What drives the Brewer-Dobson Circulation?

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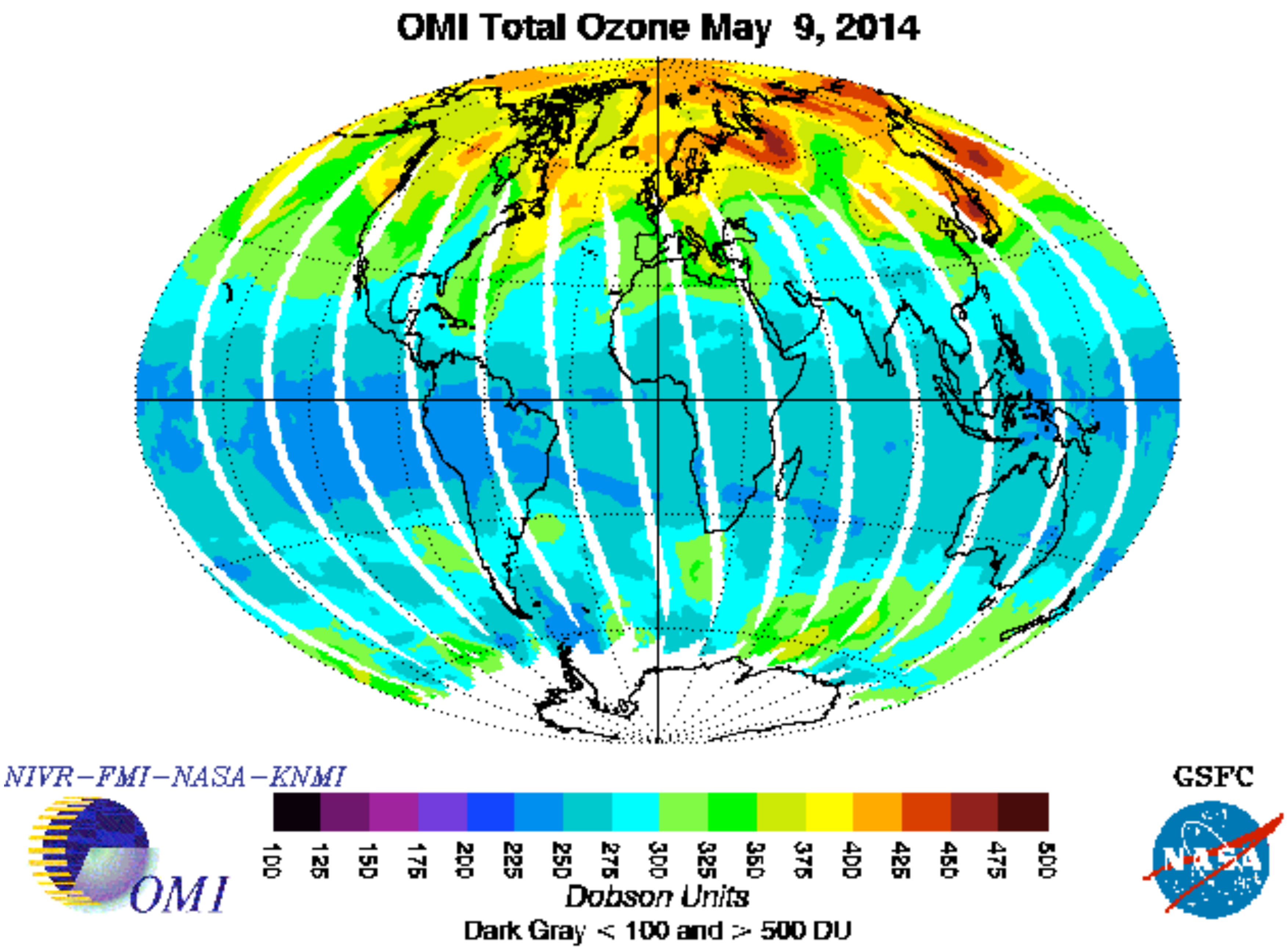
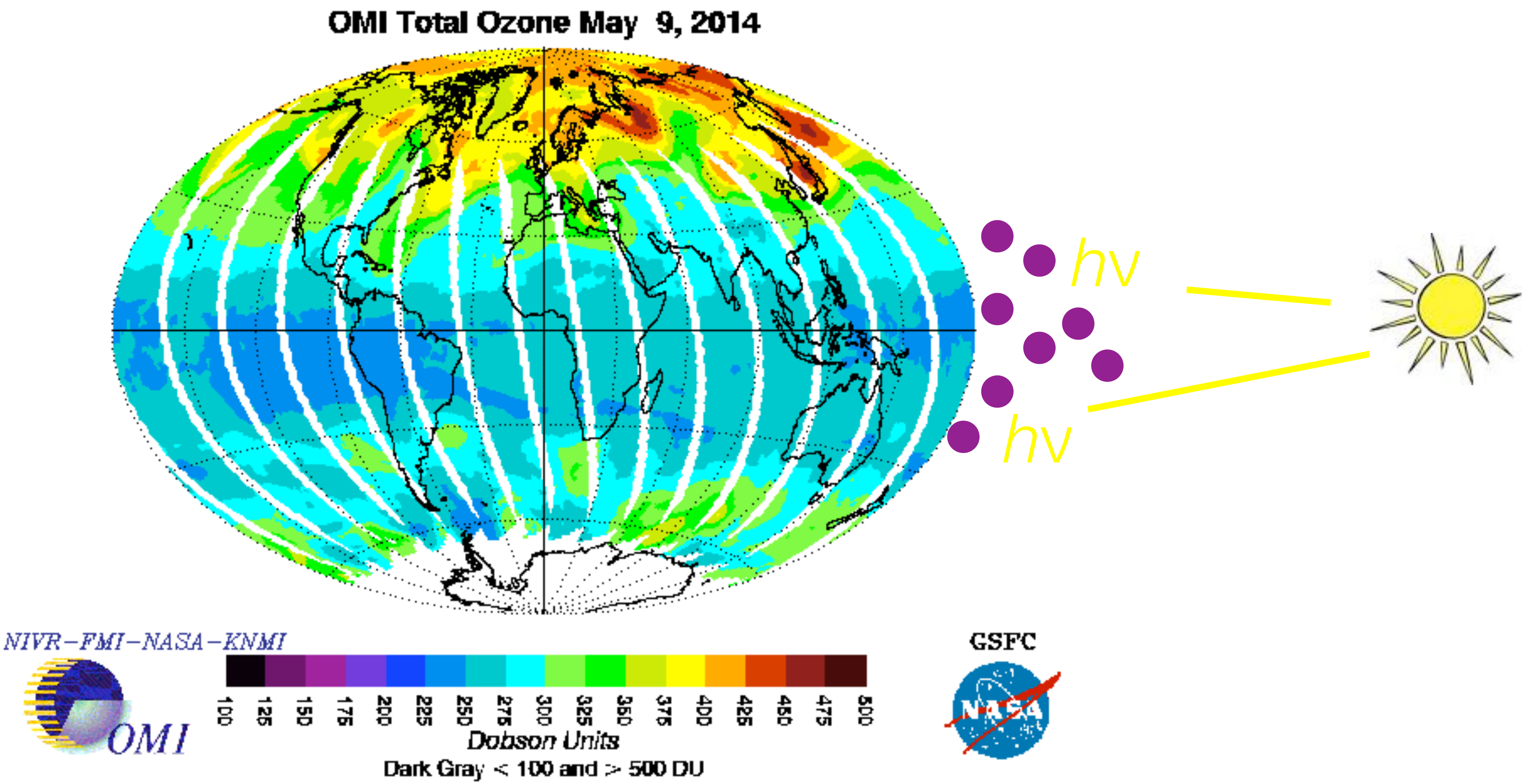
*Now at Yale University

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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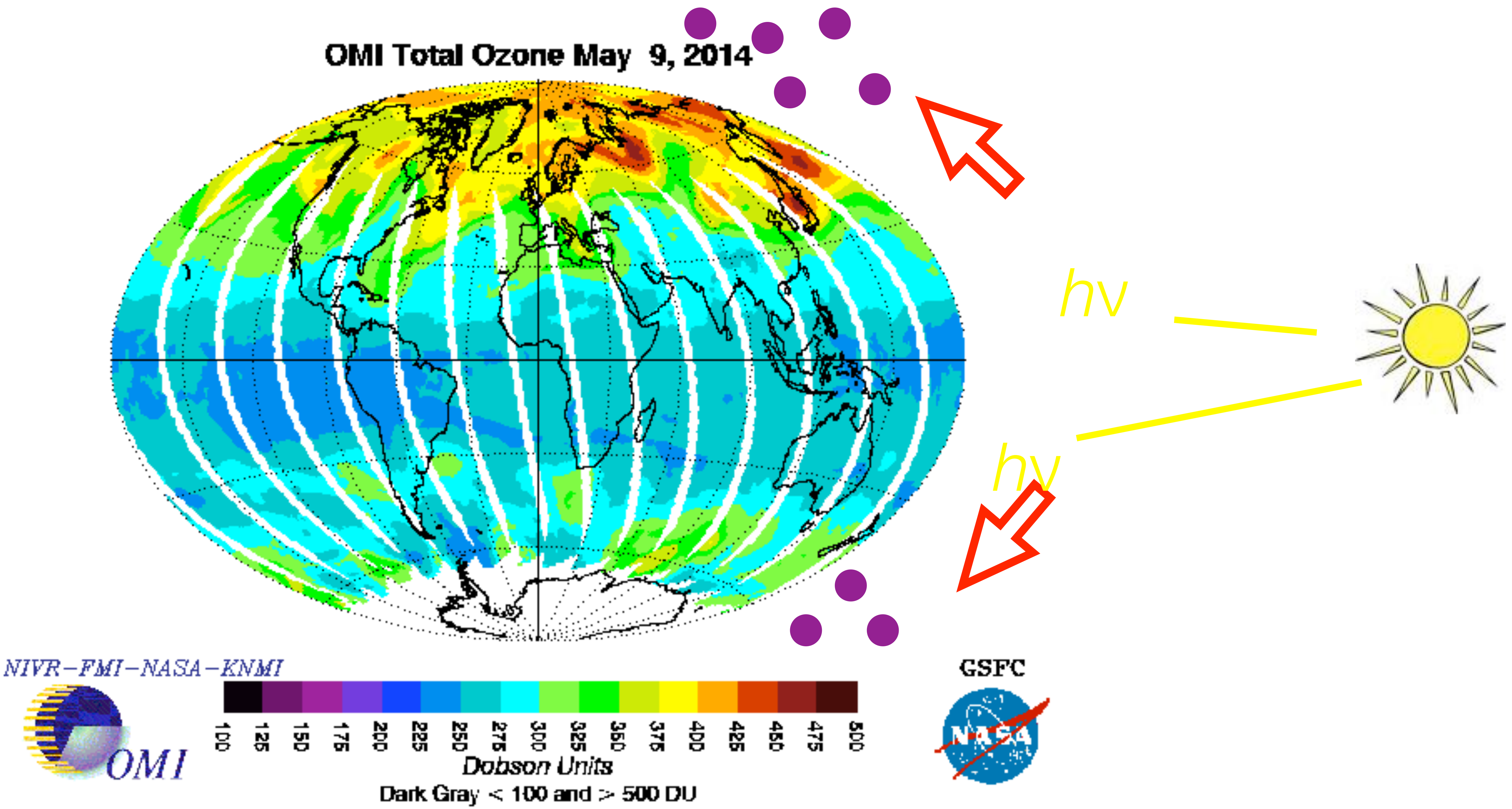

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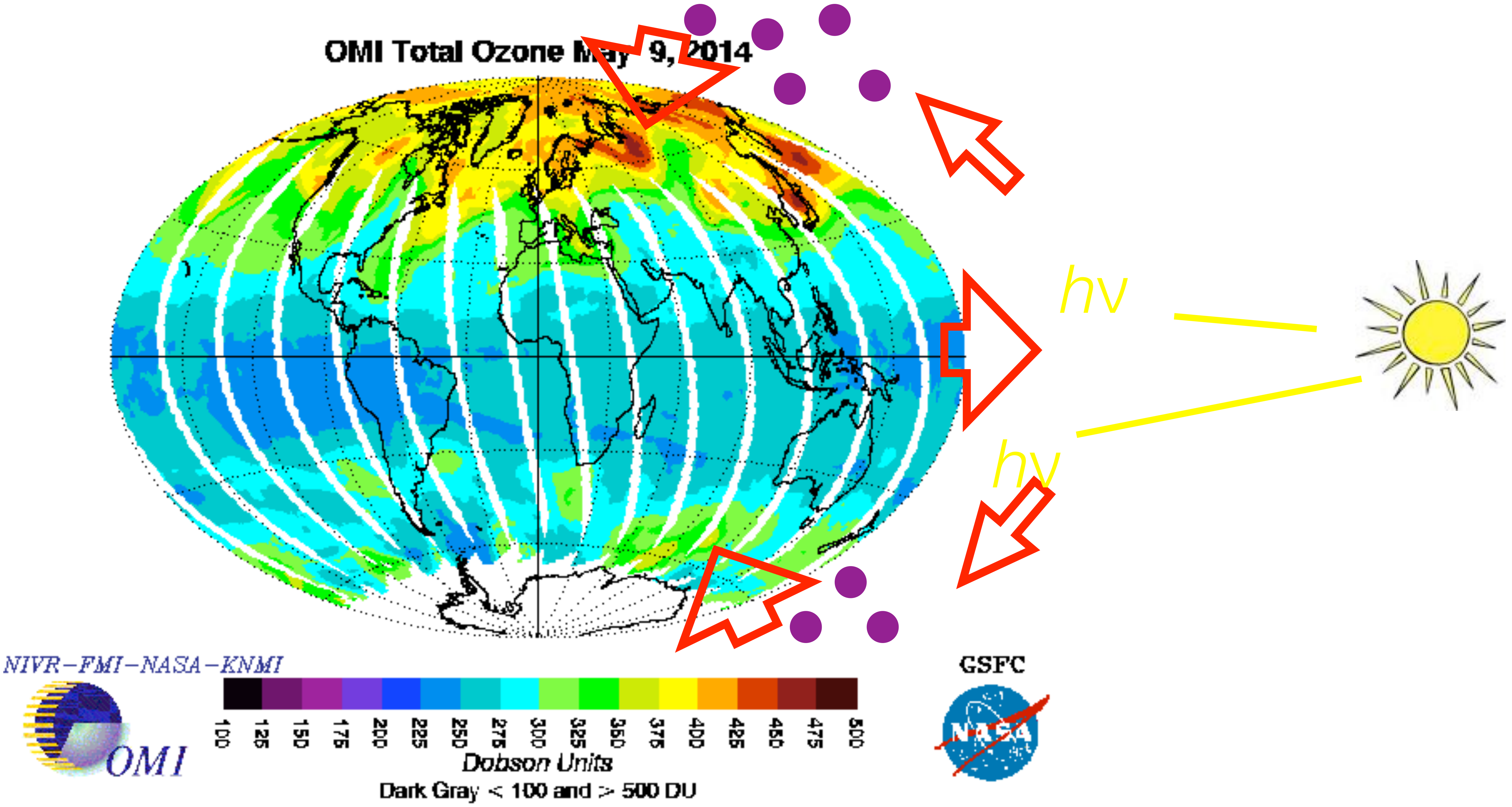

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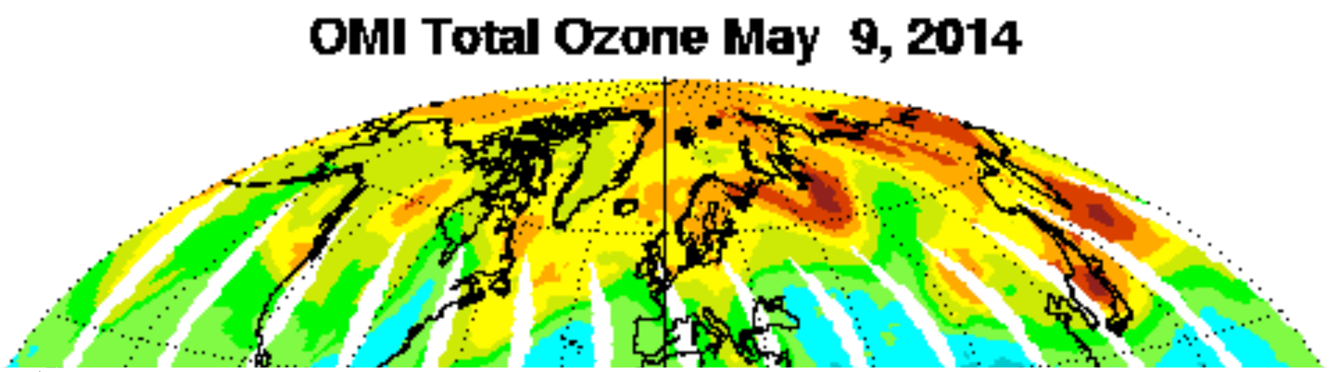
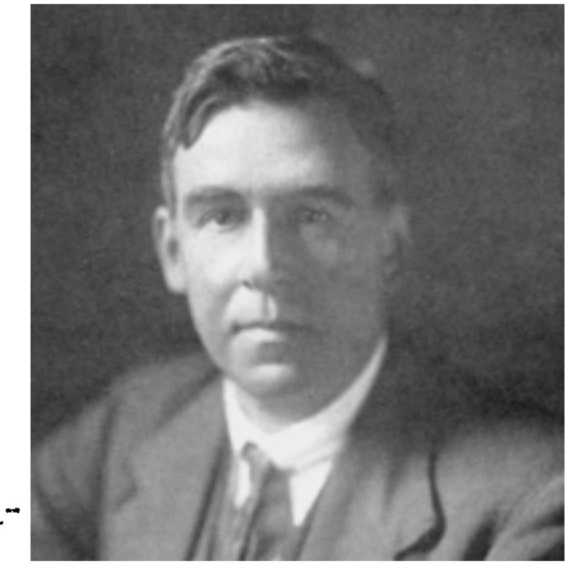
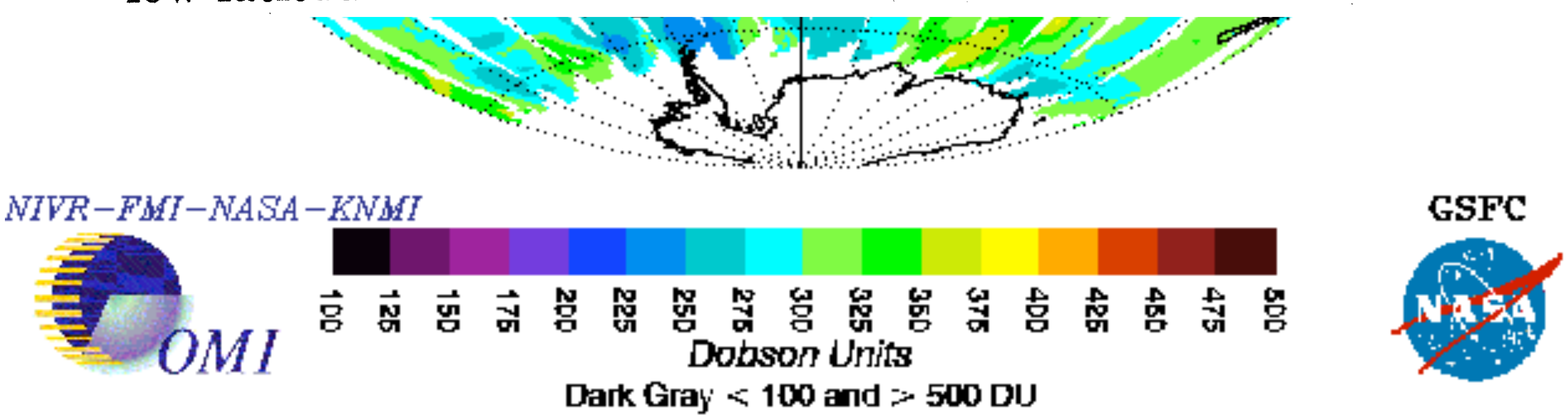




> The only way in which we could reconcile the observed high ozone concentration in the Arctic in spring and the low concentration within the Tropics, with the hypothesis that the ozone is formed by the action of sunlight, would be to suppose a general slow poleward drift in the highest atmosphere with 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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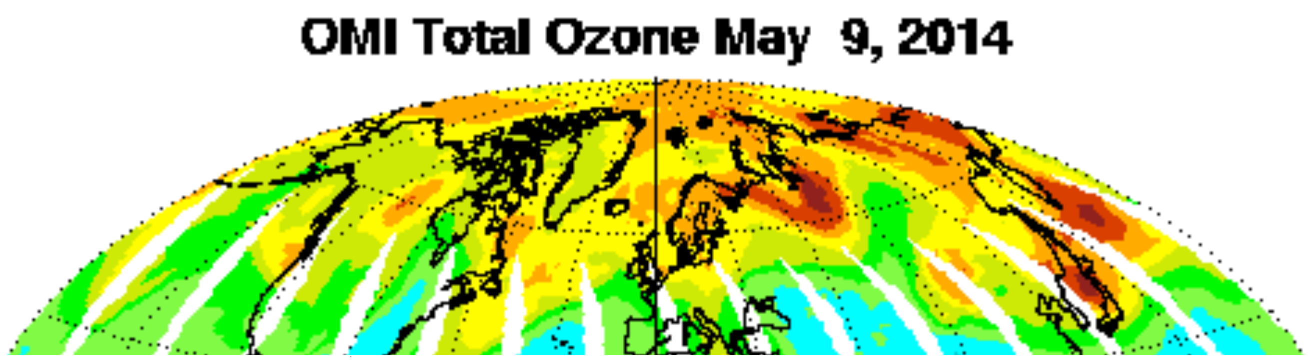
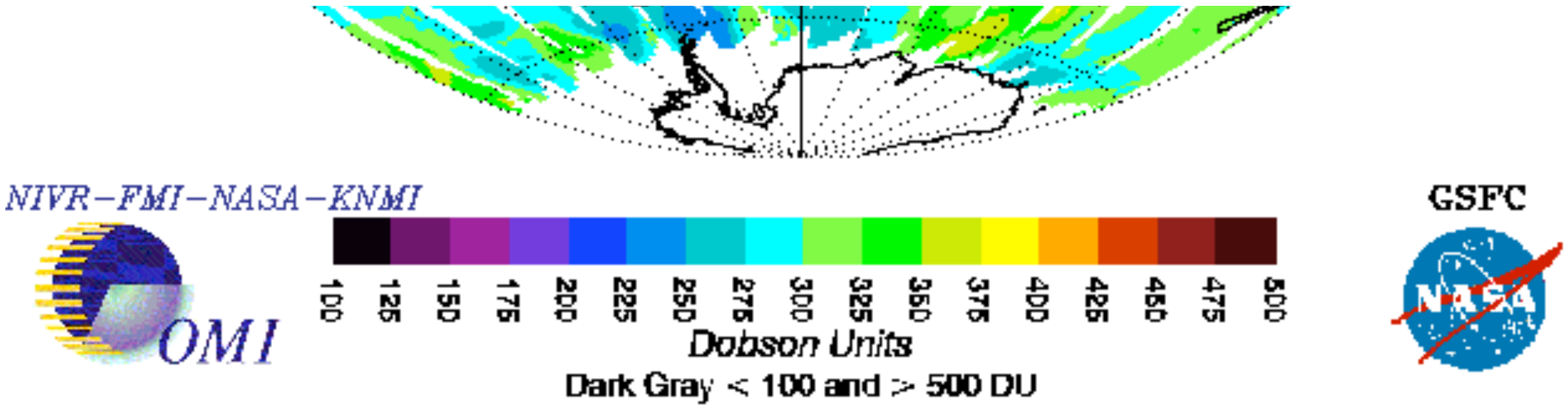


§ VI.—*The Formation and Decomposition of Atmospheric Ozone.*

It has generally been supposed in the past that the ozone present in the upper atmosphere was formed from oxygen under the influence of the sun's ultra-violet radiation of wave-length about 1600 Å., but the results of the present observations make it almost certain that this is not the chief cause of the formation of ozone. We find that the maximum ozone values are associated



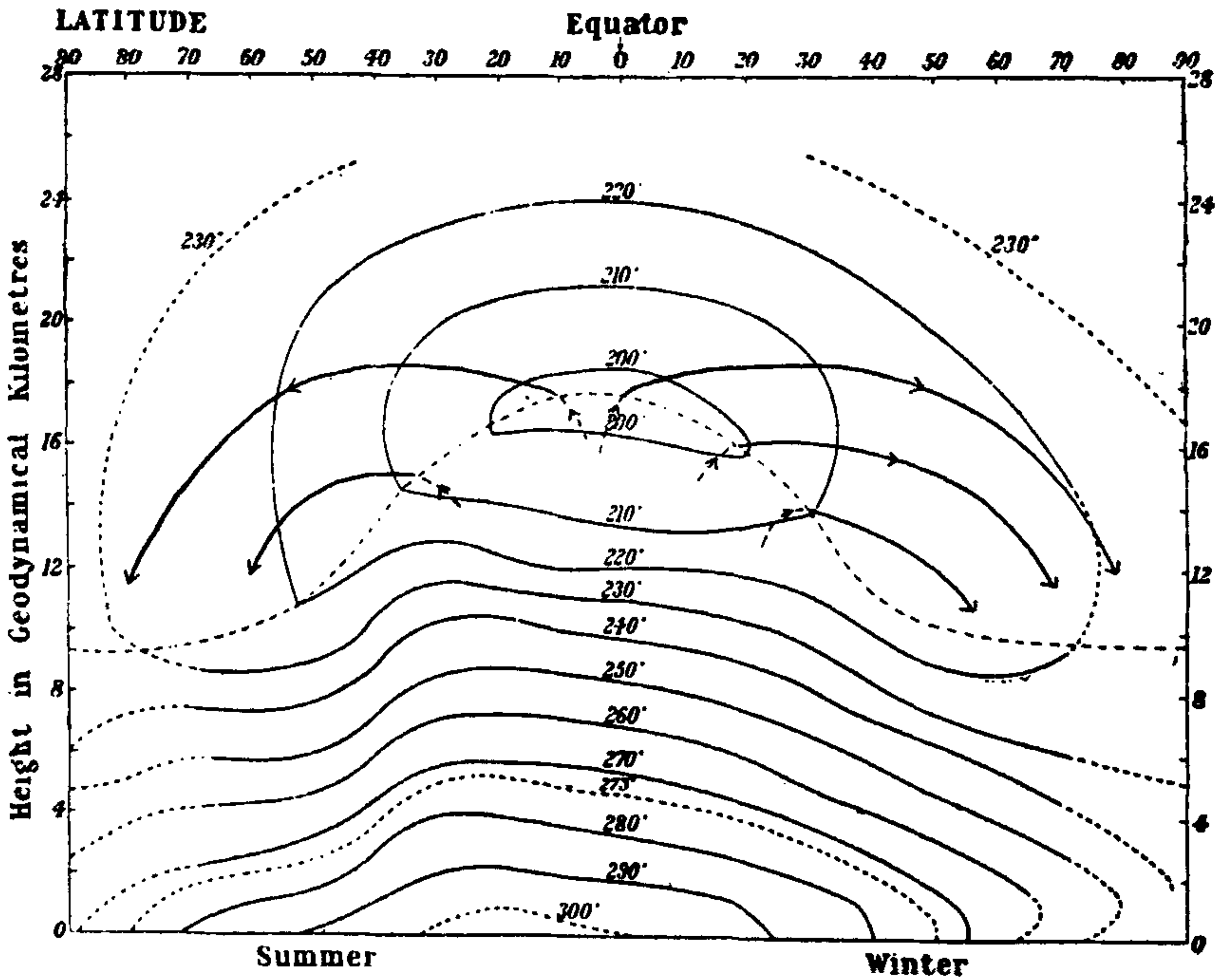
Dobson, Harrison, and Lawrence [1929]

551·510.5

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

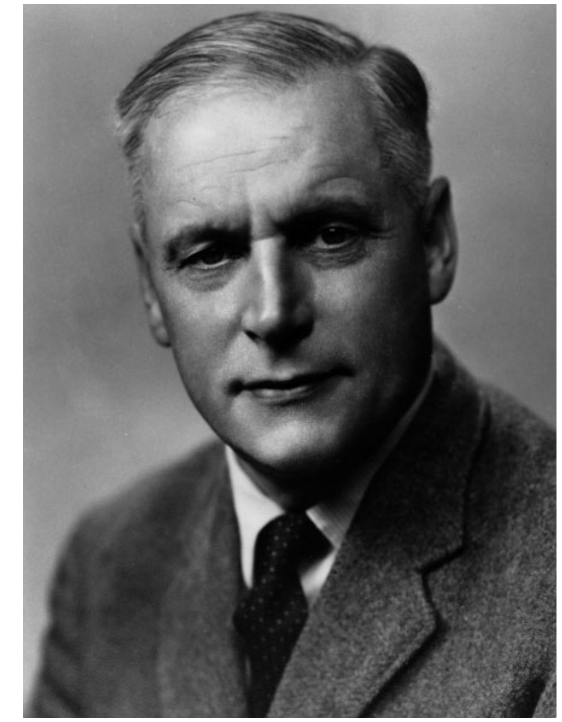
By A. W. BREWER, M.Sc., A.Inst.P.

(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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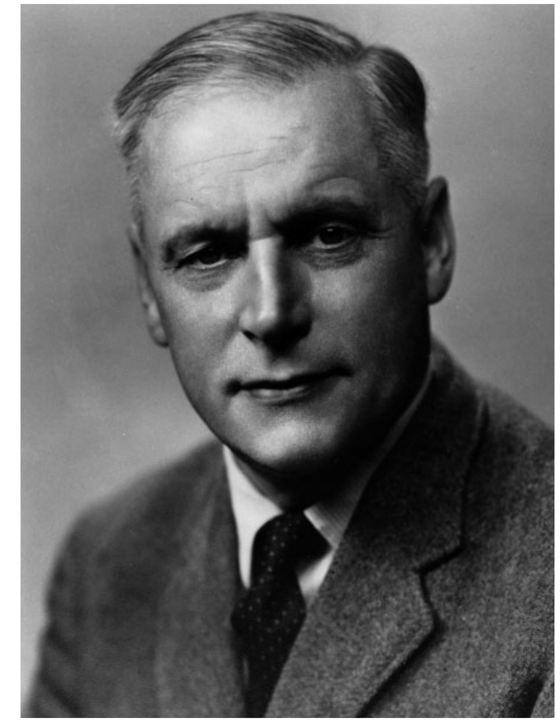

The ratio of the mean subsidence rate to the mean value of the diffusion constant just above the tropopause can be fixed by the water vapour profiles fairly closely to 3×10^{-5} cgs units. In the absence of data of the rate of radiative cooling or of the degree of turbulence of the lower stratosphere actual values for w and K cannot be fixed. The values can probably be said to lie within the limits 300 and 4,000 cgs units and 8 and 100 m/day.

The matter can only be decided by measurements of K or of the radiative conditions of the stratosphere and both are possible.

The writer considers that K will prove to be of the order of 1 or $2 \times 10^3/\text{cm}^2\ \text{sec}^{-1}$ and w about 50 m/day. If the circulation is as rapid as this it will make a significant contribution to the energy of the general circulation.

The dynamic consequences of the circulation have not been discussed. There are considerable difficulties in this respect.

Acknowledgments

The humidity measurements were carried out as part of the programme of the Meteorological Research Flight and are quoted by permisison of the Director, Meteorological Office, Air Ministry.

Particular thanks are due to Sir Nelson Johnson for his personal interest in these problems, and to members of the Meteorological Research Committee amongst whom special thanks are due to Professor G. M. B. Dobson, F.R.S., Professor Sidney Chapman, F.R.S., and Assistant Professor P. A. Sheppard for their helpful comments and discussions.

References

Bamford, C. H. 1943 Reports on Progress in Physics, London, **IX**, p. 75.

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"polar vortex catastrophe"

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Eliassen and Palm, 1961

Andrews and McIntyre, 1976

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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?

Questions

- What drives the Brewer-Dobson Circulation?

  (Which waves are responsible for balancing the Coriolis torque?)

For the primitive equations,

$$\nabla \cdot \mathbf{F} = \frac{\partial}{\partial y}\left[-\overline{u'v'} + \frac{\partial \overline{u}}{\partial z}\frac{\overline{v'\theta'}}{\overline{\theta}_z}\right] + \frac{\partial}{\partial z}\left[\left(f - \frac{\partial \overline{u}}{\partial y}\right)\frac{\overline{v'\theta'}}{\overline{\theta}_z} - \overline{u'w'}\right]$$

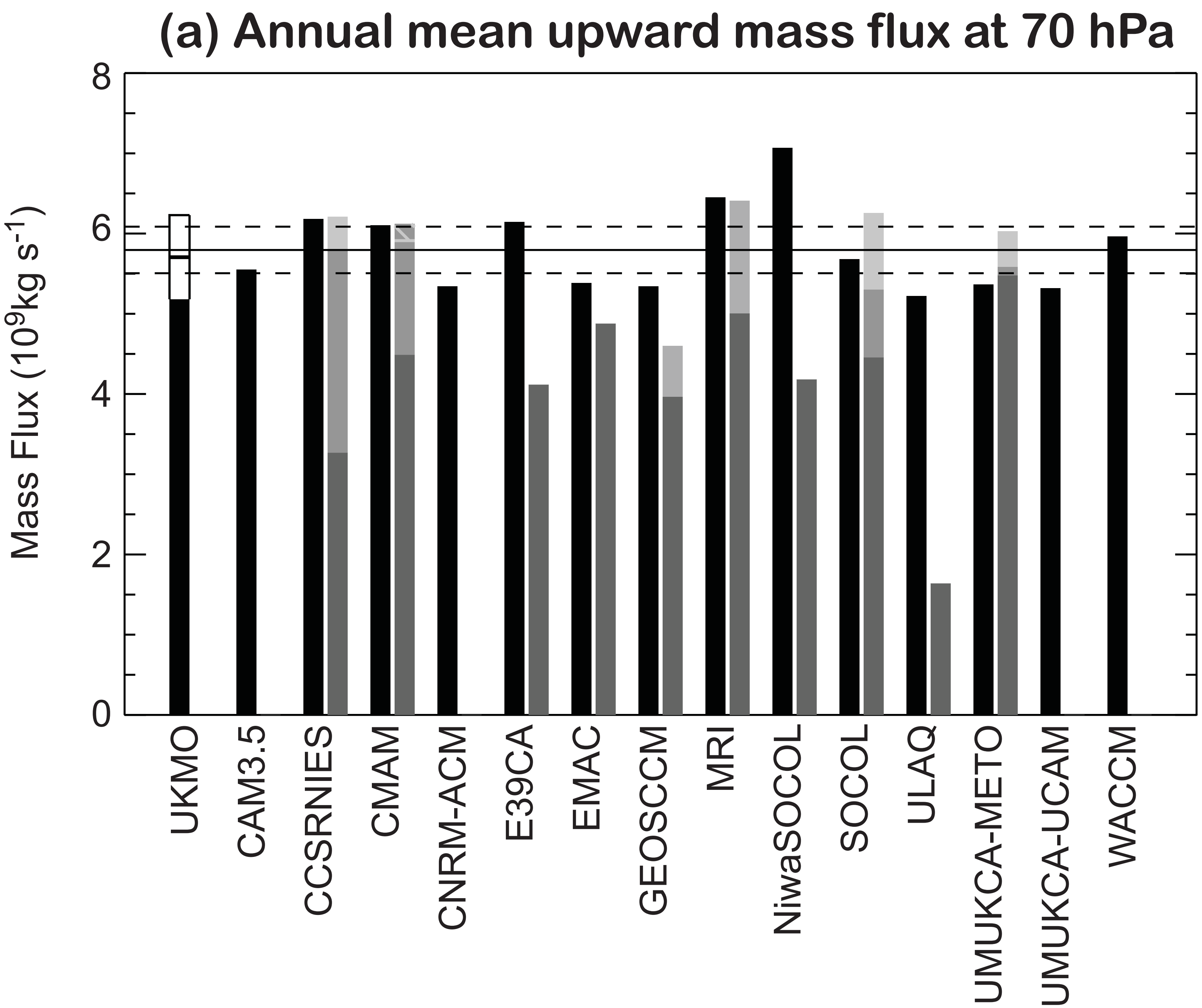
Rossby wave momentum and heat fluxes

Gravity wave momentum fluxes

Questions

- What drives the Brewer-Dobson Circulation?

