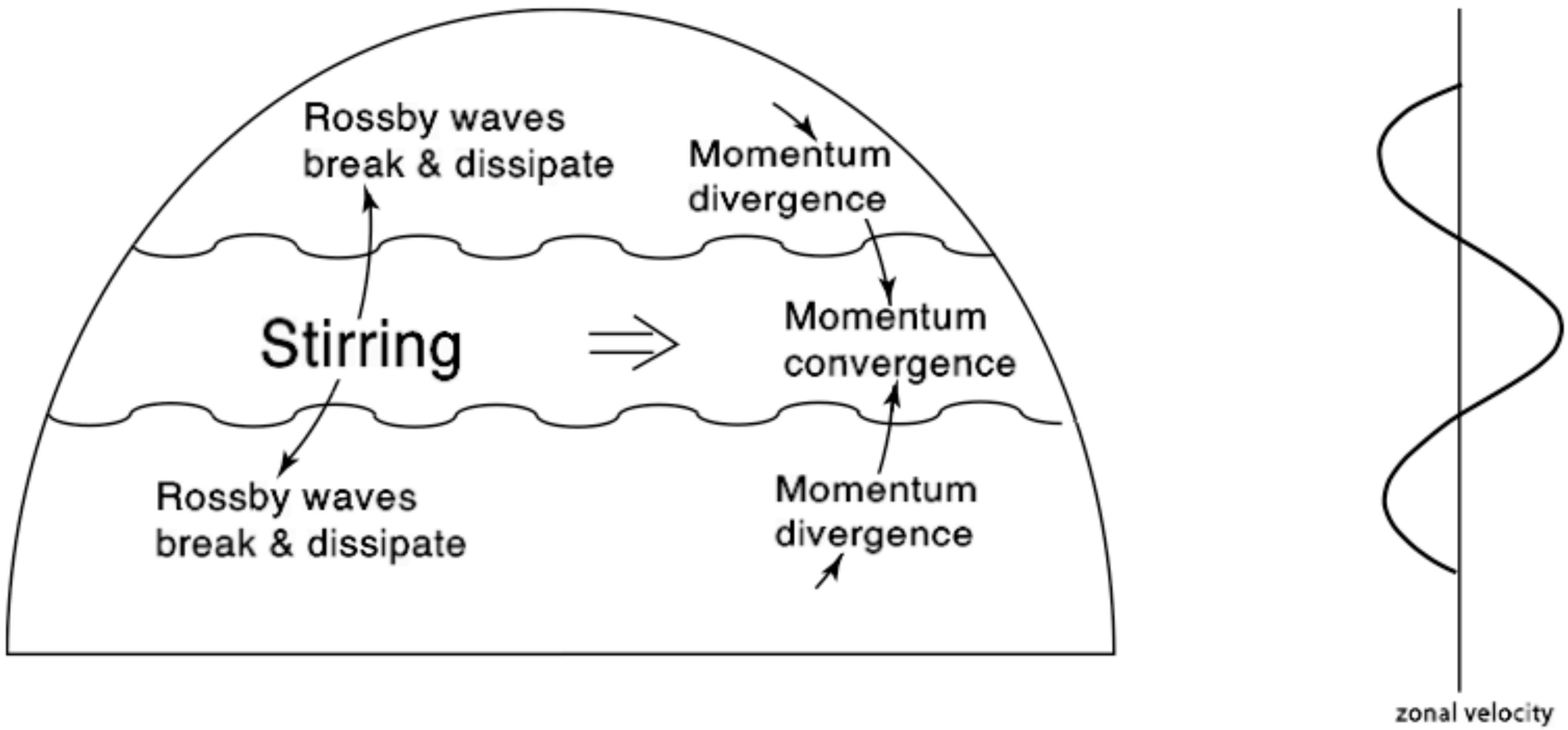
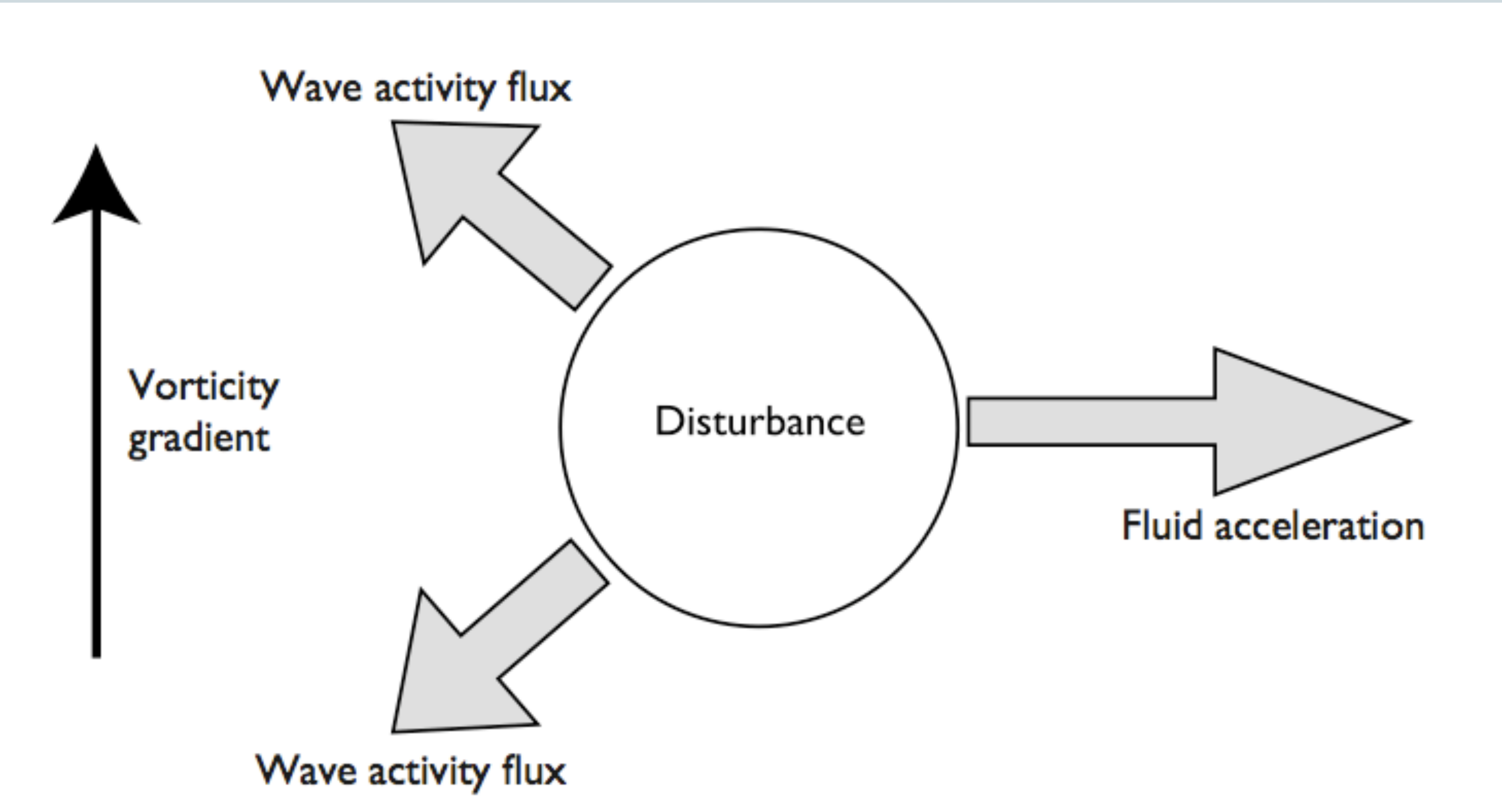
Rossby waves and the jet

- Schematic from Vallis:



Rossby waves and the jet

- Schematic from Vallis:



A Barotropic Model

- Stochastic stirring + linear damping

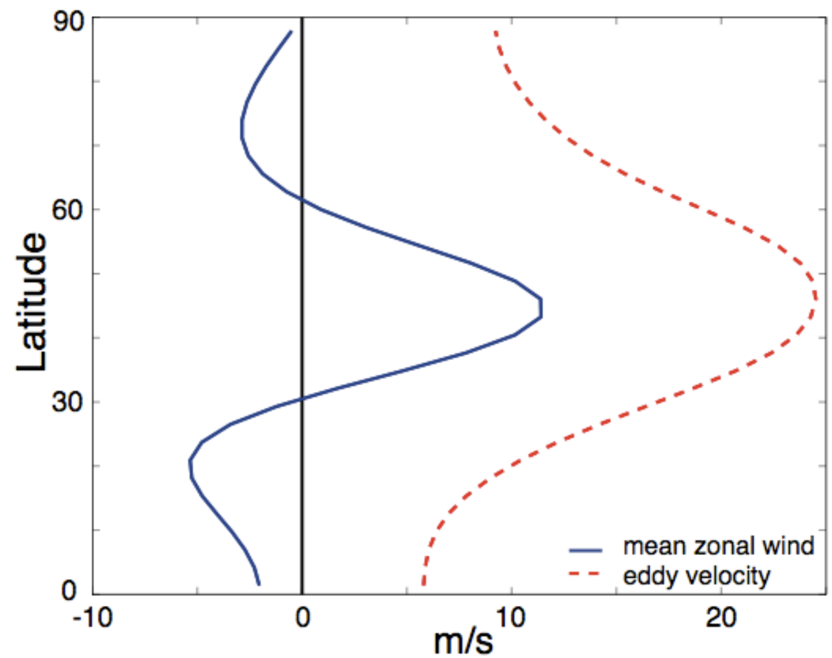


Fig. 12.7 The time and zonally averaged wind (solid line) obtained by an integration of the barotropic vorticity equation (12.37) on the sphere. The fluid is stirred in mid-latitudes by a random wavemaker that is statistically zonally uniform, acting around zonal wavenumber 8, and that supplies no net momentum. Momentum converges in the stirring region leading to an eastward jet with a westward flow to either side, and zero area-weighted spatially integrated velocity. The dashed line shows the r.m.s. (eddy) velocity created by the stirring.

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):

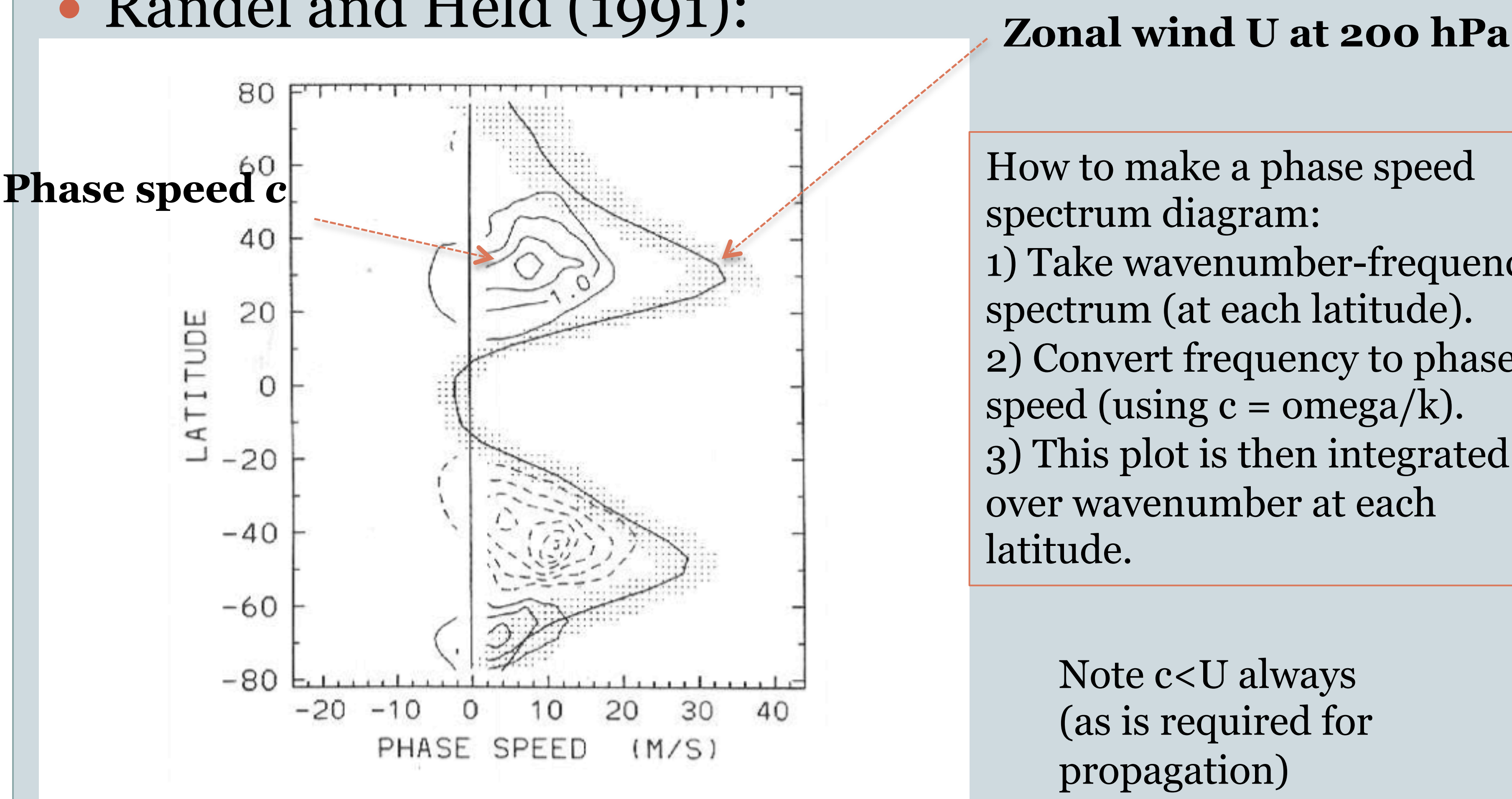


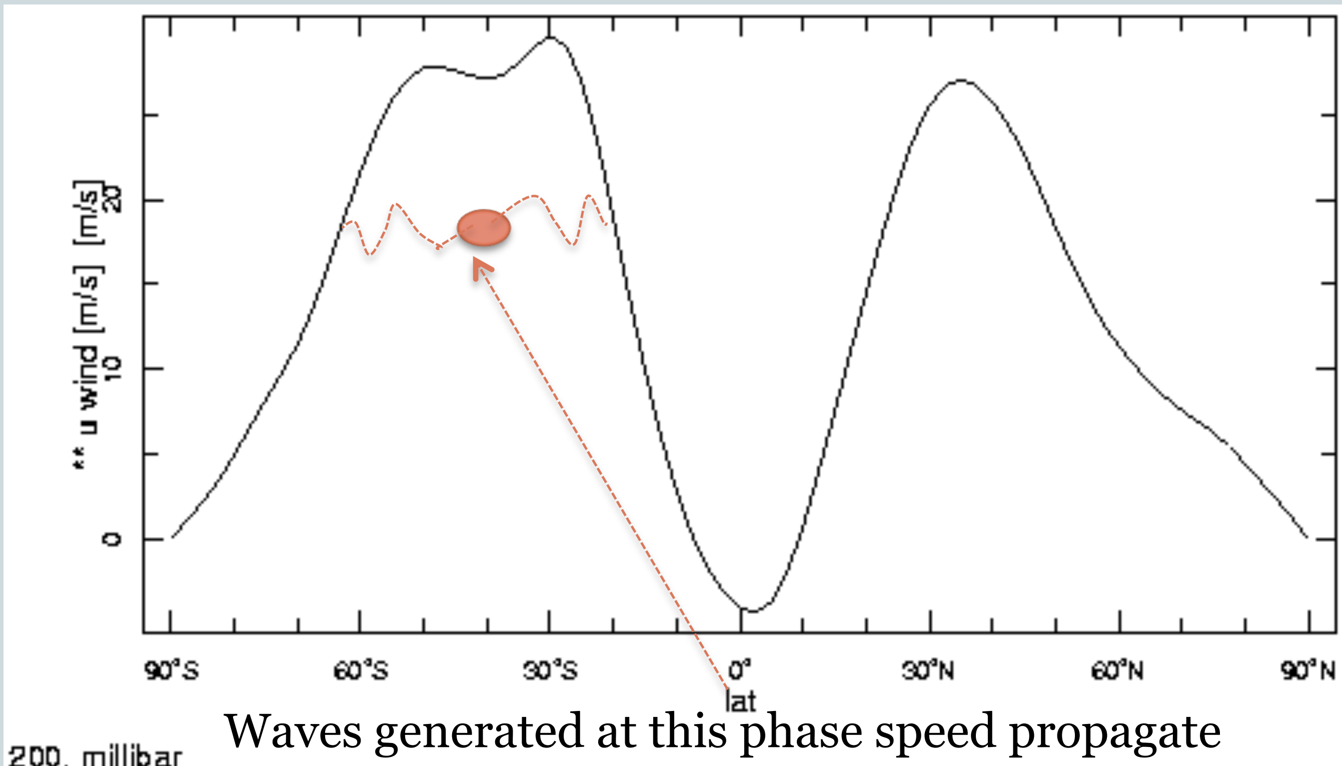
Figure 4: Phase speed spectrum of eddy momentum flux, $\overline{u'v'}$ at 200mb,

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

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

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):

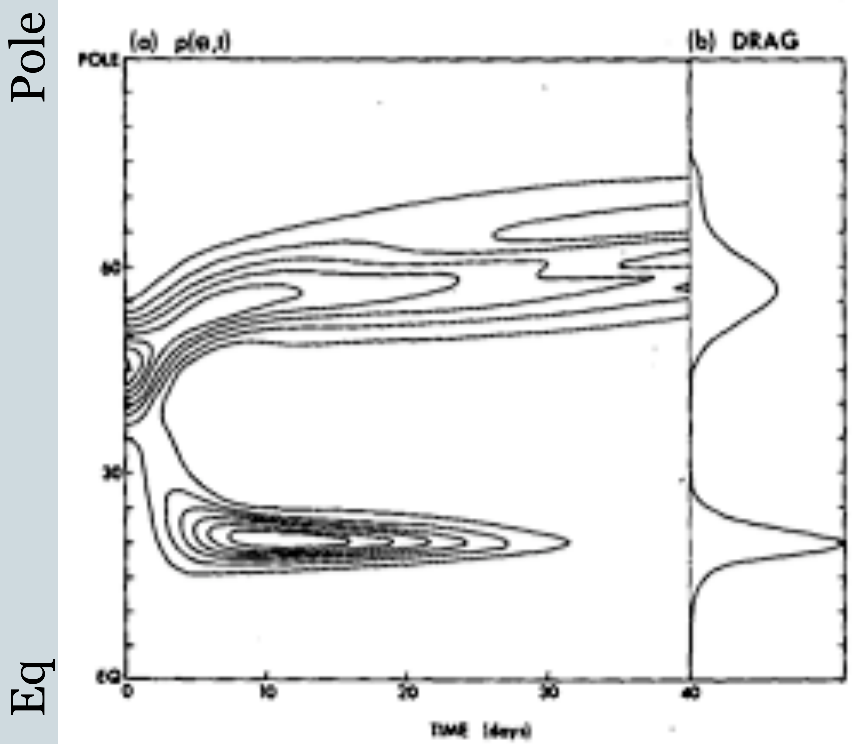


FIG. 2. The evolution of the pseudomomentum density $p(\theta, t)$ (left) and the final zonal flow deceleration (right) obtained from the integration of (1) with small linear diffusion added. The latter is computed from the final term in (5).

