How should we quantify the role of gravity wave driving in the Brewer-Dobson Circulation?

Edwin Gerber
Courant Institute of Mathematical Sciences, New York University

Sophie Oberlaender (Freie Universität)
Naftali Cohen (Columbia University)
Oliver Buhler (Courant Institute)

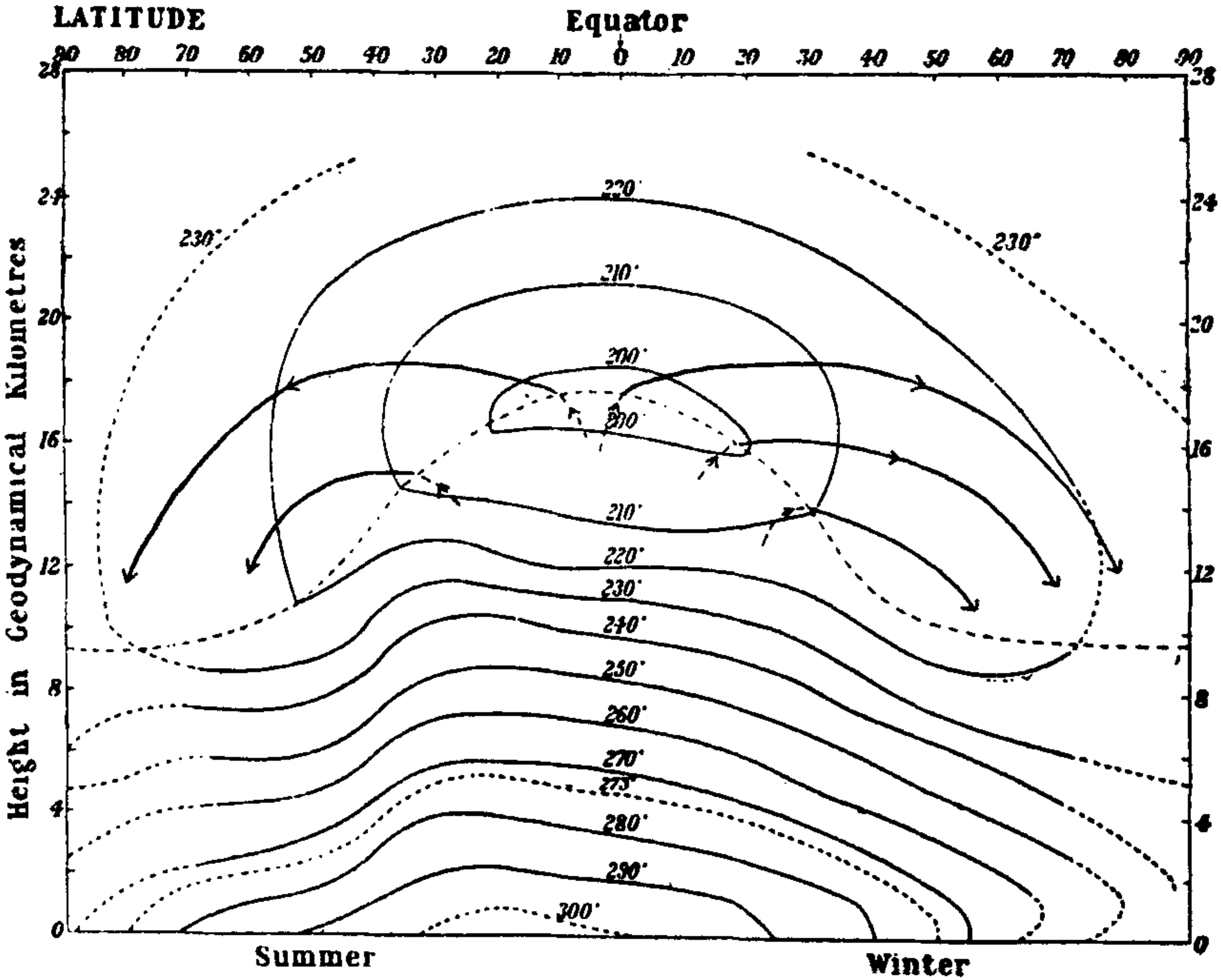
Special thanks to the U.S. National Science Foundation for their support.

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.

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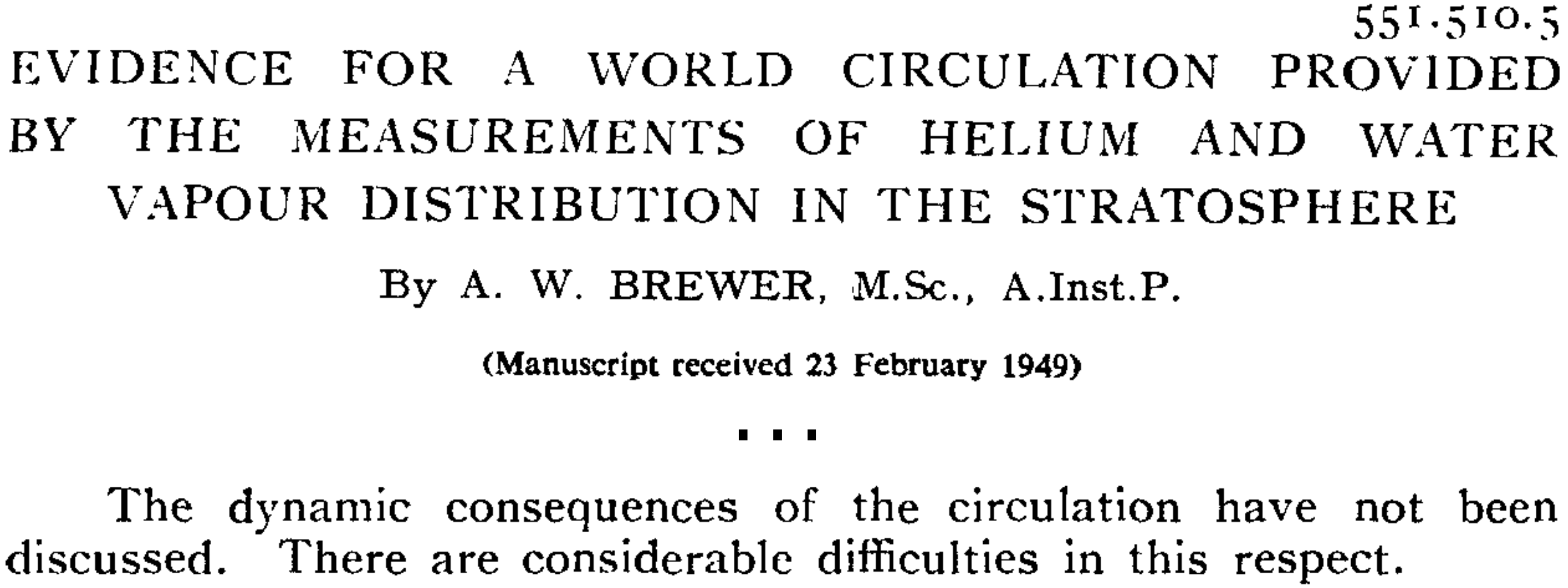

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$$\frac{\partial \overline{u}}{\partial t} - f\overline{v} = -\frac{\partial}{\partial y}\overline{u'v'}$$

overbar denotes zonal mean

prime a deviation therefrom

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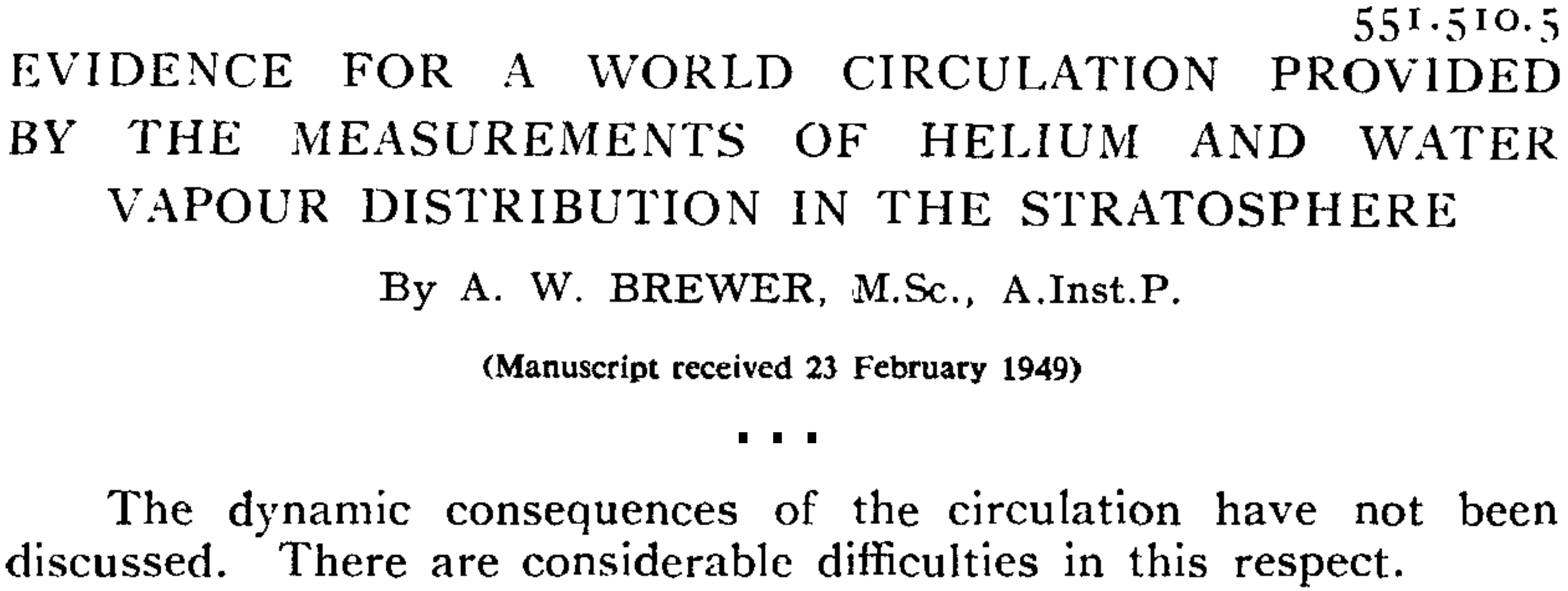
“polar vortex catastrophe”