  (Which waves are responsible for balancing the Coriolis torque?)



total

Rossby waves

orographic GW

non-orographic GW

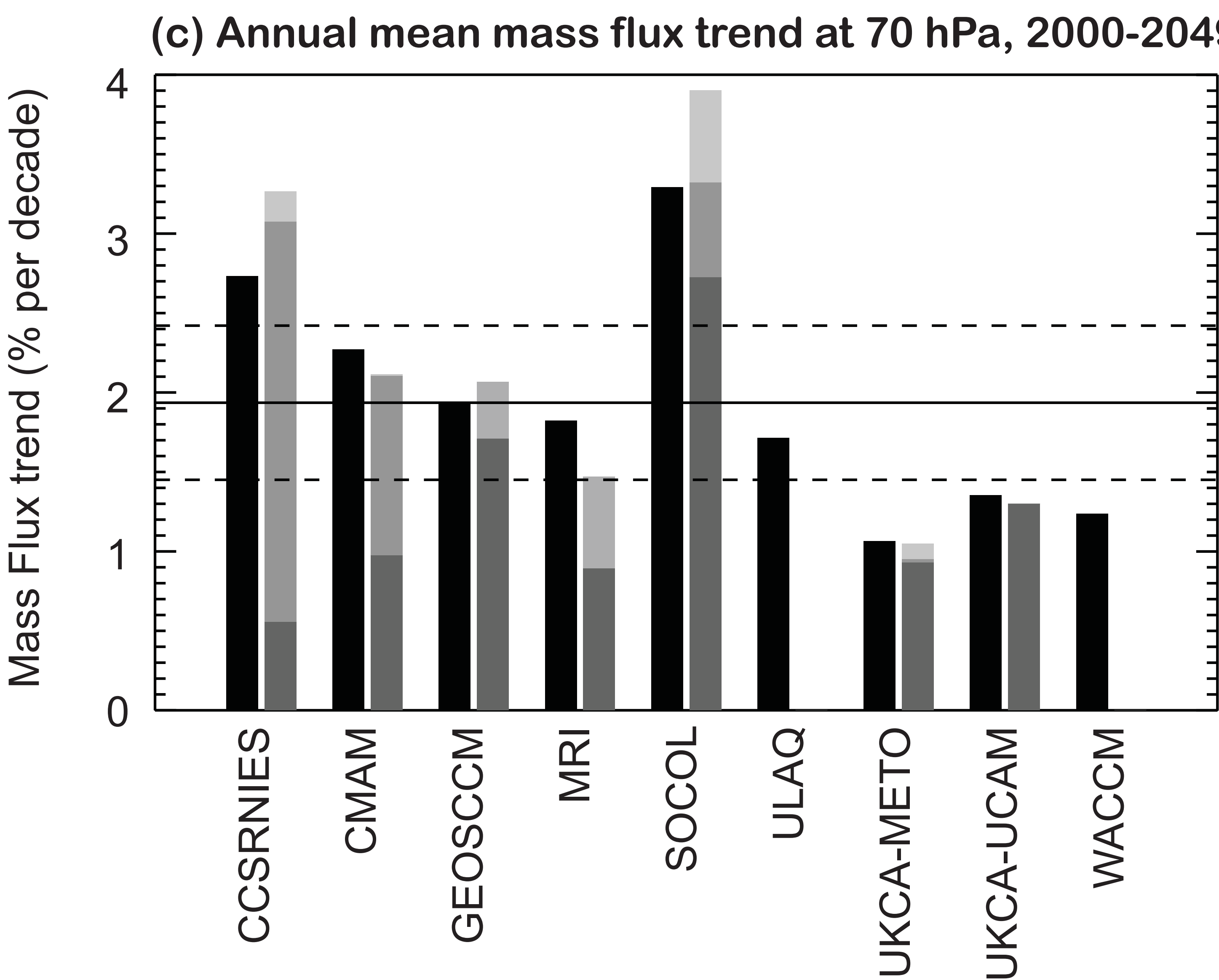
[CCMVal2 Report, Butchart et al. 2011]

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].*

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].*
  - Do we understand why?



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[CCMVal2 Report]

Questions

- What drives the Brewer-Dobson Circulation?

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

Interaction between Rossby and gravity wave driving complicates the answers…

(Did we ask the right question in the first place?)

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]*

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

zonal mean torque

steady state

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

QG (neglect relative vorticity)

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

Coriolis force must balance torque

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

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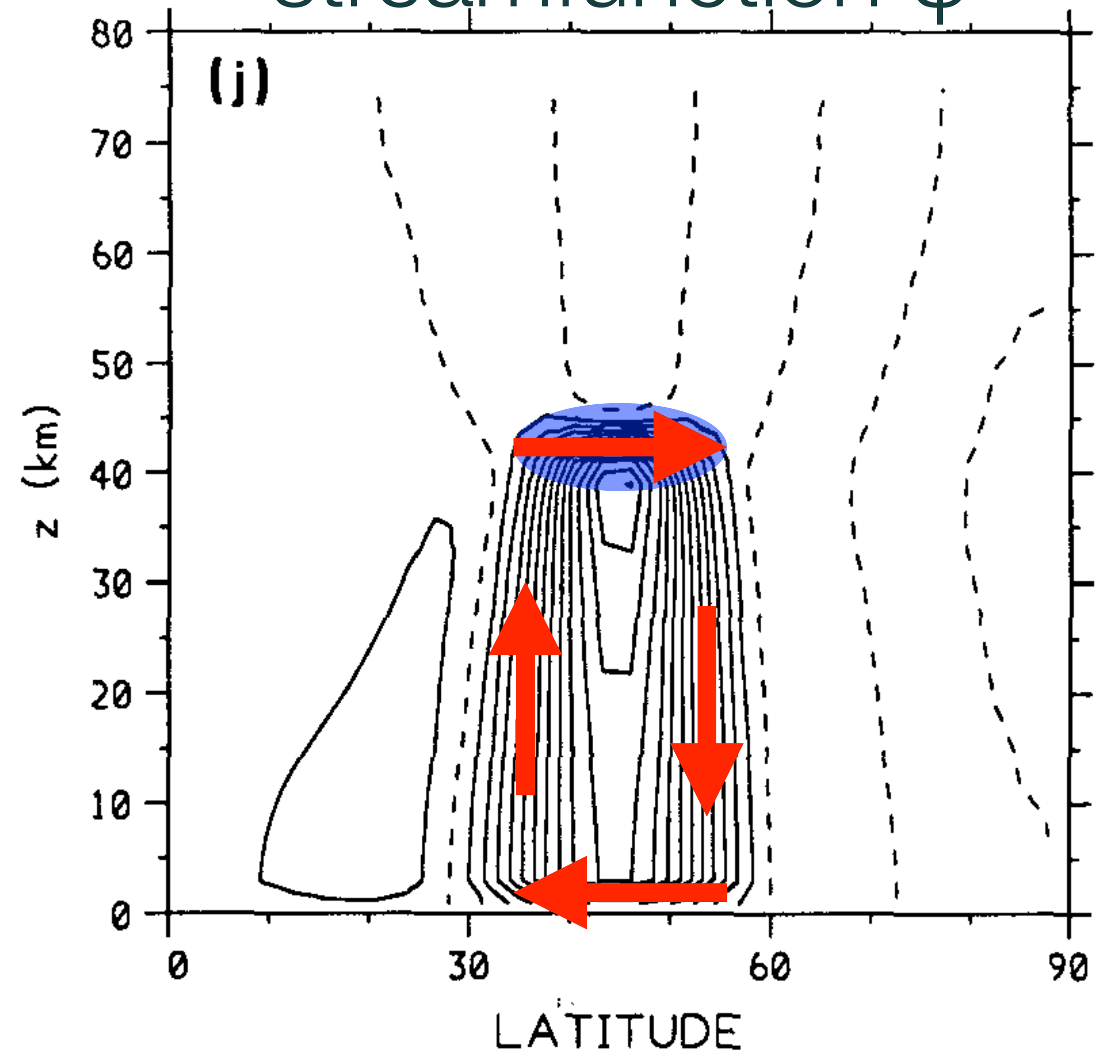
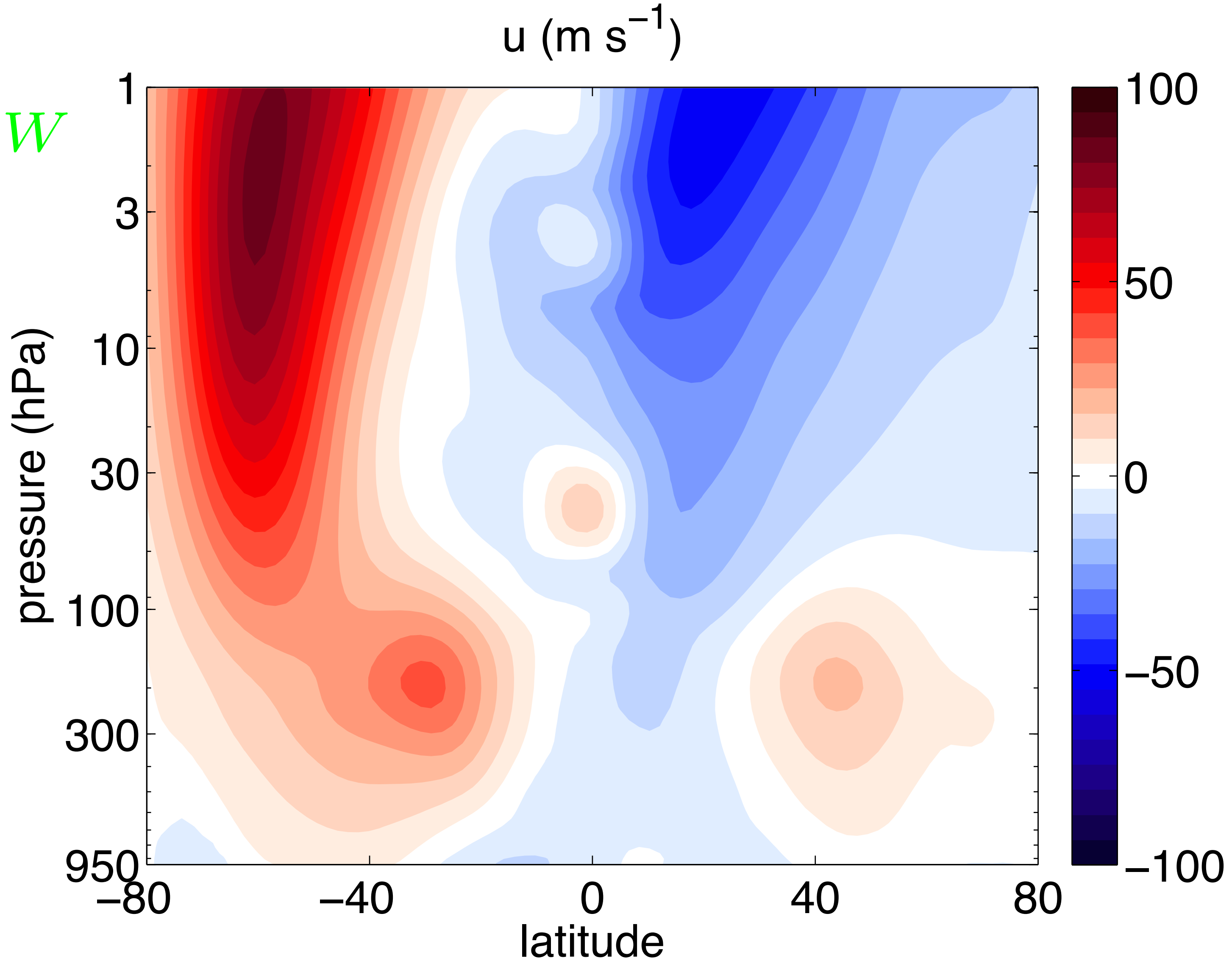
streamfunction ψ



Which waves contribute to the zonal mean torque?

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

JJA zonal mean zonal wind



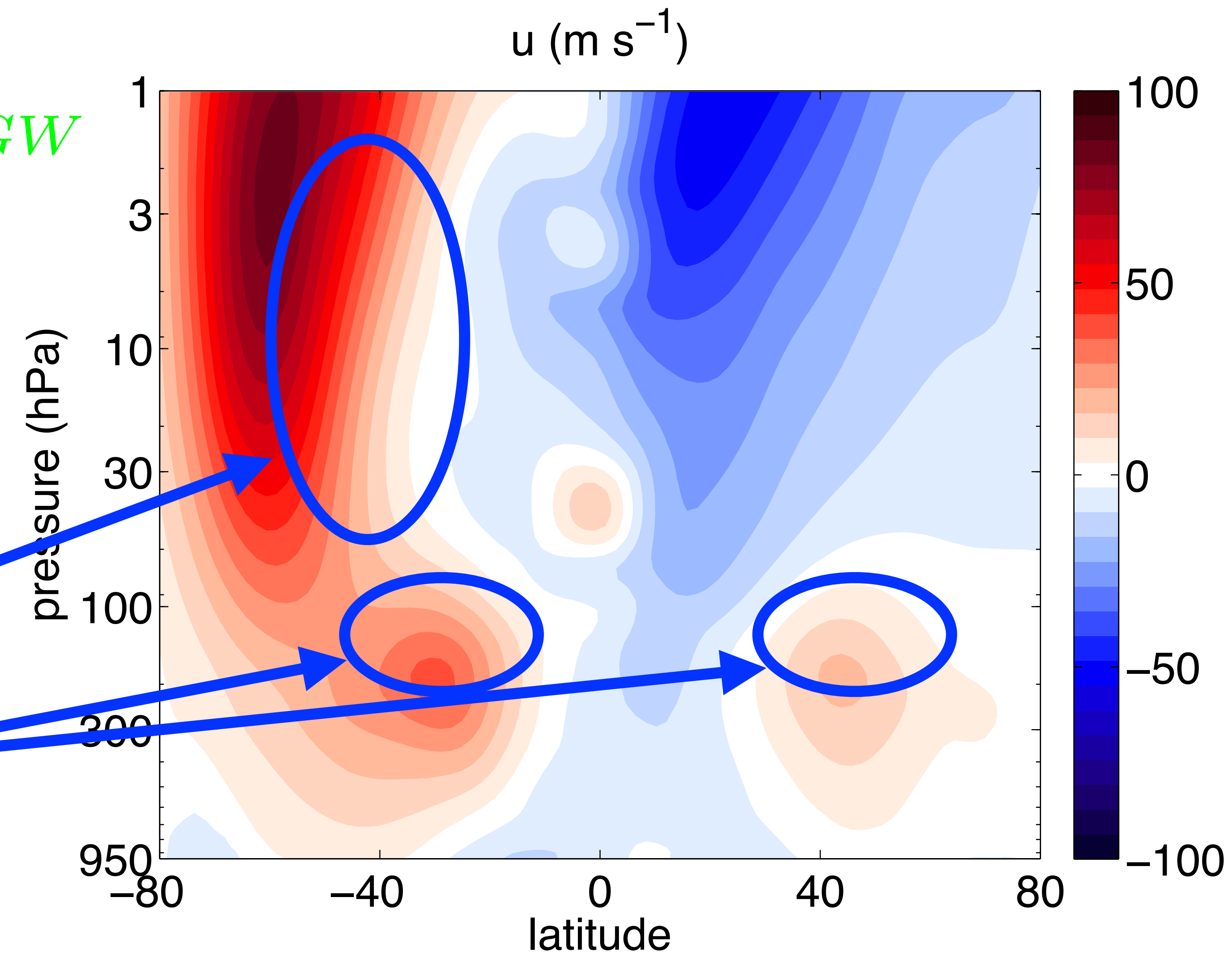
ECHAM6 (MPI-ESM-MR)
(courtesy of Felix Bunzel)

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.

JJA zonal mean zonal wind

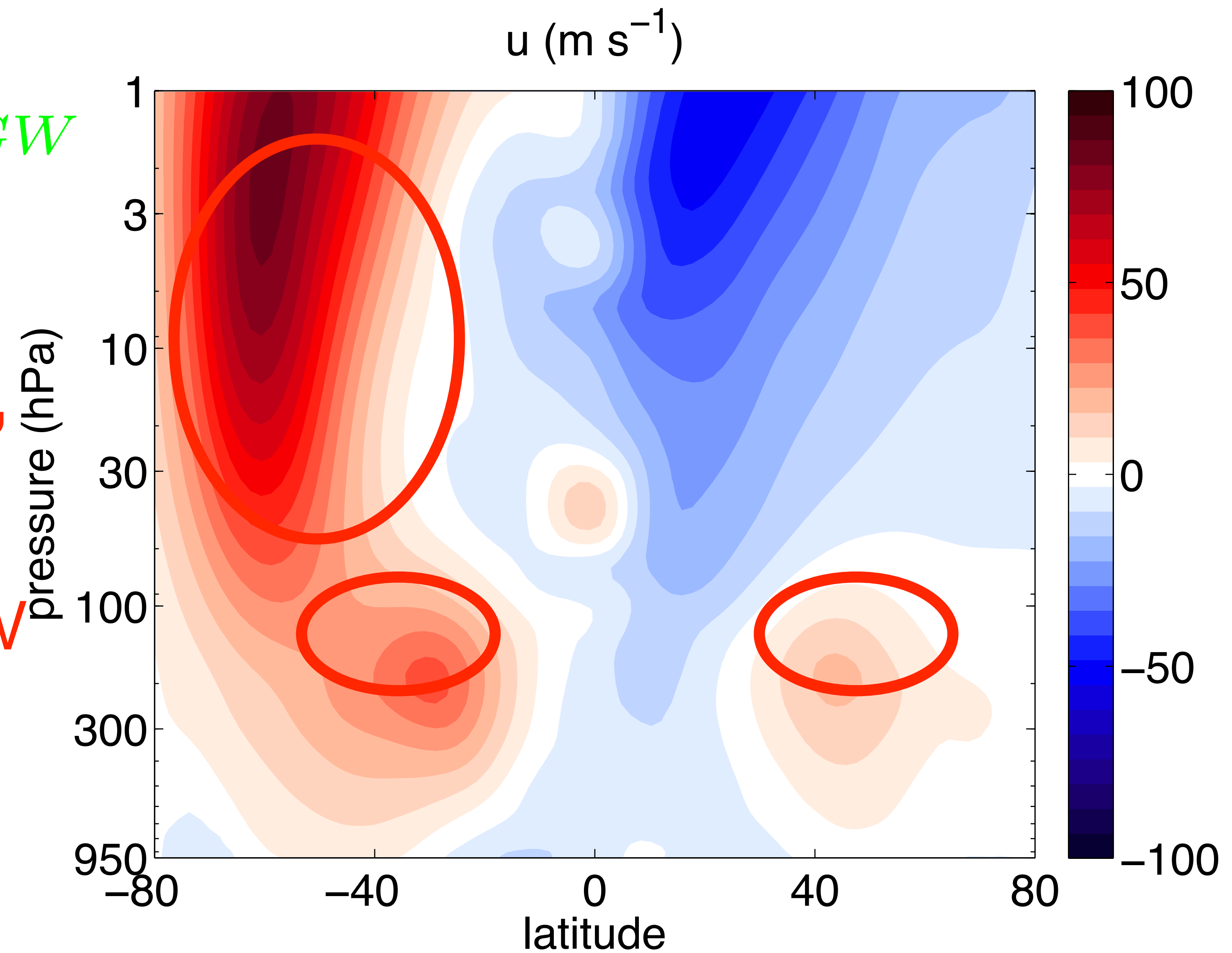


Which waves contribute to the zonal mean torque?

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

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

JJA zonal mean zonal wind

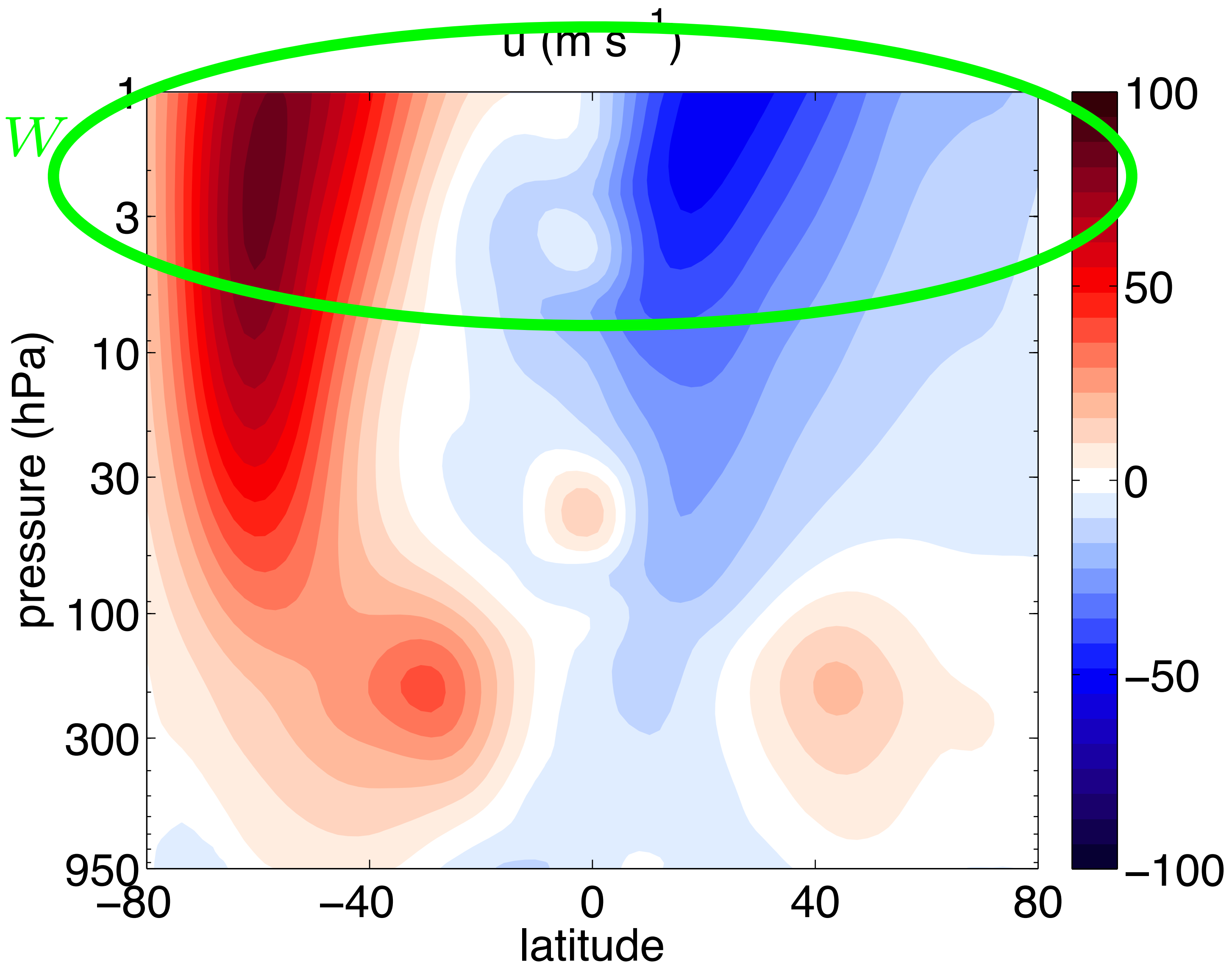


Which waves contribute to the zonal mean torque?

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

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

JJA zonal mean zonal wind



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↓

using downward control, partition the circulation

↓

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

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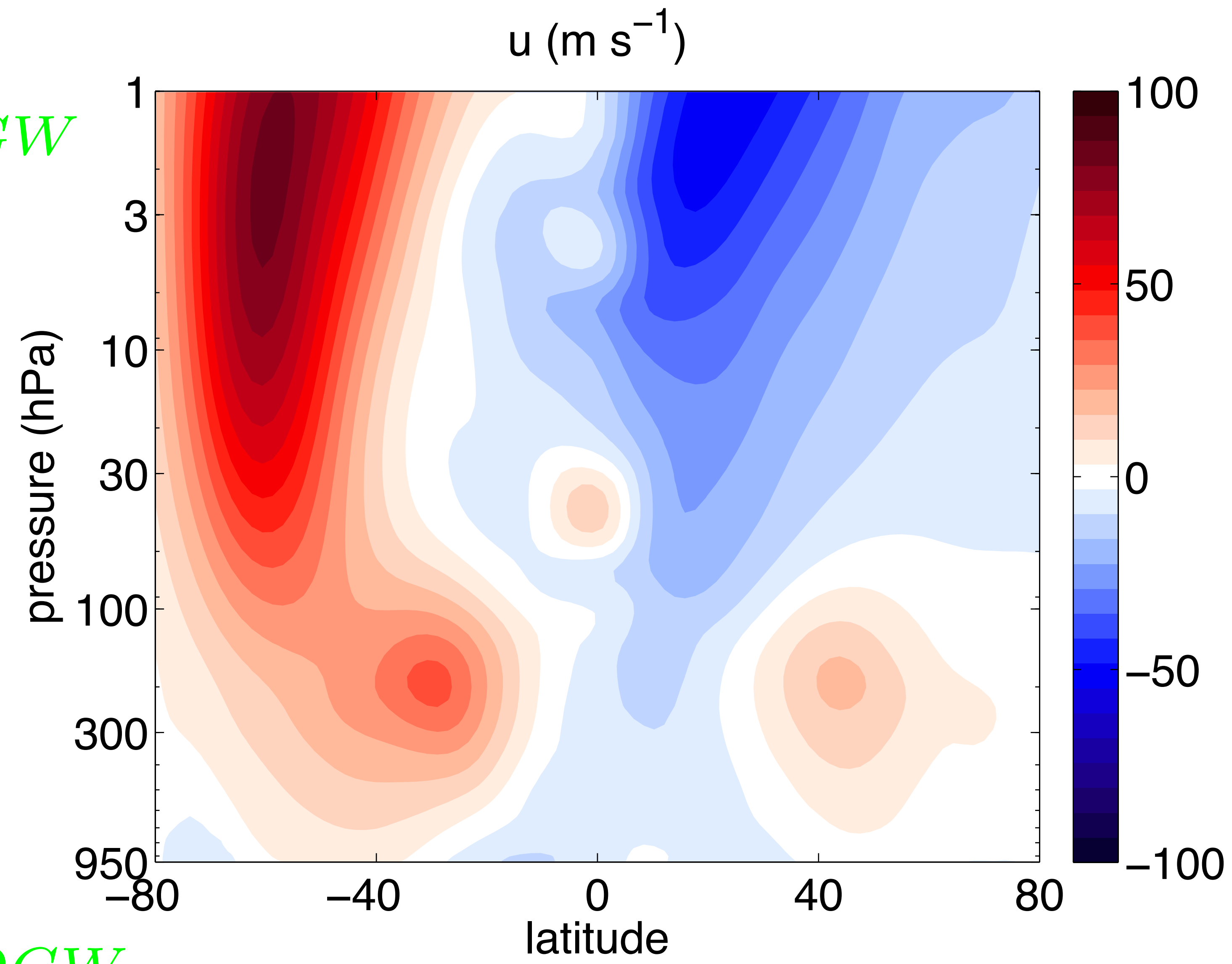

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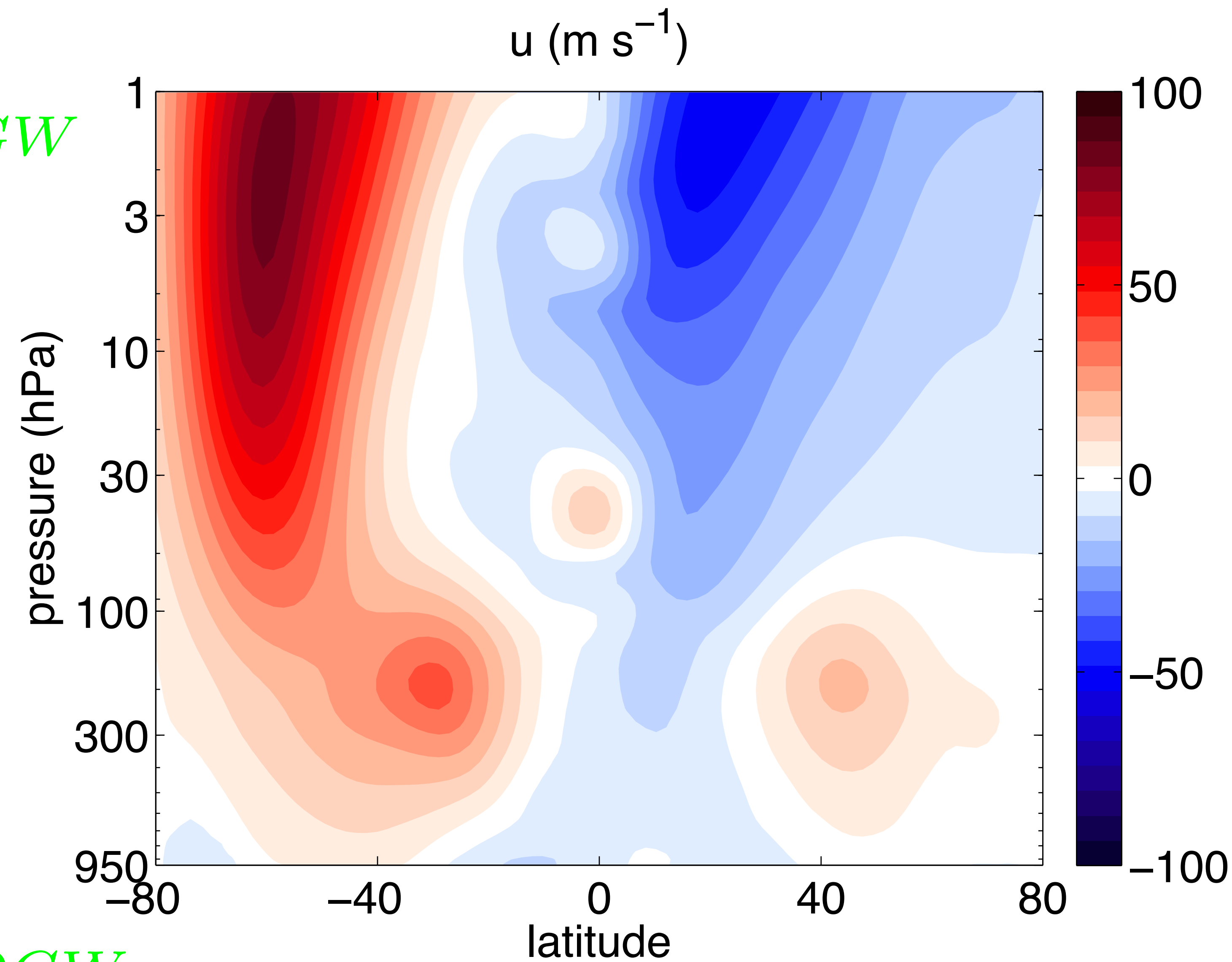
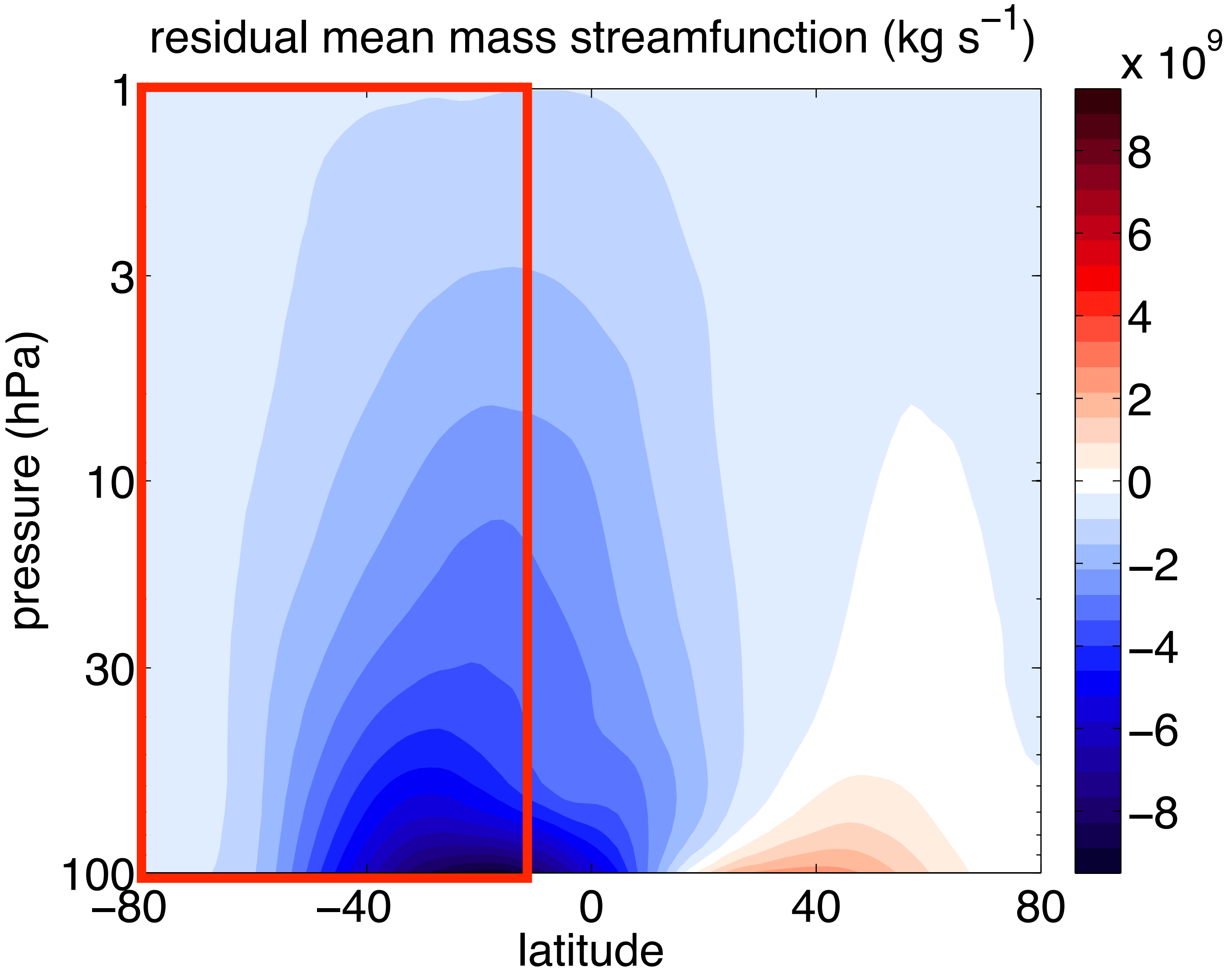