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

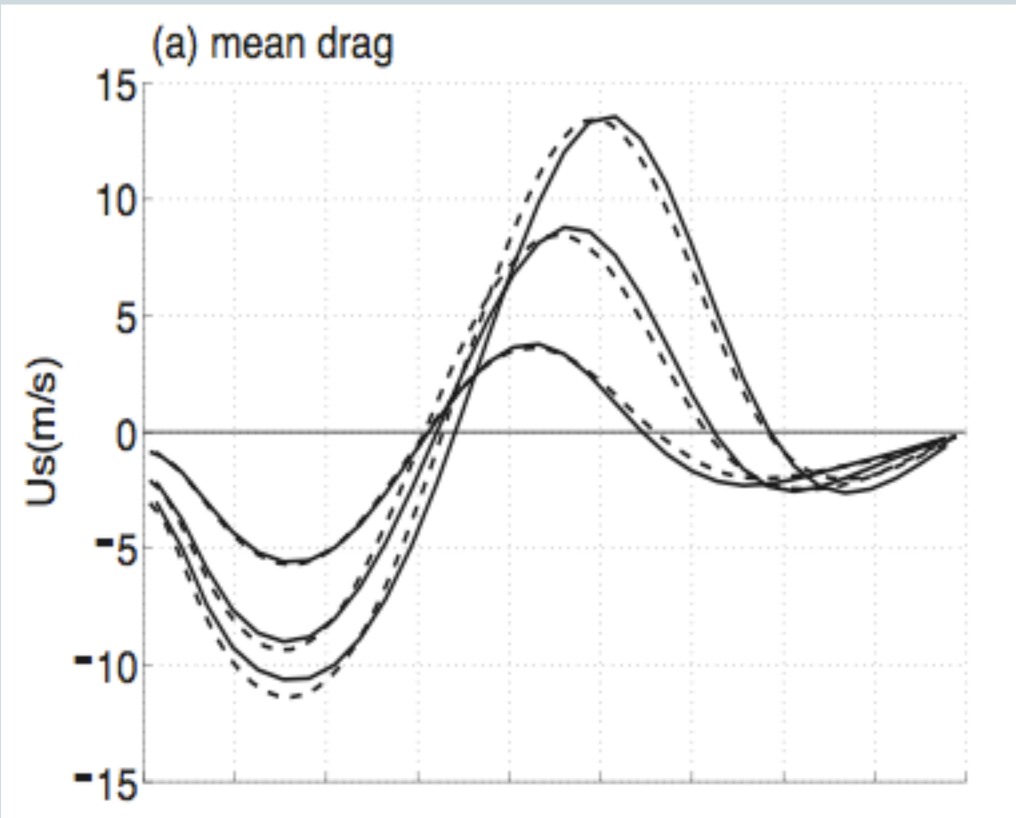
Left: evolution of pseudomomentum

Right: deceleration at the end

Drag occurs near critical latitude (but spread around more)

Changing Surface Friction in Held-Suarez

- From Chen, Held & Robinson (2007):



Equator

Latitude

Pole

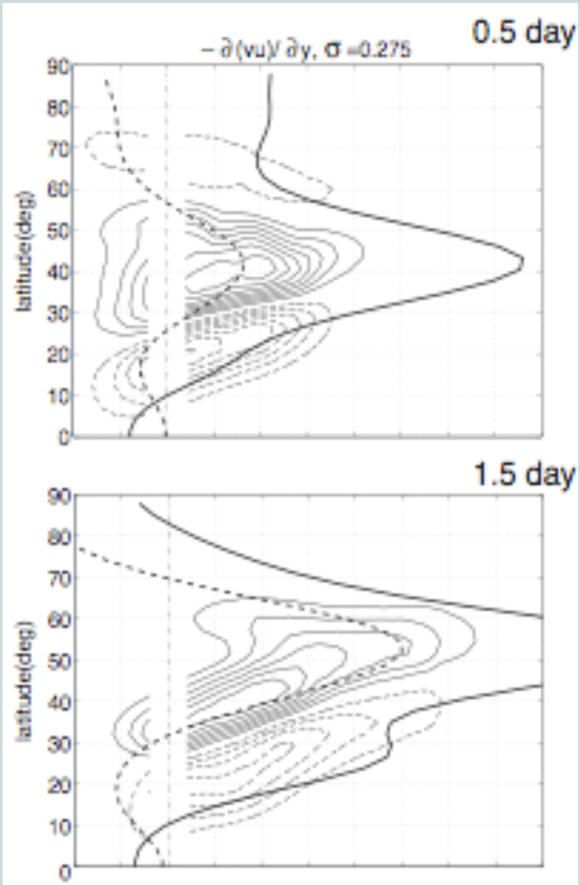
Reducing friction in H-S model causes a poleward shift of the surface westerlies

Changing Surface Friction in Held-Suarez

- From Chen, Held & Robinson (2007):

Strong drag

Weak drag



Wind speed

• Phase speed increases with weaker drag

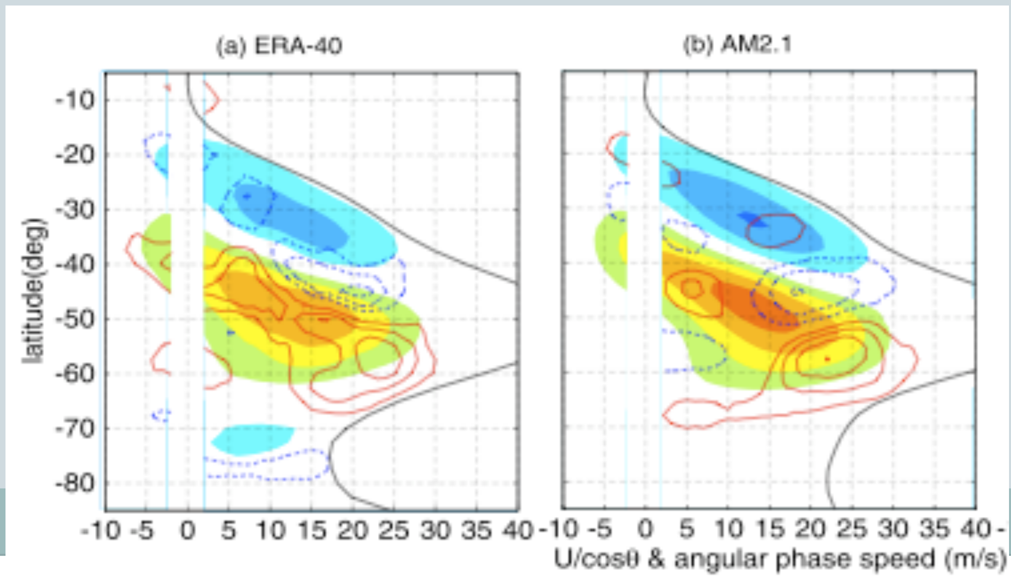
• Faster phase speed =>
Eddies don't make it as far into tropics =>
Poleward shift of breaking

• 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 => cooling the polar stratosphere => Stronger winds in lower stratosphere => Faster eddies => Poleward shift
- Change in phase speed spectra in recent shift in observations and models of SH:



Faster eddies
in obs and
in model

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?)

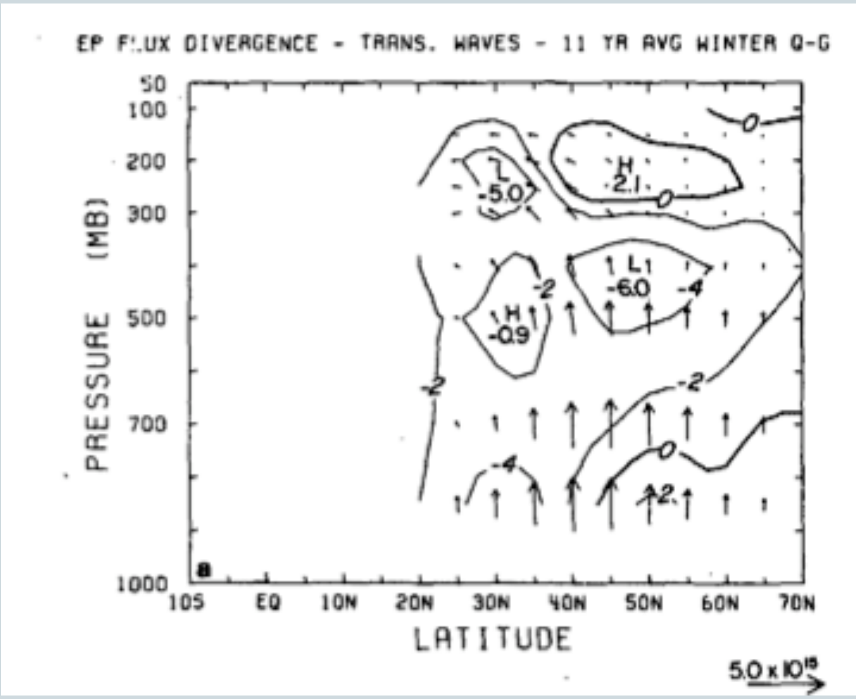
How will jet shift in future?

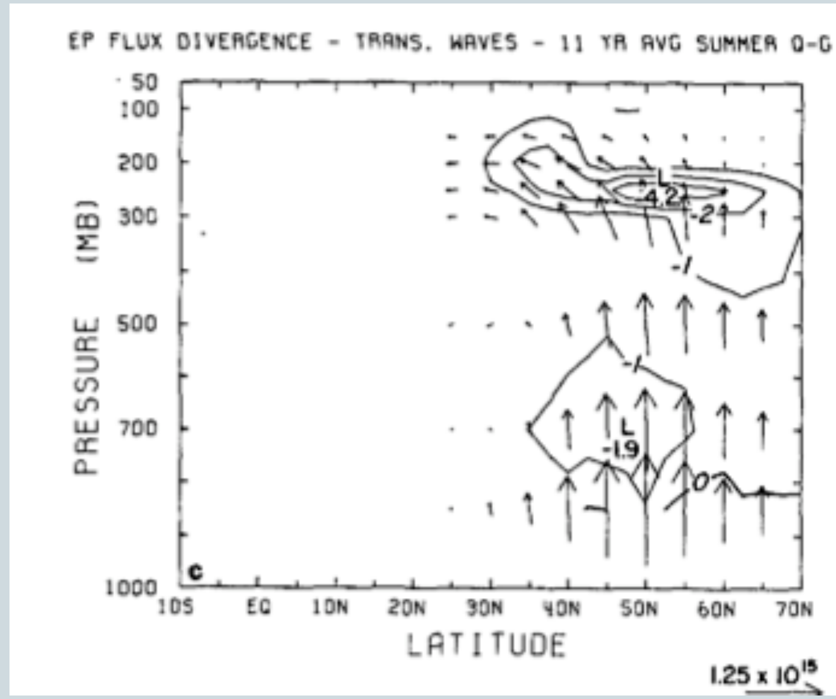
- CMIP models show continuing poleward shift (e.g., Lu et al 2007)
- Models with ozone recovery show less poleward shift (Son et al 2008)
- Better theoretical understanding would improve our confidence in these expectations

EP Fluxes in Observations

- NH winter:

NH summer:





Edmon et al 1980

EP Fluxes in HS model

- HS model:

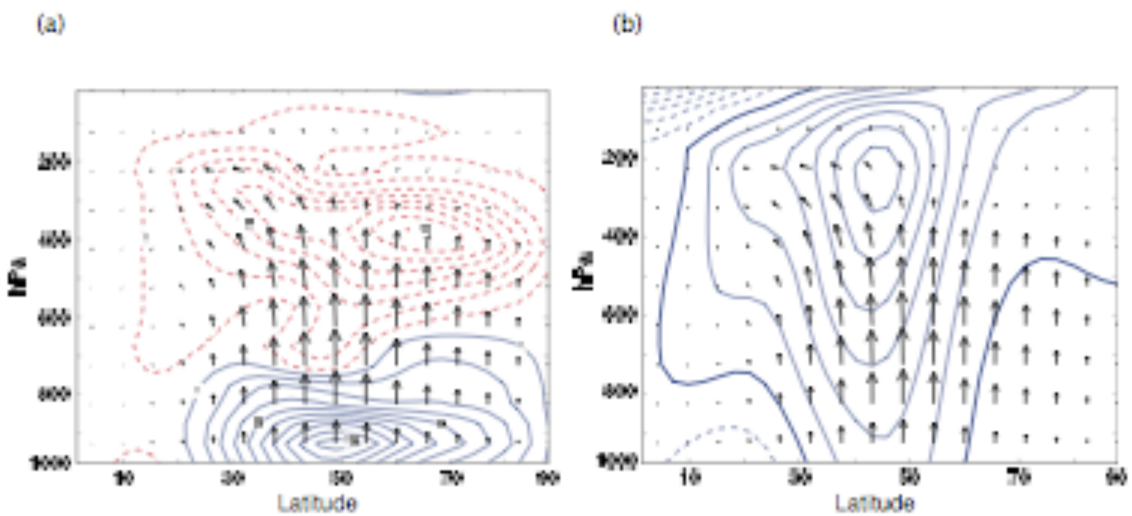


Fig. 12.17 The Eliassen-Palm flux in an idealized primitive equation of the atmosphere. (a) The EP flux (arrows) and its divergence (contours, with intervals of $2\,\mathrm{m\,s^{-1}}$/day). The solid contours denote flux divergence, a positive PV flux, and eastward flow acceleration; the dashed contours 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.

Vallis book

EP Fluxes

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

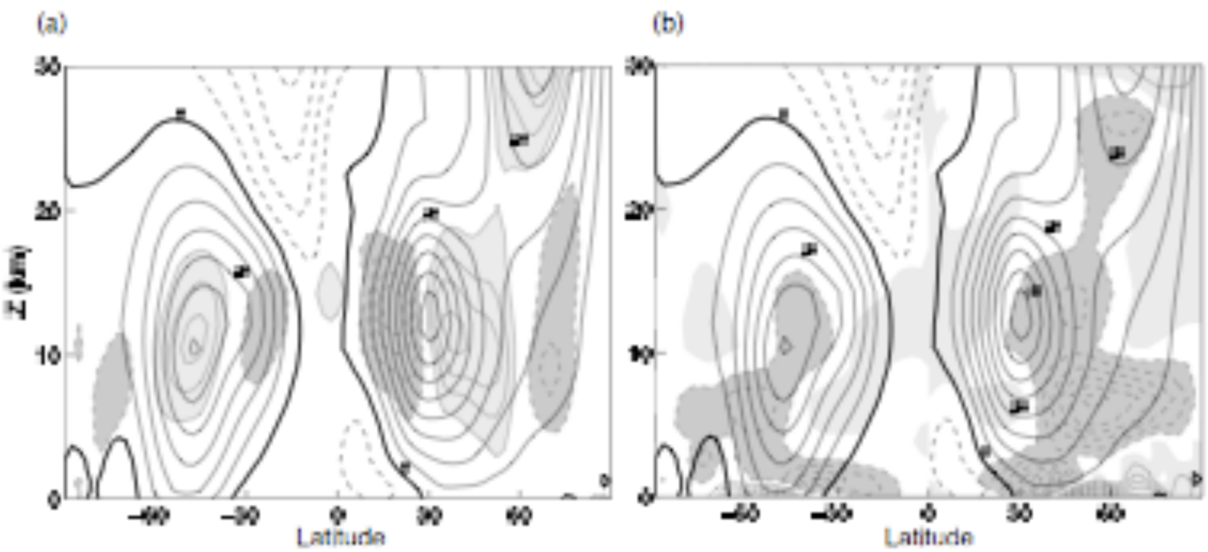


Fig. 12.20 The divergence of the two components of the EP flux (shaded), and the zonally averaged zonal wind (thicker contours) for DJF. (a) The momentum fluxes, $-\partial_y \overline{u'v'}$, contour interval is $1\ \mathrm{m\,s^{-1}/day^{-1}}$, light shaded for positive values > 1, dark shaded for negative values < -1. (b) The buoyancy flux, $f\partial_z(\overline{v'b'}/N^2)$, with contour interval and shading convention as in Fig. 12.19.

Eliassen-Palm Fluxes

- EP fluxes in Eady problem:

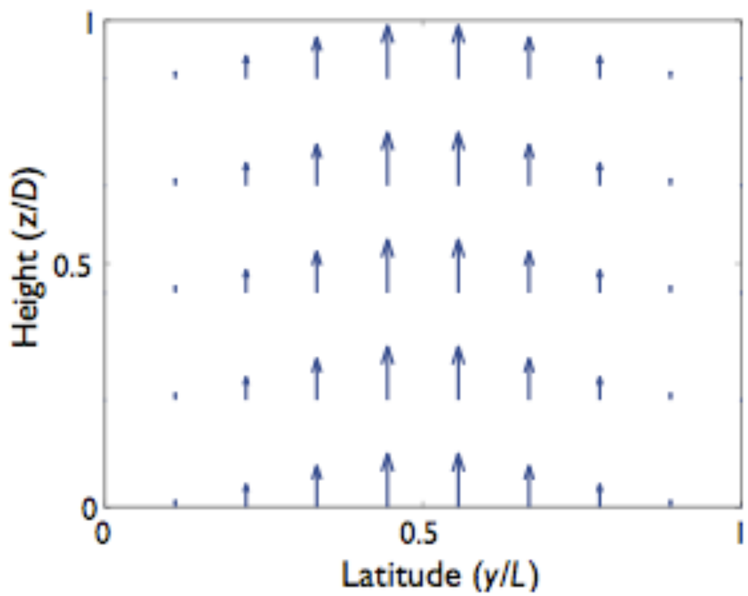


Fig. 7.2 The Eliassen-Palm vector in the Eady problem.

Vallis book

Eady problem

- Zonal wind and buoyancy tendencies in Eady problem:

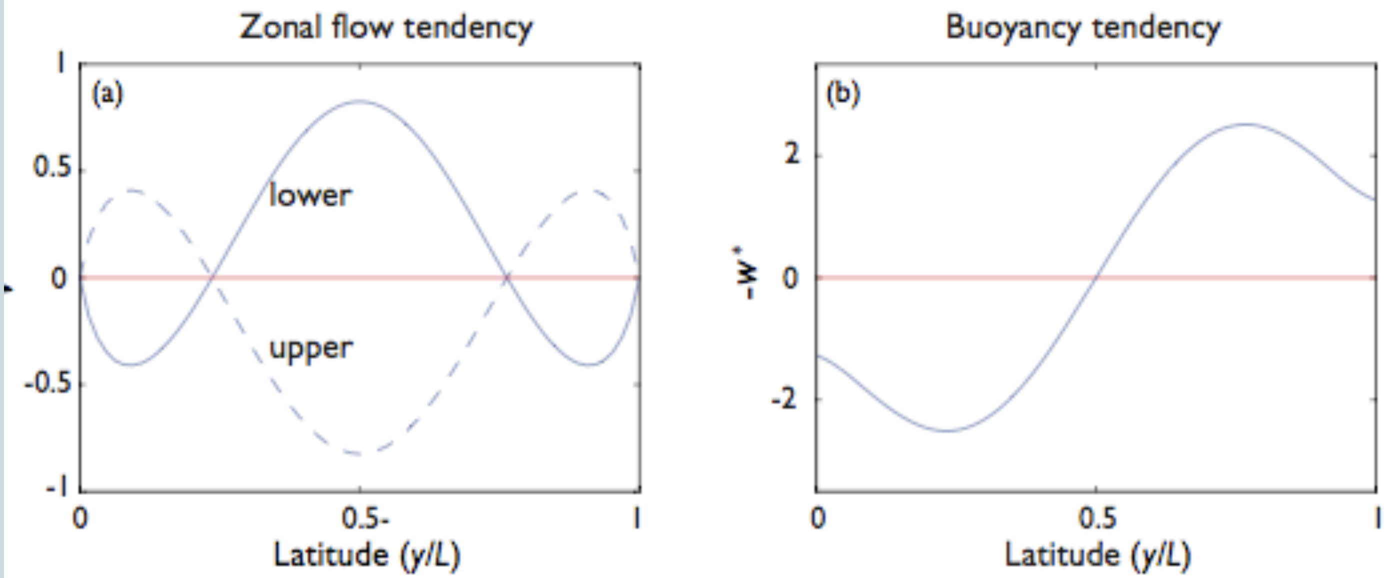


Fig. 7.5 (a) The tendency of the zonal mean flow ($\partial \overline{u} / \partial t$) just below the upper lid (dashed) and just above the surface (solid) in the Eady problem. The vertically integrated tendency is zero. (b) The vertically averaged buoyancy tendency.