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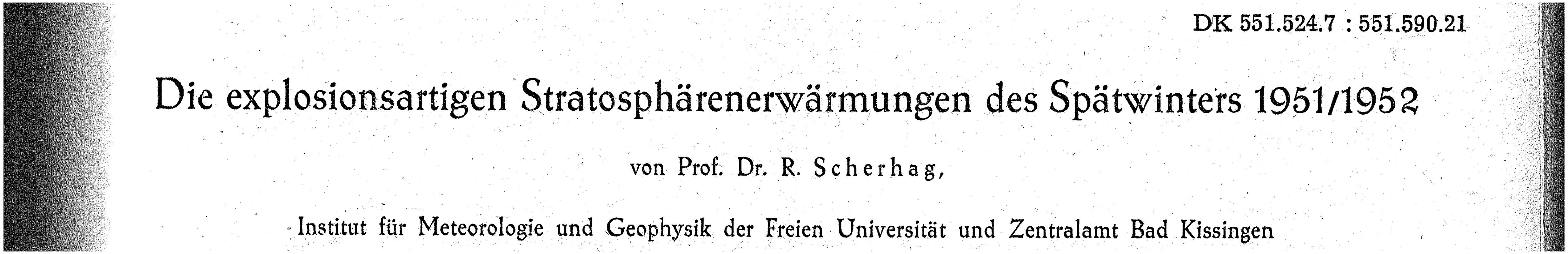


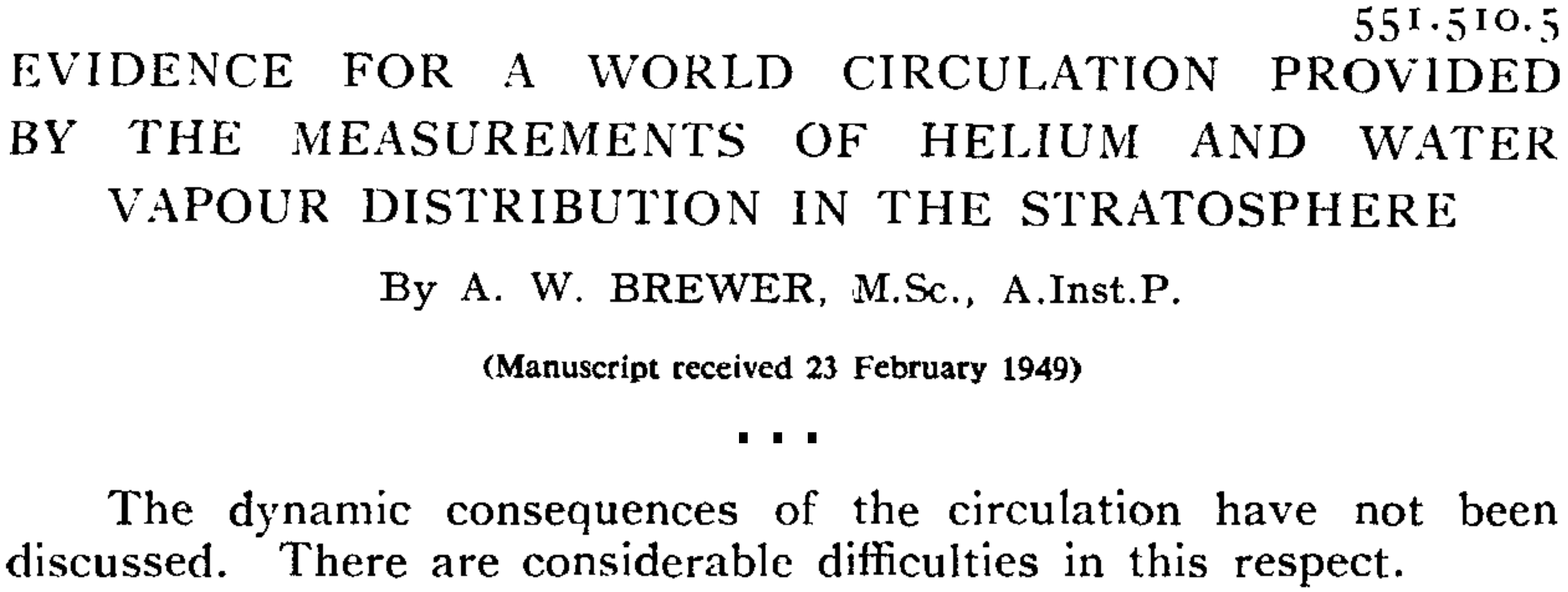
DK 551.524.7 : 551.590.21

Die explosionsartigen Stratosphärenerwärmungen des Spätwinters 1951/1952

von Prof. Dr. R. Scherhag,

Institut für Meteorologie und Geophysik der Freien Universität und Zentralamt Bad Kissingen

(The explosive stratospheric warming of late winter 1951/52)



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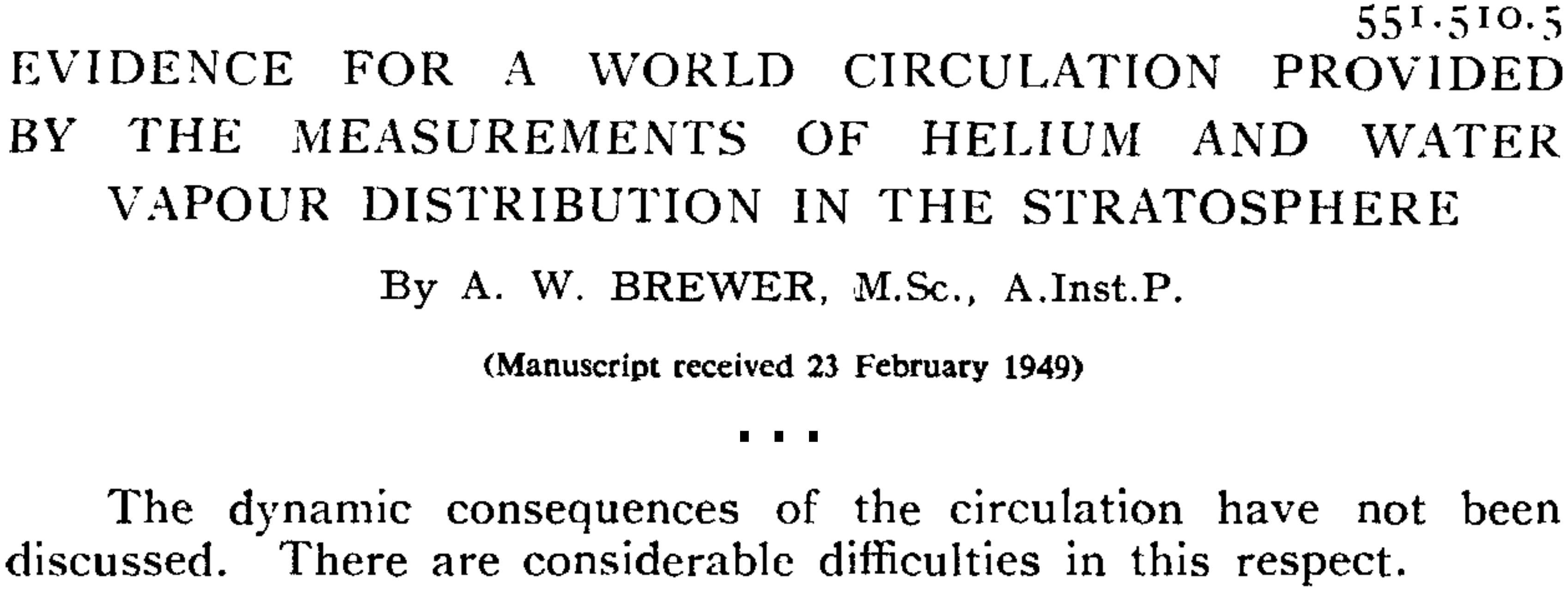
$$\frac{\partial \overline{u}}{\partial t} - f\left(\overline{v} - \frac{\partial}{\partial z}\frac{\overline{v'\theta'}}{\overline{\theta}_z}\right) = \frac{\partial}{\partial y}\left(-\overline{u'v'}\right) + \frac{\partial}{\partial z}\frac{f\overline{v'\theta'}}{\overline{\theta}_z}$$

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?

What drives the Brewer-Dobson Circulation?

