength
- Green (1970): $L \sim$ baroclinic zone width, $V$ from equipartition of APE and EKE
- Held and Larichev (1996): $L \sim$ Rhines scale, $V$ from turbulent cascade theory
General Circulation Changes with Moisture

- Vary moisture content over a wide range
  - Goal: To understand the effect of moisture on the general circulation

- Strategy:
  - Vary Clausius-Clapeyron constant $e_{s0}$

\[
e_s = e_{s0} \exp \left( -\frac{L}{R_V} \left( T^{-1} - T_{0}^{-1} \right) \right)
\]

- Control: $e_{s0} = 610.78 \text{ Pa}$
- Dry limit: $e_{s0} = 0$
- Up to: $e_{s0} = 6107.8 \text{ Pa (10 times moisture)}$
Energy Fluxes

- Moisture fluxes in idealized simulations:

![Graph showing moisture fluxes with significant increase in poleward moisture flux in midlatitudes.](image)
Energy Fluxes

- Total atmospheric flux in idealized simulations:

  MSE flux increases by less than 10%
Energy Fluxes

- Fluxes in idealized simulations:

- Moist static energy fluxes
- Dry static energy fluxes
- Moisture fluxes

Dry static energy fluxes decrease to compensate almost perfectly!
Interpreting the Energy Fluxes

- Energy balance model (diffusing moist static energy) in steady state:
  \[ Q_{solar} - \sigma T_E^4 + D \nabla^2 m = 0 \]

- Diffusive flux of moist static energy \( m \) with some diffusivity \( D \)

- Radiation forcing: solar heating \( Q_{solar} \) and longwave cooling to space \( Q_{out} = \sigma T_E^4 \)
Energy Balance Model with Exact Compensation

- The following assumptions give exact compensation:
  - Fixed diffusivity $D$
  - Fixed level of emission $z_E$
  - All moisture condensed out by emission level $q_E = 0$
  - Constant moist stability to emission level $m_E = m + \Delta m$

\[
T_E = c_p^{-1}(m_E - g z_E - L q_E)
= c_p^{-1}(m - g z_E + \Delta m)
\]

-
Energy Balance Model with Exact Compensation

- **Exact compensation assumptions:**
  - Fixed diffusivity $D$
  - Fixed level of emission $z_E$
  - Constant moist stability to emission level $m_E = m + \Delta m$

- **Energy balance equation becomes:**

$$Q_{SW} - \sigma \left( c_p^{-1} (m - g z_E + \Delta m) \right)^4 + D \nabla^2 m = 0$$

Equation is only a function of $m$

Independent of partition into dry and moist!
EBM Conclusions

- When there’s higher moisture content, more of the flux is due to moisture but total flux is the same
- Also, more of the gradient is due to moisture, but the total gradient is the same:
  - Implies that the surface temperature gradient gets weaker with higher moisture content
- A mechanism for polar amplification without ice-albedo feedback...
- Full theory for the compensation is more complicated and involves changes in diffusivity as well
Temperature Changes

- What happens to temperature structure then?

- At surface, temperature gradient gets much weaker

- In midtroposphere (where outgoing radiation comes from), temperatures stay remarkably similar
Testing Compensation Idea

- How about compensation in more comprehensive GCMs?
  - Models that also have ice-albedo feedback, clouds, continents, more realistic radiative transfer, etc
- Check compensation in the aquaplanet and CMIP simulations
Aquaplanet Full GCMs

- Simulations of Caballero and Langen (2006):
  - Fixed SST boundary conditions
  - Varying mean temperature (y-axis) and equator-pole temperature gradient (x-axis)
  - Each block is one simulation (70 simulations total):

<table>
<thead>
<tr>
<th>Moisture flux</th>
<th>Dry static energy flux</th>
<th>Total flux</th>
</tr>
</thead>
</table>

[Graph showing moisture flux, dry static energy flux, and total flux with arrows indicating increased gradient and hotter conditions]
Aquaplanet Full GCM and Simplified Moist GCM

- Simulations of Caballero and Langen (2006):
  - Moisture flux
  - Dry static energy flux
  - Total flux

Simplified GCM over same boundary conditions:
Aquaplanet GCMs and Moist EBMs

- Comparison w/ **fixed diffusion** energy balance model:

  - Full GCM
  - Simplified moist GCM
  - Fixed diffusivity EBM

Too much flux at high moisture content is primary deficiency of EBM
Energy Fluxes in AR4 Models

- **Change in energy fluxes** with global warming in slab and coupled models:

  \[ \text{Increase in moisture flux in midlatitudes} \]

  (more moisture content → more moisture flux)

