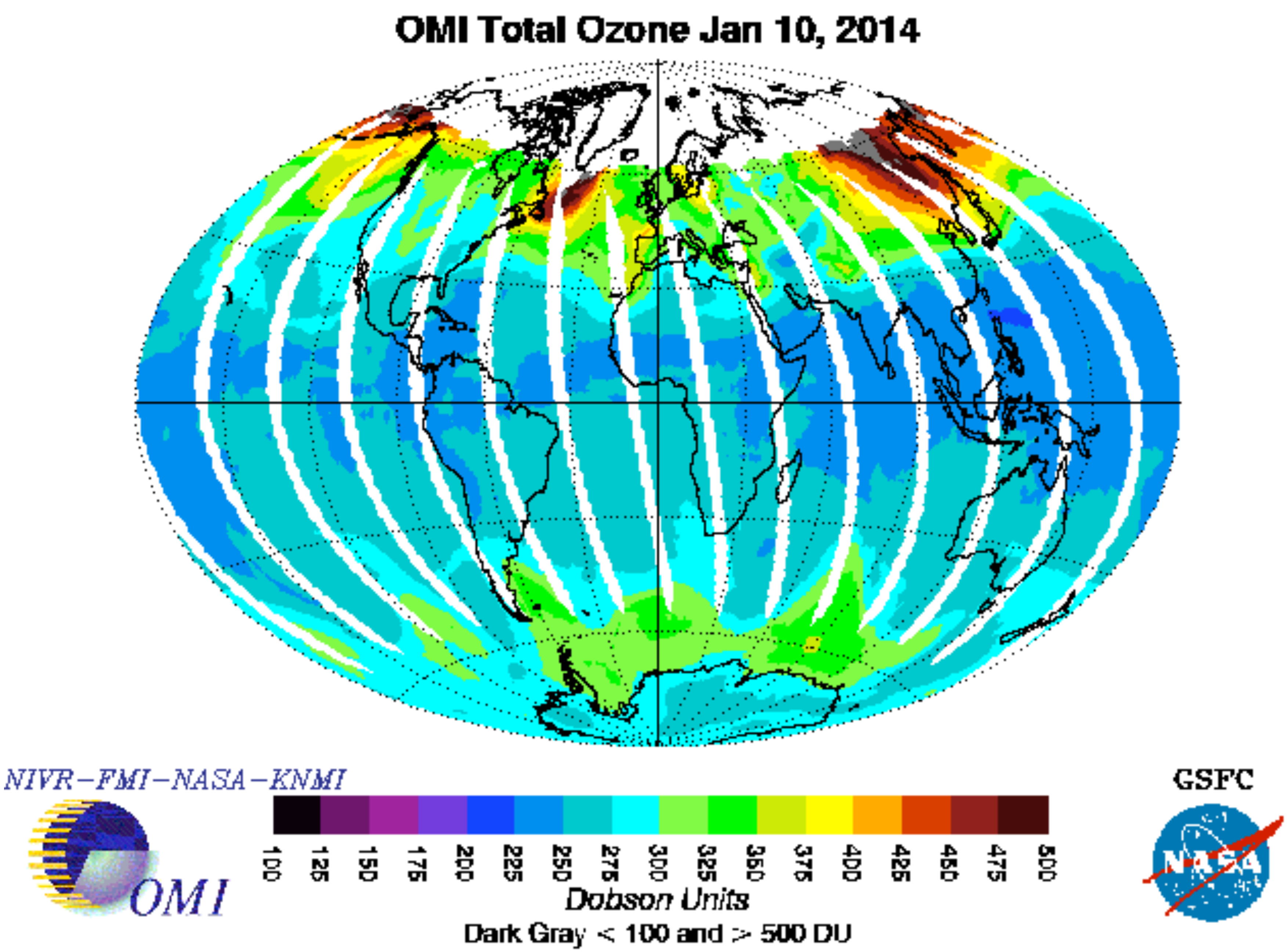
Understanding and predicting the Brewer-Dobson Circulation

Edwin Gerber and Naftali Cohen*
Center for Atmosphere Ocean Science
Courant Institute of Mathematical Sciences, New York University

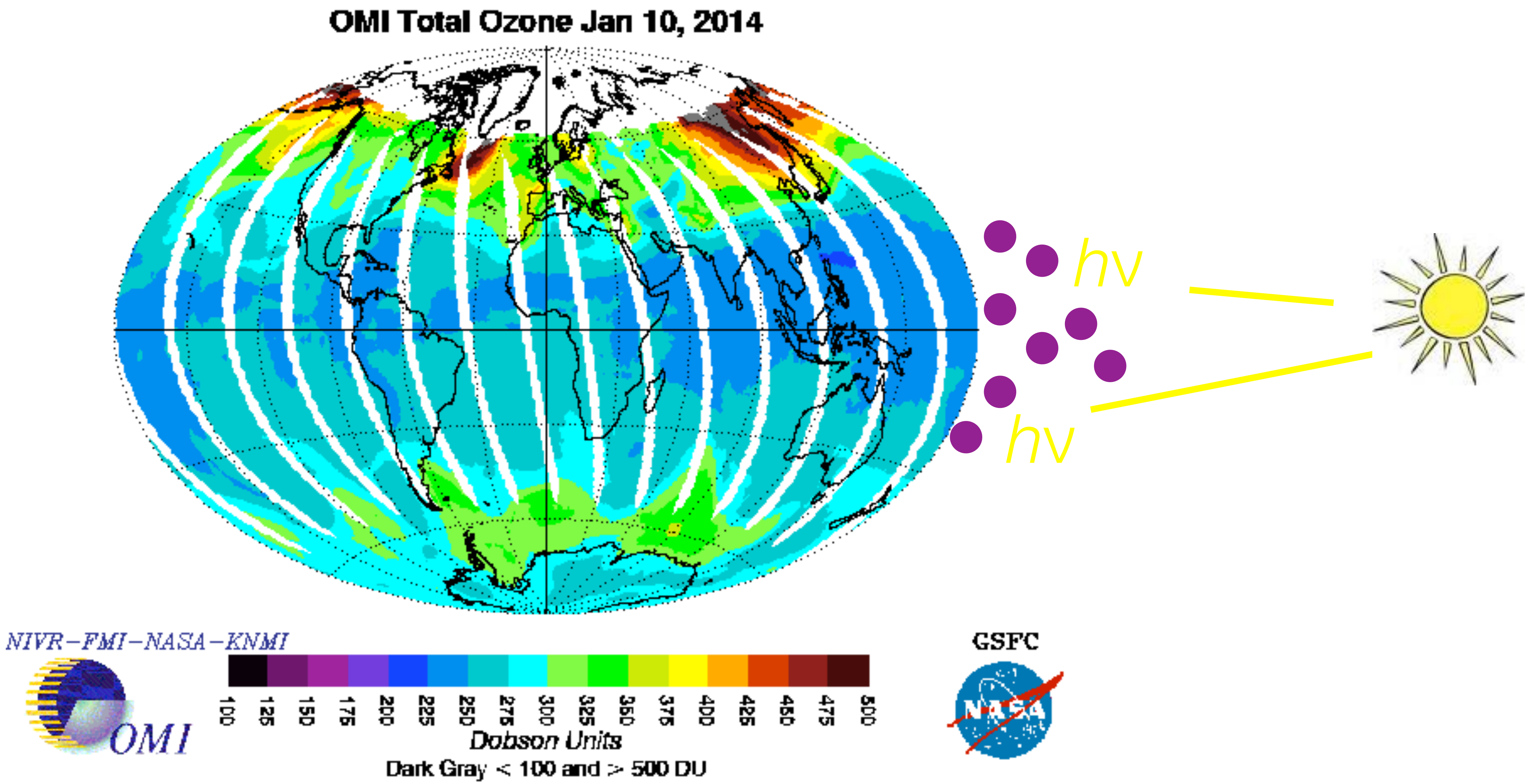
*Soon to be at Yale University

Special thanks to the U.S. National Science Foundation

Recent Ozone



Recent Ozone: the Brewer-Dobson Circulation



Dobson, Harrison, and Lawrence [1929]

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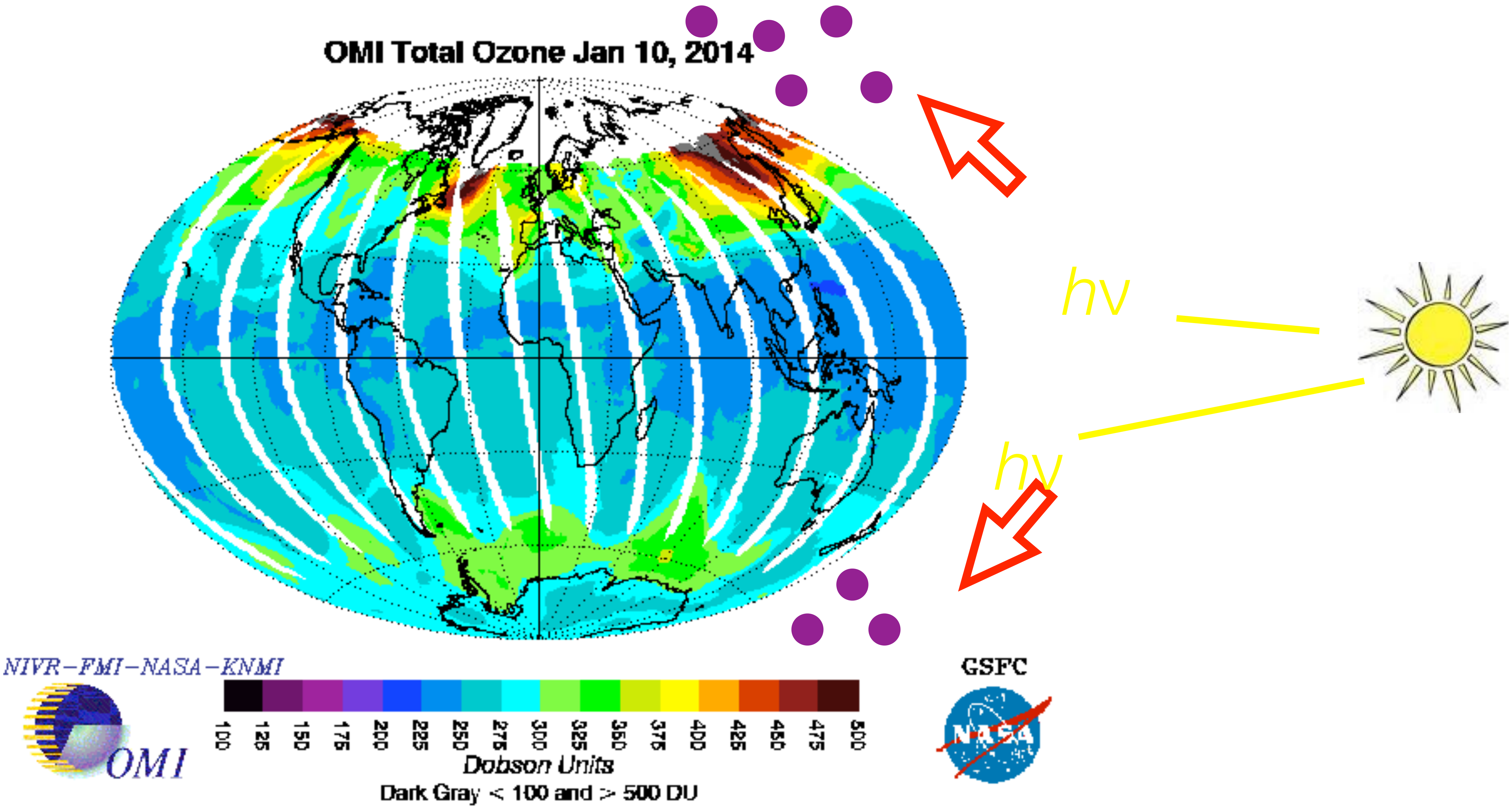

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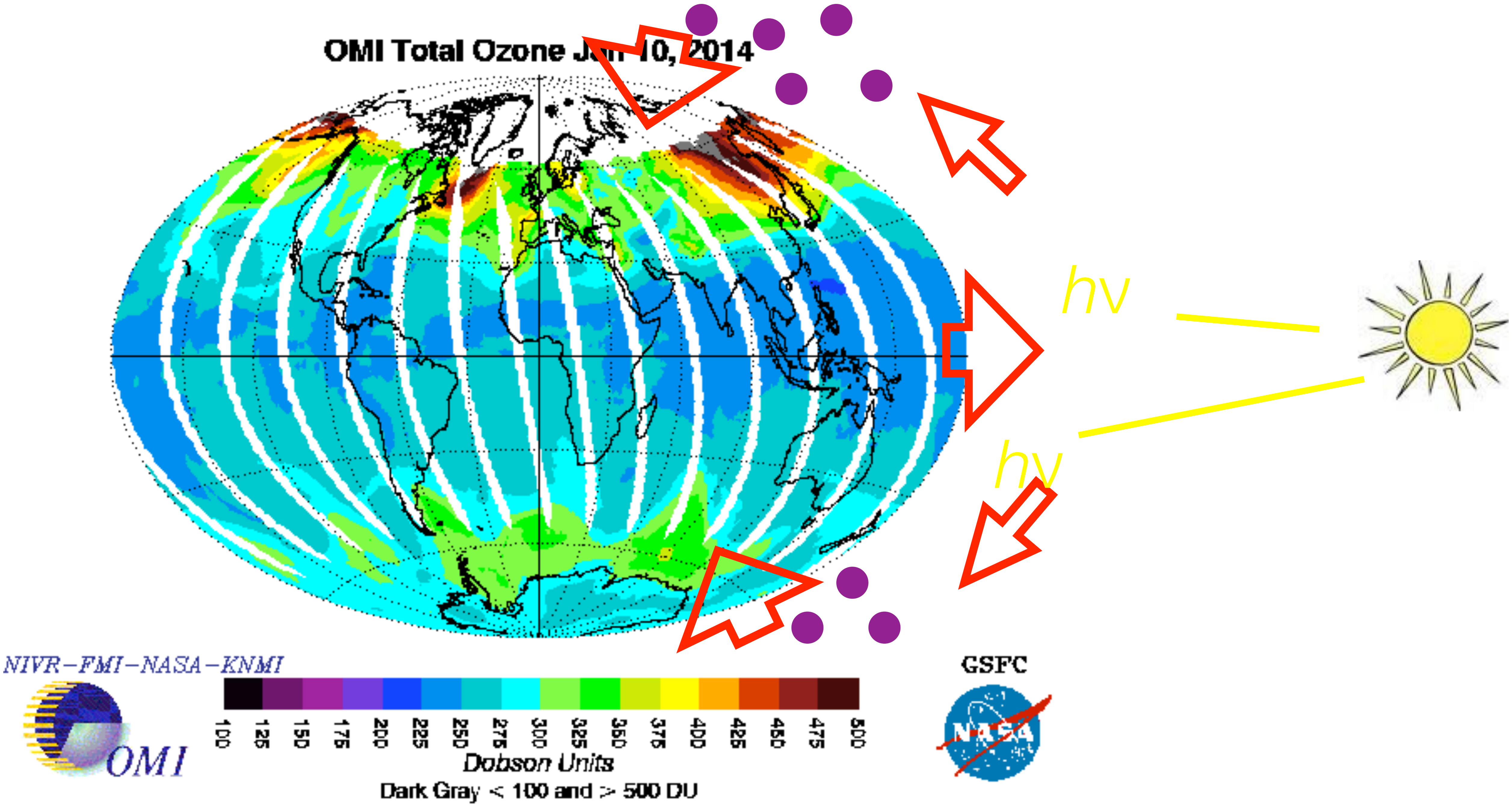

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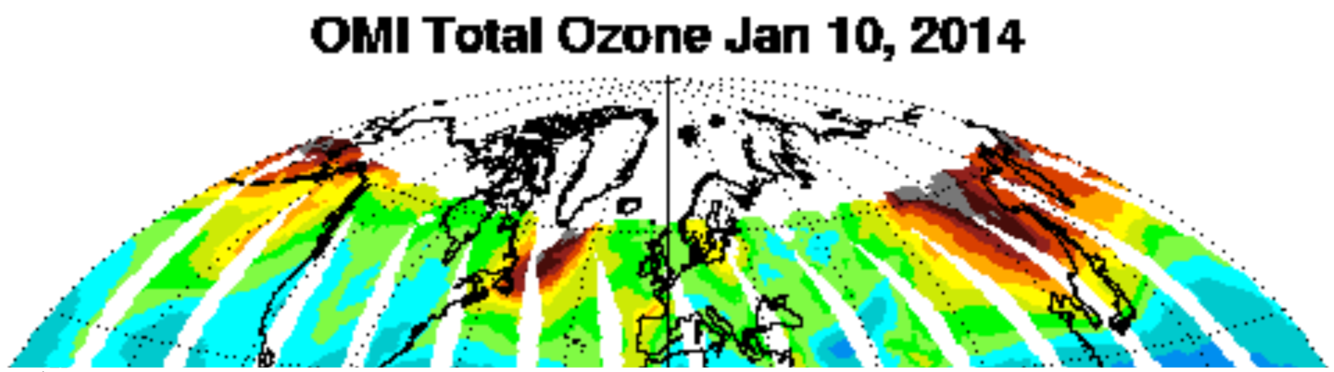
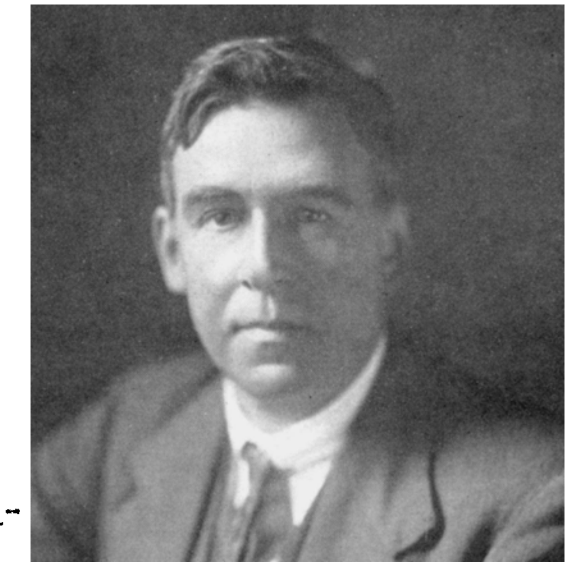
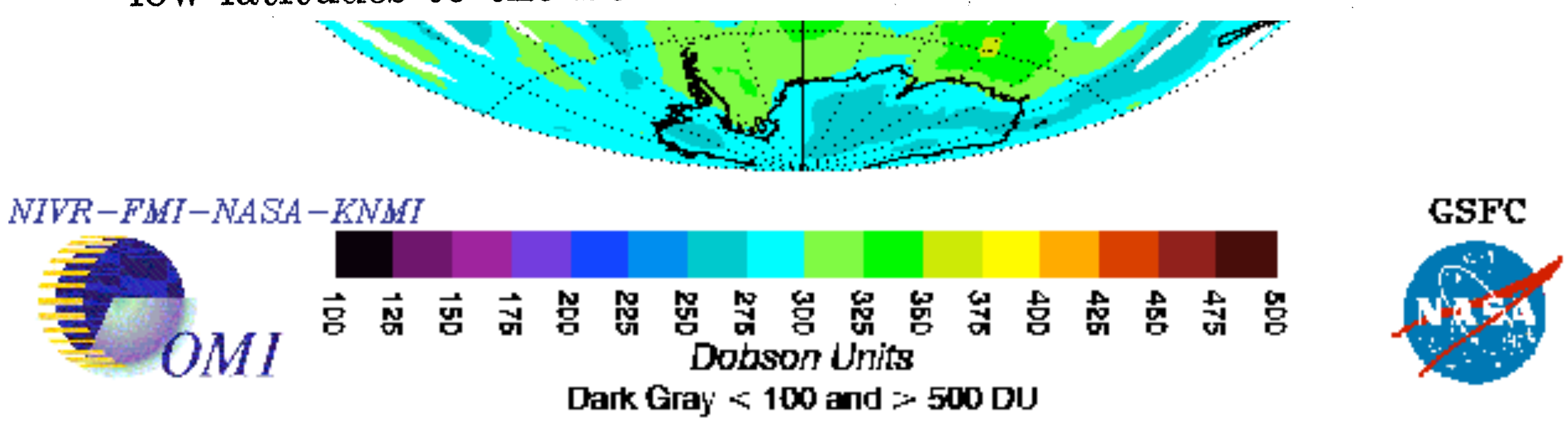


The only way in which we could reconcile the observed high ozone concentration in the Arctic in spring and the low concentration within the Tropics, with the hypothesis that the ozone is formed by the action of sunlight, would be to suppose a general slow poleward drift in the highest atmosphere with a slow descent of air near the Pole. Such a current would carry ozone formed in low latitudes to the Pole and concentrate it there. If this were the case the





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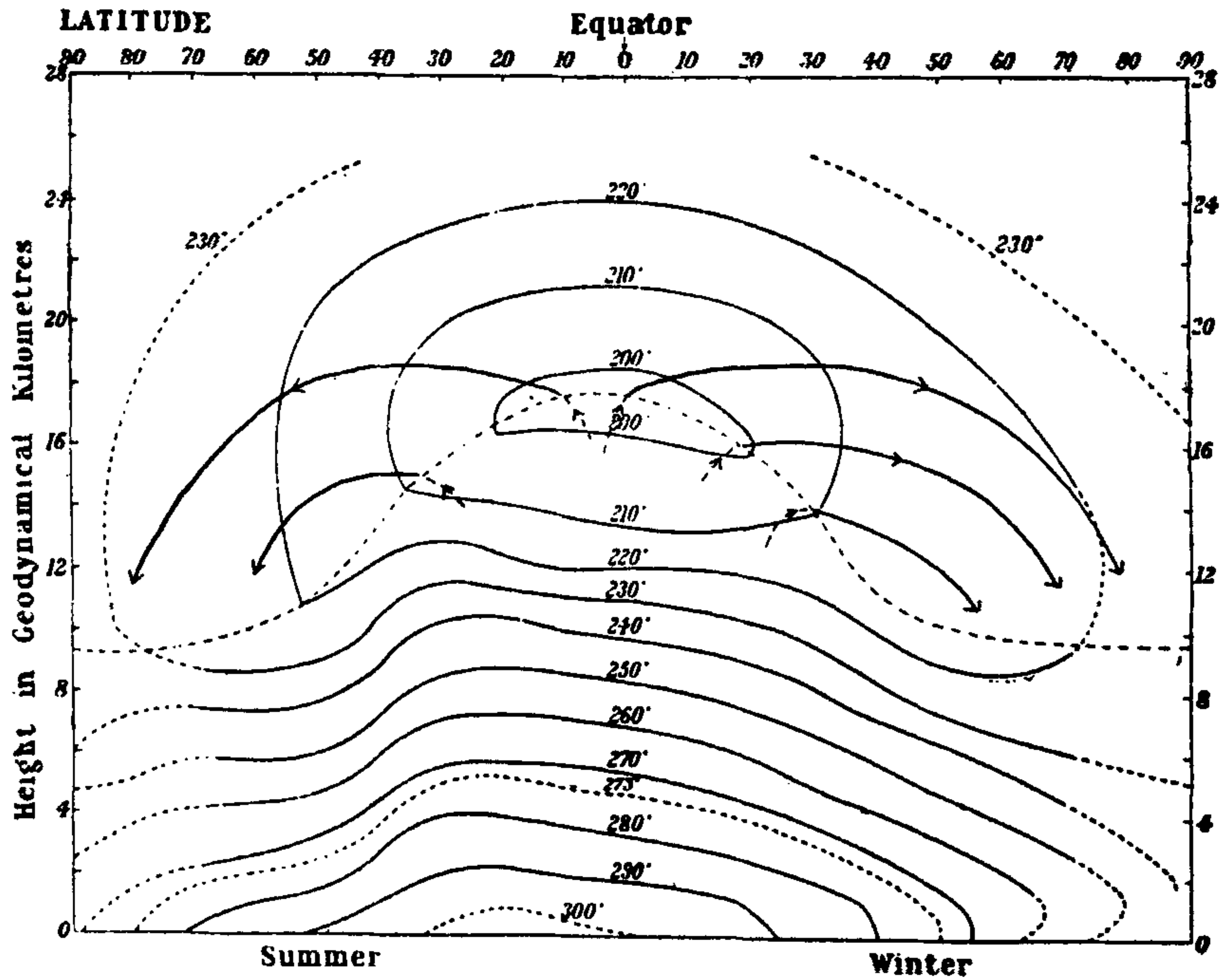
551.510.5

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY THE MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

By A. W. BREWER, M.Sc., A.Inst.P.

(Manuscript received 23 February 1949)



Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

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“polar vortex catastrophe”

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$$\frac{\partial \overline{u}}{\partial t} - f\overline{v}^* = \nabla \cdot \mathbf{F}$$

Eliassen and Palm, 1961

Andrews and McIntyre, 1976

Questions

- What drives the Brewer-Dobson Circulation?

- How will the Brewer-Dobson Circulation respond to anthropogenic forcing?

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Focus will be on the residual circulation, which transports mass across isentropic surfaces.

Tracer transport — which Brewer and Dobson actually observed — also depends critically on mixing along isentropes … please see Alan Plumb and/or me over coffee / beer!

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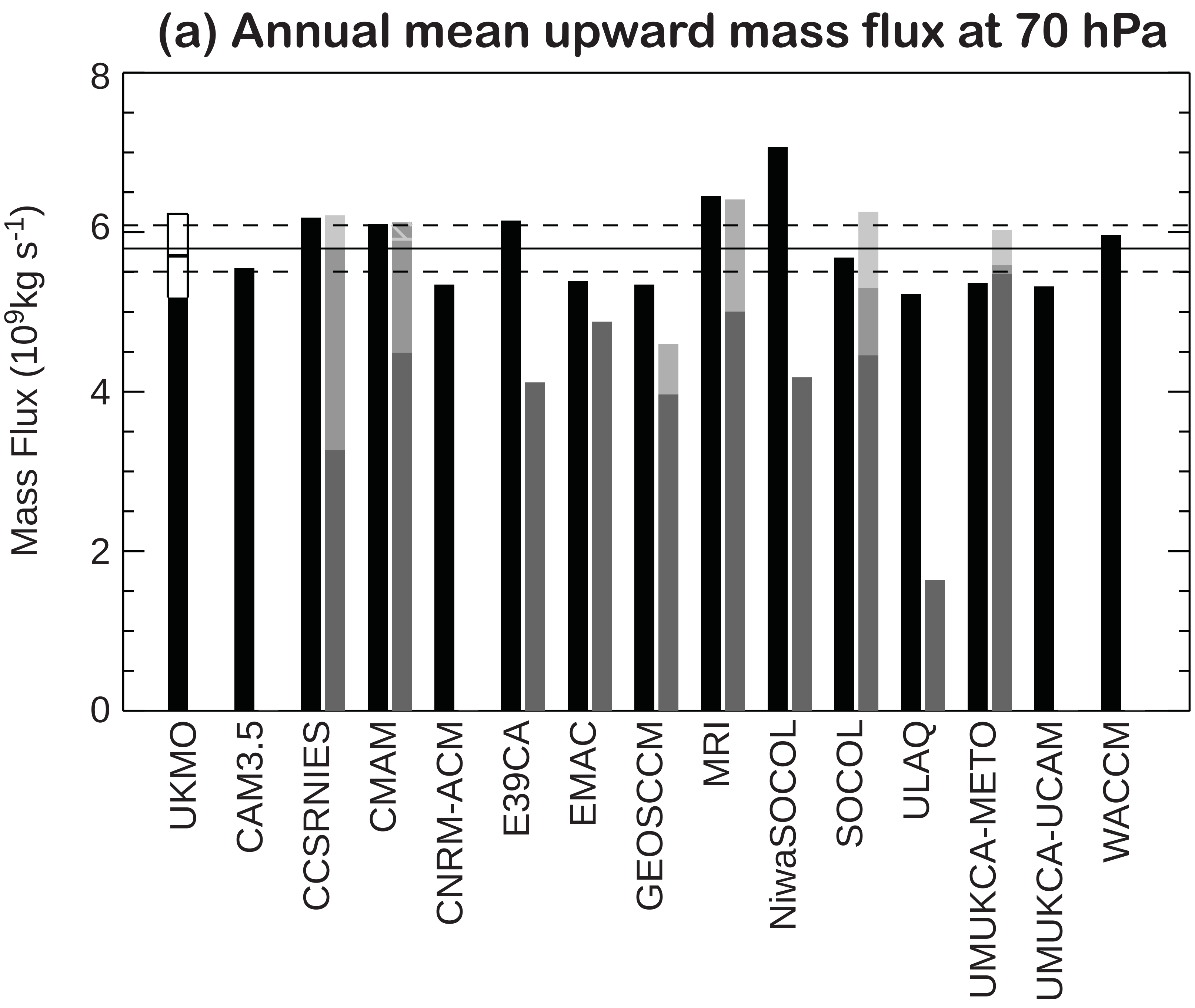

total

Rossby waves

orographic GW

non-orographic GW

[CCMVal2 Report, Butchart et al. 2011]

Questions

- How will the Brewer-Dobson Circulation respond to anthropogenic forcing?
  - Models uniformly predict that it will increase *[e.g. Butchart et al. 2010]*, but can't be validated w/ available measurements *[e.g. Garcia et al. 2011].*
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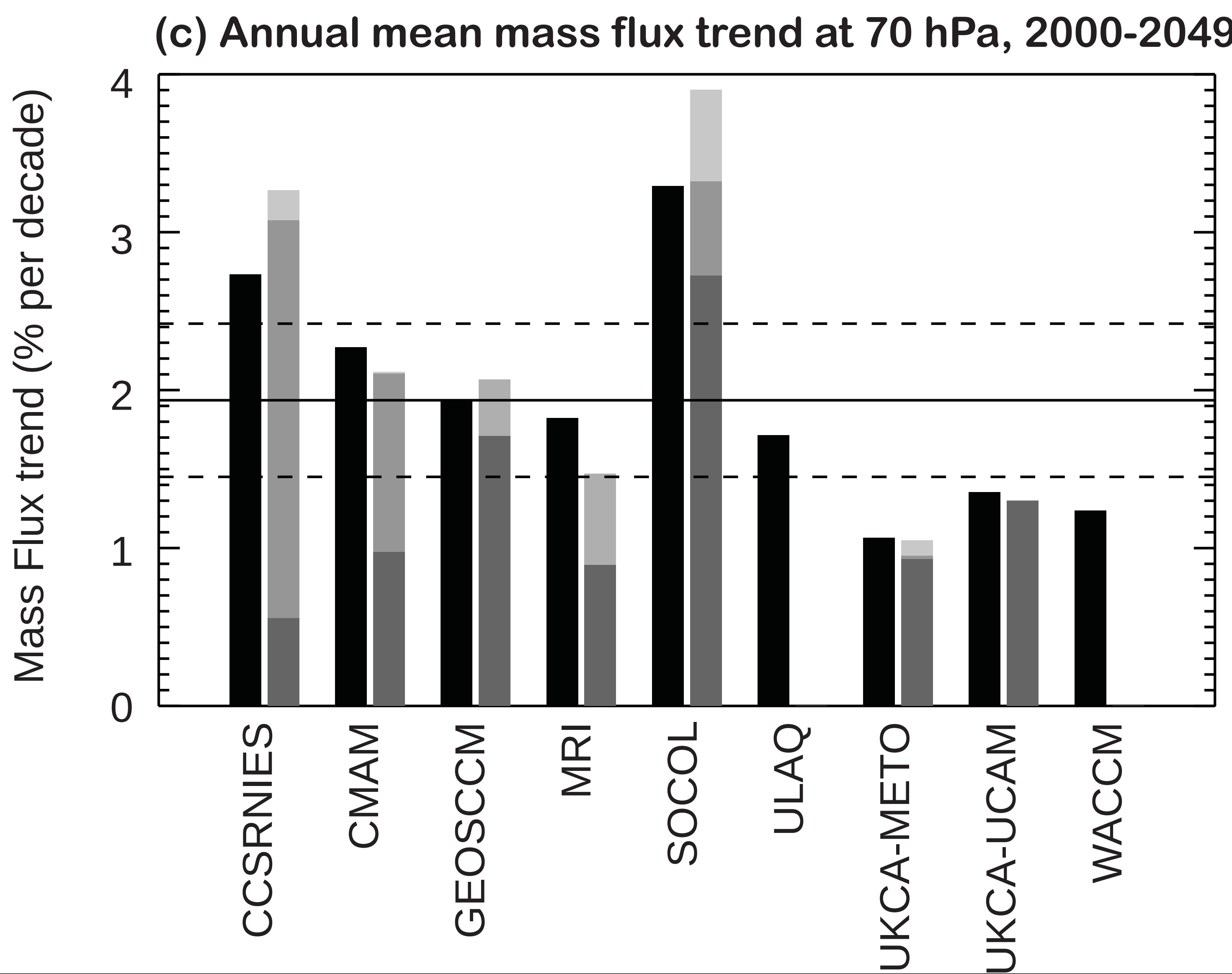
  - Models uniformly predict that it will increase *[e.g. Butchart et al. 2012]*, but can't be validated w/ available measurements *[e.g. Garcia et al. 2011].*
  - Do we understand why? Yes *[e.g. Shepherd and McLandress 2011]*, but…



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[CCMVal2 Report]

Questions

- What drives the Brewer-Dobson Circulation?

- How will the Brewer-Dobson Circulation respond to anthropogenic forcing?

Interactions between Rossby and gravity wave driving complicate the answer to these questions.

What drives the Brewer-Dobson Circulation?