For the primitive equations

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

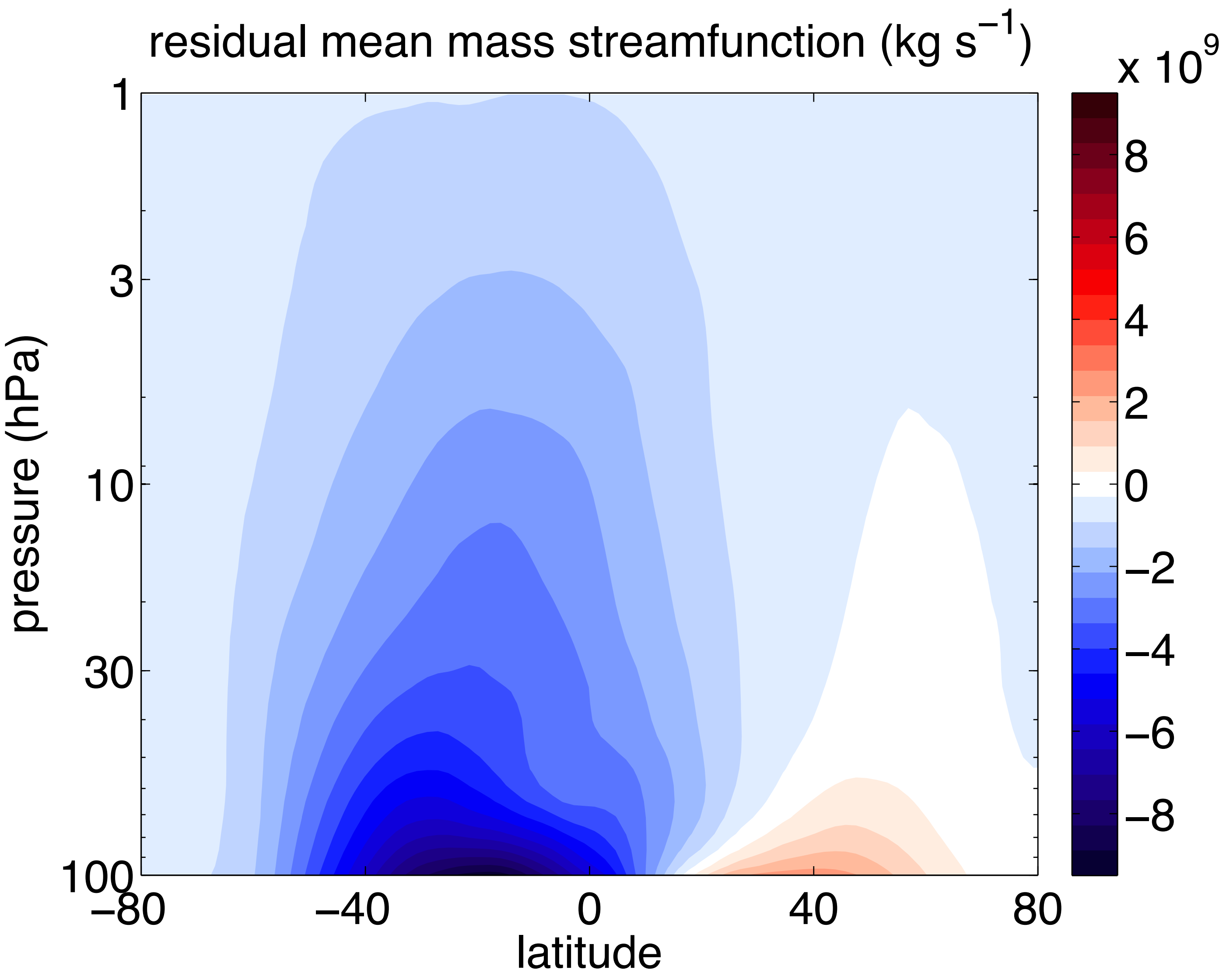
What drives the Brewer-Dobson Circulation?

In models …

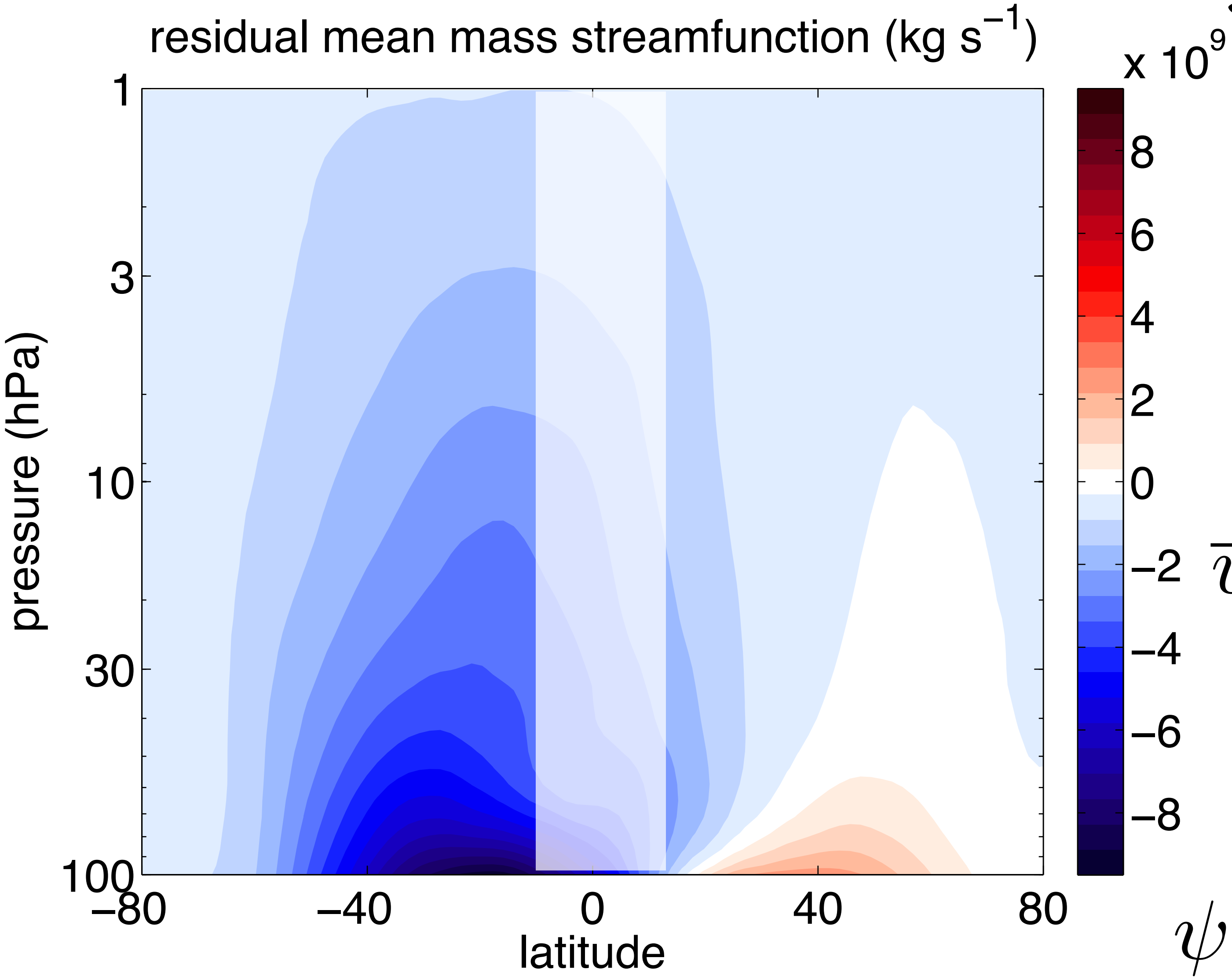
$$\nabla \cdot \mathbf{F} = \frac{\partial}{\partial y}\left[-\overline{u'v'} + \frac{\partial \overline{u}}{\partial z}\frac{\overline{v'\theta'}}{\overline{\theta}_z}\right] + \frac{\partial}{\partial z}\left[\left(f - \frac{\partial \overline{u}}{\partial y}\right)\frac{\overline{v'\theta'}}{\overline{\theta}_z}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

$$+ G_{OGW} + G_{NOGW}$$

The JJA Residual Circulation in ECHAM6



The JJA Residual Circulation in ECHAM6



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

↓

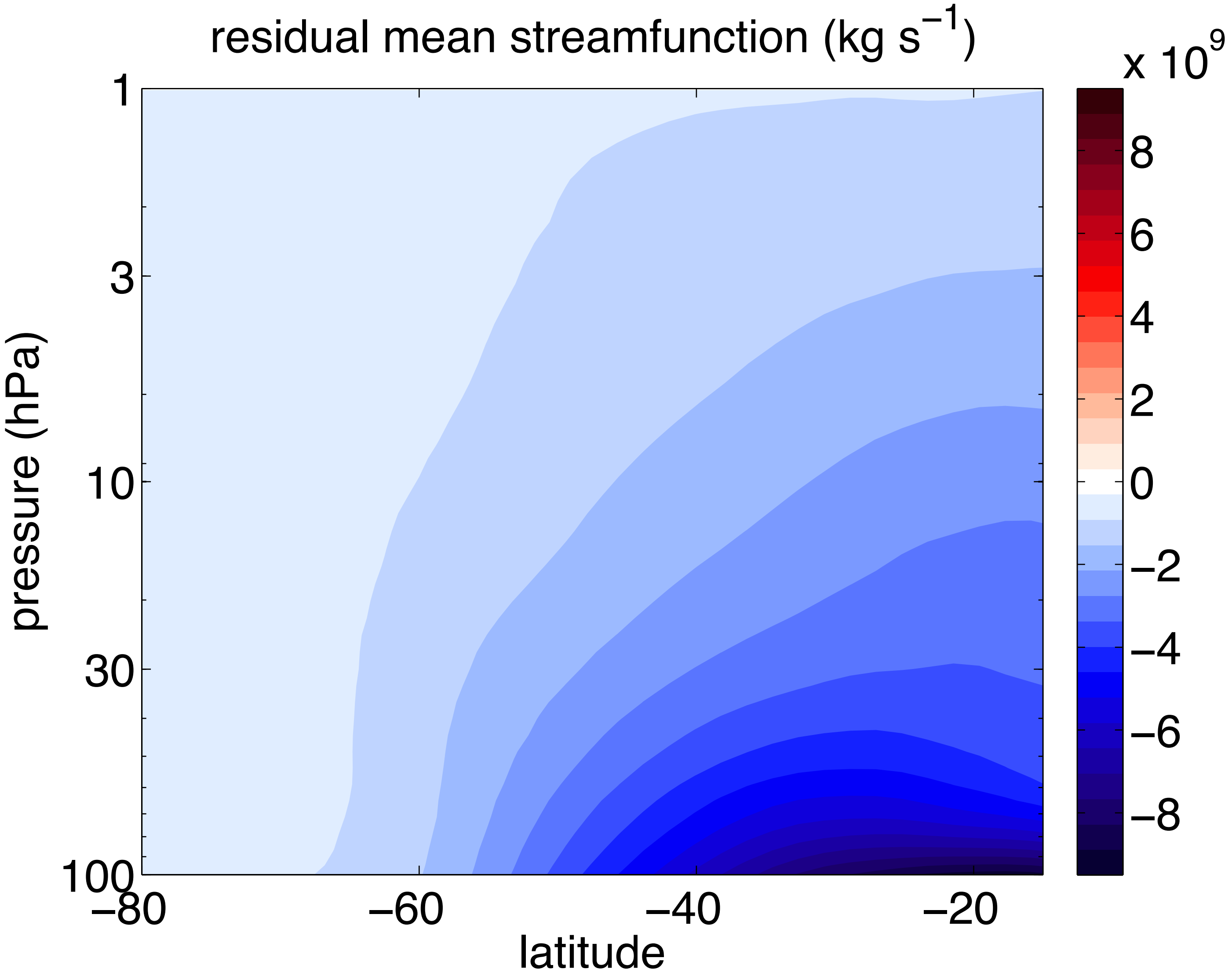
downward control

$$\overline{v}^* = \overline{v}^*_{EPFD} + \overline{v}^*_{OGW} + \overline{v}^*_{NOGW}$$