implicit assumption: the wave forcings are independent

The JJA Residual Circulation in ECHAM6



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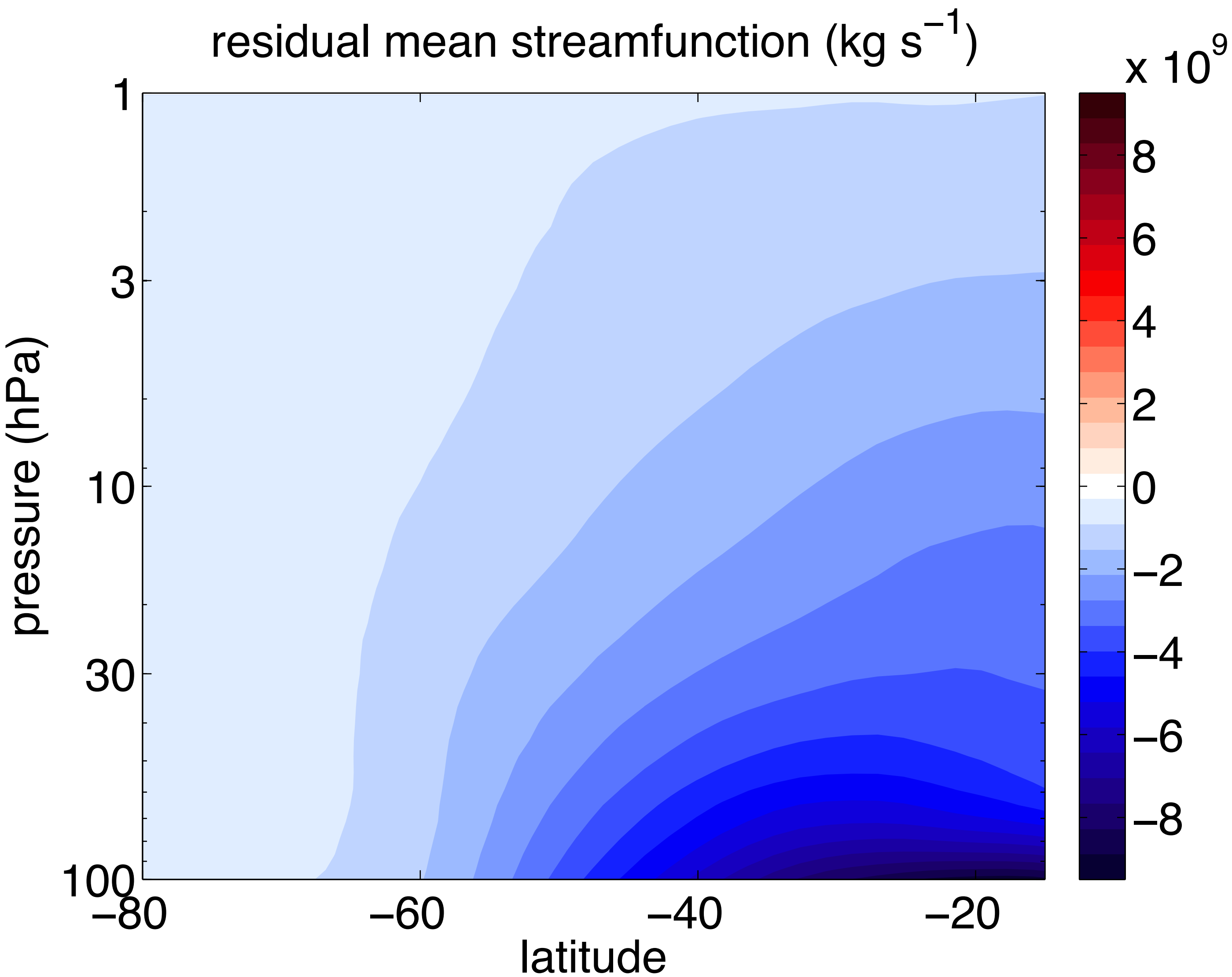
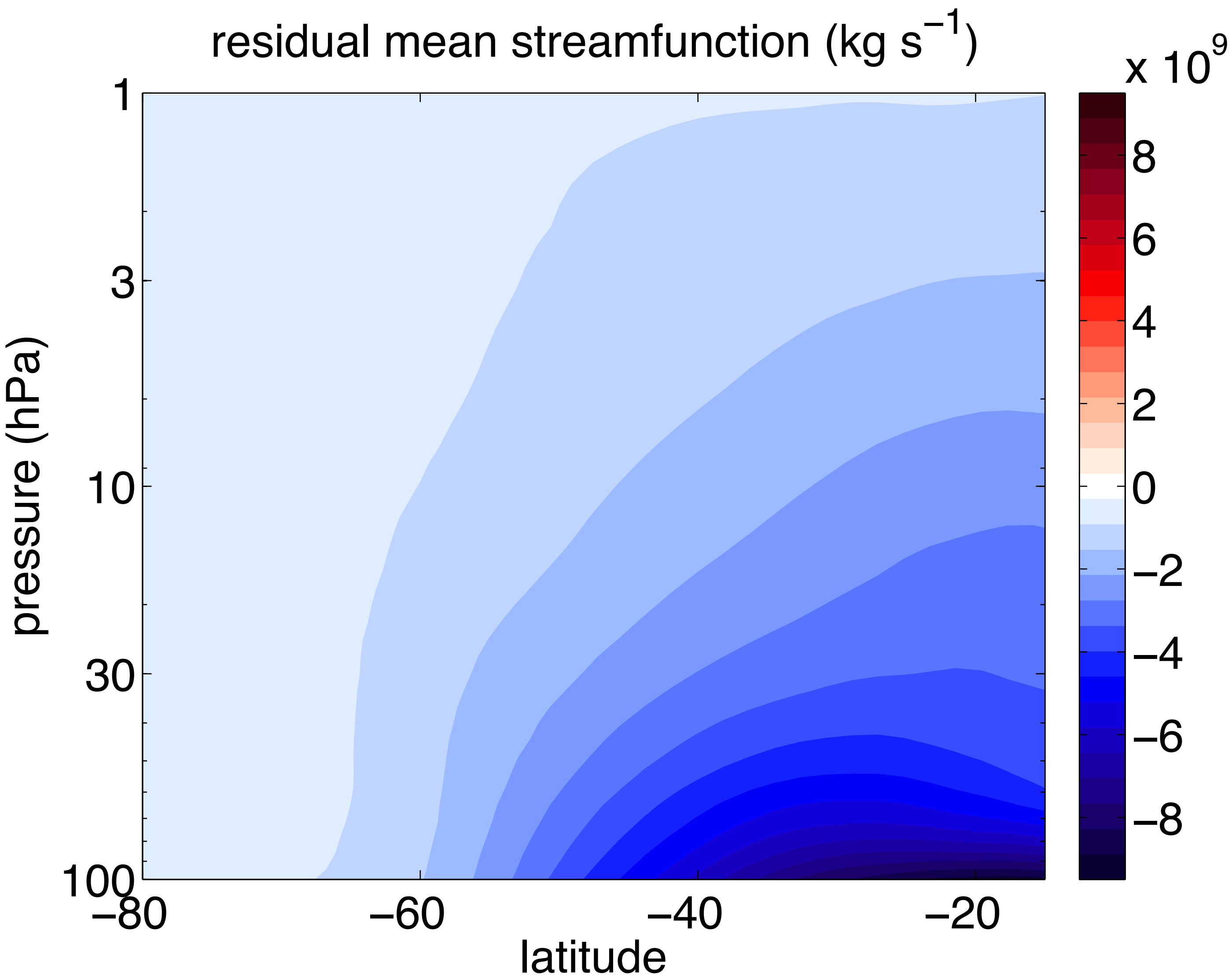
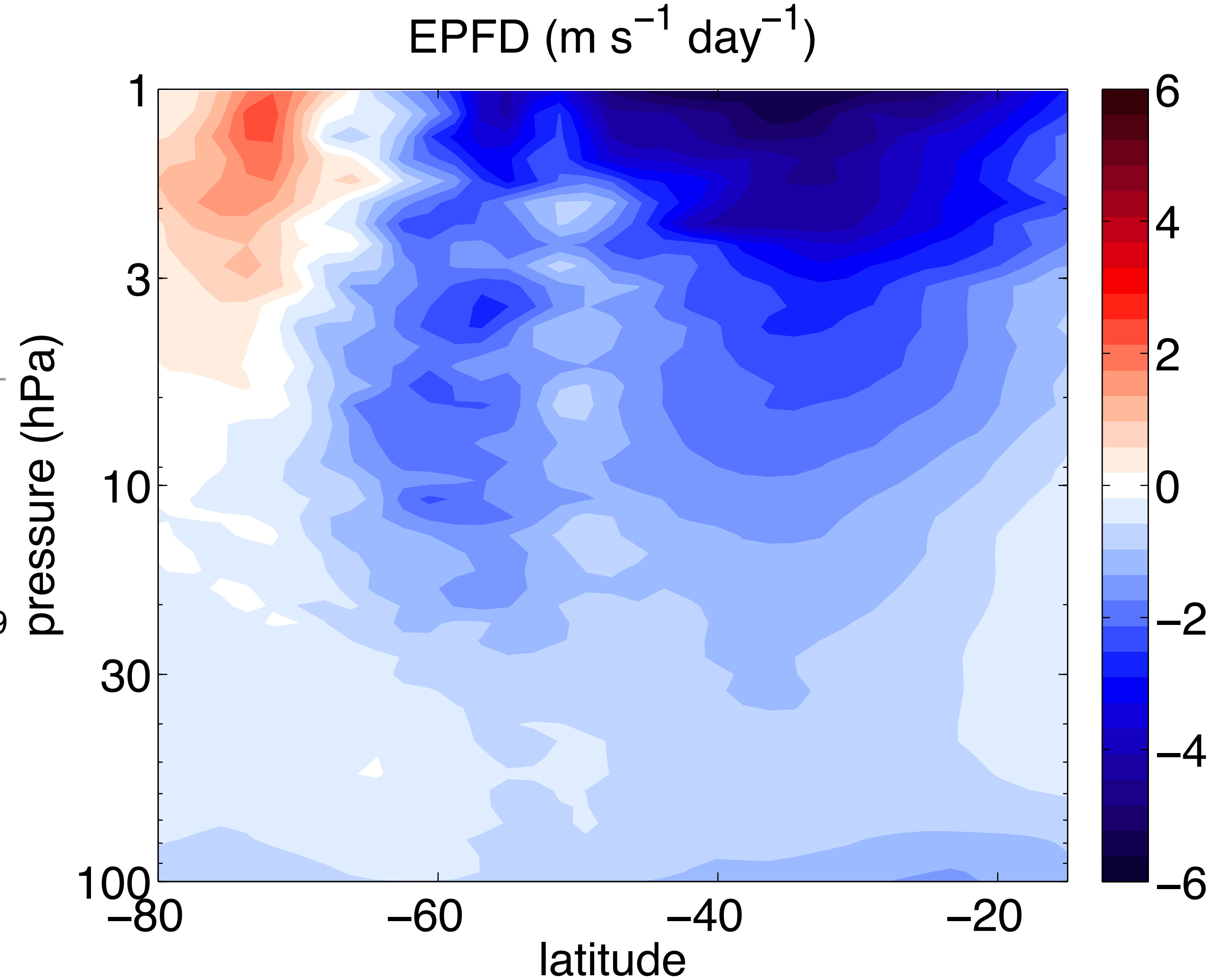


Breaking down the streamfunction





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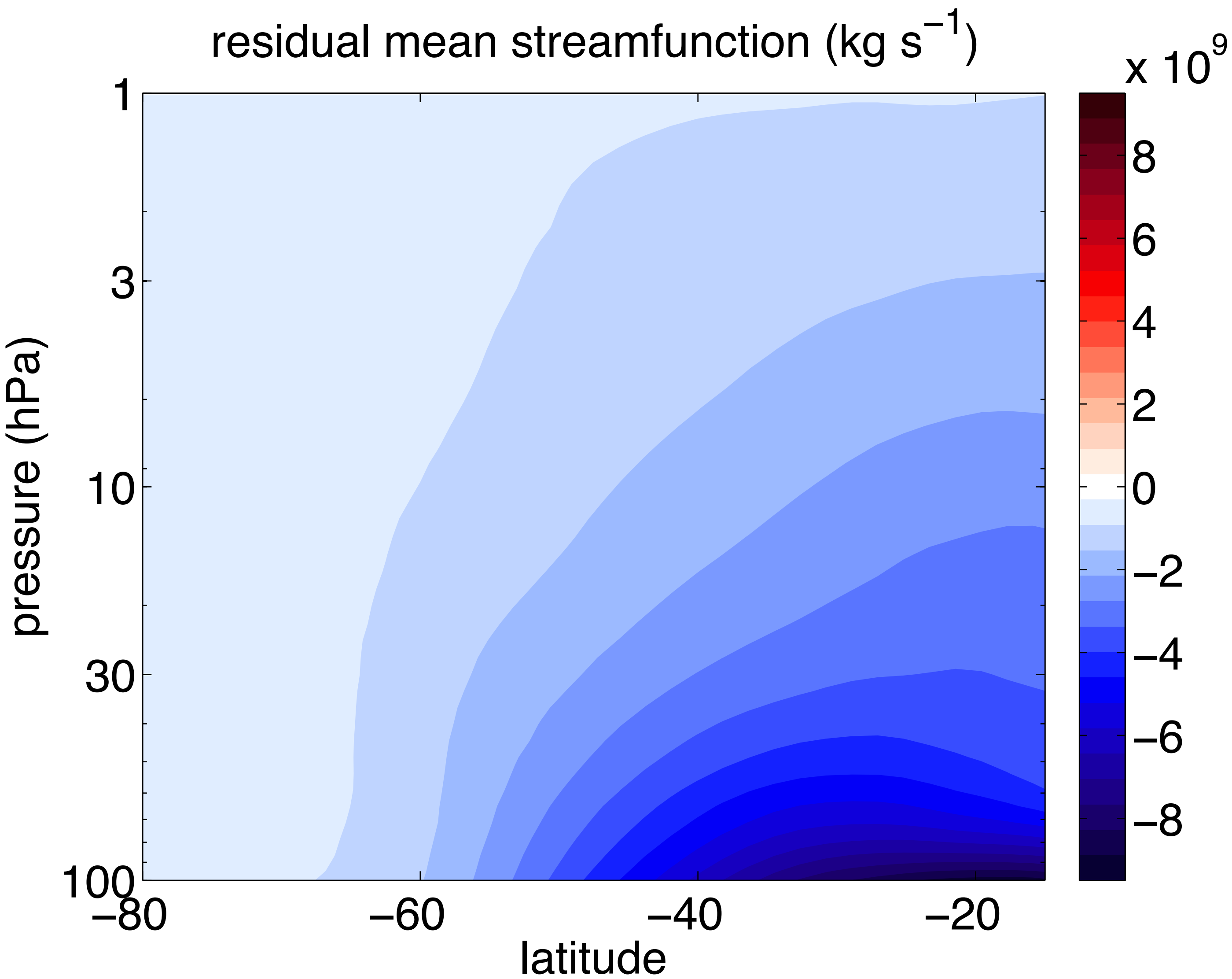

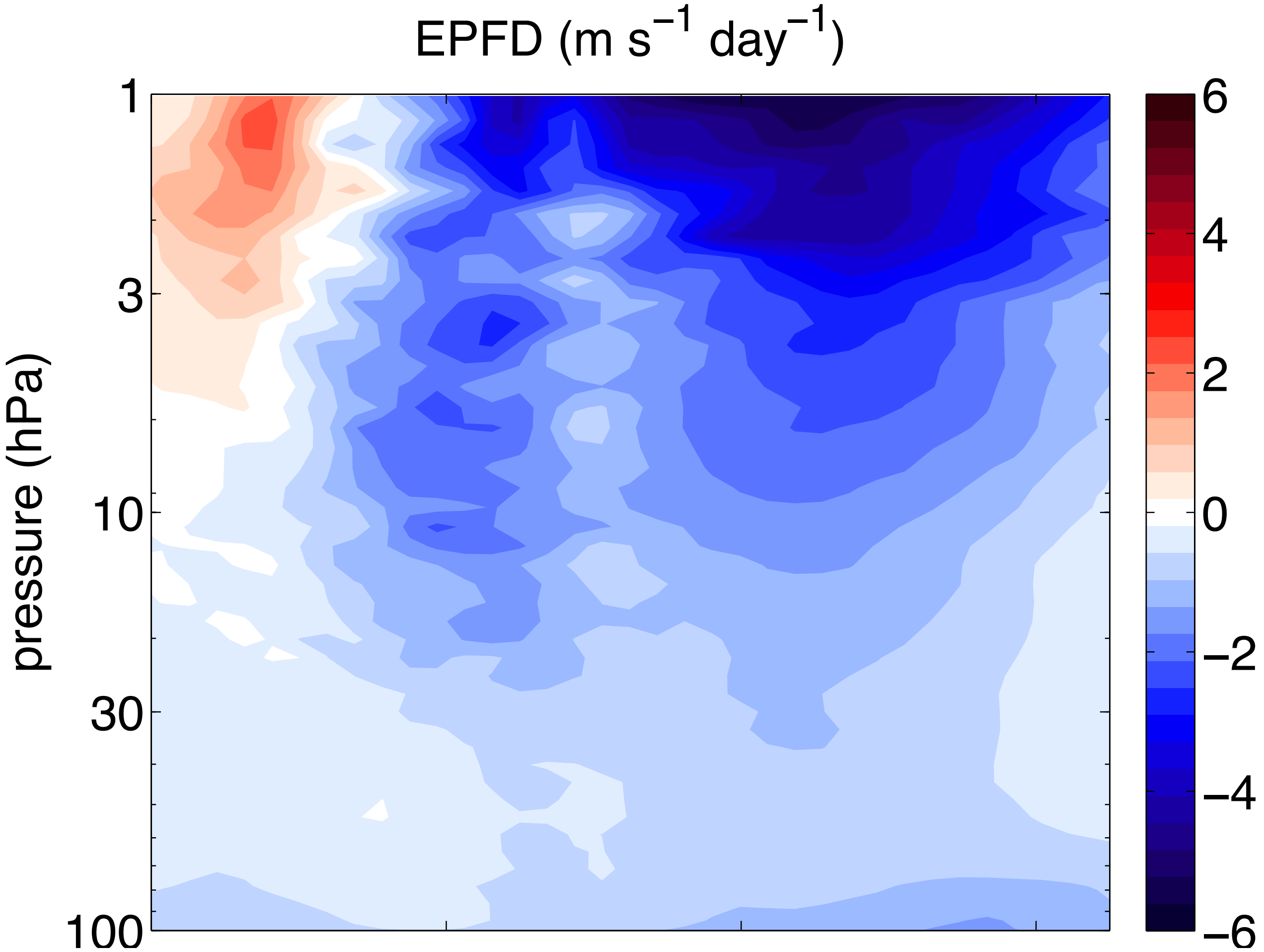

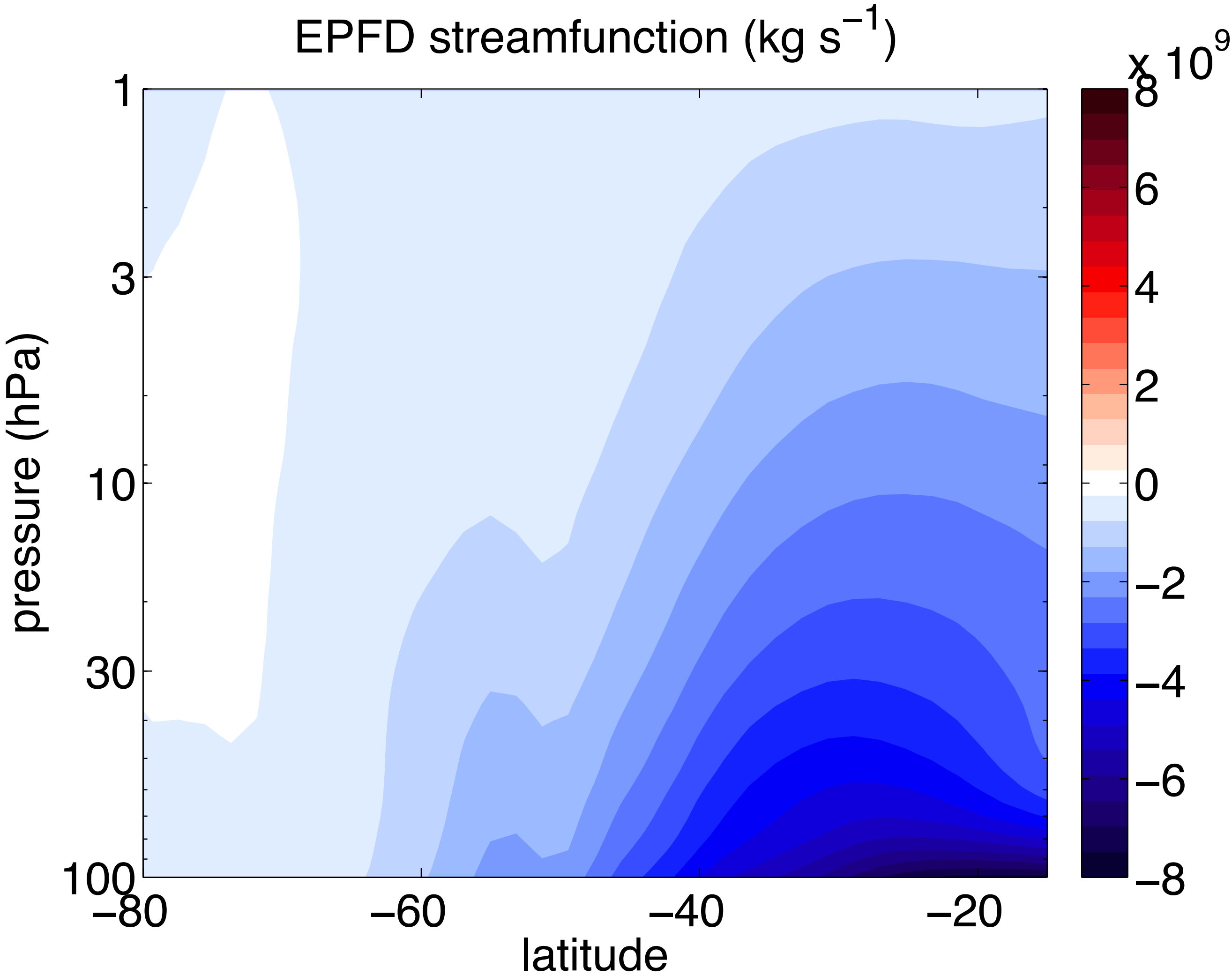

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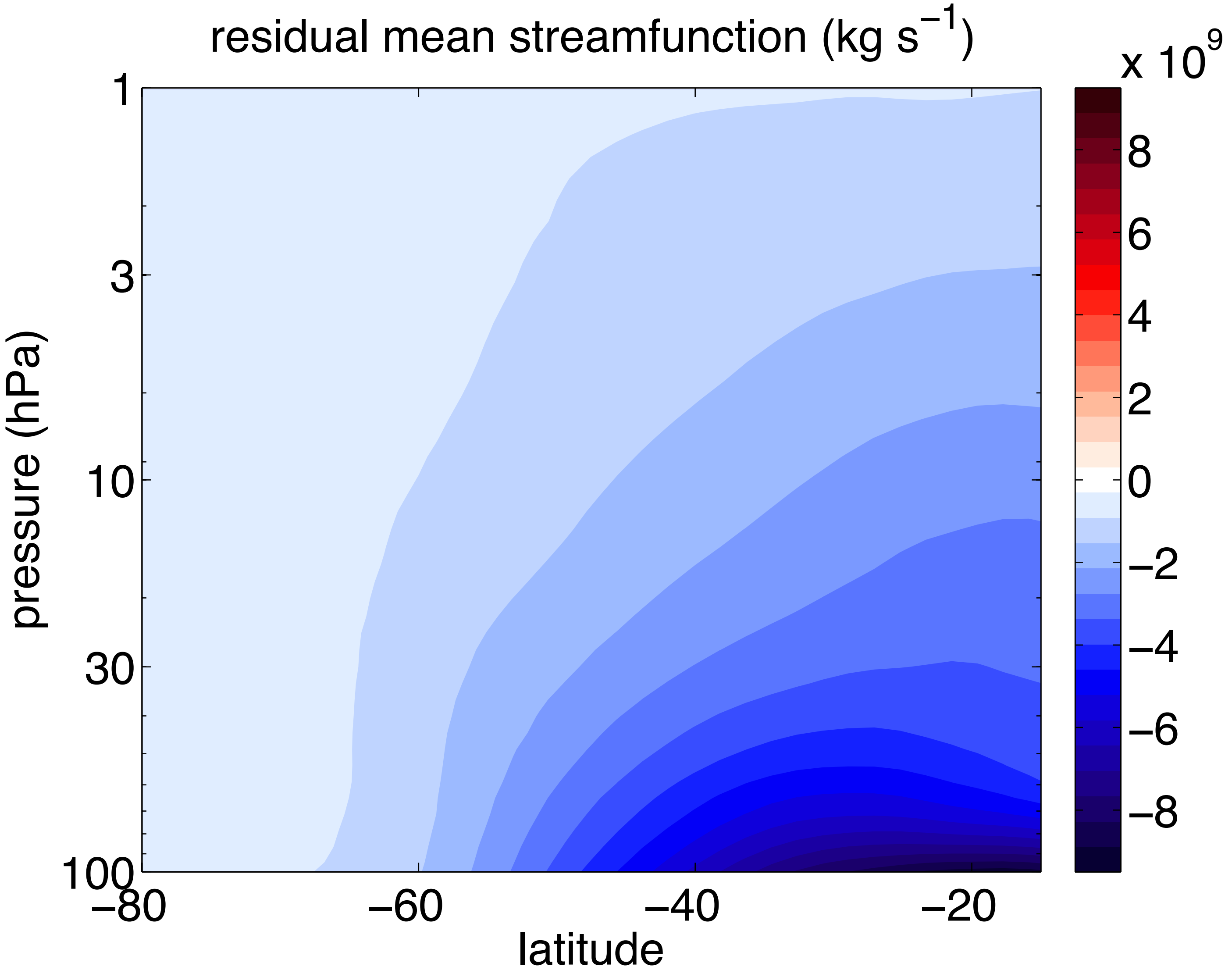

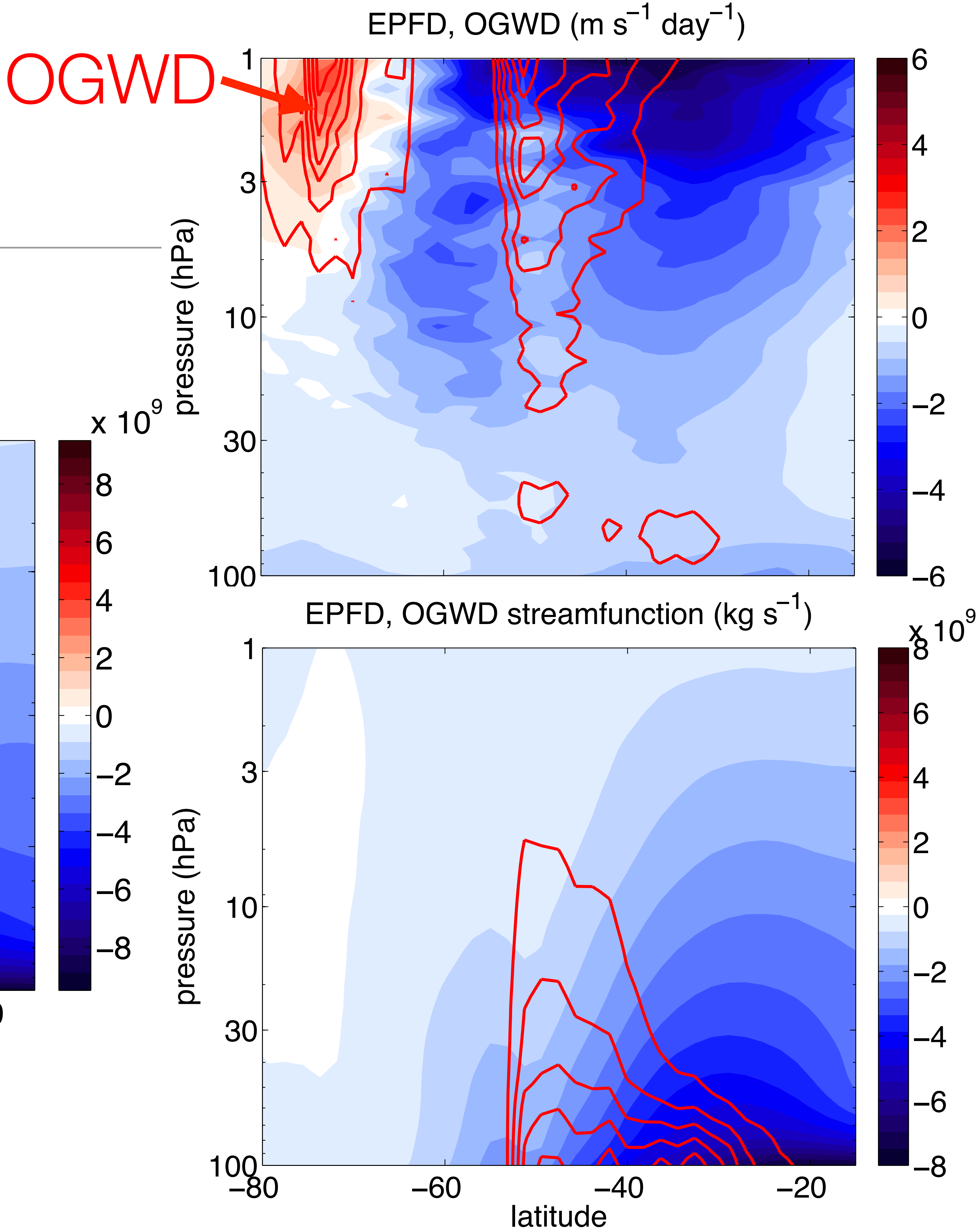

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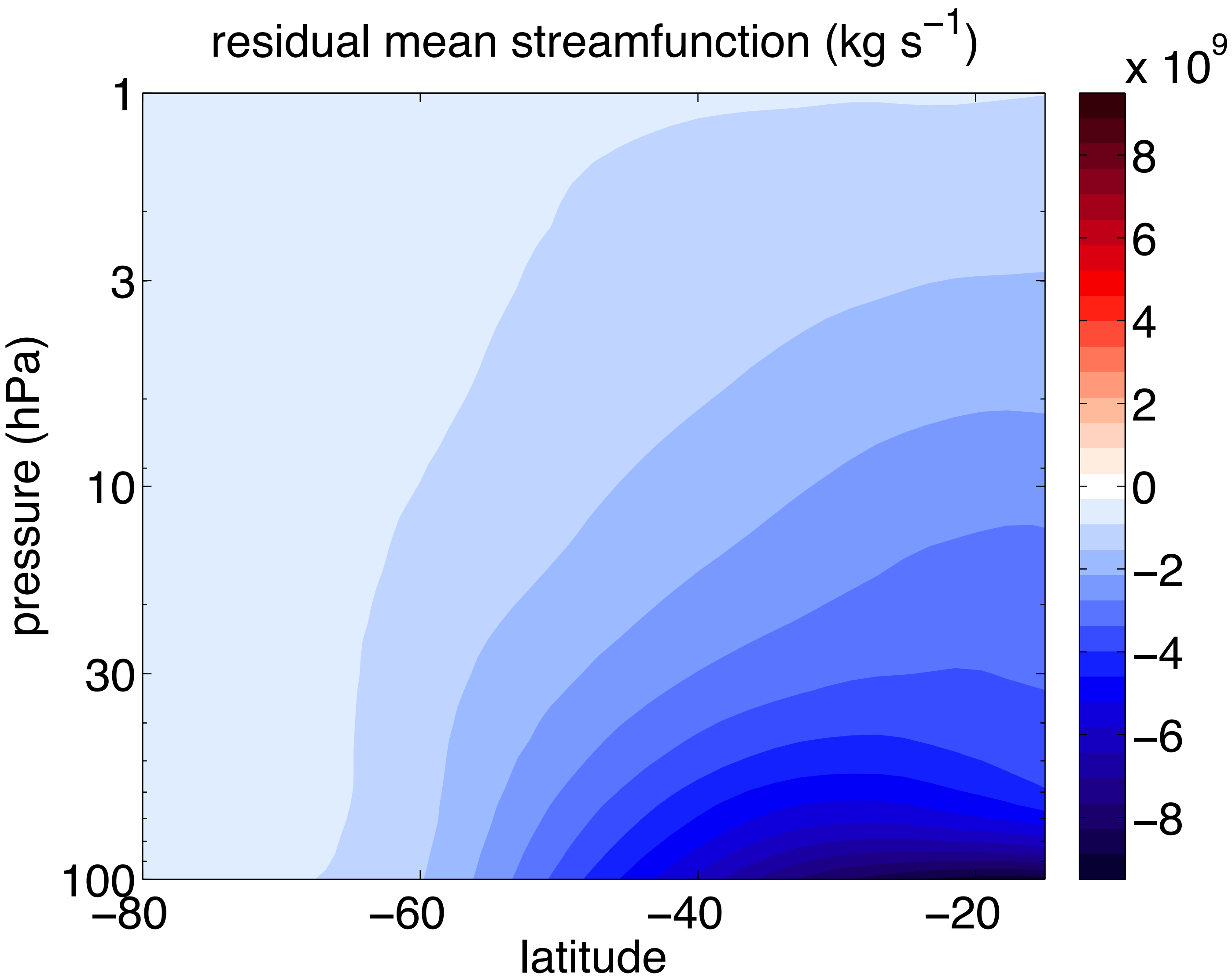
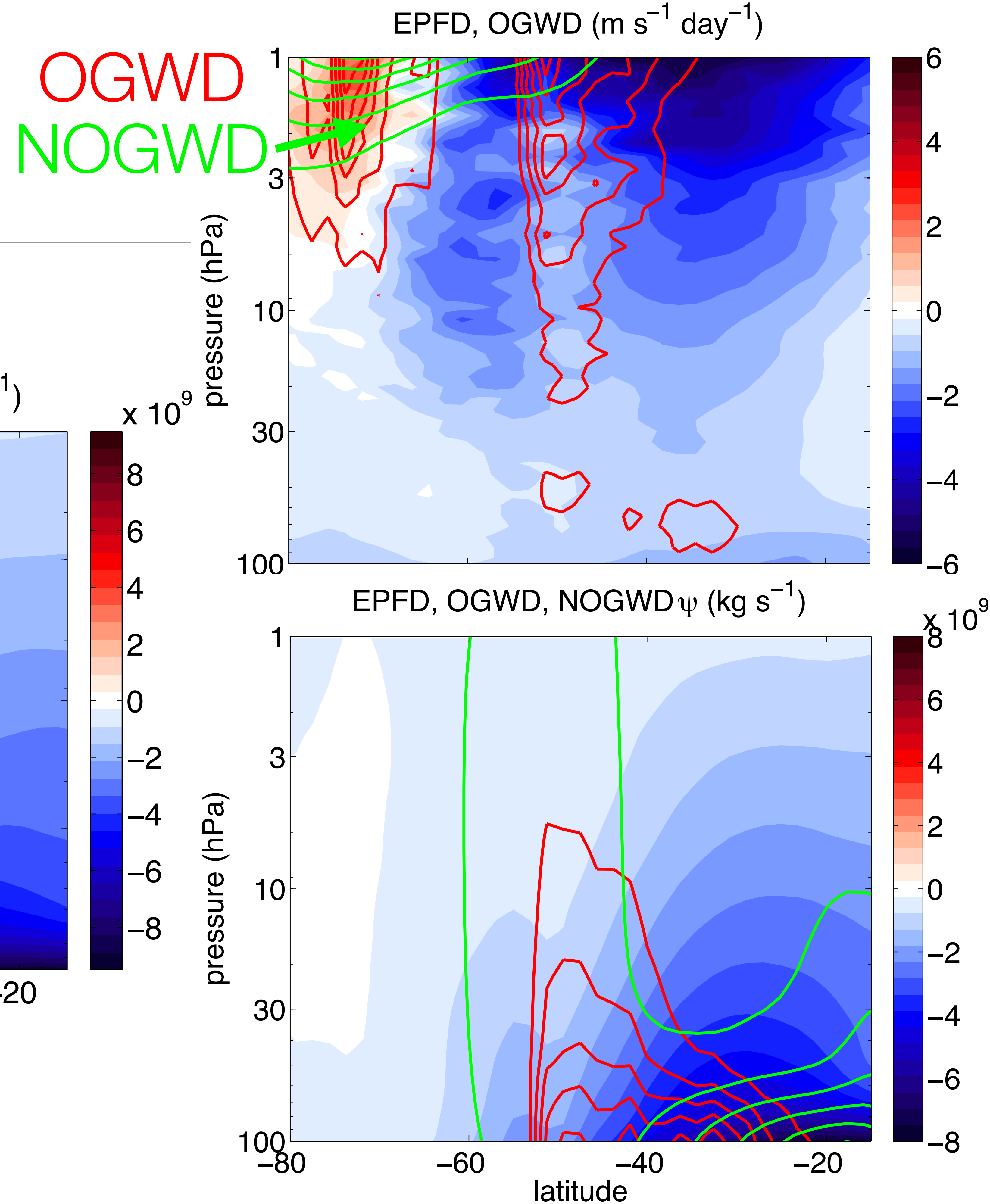
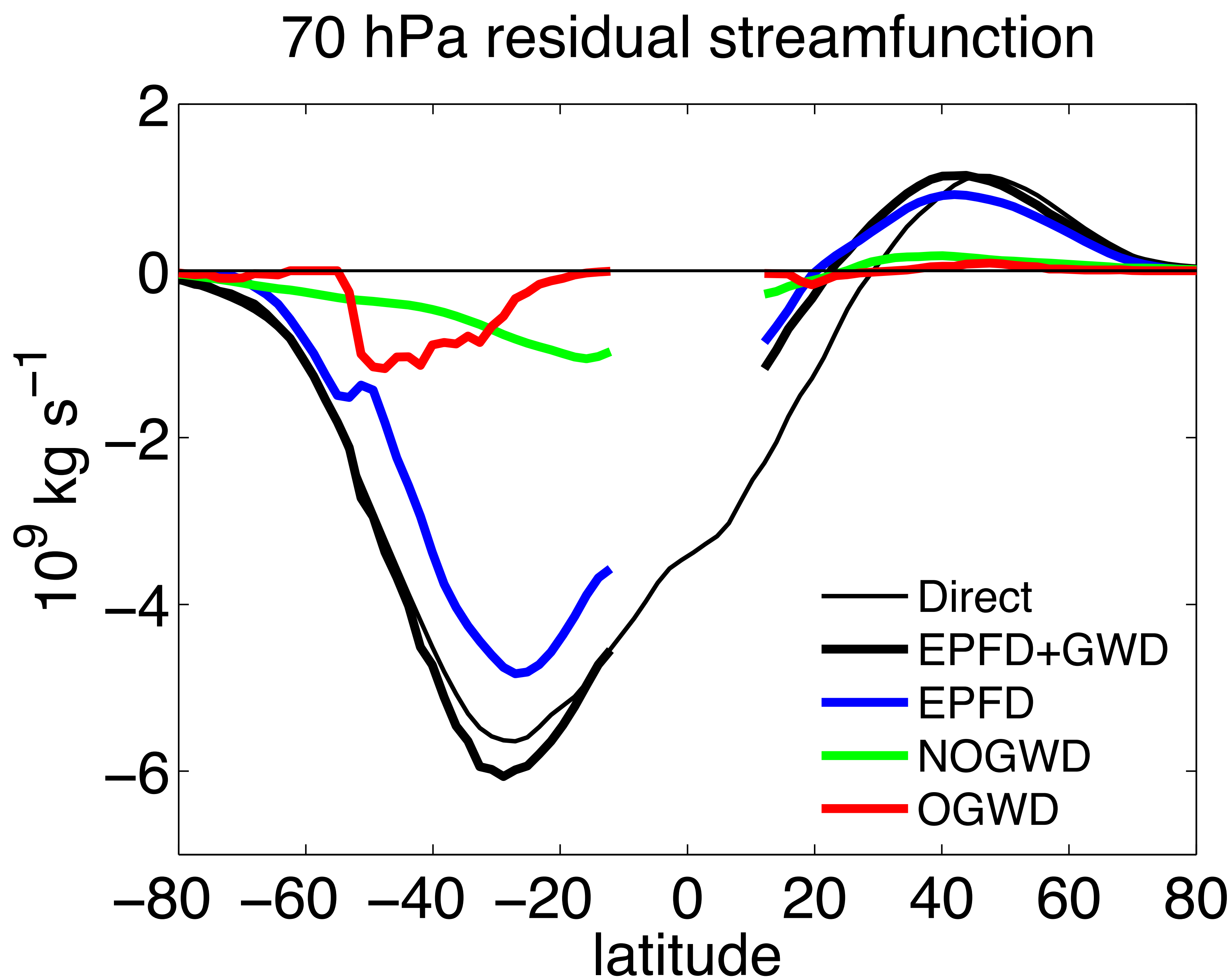
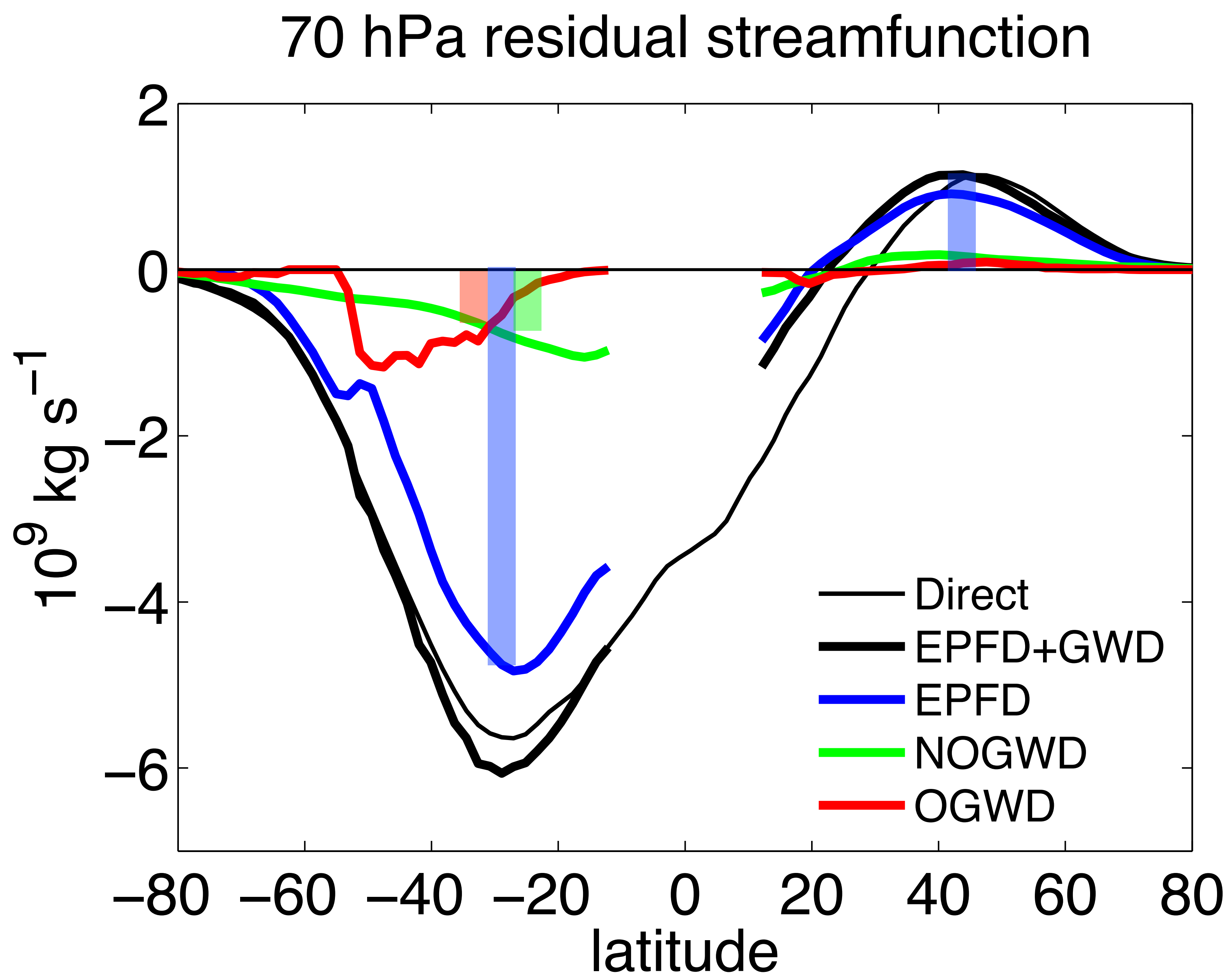




Puzzle pieces fit together to provide a smooth circulation!