Downward Control *[Haynes et al. 1991]*

$$\frac{\partial \overline{u}}{\partial t} - \overline{v}^*(f - \frac{\partial \overline{u}}{\partial y}) + \overline{w}^* \frac{\partial \overline{u}}{\partial z} = \mathcal{F}$$

zonal mean torque

(Transformed Eulerian Mean momentum equation)

Downward Control *[Haynes et al. 1991]*

$$\cancel{\frac{\partial \overline{u}}{\partial t}} - \overline{v}^*(f - \frac{\partial \overline{u}}{\partial y}) + \overline{w}^* \frac{\partial \overline{u}}{\partial z} = \mathcal{F}$$

zonal mean torque

steady state

Downward Control *[Haynes et al. 1991]*

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zonal mean torque

QG (neglect relative vorticity)

Downward Control *[Haynes et al. 1991]*

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zonal mean torque

Coriolis force must balance torque

$$\overline{v}^* = -\frac{\mathcal{F}}{f}$$

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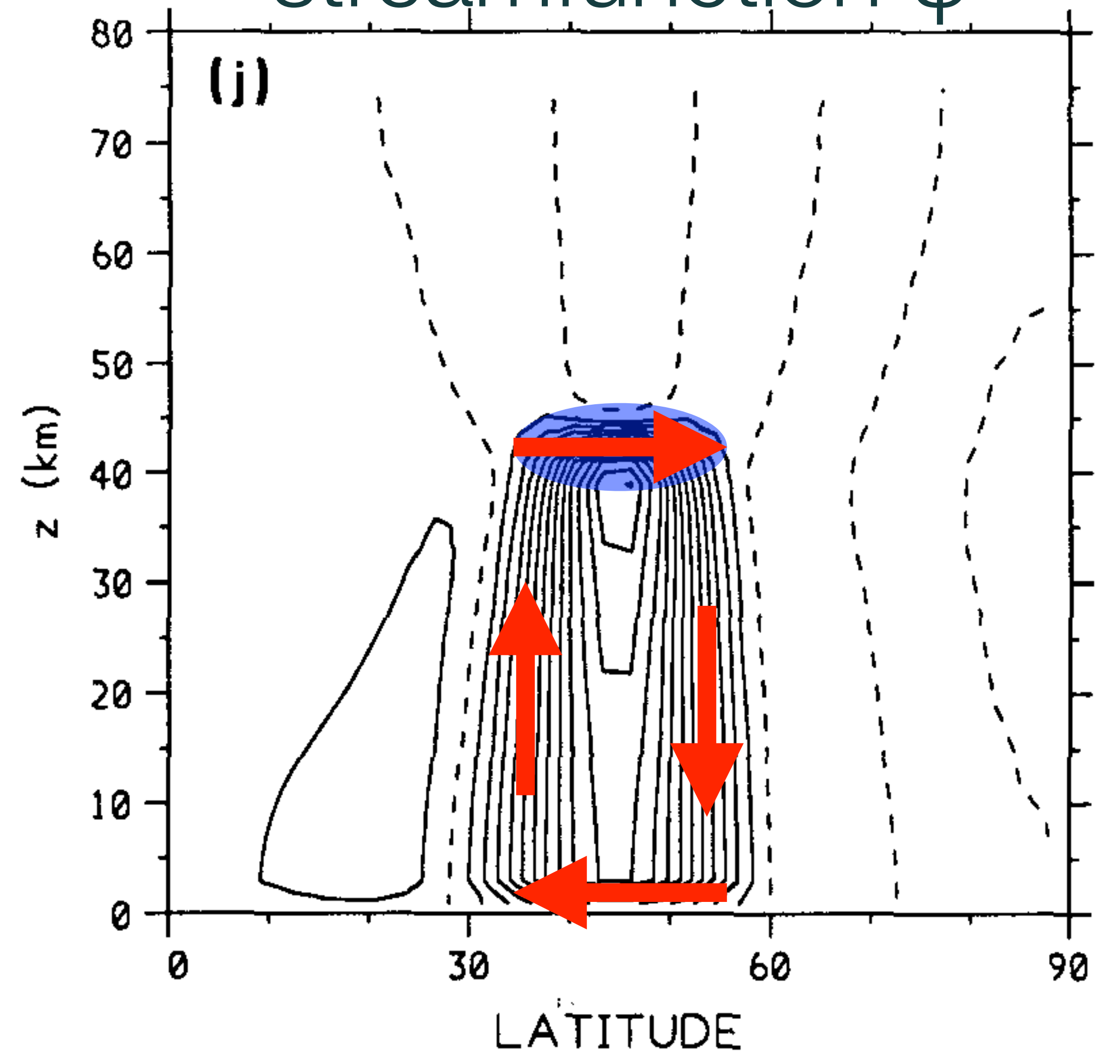
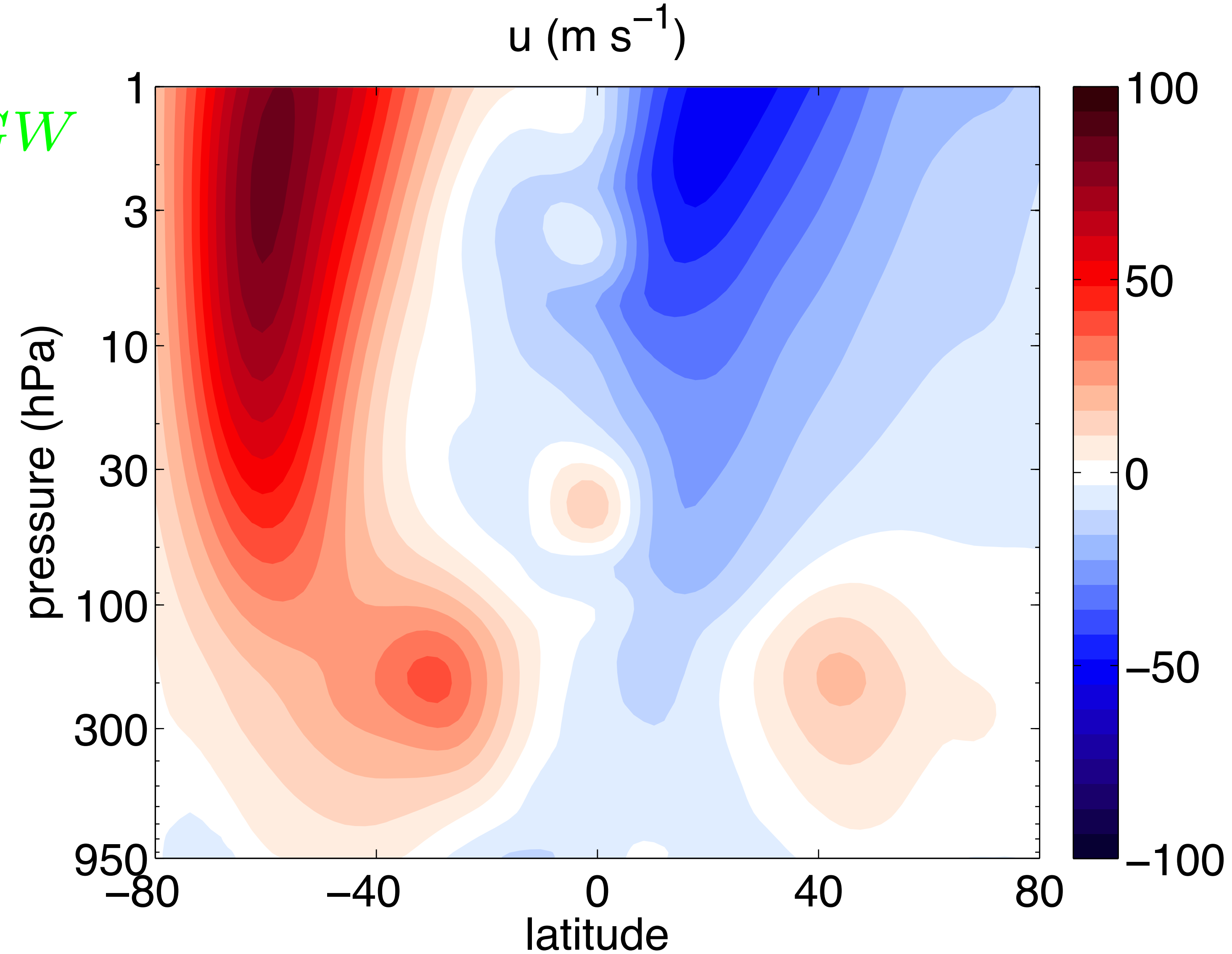
streamfunction ψ



Which waves contribute to the zonal mean torque?

$$\mathcal{F} = \nabla \cdot F + G_{OGW} + G_{NOGW}$$

JJA zonal mean zonal wind



ECHAM6 (MPI-ESM-MR)
(courtesy of Felix Bunzel)

Which waves contribute to the zonal mean torque?

$$\mathcal{F} = \nabla \cdot F + G_{OGW} + G_{NOGW}$$

Eliassen-Palm flux divergence: Rossby waves, planetary and synoptic; fairly well observed, resolved in models.

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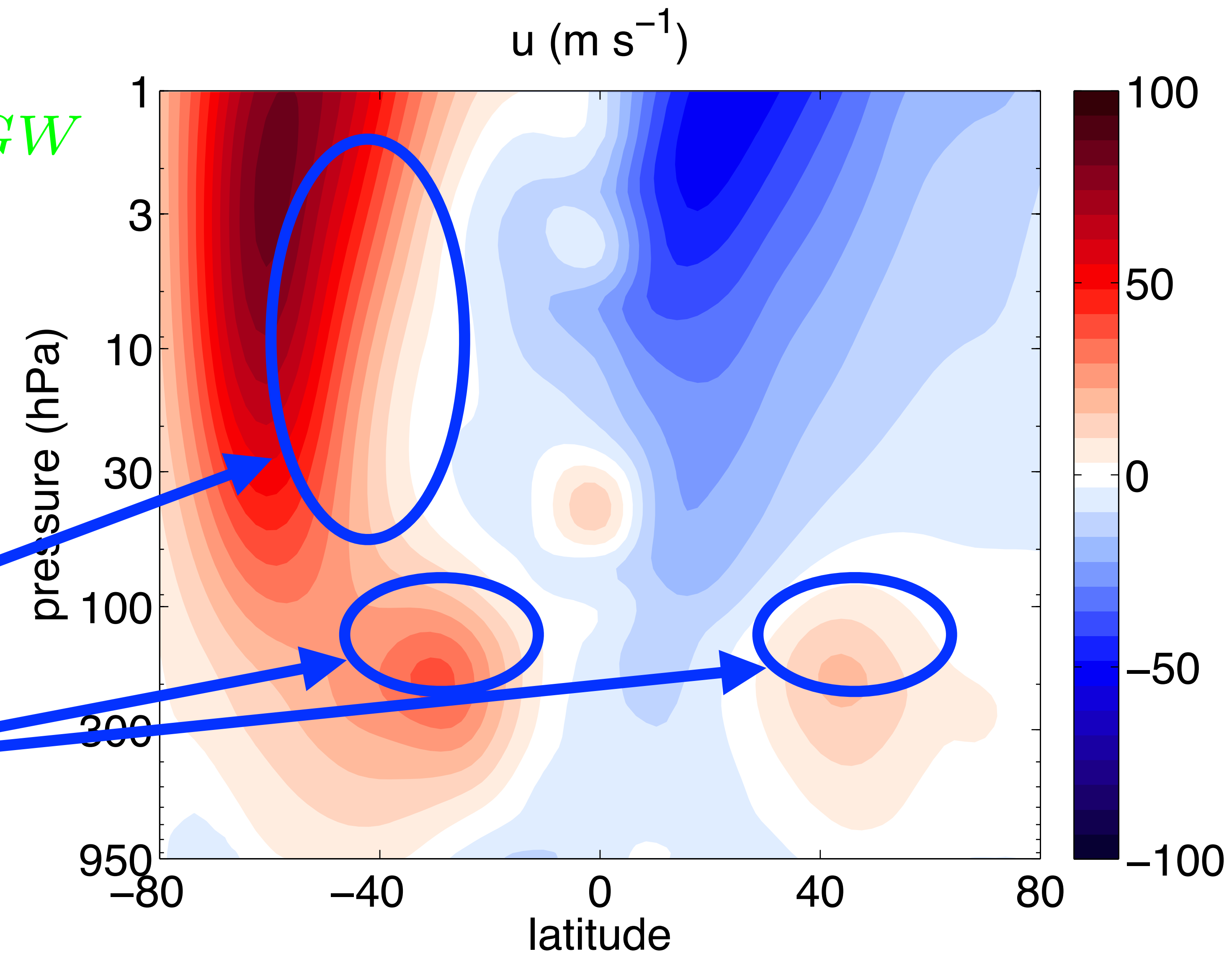

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orographic gravity waves, of scale 10-1000 km, generated in stratified flow over topography; marginally observed, parameterized in models

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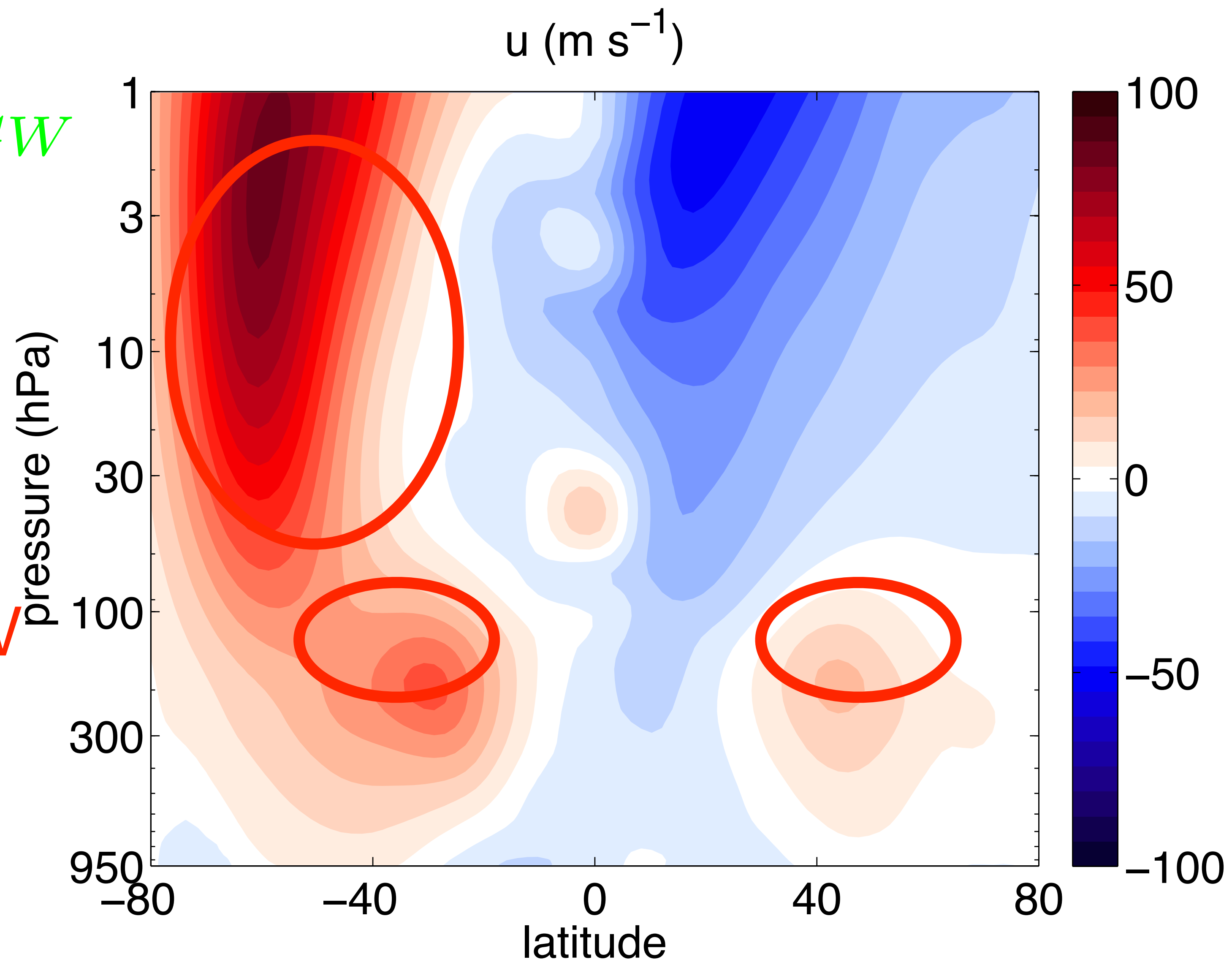

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non-orographic gravity waves: generated via convection, frontal instabilities (thus have non-zero phase speed), less well observed, parameterized in models

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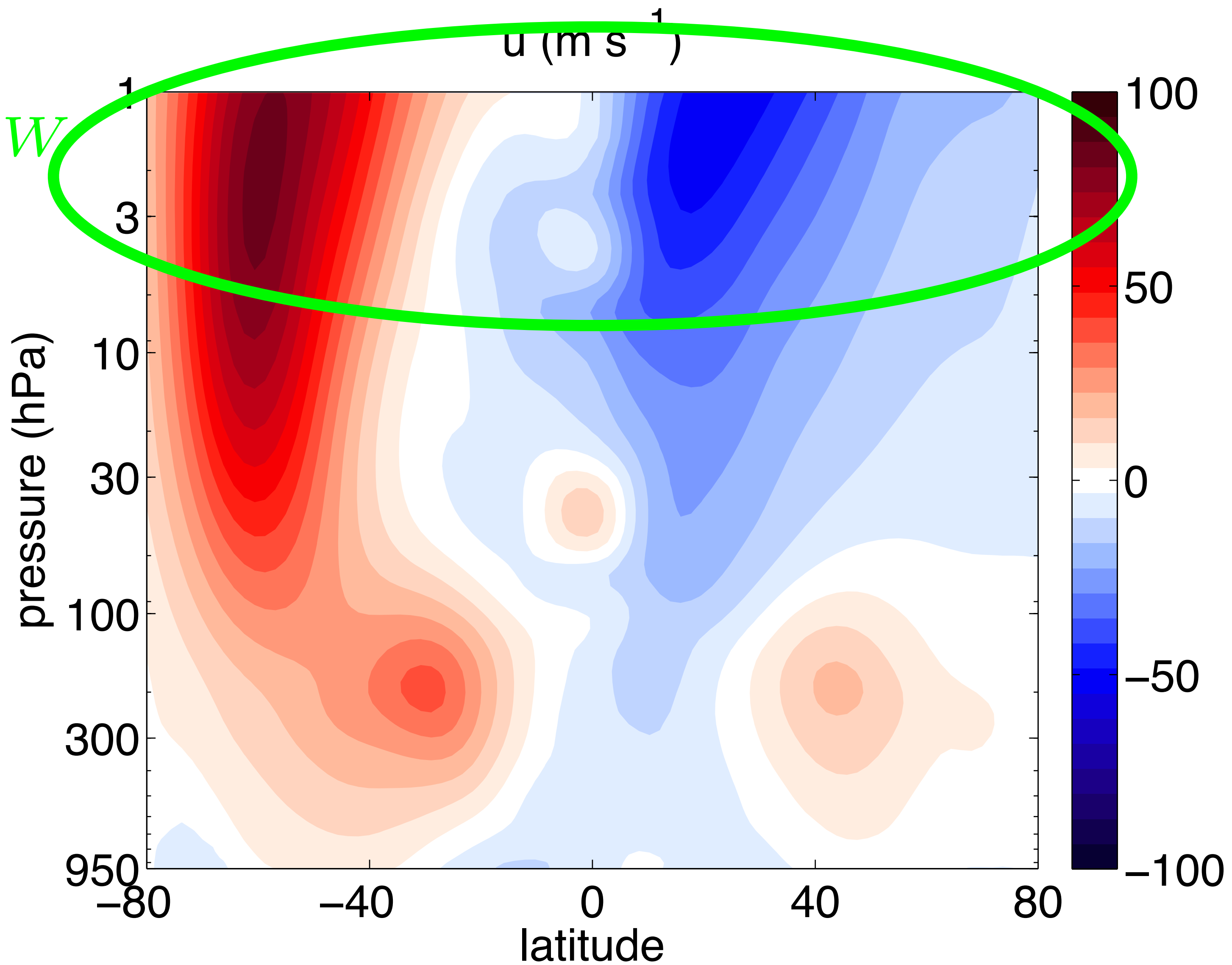

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using downward control, one can partition the circulation

$$\psi = \psi_{EPFD} + \psi_{OGW} + \psi_{NOGW}$$

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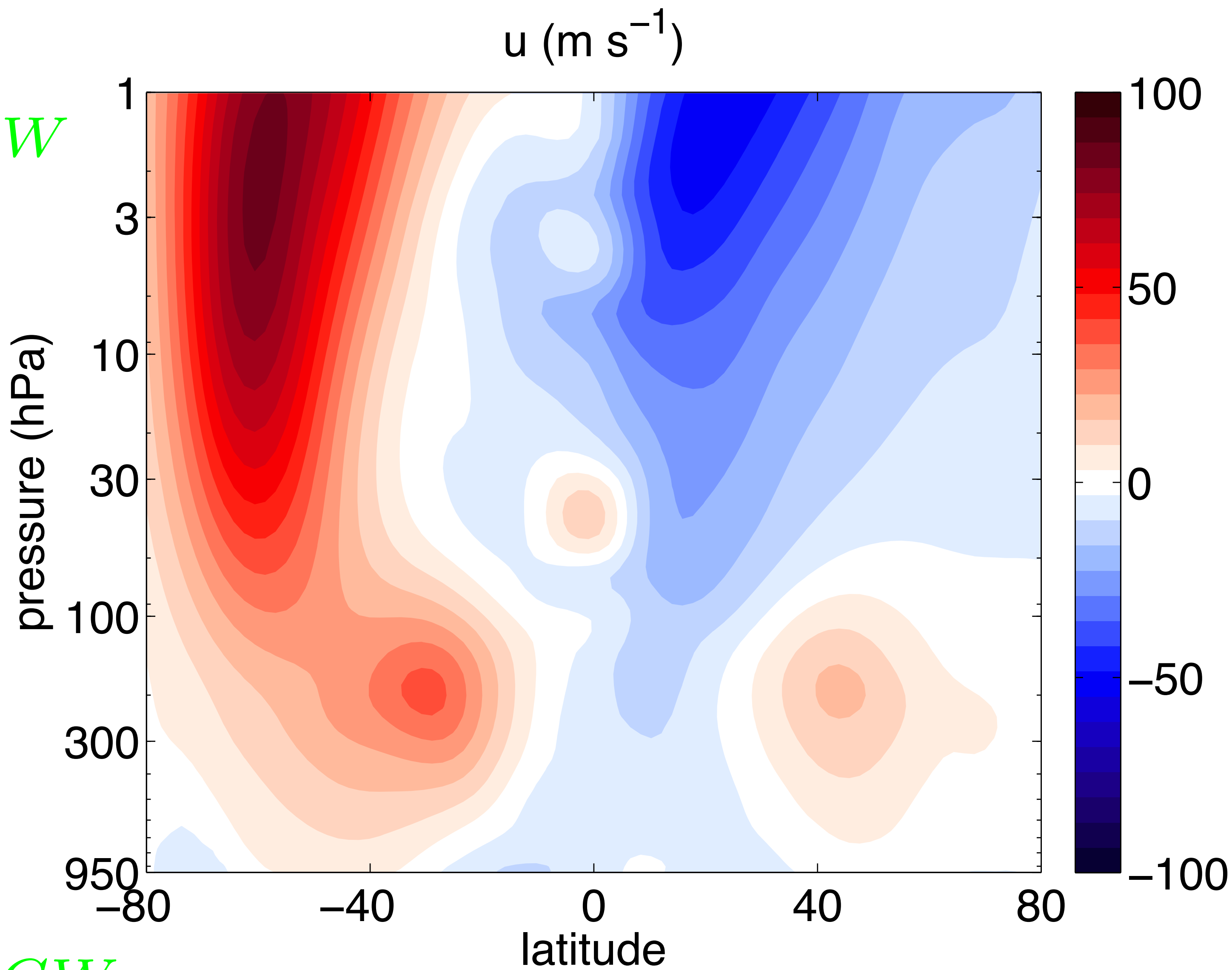

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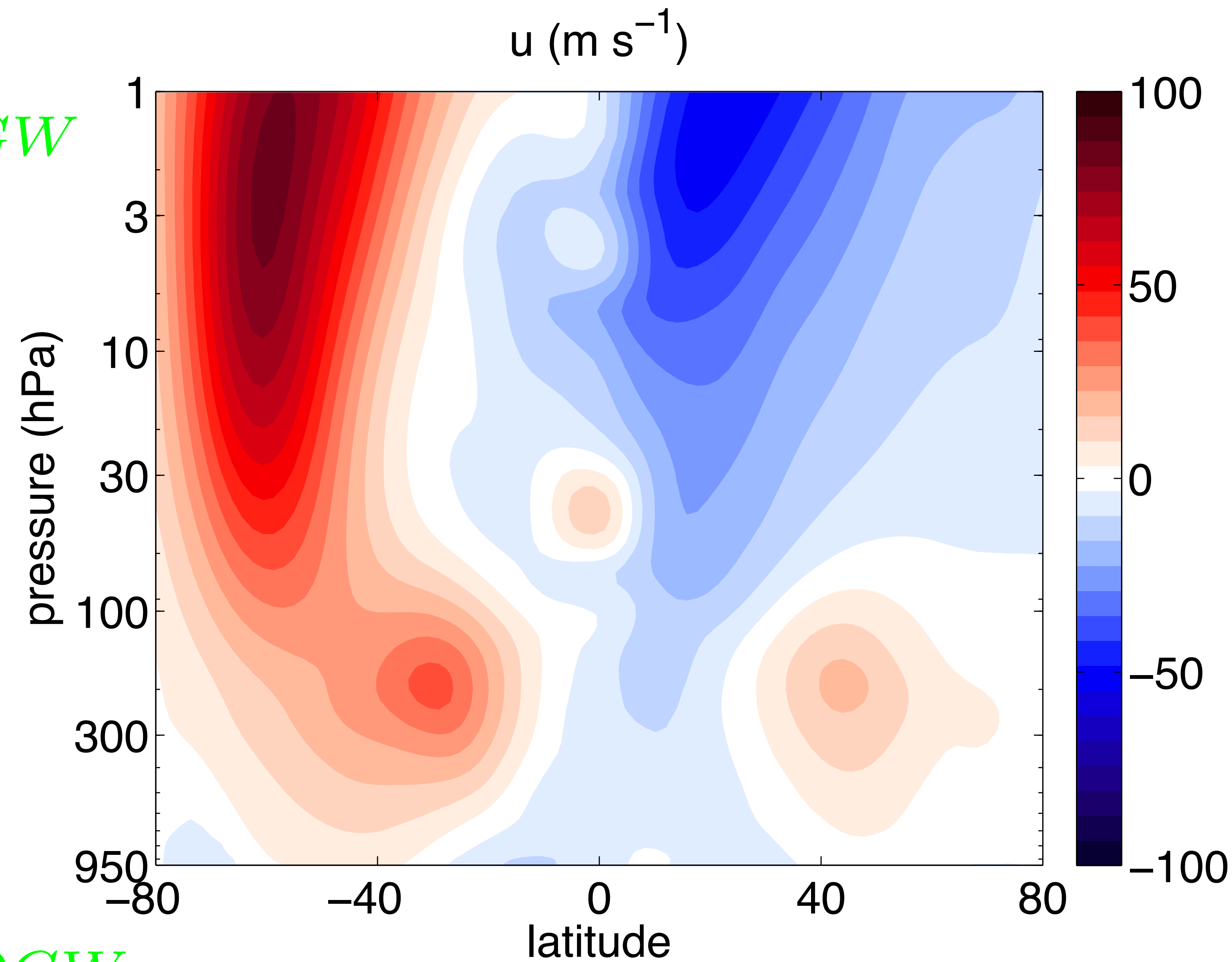
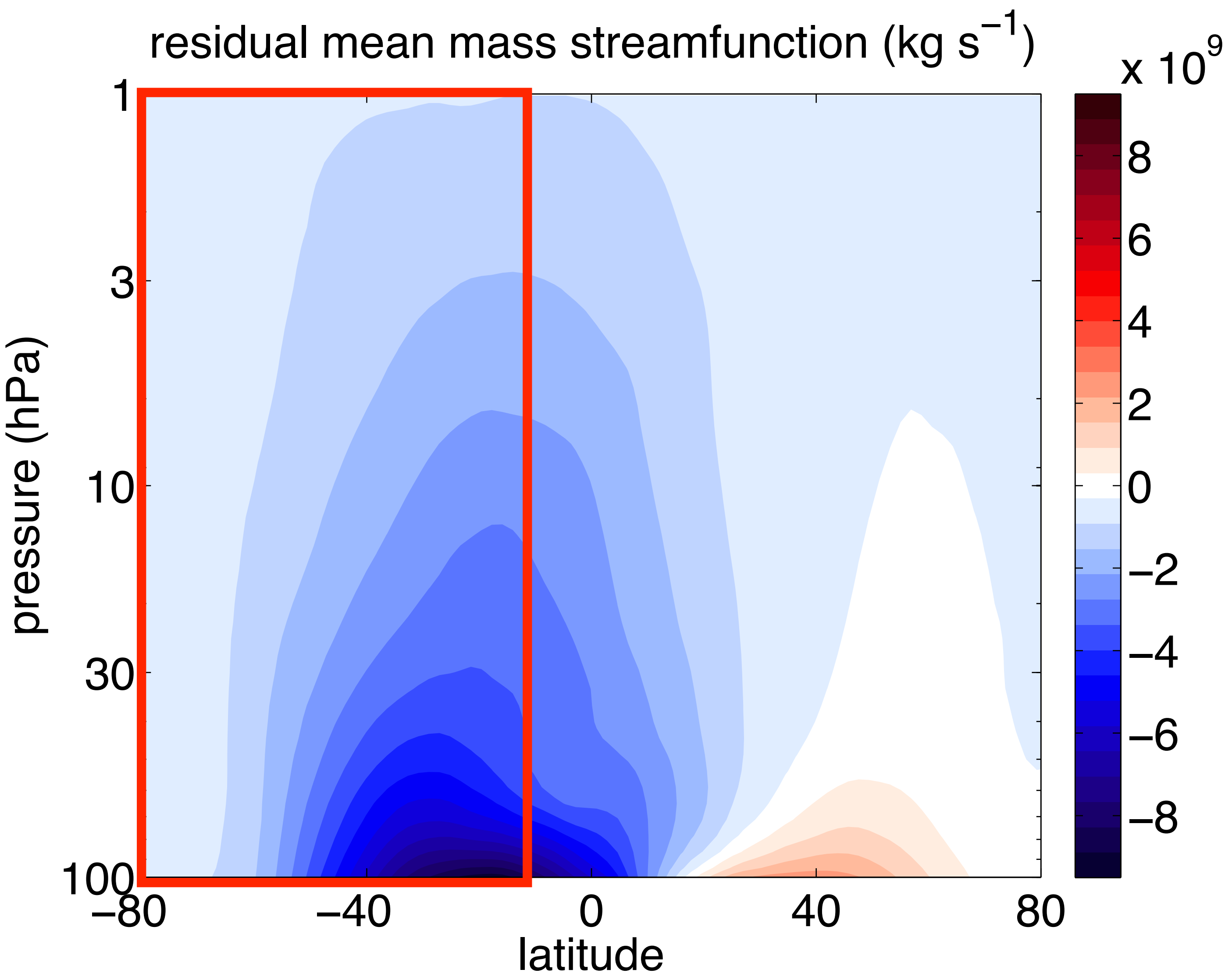