EP Fluxes in Baroclinic Lifecycles

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

From Edmon et al (1980)

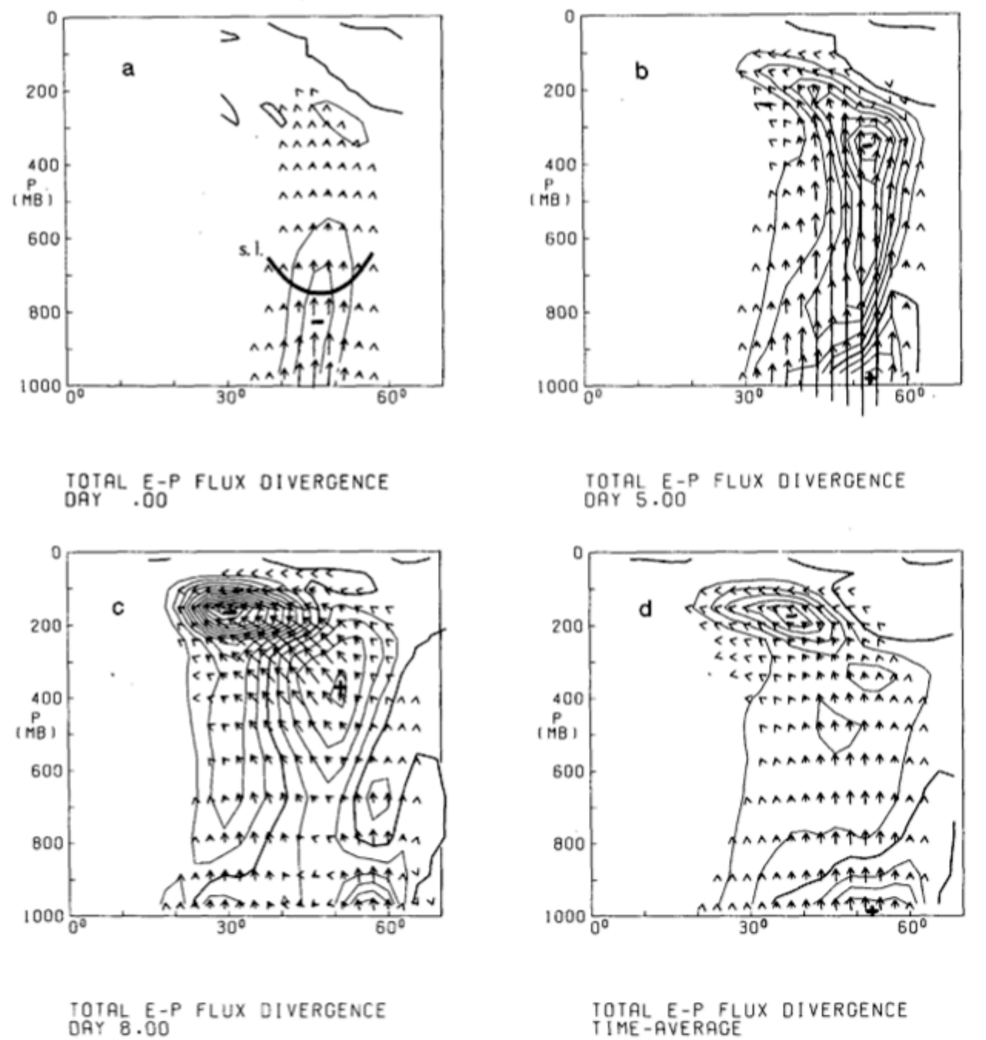
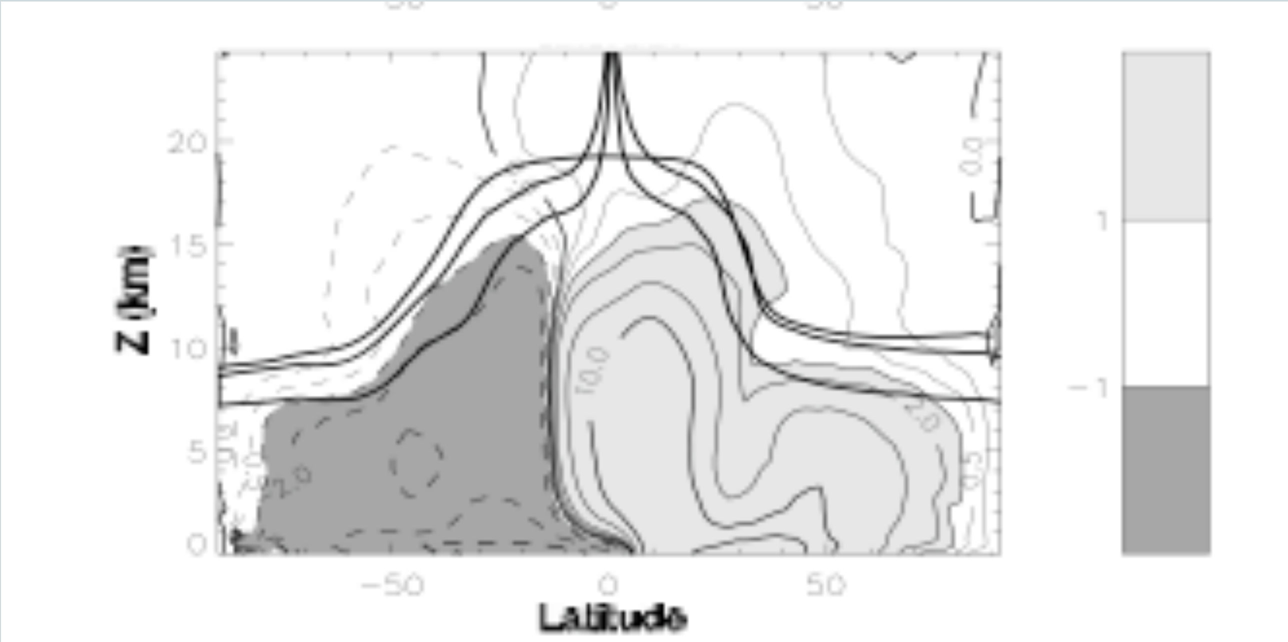


FIG. 3. (a) Eliassen-Palm cross section for a linear, growing baroclinic instability on a realistic mean state [the first case studied in Simmons and Hoskins (1980); (b), (c) cross sections for two stages in the life cycle of the same disturbance after it goes nonlinear; (d) time-averaged cross section for the life cycle. The contour interval is 4×10^{15} m^3 for (b) and (c), and 1.5×10^{15} m^3 for (d). The arrow scales are the same in all three, and such that the distance occupied by 10° of latitude represents a value 12.5×10^{15} m^3 of $\hat{F}_{(\varphi)}$, and that occupied by 100 mb represents a value 7150×10^{15} m^3 mb, or 715×10^{15} m^3 kPa, of $\hat{F}_{(p)}$.

TEM Residual Circulation

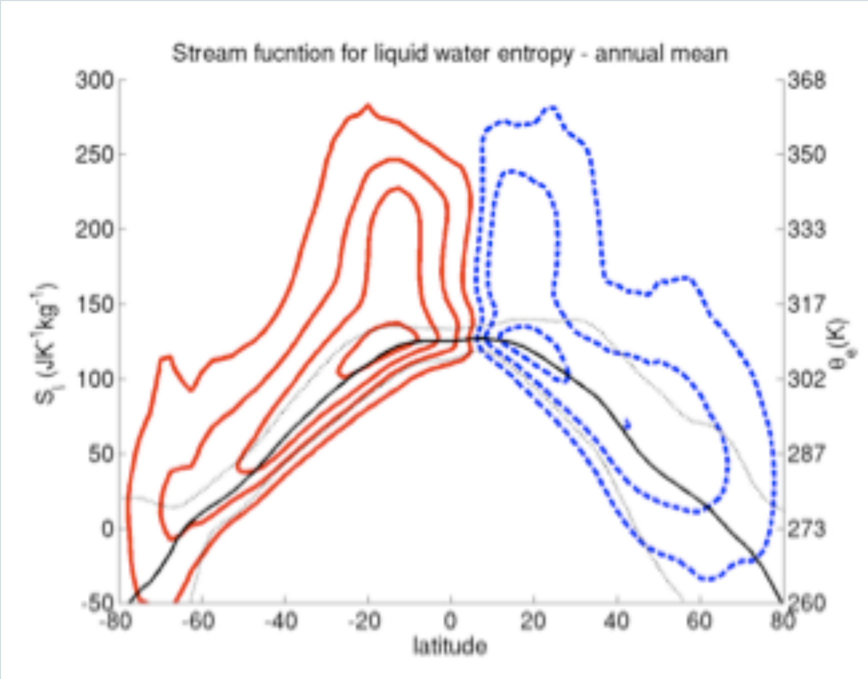
- Residual circulation in observations:



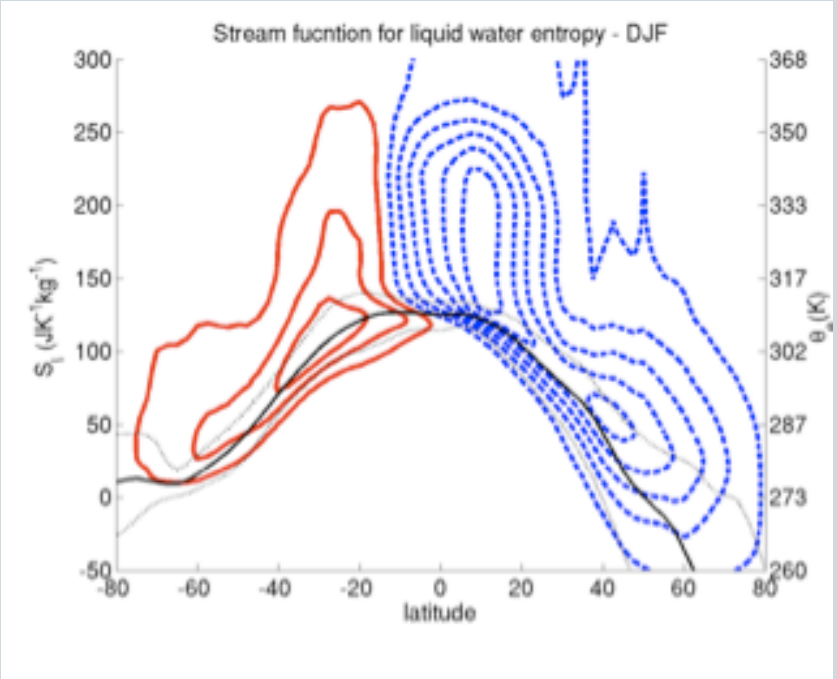
Alternative "Lagrangian" circulations

- Circulation on dry isentropes:

Annual mean



DJF

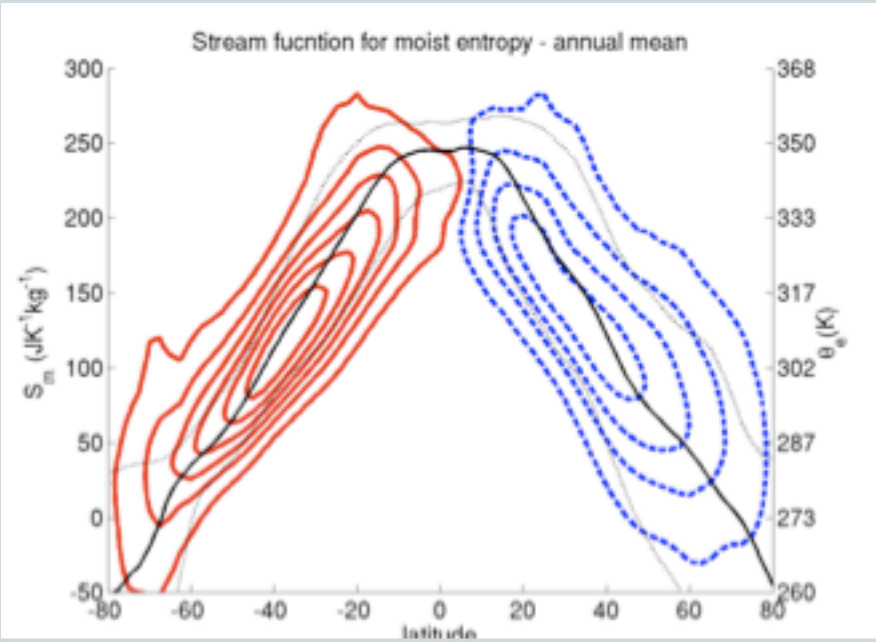


From Pauluis et al (J Climate 2009, see also Pauluis et al 2008, Science)

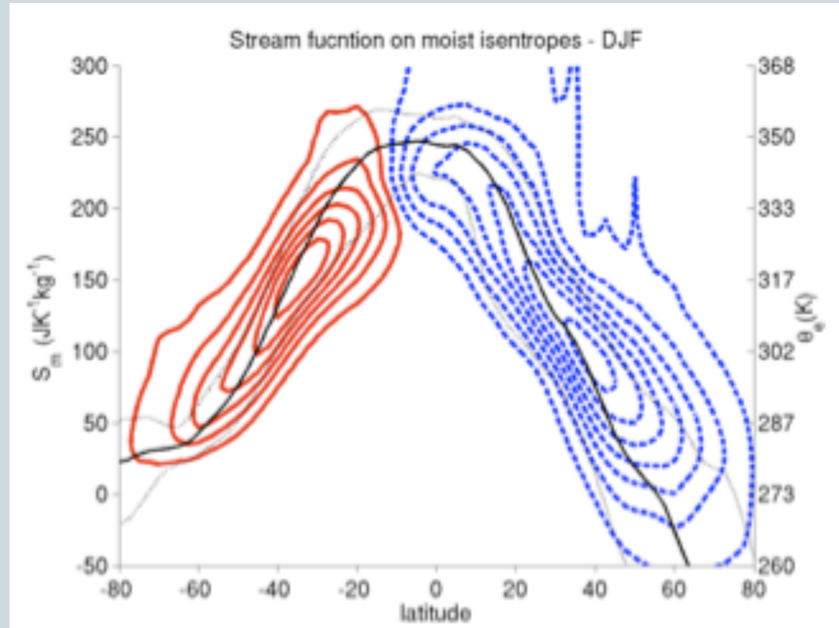
Alternative "Lagrangian" circulations

- Circulation on *moist* isentropes:

Annual mean



DJF

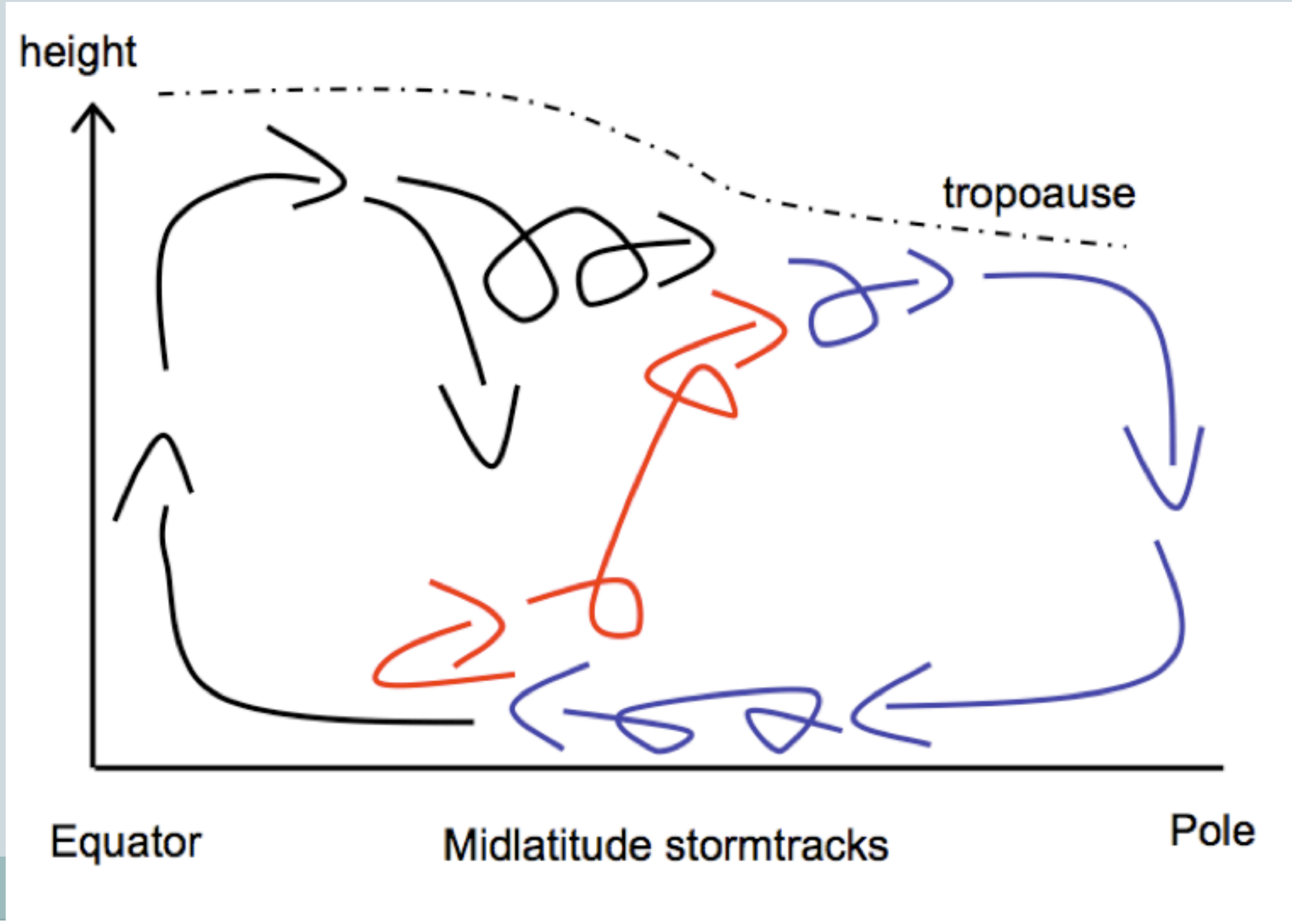


Moist circulation is slower in tropics, stronger in midlats
Large amounts of convection occurs within midlatitude storm tracks

From Pauluis et al (J Climate 2009, see also Pauluis et al 2008, Science)

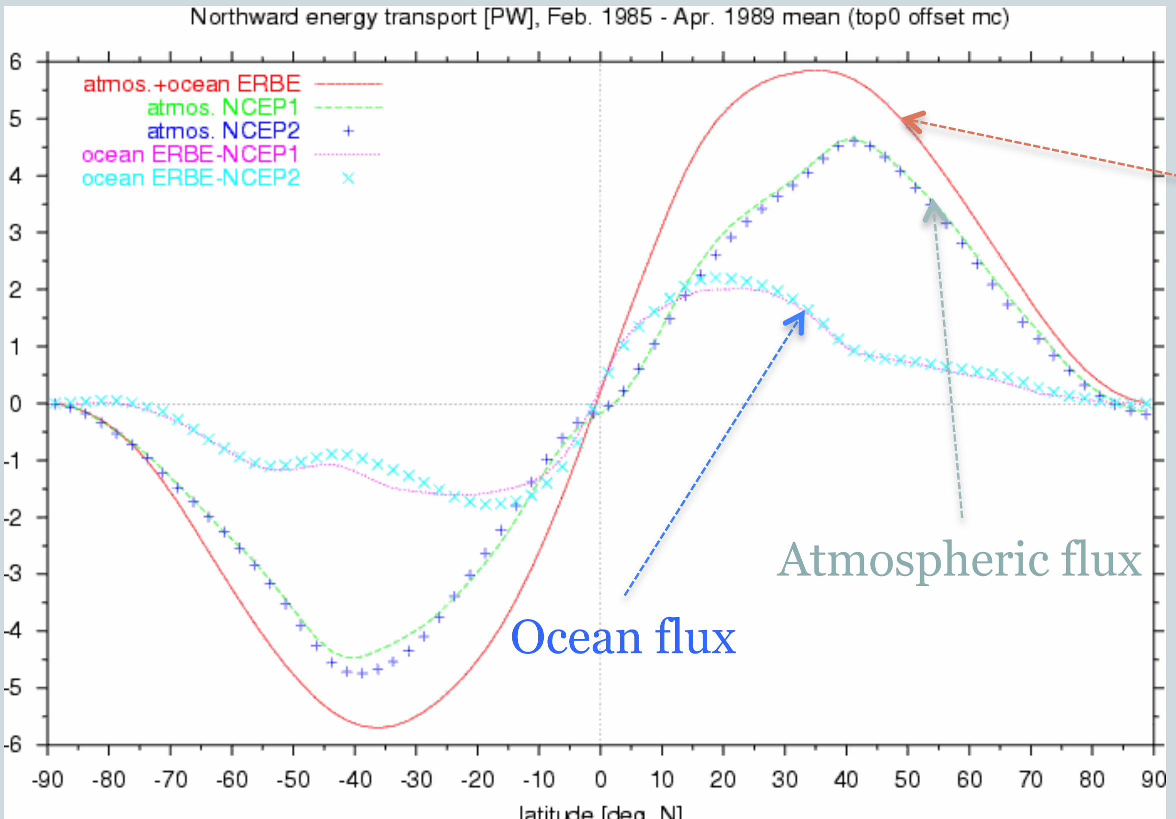
Schematic of Lagrangian Circulation

- From Pauluis et al 2008 (Science):



Next topic: Midlatitude Energy Fluxes

- Atmospheric and oceanic heat transports make temperature gradients significantly weaker