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



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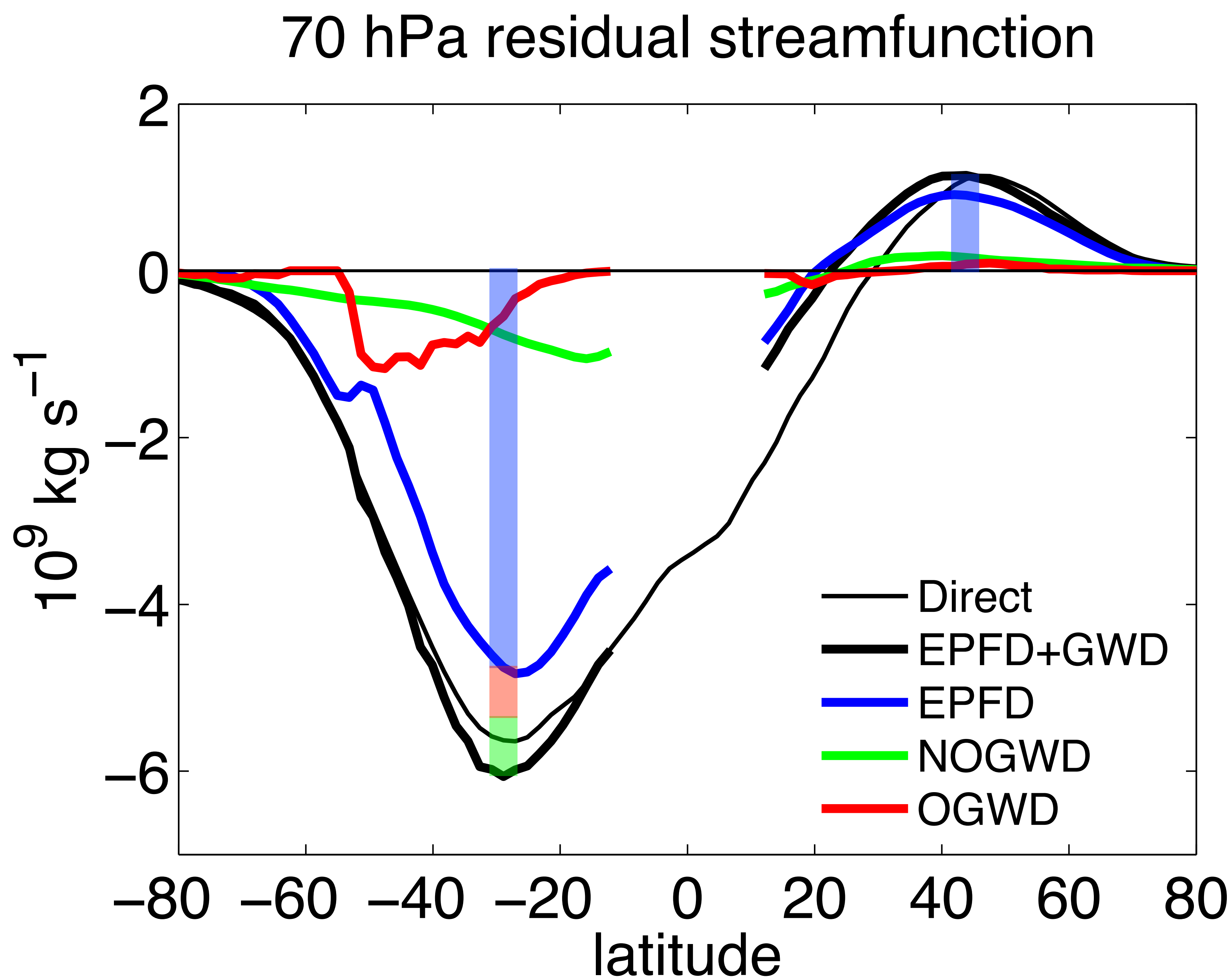
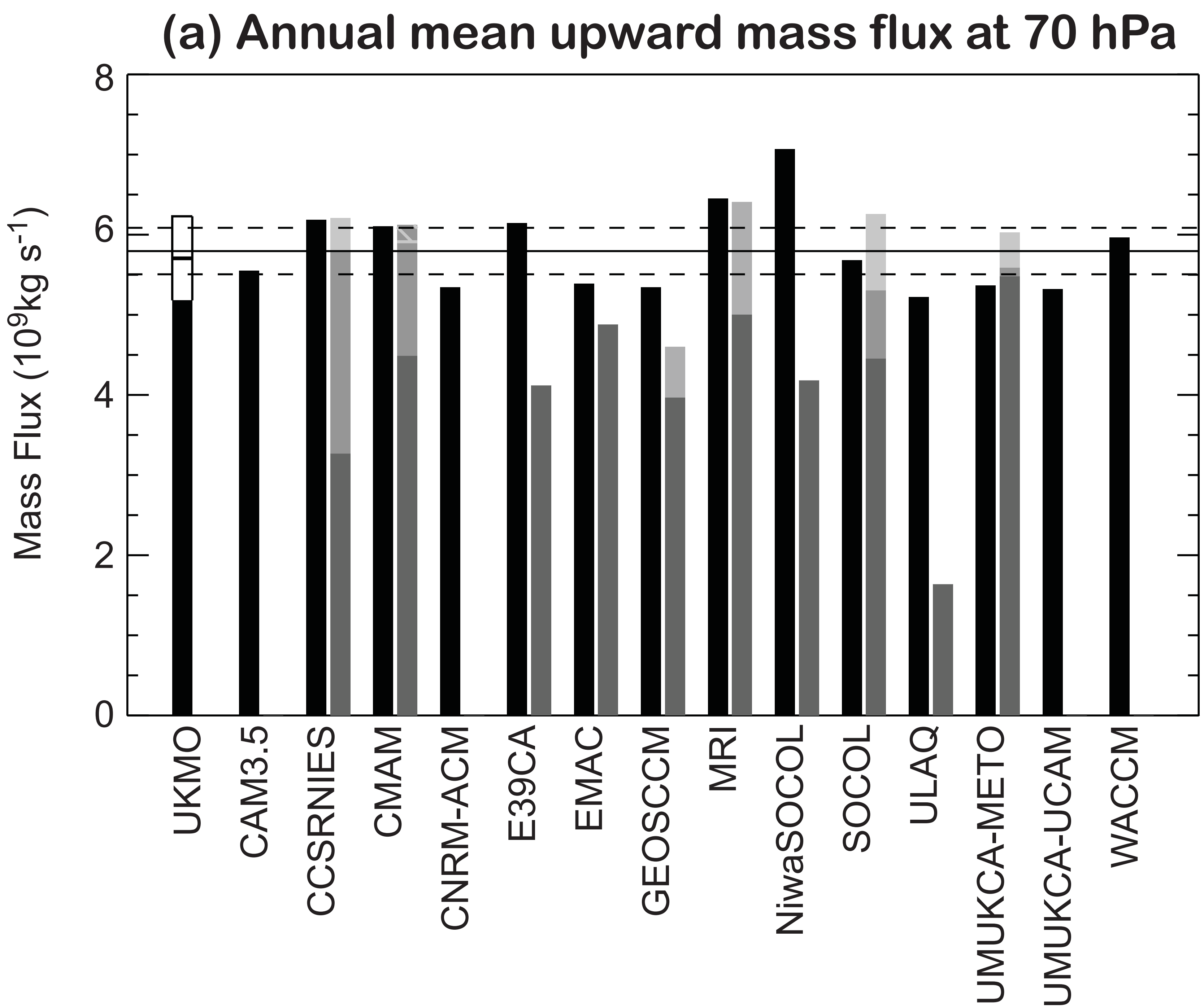


What drives the Brewer-Dobson Circulation?



total

Rossby waves

orographic GW

non-orographic GW

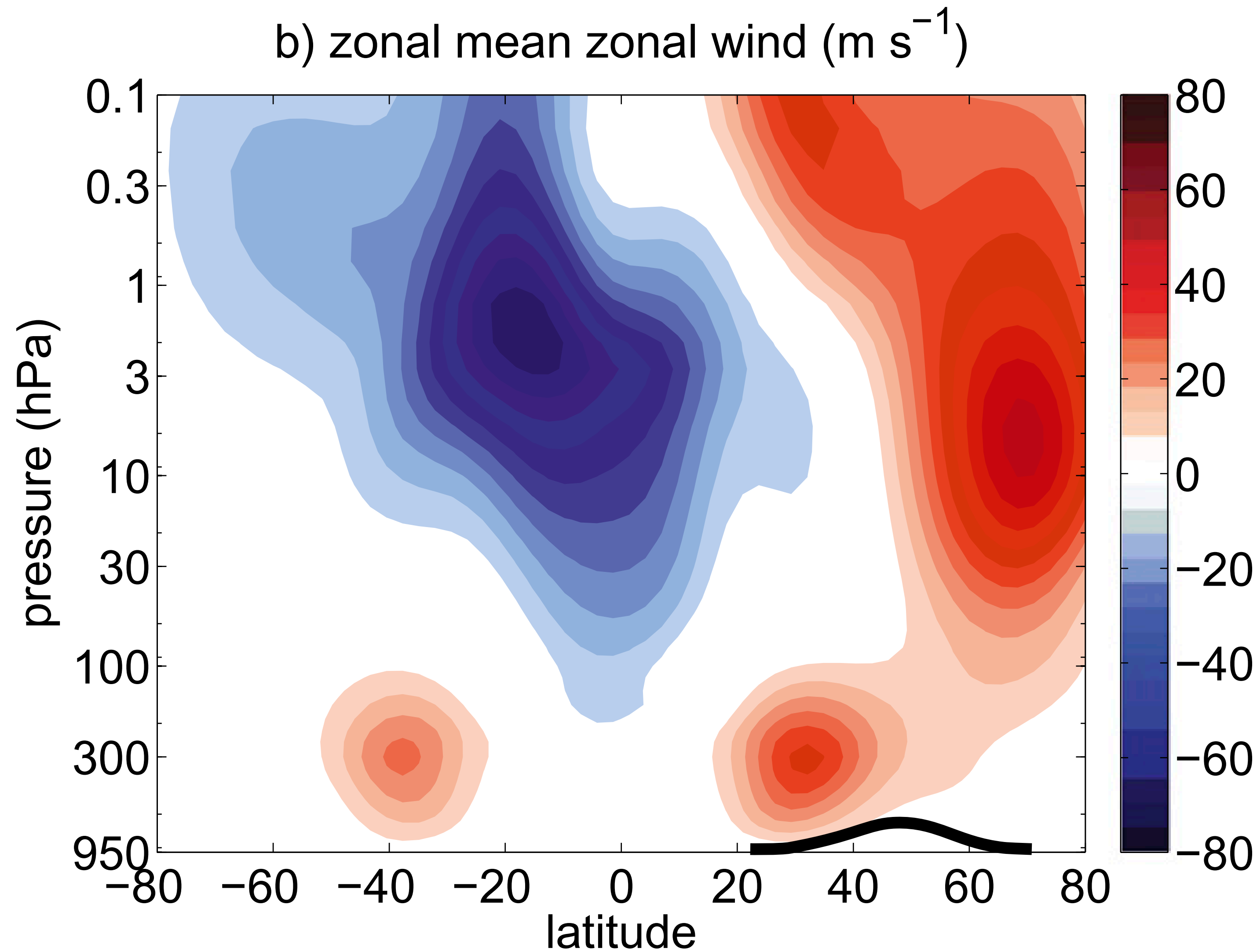
[CCMVal2 Report, Chpt 4]

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?

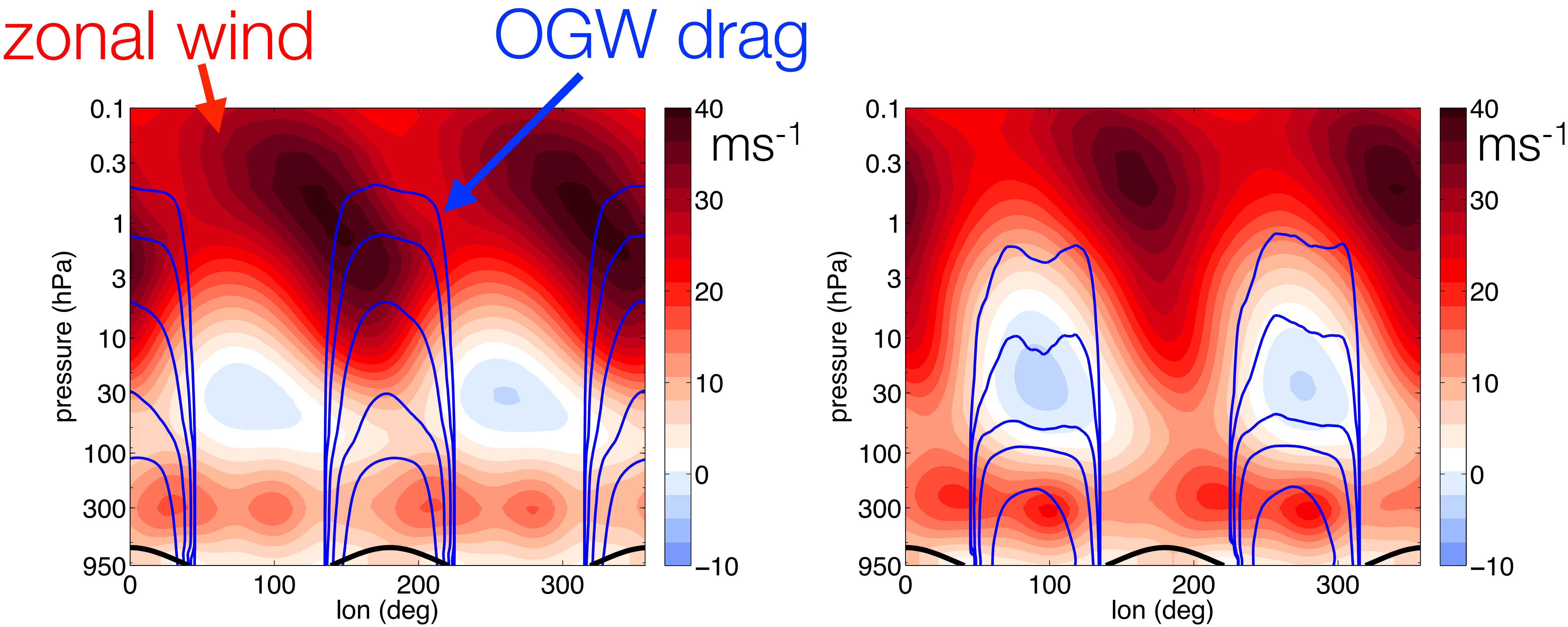
An idealized Atmospheric GCM

- 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]

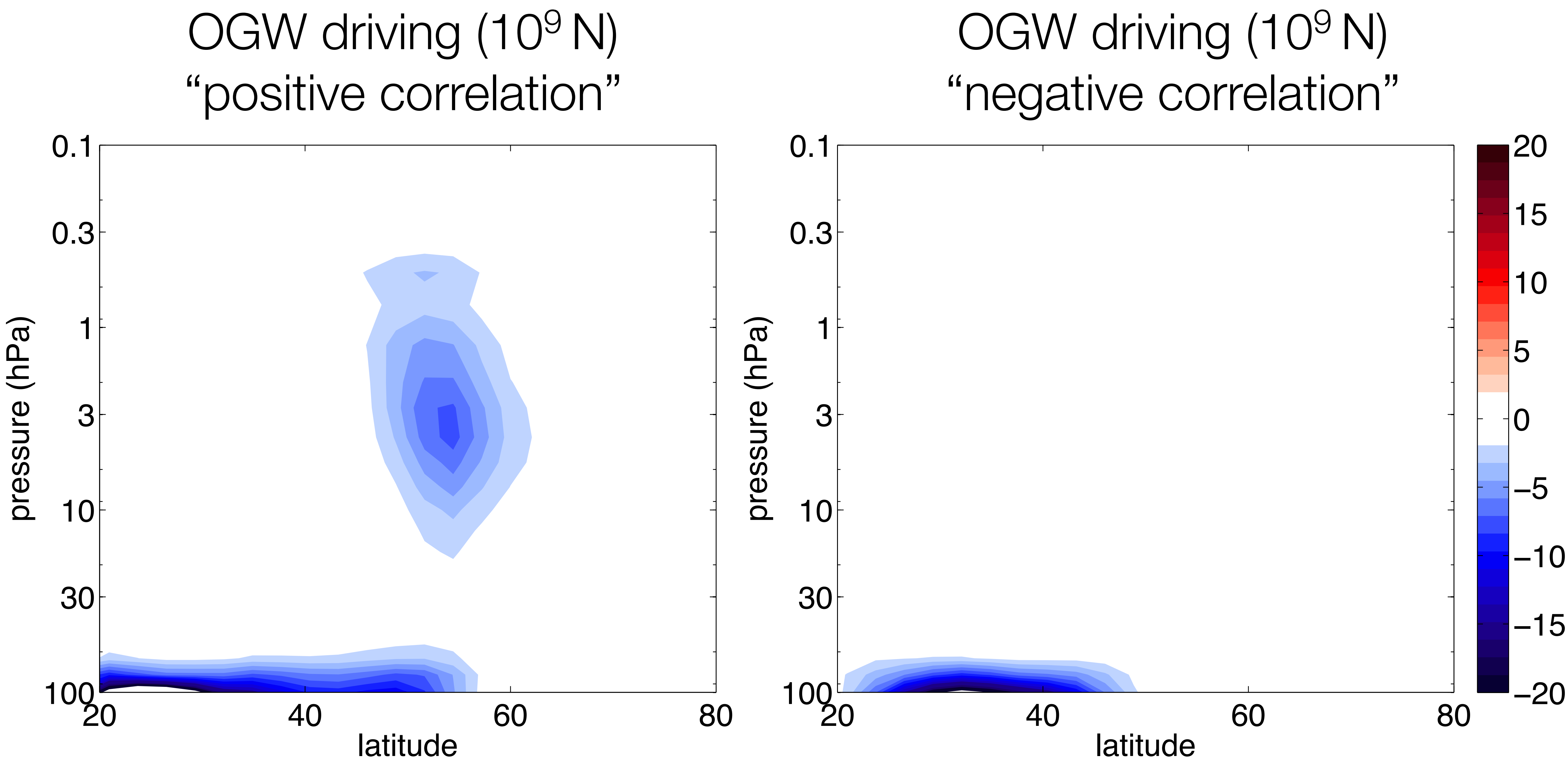
Two experiments:
Perturb the Orographic Gravity Wave Drag



Model A: positive correlation　　Model B: negative correlation

[Cohen et al. 2013]

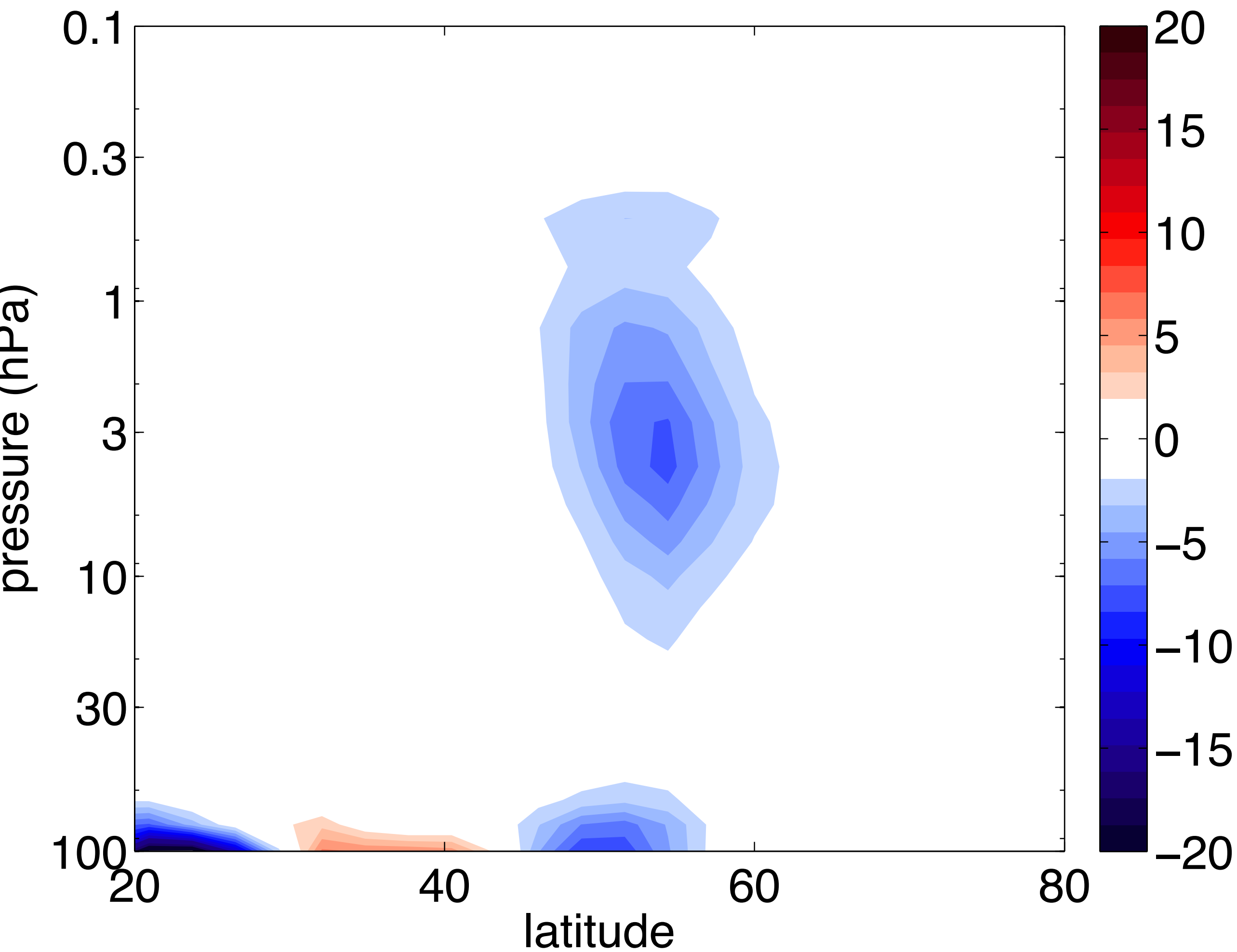
Impact of differences in OGW configuration



[Cohen et al. 2013]

Impact on BDC

difference in OGW driving (10^9 N)



[Cohen et al. 2013]

Impact on BDC

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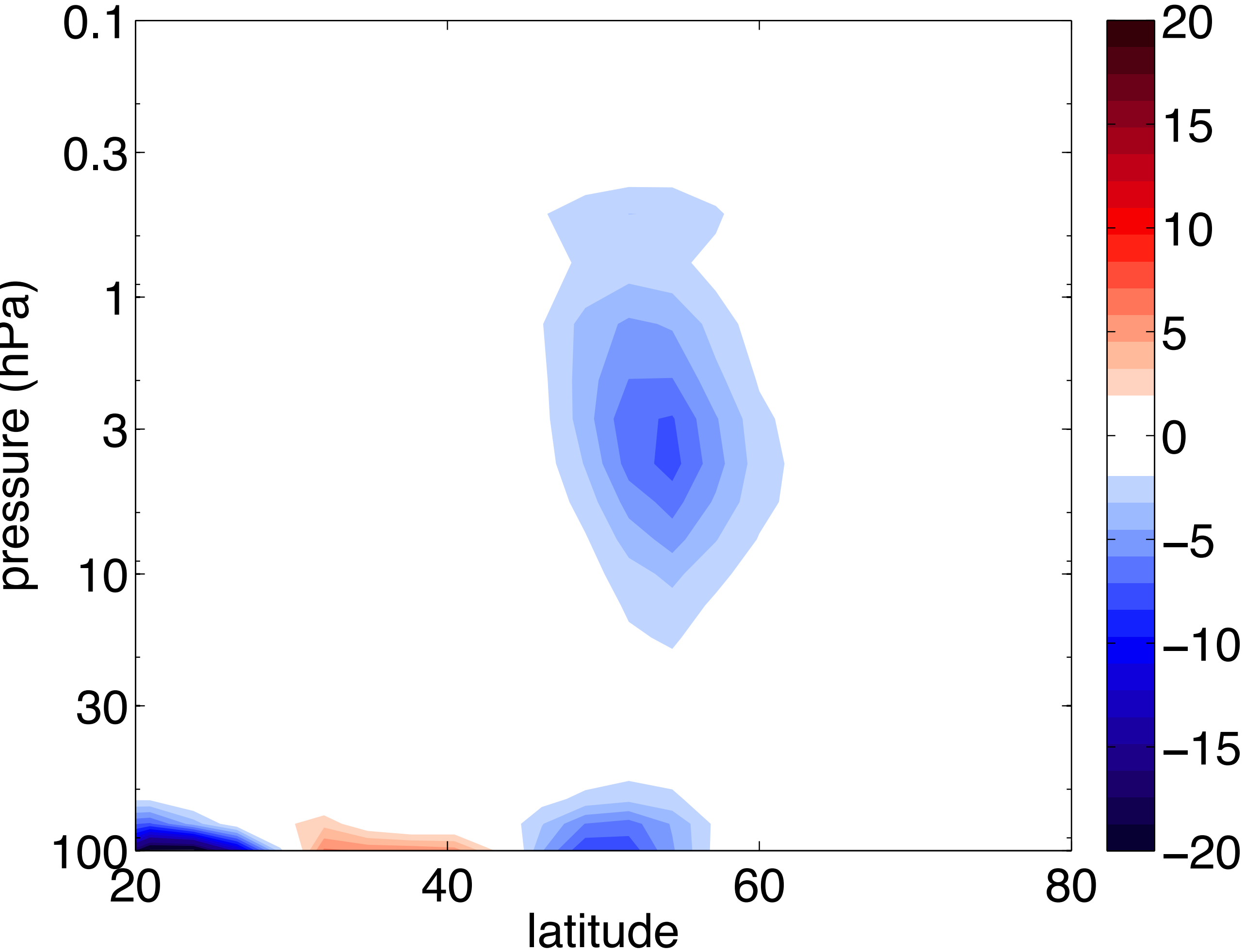

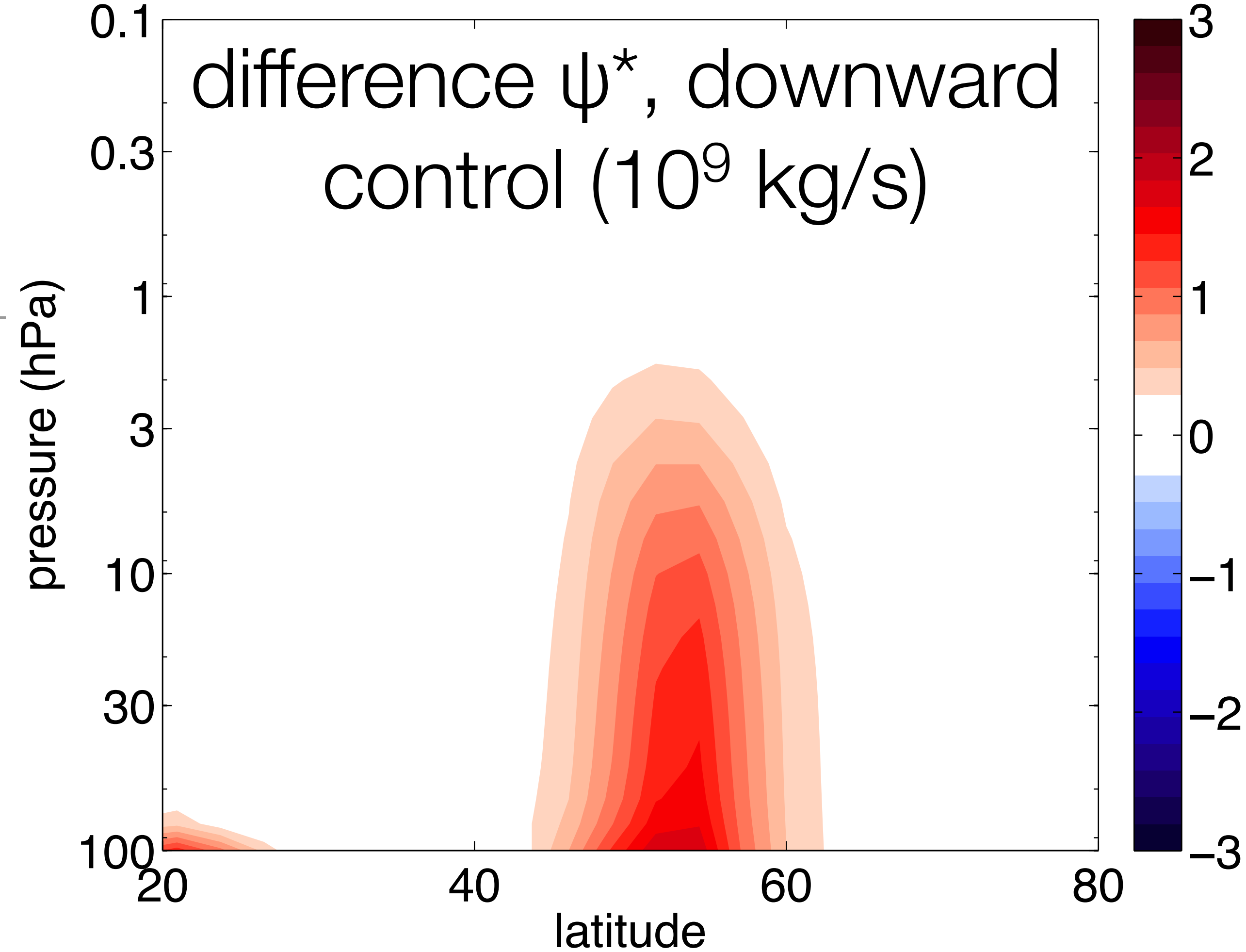

[Cohen et al. 2013]