Hwang and Frierson (2010)
See also Hwang, Frierson, Held and Soden (2010)
Energy Fluxes in AR4 Models

- **Change in energy fluxes** with global warming in slab and coupled models:

  Decrease in dry static energy flux in midlatitudes

  (compensates for moisture flux increase – but not perfectly)

  Hwang and Frierson (2010)

  See also Hwang, Frierson, Held and Soden (2010)
Energy Fluxes in AR4 Models

- **Change in energy fluxes** with global warming in slab and coupled models

![Graph showing changes in atmospheric fluxes](image)

- Total atmospheric energy flux increases in midlatitudes
- Solid lines = total atmospheric flux

Hwang and Frierson (2010)
See also Hwang, Frierson, Held and Soden (2010)
Energy Fluxes in AR4 Models

- **Change in energy fluxes** with global warming in slab and coupled models

Differences between coupled and slab:

- More increase in moisture flux in slab runs (slab $\rightarrow$ more warming)
- Total energy flux increase is more for coupled runs in SH, similar in NH

Why?

Hwang and Frierson (2010)
See also Hwang, Frierson, Held and Soden (2010)
Individual models show a wide range of changes in total atmospheric transport though:

Multi-model mean (black) does not represent the behavior of individual models

Hwang and Frierson (2010)
Comparison of Extreme Cases

- CCCMA (T63) has less increase in flux in S. Hem., MPI has more increase

Factor of two difference in total atmospheric flux
Sea Ice and Cloud Forcing

Feedback terms calculated with approximate piecewise radiative perturbation (APRP) method (Taylor et al 2007)

More ice melts in CCCMA

More negative CRF in MPI
Forcing: Sea Ice + CRF

CCCMA has **more net heating** in SH high latitudes:
Energy transports **increase less**

MPI has cooling in SH b/w 45-65 degrees:
Energy transports **increase more**
Our Argument

- We claim: Differences in energy fluxes are due to differences in heating
  - Forcing by ice-albedo, clouds, aerosols, or ocean heat uptake (in coupled models)
- Take sea ice as an example:
  - More sea ice melting => more heating at high latitudes => less flux into that region
- Can be modeled with a (moist) energy balance model
Energy Balance Model Results

- Using **constant diffusivity** (tuned to best fit the 20th century climate), predict fluxes at 40 degrees N/S
  - Ice-albedo, aerosols, clouds & ocean uptake as forcings

Captures differences among models

**Underpredicts** fluxes in NH, **overpredicts** fluxes in SH

Hwang and Frierson (2010)
Energy Balance Model Results

- Energy balance model can tell **why coupled flux is more than slab flux** (esp. in S. Hem.)

Lots of **ocean uptake** in SH in coupled simulations (increases flux)

Also **less sea ice melting** (sea ice melting decreases flux)

From Hwang and Frierson (2010)
Polar Energy Transports w/ Global Warming

- Might think with *more energy transport* into the Arctic, there would be *more Arctic warming* – *wrong*!

Models with **more** energy flux across 70 N have **less** polar amplification

Hwang, Frierson, and Kay (2011)
Polar Energy Transports with Global Warming

- Anticorrelation because flux is \textbf{diffusive}: weaker $rac{dT}{dy}$ means less transport

\textbf{Energy balance model} is accurate at predicting transports given cloud, ice, ocean changes

See Hwang, Frierson & Kay 2011 for details
Tropical-Extratropical Connections

- Diffusive flux means high latitudes have impact on the tropics too
- Let’s discuss how ITCZ is affected by extratropical forcing
ITCZ Response to High Latitudes?

- **Yes!** Work by Chiang/Bitz/Biasutti/Battisti demonstrated this
  - Strong sensitivity of ITCZ to high latitude sea ice and land ice in Last Glacial Maximum simulation

See also simulations by Zhang and Delworth, theoretical work of Kang et al, Broccoli et al, etc.

From Chiang and Bitz (2005)
Extratropical Influences on ITCZ

  - **Simplified moist GCM and aquaplanet full GCM (AM2)** runs w/ idealized forcing only in the **extratropics**:
    - NH cooling
    - SH warming

Think glaciers + sea ice in NH, plus warming in SH (to keep global mean temperature the same)

From Kang, Held, Fri., & Zhao (2008, J Clim) and Kang, Fri. & Held (2009, JAS)
In response to forcing, ITCZ precipitation shifts towards **warmed hemisphere**

With strong forcing, ITCZ shifts up to 18 degrees

Maximum amplitude of forcing = 0, 10, 30, 60 W/m²

From Kang, Held, Fri., & Zhao (2008, J Clim) and Kang, Fri. & Held (2009, JAS)
We argue **energy transport** is of key importance.