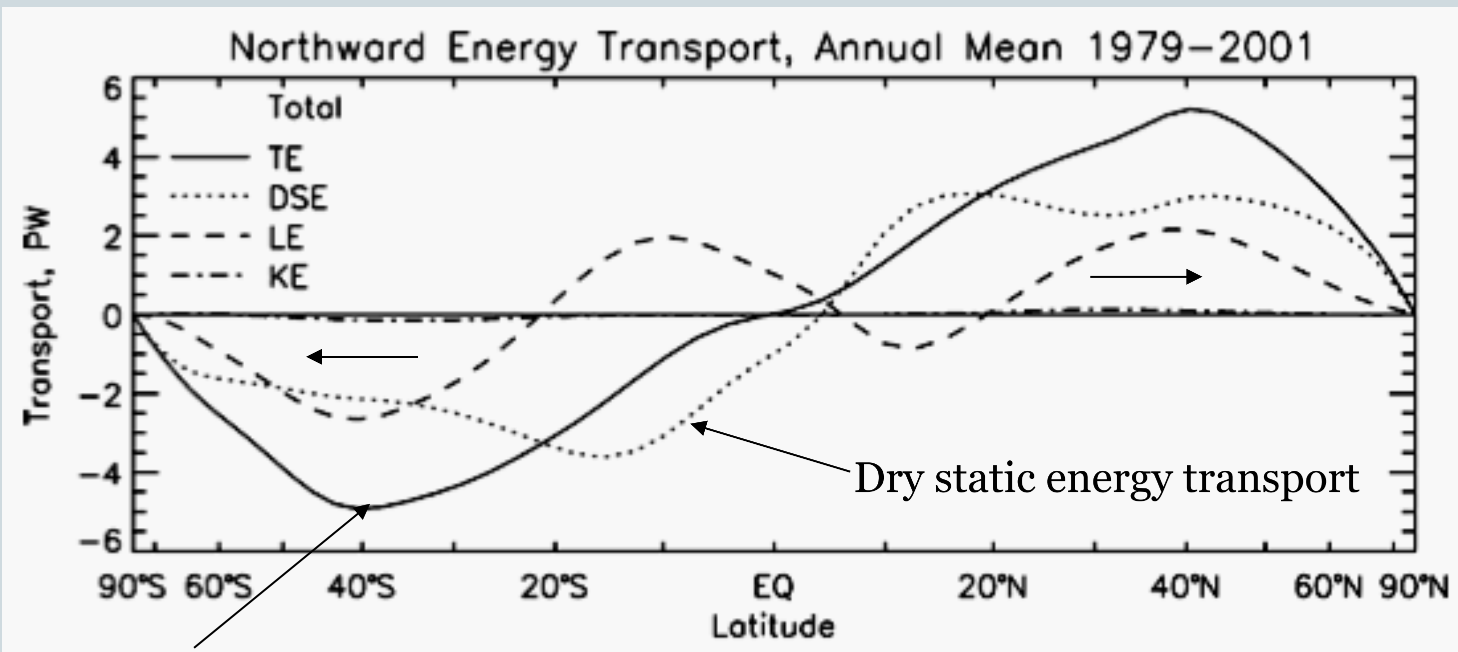


Latitude

Atmospheric transport dominates in extratropics

Extratropical Energy Fluxes

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



Total atmospheric 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 ξ by eddies: $\overline{v'\xi'}$

Overbar: time mean
Prime: deviation from time mean

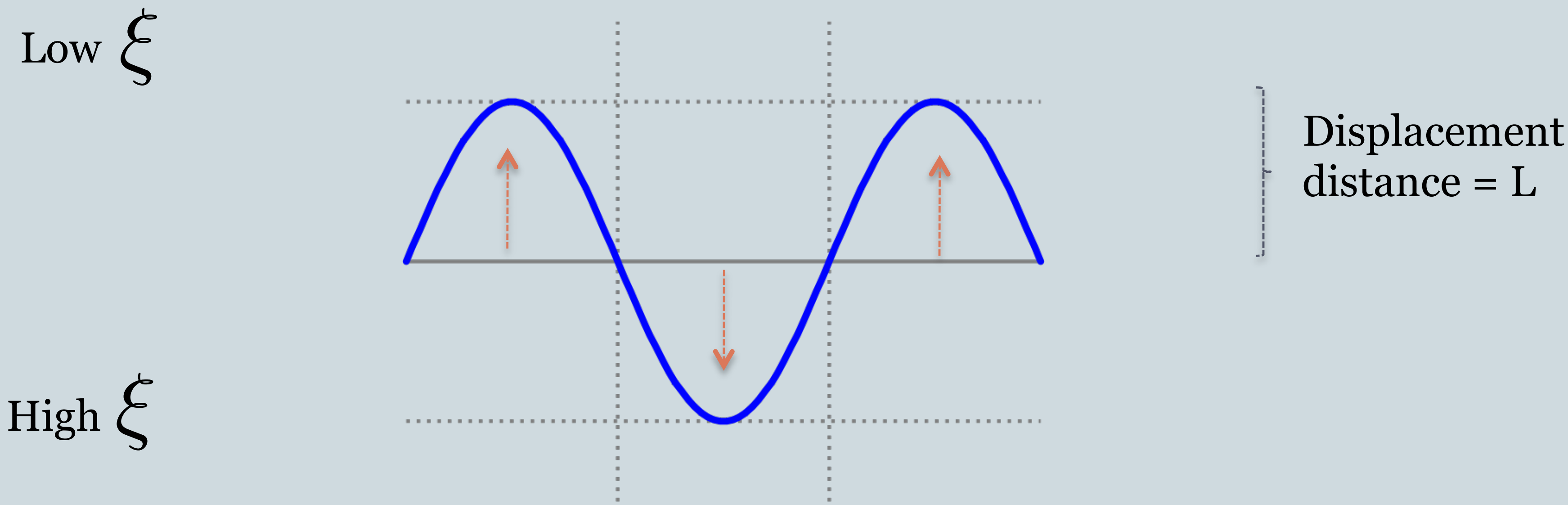
- First, write the flux as the product of the standard deviations of the quantities, and a correlation coefficient

$$\overline{v'\xi'} = k|v'||\xi'|$$

  - This can be considered to be the definition of the correlation coefficient

Mixing Length Theory

- Next, consider fluctuations of the scalar occuring within a mean gradient:



If ξ is conserved over its displacement, this generates fluctuations in ξ that are equal to

$$|\xi'| = -L\frac{\partial \xi}{\partial y}$$

Mixing Length Theory

- Combining, we have

$$\overline{v'\xi'} = k|v'||\xi'|$$
$$= -kL|v'|\frac{\partial \xi}{\partial y}$$

- Or, $\overline{v'\xi'} = -D\frac{\partial \xi}{\partial y}$ 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 $m = c_p T + gz + Lq$
- 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 ~ Rossby radius, V ~ mean jet strength
- Green (1970): L ~ baroclinic zone width, V from equipartition of APE and EKE
- Held and Larichev (1996): L ~ 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}

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

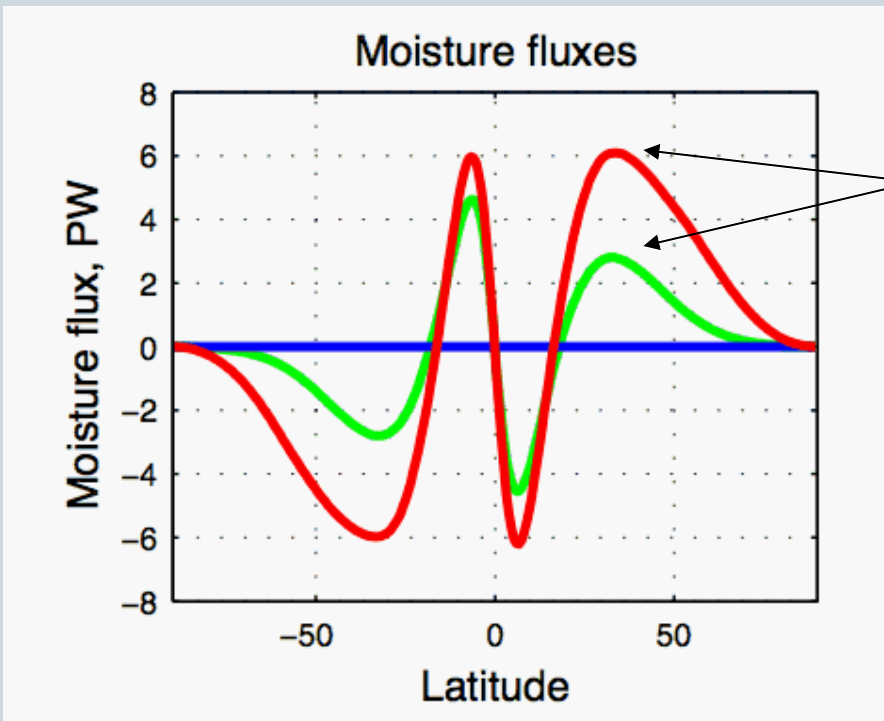
Control: $e_{s0} = 610.78\ Pa$

Dry limit: $e_{s0} = 0$

Up to: $e_{s0} = 6107.8\ Pa$ (10 times moisture)

Energy Fluxes

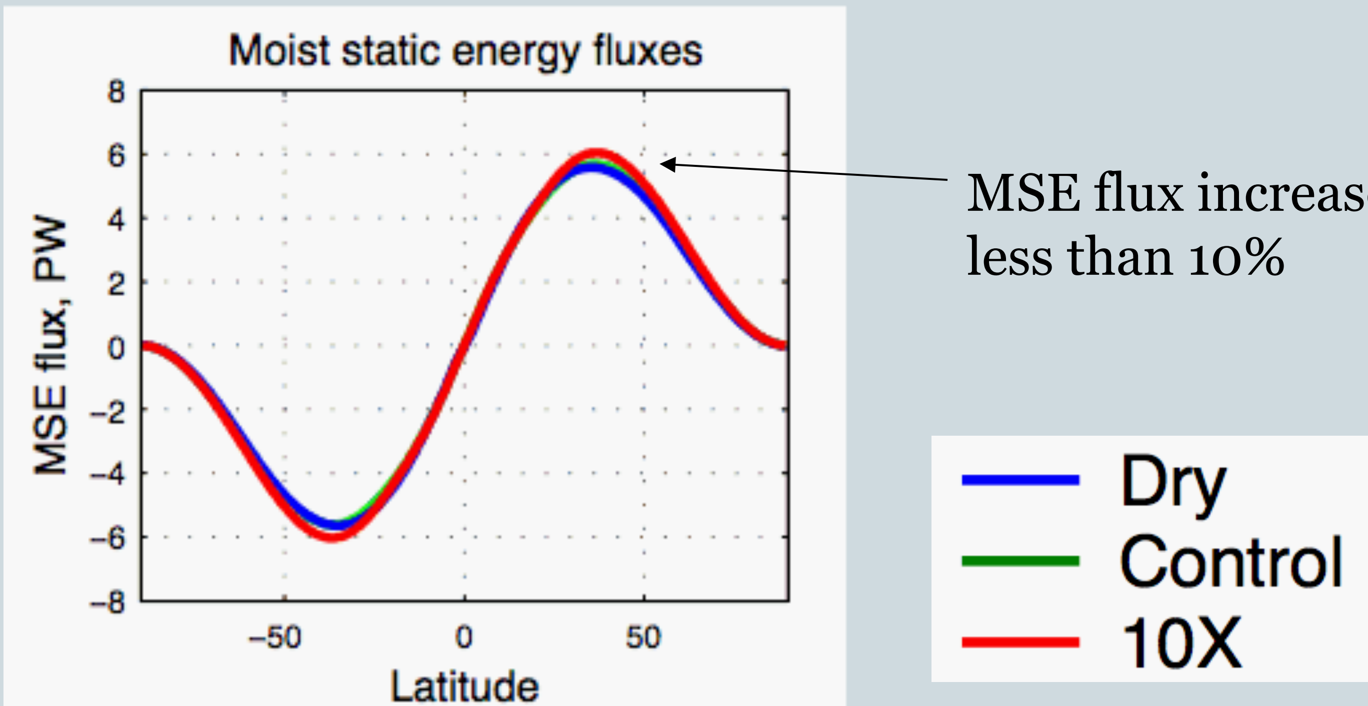
- Moisture fluxes in idealized simulations:



Significant increase in poleward moisture flux in midlatitudes

Energy Fluxes

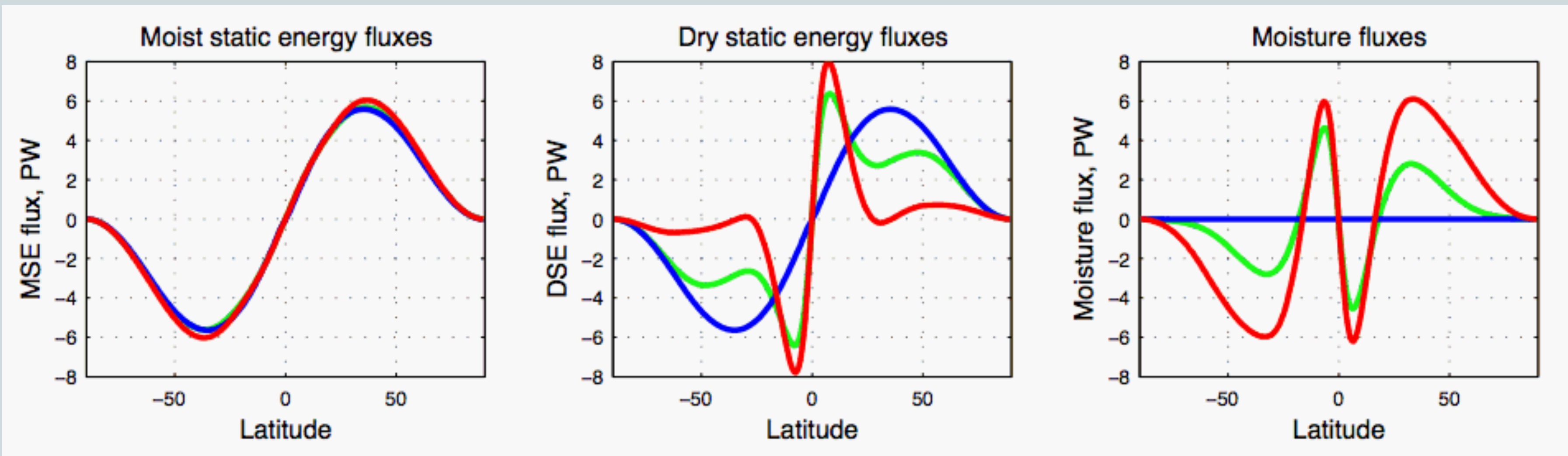
- Total atmospheric flux in idealized simulations:

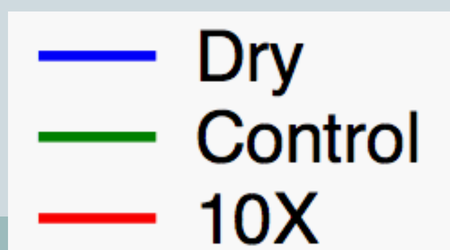


MSE flux increases by less than 10%

Energy Fluxes

- Fluxes in idealized simulations:





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 $m_E = m + \Delta_m$

$$\begin{aligned} T_E &= c_p^{-1}(m_E - g z_E - L q_E) \\ &= c_p^{-1}(m - g z_E + \Delta_m) \end{aligned}$$

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

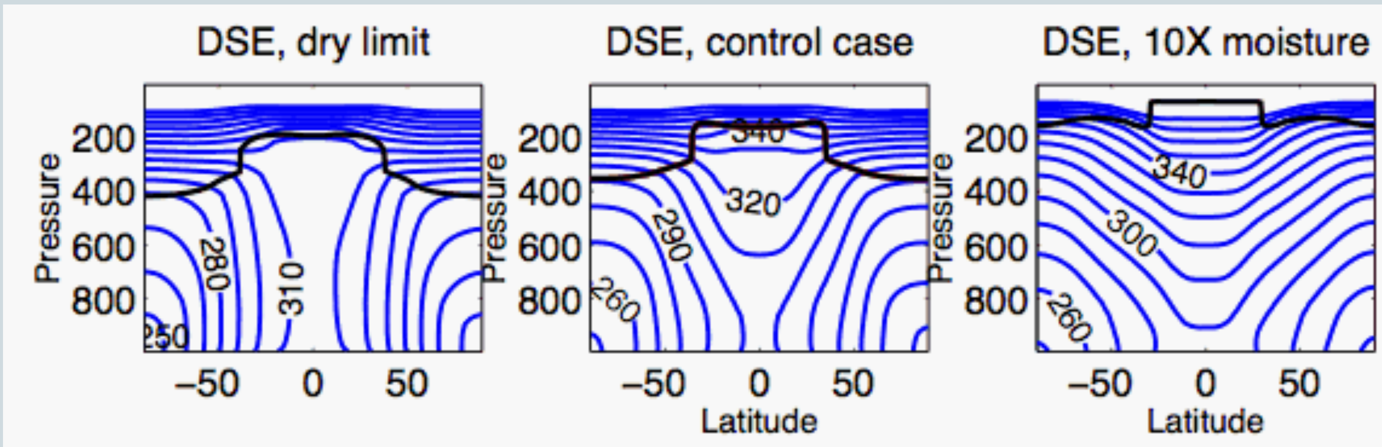
Independent of partition into dry and moist!