Impact on BDC

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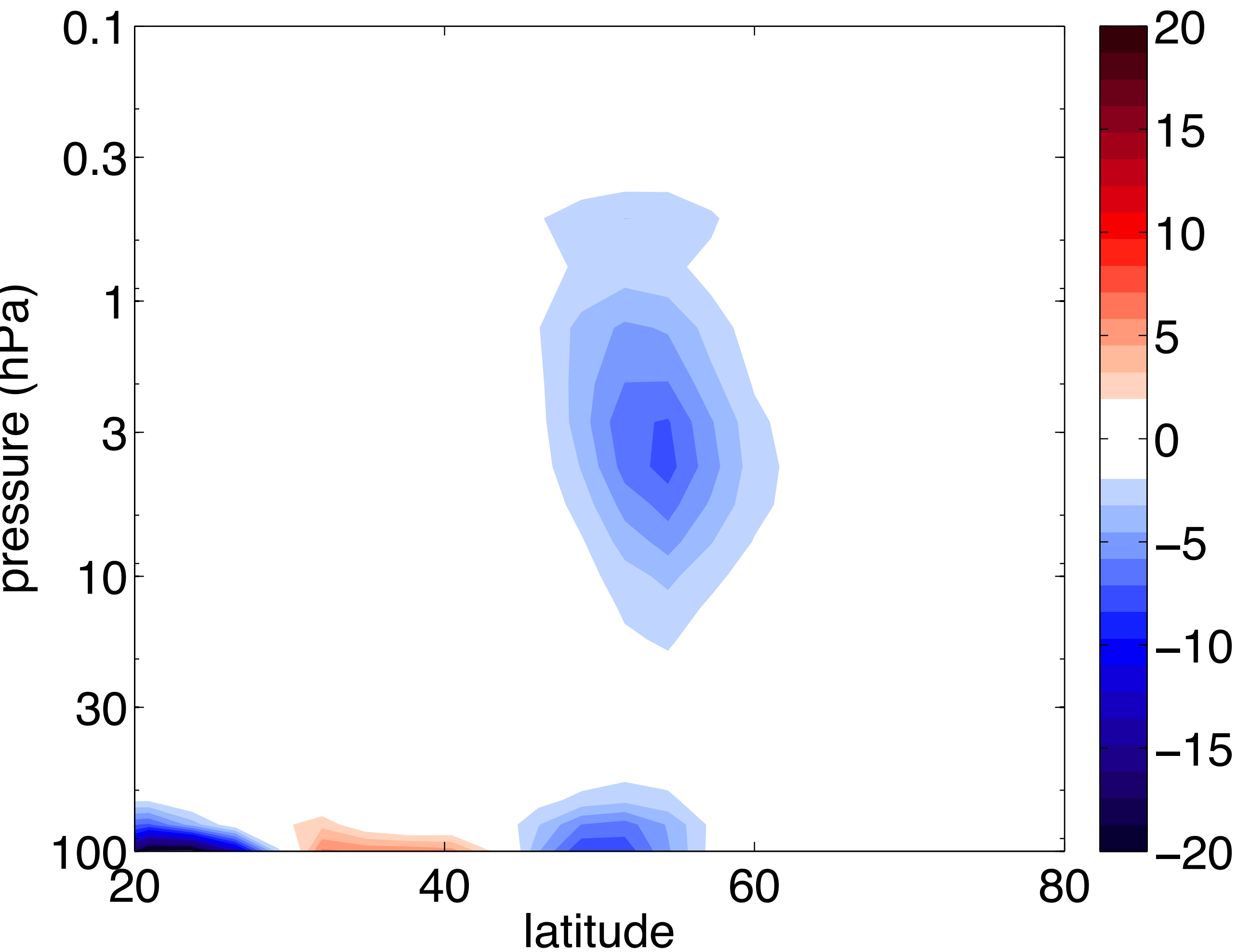
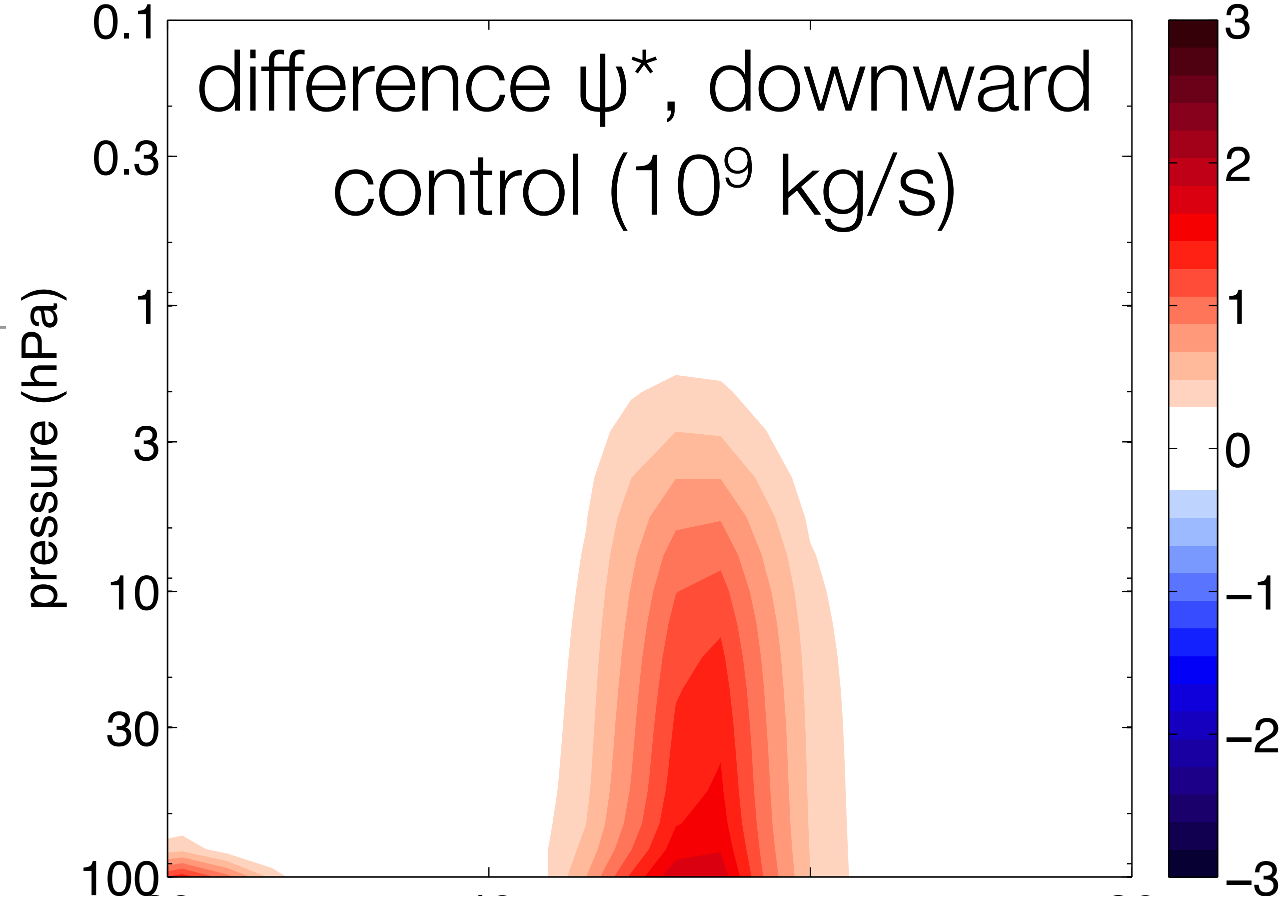
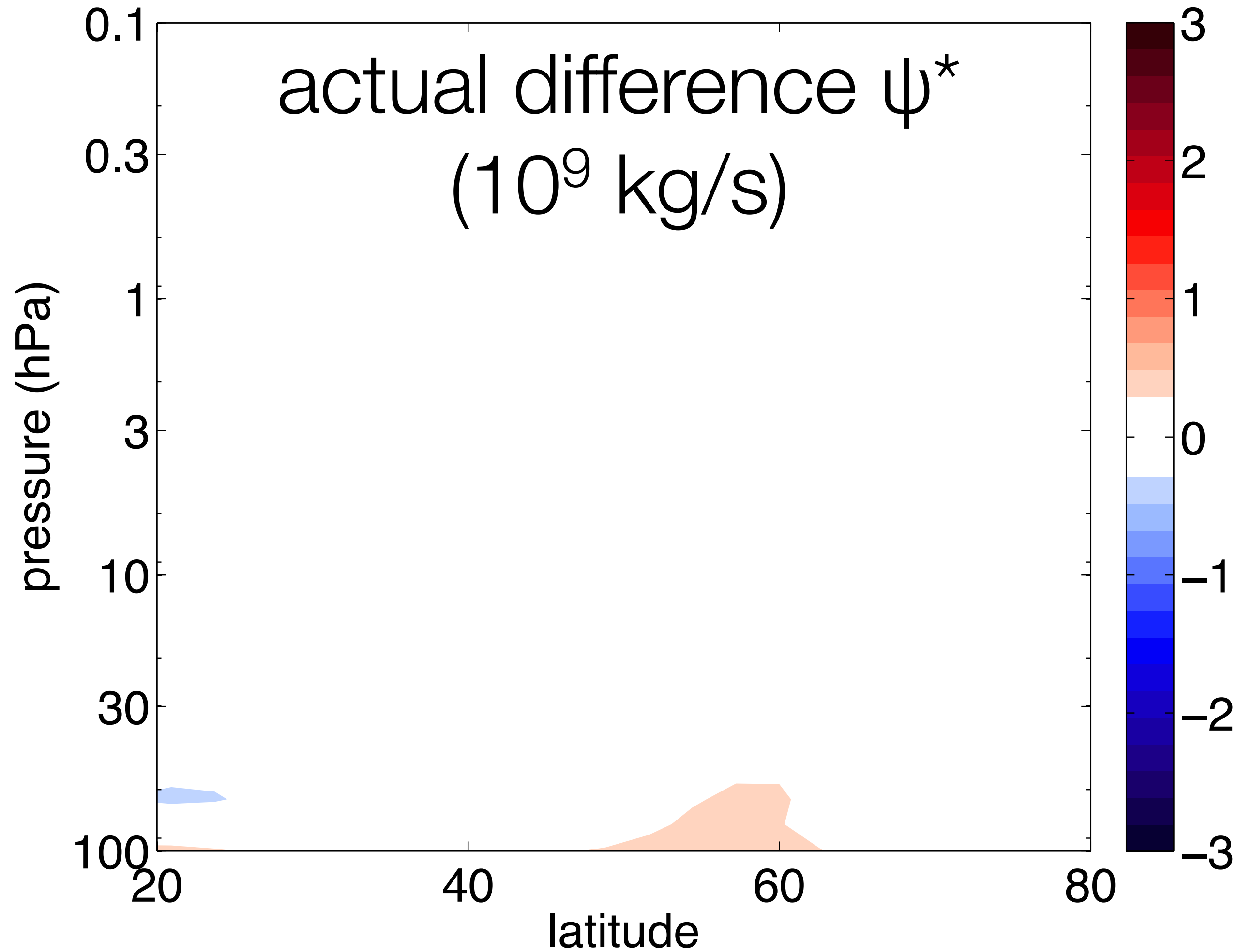
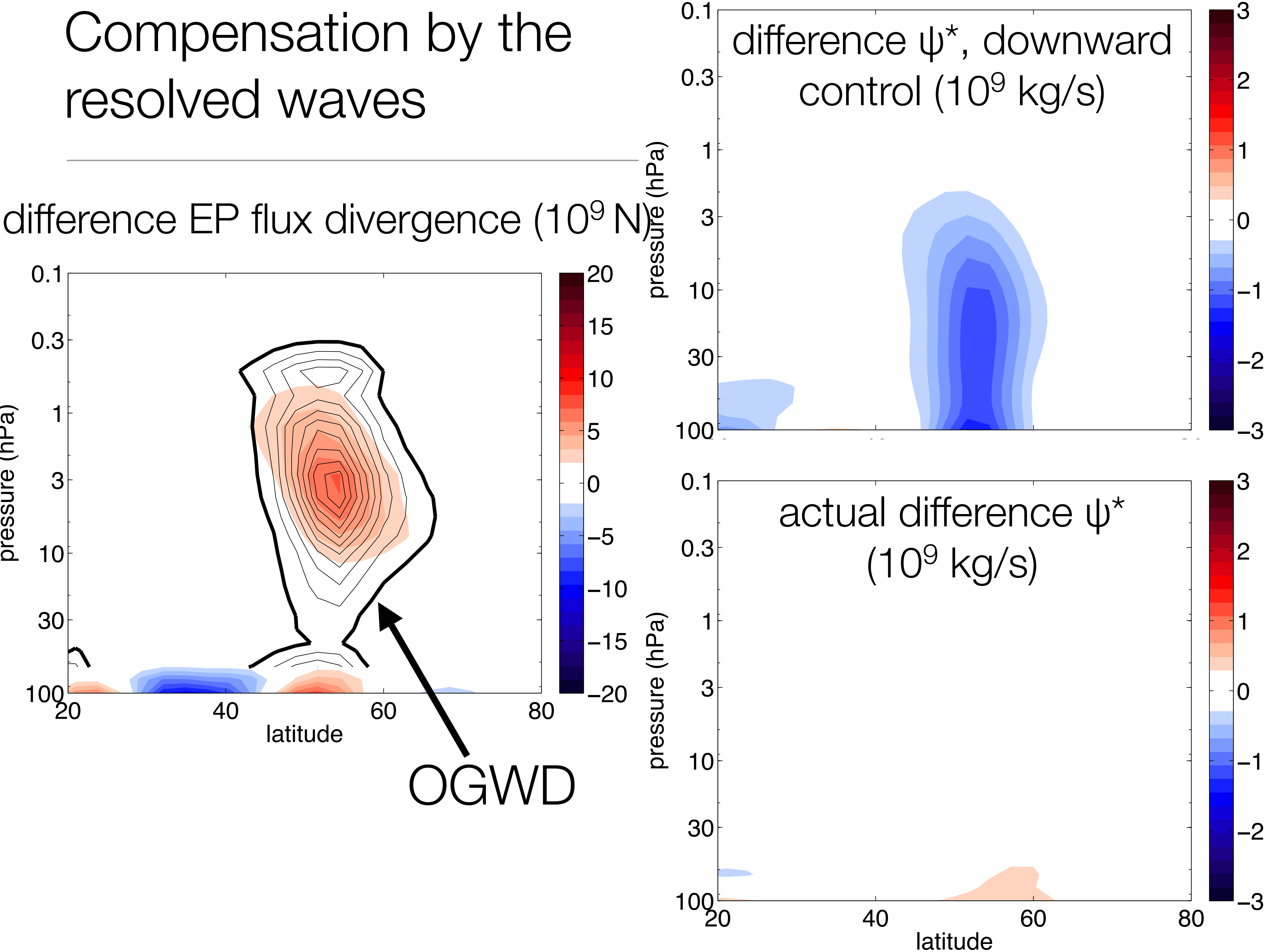




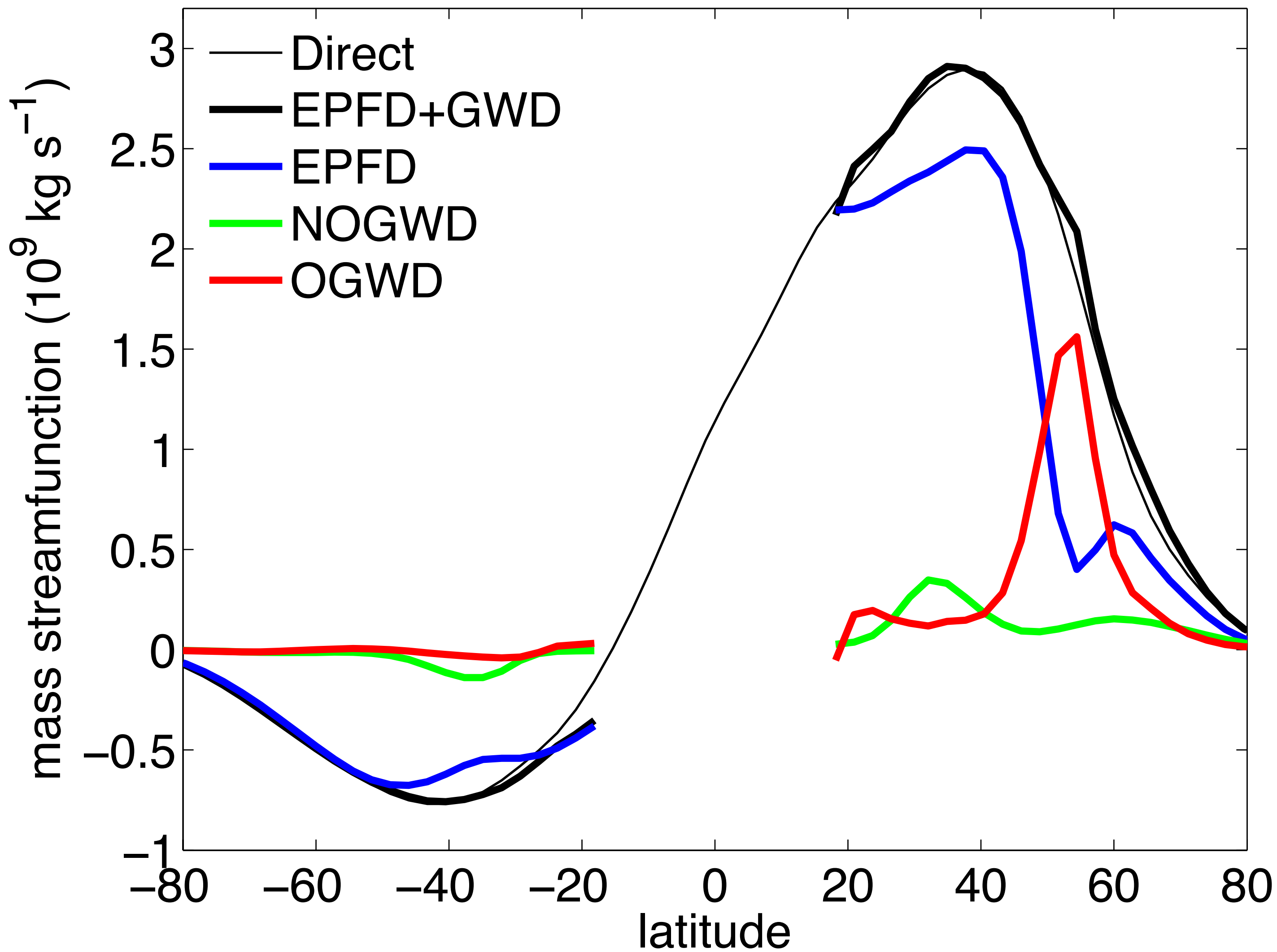


Compensation by the resolved waves

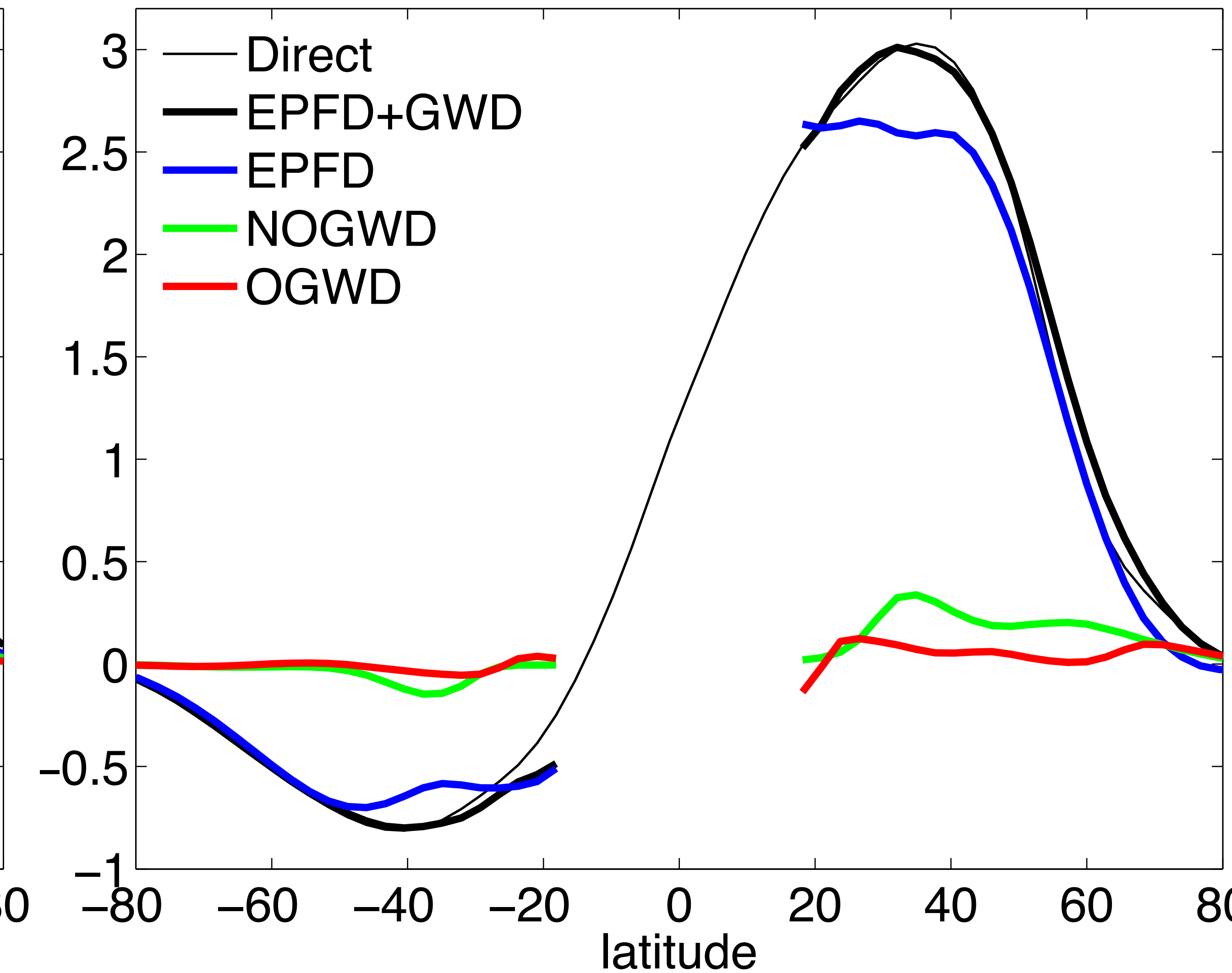


What "drives" the BDC?

Residual Mean Streamfunction at 70 hPa



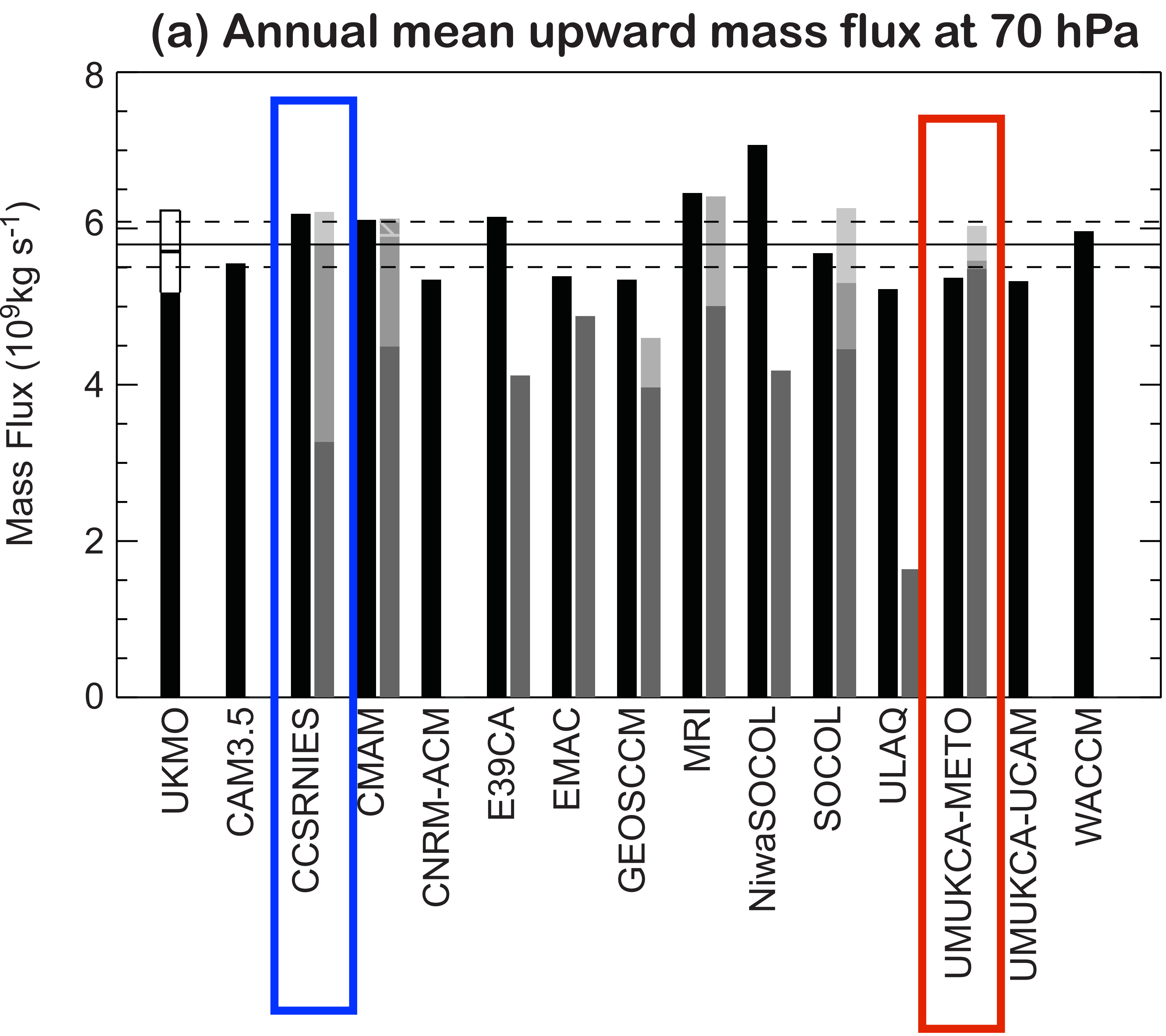
Model A

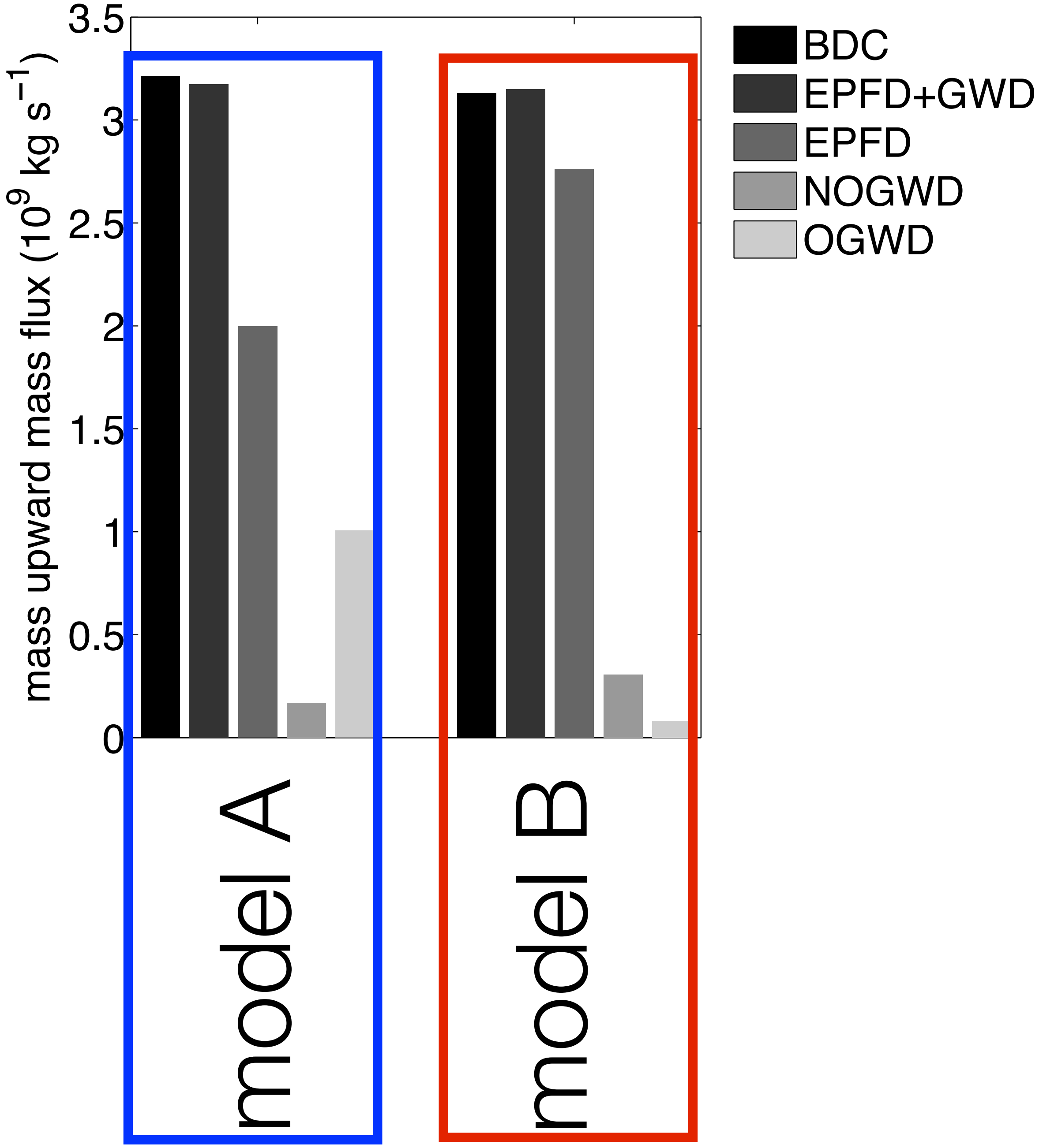


Model B

[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!

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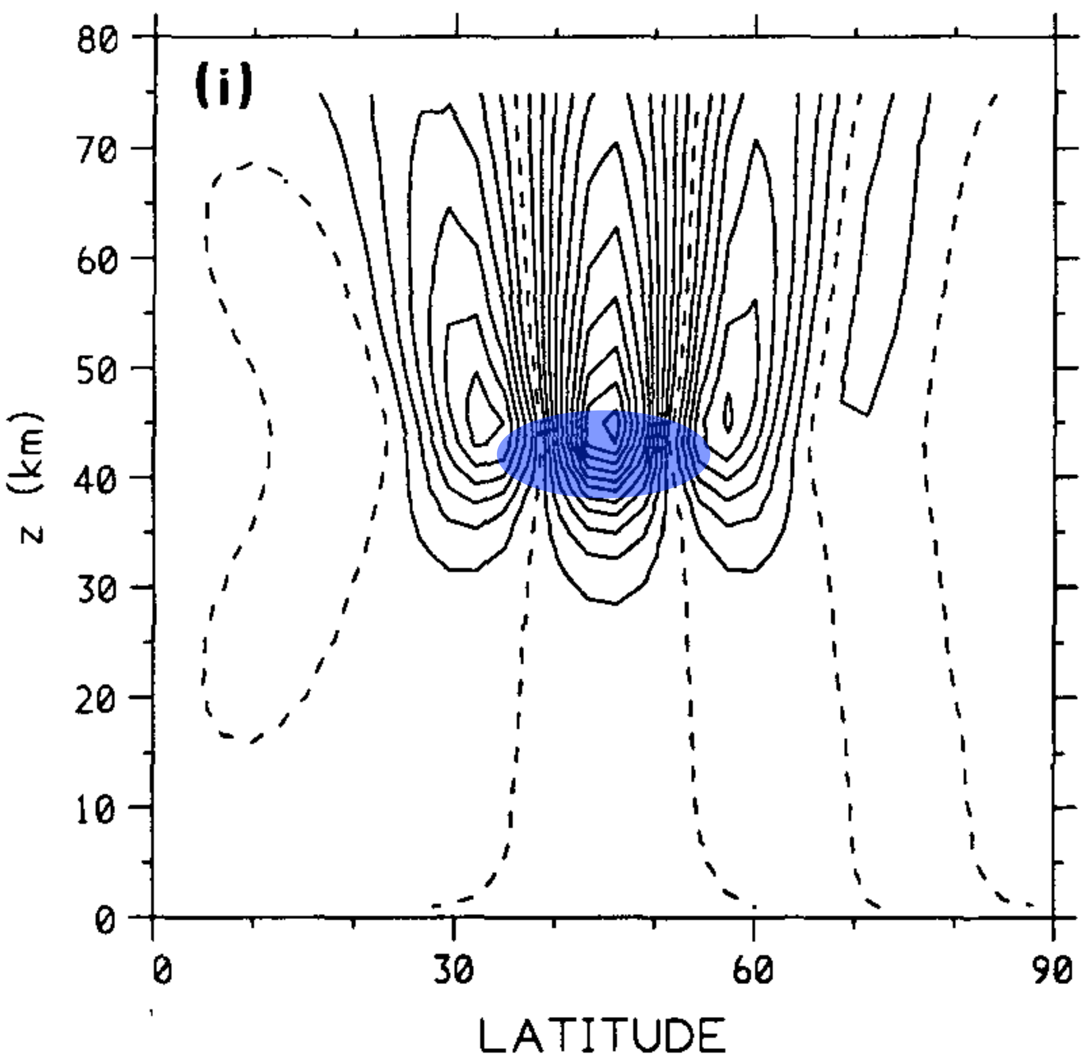
(That is, how do the wave forcings affect the potential vorticity.)

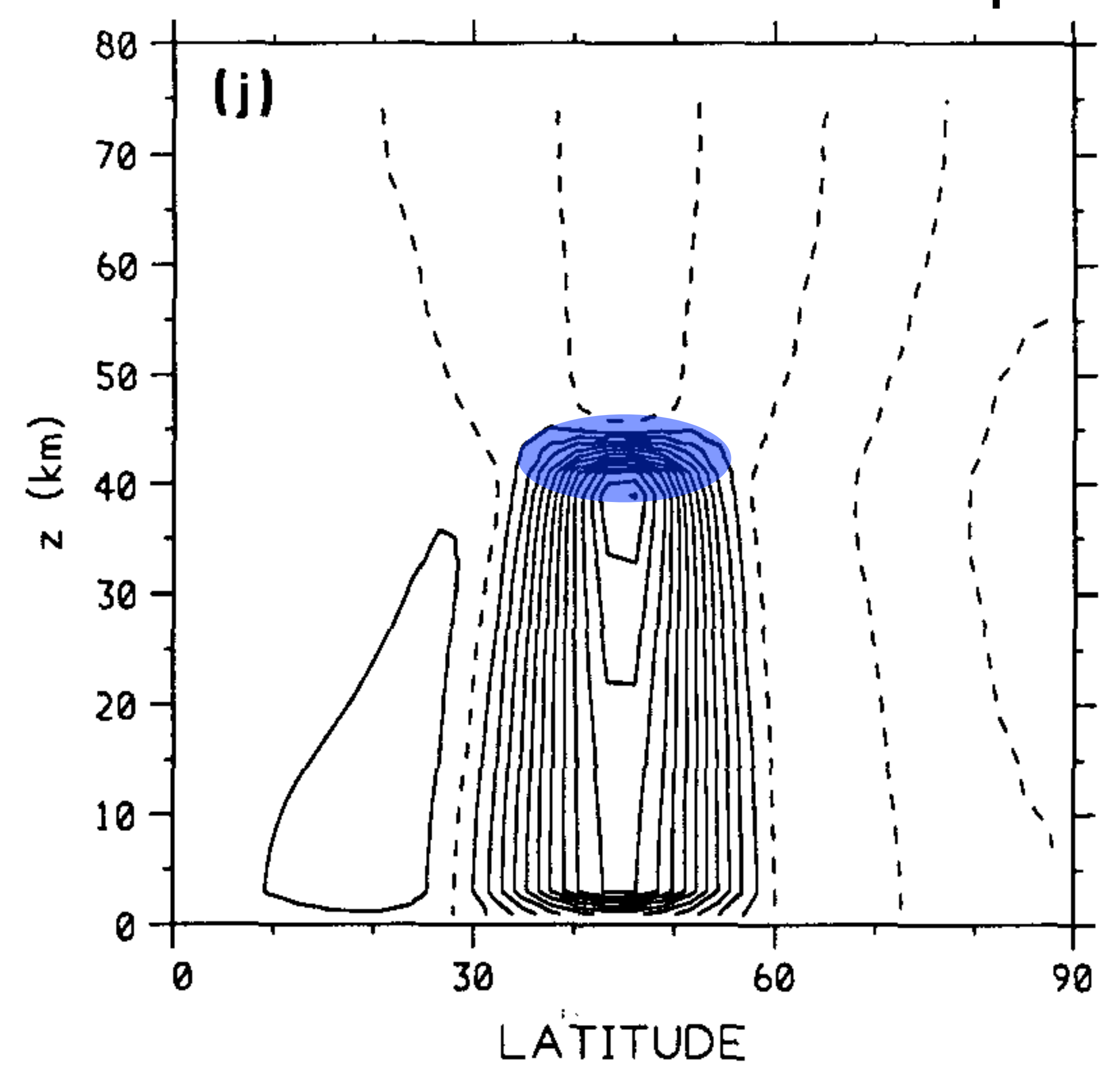
Back to Basics: Haynes et al. 1991

(Near) steady response to a localized torque

zonal wind

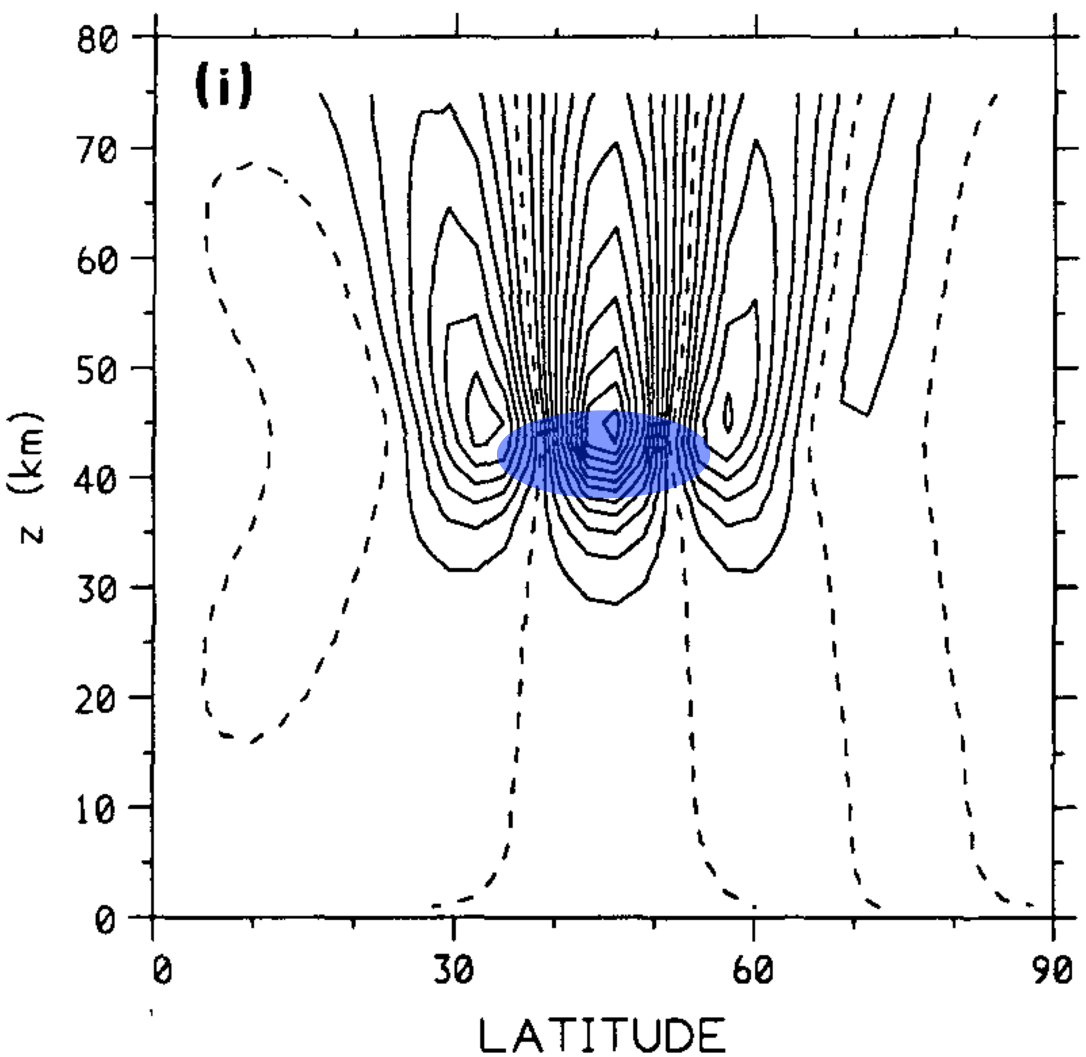


streamfunction ψ



For what torques is the circulation reasonable?