implicit assumption: the wave forcings are independent

The JJA Residual Circulation in ECHAM6



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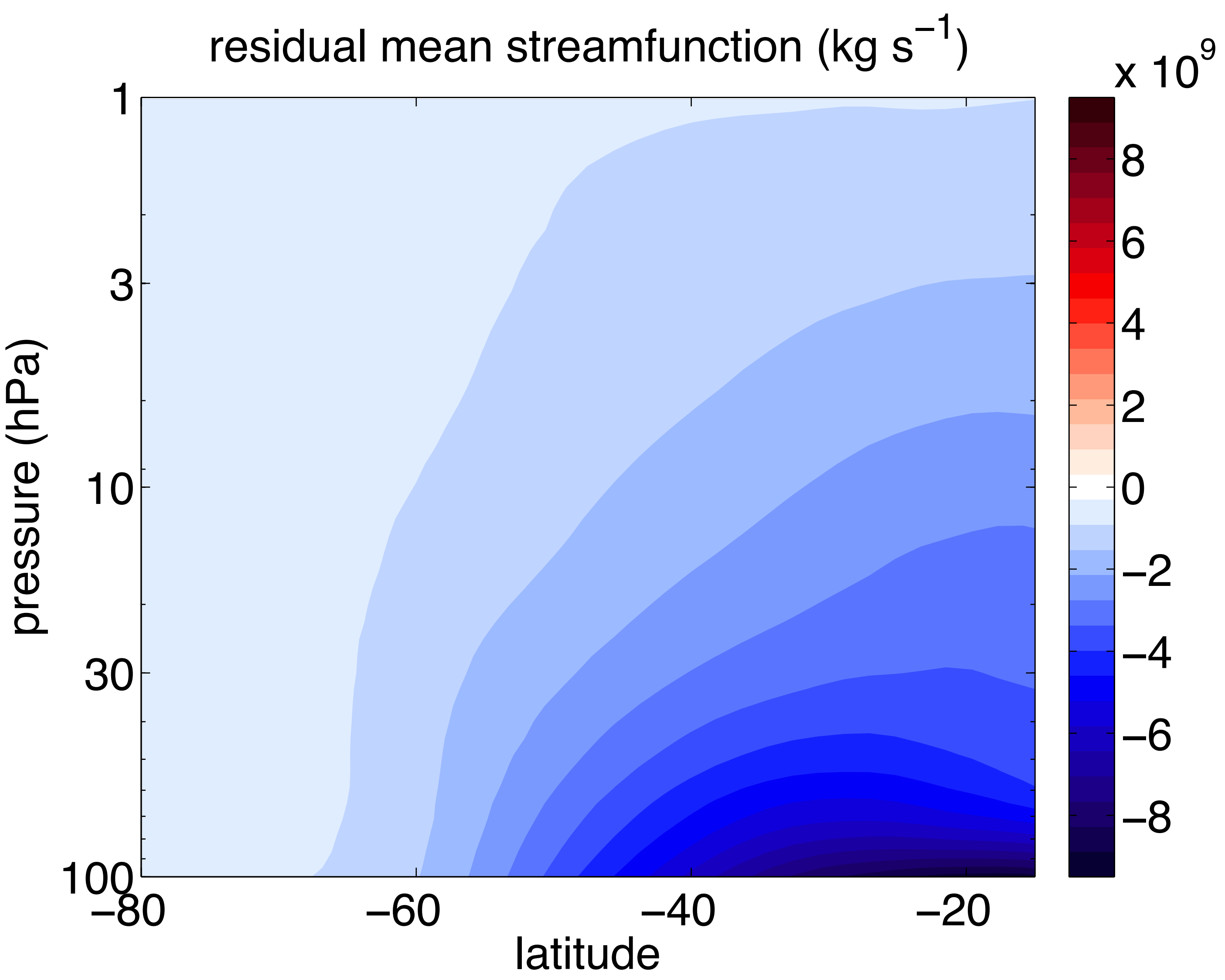
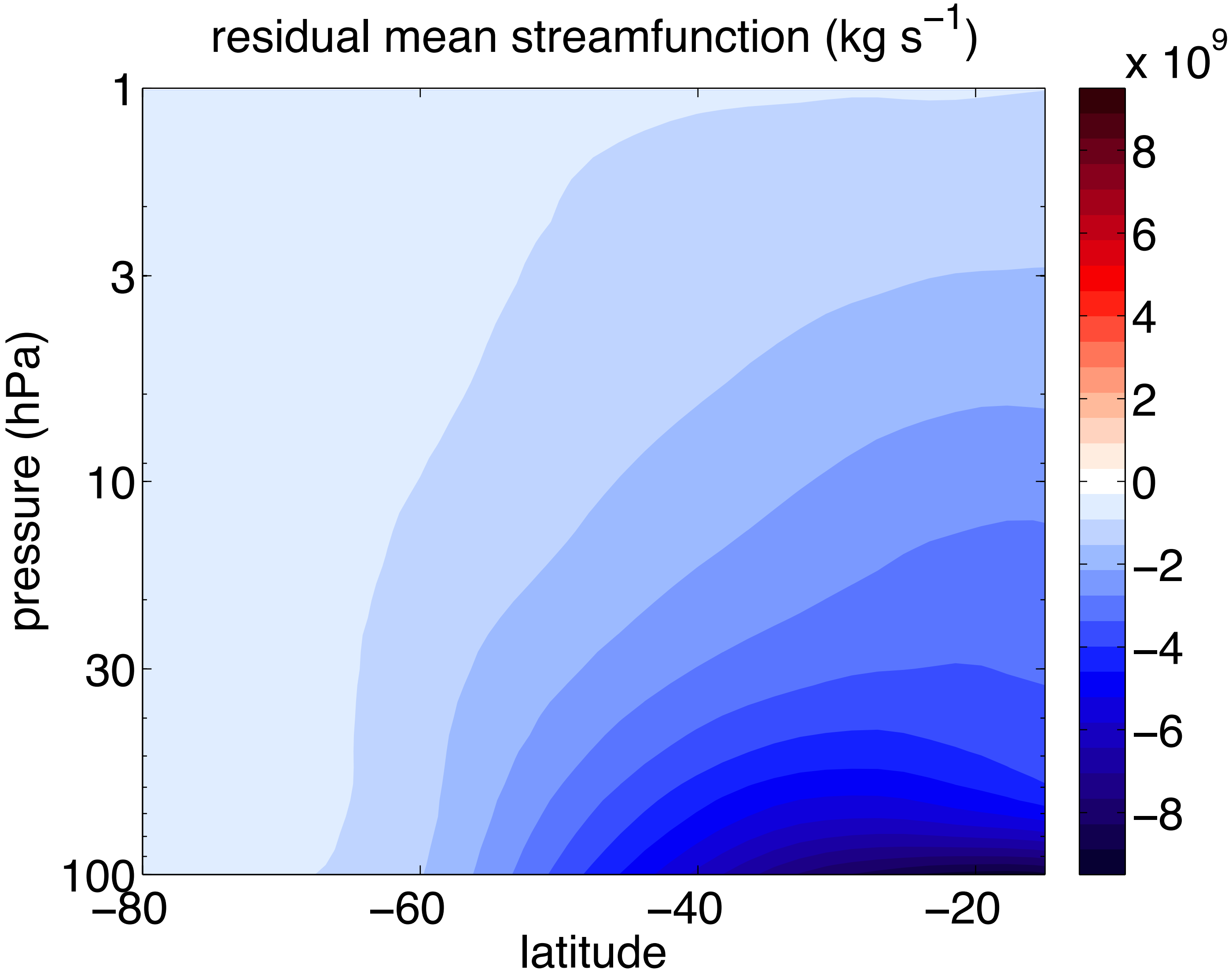
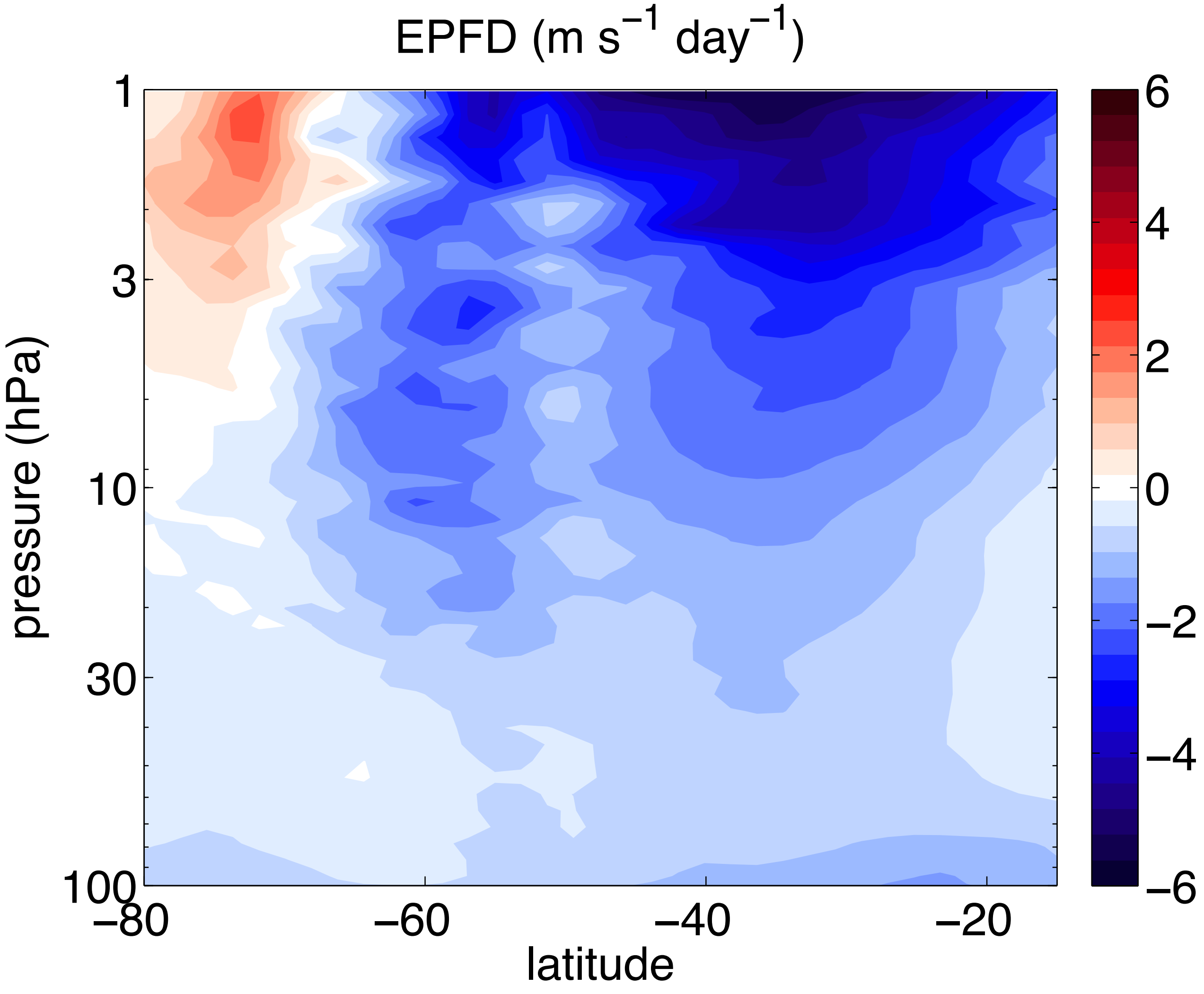


Breaking down the streamfunction





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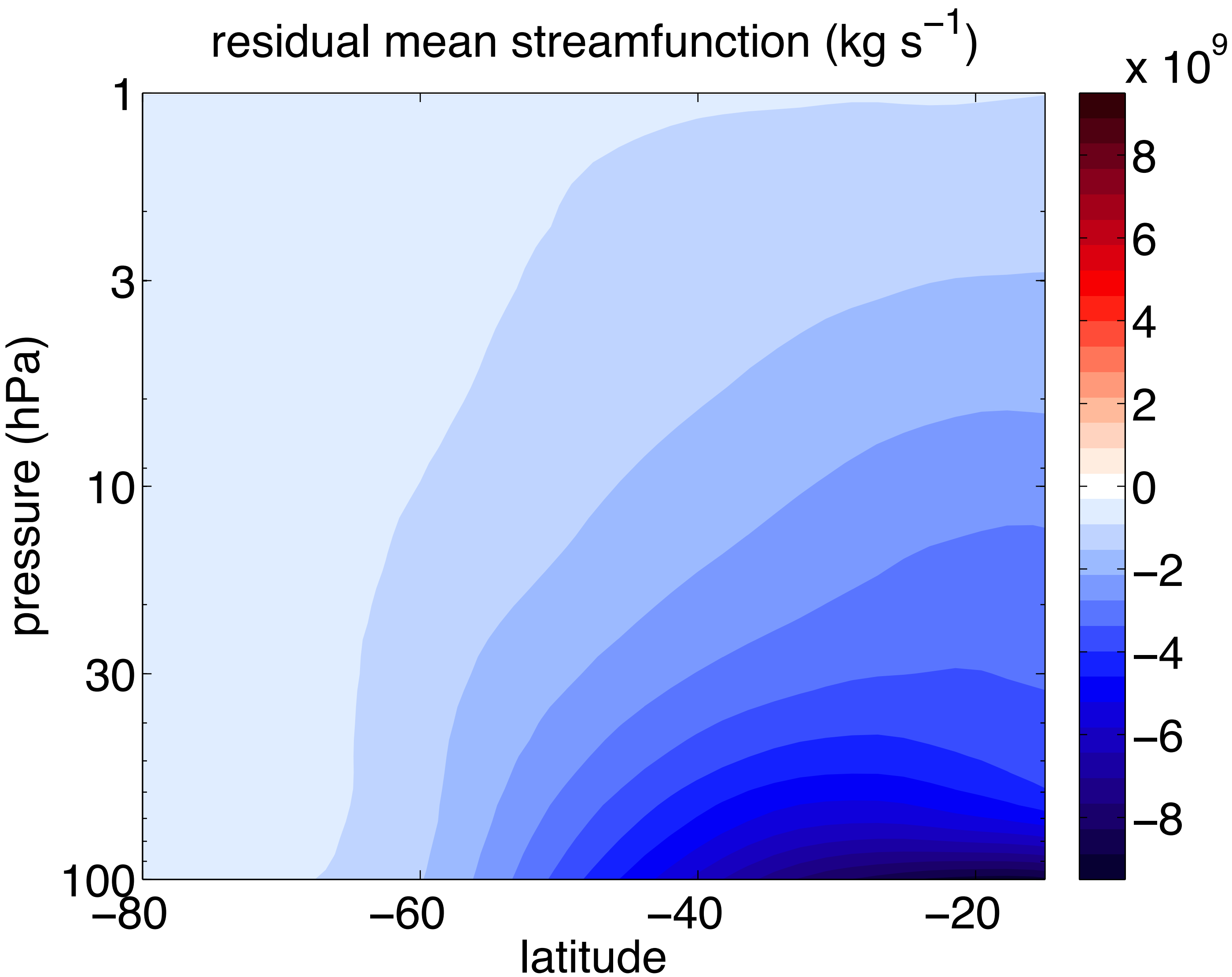

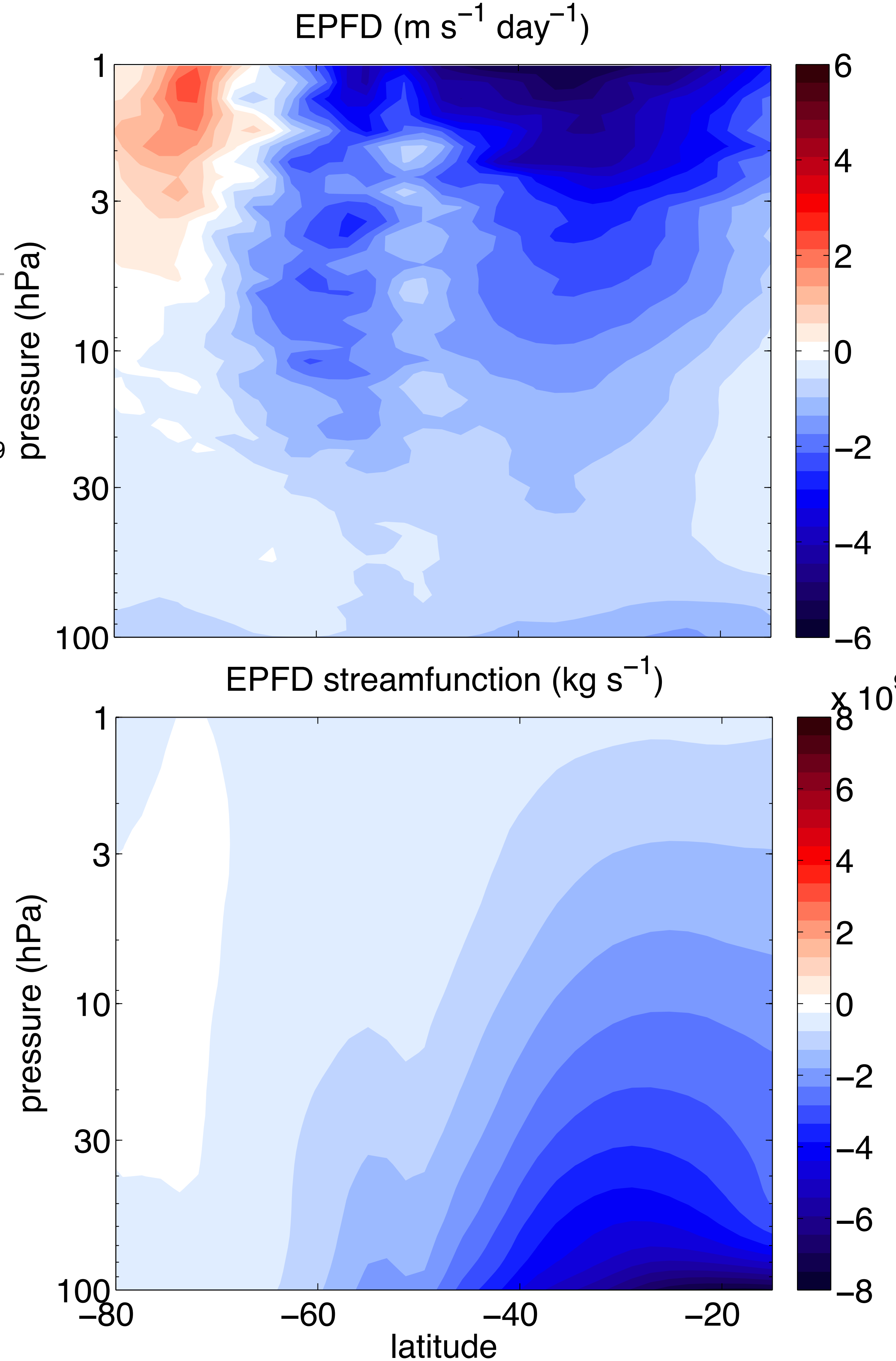

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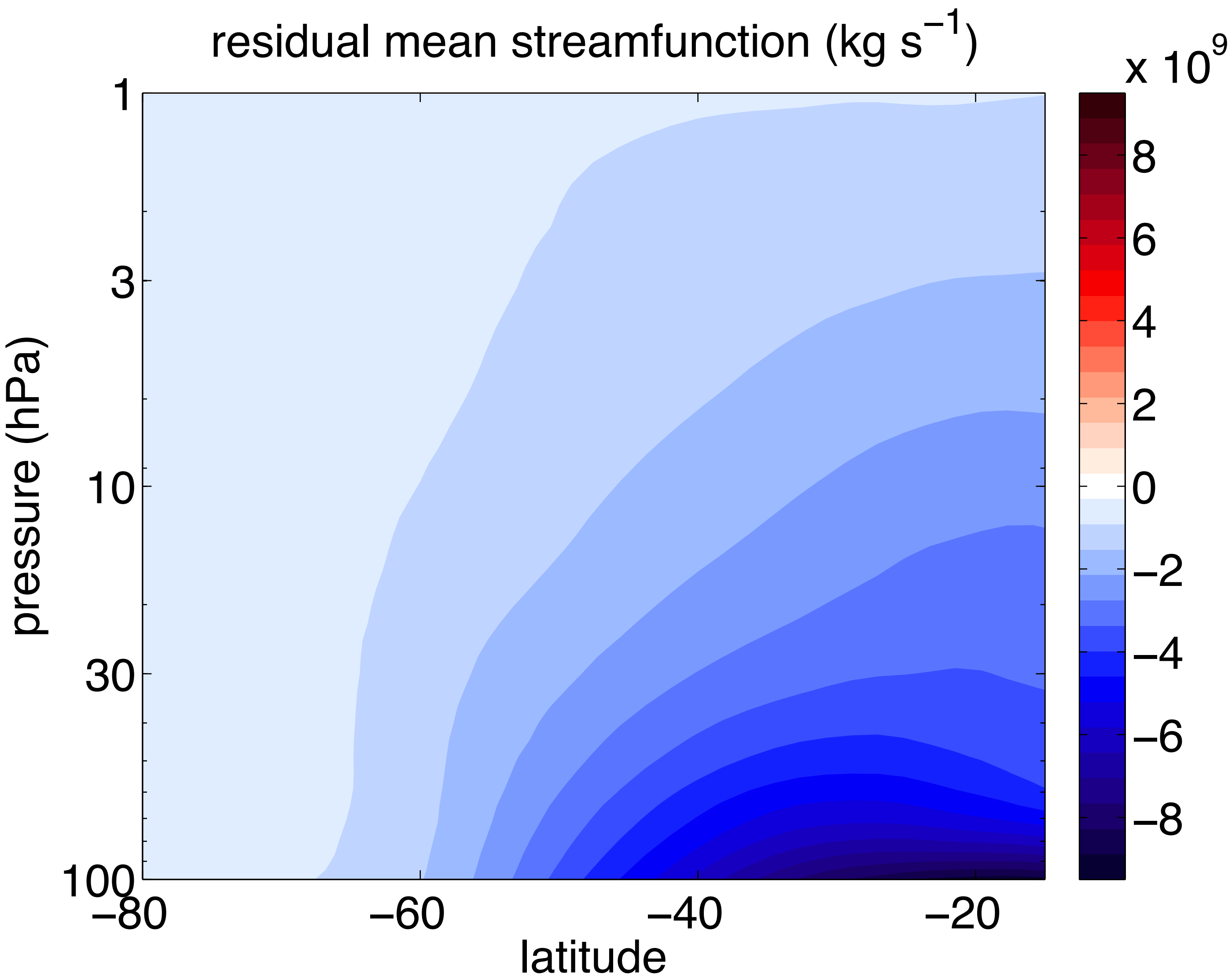