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

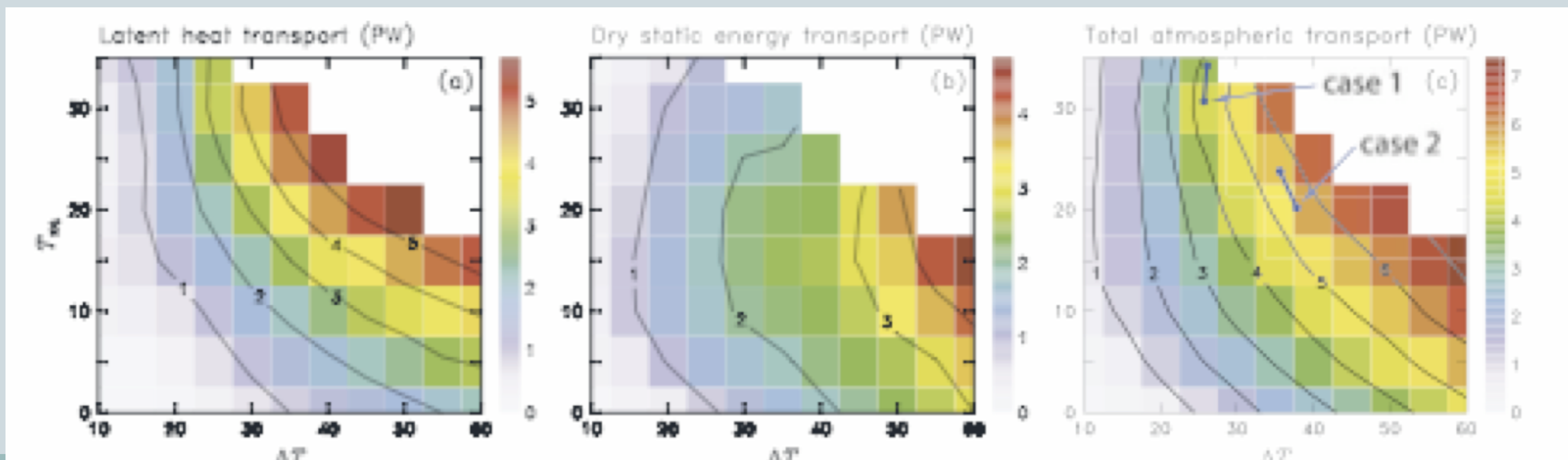
Testing Compensation Idea

- 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):

Moisture flux | Dry static energy flux | Total flux



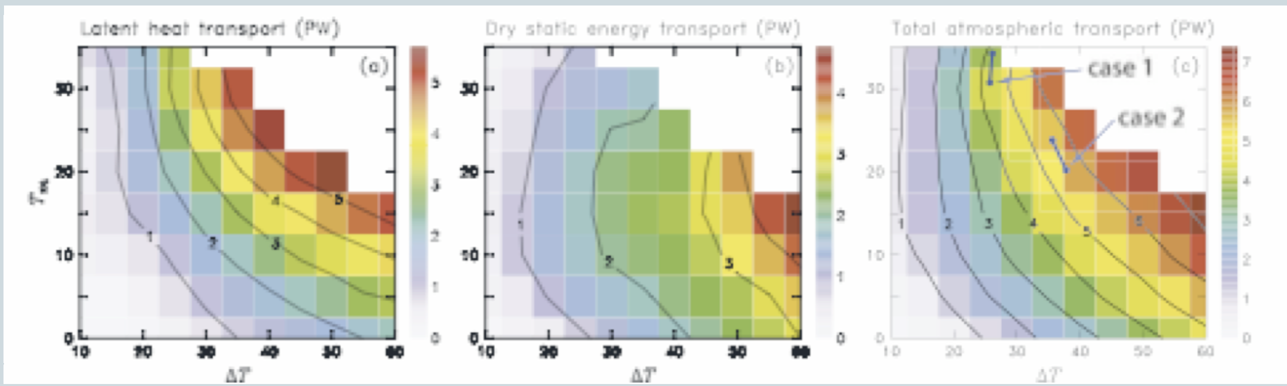
Hotter →

Increased gradient →

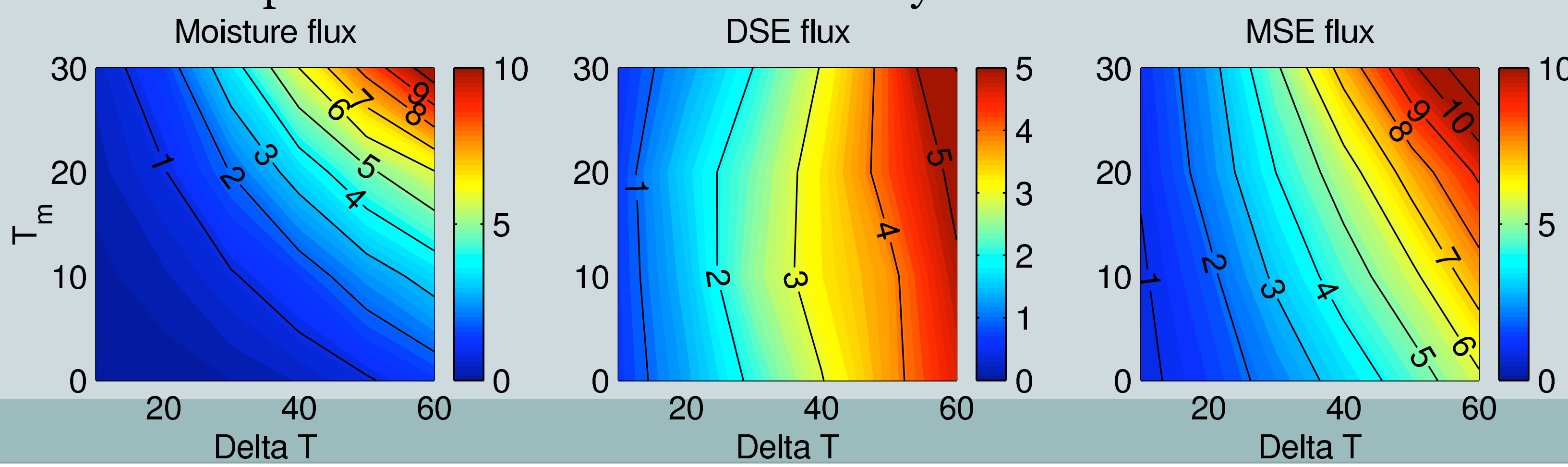
Aquaplanet Full GCM and Simplified Moist GCM

- Simulations of Caballero and Langen (2006):

Moisture flux Dry static energy flux Total flux



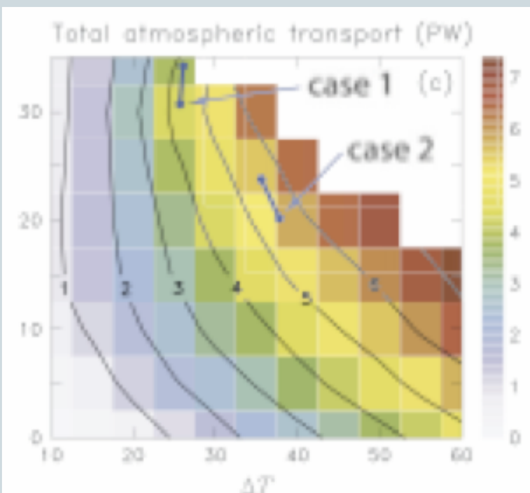
Simplified GCM over same boundary conditions:



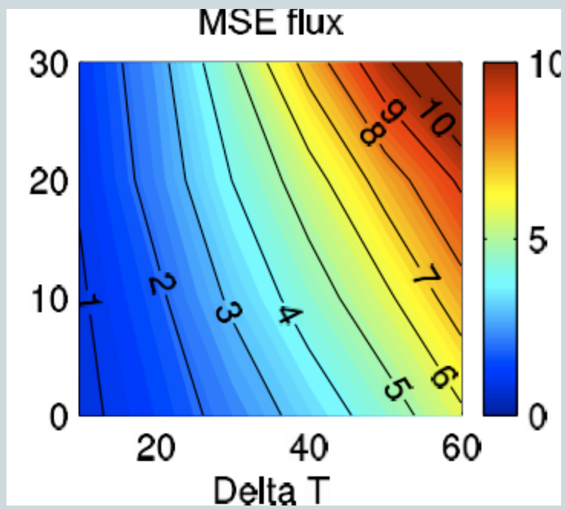
Aquaplanet GCMs and Moist EBMs

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

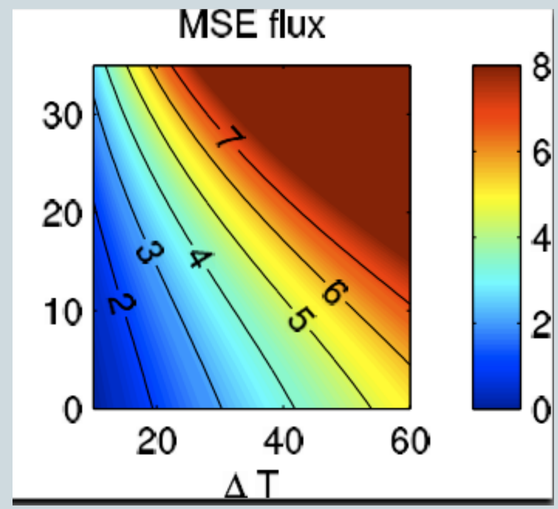
Full GCM



Simplified moist GCM



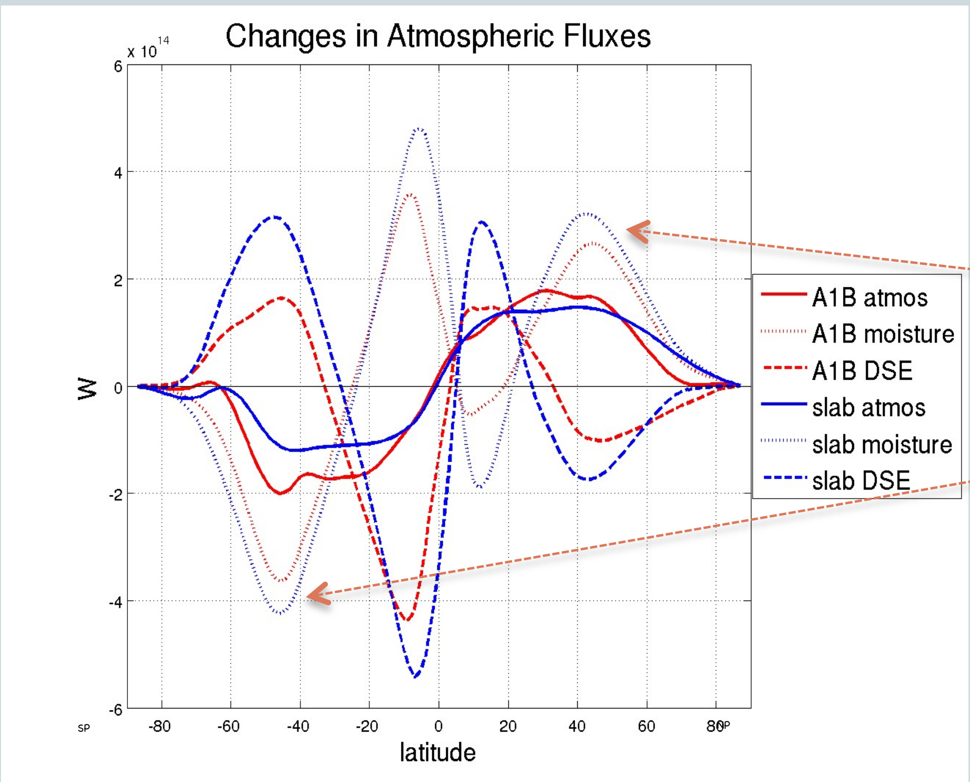
Fixed diffusivity EBM



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:



Increase in moisture flux in midlatitudes

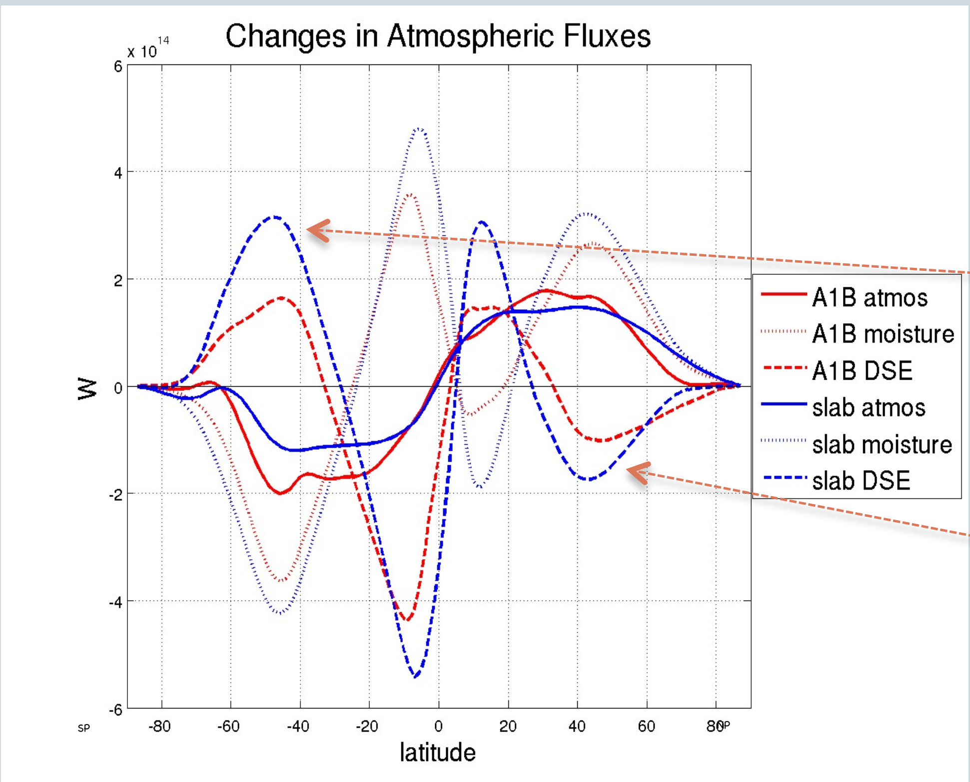
(more moisture content → more moisture flux)

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

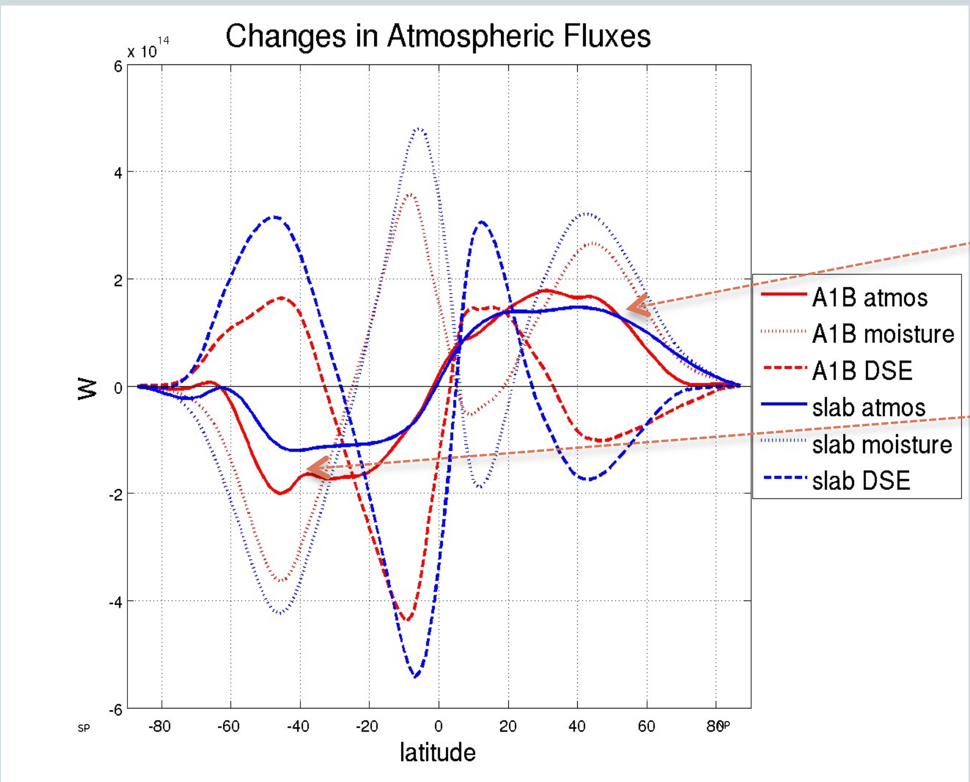
(compensates for moisture flux increase – but not perfectly)

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



Total atmospheric energy flux increases in midlatitudes

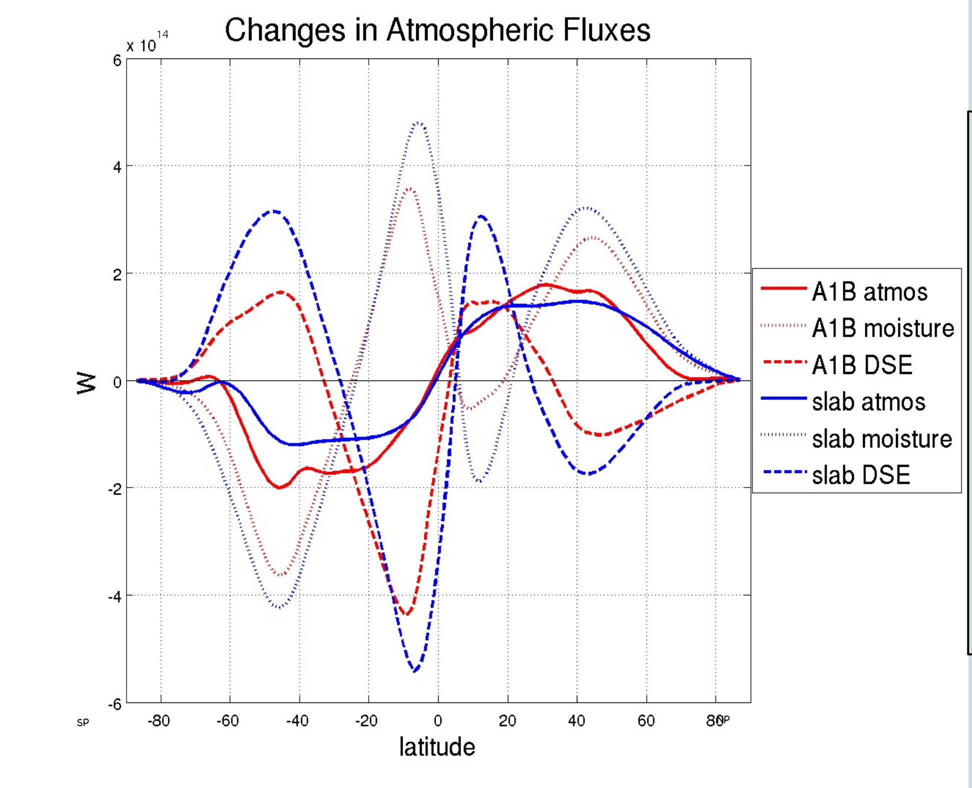
Solid lines = total atmospheric flux

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 → more warming)

• Total energy flux increase is more for coupled runs in SH, similar in NH

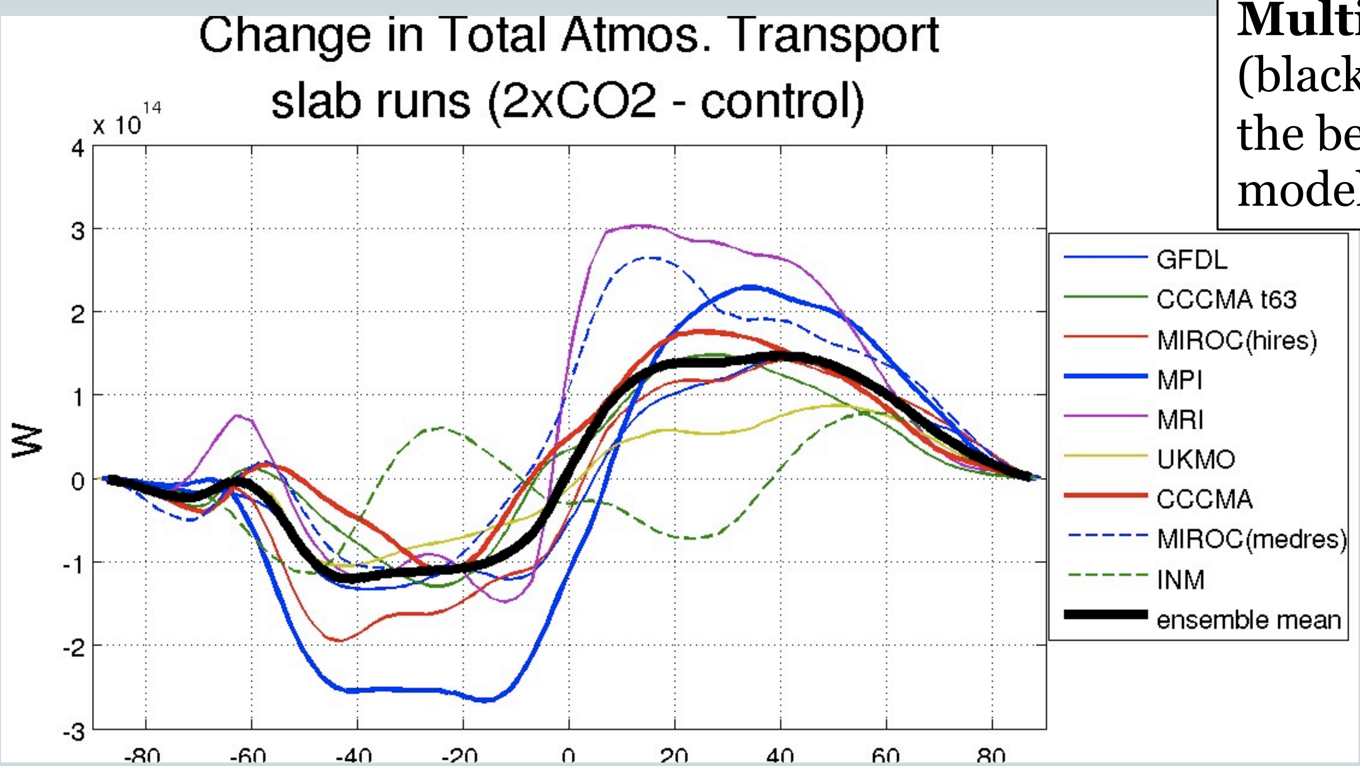
Why?