Northward energy transport in simplified GCM:

- Anomalous energy transport into cooled region.
- Less transport into warmed region.
- This diffusive transport acts to spread cooling/warming into lower latitudes.
Mechanism for ITCZ Response

- ITCZ latitude ~ “Energy transport equator”

Northward MSE transport in simplified GCM

Define "energy transport equator" as zero crossing of energy transport

Shifted into SH in perturbed case

In tropics, mean circulation does most of the flux => v=0 there => ITCZ is nearby

ITCZ location (-) is approximately same as energy trans equator (--) for full GCM
Mechanism for Energy Transport Change

- Eddies modify fluxes in midlatitudes
  - *Diffusively*: moist static energy transport proportional to moist static energy gradient

- Anomalous **Hadley circulation** modifies fluxes in tropics

See Kang, Held, Fri., & Zhao (2008, J Clim) & Kang, Fri. & Held (2009, JAS) for more
Role of Cloud Responses

- ITCZ shift is hugely sensitive to cloud feedbacks!
  - Factor of 2 difference in response even for the same forcing!
  - Varied Tokioka entrainment limiter in Relaxed Arakawa-Schubert convection scheme
  - Caused large SW CRF differences primarily in midlatitudes & subtropics

Which Latitudes are Most Important?

- Kang et al (2008) forcing applied to different ranges of latitudes:

  0-10°  30-40°  80-90°

  Forcing latitude

  Largest response for **high latitude** forcing!

Seo, Kang and Frierson, 2014
Uncertainty in Feedbacks Also Causes Uncertainty in Temperature Response

• Roe, Feldl, Armour, Hwang, & Frierson (2015, Nature Geoscience)
Caveats

- “Gross moist stability”
  - Ratio between energy and mass/moisture transport may not always be constant

- Eddy moisture fluxes
  - Some energy flux is done by transport of moisture by eddies out of the tropics

- Causality?

- Next, an example of our framework applied to slab ocean simulations of global warming
  - Frierson and Hwang (2012, J. Climate)
Part I: Change in Precip with Doubled CO$_2$

**Moistening** in tropics and mid/high latitudes

Drying in subtropics

Frierson and Hwang (2012)
Change in Precip with Doubled CO$_2$

Huge variance in tropics though!

Frierson and Hwang (in press)
Change in Precip with Doubled CO$_2$

Big differences in SH too:
10 cm/yr

Frierson and Hwang (in press)
Change in Energy Transport with Doubled CO$_2$

Coloring by cross-equatorial energy transport change
Precip shift versus cross-eq energy flux

- Anticorrelated: Hadley cell governs both

- If we can explain the energy flux changes, we can explain the ITCZ shifts

Frierson and Hwang (in press)
Change in Precipitation in Extreme Cases

**CCCMA (most S-ward)**

**MPI (most N-ward)**

seen across most longitudes, and over continents as well.
Surface Albedo + Cloud Effects

Net Heating from Clouds plus Surface Albedo

CCCMA has more net heating in SH: ITCZ shifts south

MPI has more heating in NH: ITCZ shifts north
Feedbacks

Surface albedo

- Lots of ice melting

Cloud shortwave

- Low clouds form
1-D PDE Model for Energy Fluxes: IPCC Models

- **Prescribe latitudinal structure of forcings/feedbacks:**
  - Surface albedo changes
  - Cloud radiative feedbacks
  - Ocean heat uptake
  - Aerosol scattering/absorption

- **Predict:**
  - Energy fluxes
  - Temperature changes
  - Clear sky outgoing radiation changes

- **Assumes constant diffusivity!**

See Frierson and Hwang (J. Clim, 2012) for the details
EBM Prediction for Slab Models

\[ R = 0.91 \]
Importance of Extratropical Forcing

- EBM forced by terms outside of the tropics only (poleward of $20^\circ$ N/S)

Extratropical forcing explains the range in ITCZ shifts

$R = 0.86$
Midlatitude Dynamics

- Zonal winds:

Surface winds are frictionally damped: require momentum flux to support

Zonally averaged zonal winds from NCEP reanalysis
Midlatitude Dynamics: Big Picture

- Horizontal momentum fluxes $\Rightarrow$ surface winds
  - (Barotropic component of winds)
  - Remember can also get Ferrel cell transport from this too

- Thermal wind balance: shear $\Leftrightarrow$ temperature gradients
  - Energy fluxes $\Rightarrow$ vertical shear
  - Or, vertical momentum flux $\Rightarrow$ meridional temperature gradient!
Zonal winds in central Pacific