zonal wind



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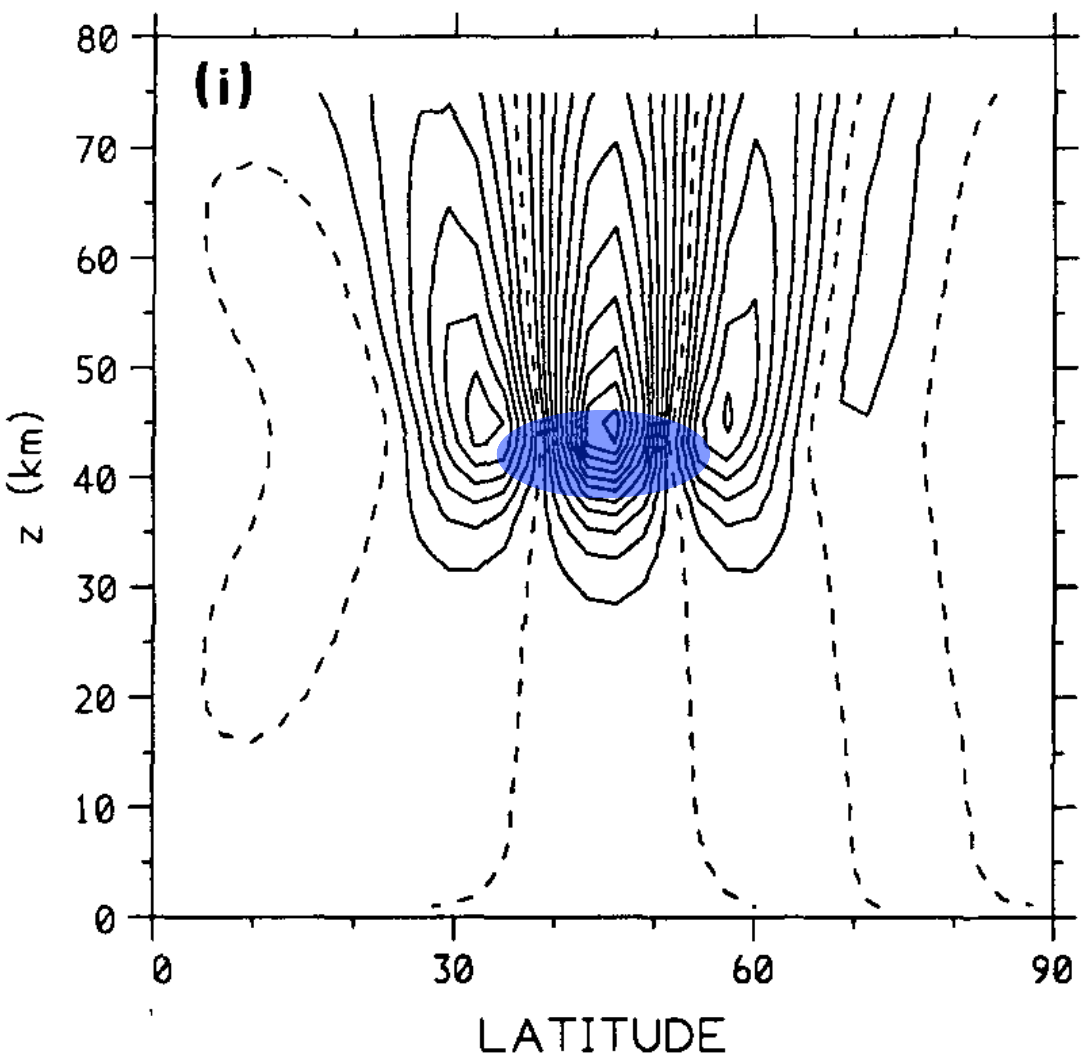
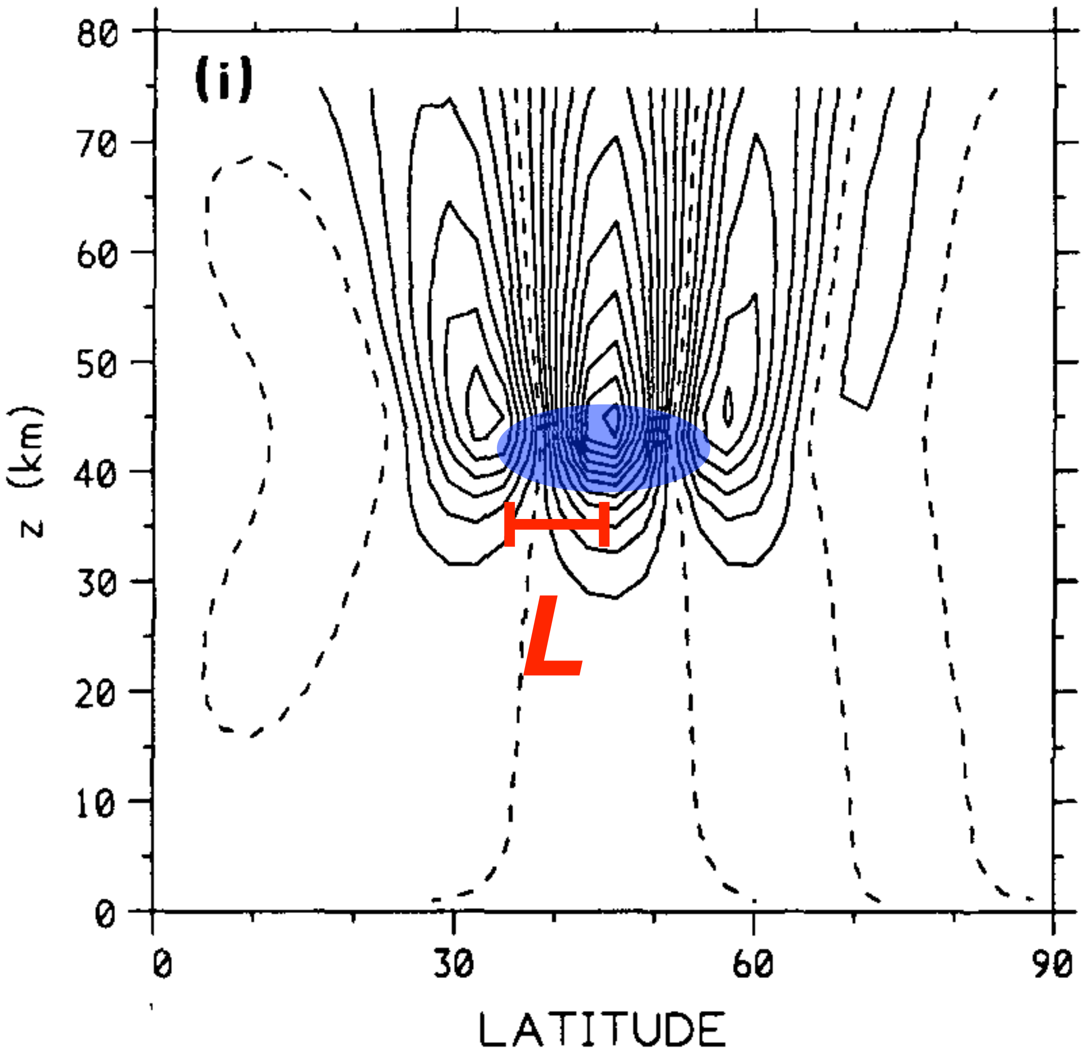


QG Potential Vorticity

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

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

zonal wind



amplitude *A*,
meridional scale *L*

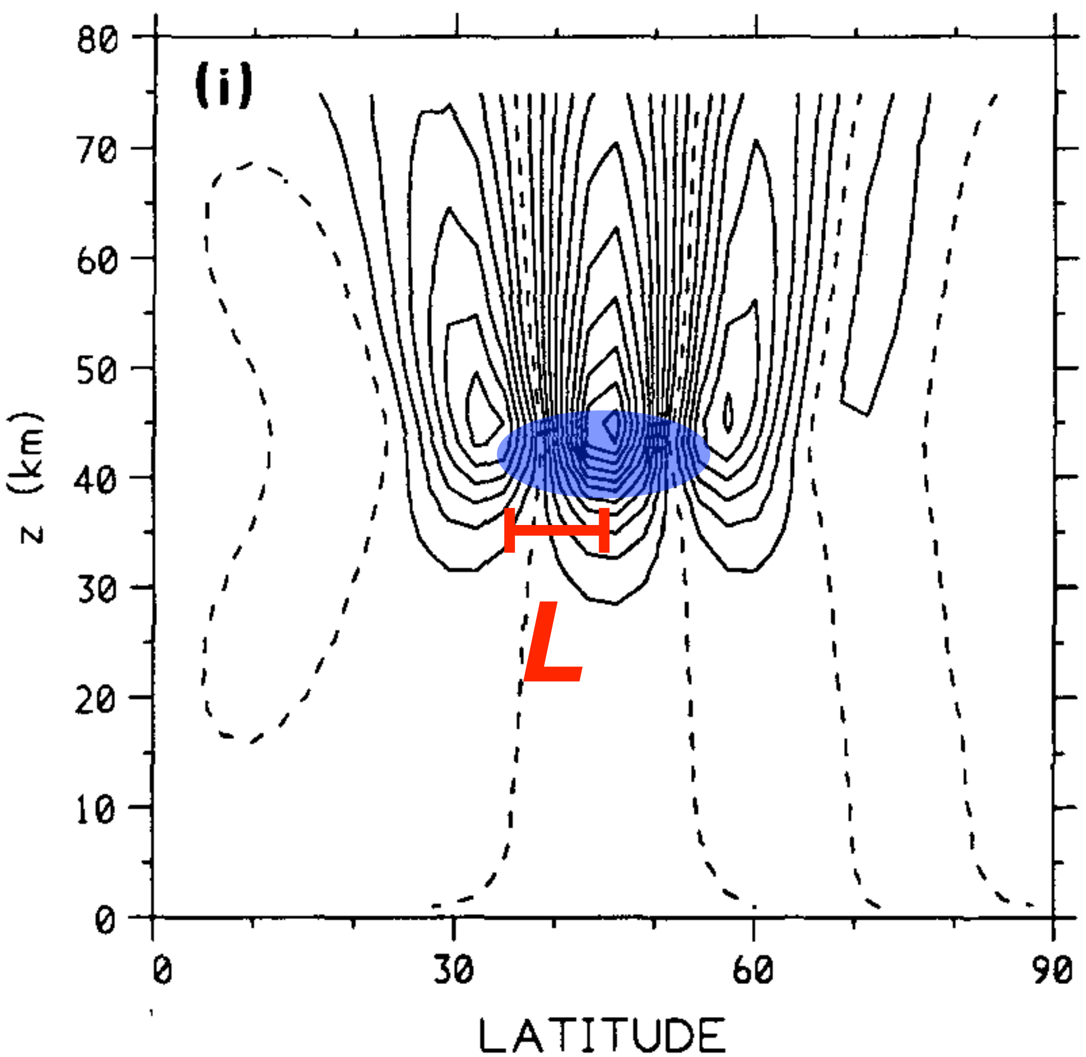
QG Potential Vorticity

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

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

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

zonal wind



amplitude *A*,
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QG Potential Vorticity

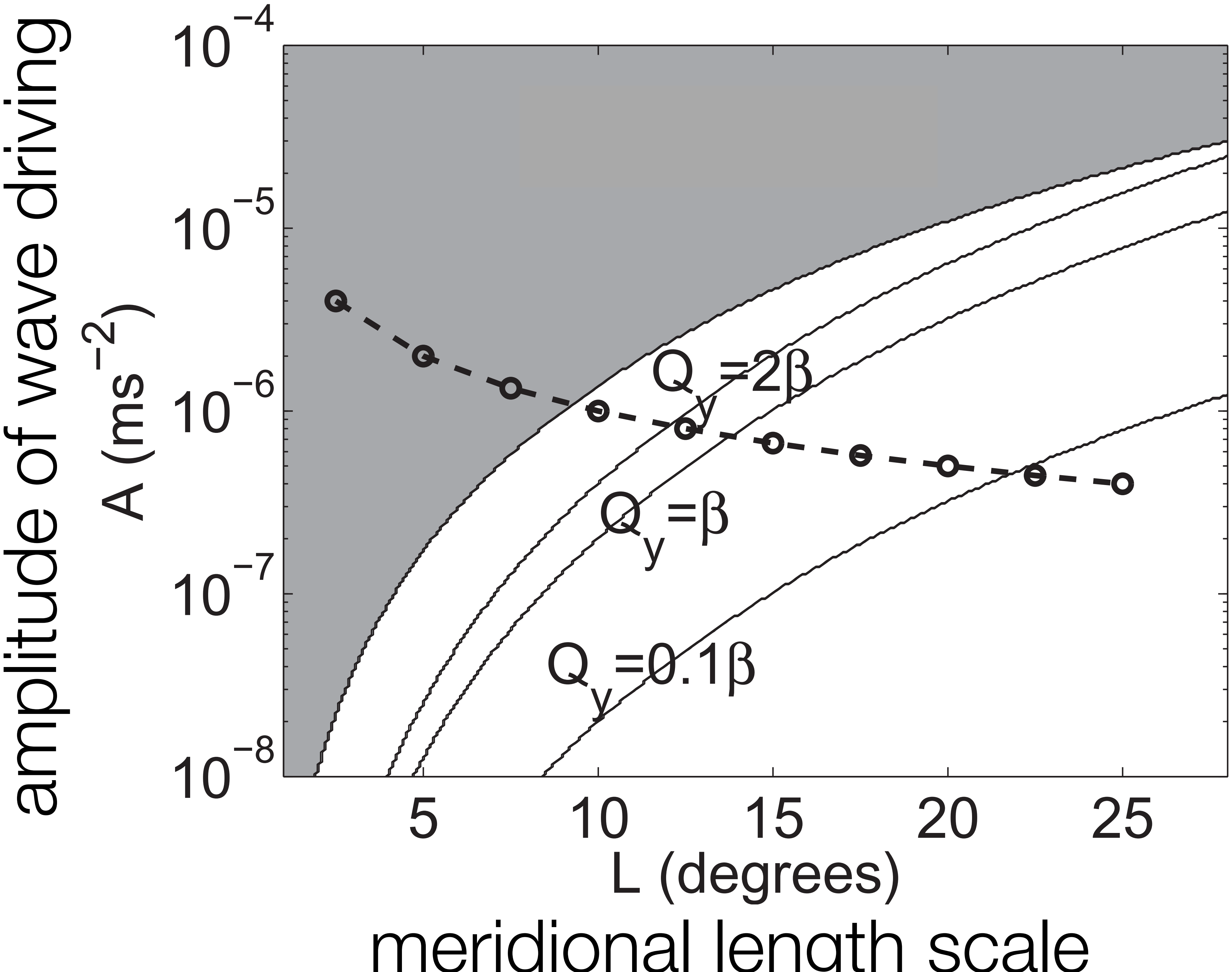
$$\bar{q}_y = \beta - \bar{u}_{yy} + f\frac{\bar{\theta}_y}{\bar{\theta}_p}$$

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

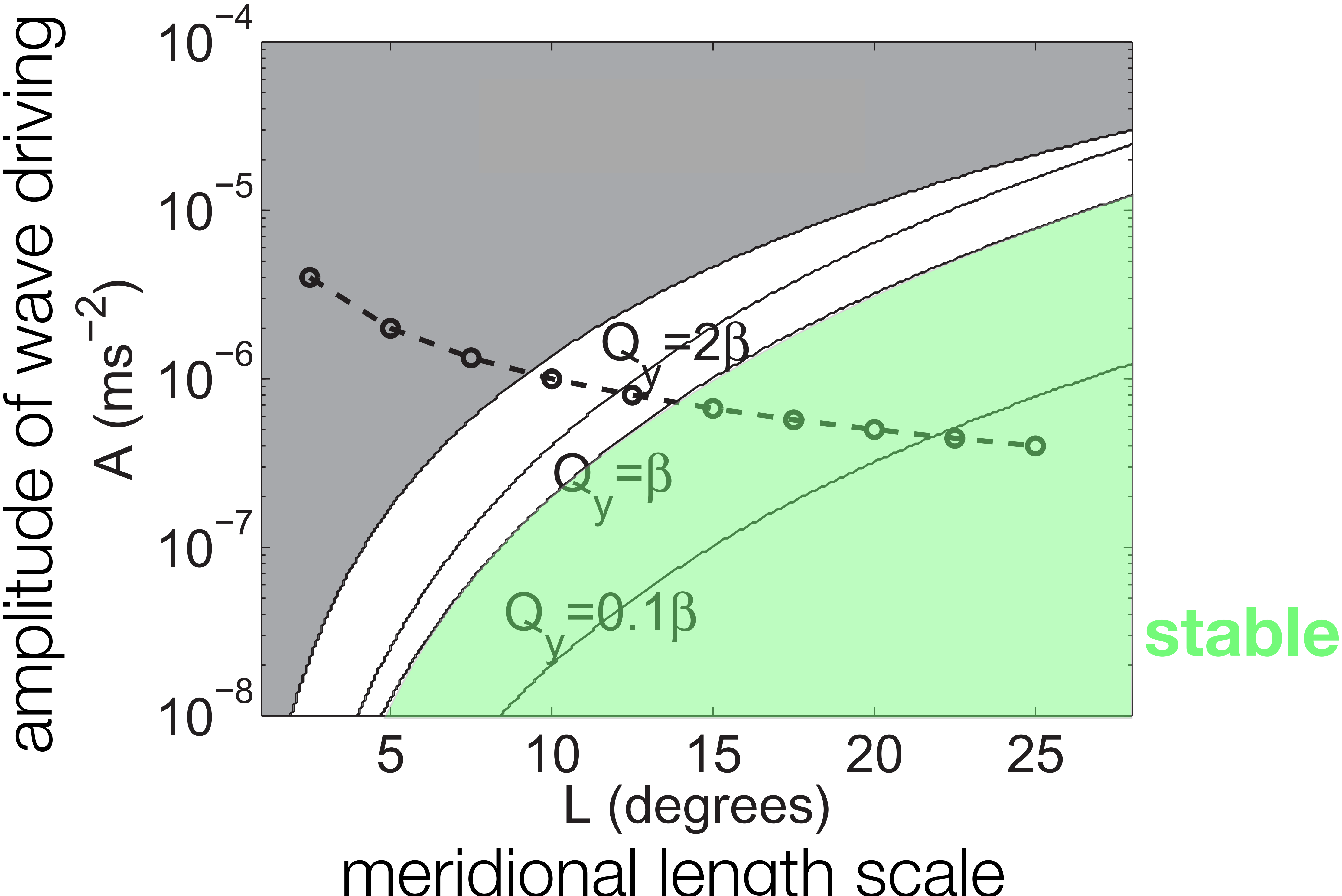
For $L << L_R$

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



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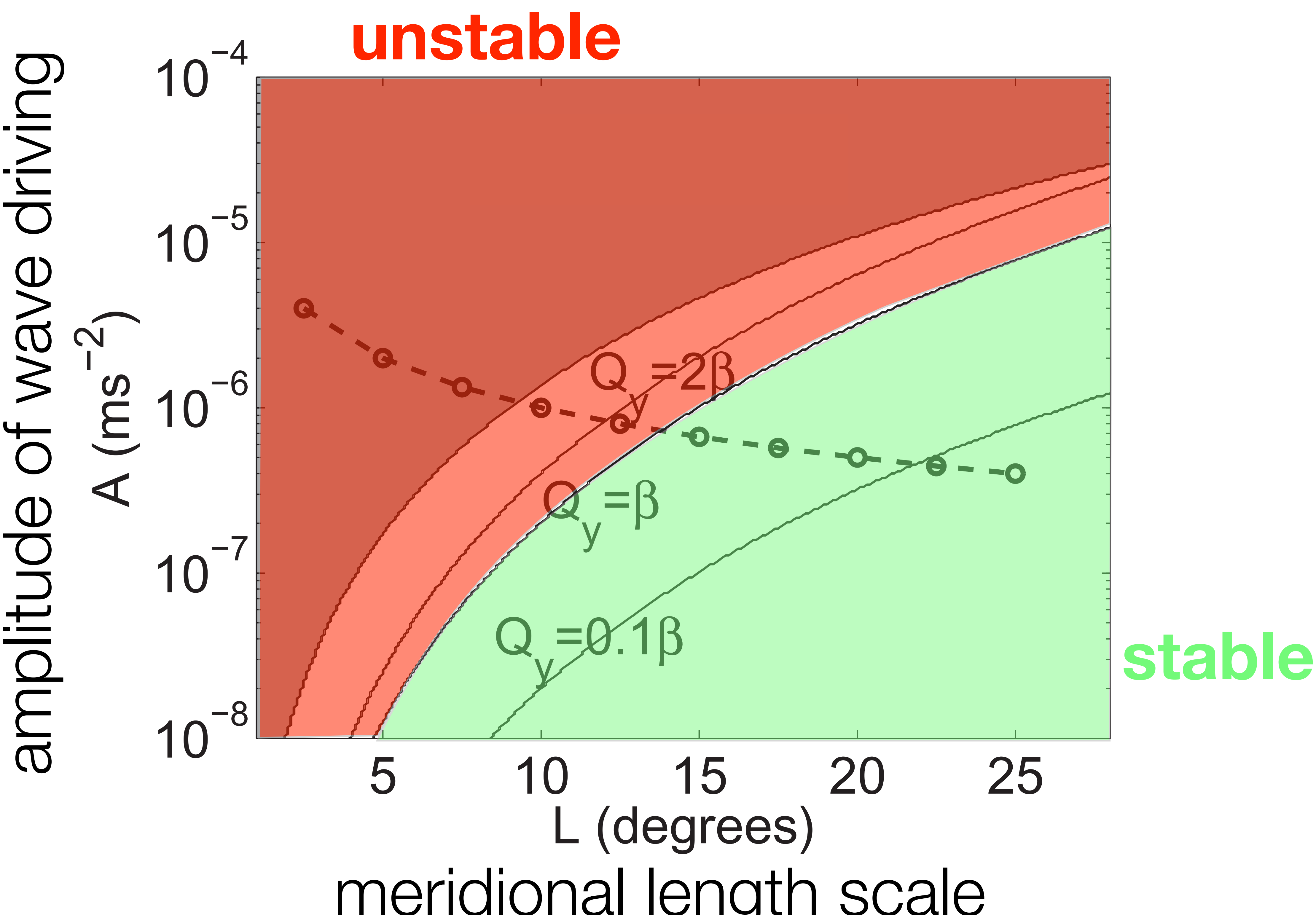
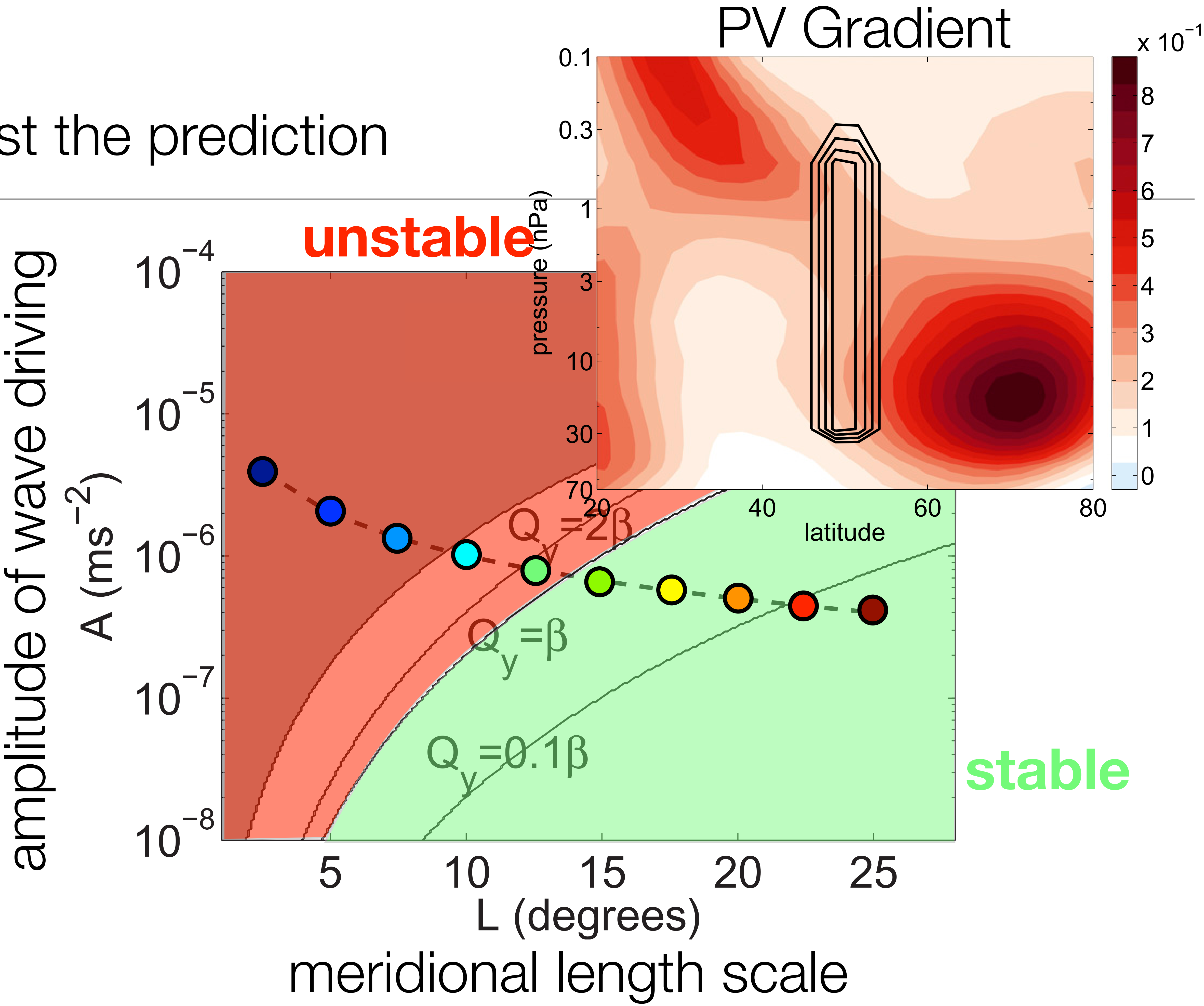
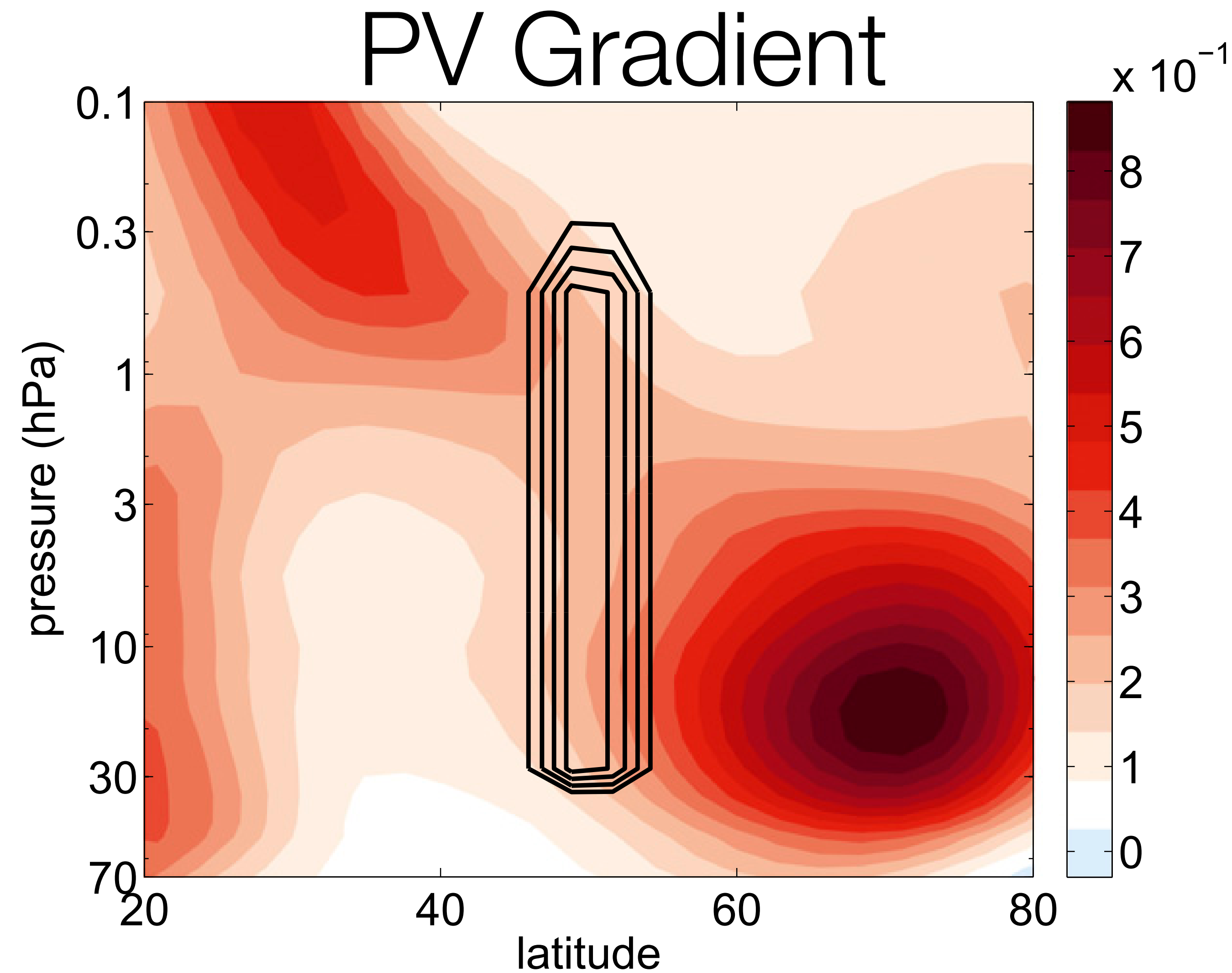
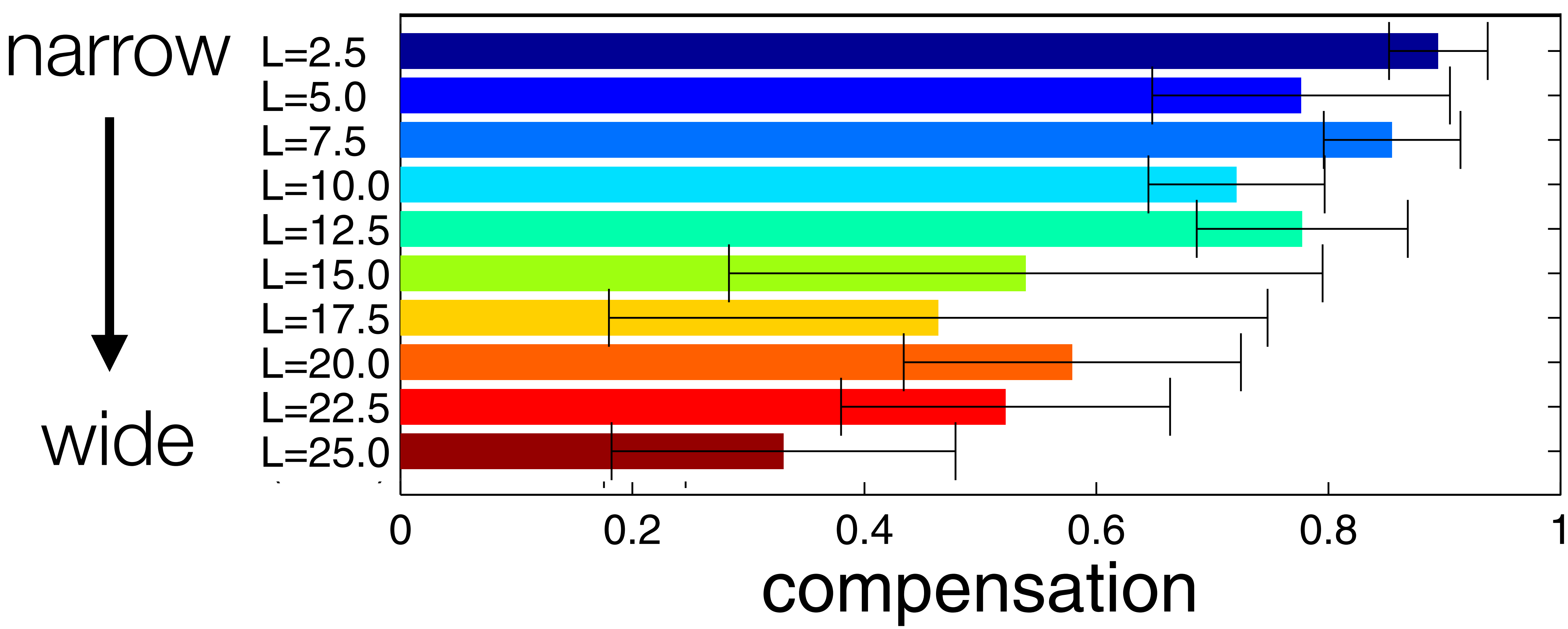