Hwang and Frierson (2010)

See also Hwang, Frierson, Held and Soden (2010)

Individual Model Changes

- Individual models show a wide range of changes in total atmospheric transport though:

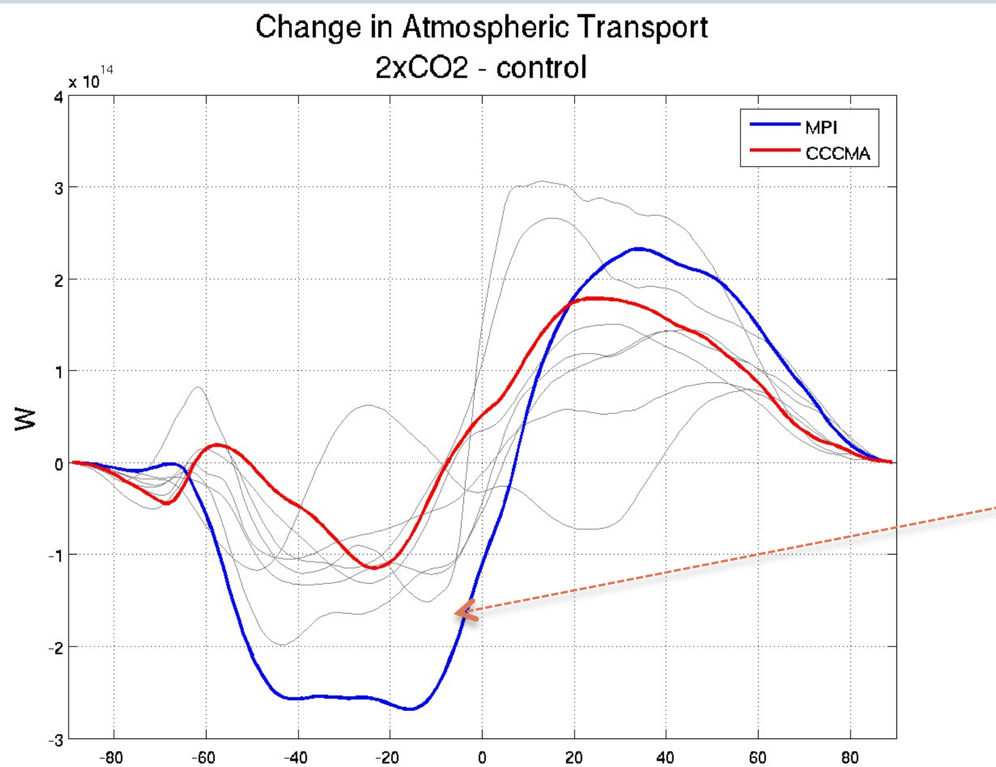


Multi-model mean (black) does not represent the behavior of individual models

Hwang and Frierson (2010)

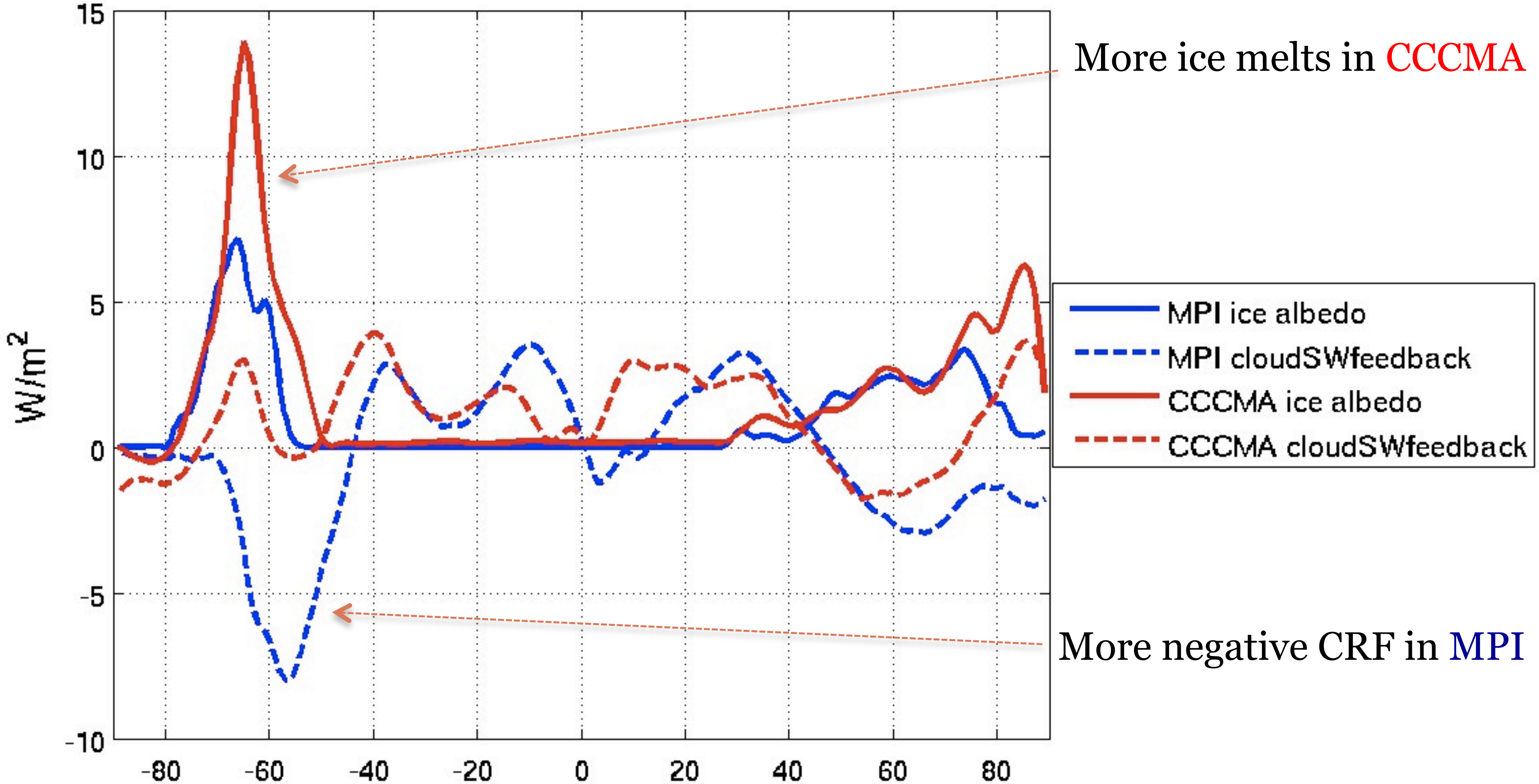
Comparison of Extreme Cases

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



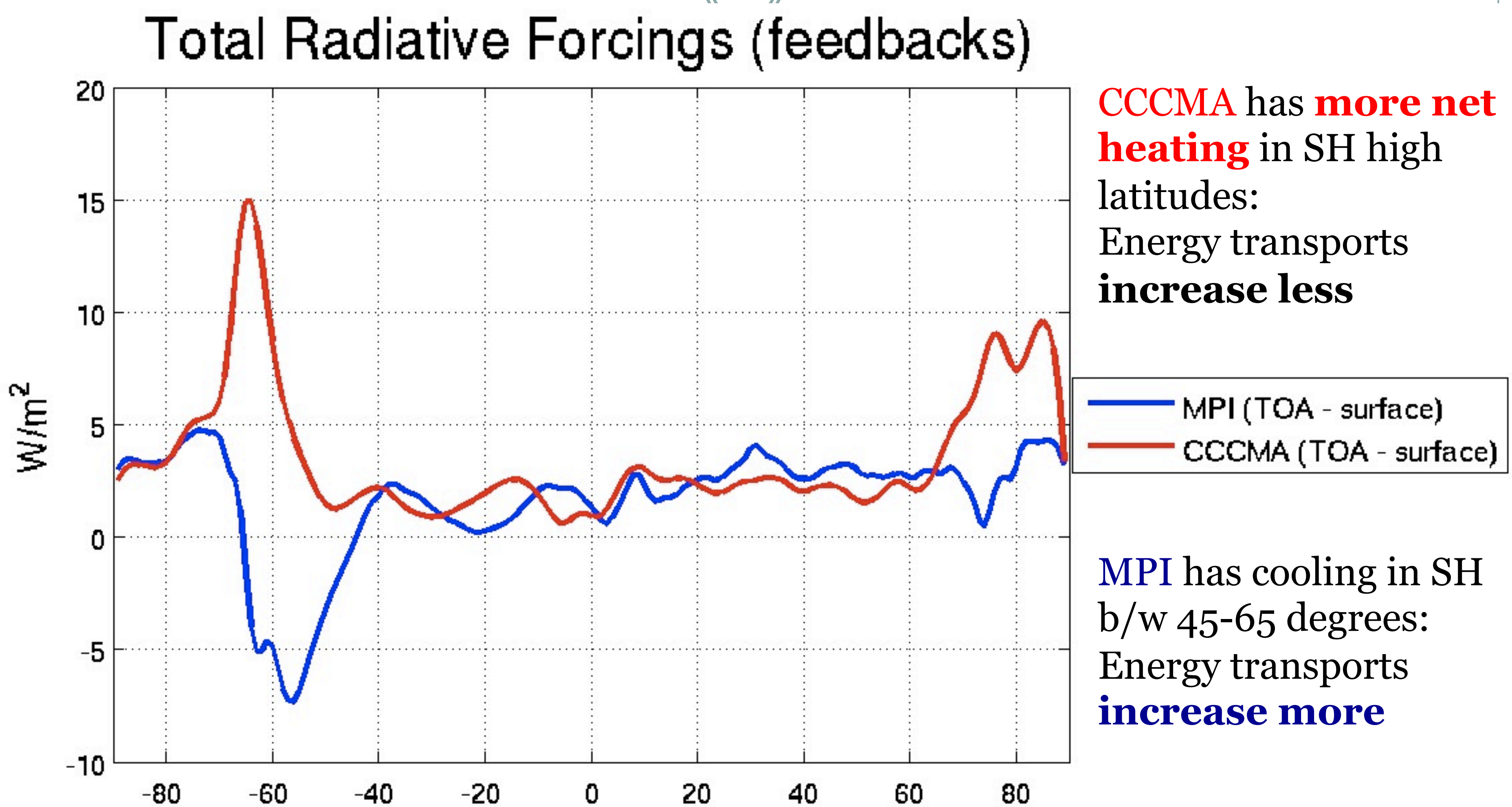
Factor of two difference in total atmospheric flux

Sea Ice and Cloud Forcing



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

Forcing: Sea Ice + CRF



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

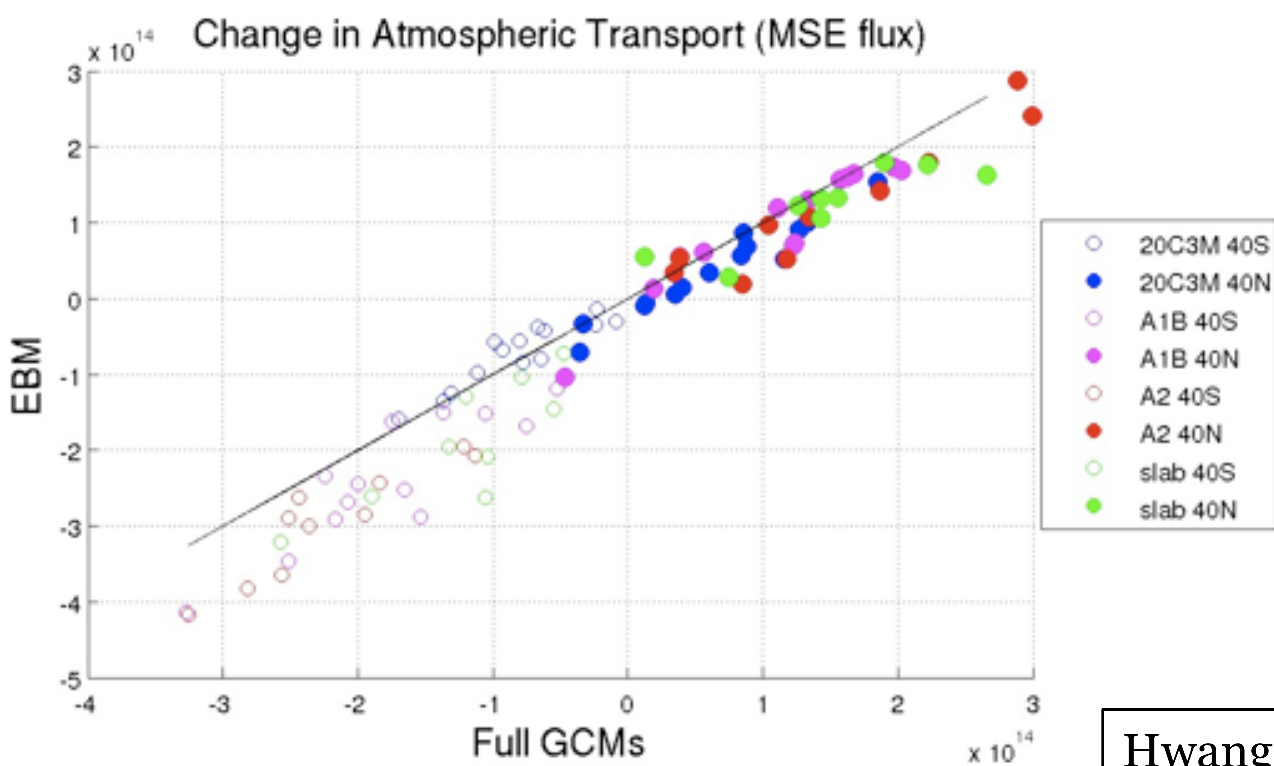
MPI has cooling in SH b/w 45-65 degrees:
Energy transports **increase more**

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 20^{th} century climate), predict fluxes at 40 degrees N/S
  - **Ice-albedo**, **aerosols**, **clouds** & **ocean uptake** as forcings



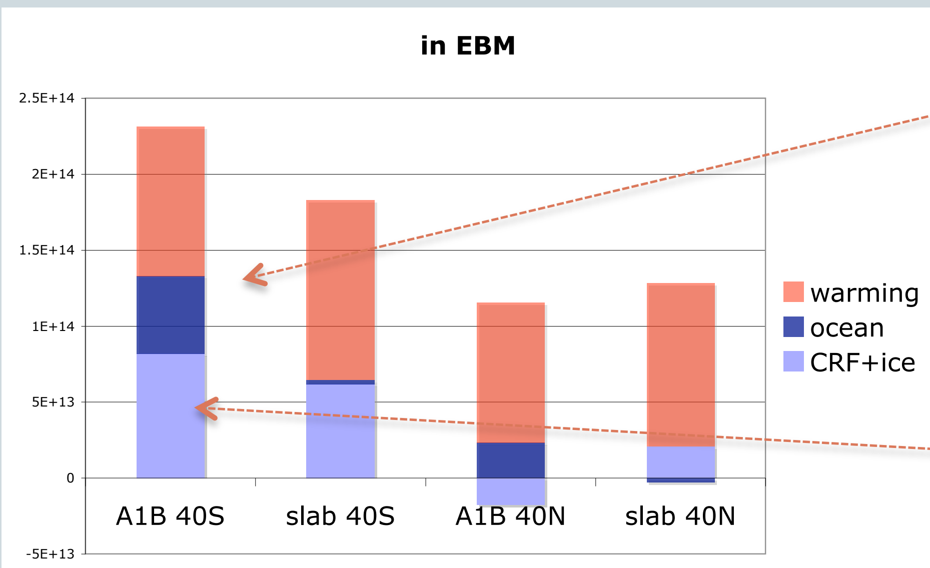
Captures differences among models

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)

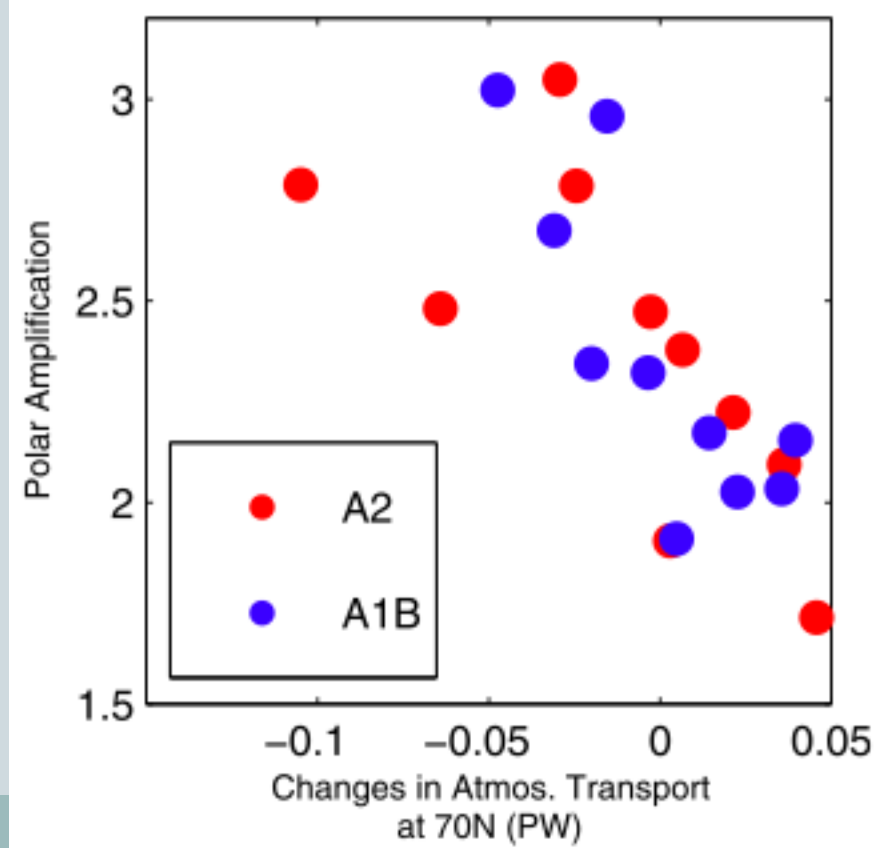
Also **less sea ice melting** (sea ice melting decreases flux)

From Hwang and Frierson (2010)

Polar Energy Transports w/ Global Warming

- Might think w/ **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

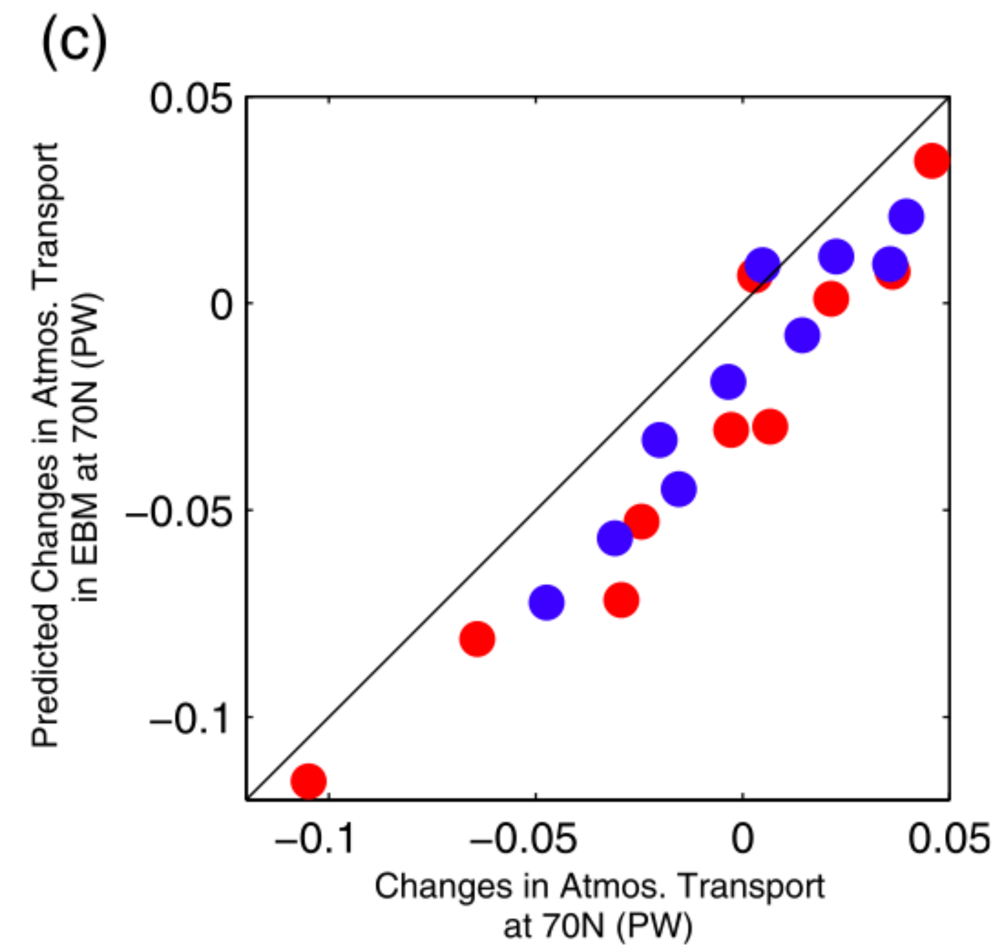


Hwang, Frierson, and Kay (2011)

Polar Energy Transports with Global Warming

- Anticorrelation because flux is **diffusive**: weaker dT/dy means less transport

Energy balance model is accurate at predicting transports given cloud, ice, ocean changes

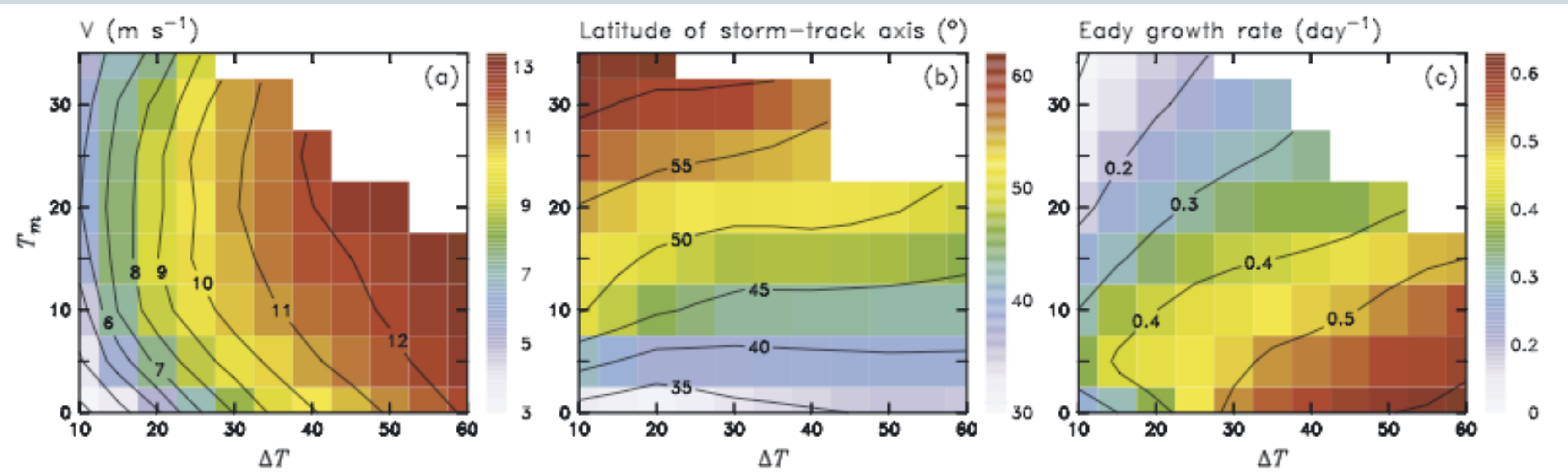


See Hwang, Frierson & Kay 2011 for details

What else happens in those aquaplanet simulations?