- Zonal winds at 150°W (central Pacific) from Vallis:
  - DJF
  - MAM
Big Picture Part 2

- **Subtropical jet = Hadley cell jet**
  - Baroclinic but no surface westerlies underneath

- **Midlatitude jet = subpolar jet = eddy-driven jet**
  - Large barotropic component
  - Requires momentum transport into the jet
  - Baroclinic eddies do the driving
  - However can understand with a barotropic model!
Barotropic Vorticity Equation

- Two-dimensional, non-divergent flow
- Everything can be written in terms of 1 variable (streamfunction)
- Balanced model
- Simplest model w/ Rossby waves
- Used for first successful NWP experiment
- Rossby wave momentum transport derivation
Rossby waves and the jet

Schematic from Vallis:
Rossby waves and the jet

- Schematic from Vallis:

[Diagram showing wave activity flux, disturbance, vorticity gradient, and fluid acceleration.]
A Barotropic Model

- Stochastic stirring + linear damping

Force barotropic vort. eqn. with white noise in “storm tracks”.

Damp proportional to wind everywhere.

Generates a jet stream in stirred region.

This model also has an annular mode!

From Vallis, Gerber, Kushner and Cash 2004
Phase speed spectra

Randel and Held (1991):

- How to make a phase speed spectrum diagram:
  1) Take wavenumber-frequency spectrum (at each latitude).
  2) Convert frequency to phase speed (using $c = \frac{\omega}{k}$).
  3) This plot is then integrated over wavenumber at each latitude.

Note $c < U$ always (as is required for propagation).

Figure 4: Phase speed spectrum of eddy momentum flux, $\overline{uv}$ at 200mb.
Schematic of Wave Absorption

- Wave propagates until critical latitude (where it’s absorbed)

Waves generated at this phase speed propagate until they hit their critical latitude.
Rossby Wave Absorption in a Barotropic Model

- From Held and Phillips (1987):

A Rossby wave is started at 45 degrees and propagates on a realistic flow.

Left: evolution of pseudomomentum

Right: deceleration at the end

Drag occurs near critical latitude (but spread around more)
Reducing friction in H-S model causes a poleward shift of the surface westerlies.
Changing Surface Friction in Held-Suarez

- From Chen, Held & Robinson (2007):

  - Phase speed increases with weaker drag
  - Faster phase speed => Eddies don’t make it as far into tropics => Poleward shift of breaking
  - Full physical mechanism of shift of source region not entirely clear
  - It shifts even in a shallow water model in which stirring is fixed though! (suggests wave breaking is behind this)
Applicability to observed shift in SH?

- Argument (Chen and Held 2007):
  - Ozone depletion $\Rightarrow$ cooling the polar stratosphere $\Rightarrow$
    Stronger winds in lower stratosphere $\Rightarrow$ Faster eddies $\Rightarrow$
    Poleward shift

- Change in phase speed spectra in recent shift in observations and models of SH:

![Graph showing faster eddies in observations and models.](image)
How will jet shift in future?

- Ozone hole expected to recover (equatorward shift?)
- Moisture content will increase more (poleward shift?)
- Tropopause height will increase more (poleward shift?)
How will jet shift in future?

- CMIP models show continuing poleward shift (e.g., Lu et al 2007)
- Models with ozone recovery show less poleward shift (Son et al 2008)
- Better theoretical understanding would improve our confidence in these expectations
EP Fluxes in Observations

- NH winter:
- NH summer:

Edmon et al 1980
EP Fluxes in HS model

- HS model:

Vallis book

Fig. 12.17 The Eliassen-Palm flux in an idealized primitive equation of the atmosphere. (a) The EP flux (arrows) and its divergence (contours, with intervals of 2 m s$^{-1}$ day$^{-1}$). The solid contours denote flux divergence, a positive PV flux, and eastward flow acceleration; the dashed contours denote flux convergence and deceleration. (b) The EP flux (arrows) and the time and zonally averaged zonal wind (contours). See the appendix for details of plotting EP fluxes.
EP Fluxes

- Observed EP Divergence (separated into momentum and heat flux components) and zonal winds
Eliassen-Palm Fluxes

- EP fluxes in Eady problem:

Fig. 7.2 The Eliassen-Palm vector in the Eady problem.