Test the prediction

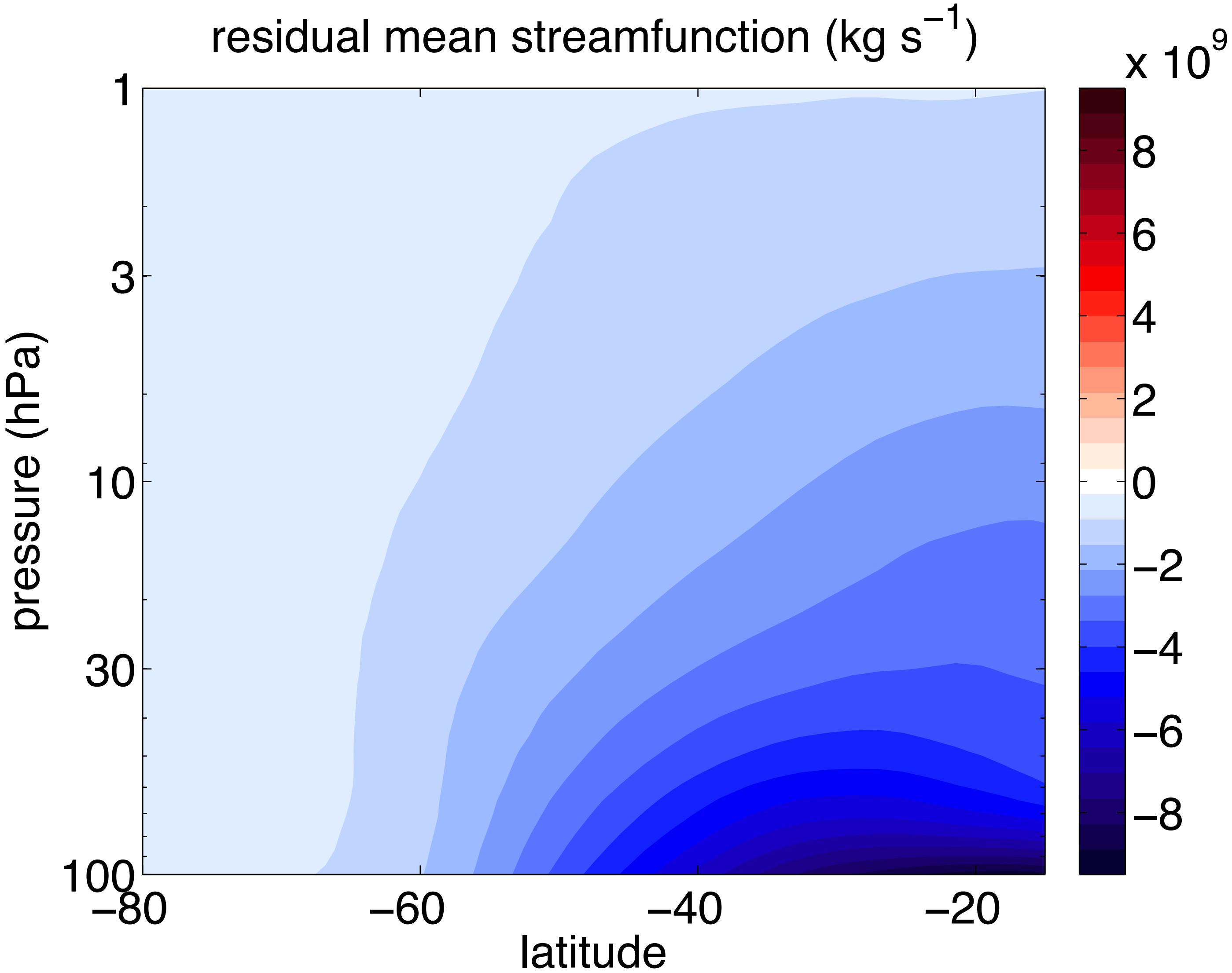


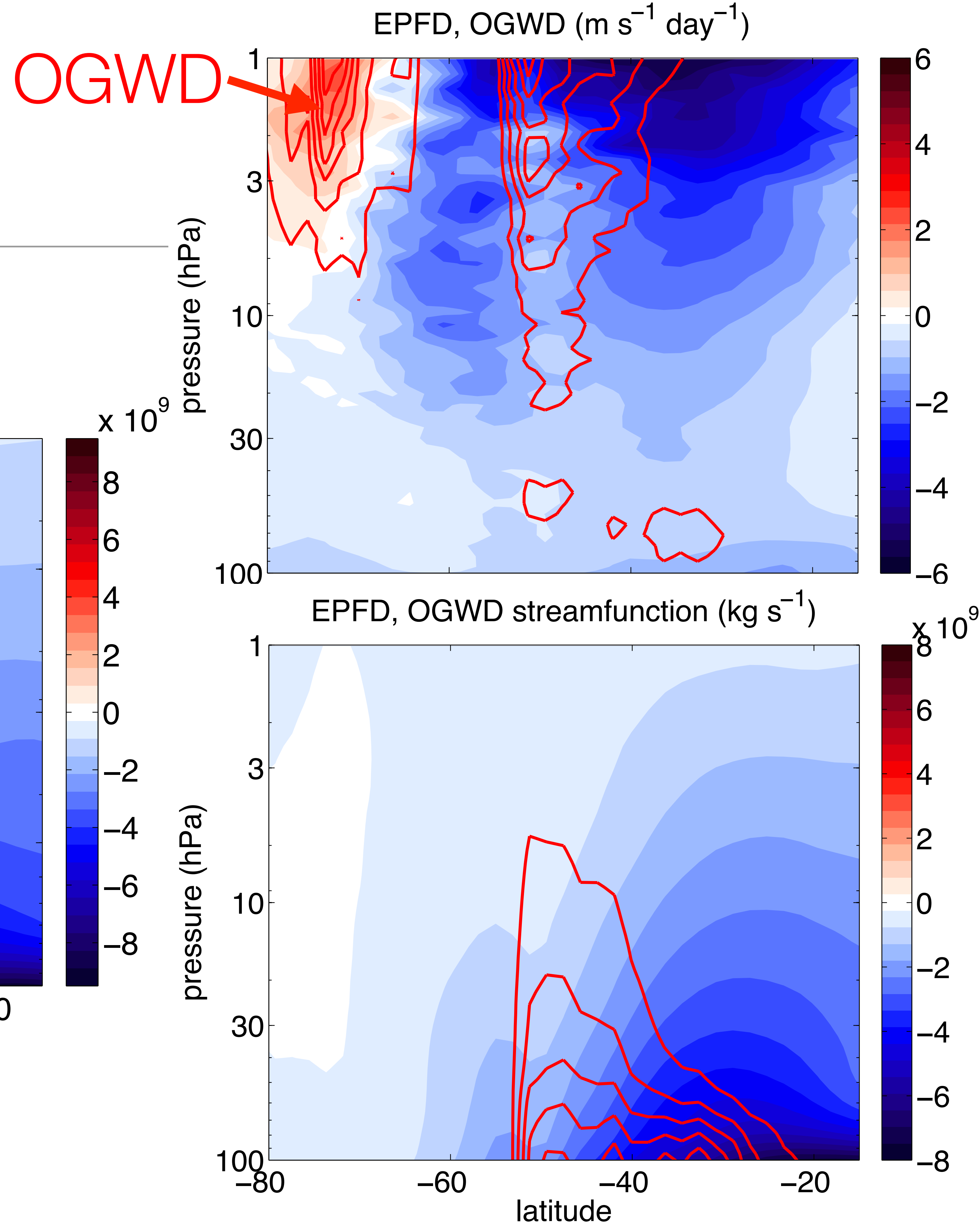
Test the prediction





Breaking down the streamfunction





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

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

↓ ↓ ↓

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

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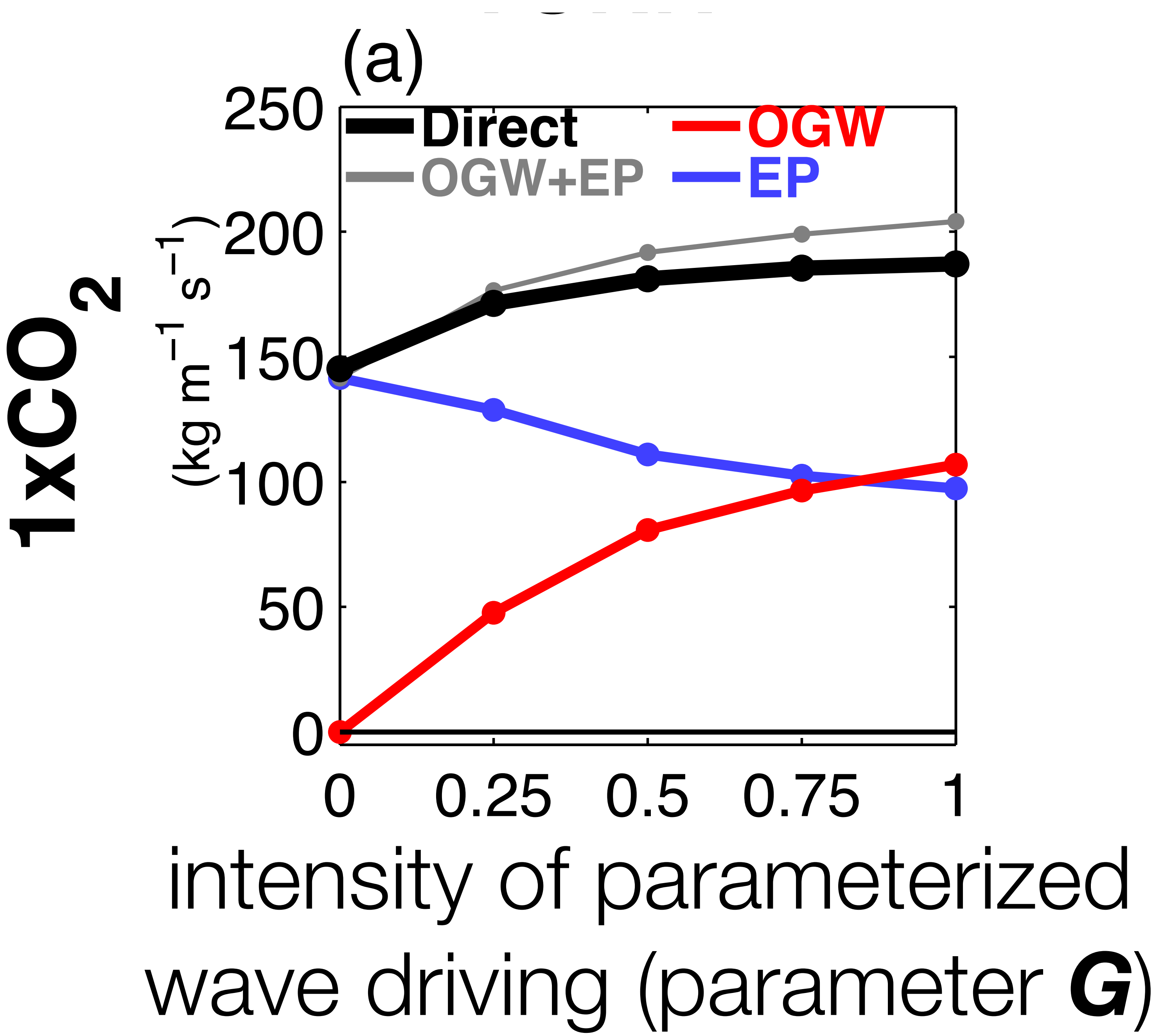
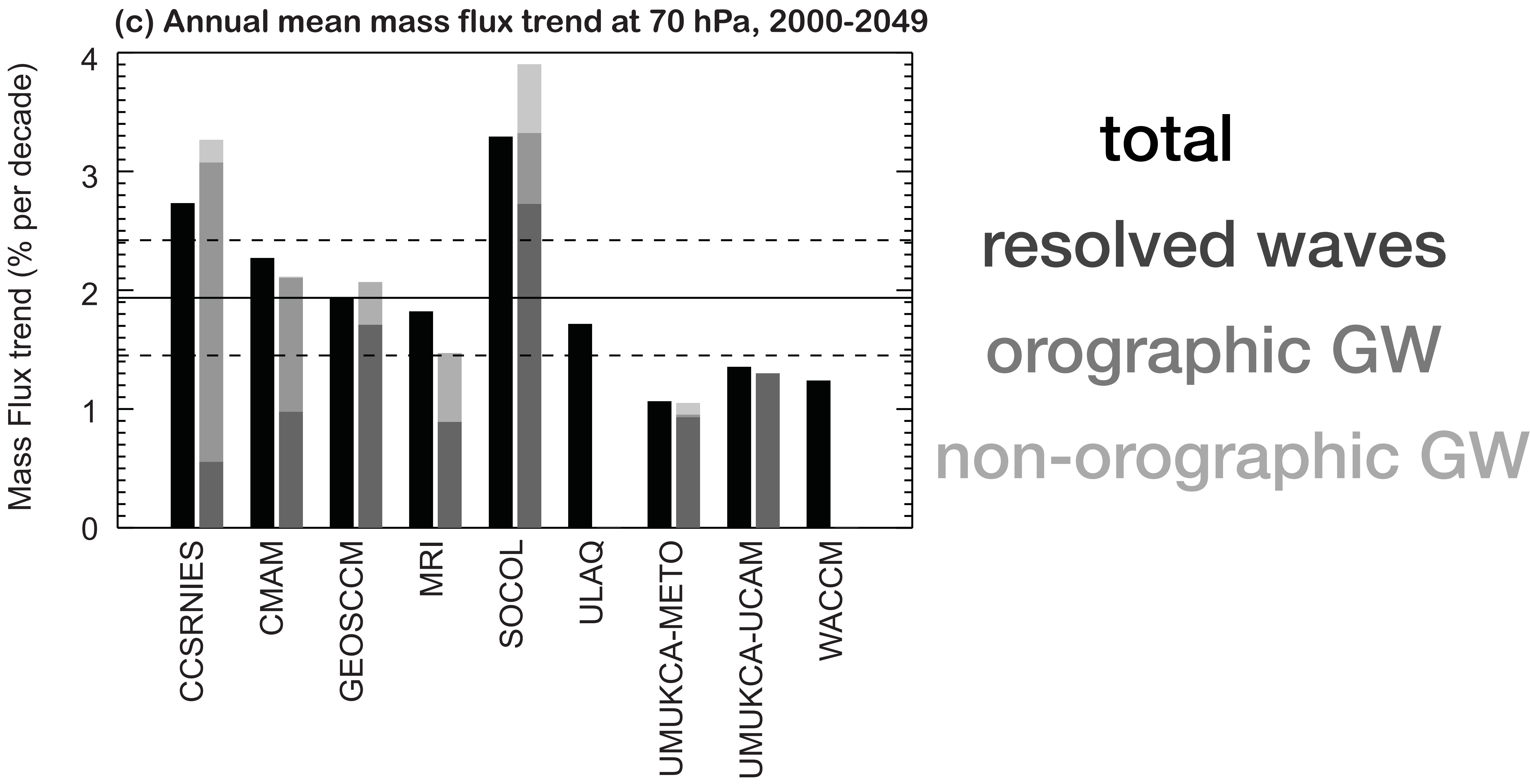
Compensation makes total circulation more robust than components *[Sigmond and Shepherd, 2014]*

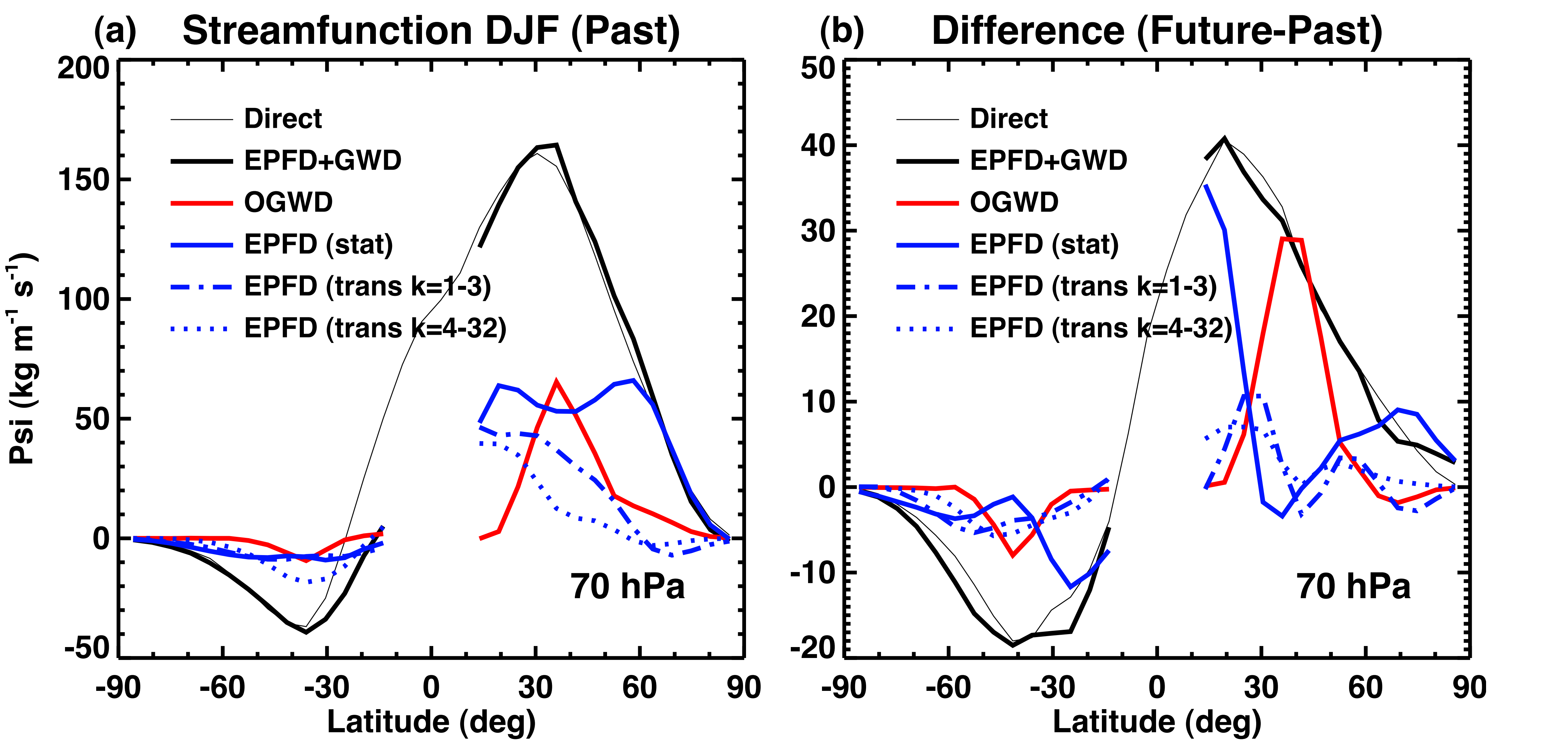


Uncertainty in “forcing” increases with future trends



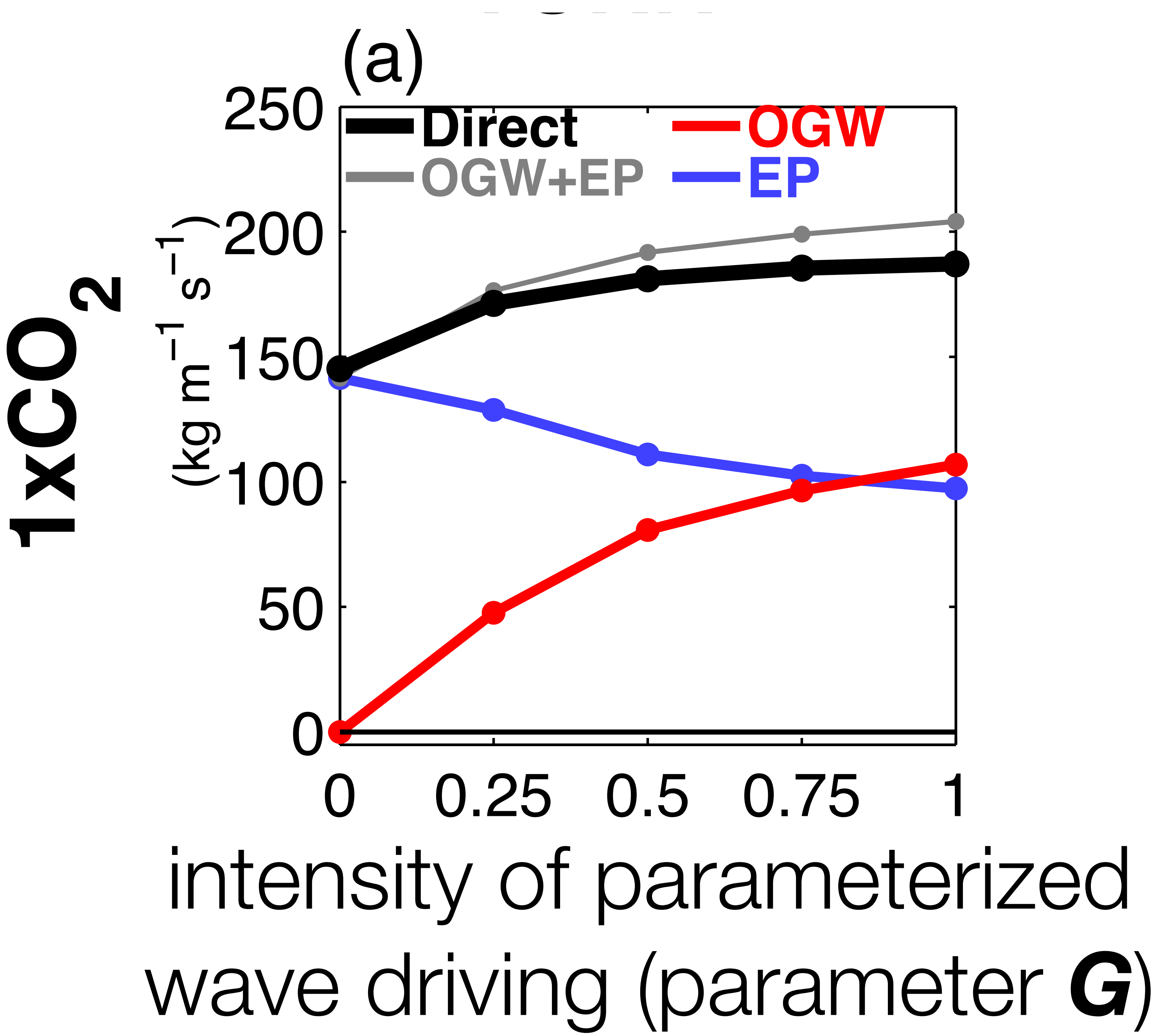
[CCMVal2 Report, Chpt 4]

… but compensation may affect response to CO_2

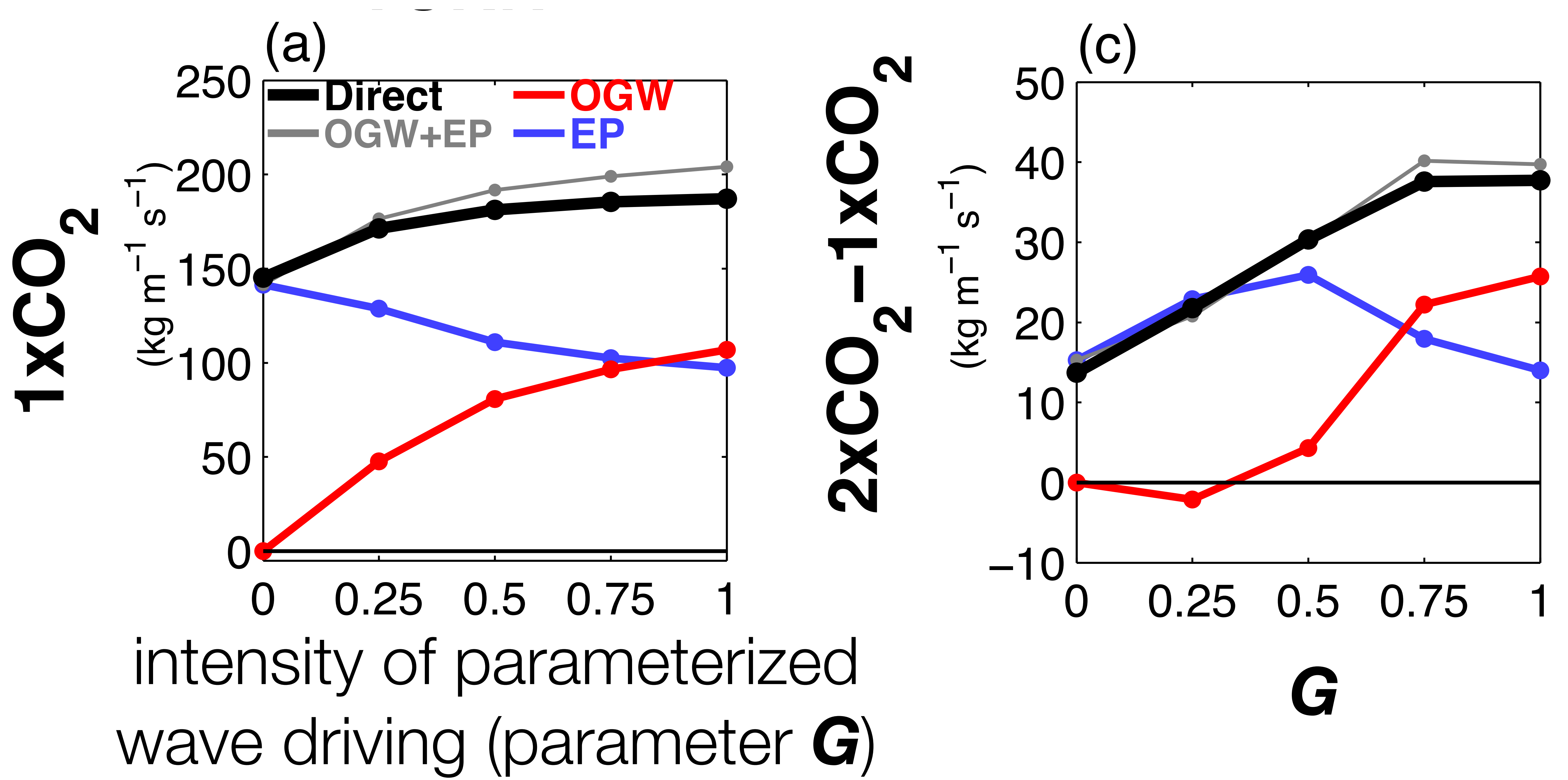


[Shepherd and McLandress 2011]

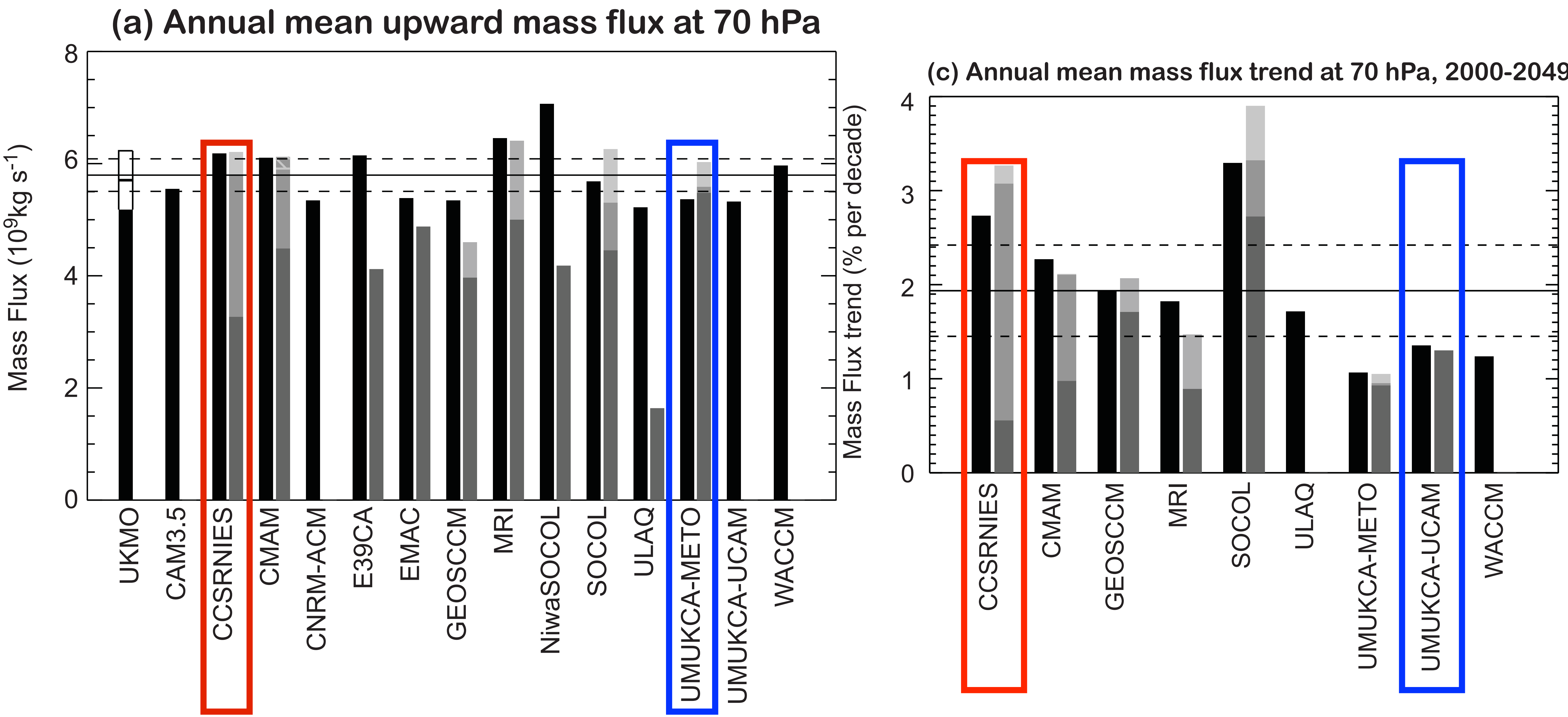
Impact of GW depends on basic state of the model *[Sigmond and Shepherd, 2014]*



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

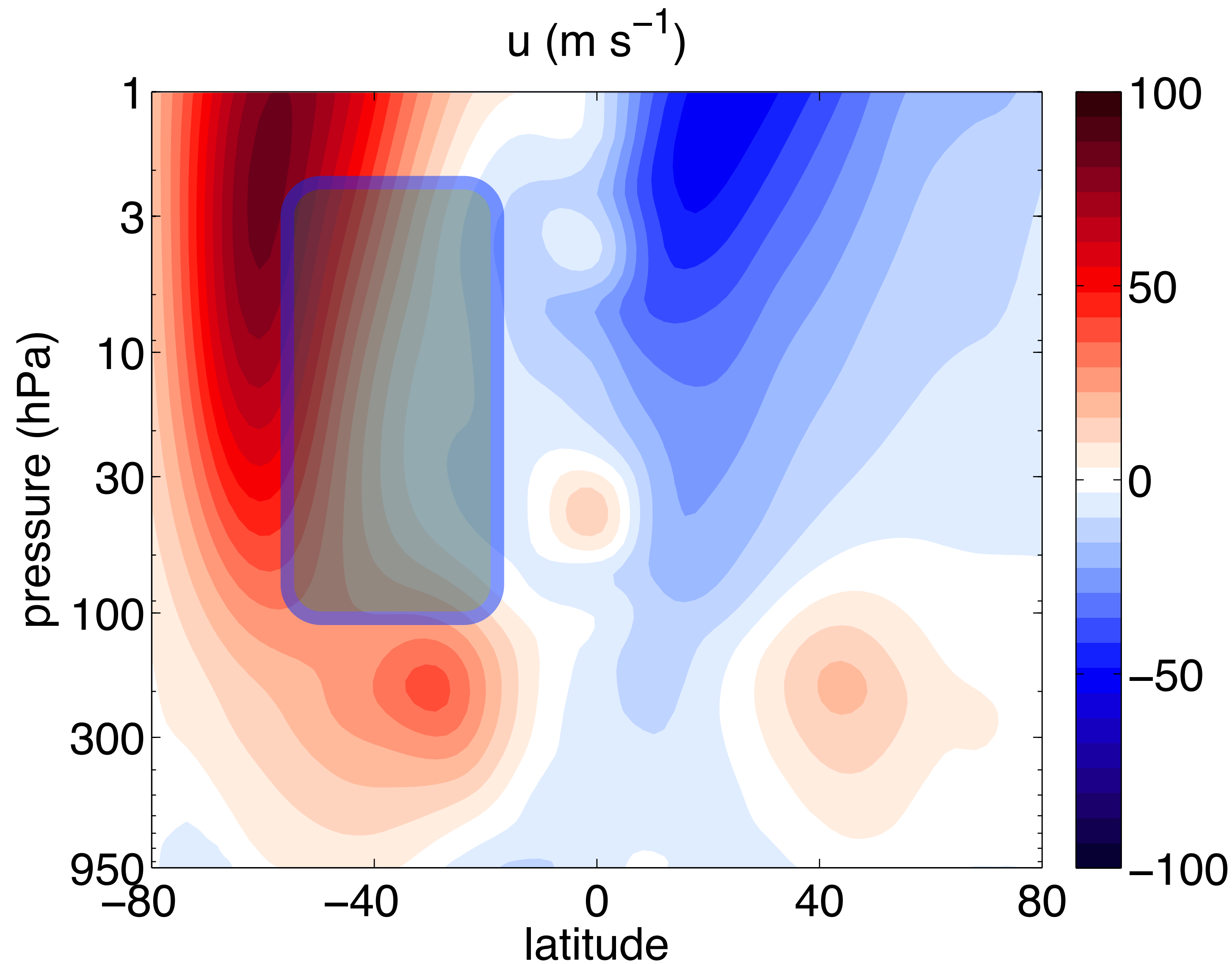


[CCMVal2 Report, Chpt 4]

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



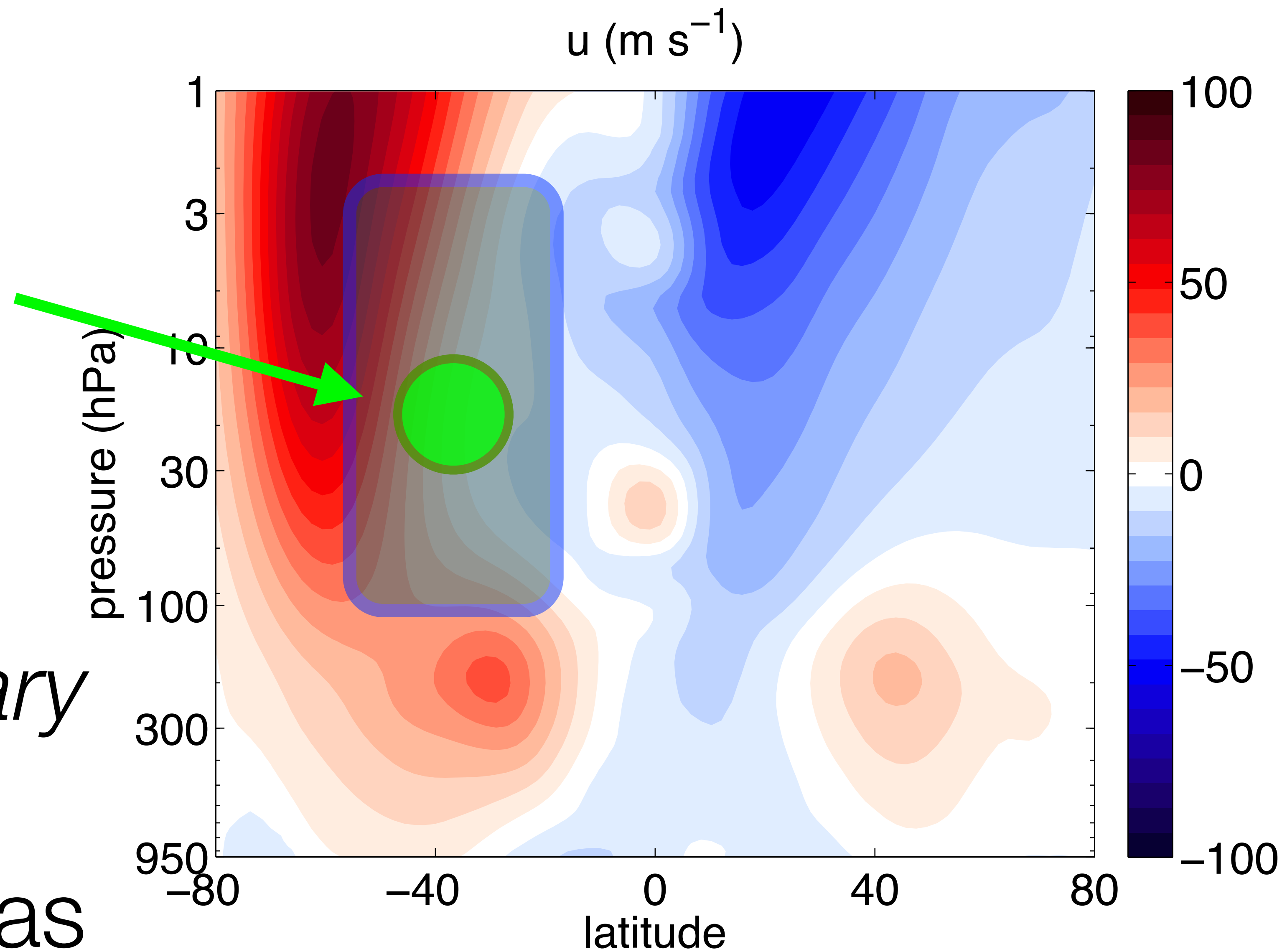
[McIntyre and Palmer, 1983]

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

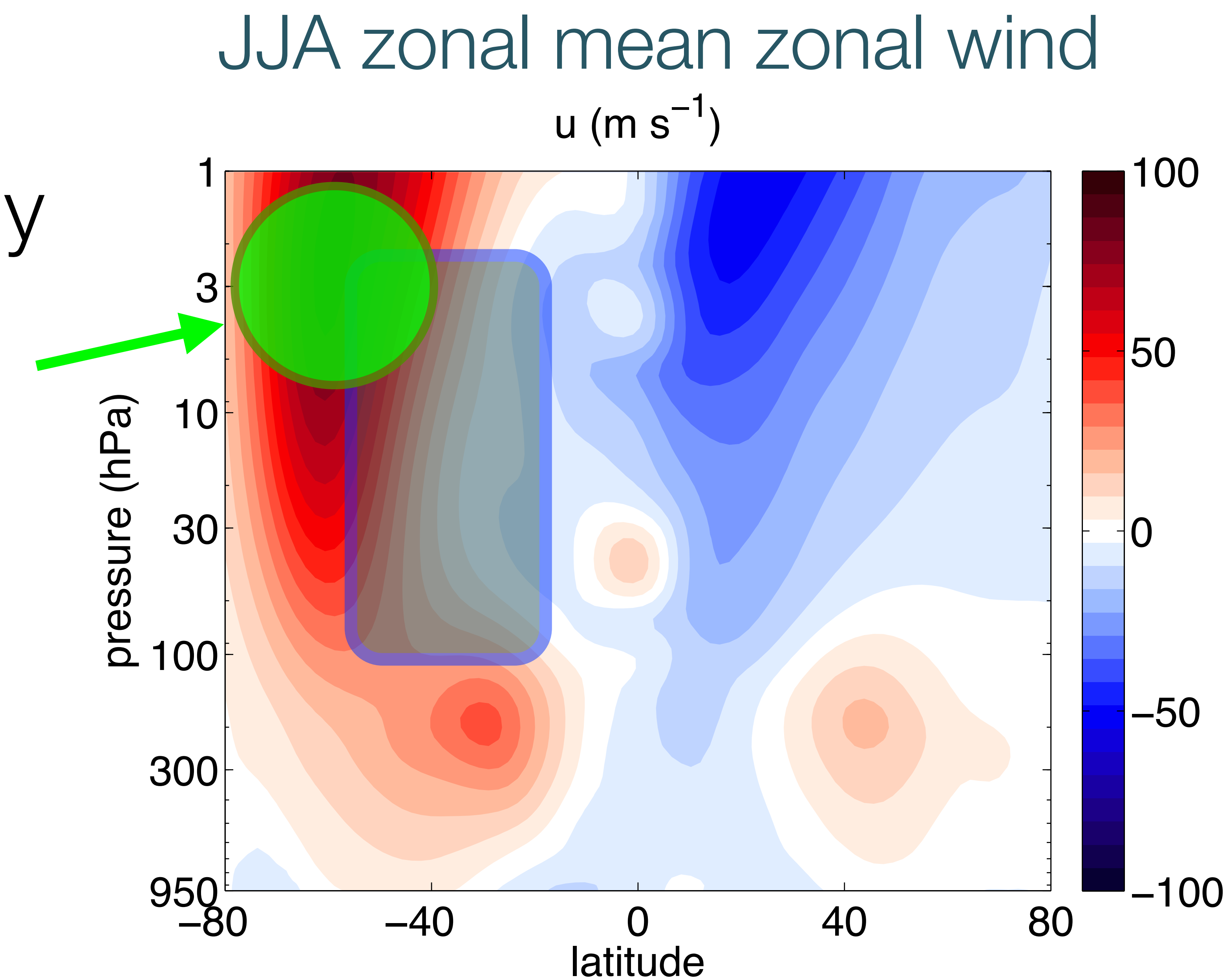


[Cohen et al. 2014]

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.

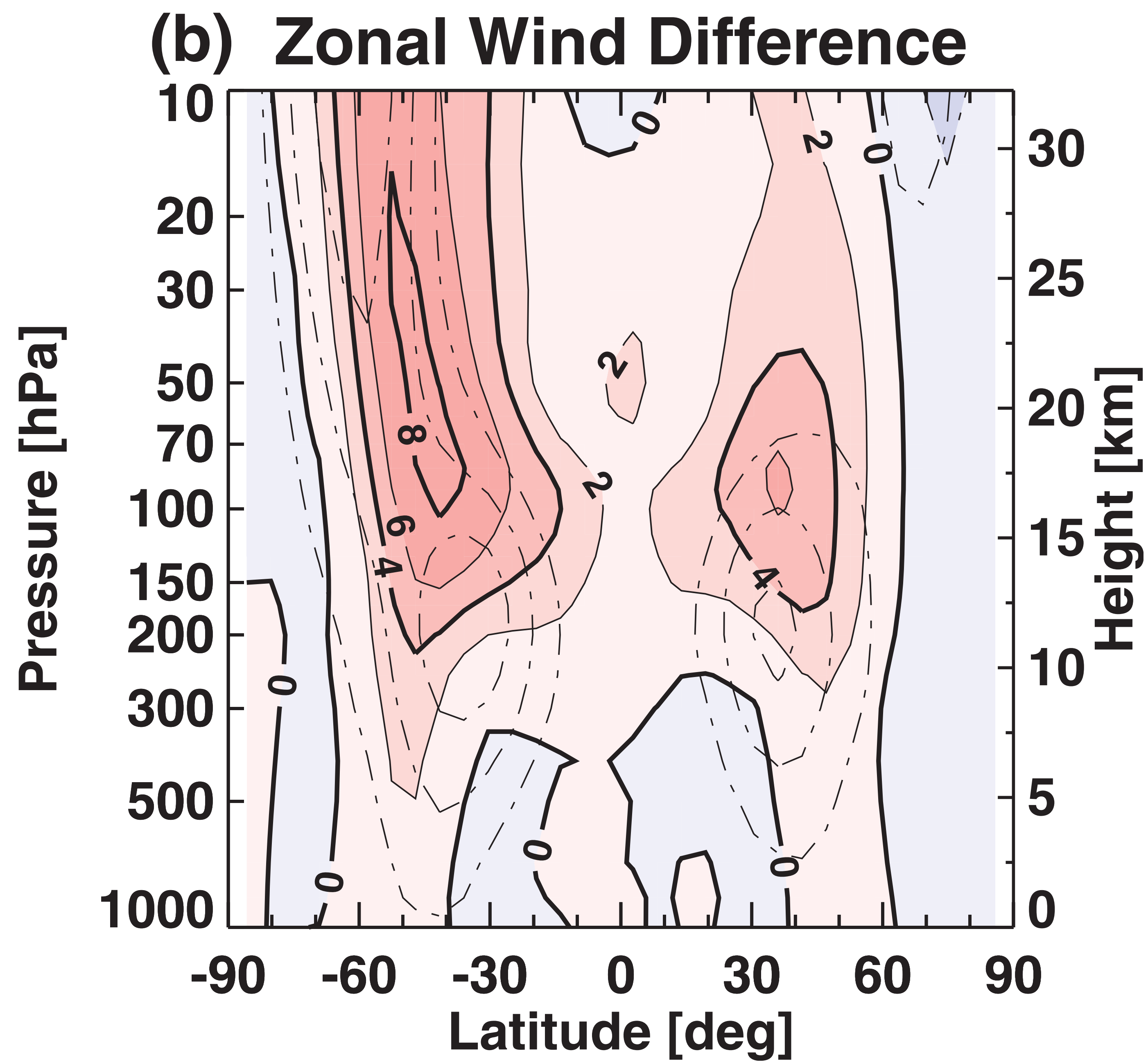


[Cohen et al. 2014]

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!)