- From Caballero and Langen (2005):

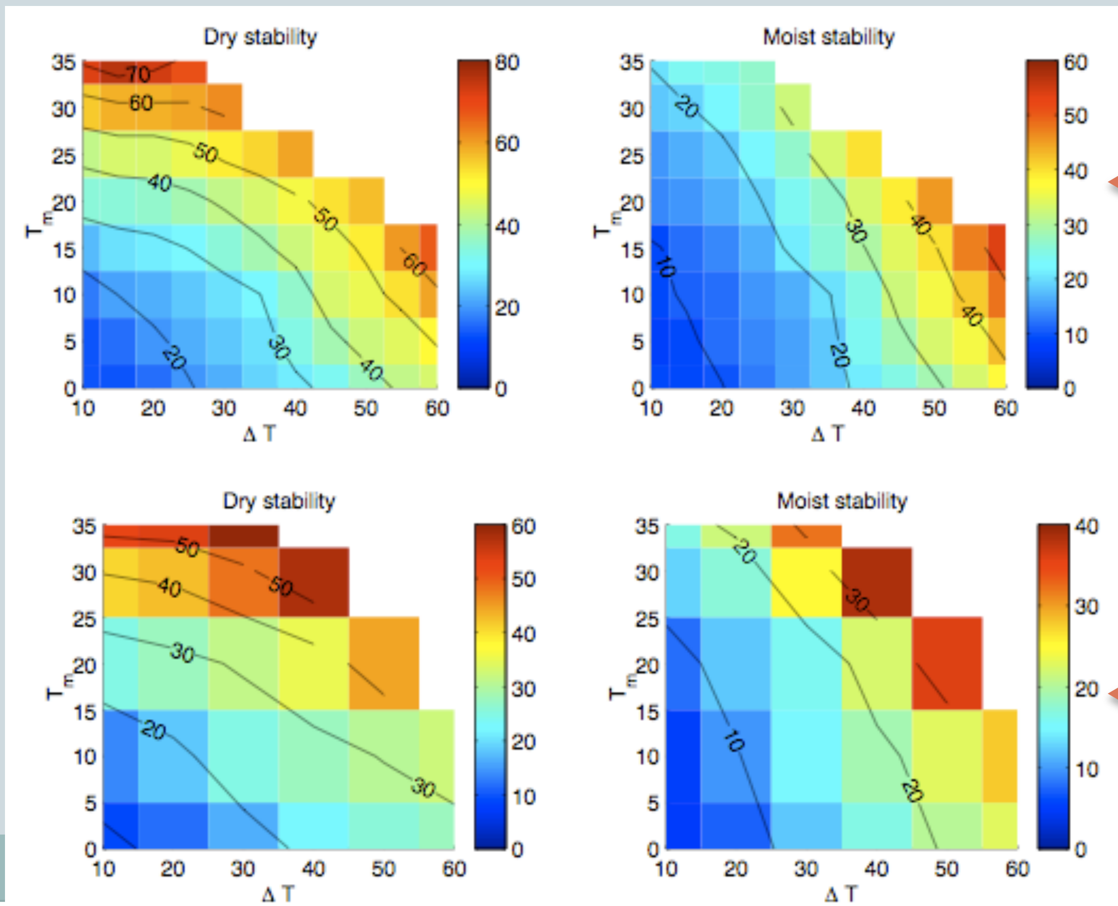
Eddy velocity scale | Latitude of storm track | Eady growth rate



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*:



Full GCM

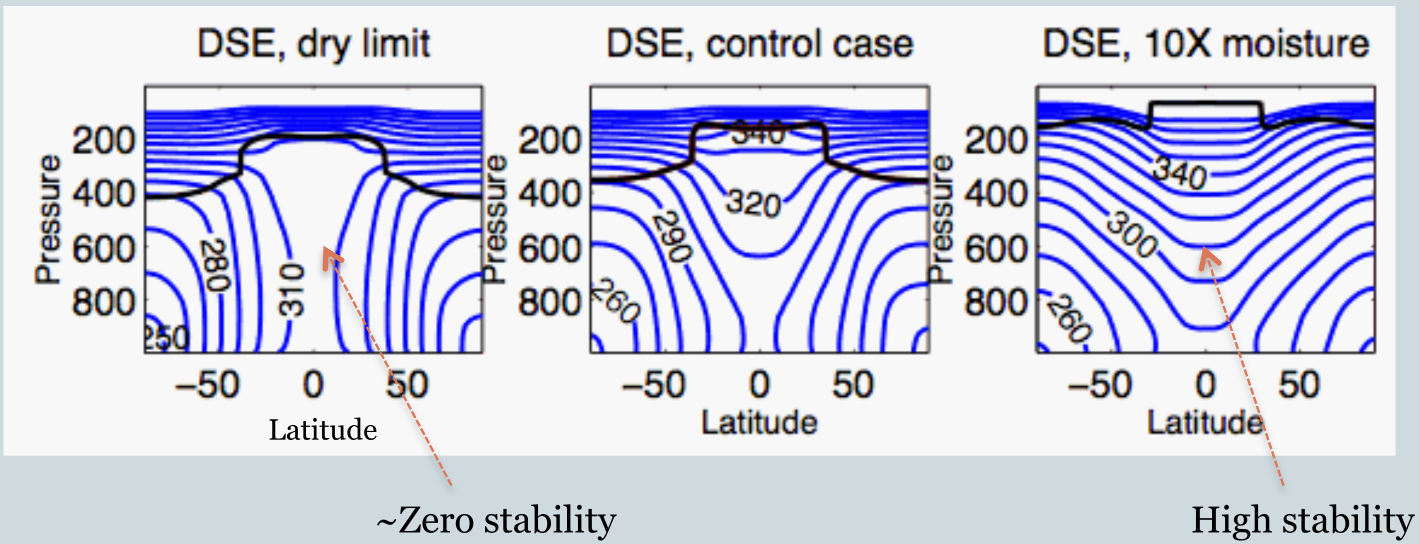
Dry stability and moist stability averaged over baroclinic zone

Idealized moist GCM

From Frierson (2008)

Static Stability Changes

- Dry static energy, idealized GCM simulations:

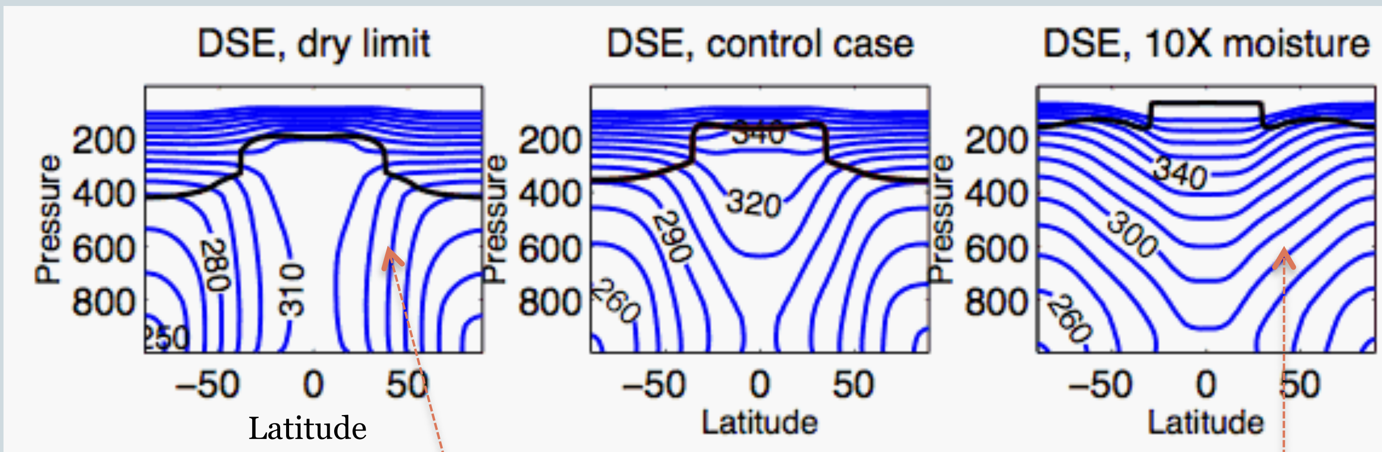


- Static stability ($\frac{d\theta}{dz}$) increases in tropics (as expected)

From Frierson, Held and Zurita-Gotor (2006)

Static Stability Changes

- Dry static energy, idealized GCM simulations:



~Zero stability

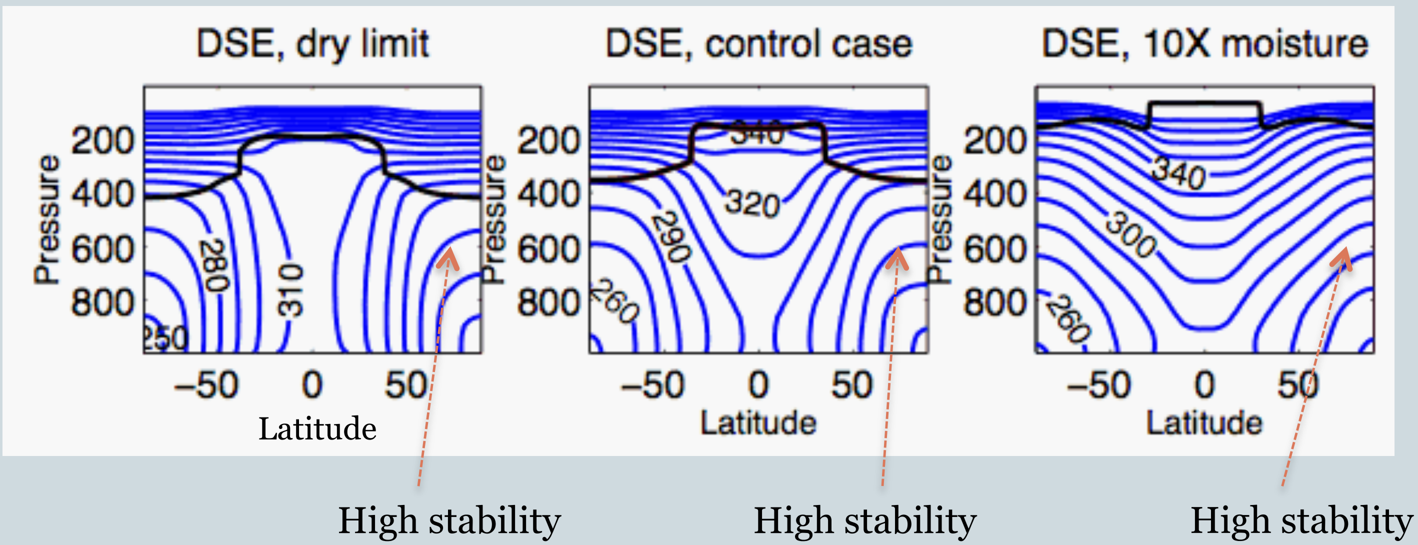
High stability

- Static stability also increases in midlatitudes (surprisingly)

From Frierson, Held and Zurita-Gotor (2006)

Static Stability Changes

- Dry static energy, idealized GCM simulations:

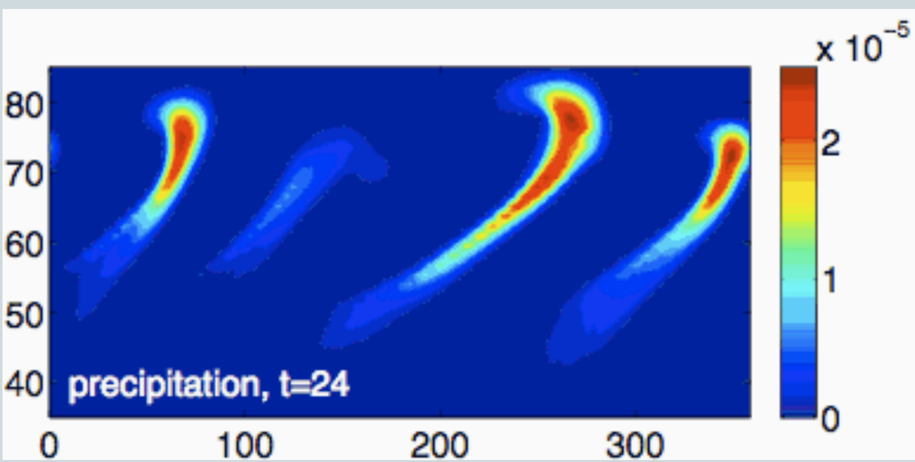


- Polar static stability is largely unchanged

From Frierson, Held and Zurita-Gotor (2006)

Moisture Effects on Midlatitude Stability

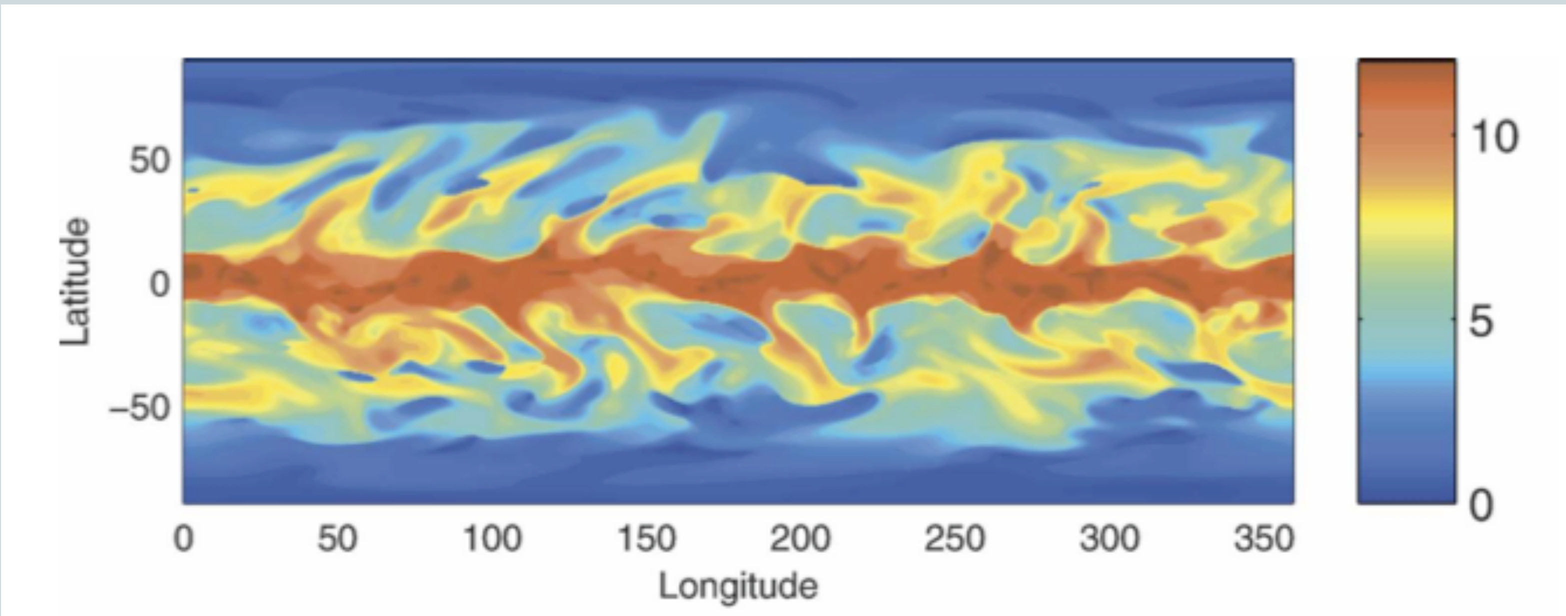
- Moist convection (possibly slantwise) occurs within frontal regions in baroclinic eddies (Emanuel 1988)
- Mean moist stability is expected to be stable though
- Scaling theory of Juckes (2000): bulk moist stability proportional to surface standard deviation