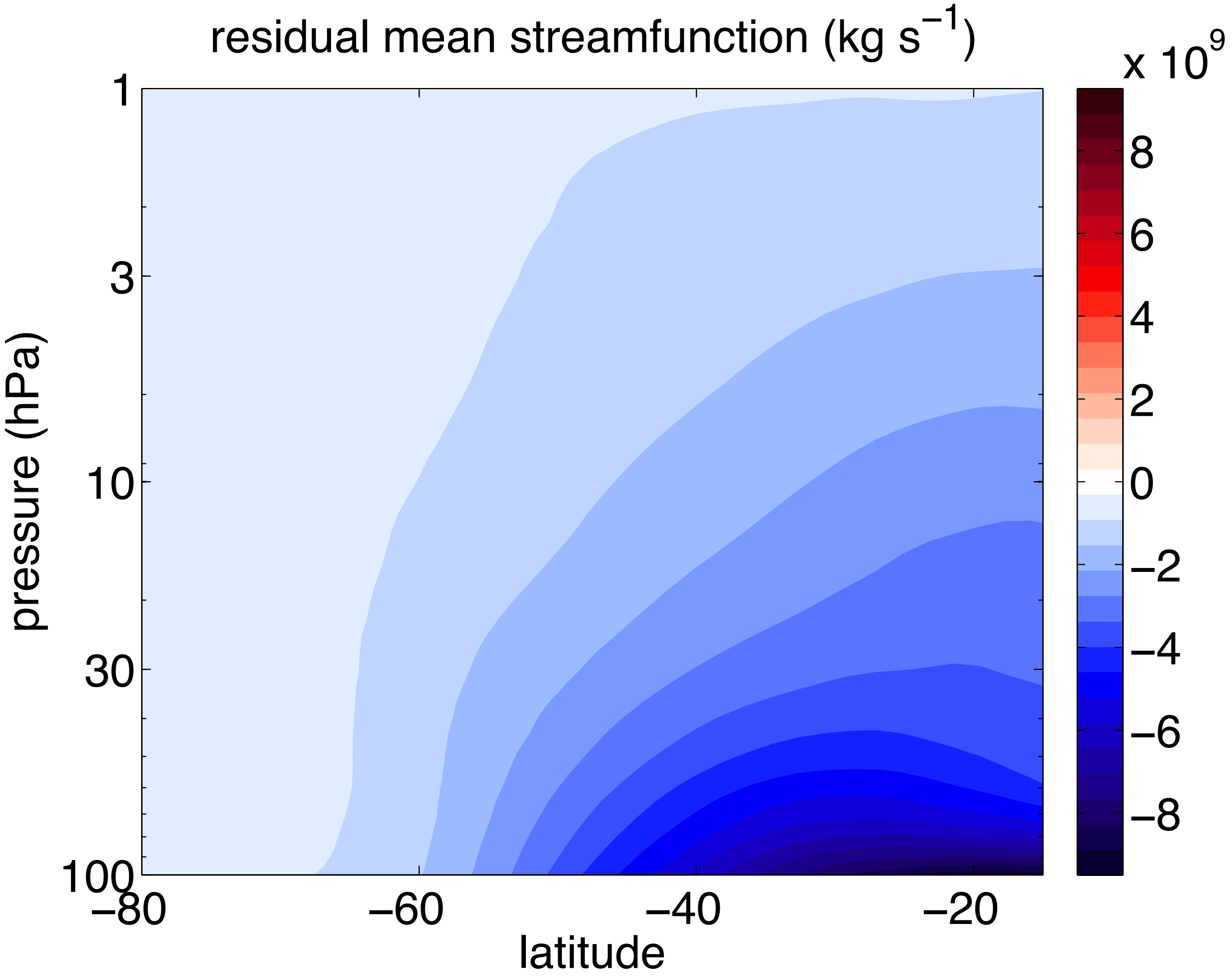
↓

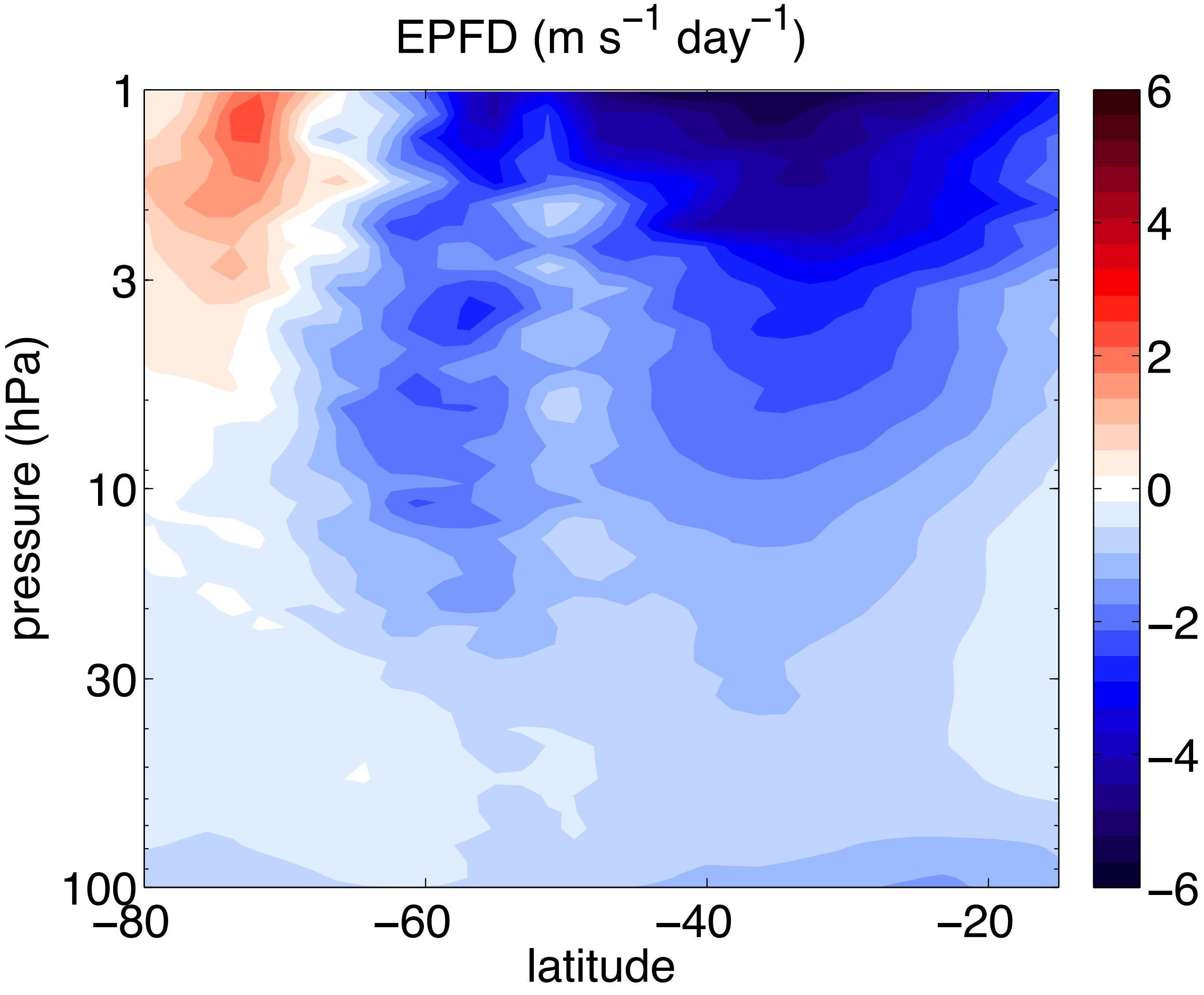
$$\psi^* = \psi^*_{EPFD} + \psi^*_{OGW} + \psi^*_{NOGW}$$