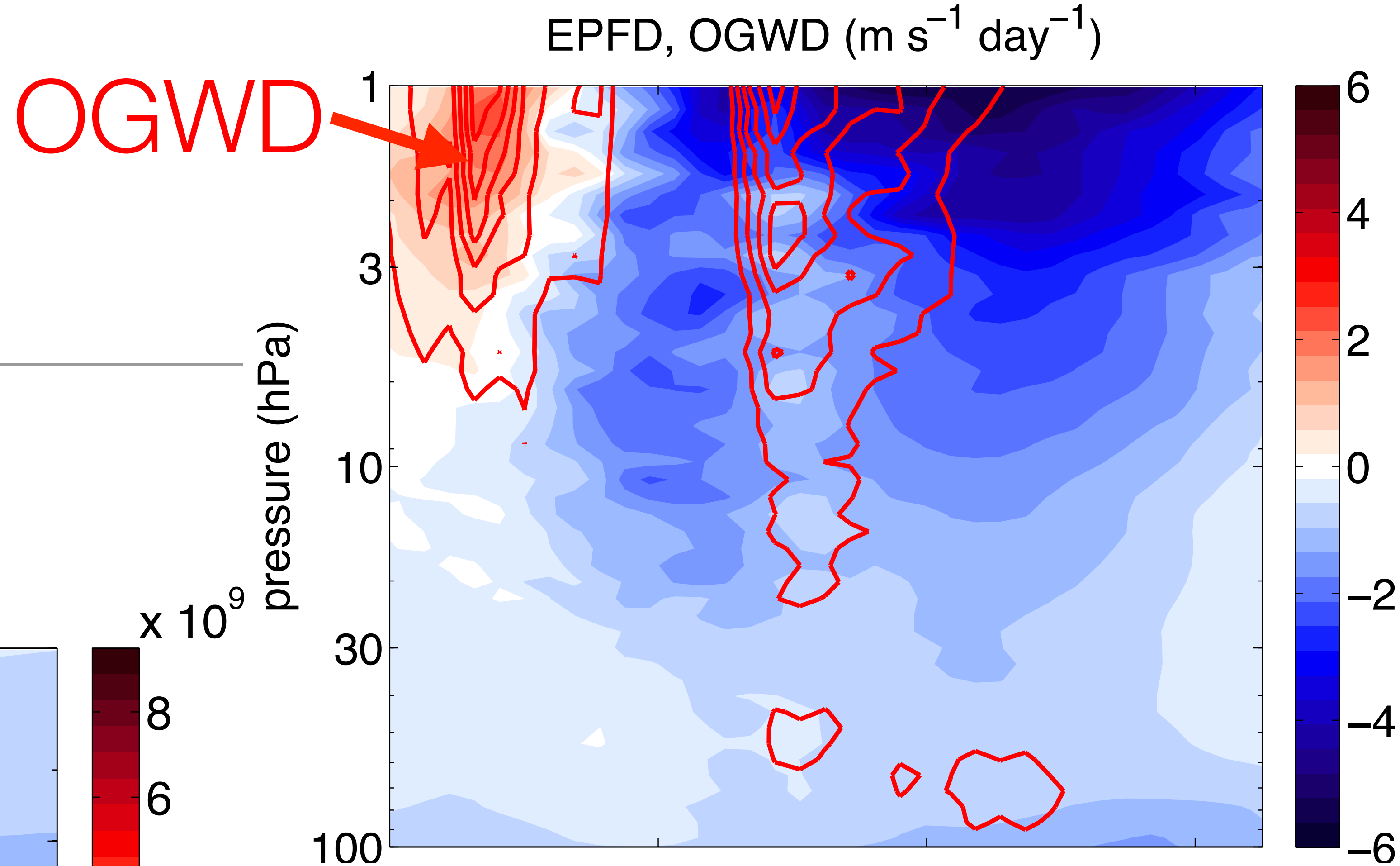

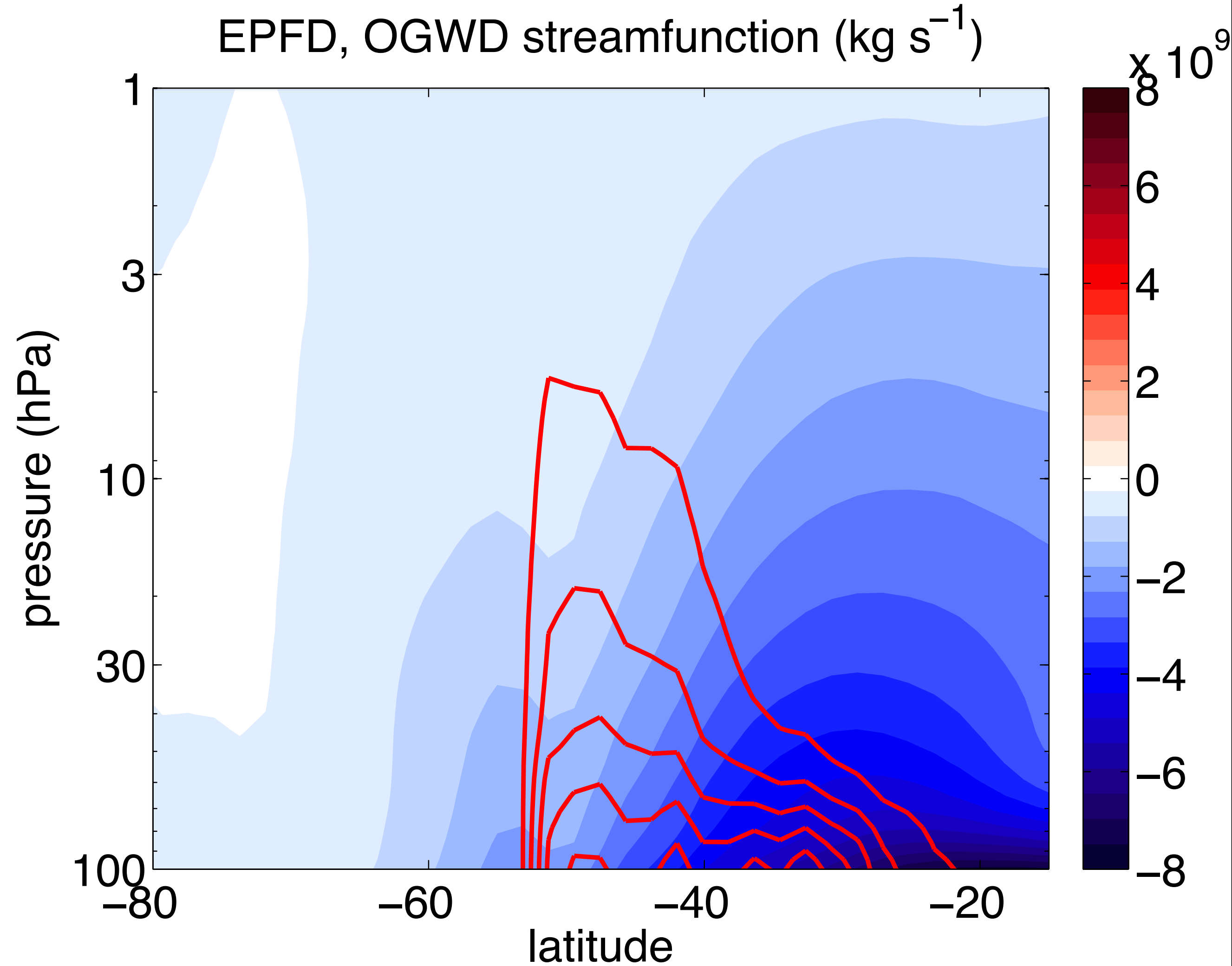

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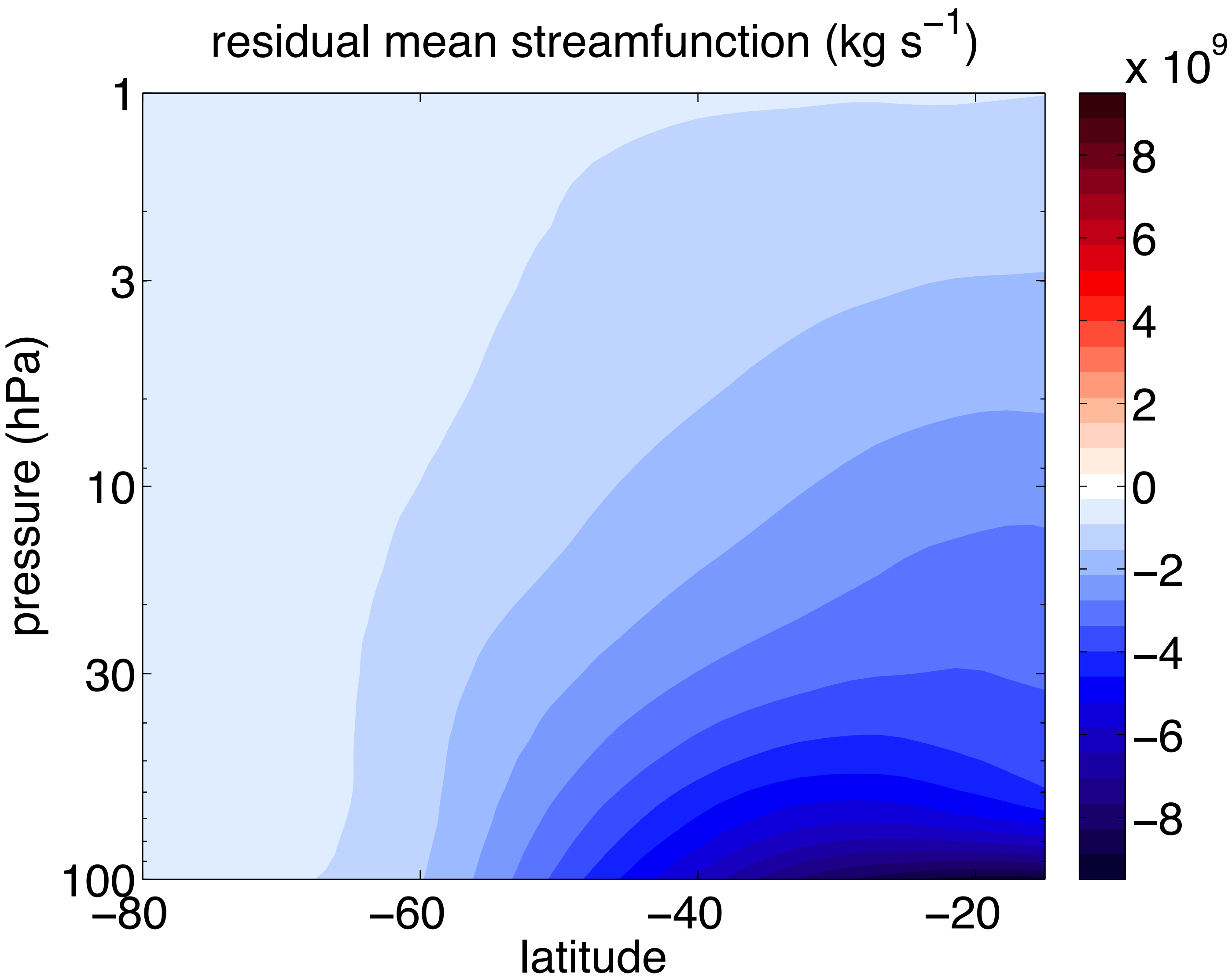
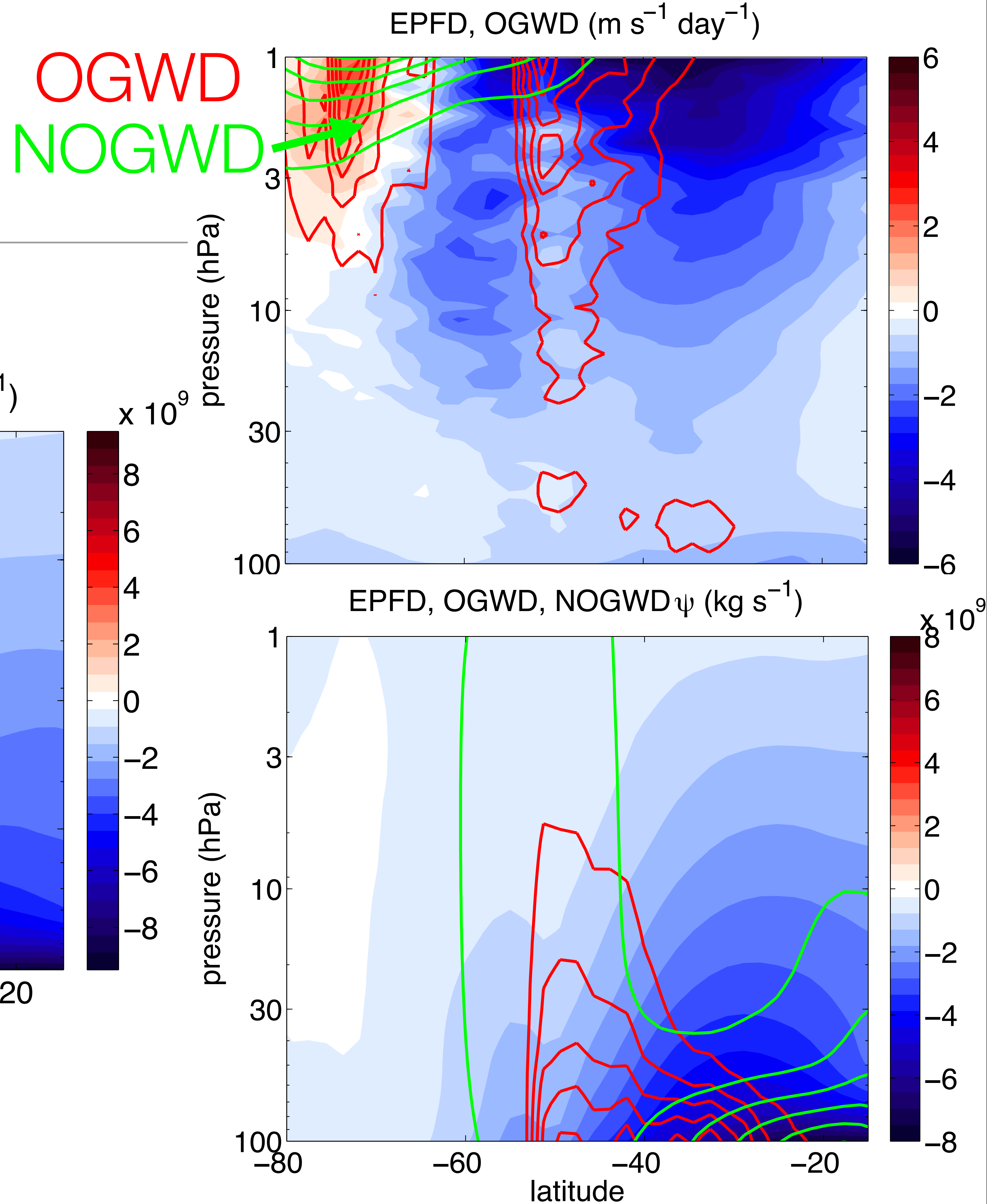
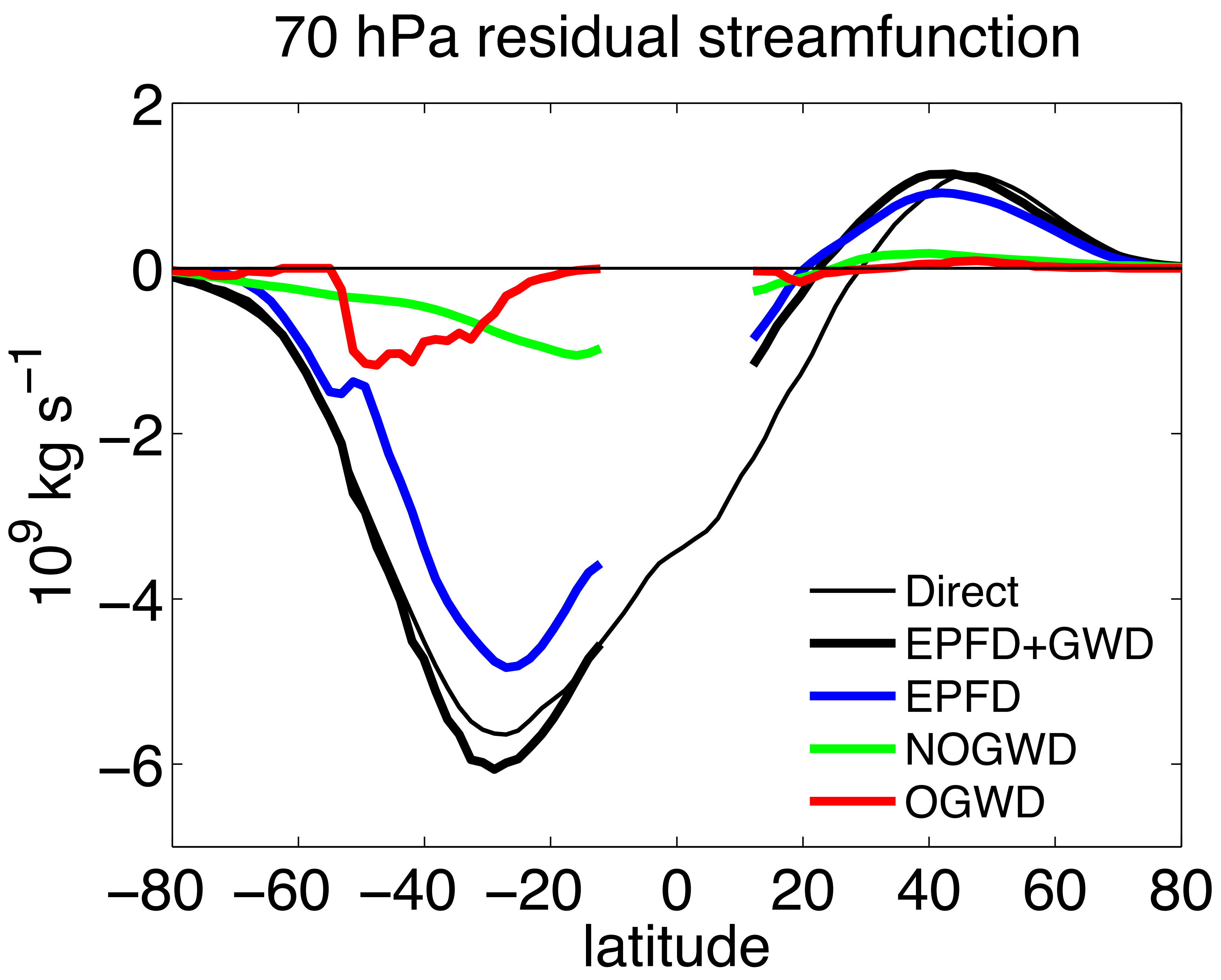
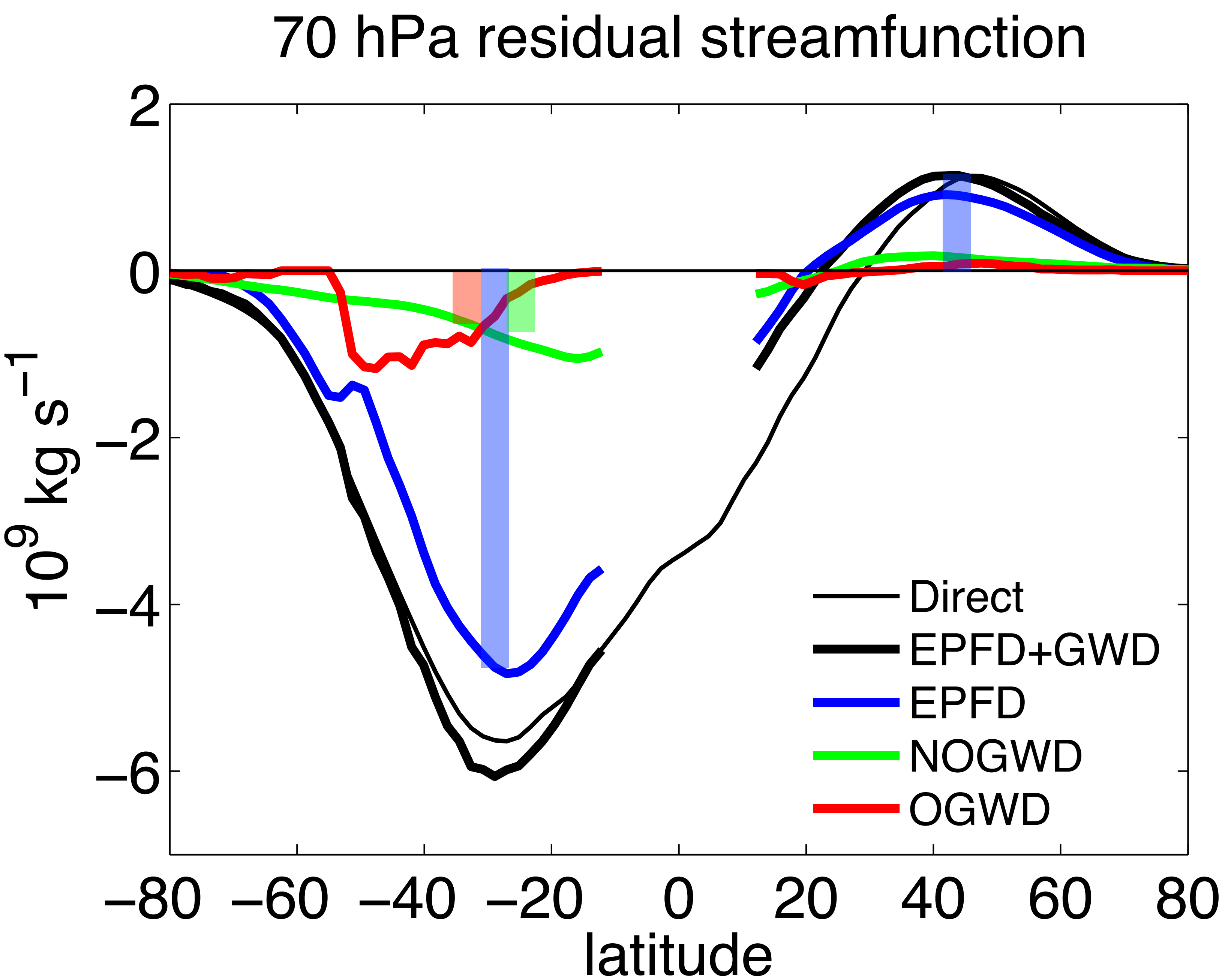




Puzzle pieces fit together to provide a smooth circulation!



This decomposition of the BDC is used to assess the roles of each type of wave driving.



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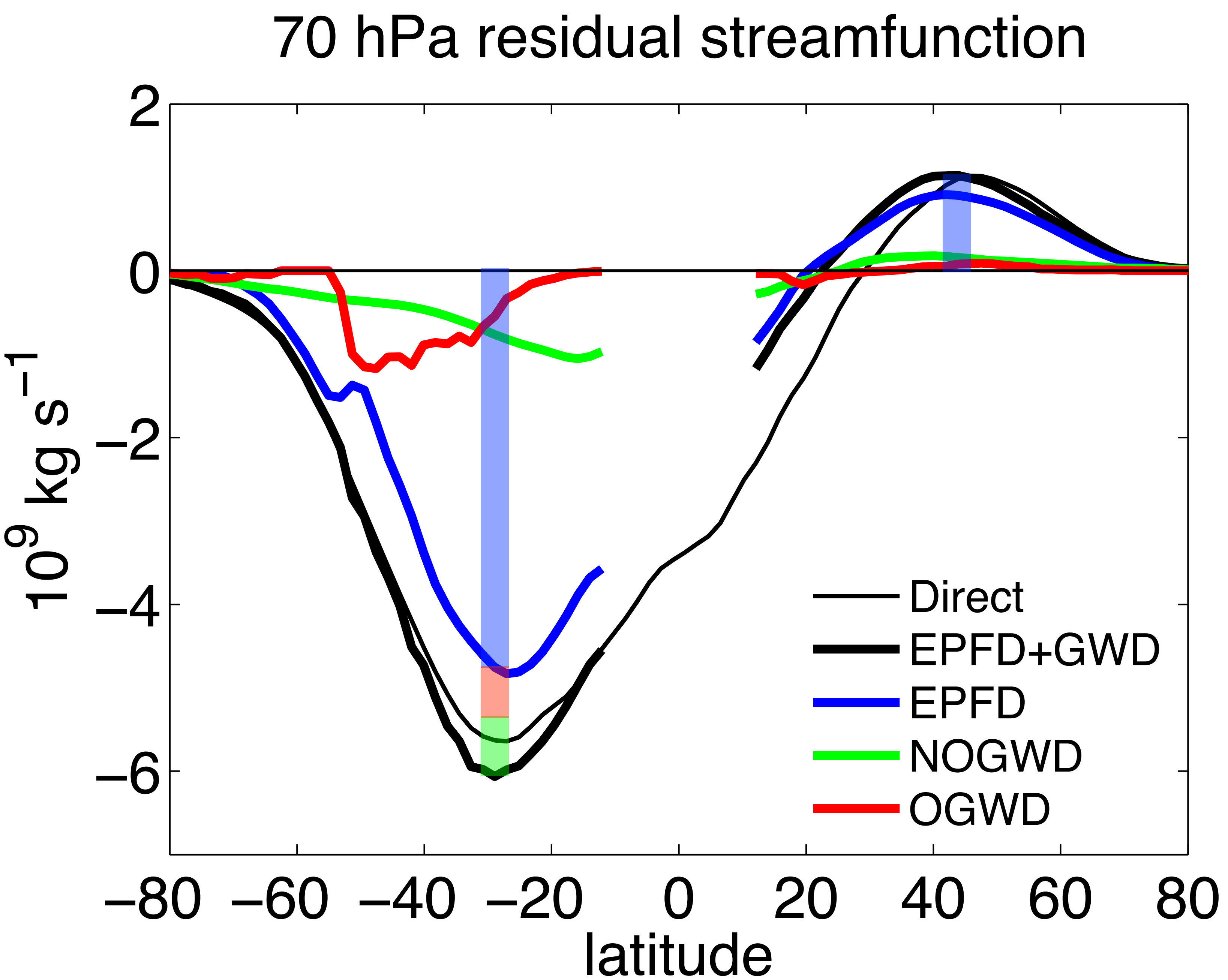
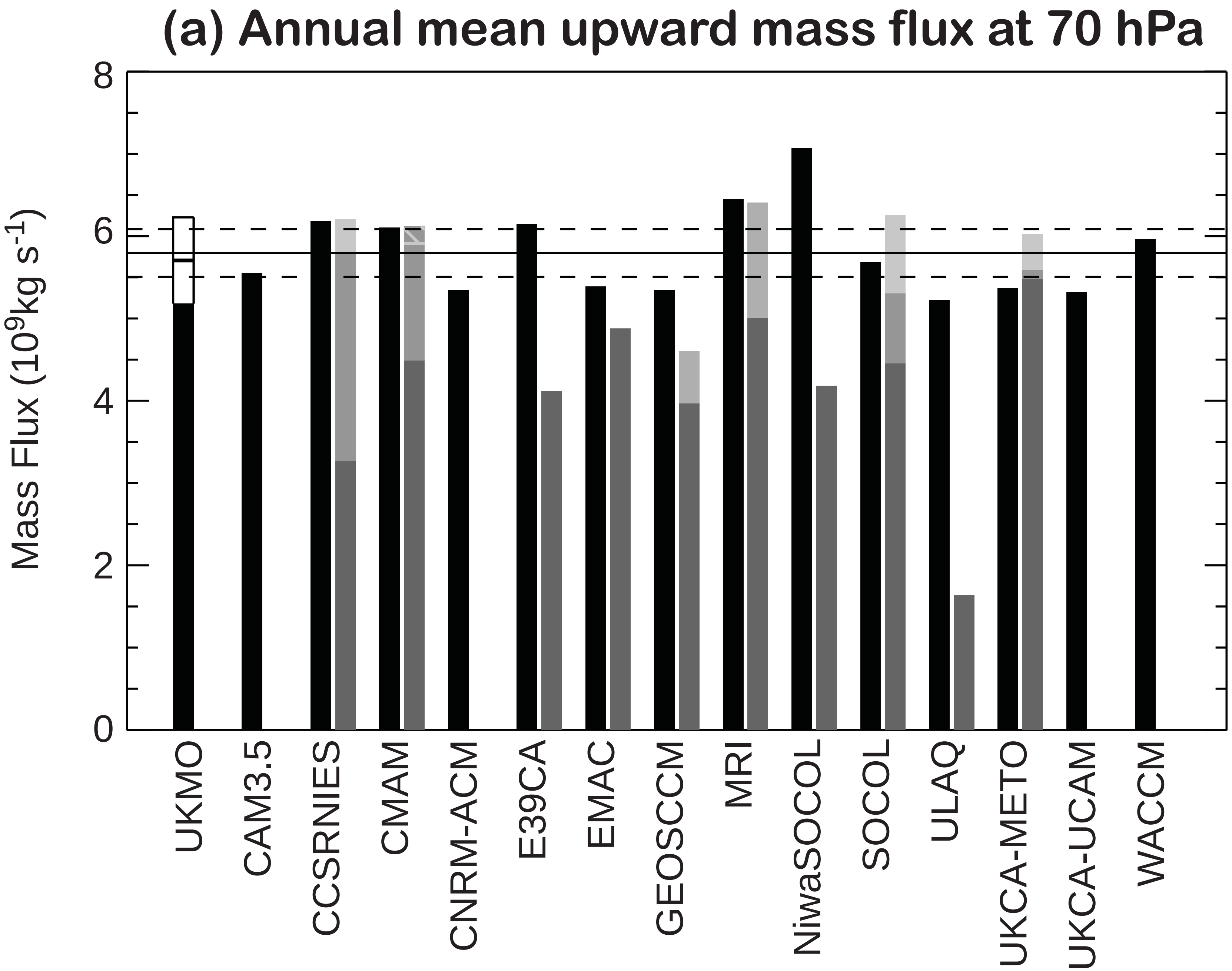


What drives the Brewer-Dobson Circulation?



total

Rossby waves

orographic GW

non-orographic GW

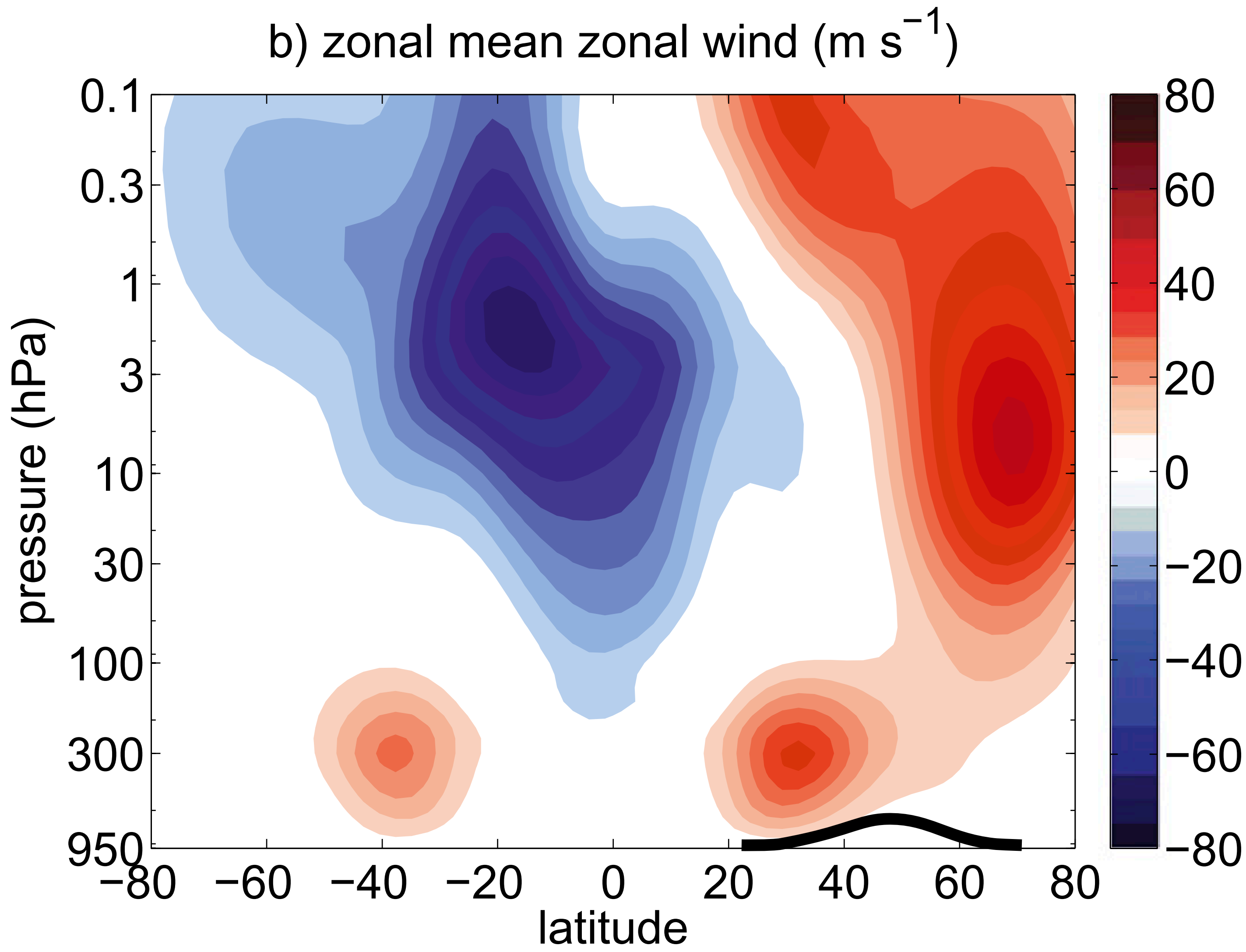
[CCMVal2 Report, Chpt 4]

Why do the models agree more on
the total circulation than on
the components?

How do the components fit together
so nicely to produce a smooth circulation?

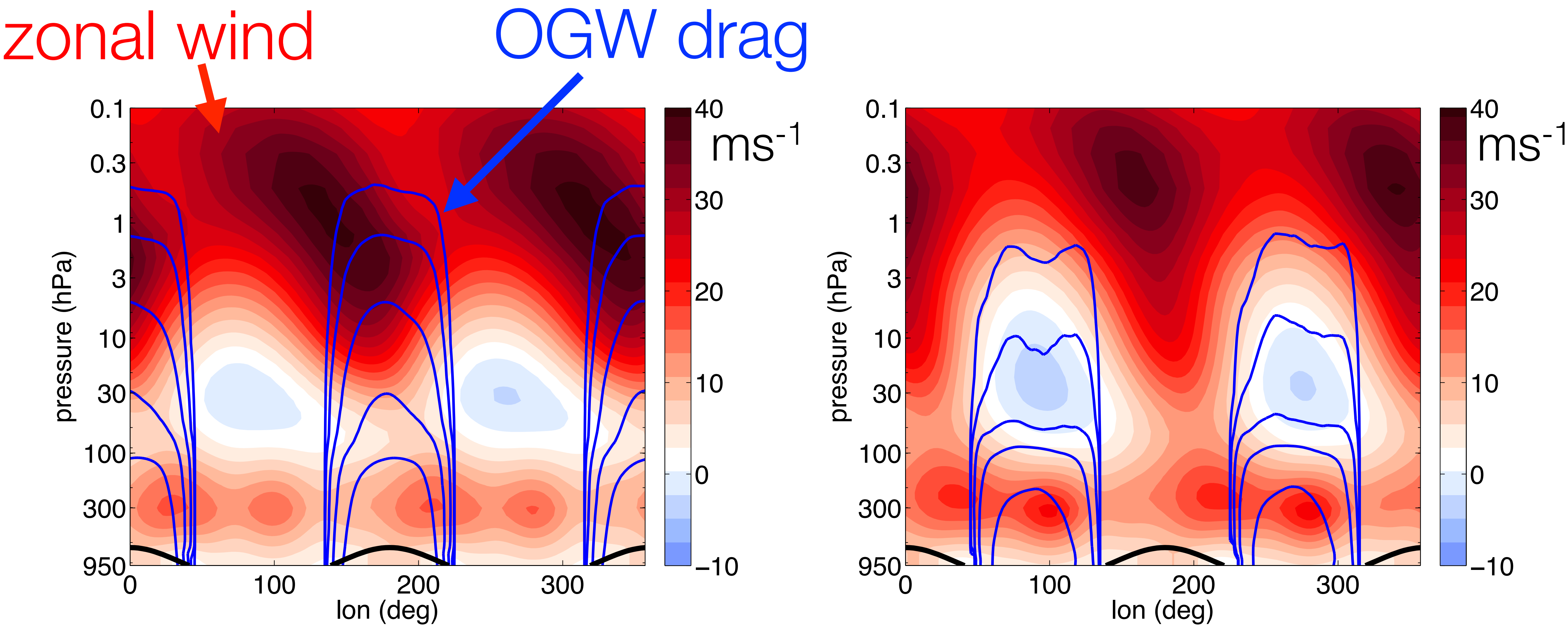
An idealized Atmospheric GCM

- dry primitive equations on the sphere
- Newtonian relaxation of temperature to radiative-convective equilibrium profile *[Held and Suarez 1994; Polvani and Kushner 2002]*
- Simple large scale topography *[Gerber and Polvani, 2009]*
- *Alexander and Dunkerton [1999]* non-orographic gravity wave drag
- *Pierrehumbert [1987]* orographic gravity wave drag



[Cohen et al. 2013]

Two experiments:
Perturb the Orographic Gravity Wave Drag

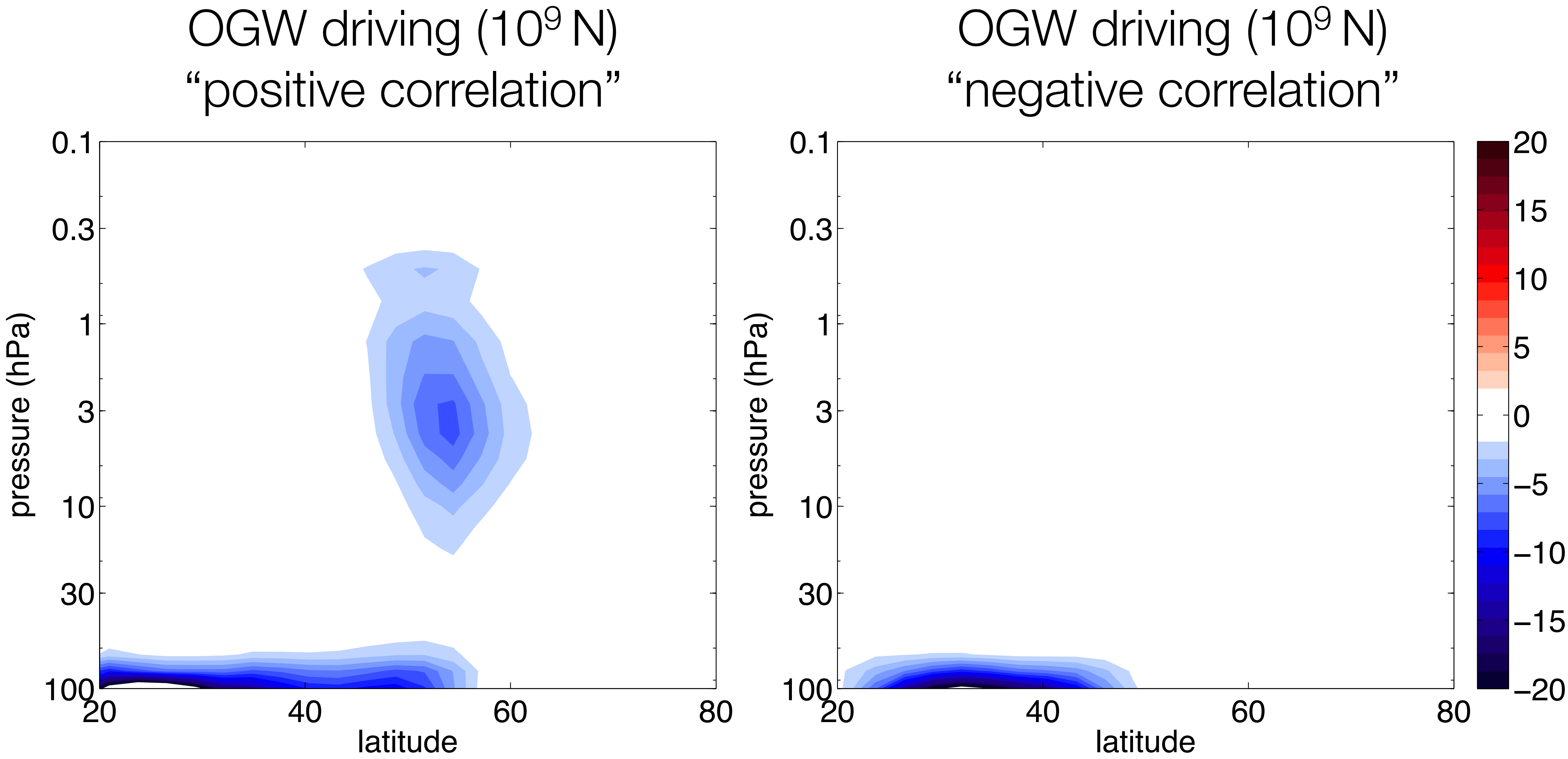


Model A: positive correlation

Model B: negative correlation

[Cohen et al. 2013]

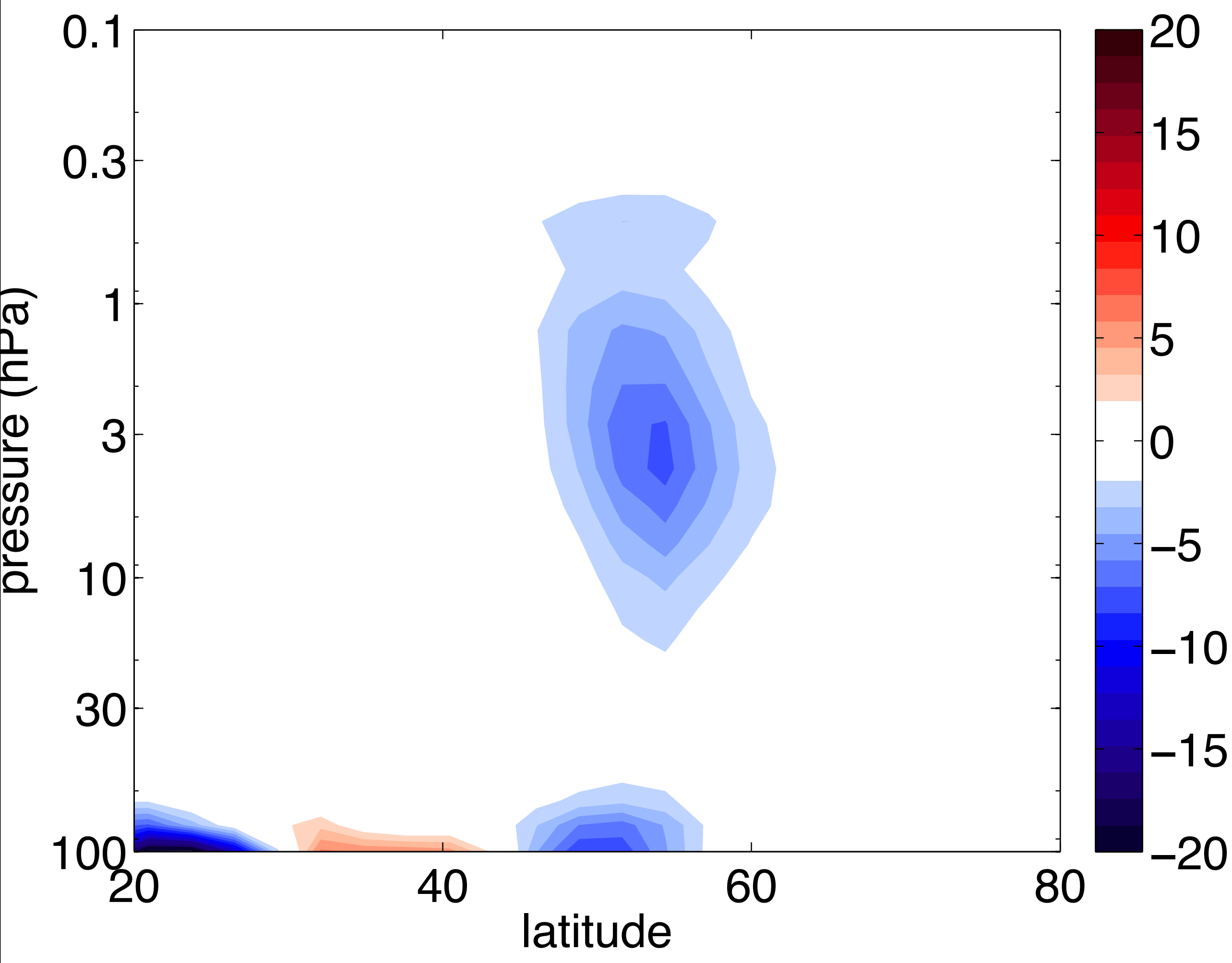
Impact of differences in OGW configuration



[Cohen et al. 2013]

Impact on BDC

difference in OGW driving (10^9 N)