Vallis book
Eady problem

- Zonal wind and buoyancy tendencies in Eady problem:

![Diagram showing zonal flow tendency and buoyancy tendency](image)

**Fig. 7.5** (a) The tendency of the zonal mean flow (\(\partial \overline{u} / \partial t\)) just below the upper lid (dashed) and just above the surface (solid) in the Eady problem. The vertically integrated tendency is zero. (b) The vertically averaged buoyancy tendency.
EP Fluxes in Baroclinic Lifecycles

- Zonal wind and buoyancy tendencies in Simmons & Hoskins baroclinic lifecycle calculations:

From Edmon et al (1980)
TEM Residual Circulation

- Residual circulation in observations:

Vallis book
Alternative “Lagrangian” circulations

- Circulation on dry isentropes:
  - Annual mean
  - DJF

From Pauluis et al (J Climate 2009, see also Pauluis et al 2008, Science)
Alternative “Lagrangian” circulations

- **Circulation on moist isentropes:**
  - Annual mean
  - DJF

Moist circulation is slower in tropics, stronger in midlats
Large amounts of convection occurs within midlatitude storm tracks

From Pauluis et al (J Climate 2009, see also Pauluis et al 2008, Science)
Schematic of Lagrangian Circulation

- From Pauluis et al 2008 (Science):
What else happens in those aquaplanet simulations?

- From Caballero and Langen (2005):

  - Eddy velocity scale
  - Latitude of storm track
  - Eady growth rate

  With warmer temperatures:
  - Eddy kinetic energy stays similar
  - Storm track shifts poleward
  - Eady growth rate gets weaker
Static Stability Changes

- Eady growth rate changes are due to *increases in midlatitude static stability*:

  ![Graphs showing static stability changes](image)

  - Full GCM
  - Dry stability and moist stability averaged over baroclinic zone
  - Idealized moist GCM

  From Frierson (2008)
Static Stability Changes

- Dry static energy, idealized GCM simulations:

- Static stability $\left(\frac{d\theta}{dz}\right)$ increases in tropics (as expected)

From Frierson, Held and Zurita-Gotor (2006)
Static Stability Changes

- Dry static energy, idealized GCM simulations:

  ![Graph showing static stability changes](image)

  - ~Zero stability
  - High stability

- Static stability also increases in midlatitudes (surprisingly)

From Frierson, Held and Zurita-Gotor (2006)
Static Stability Changes

- Dry static energy, idealized GCM simulations:

  - Polar static stability is largely unchanged

From Frierson, Held and Zurita-Gotor (2006)
Moisture Effects on Midlatitude Stability

- Moist convection (possibly slantwise) occurs within frontal regions in baroclinic eddies (Emanuel 1988)
- Mean moist stability is expected to be stable though
- Scaling theory of Juckes (2000): bulk moist stability proportional to surface standard deviation

Moist baroclinic lifecycle simulations (with Ed Gerber and Lorenzo Polvani)
Convection in the Dry Limit

- In dry limit, only convection is due to the boundary layer
  - This has a well-defined depth, the PBL depth
- Instantaneous time slice of PBL depth:

Convection frequently occurs up to the tropopause in midlatitudes
Convection in the Dry Limit

- In dry limit, only convection is due to the boundary layer (up to the PBL depth)
- PDF of PBL depth:

  Convection is always up to the tropopause in the tropics
  Convection frequently occurs up to the tropopause in midlatitudes
  Convection is never deep in high latitudes

From Frierson, Held & Zurita-Gotor 2006
Testing the Juckes scaling

- Vary mean SST (from 0 to 35°C) and temperature gradients (from 10-60 K) in 24 experiments with the simplified GCM
- Moist scaling relation:

From Frierson (2008)
Static Stability in Aquaplanet Full GCM

- Vary mean SST (from 0 to 35 °C) and temperature gradients (from 10-60 K) in 70 full GCM experiments
- Midlatitude dry stabilities and moist scaling relation:

From Frierson (2008)
Temperature Changes: IPCC Models

- Next, look at global warming simulations (21 models)
- *Change* in potential temperature is plotted here:

Tropical upper tropospheric warming (due to moisture)

From Frierson (2006)
Temperature Changes: IPCC Models

- Global warming simulations *change* in potential temp:

From Frierson (2006)
Temperature Changes: IPCC Models

- Global warming simulations change in potential temp:

Midlatitude static stability increases as well

From Frierson (2006)
Temperature Changes: IPCC Models

- Global warming simulations change in potential temp:
  - Clear increase in midlatitude static stability with global warming
    - Especially in Southern Hemisphere and in summer
    - Happens in 158 out of 160 model-season-hemispheres.

From Frierson (2006)
Equiv Potential Temp Change in IPCC Models

- AR4 simulations change in saturated equivalent potential temperature:

Over ocean only
Longitudinal Structure of Moist Stability Change

- Moist stability change in AR4 models:

Land causes biggest deviation from Juckes theory:
Over land and just downwind of land the stability changes are the least