Breaking down the streamfunction



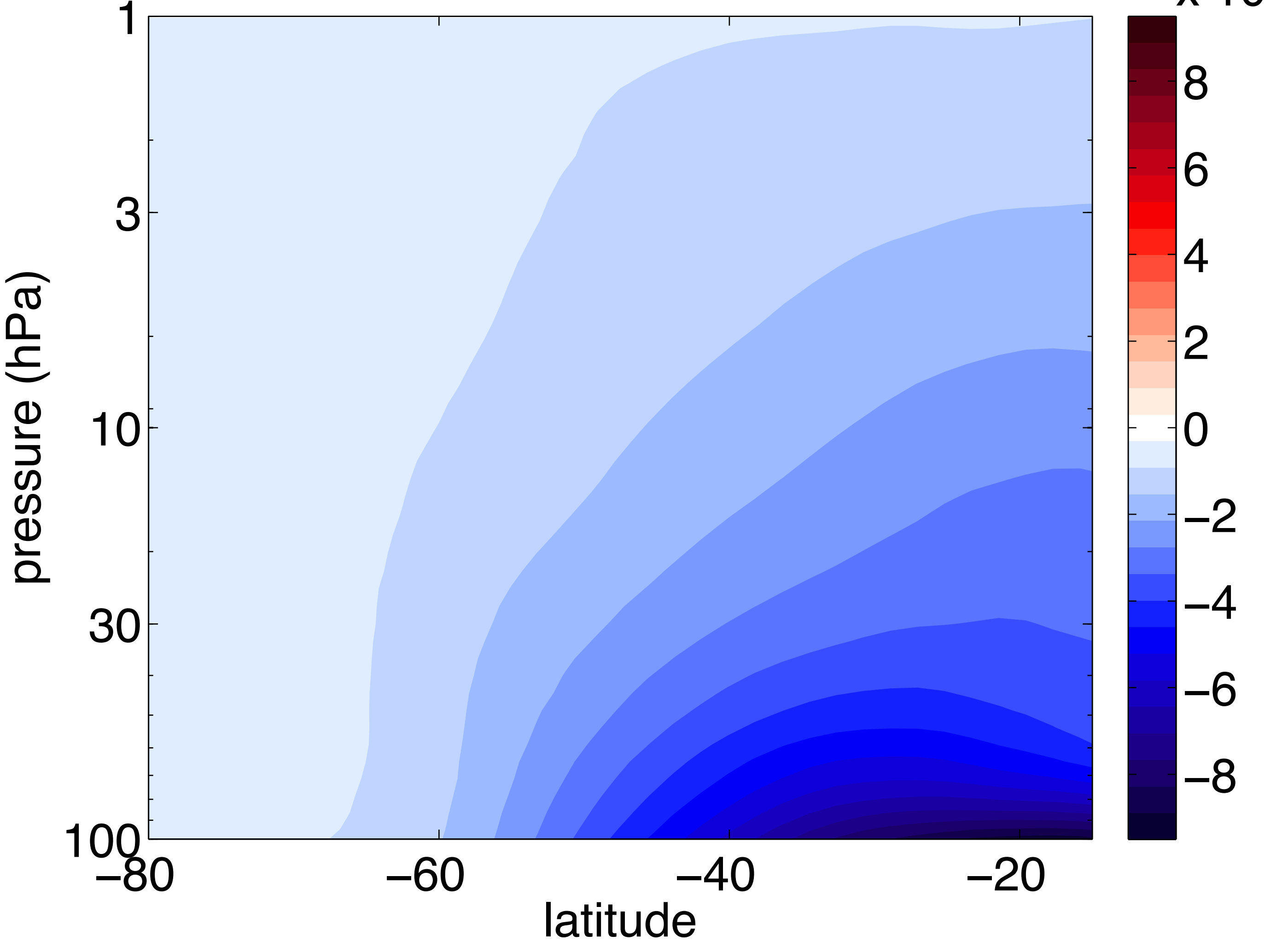
Breaking down the streamfunction



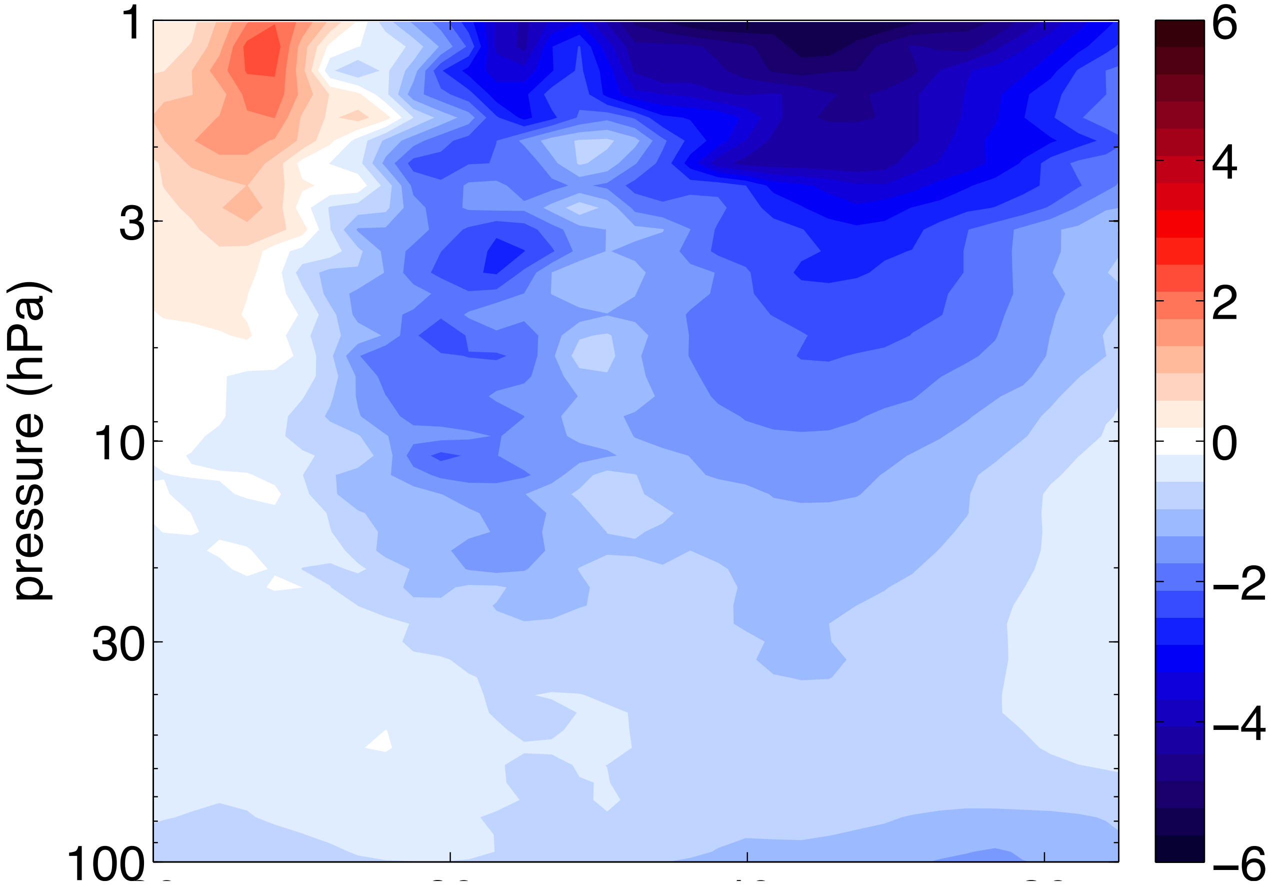


Breaking down the streamfunction

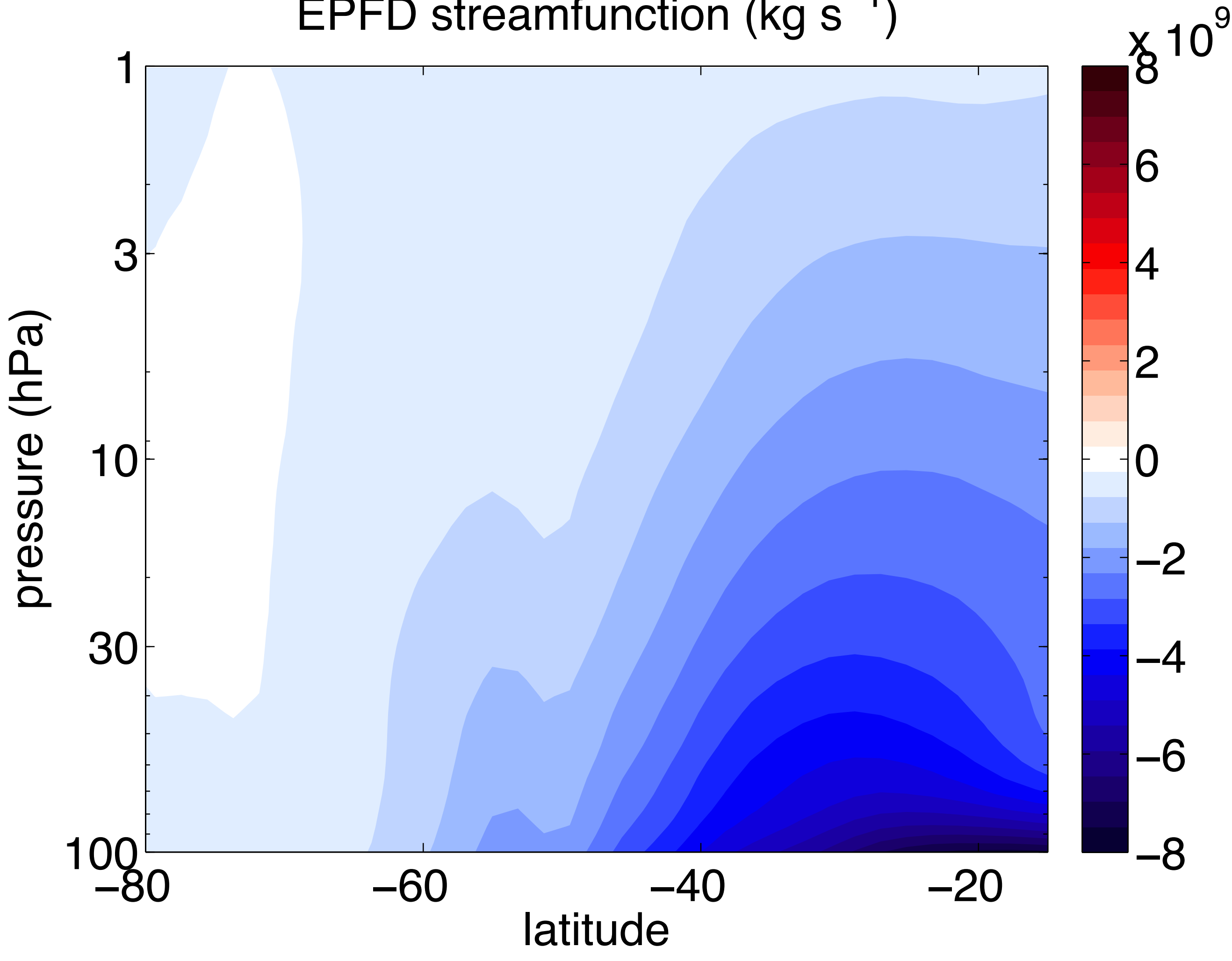
residual mean streamfunction (kg s^{-1})