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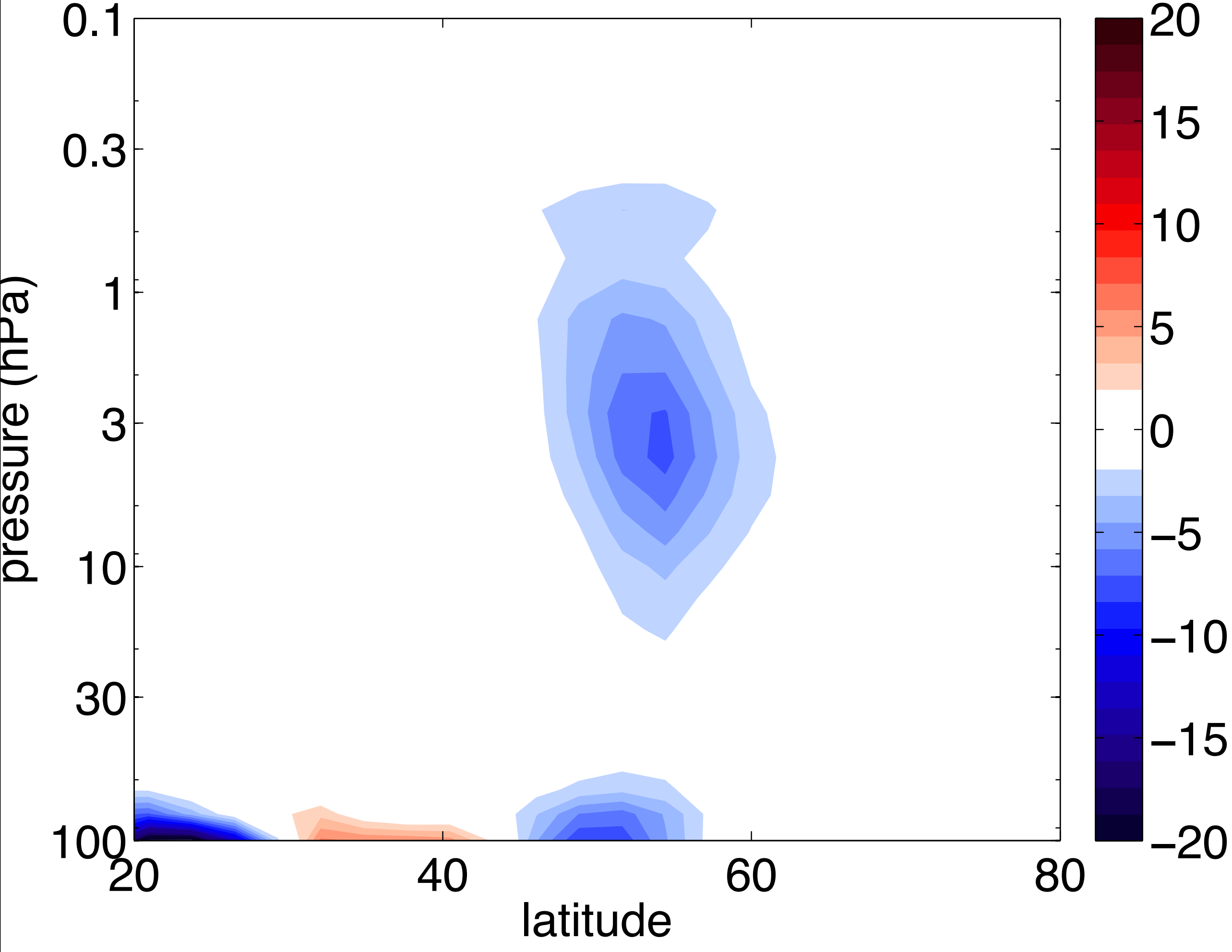

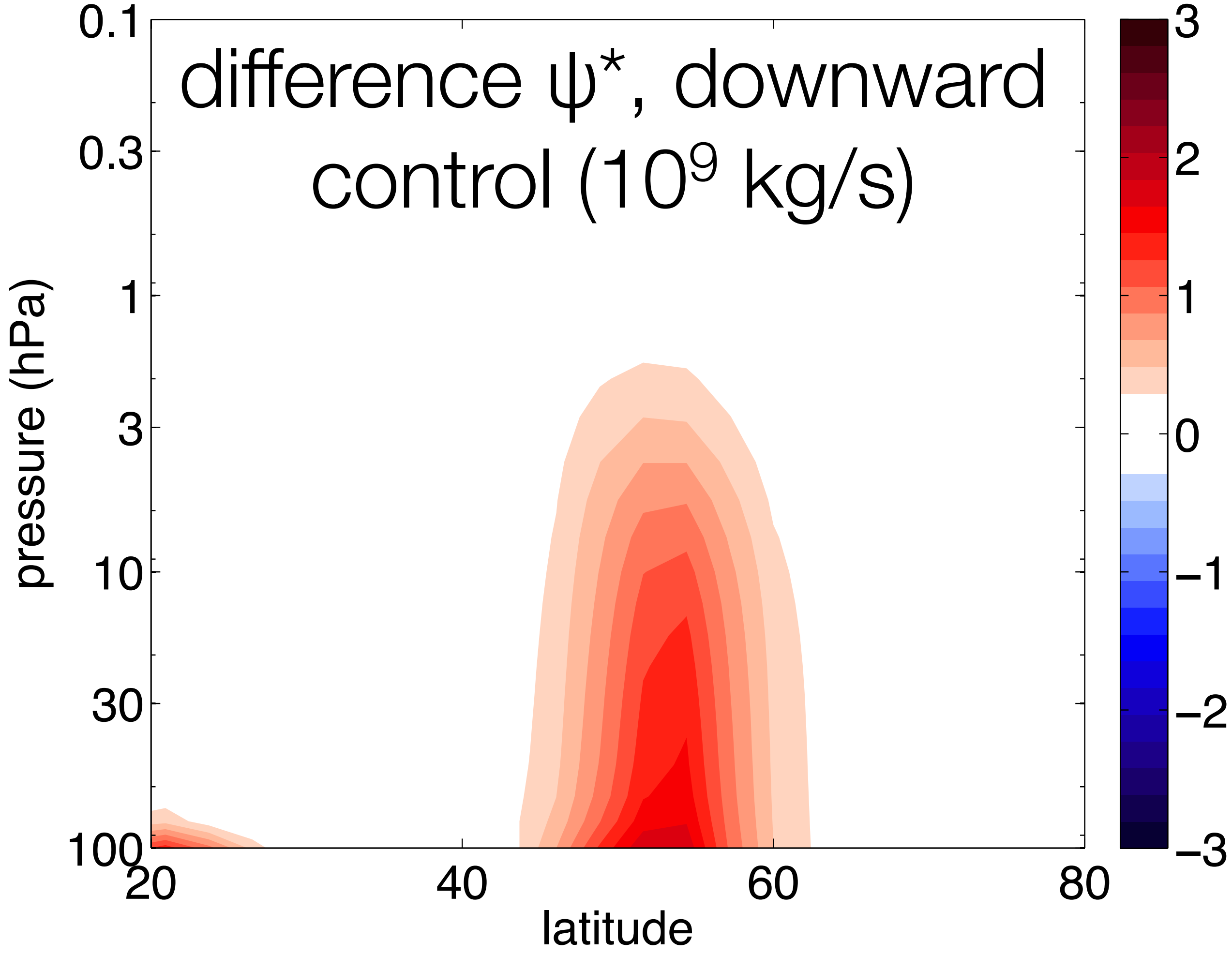

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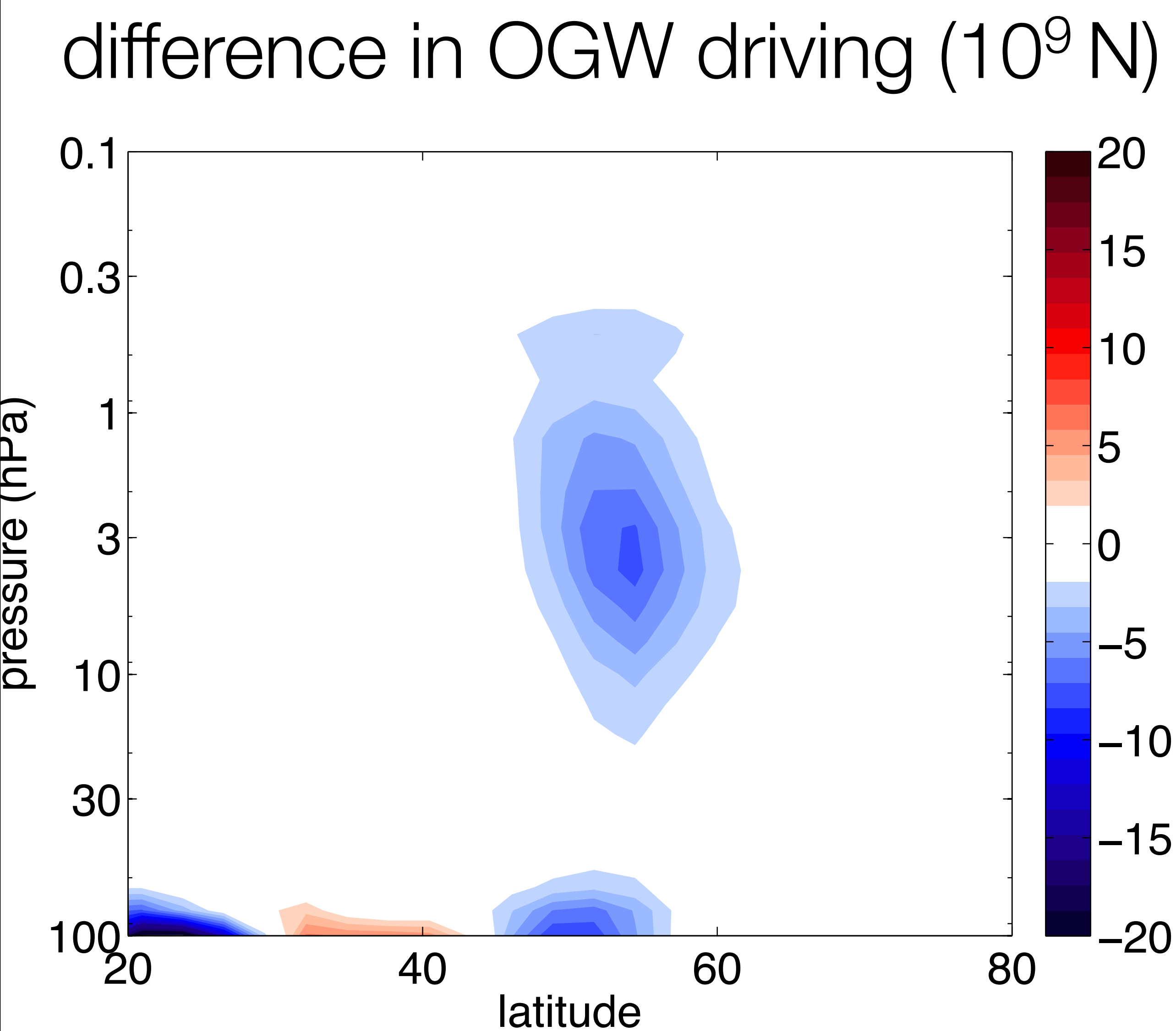
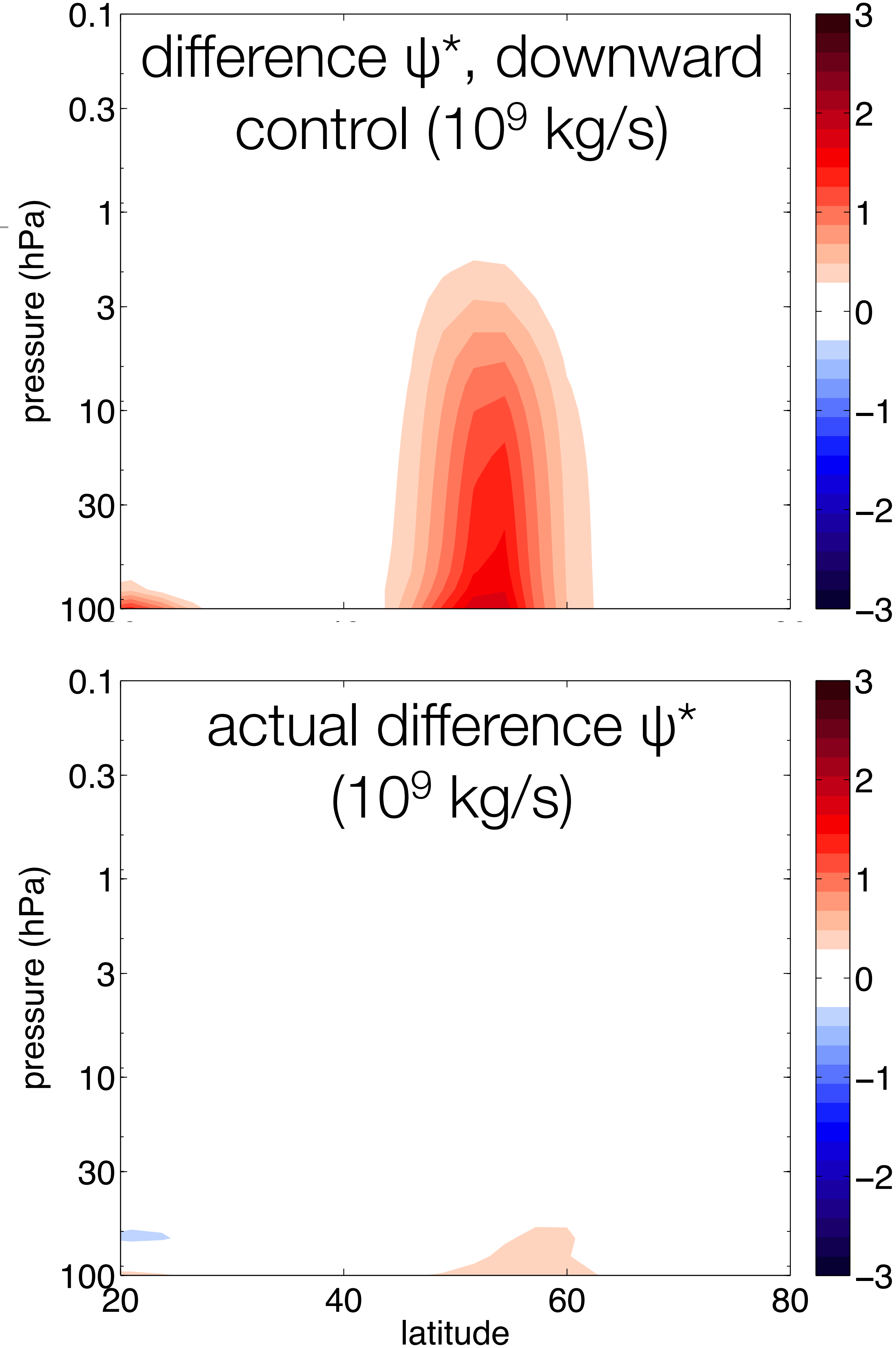
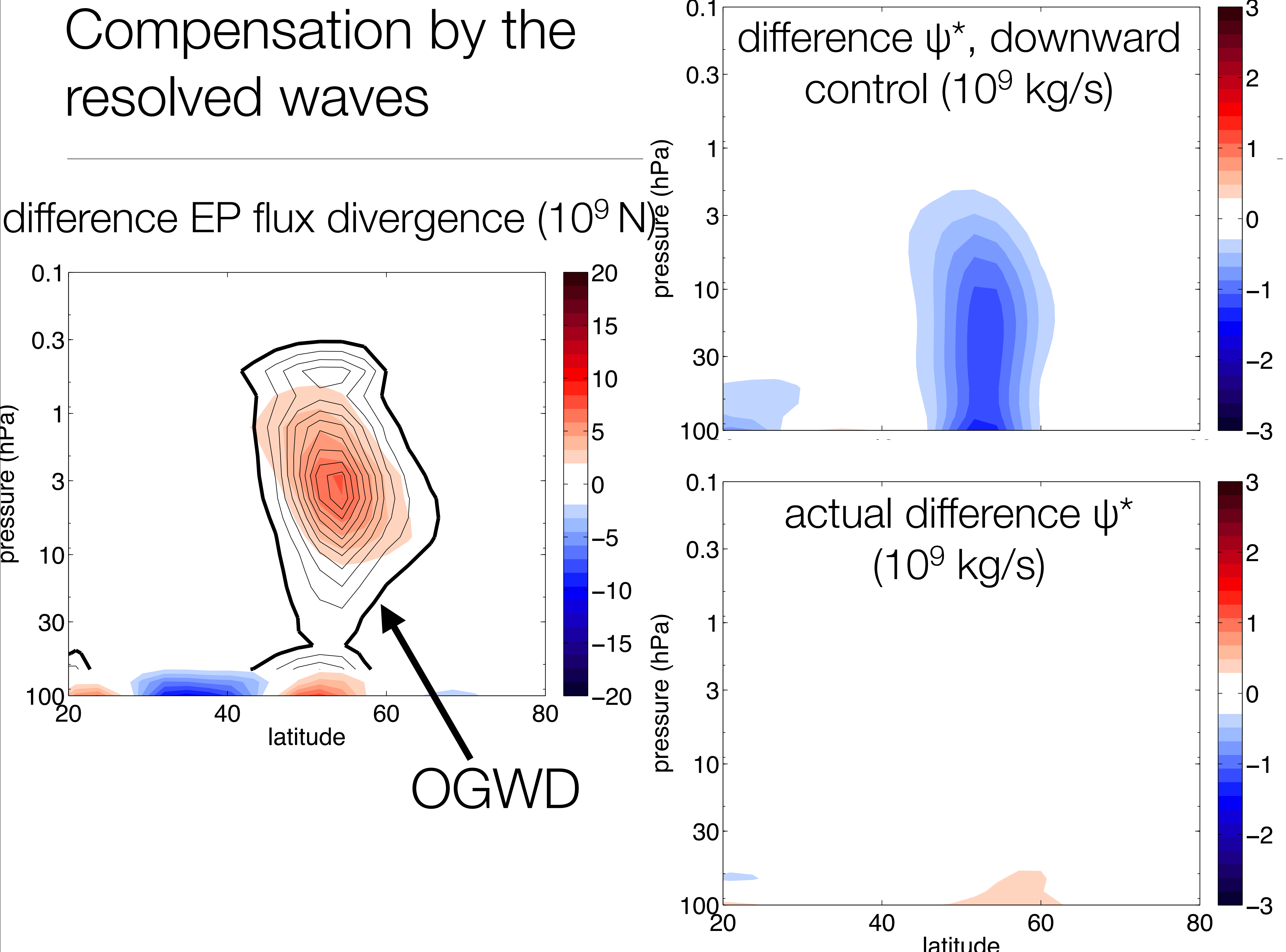


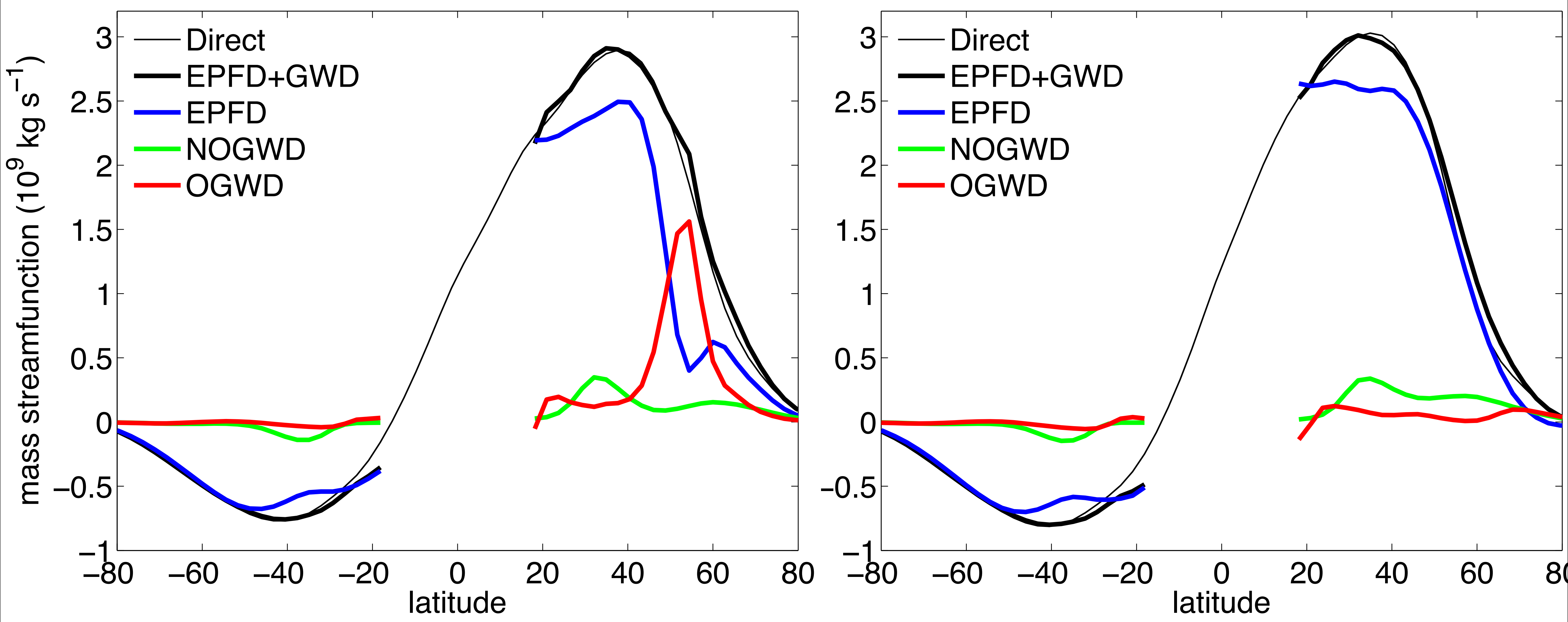


Compensation by the resolved waves



What “drives” the BDC?

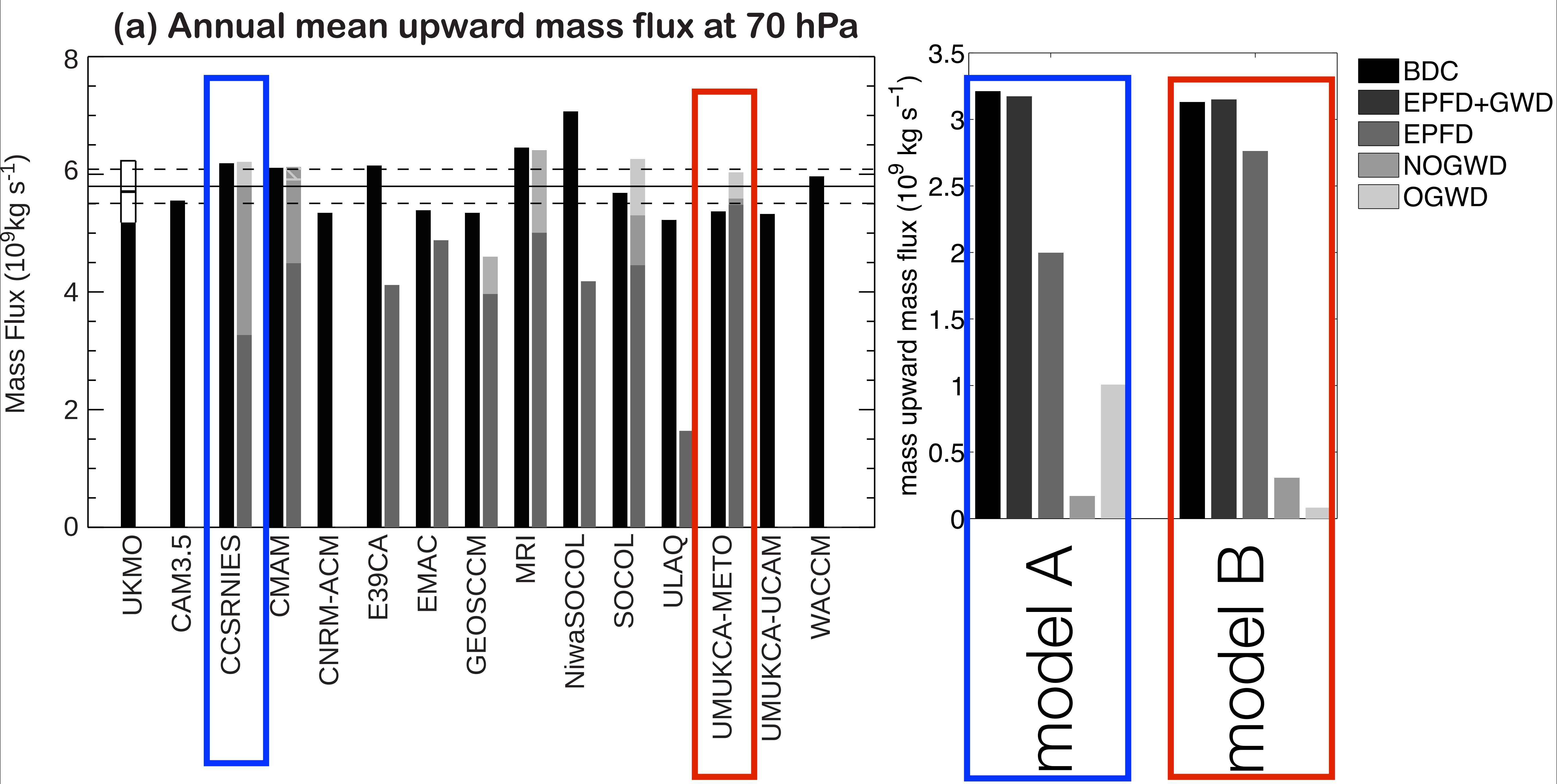
Residual Mean Streamfunction at 70 hPa



Model A　　　Model B

[Cohen et al. 2013]

Implication of compensation for BDC driving…



What is going on here?

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When I find myself in times of trouble,
Father Hoskins comes to me,
speaking words of wisdom …

PV … PV!

What is going on here?

When I find myself in times of trouble,
Father Hoskins comes to me,
speaking words of wisdom …

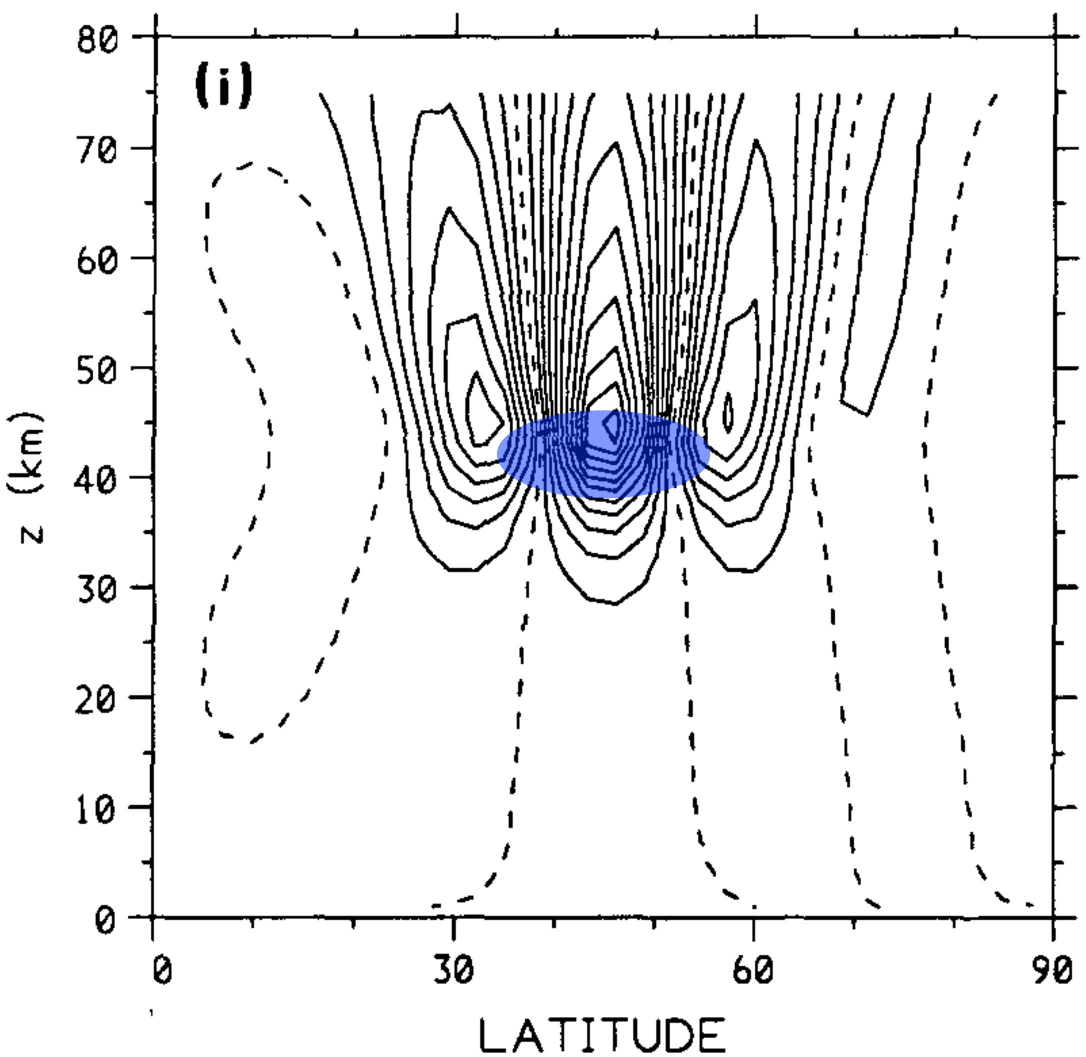
PV … PV!

(That is, how do the wave forcings affect the potential vorticity.)