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

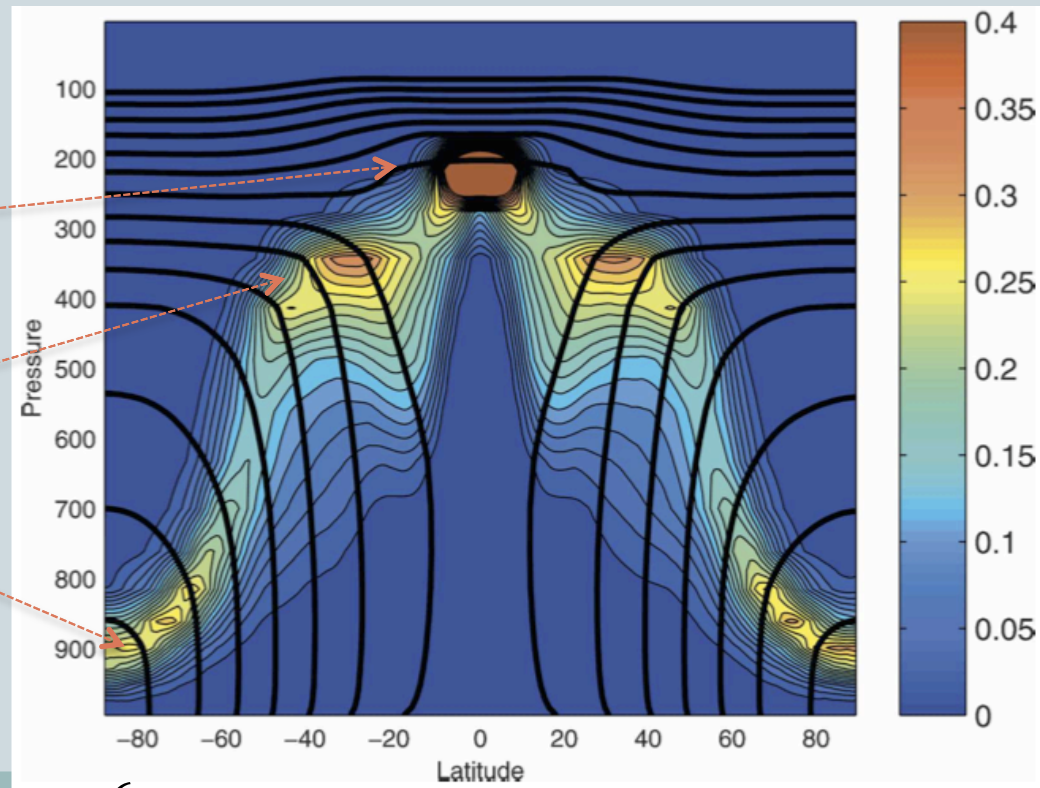
Convection in the Dry Limit

- 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

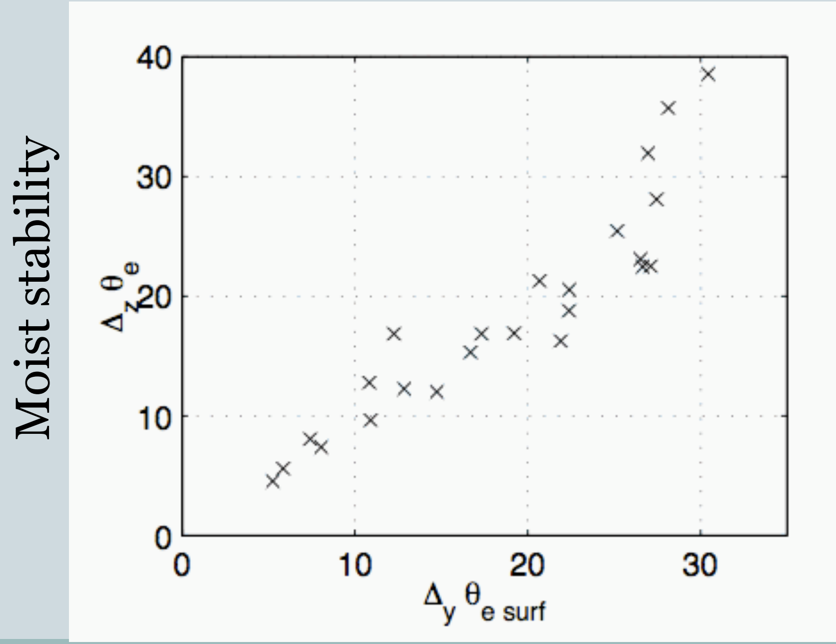
Convection is never deep in high latitudes



From Frierson, Held & Zurita-Gotor 2006

Testing the Juckes scaling

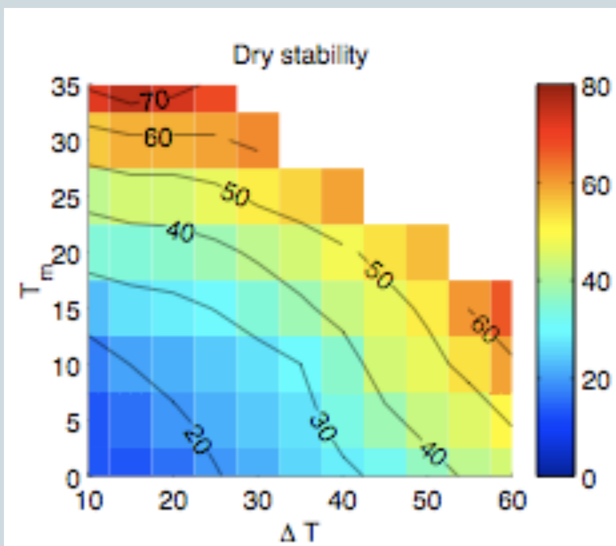
- Vary mean SST (from 0 to 35 C) and temperature gradients (from 10-60 K) in 24 experiments with the simplified GCM
- Moist scaling relation:

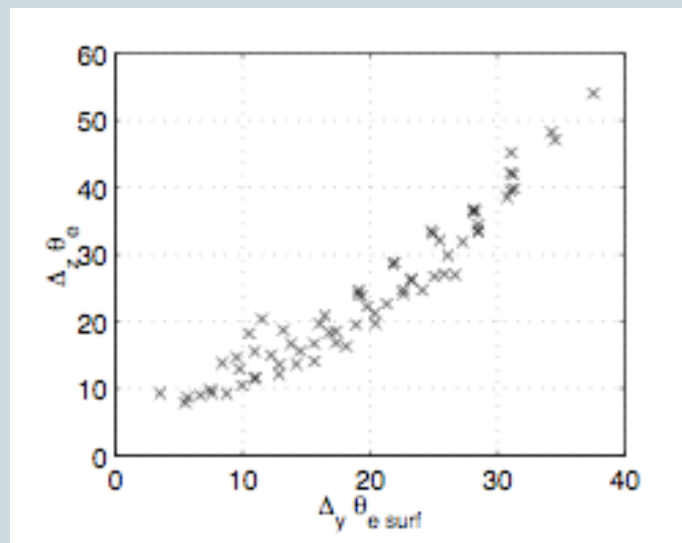


From Frierson (2008)

Static Stability in Aquaplanet Full GCM

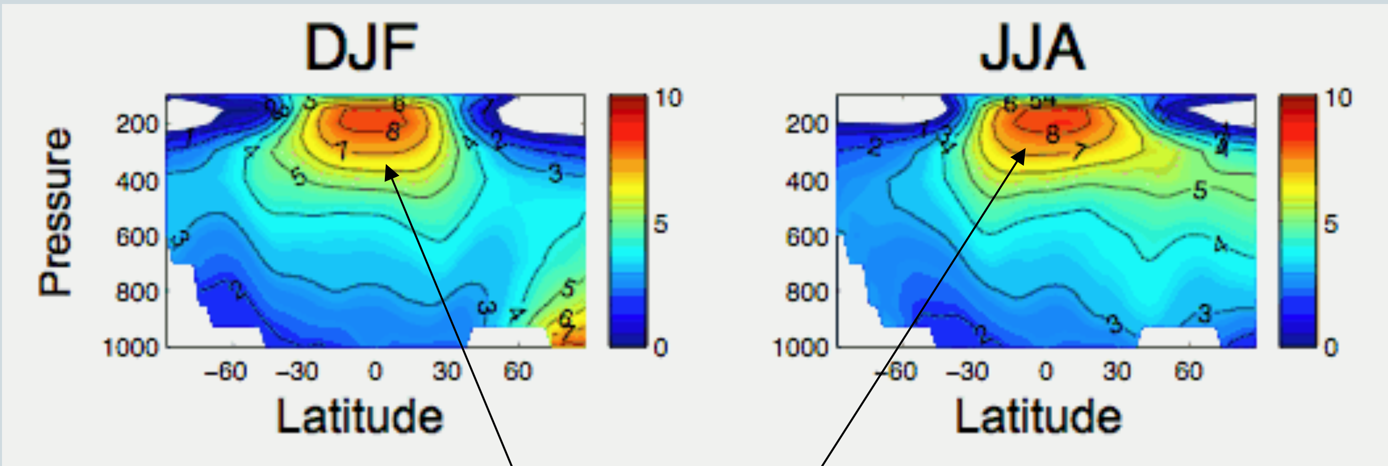
- Vary mean SST (from 0 to 35 C) and temperature gradients (from 10-60 K) in 70 **full GCM** experiments
- Midlatitude dry stabilities and moist scaling relation:





Temperature Changes: IPCC Models

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

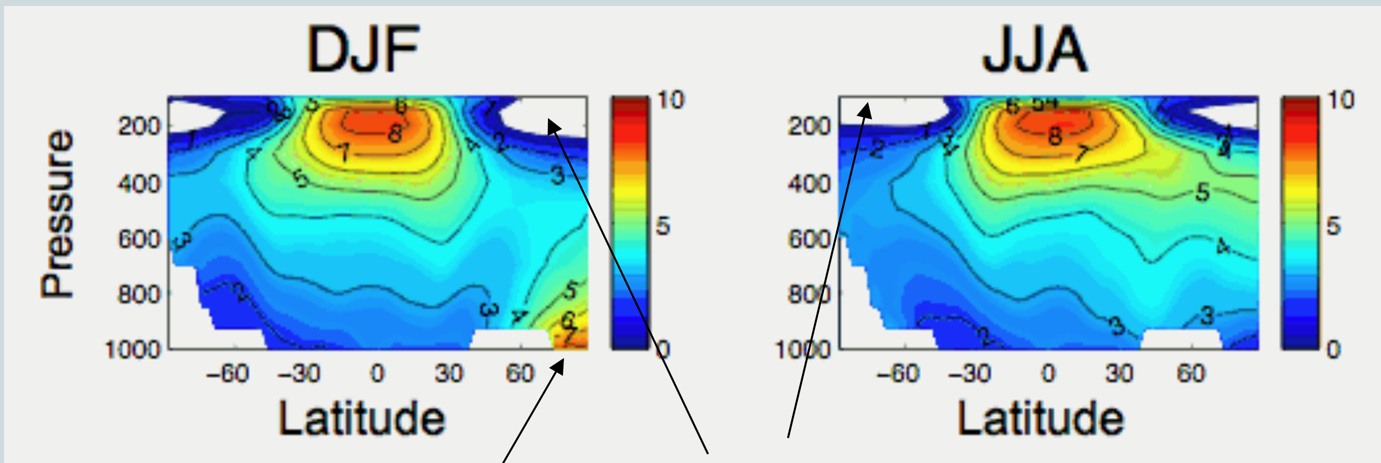


Tropical upper tropospheric warming (due to moisture)

From Frierson (2006)

Temperature Changes: IPCC Models

- Global warming simulations *change* in potential temp:



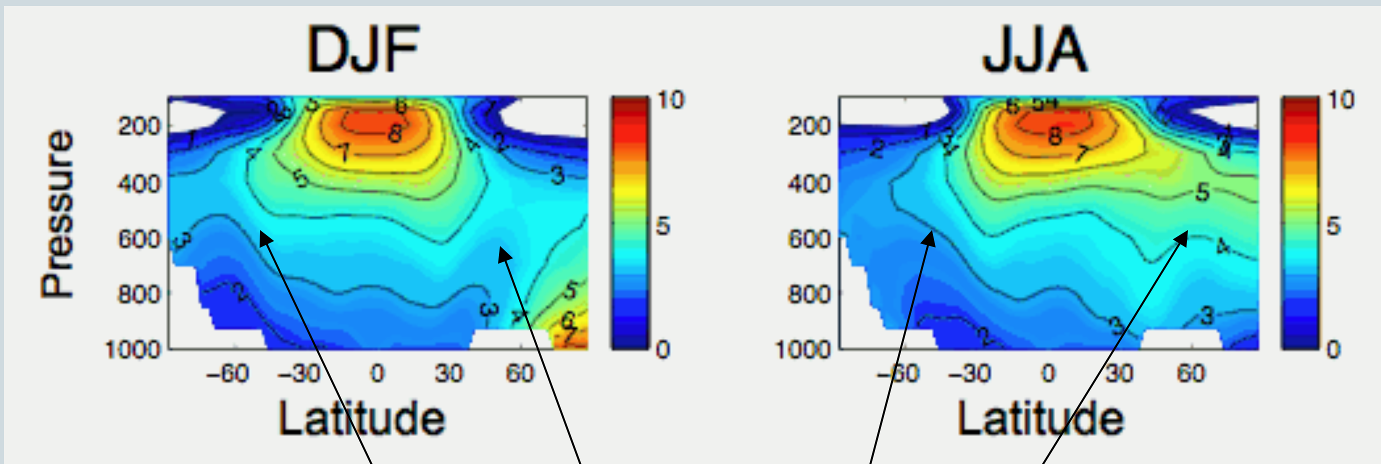
Stratospheric cooling

Polar amplification

From Frierson (2006)

Temperature Changes: IPCC Models

- Global warming simulations *change* in potential temp:

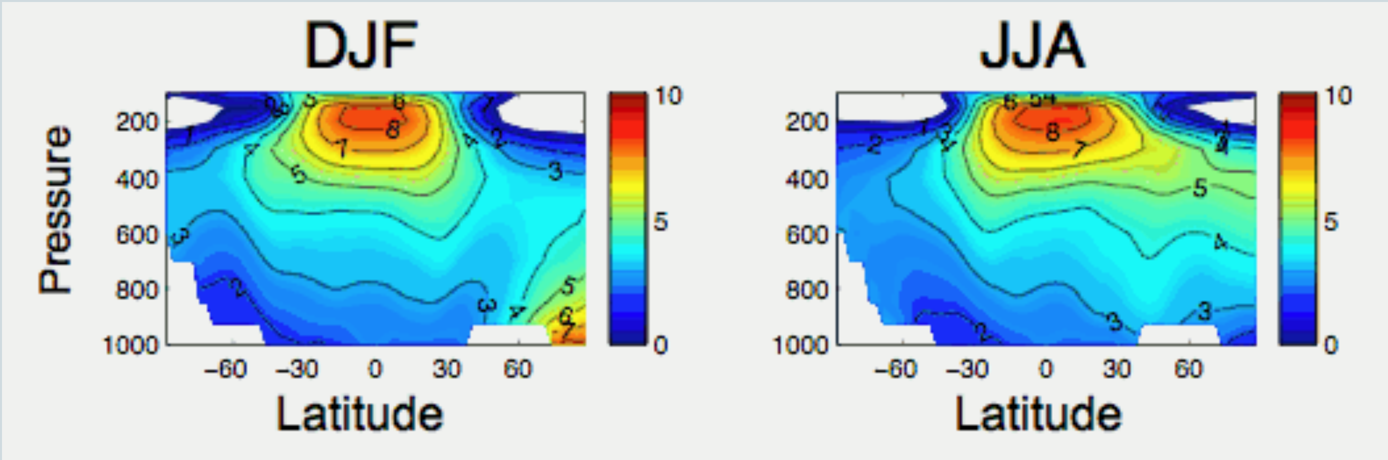


Midlatitude static stability increases as well

From Frierson (2006)

Temperature Changes: IPCC Models

- Global warming simulations change in potential temp:

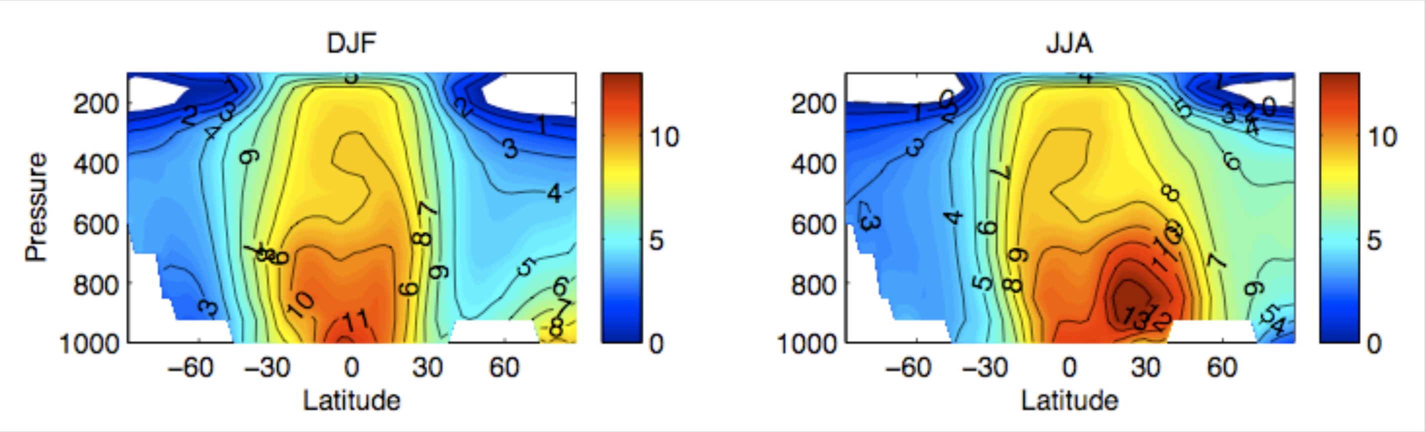


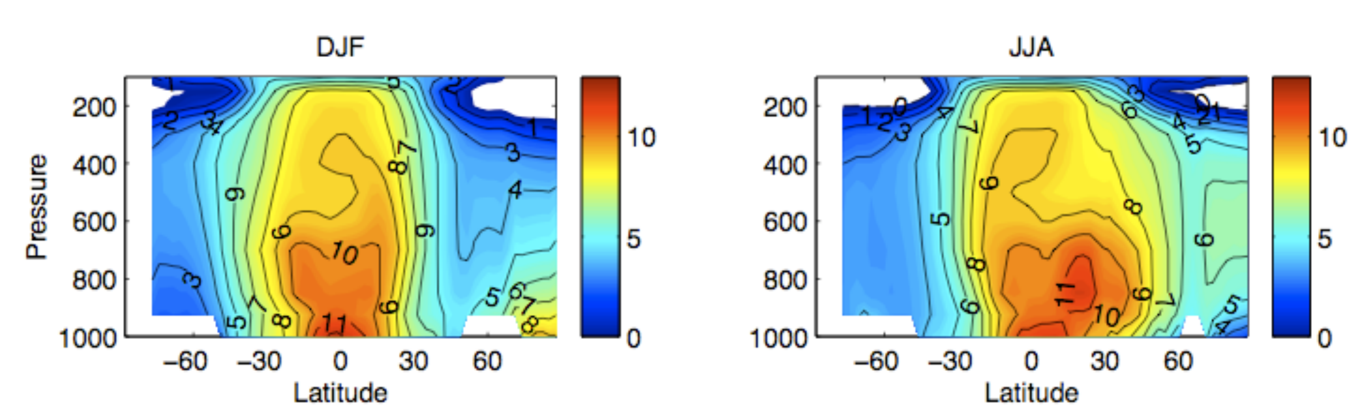
- Clear increase in midlatitude static stability with global warming
  - Especially in Southern Hemisphere and in summer
  - Happens in 158 out of 160 model-season-hemispheres.

From Frierson (2006)

Equiv Potential Temp Change in IPCC Models

- AR4 simulations change in saturated equivalent potential temperature:

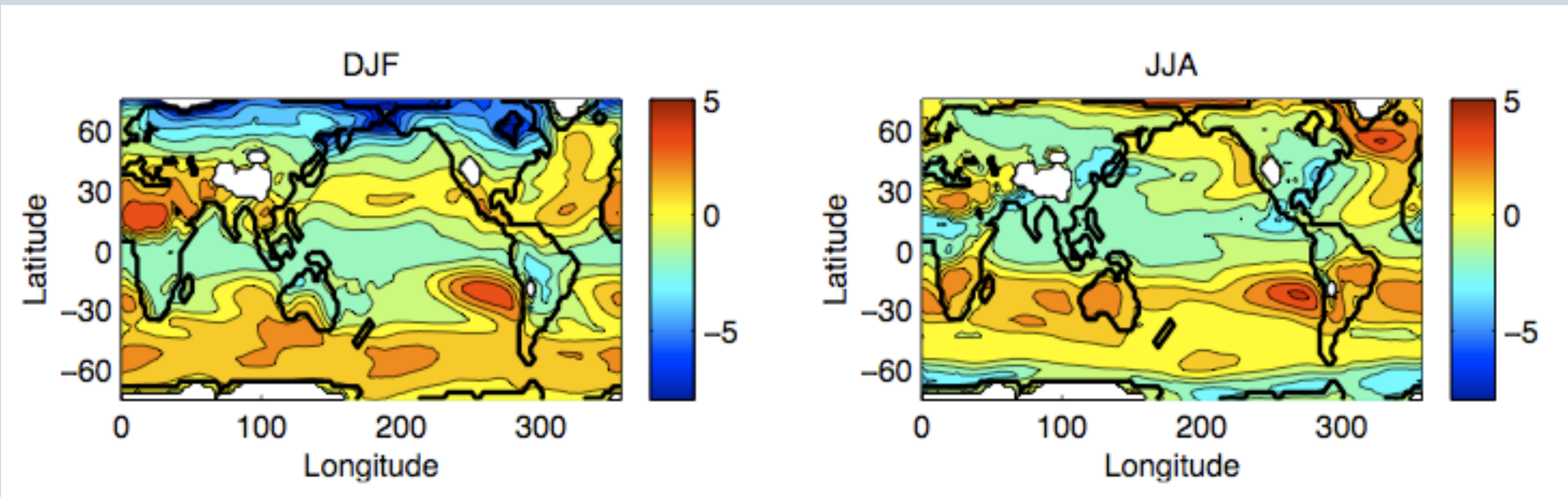




Over ocean only

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