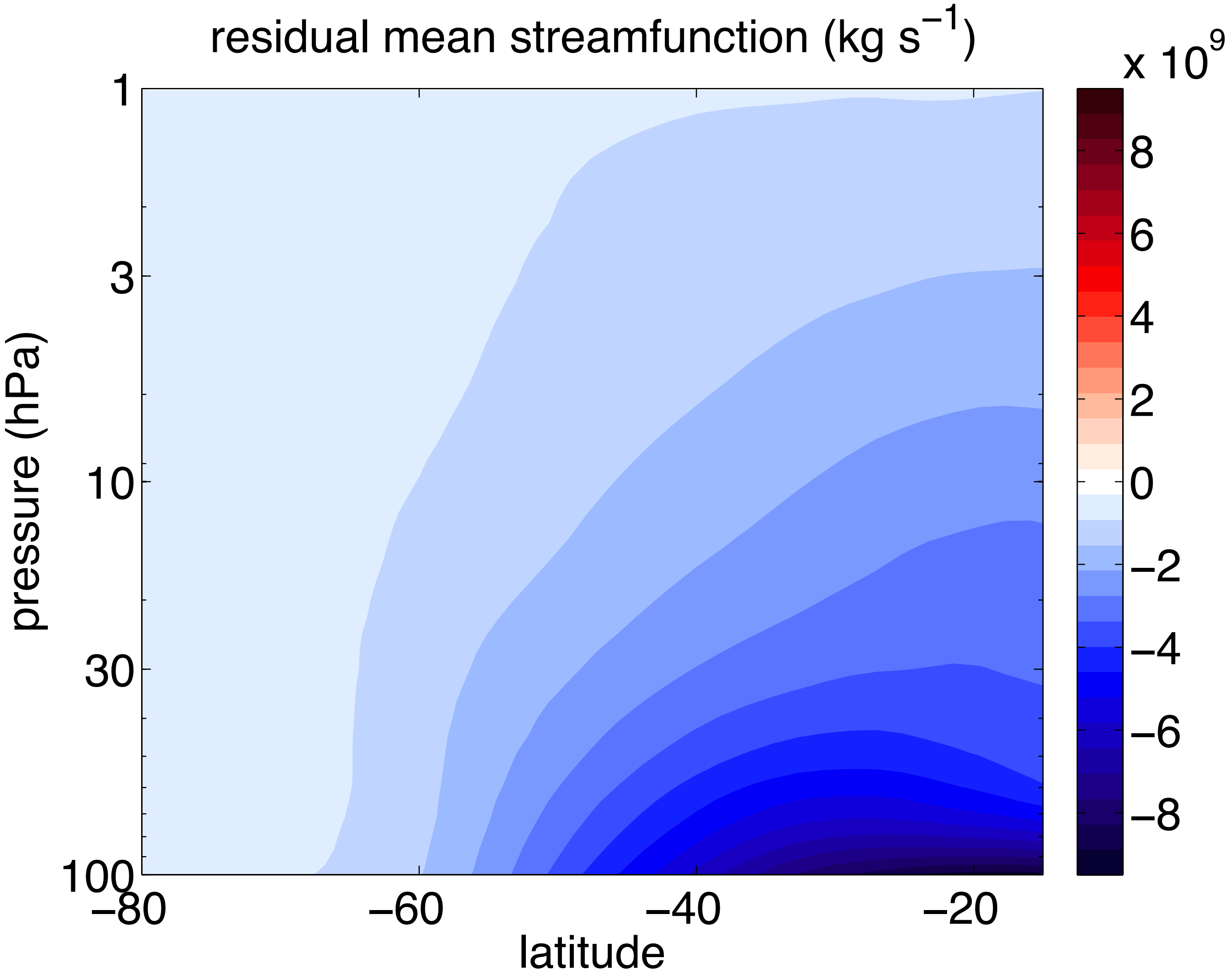
EPFD (m s^{-1} day^{-1})



EPFD streamfunction (kg s^{-1})



Breaking down the streamfunction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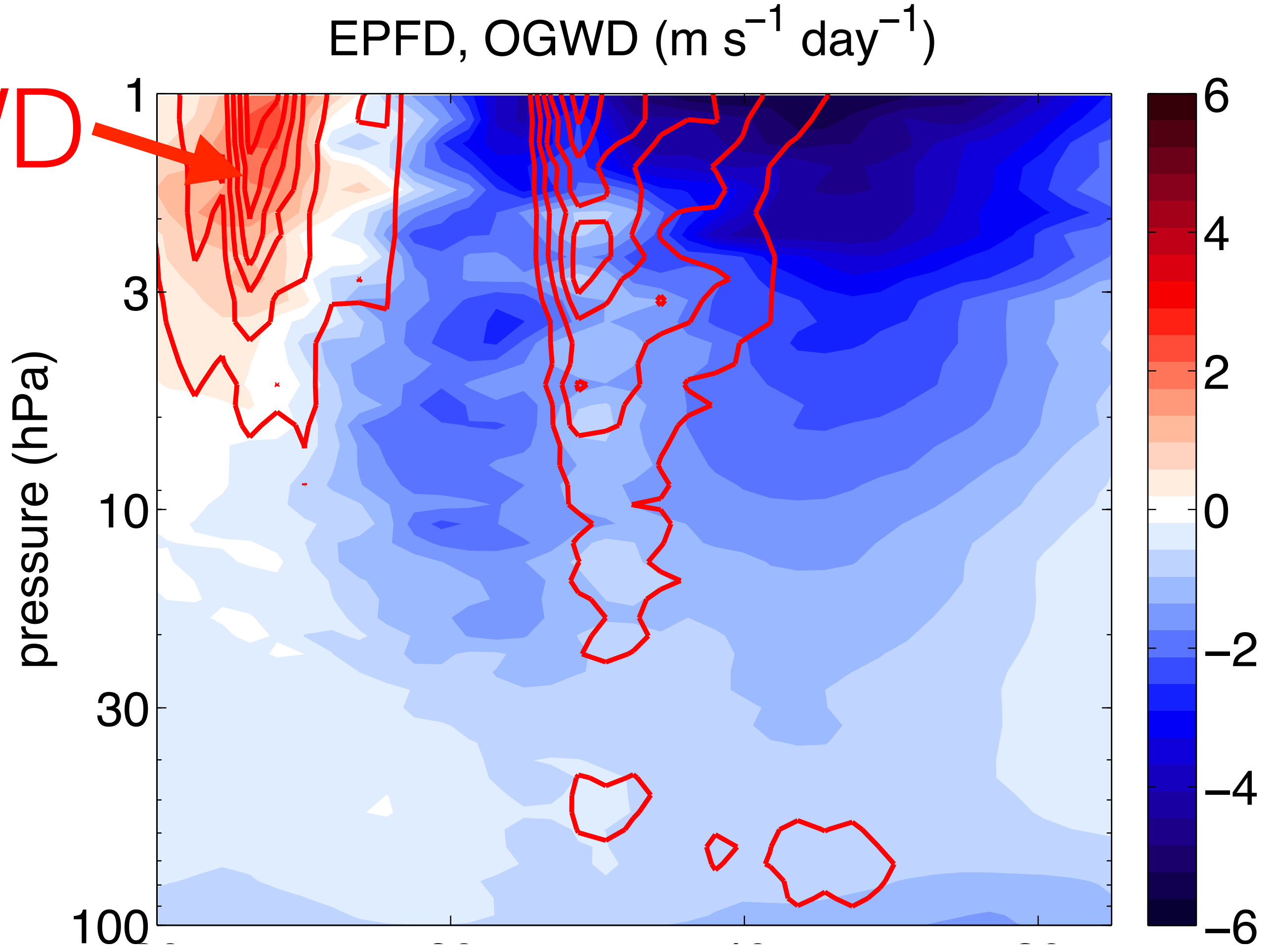
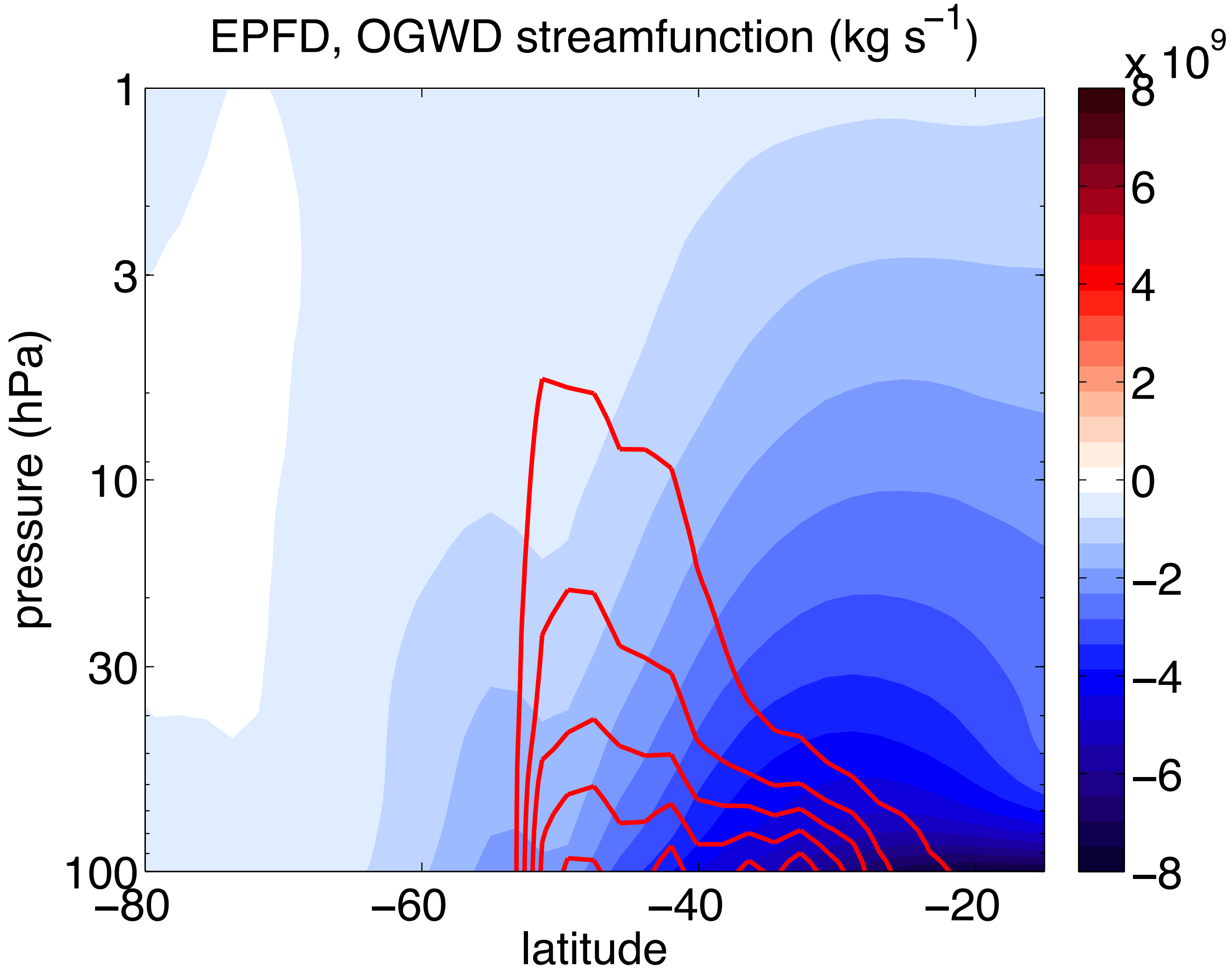
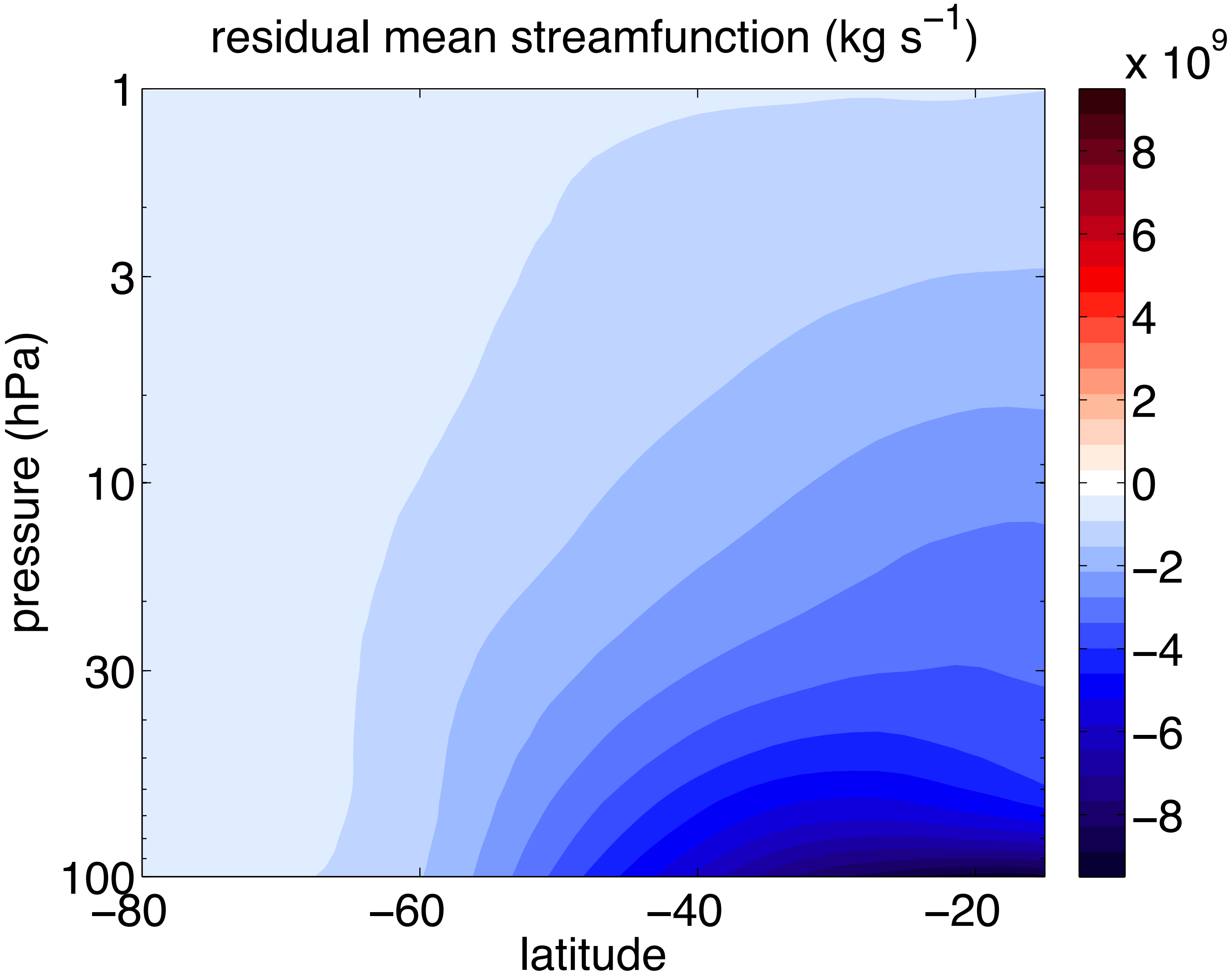