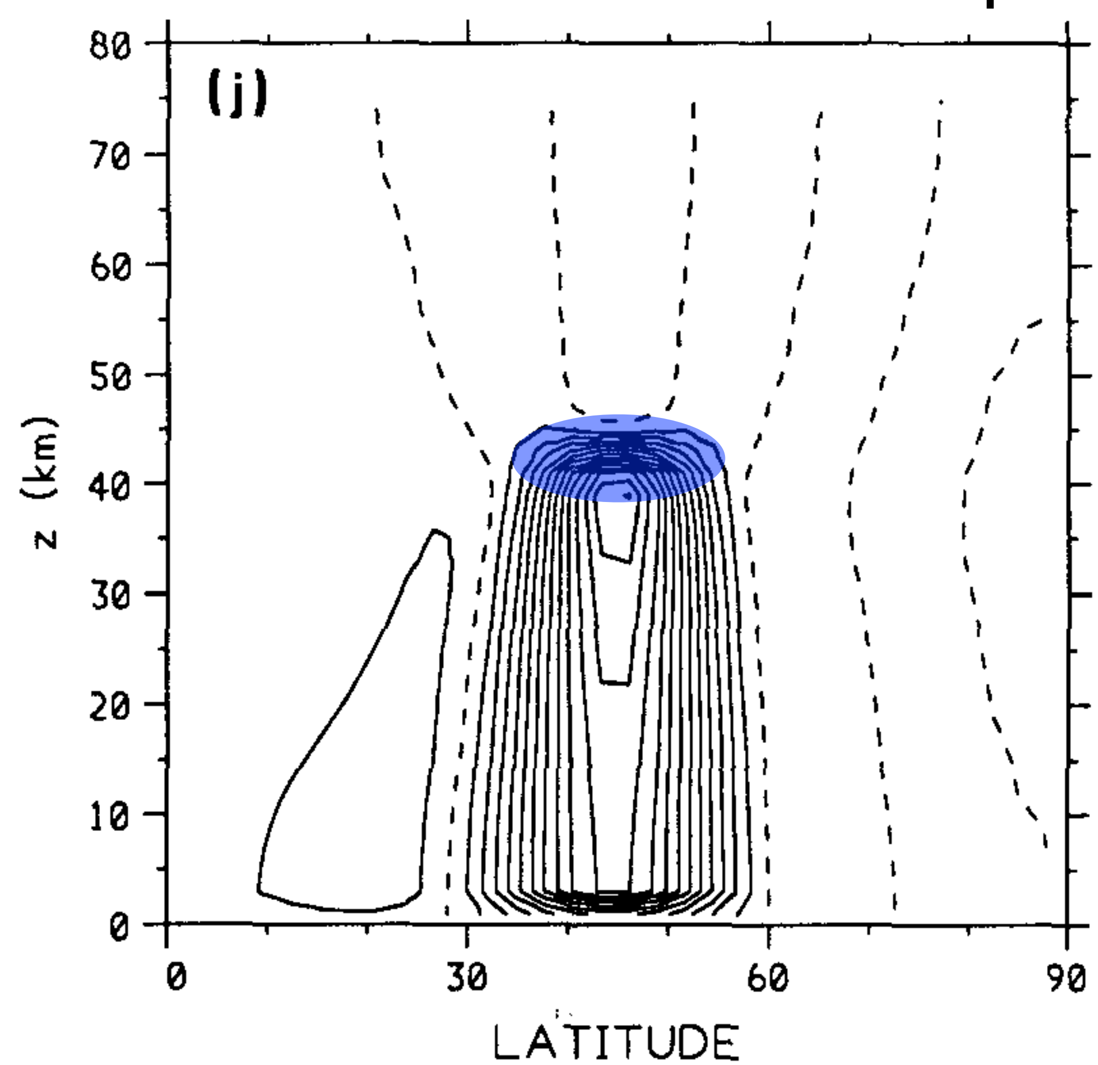
Back to Basics: Haynes et al. 1991

(Near) steady response to a localized torque

zonal wind

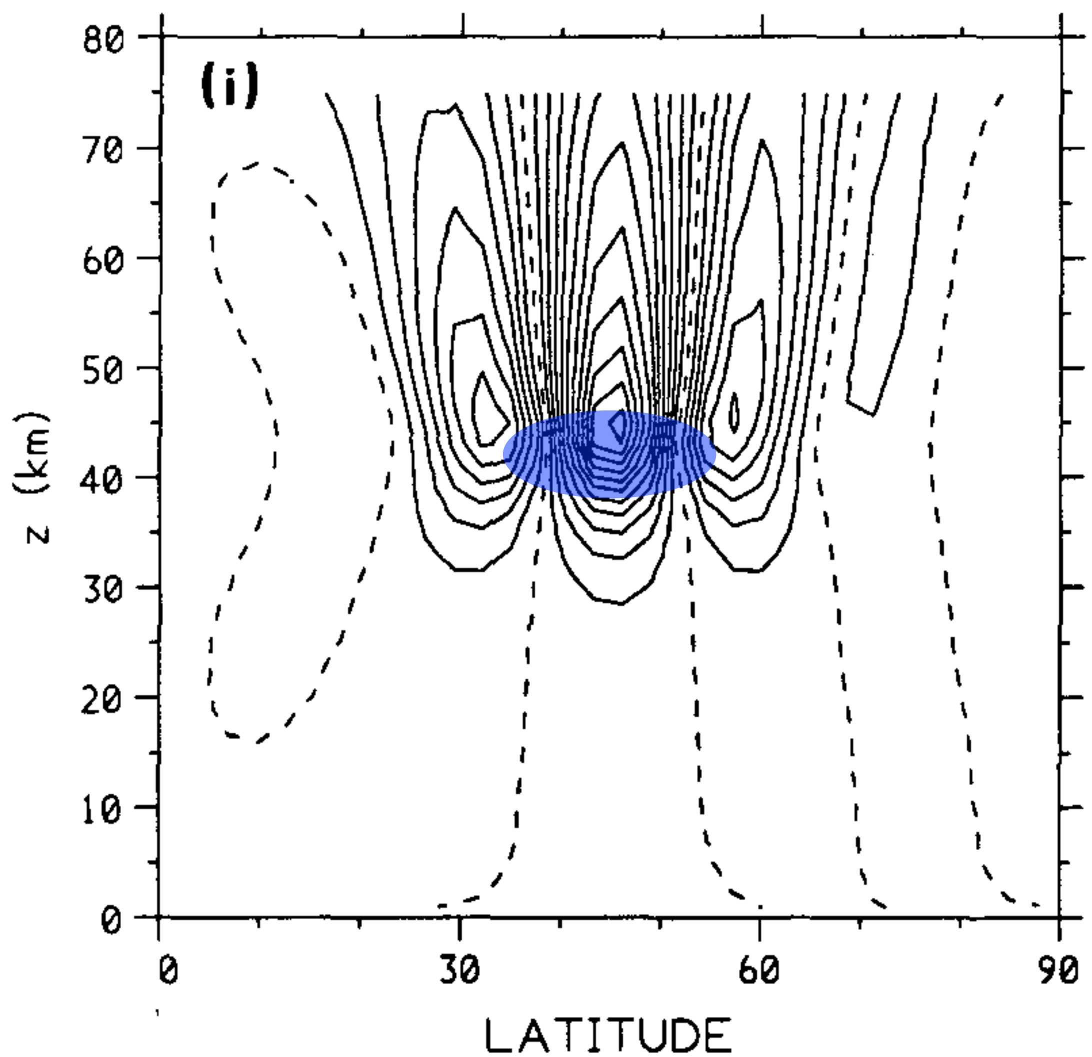


streamfunction ψ



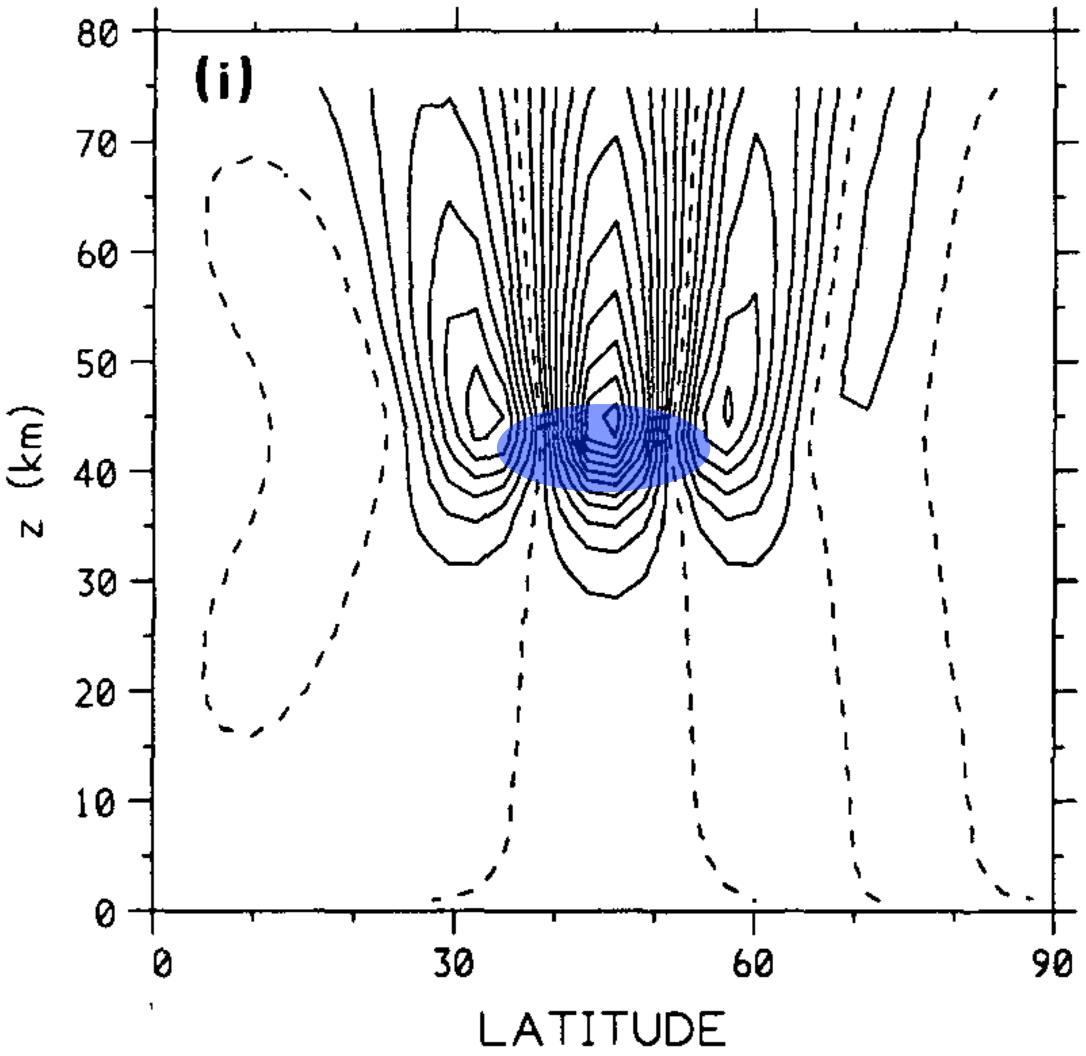
For what torques is the circulation reasonable?

zonal wind



For what torques is the circulation reasonable?

zonal wind

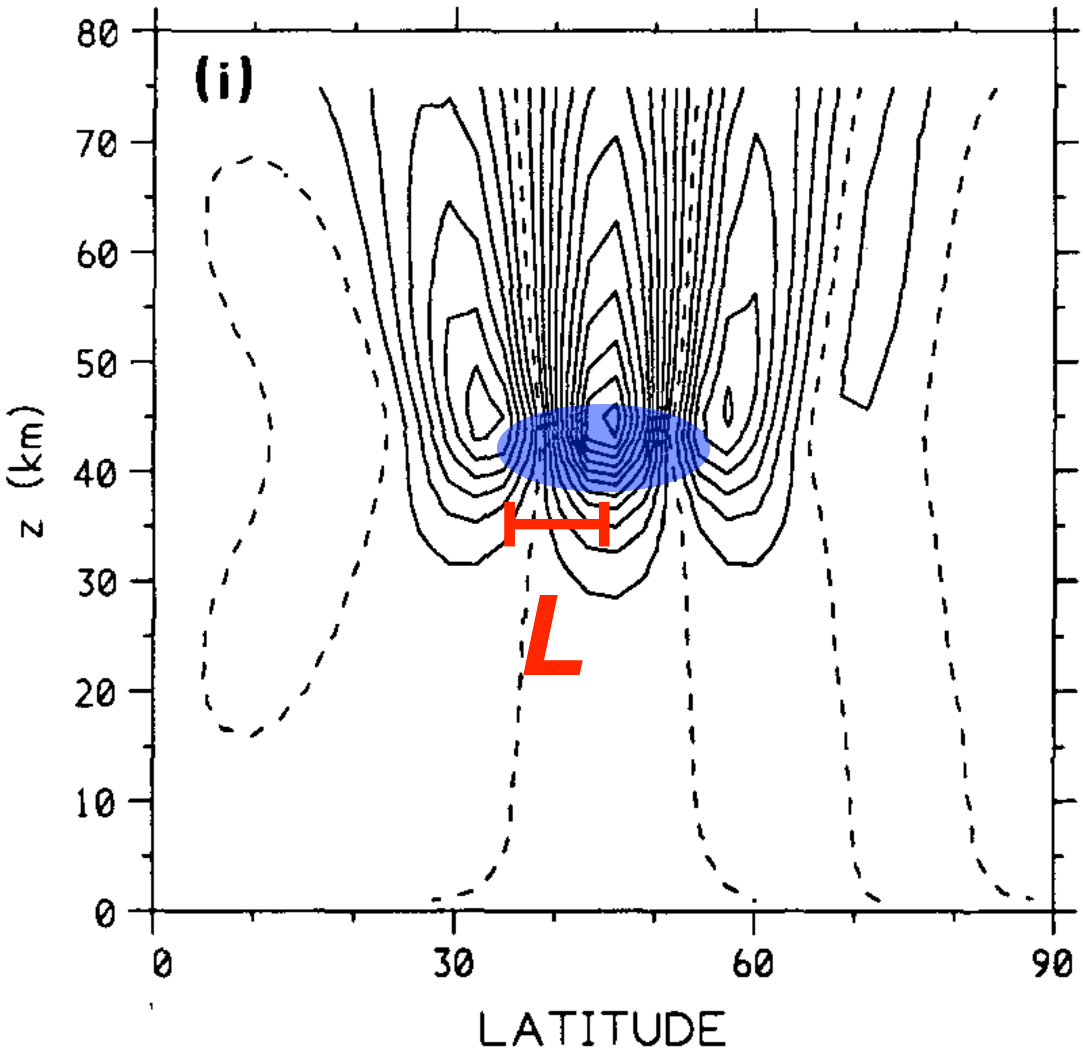


QG Potential Vorticity

$$\overline{q}_y = \beta - \overline{u}_{yy} + f\frac{\overline{\theta}_y}{\overline{\theta}_p}$$

For what torques is the circulation reasonable? Stability depends critically on meridional scale

zonal wind



amplitude *A*,
meridional scale *L*

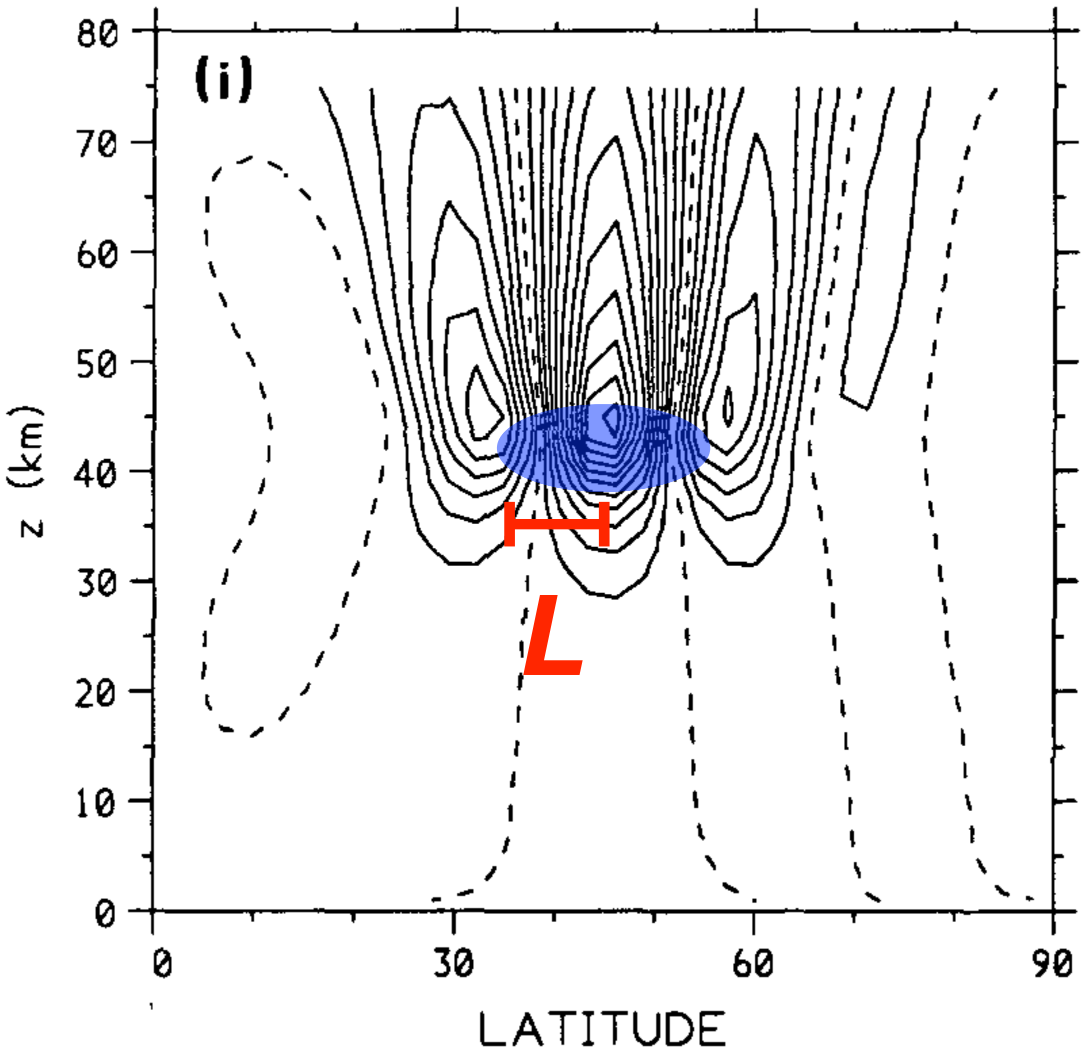
QG Potential Vorticity

$$\overline{q}_y = \beta - \overline{u}_{yy} + f\frac{\overline{\theta}_y}{\overline{\theta}_p}$$

$$\overline{u} \sim \frac{A}{L^2}$$

For what torques is the circulation reasonable? Stability depends critically on meridional scale

zonal wind



amplitude A, meridional scale L

QG Potential Vorticity

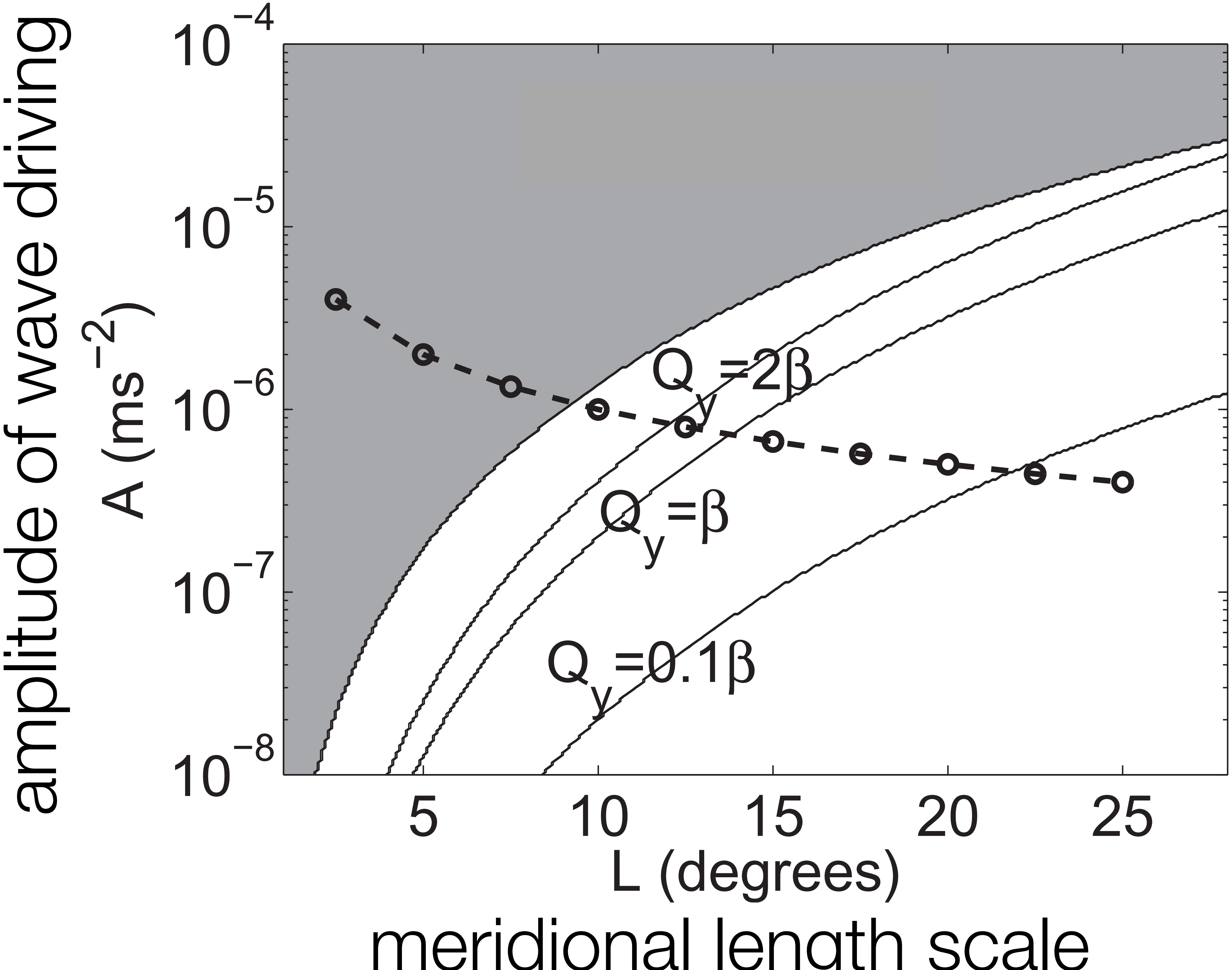
$$\bar{q}_y = \beta - \bar{u}_{yy} + f\frac{\bar{\theta}_y}{\bar{\theta}_p}$$

$$\bar{u} \sim \frac{A}{L^2}$$

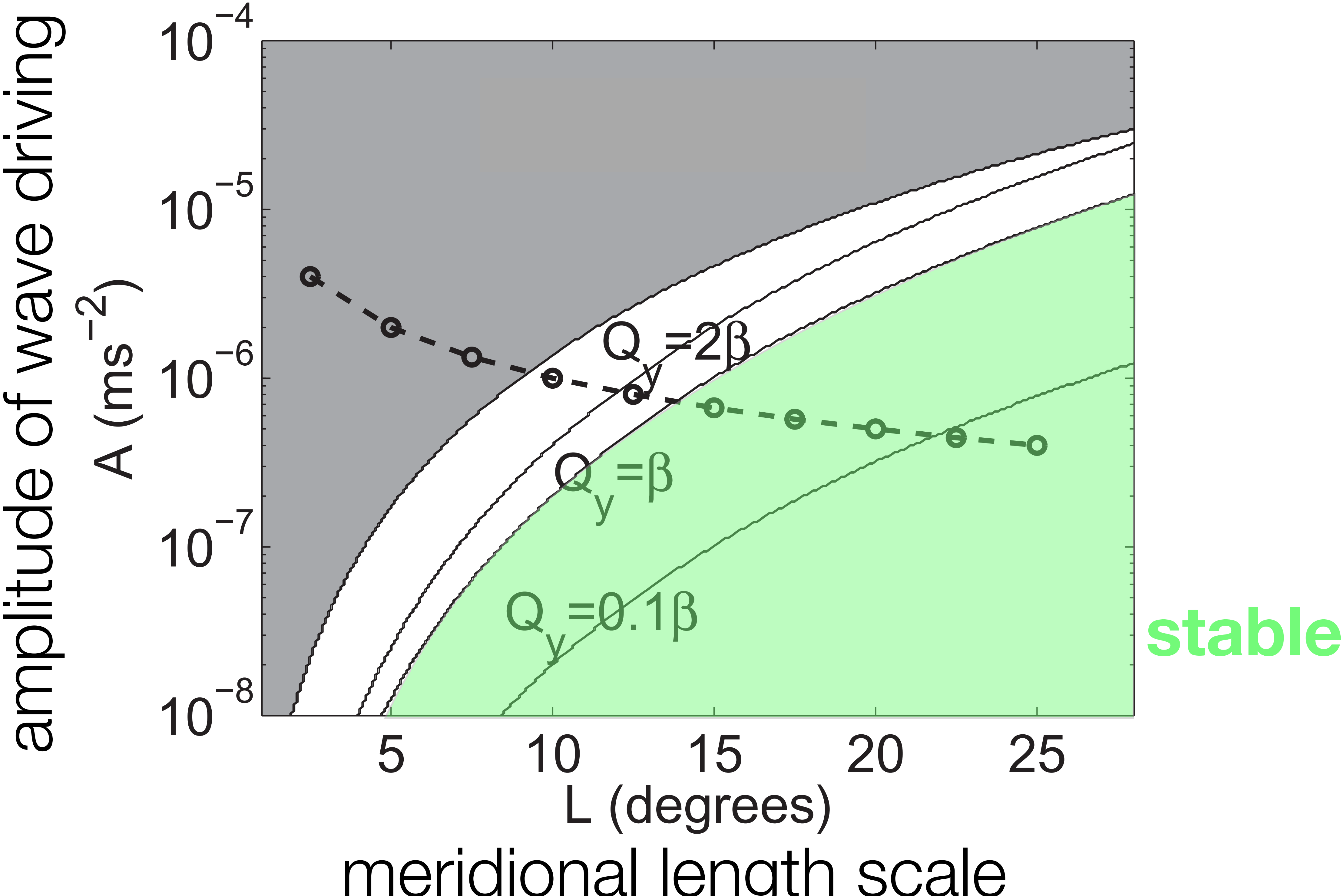
For $L << L_R$

perturbation to PV gradient $\sim \dfrac{A}{L^4}$

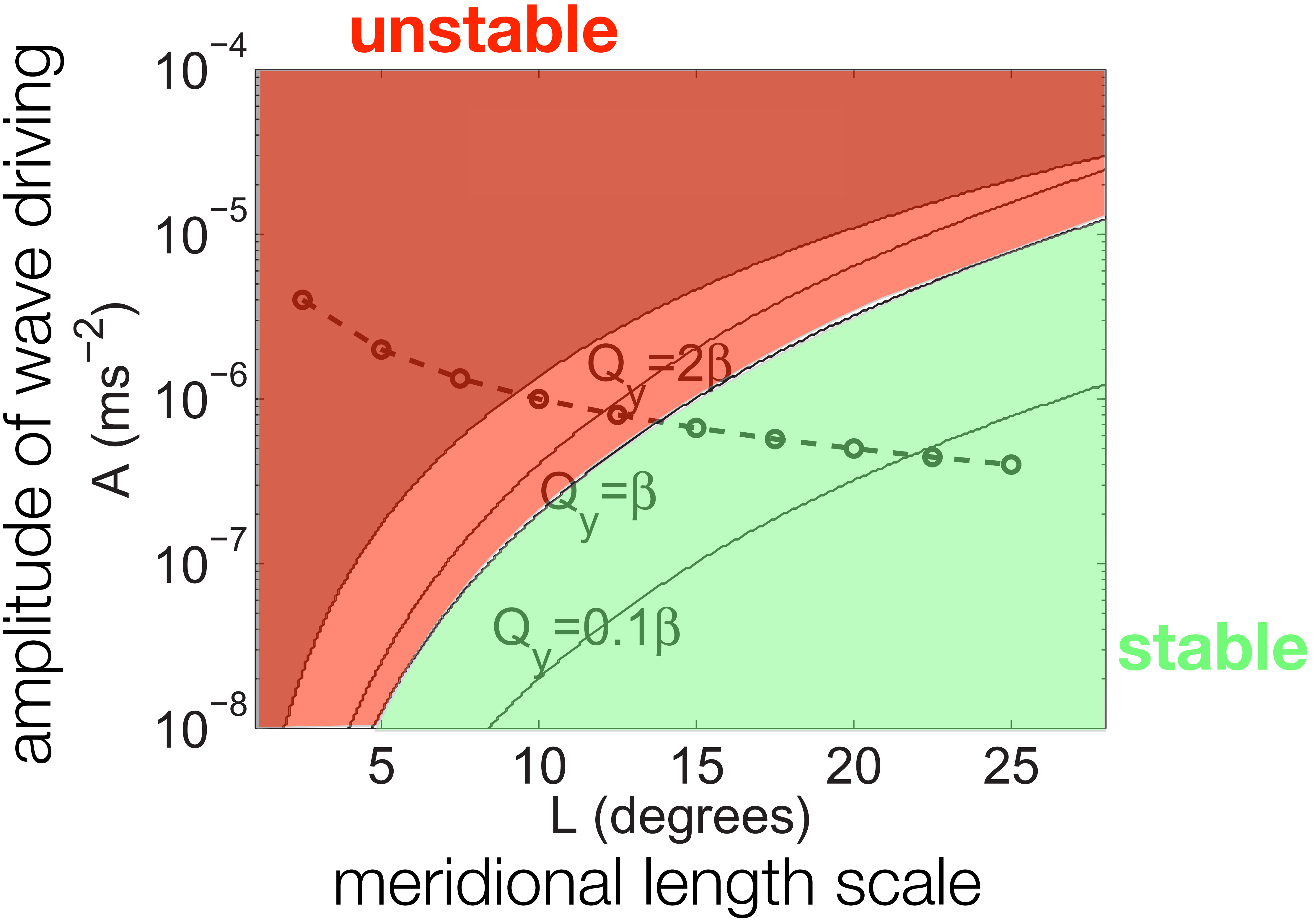
Stability of the circulation for a compact torque



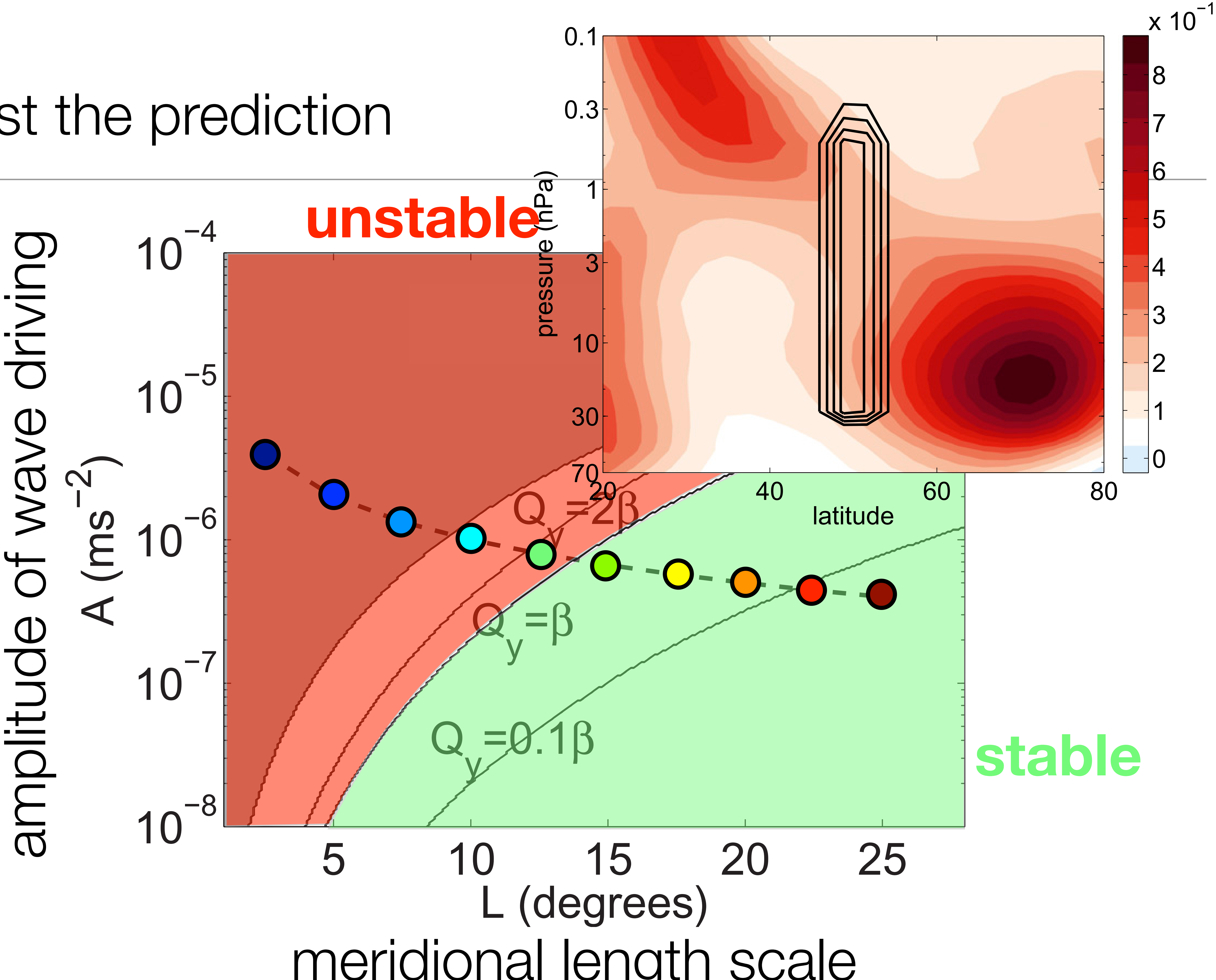
Stability of the circulation for a compact torque



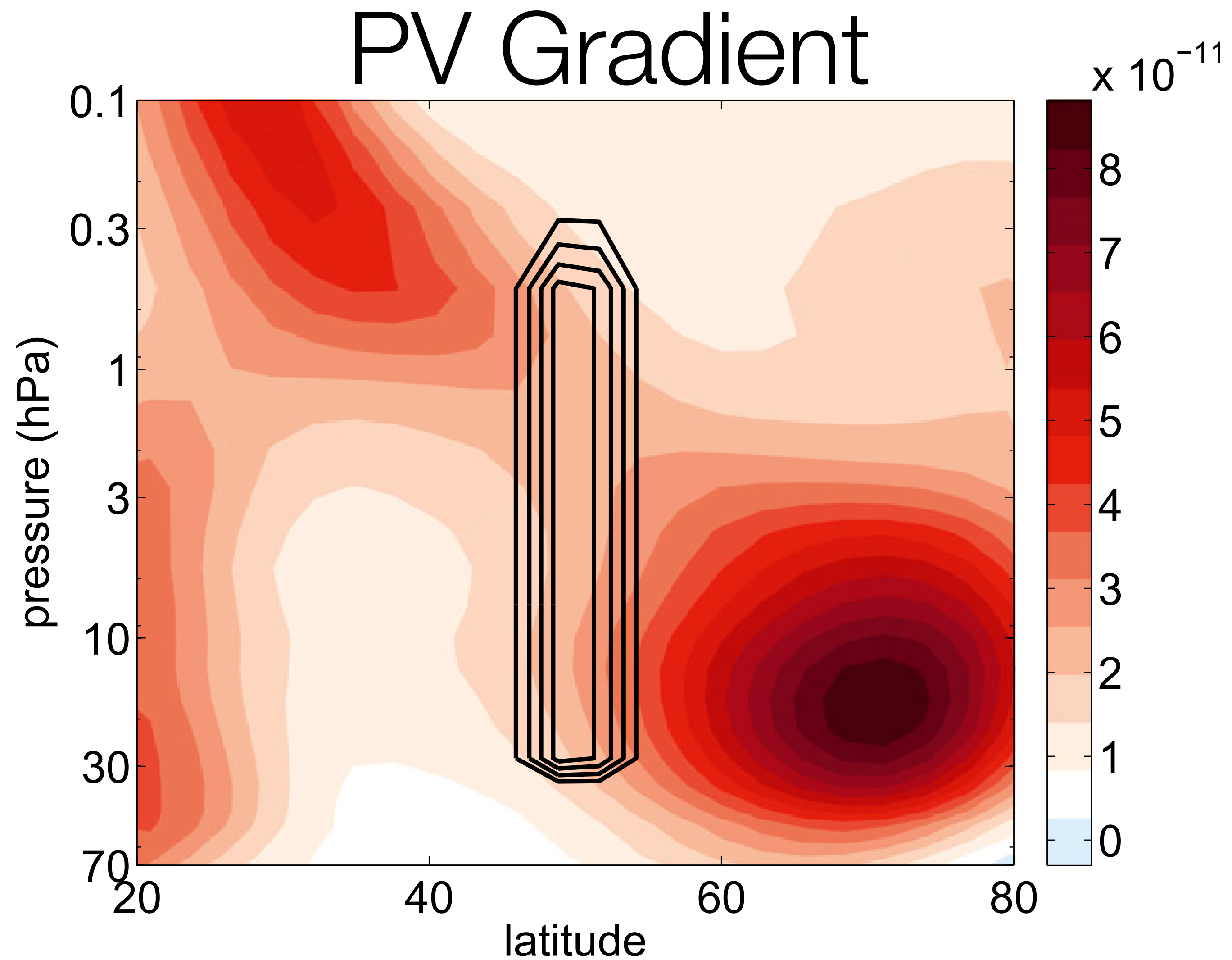
Stability of the steady state for compact torque