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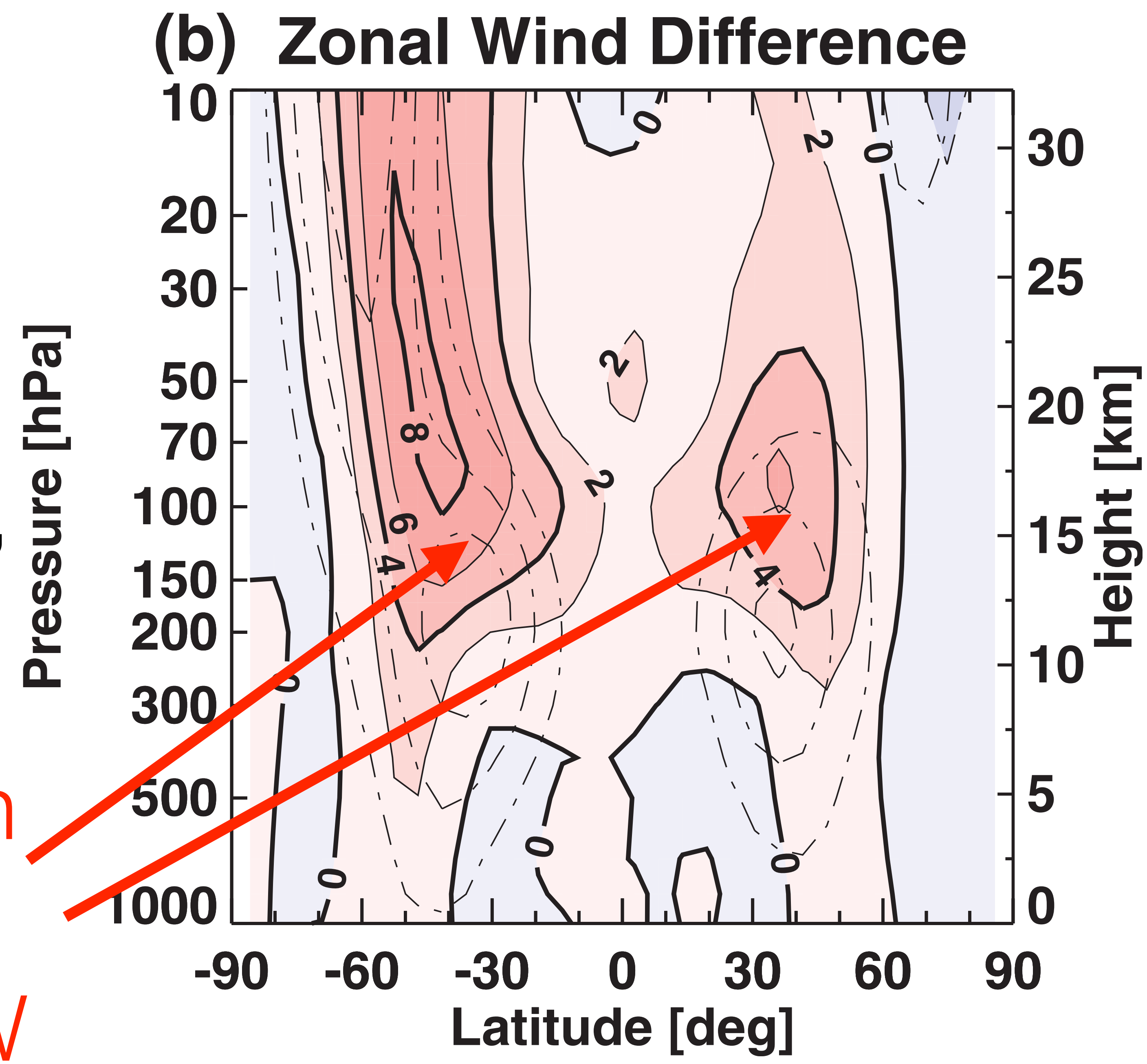


key to differences in downward control diagnostics is in GW forcing here

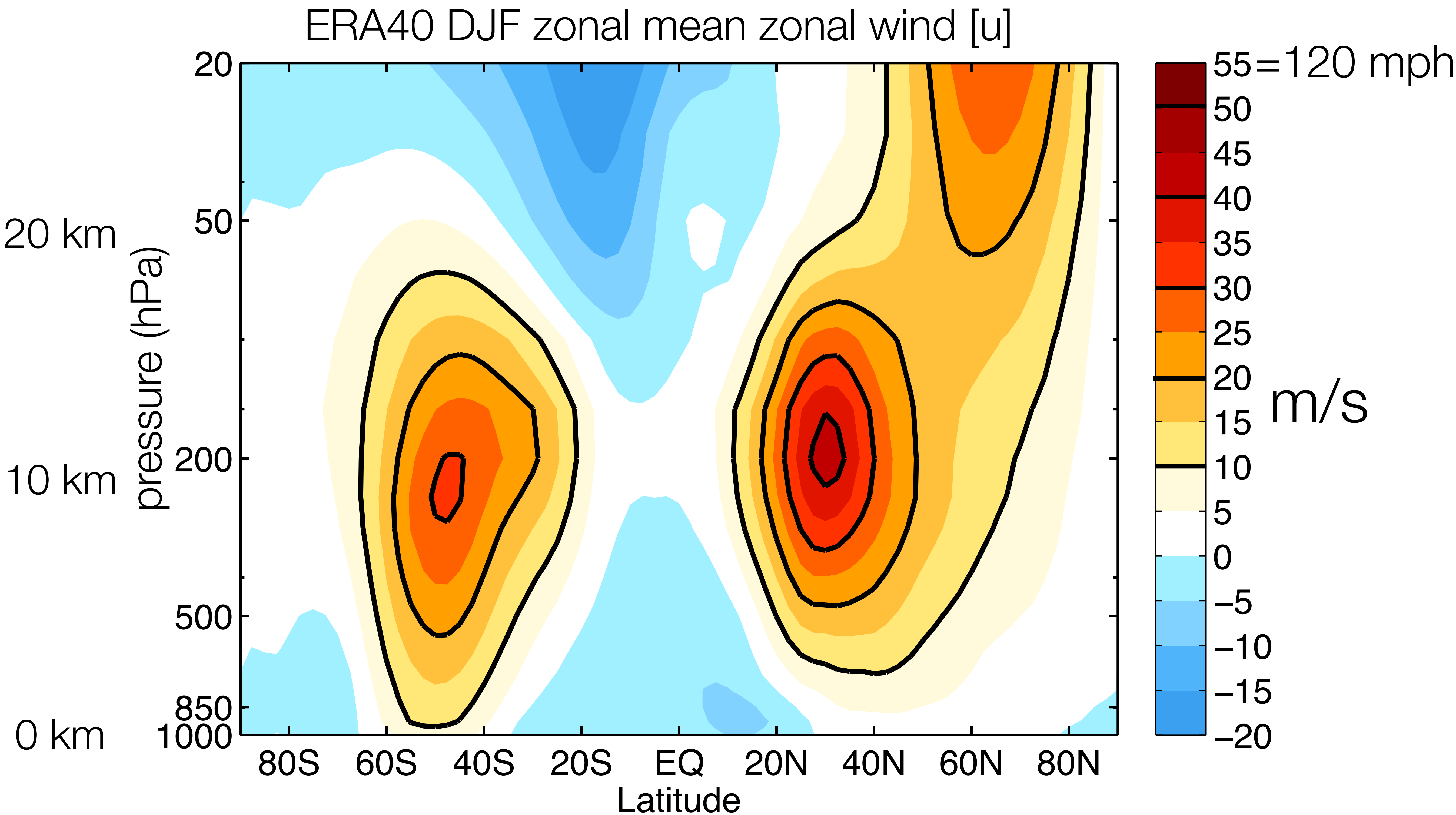
Conclusions

- The Brewer-Dobson Circulation is wave driven, but defining the precise role of Rossby vs. gravity waves is problematic.
    - resolved waves 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*

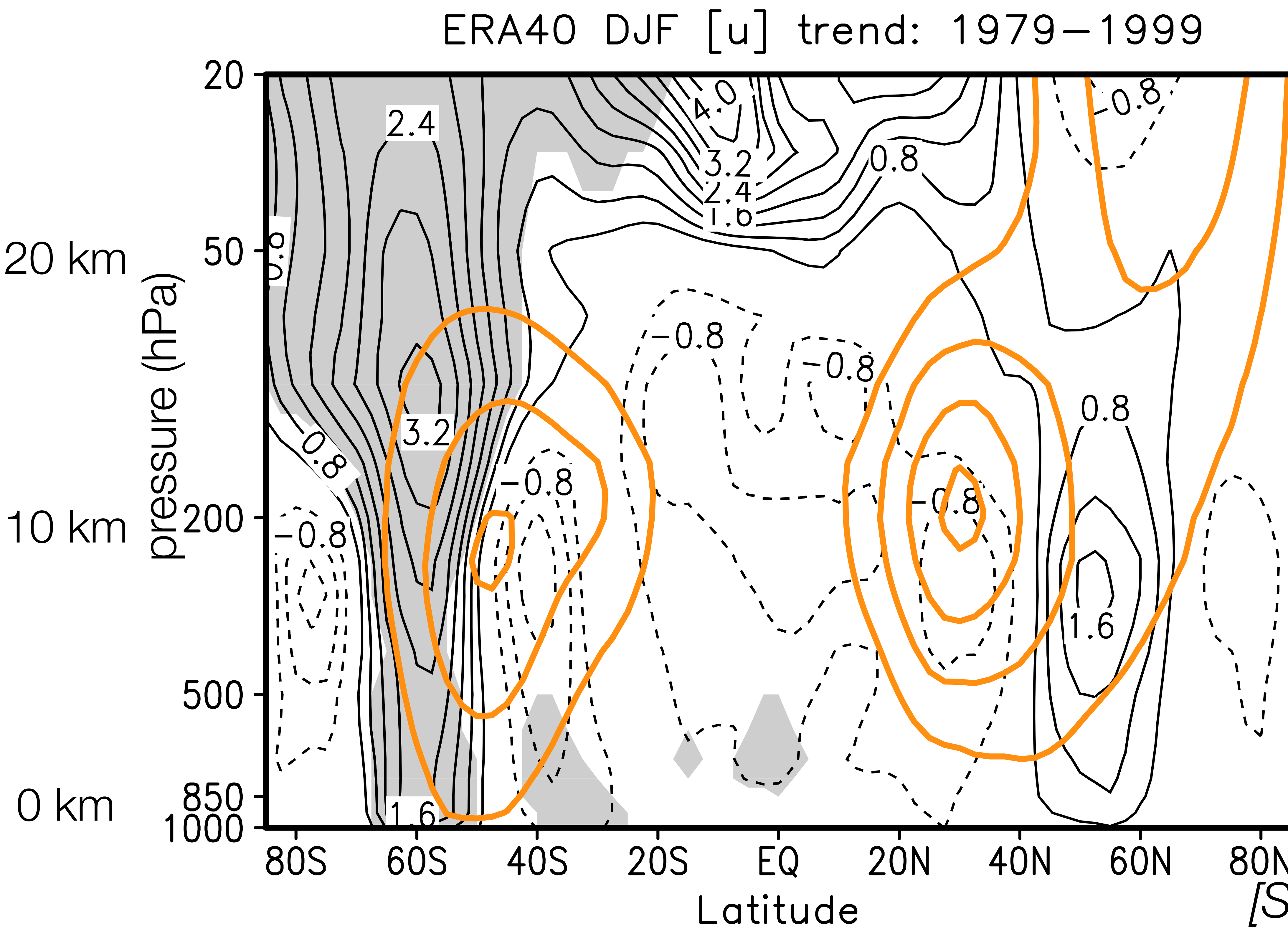
Why might we care about the Brewer-Dobson Circulation and stratospheric ozone?

(bonus slides)

The jet streams in austral summer (Dec.-Feb.)



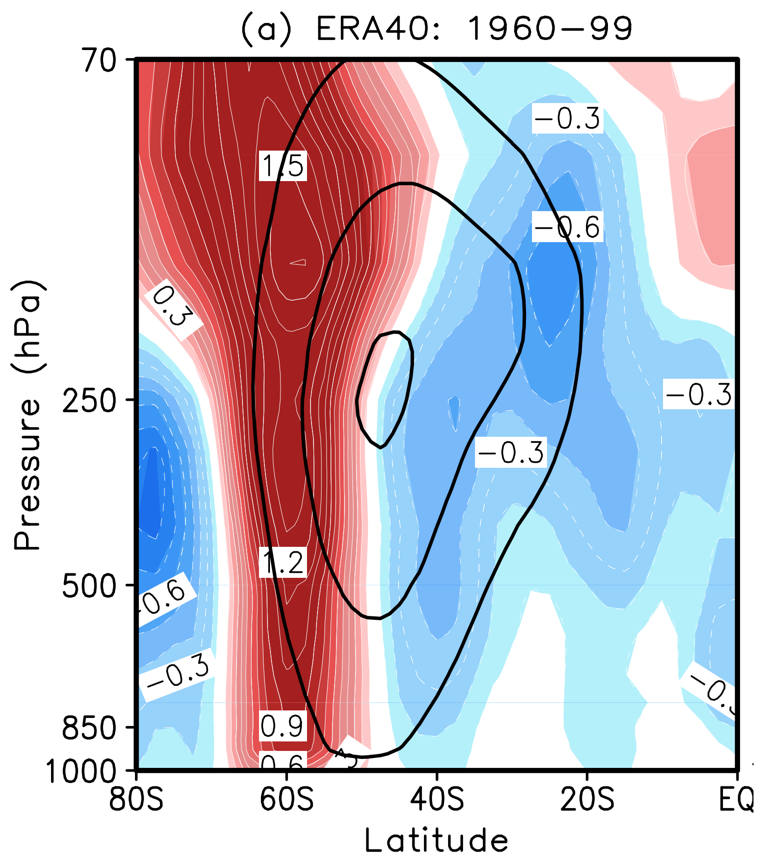
The jet streams in austral summer (Dec.-Feb.) Recent trends



[Son et al. 2010]

DJF Trends in zonal mean zonal wind

late 20th century



reanalysis

[Son et al. 2008; Gerber et al. 2011]

DJF Trends in zonal mean zonal wind

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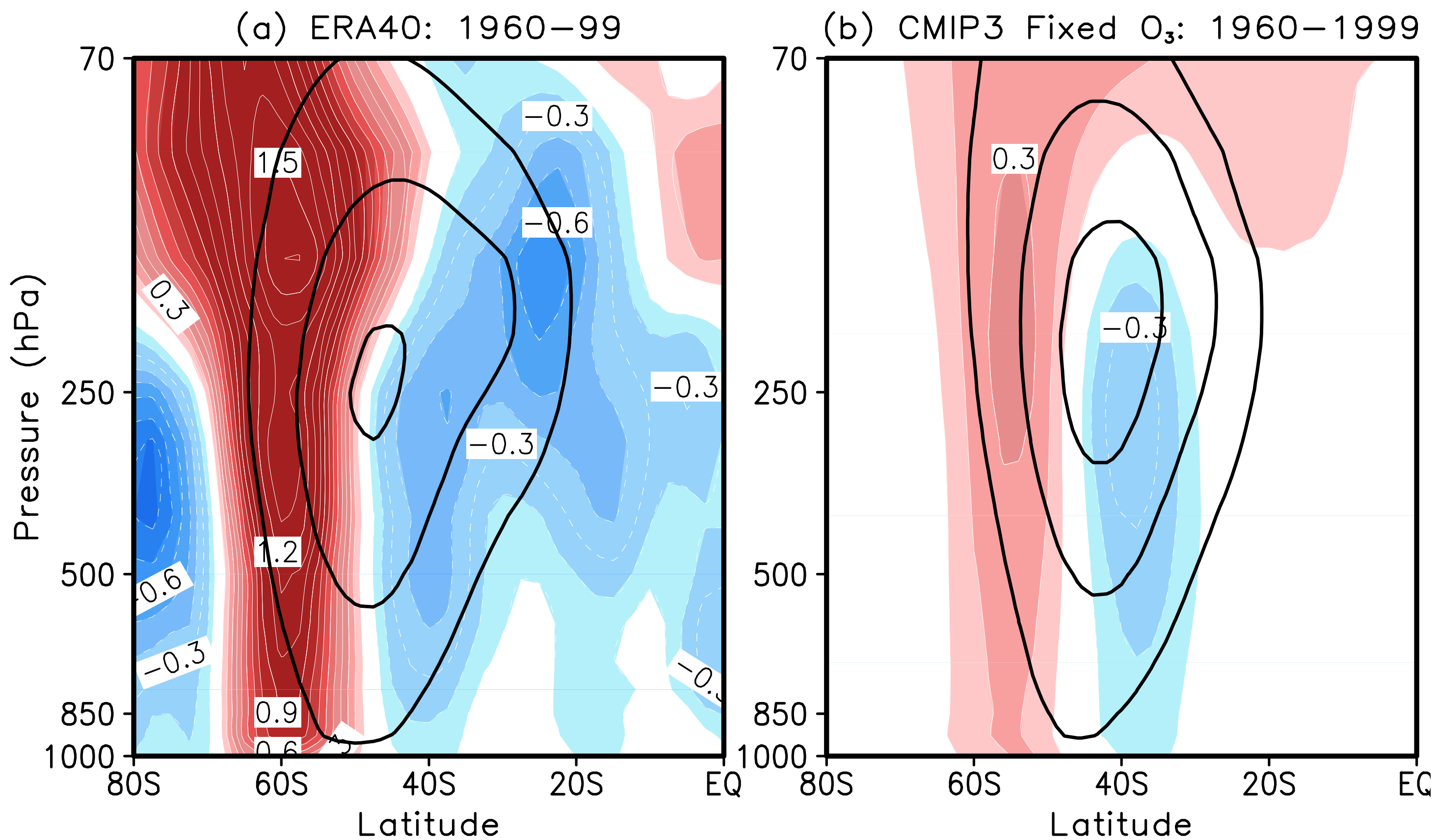

reanalysis

models w/GHGs

[Son et al. 2008; Gerber et al. 2011]

DJF Trends in zonal mean zonal wind

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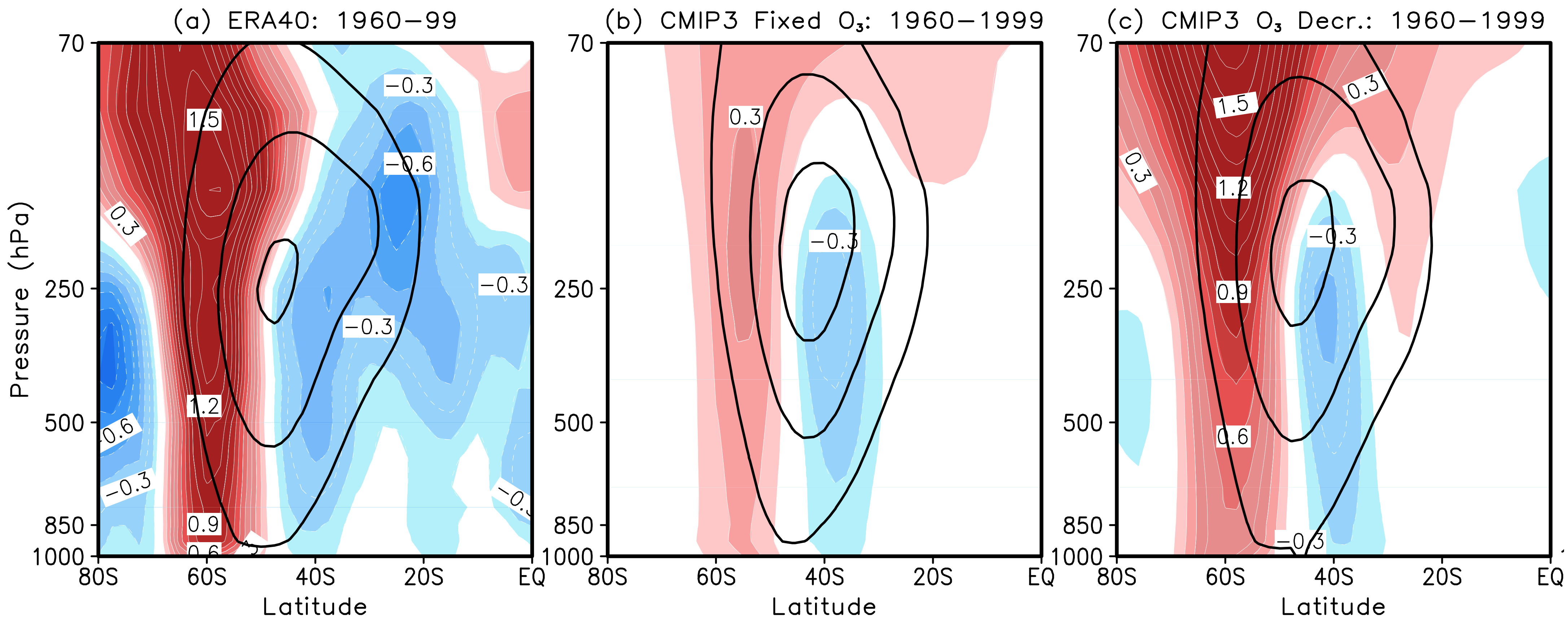

reanalysis | models w/GHGs | models w/ GHGs+O_3

[Son et al. 2008; Gerber et al. 2011]

DJF Trends in zonal mean zonal wind

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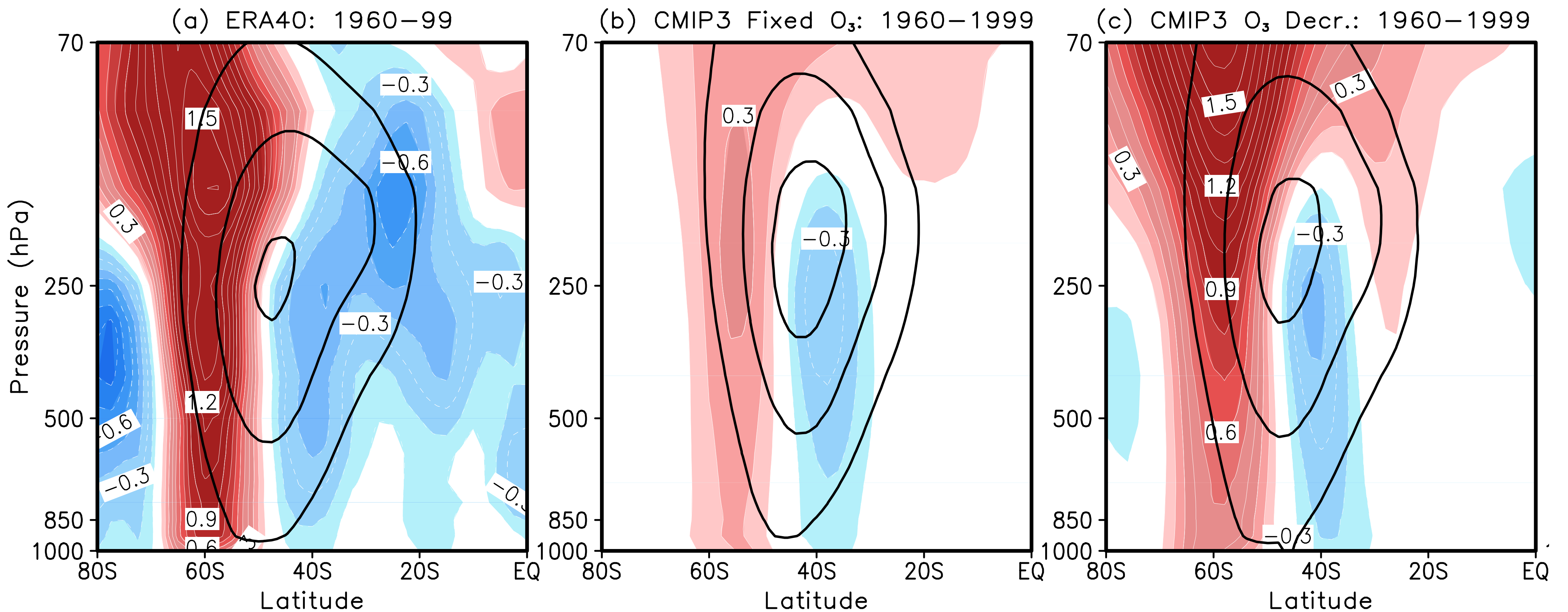


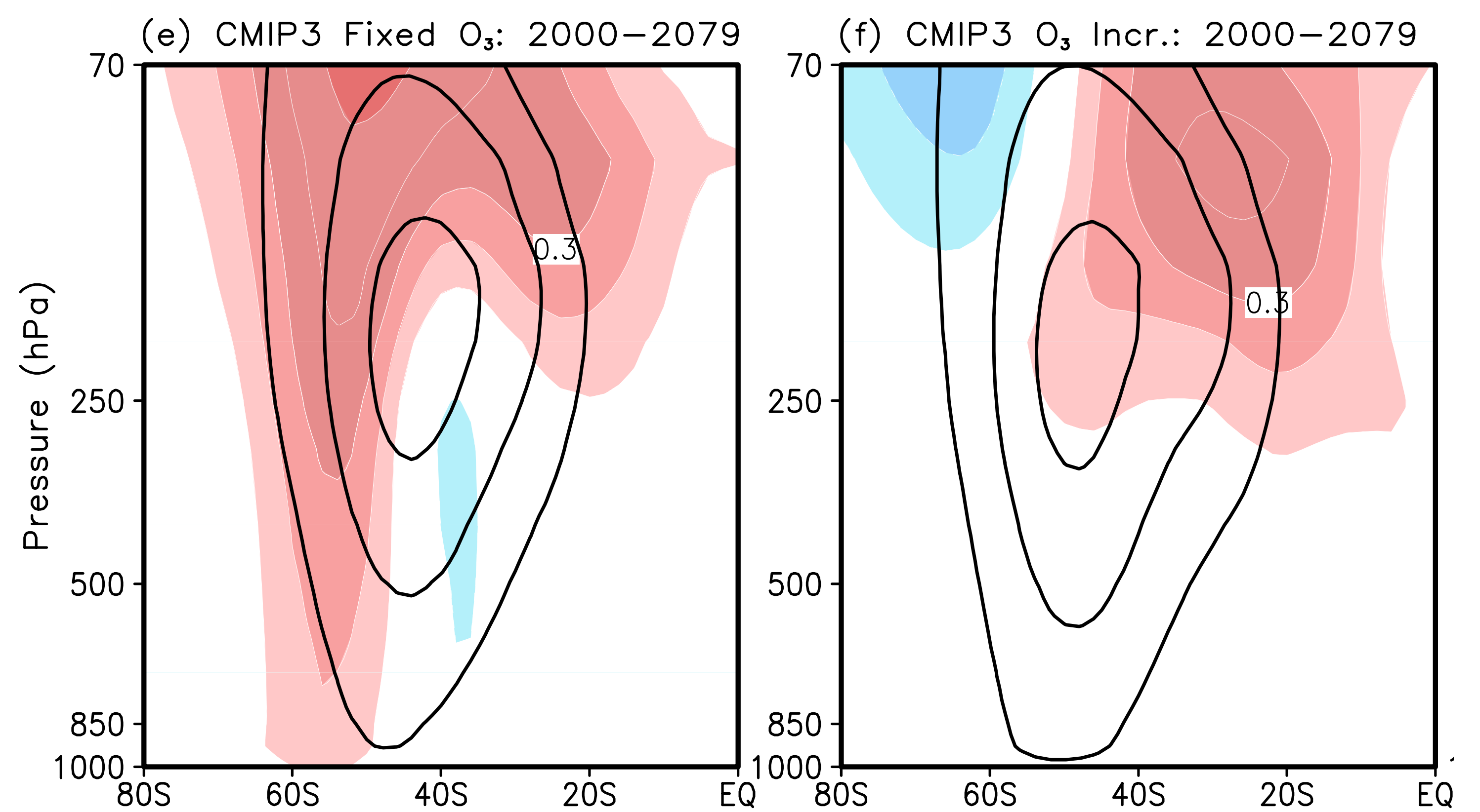
reanalysis

models w/GHGs

models w/ GHGs+O_3

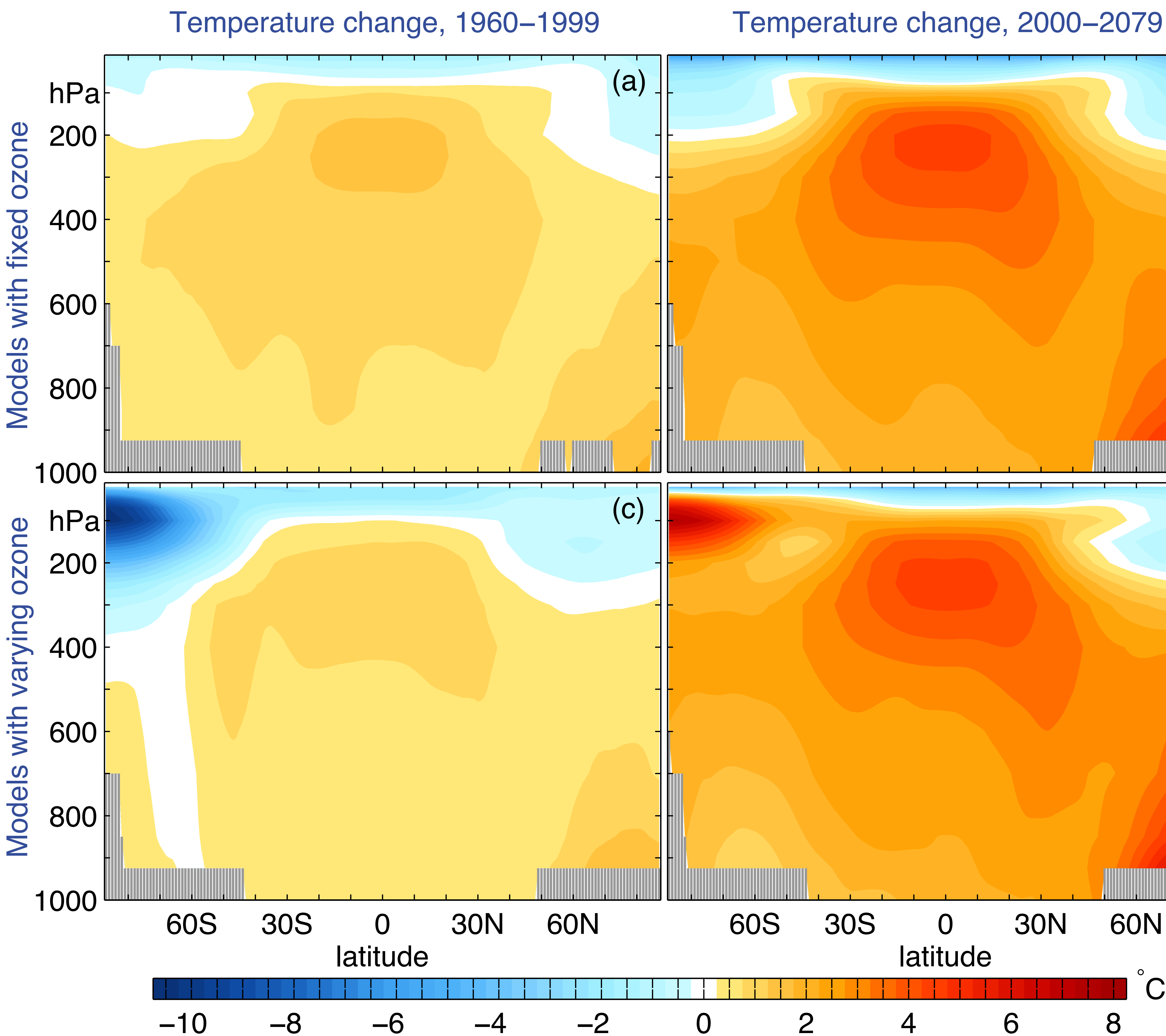
predictions 2000-2079

?

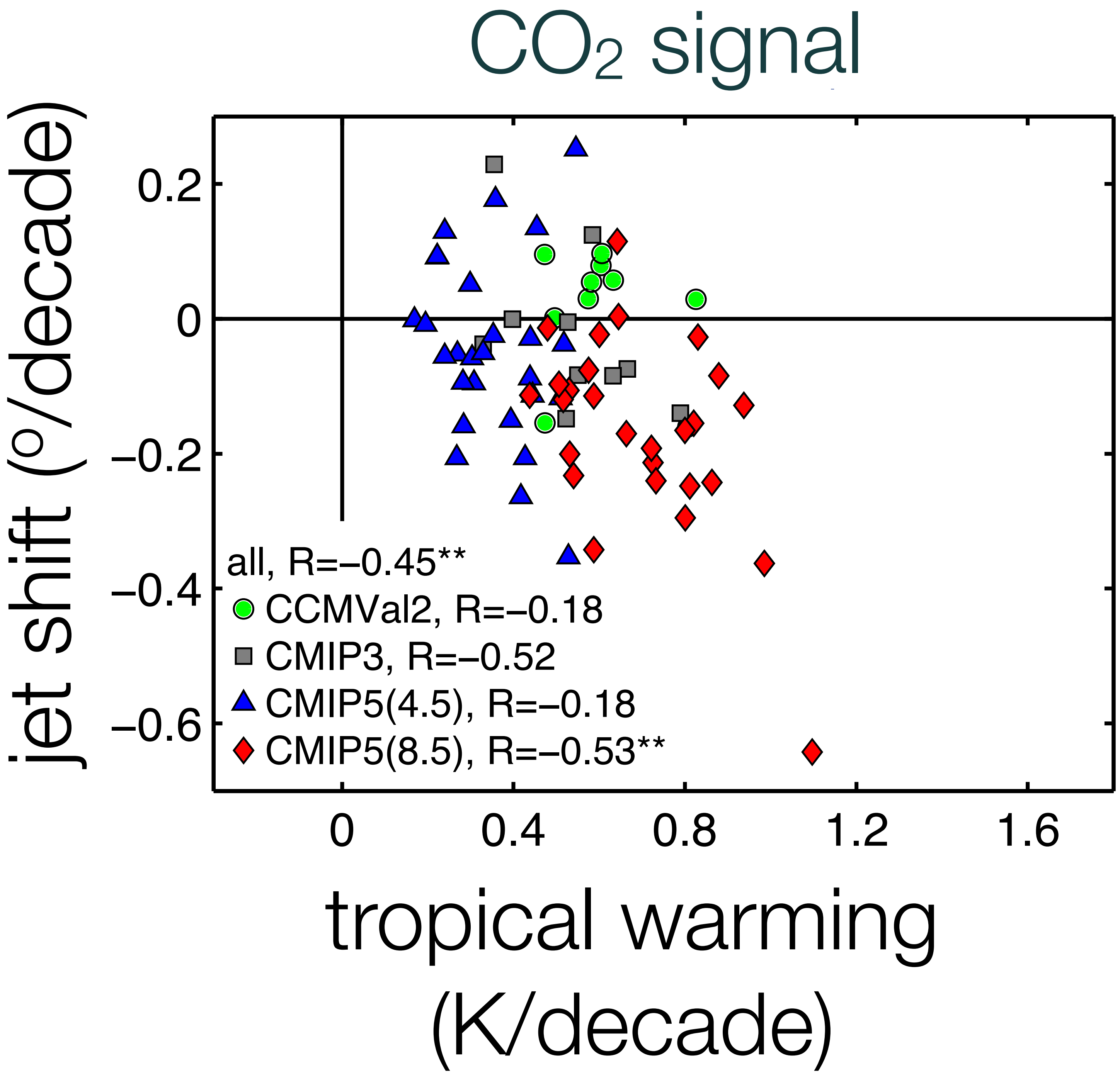


[Son et al. 2008; Gerber et al. 2011]

Temperature Signature of Anthropogenic Forcing



21st century Southern Hemisphere jet stream trends in summer (DJF)



[Gerber and Son 2014]

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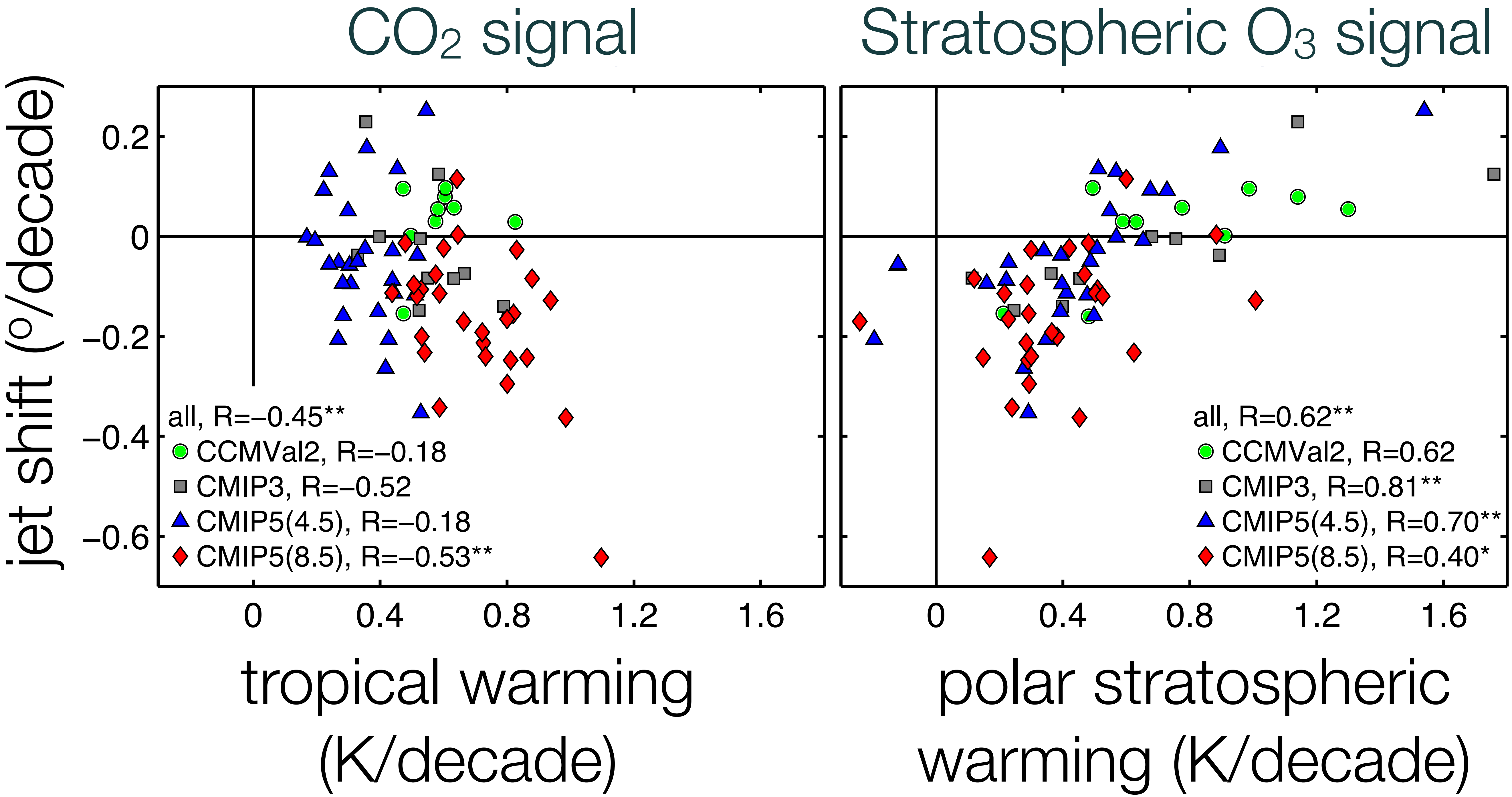

[Gerber and Son 2014]