EPFD, OGWD (m s^{-1} day^{-1})

OGWD

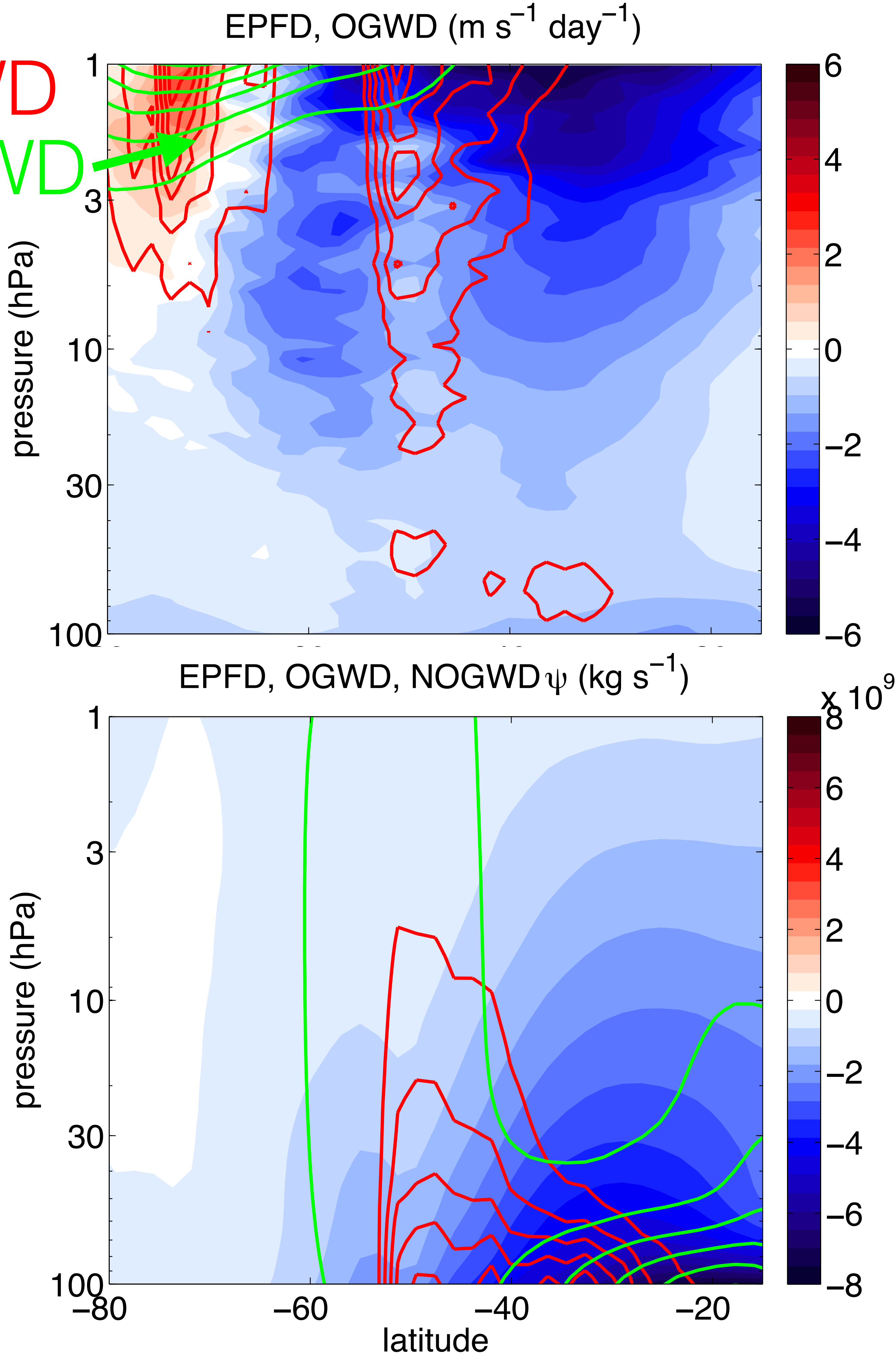

EPFD, OGWD streamfunction (kg s^{-1})

Breaking down the streamfunction


residual mean streamfunction (kg s^{-1})