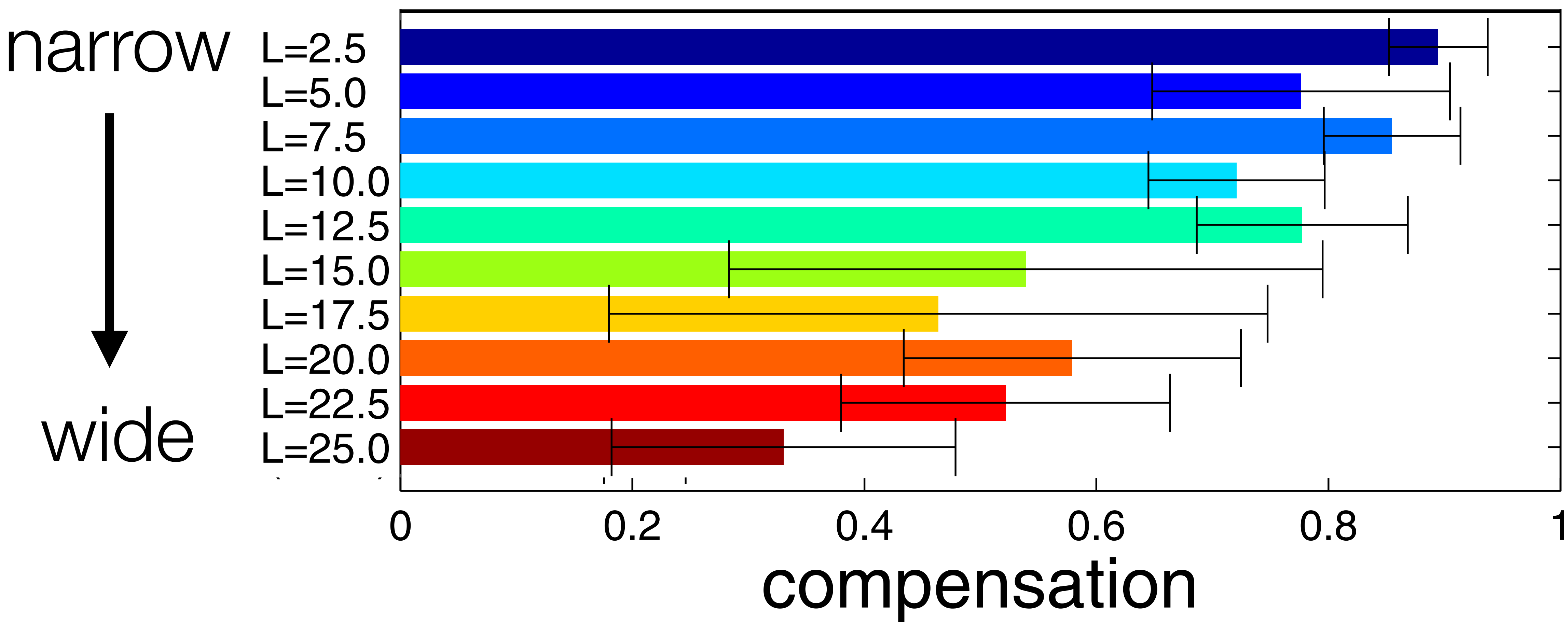


Test the prediction

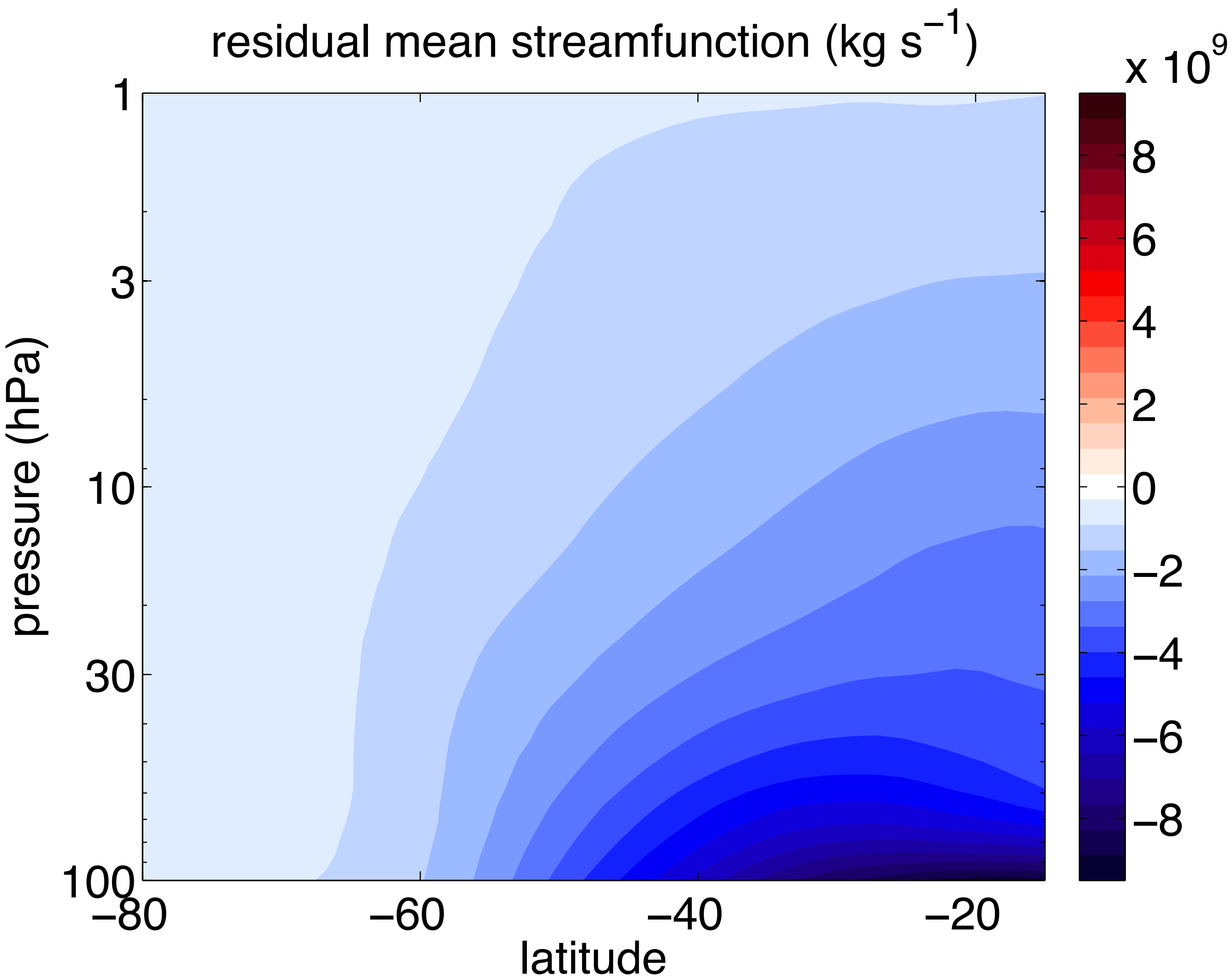


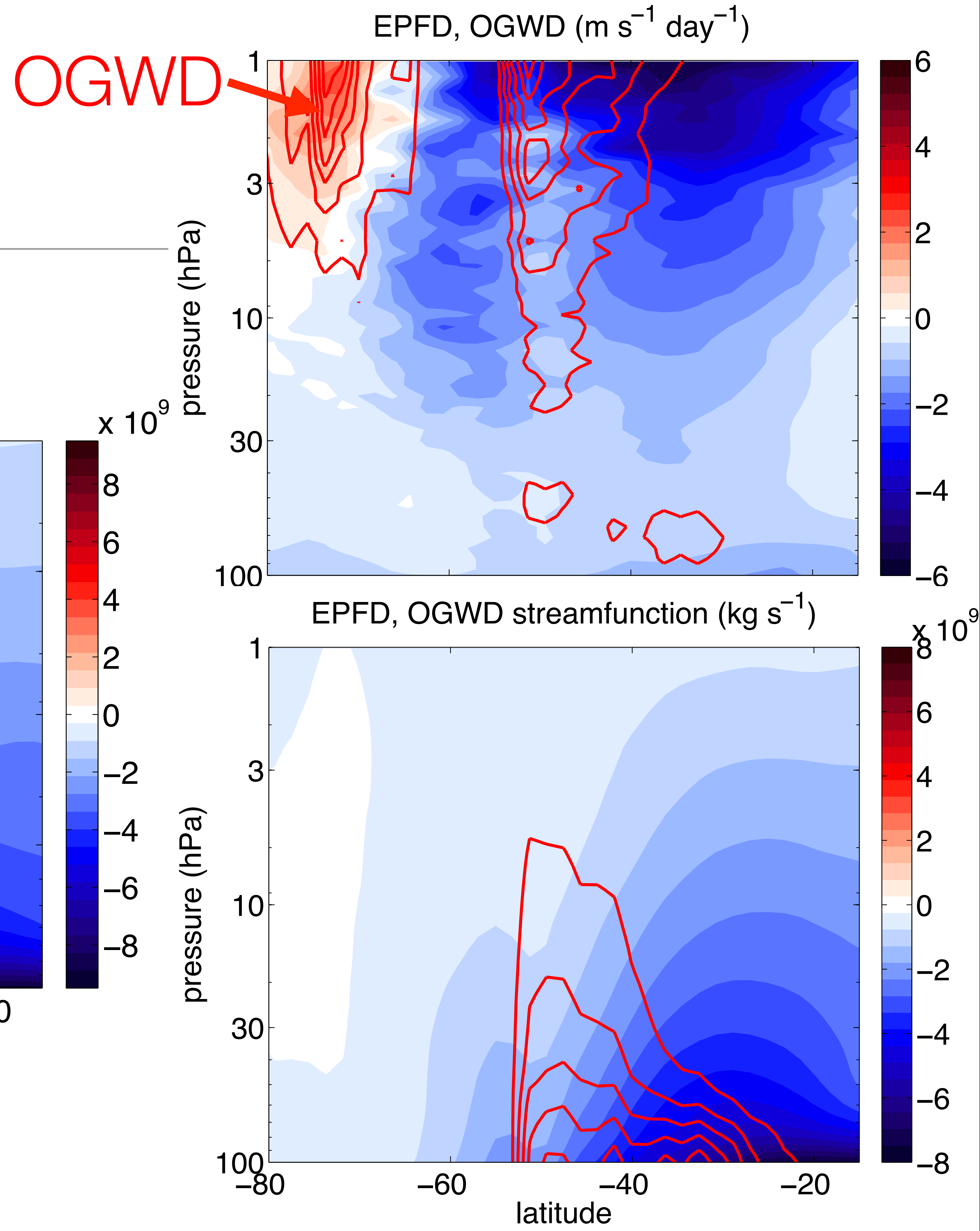
Test the prediction





Breaking down the streamfunction





Interaction between wave driving suggest that the "forcings" are somewhat fungible.

$$\mathcal{F} = \nabla \cdot F + G_{OGW} + G_{NOGW}$$

$$\downarrow \qquad \downarrow \qquad \downarrow$$

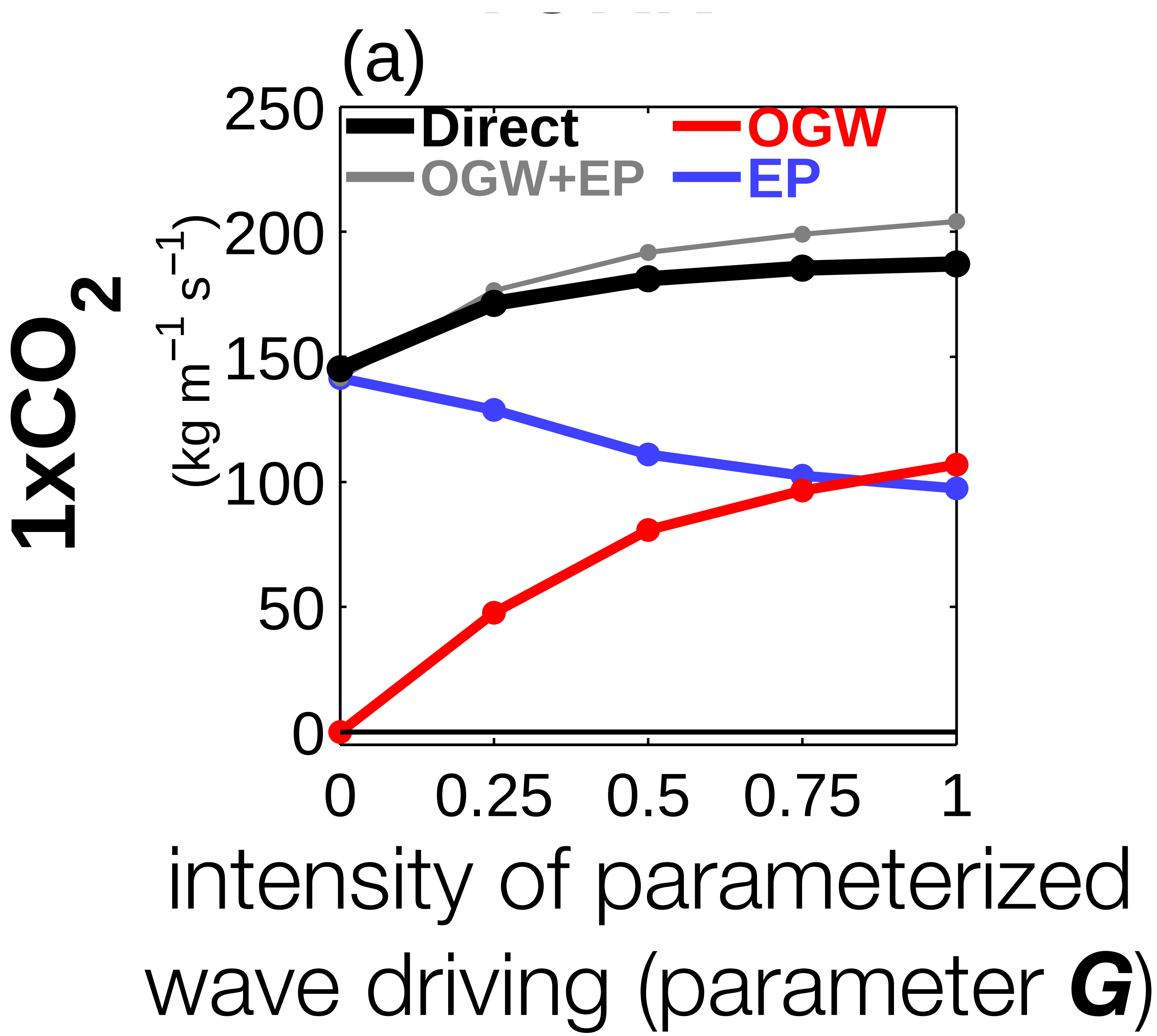
$$\psi = \psi_{EPFD} + \psi_{OGW} + \psi_{NOGW}$$

Interaction between wave driving suggest that the “forcings” are somewhat fungible.

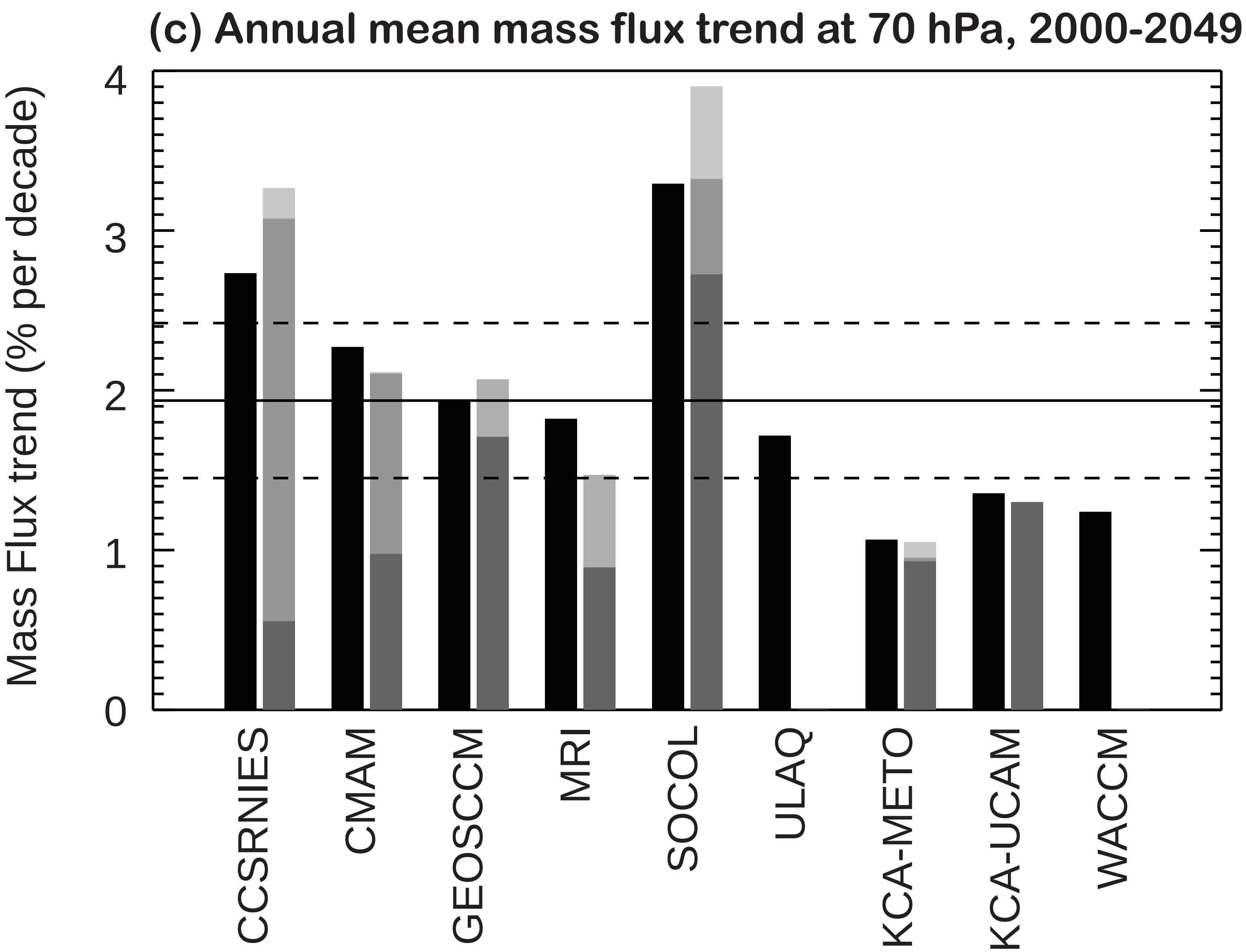
$$\mathcal{F} = \nabla \cdot F + G_{OGW} + G_{NOGW}$$

$$\psi = \psi_{EPFD} + \psi_{OGW} + \psi_{NOGW}$$

Compensation makes total circulation more robust than components *[Sigmond and Shepherd, 2014]*



Uncertainty in "forcing" increases with future trends



total

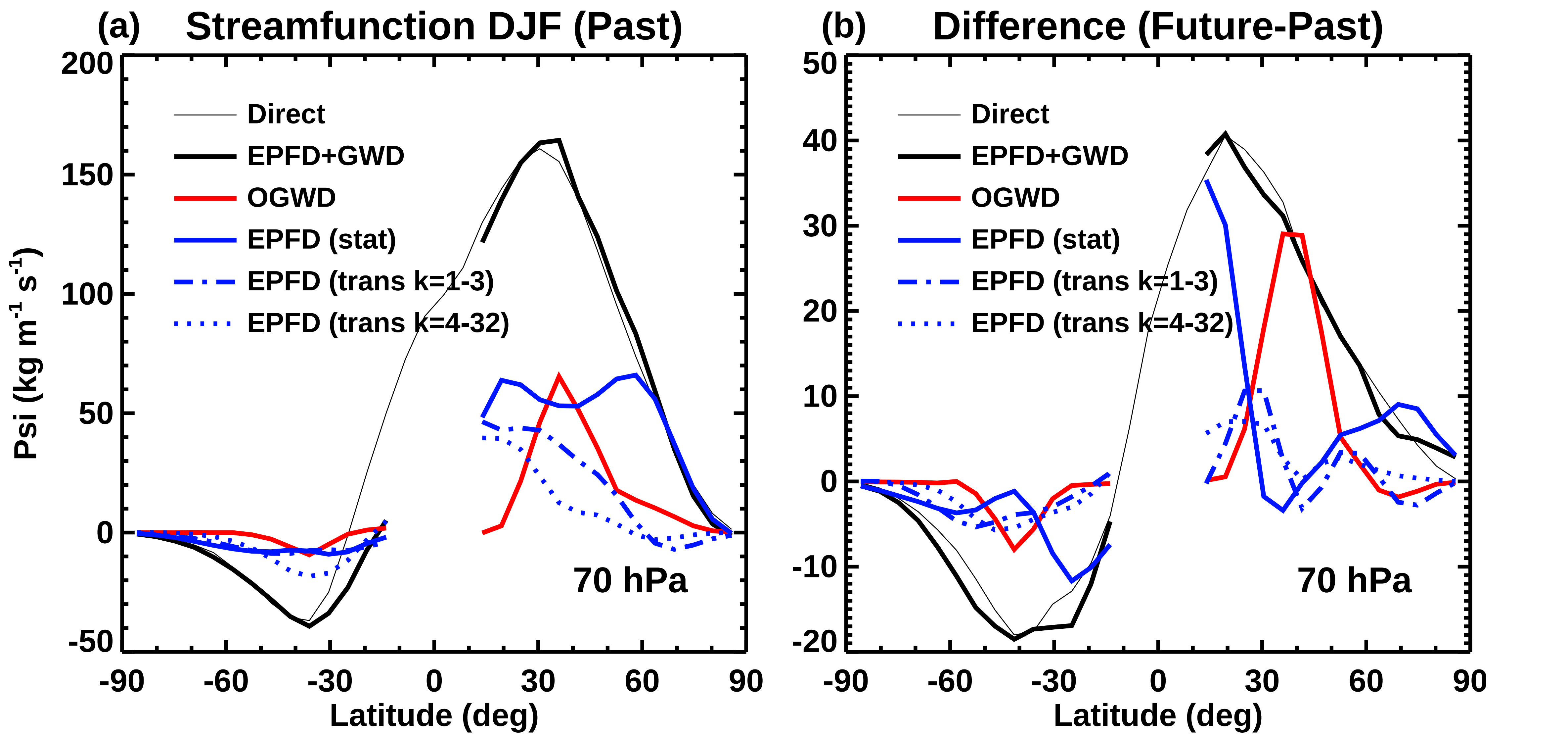
resolved waves

orographic GW

non-orographic GW

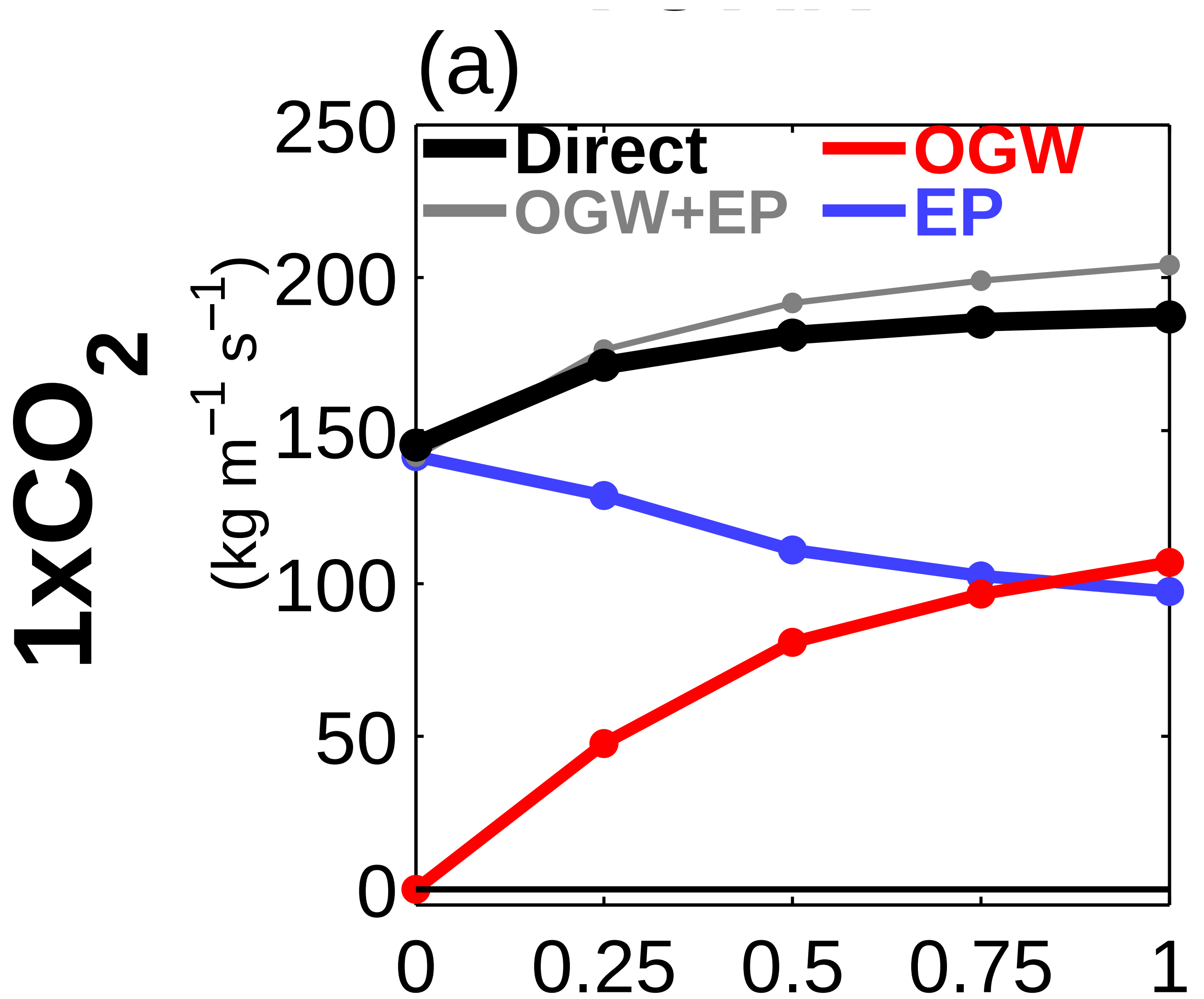
[CCMVal2 Report, Chpt 4]

… but compensation may affect response to CO_2



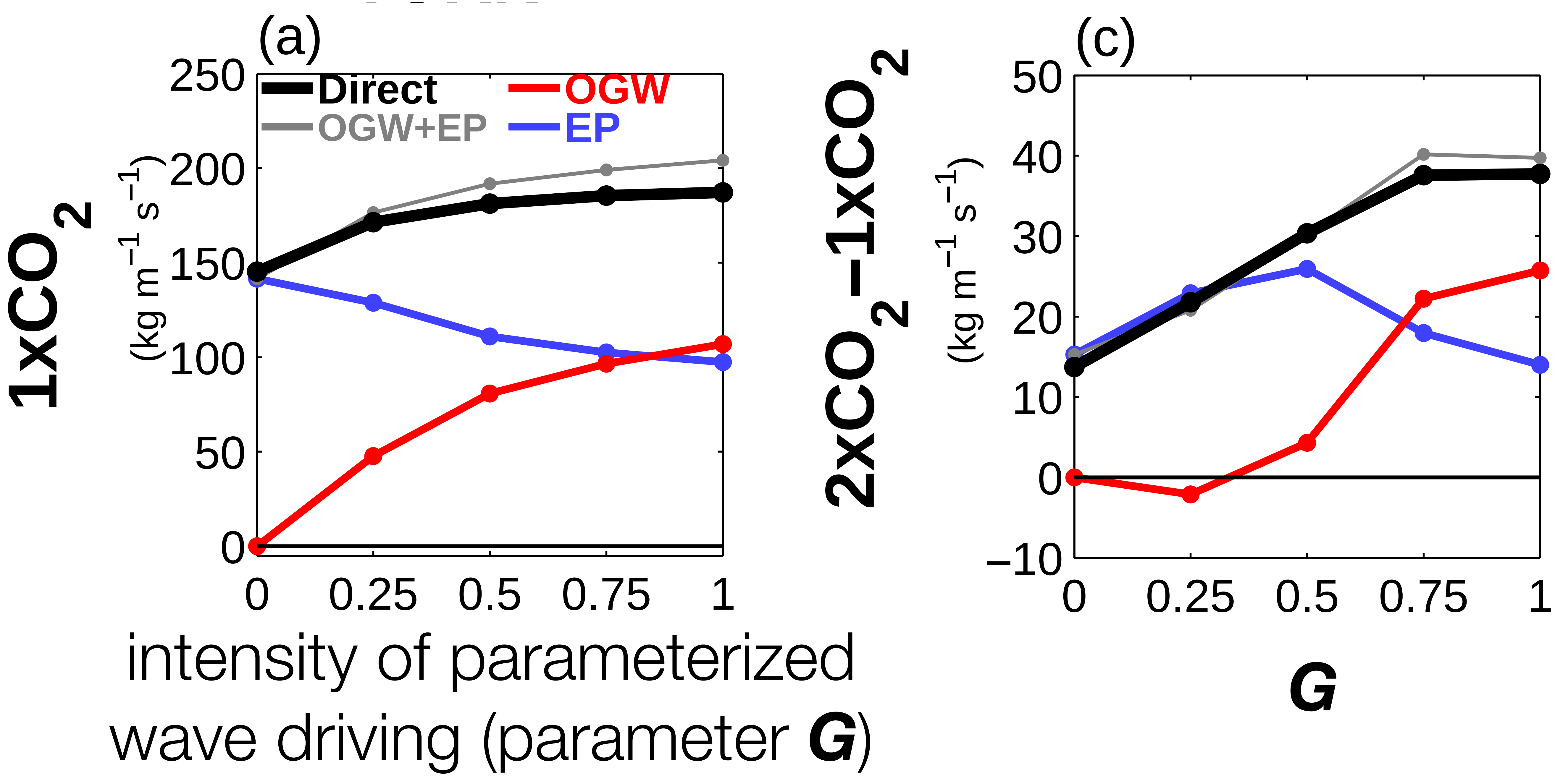
[Shepherd and McLandress 2011]

Impact of GW depends on basic state of the model *[Sigmond and Shepherd, 2014]*

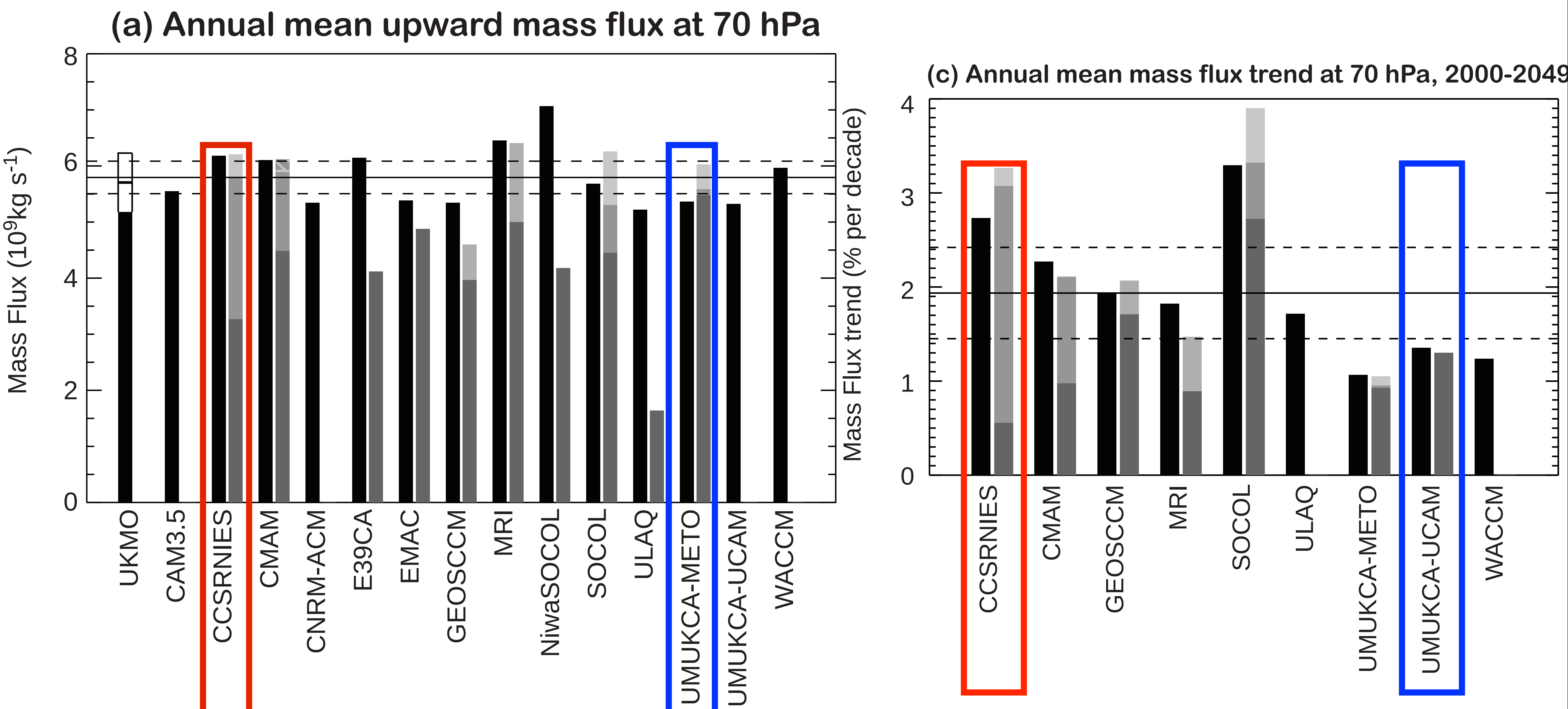


intensity of parameterized wave driving (parameter ***G***)

Impact of GW depends on basic state of the model *[Sigmond and Shepherd, 2014]*



Tuning of the basic state influences the relative role of wave forcings in climate response

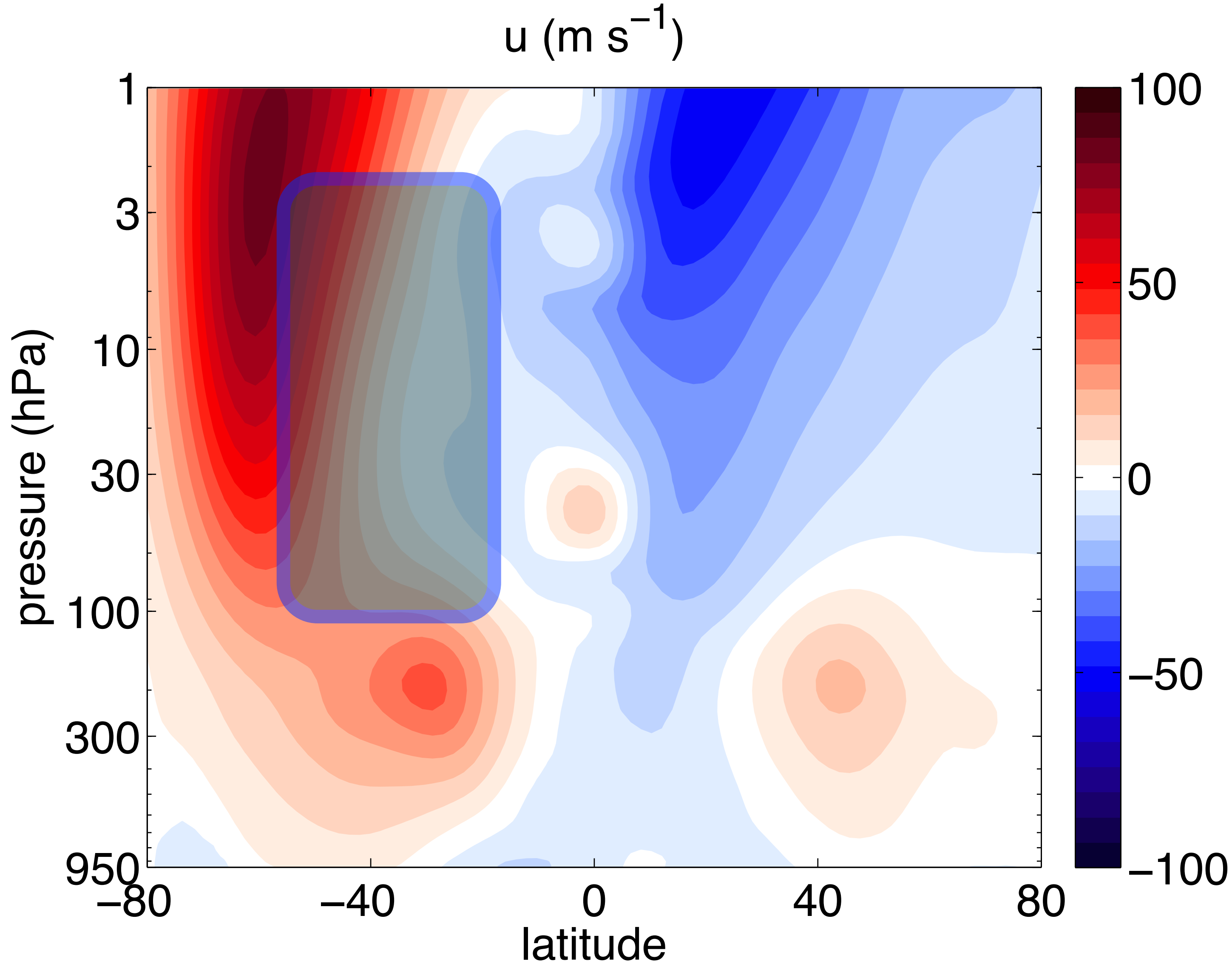


[CCMVal2 Report, Chpt 4]

A potential vorticity, surf zone perspective

Action of Rossby waves is to mix potential vorticity in the surf zone between the polar vortex and tropical stratosphere.

JJA zonal mean zonal wind



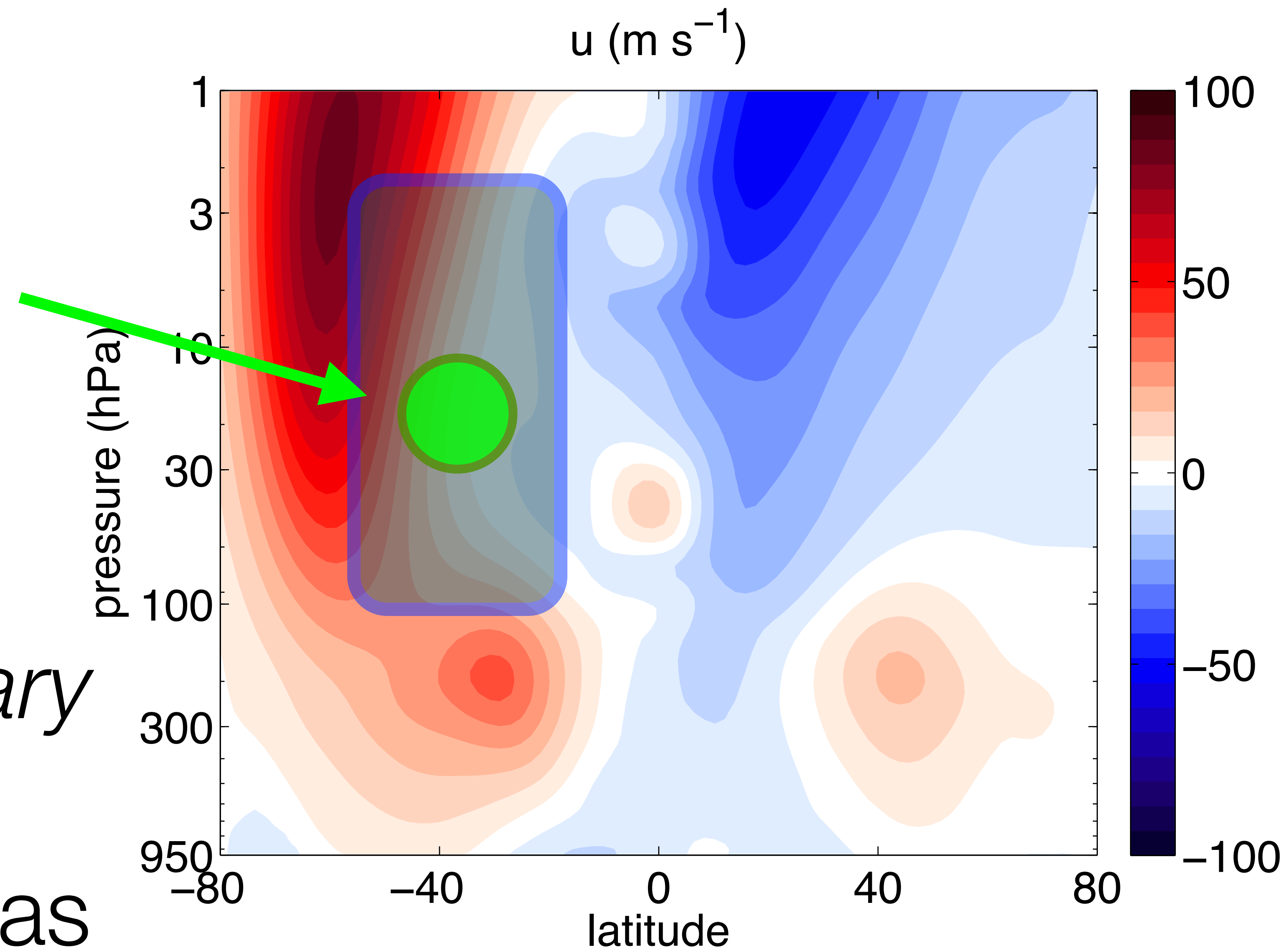
[McIntyre and Palmer, 1983]

A potential vorticity, surf zone perspective

Gravity wave driving inside surf zone will have limited impact on the BDC.

More likely for *stationary* OGW, which break at same critical levels as stationary Rossby waves

JJA zonal mean zonal wind



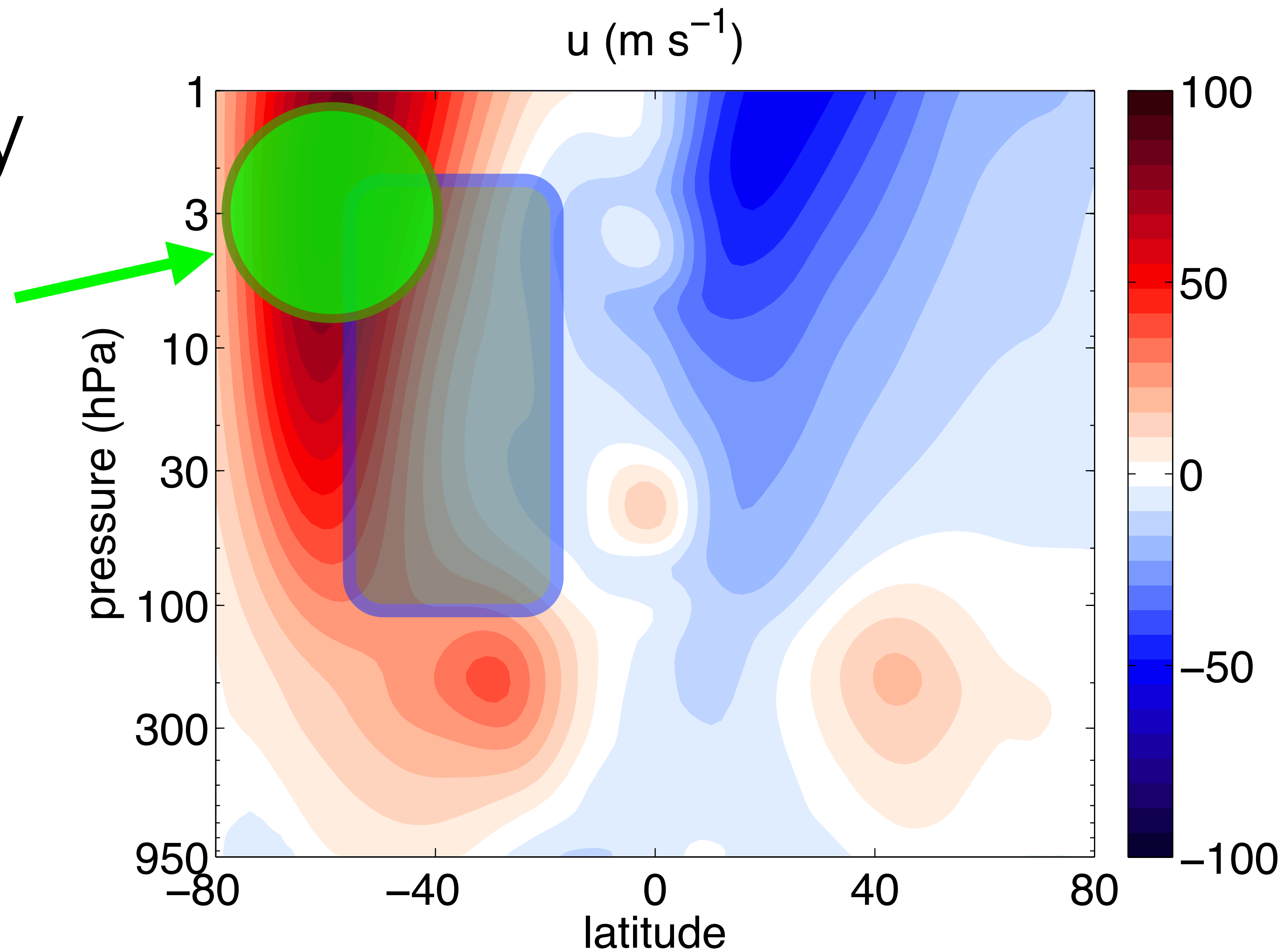
[Cohen et al. 2014]

A potential vorticity, surf zone perspective

Gravity wave driving outside surf zone likely to have large impact on the BDC.

More likely for NOGW, which can modify polar vortex.

JJA zonal mean zonal wind

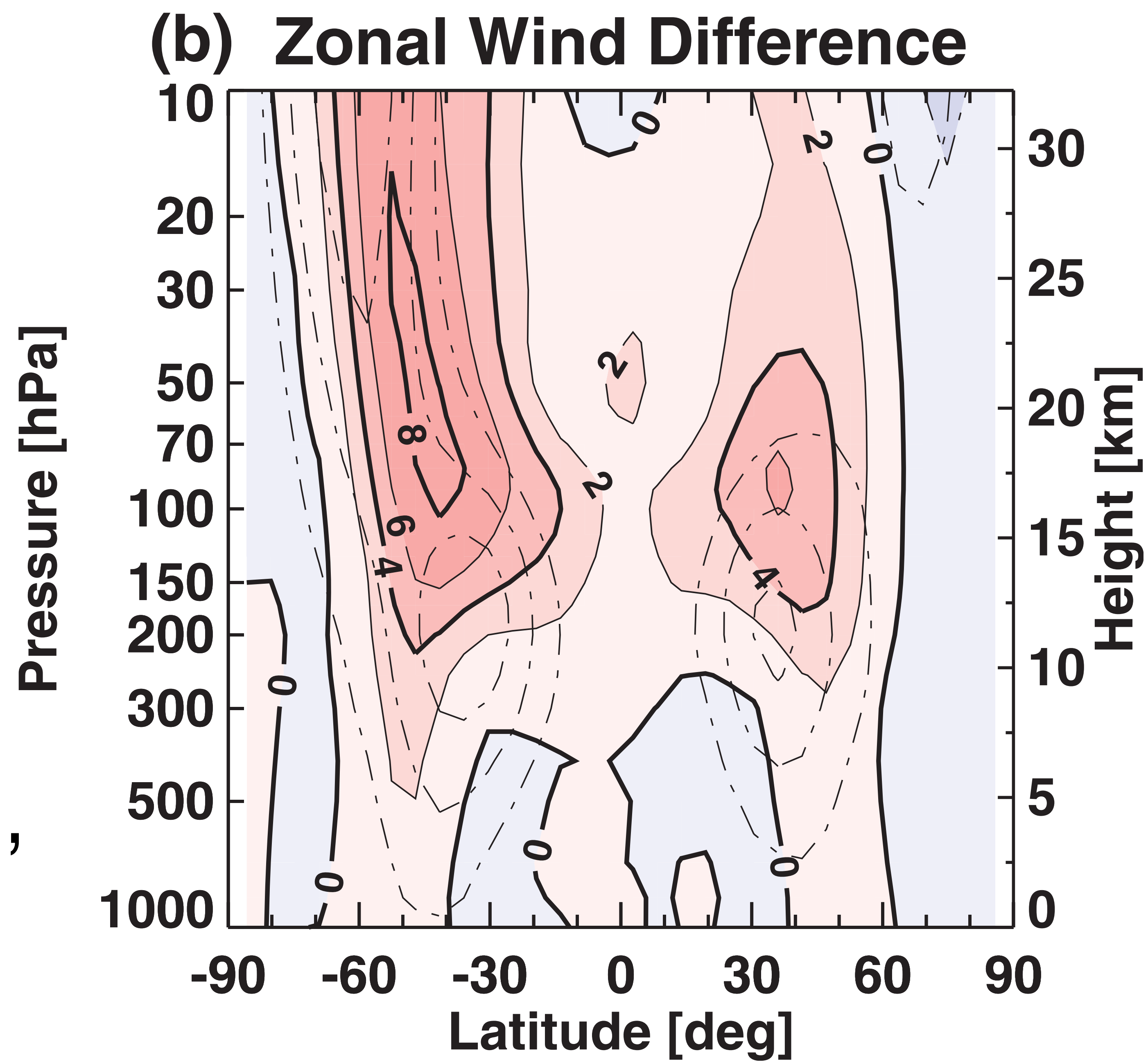


[Cohen et al. 2014]

Anthropogenic forcing modifies surf zone *[Shepherd and McLandress 2011]*

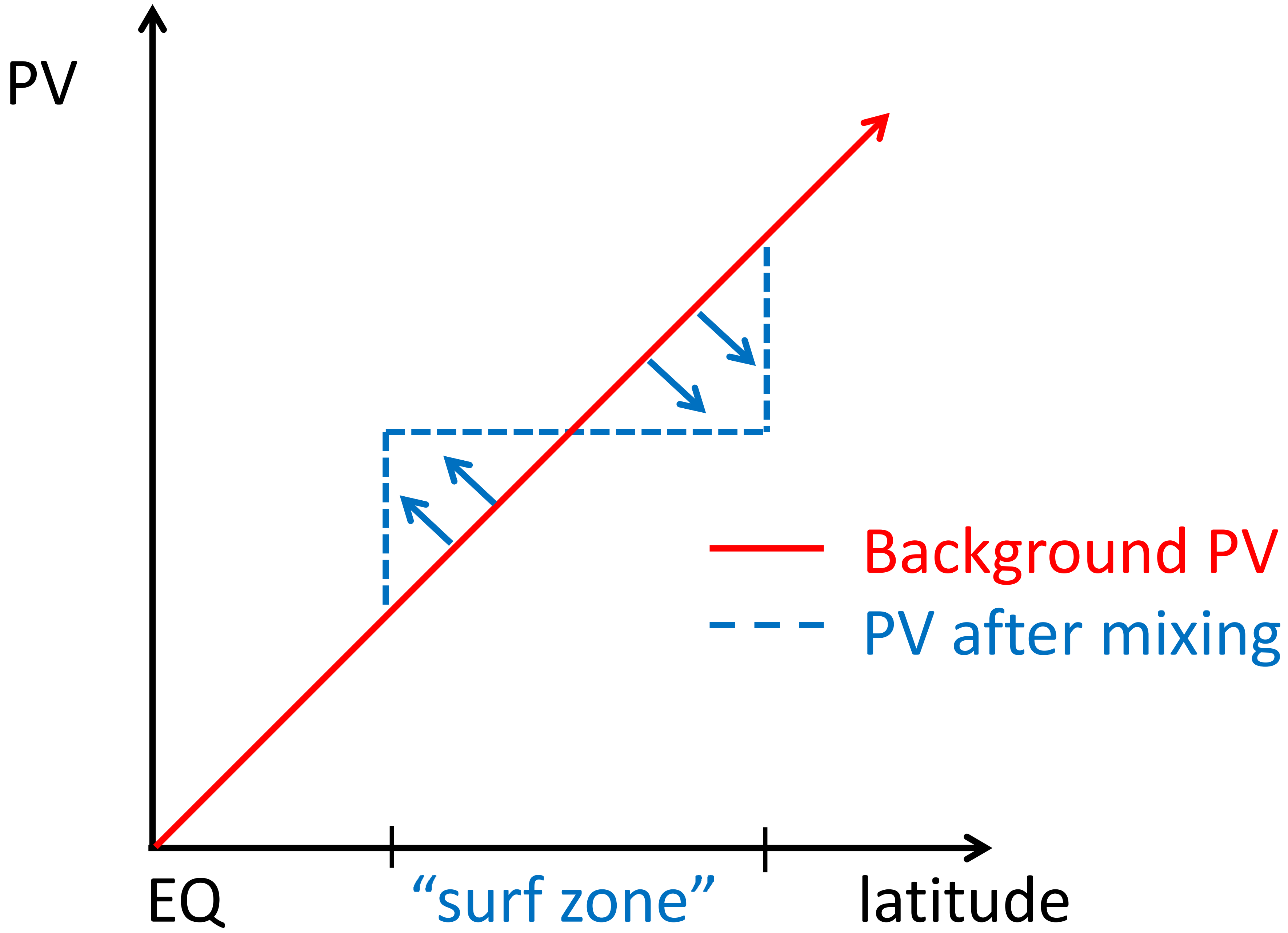
Expansion of subtropical jets raises critical level for wave breaking.

Stratosphere is shrinking, lifting the surf zone!

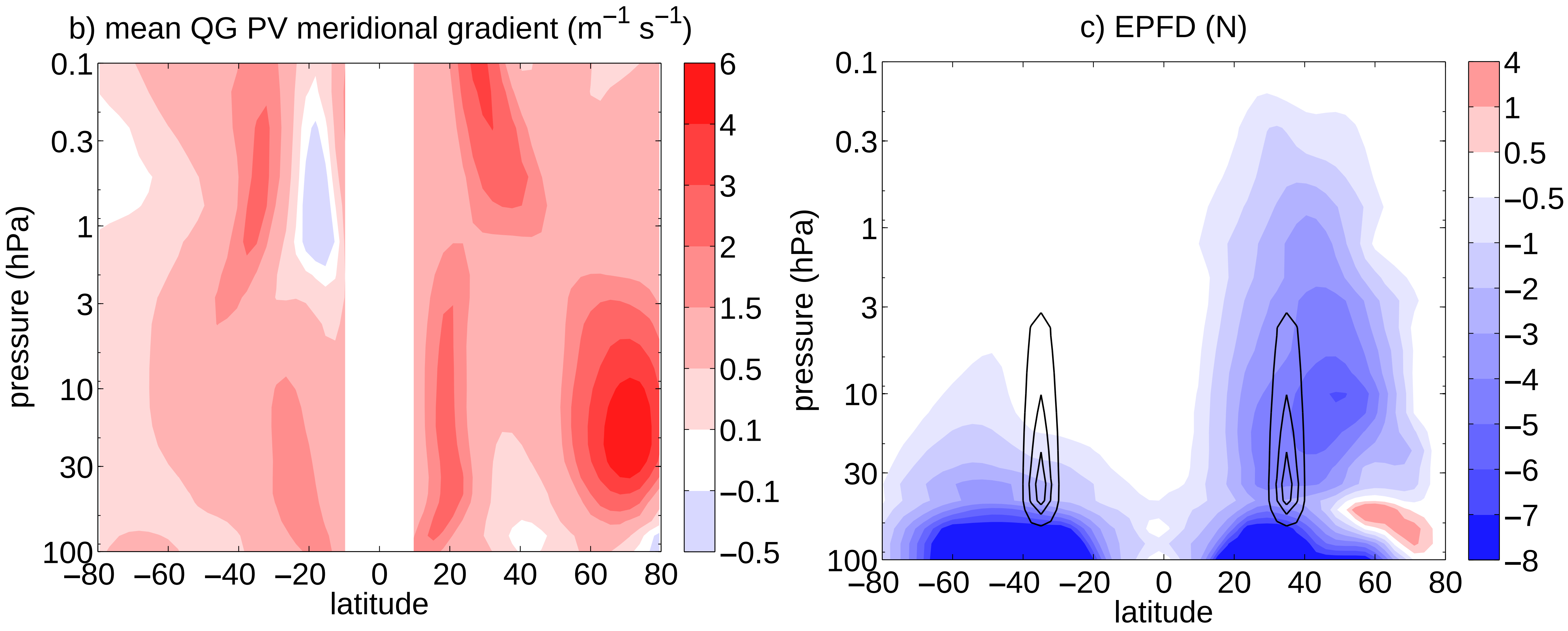


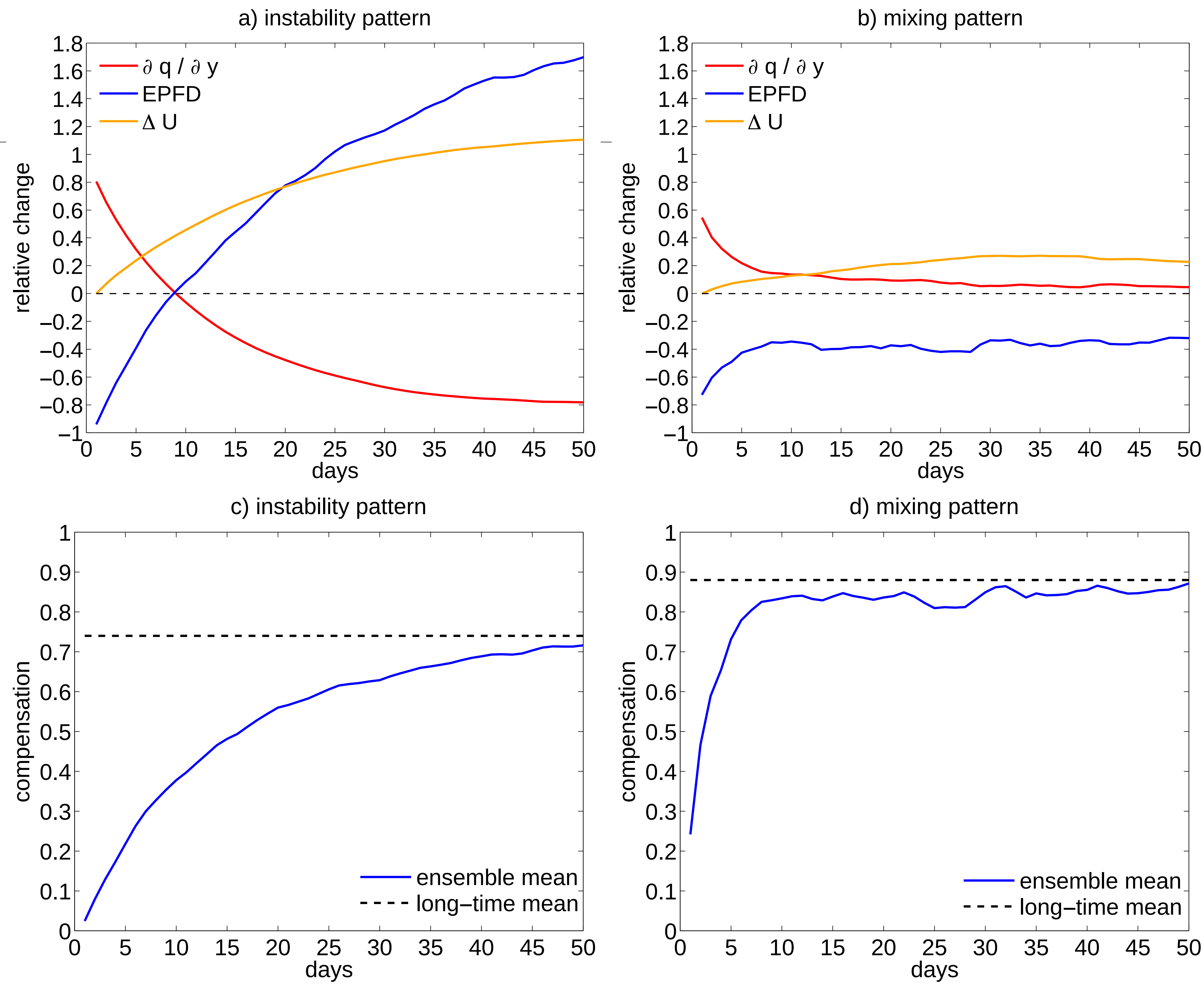
Conclusions

- The Brewer-Dobson Circulation is wave driven, but defining the precise role of Rossby vs. gravity waves is problematic, given their interactions.
    - resolved waves clearly dominant in the stratosphere: mixing PV
    - impact of gravity waves, particularly non-orographic waves, may largely be indirect, by shaping the Rossby wave forcing
    - intermodel differences in wave driving likely reflect tuning, not fundamental limitations in our understanding
- Models accurately simulate the current BDC (albeit with tuning), and robustly predict an increase in the future
    - differences in role of GW vs. resolved waves may be a red herring
    - Mechanism of rising critical latitudes (i.e. a shrinking of the stratosphere) is robust
- Idealized GCMs provide a bridge to connect theoretical insights with the observed and modeled Brewer-Dobson Circulation


PV
Background PV
PV after mixing
EQ
"surf zone"
latitude

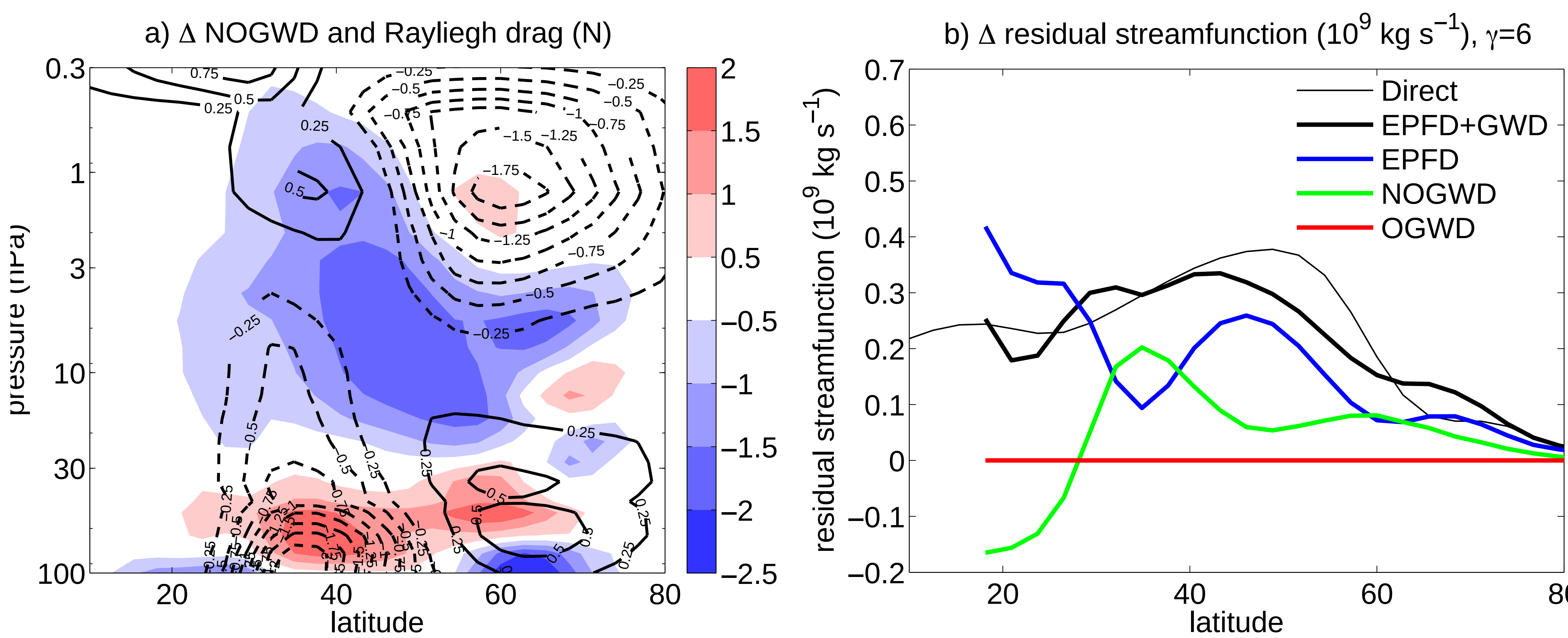
Experiment to separate mixing and instability pathways towards compensation



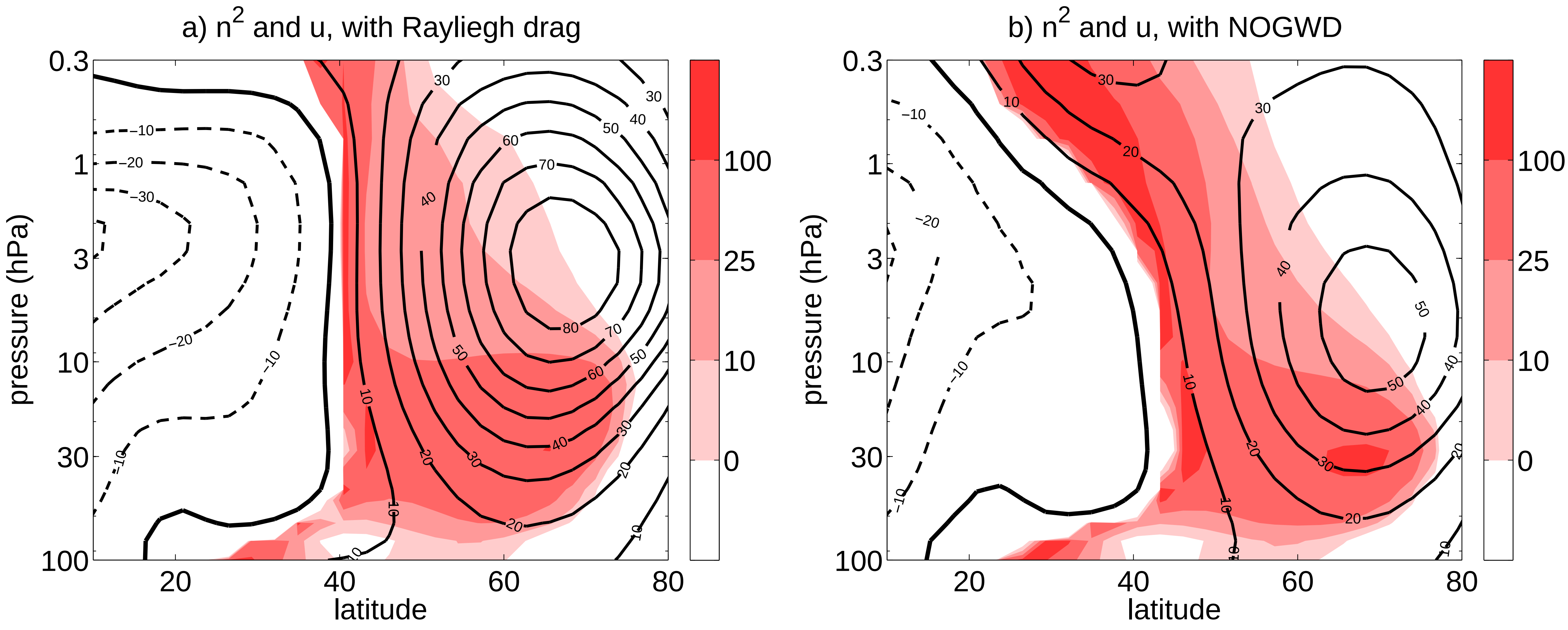


a) instability pattern
b) mixing pattern
∂ q / ∂ y
EPFD
Δ U
relative change
days
c) instability pattern
d) mixing pattern
compensation
ensemble mean
long−time mean

Amplifying effect of NOGW



Impact on index of refraction



The wave forcings in ECHAM6