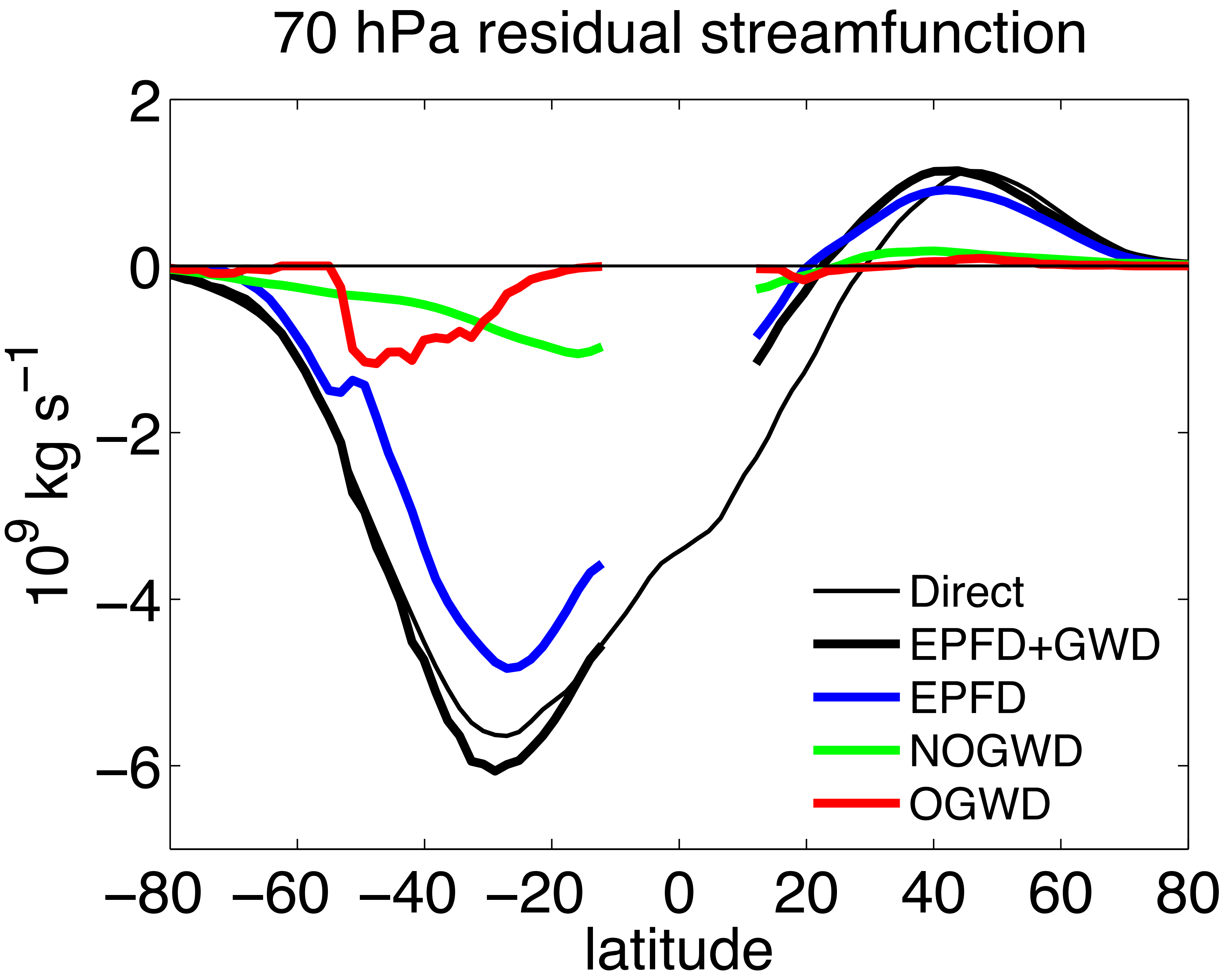
OGWD

NOGWD

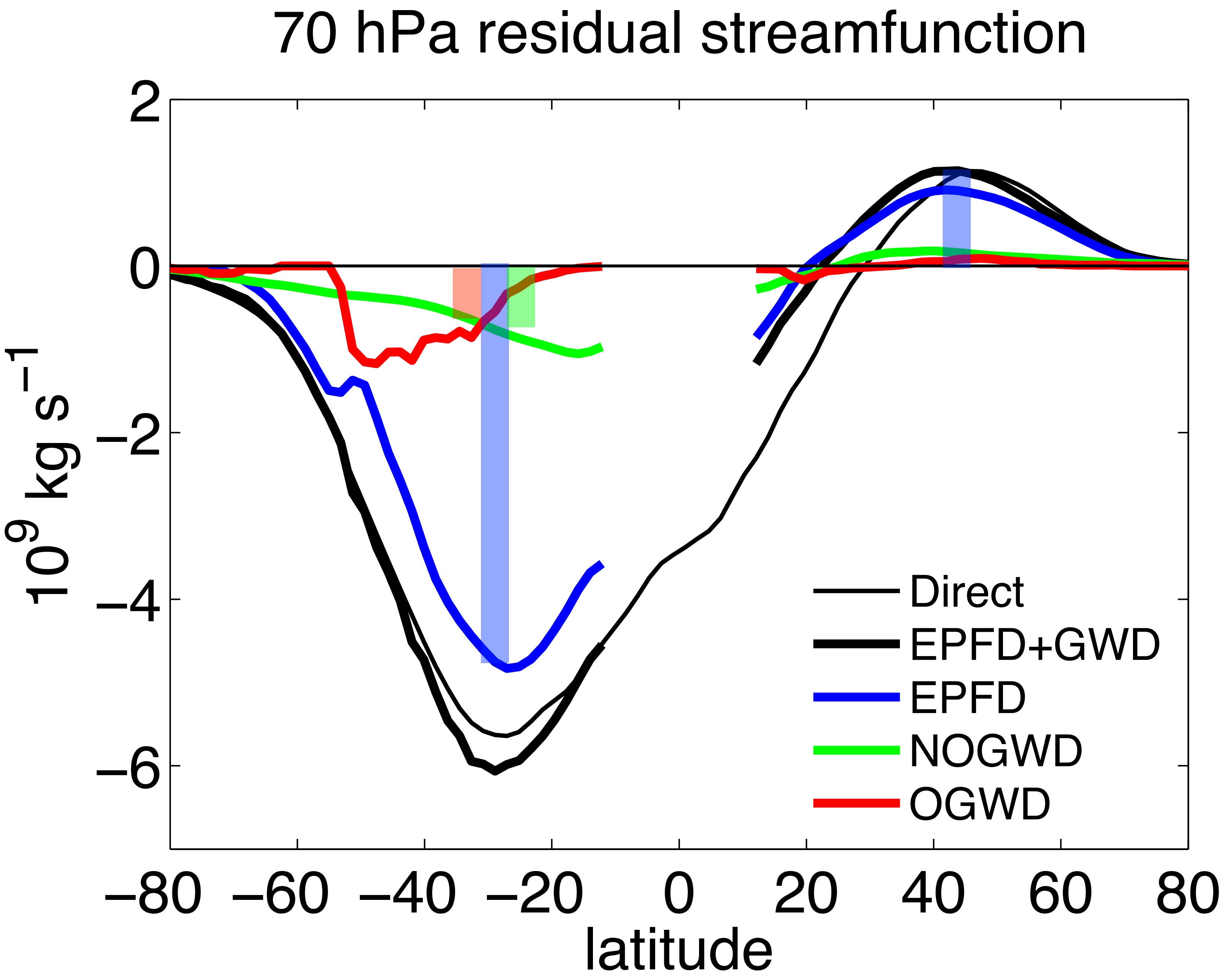

EPFD, OGWD (m s^{-1} day^{-1})

EPFD, OGWD, NOGWD ψ (kg s^{-1})

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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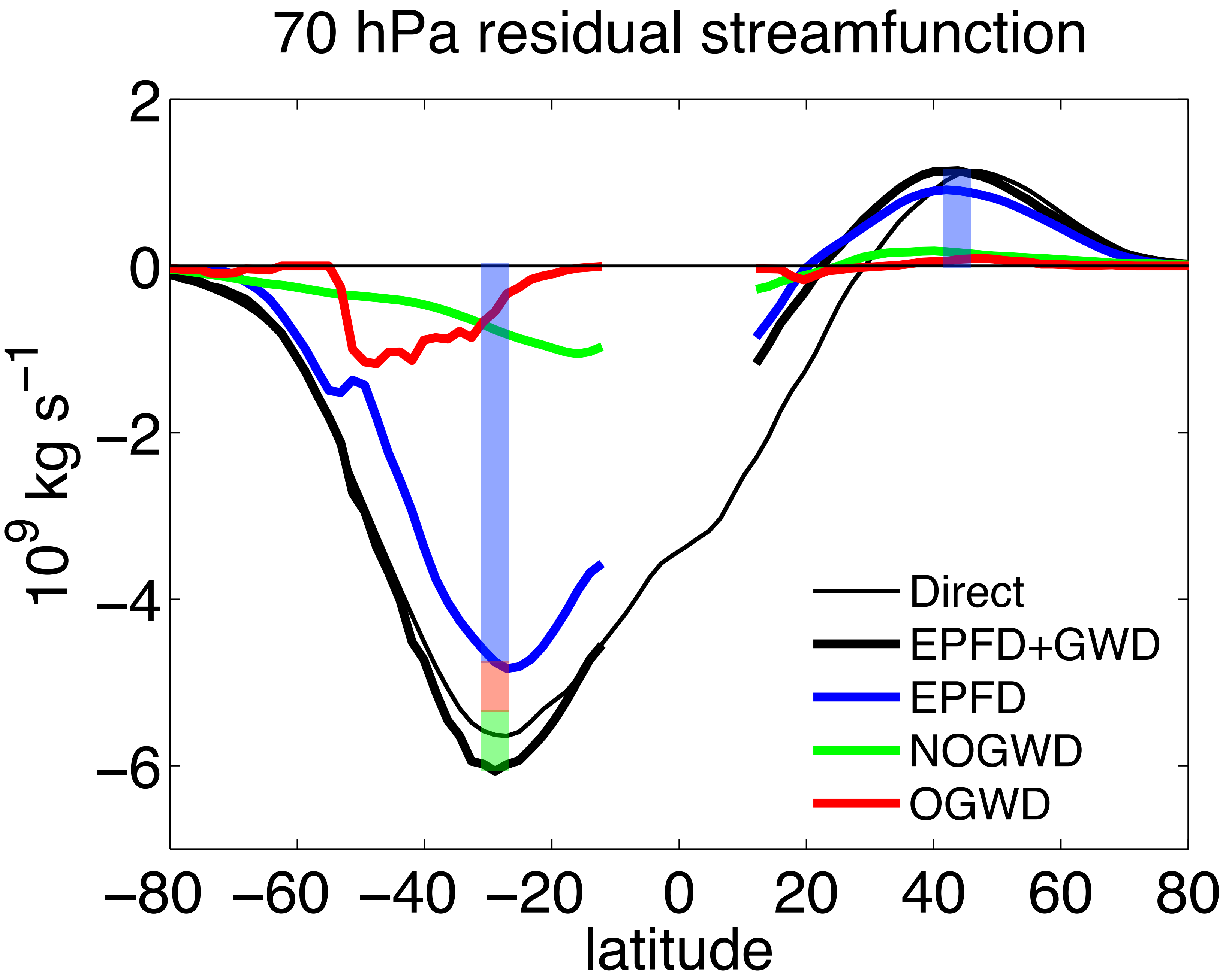
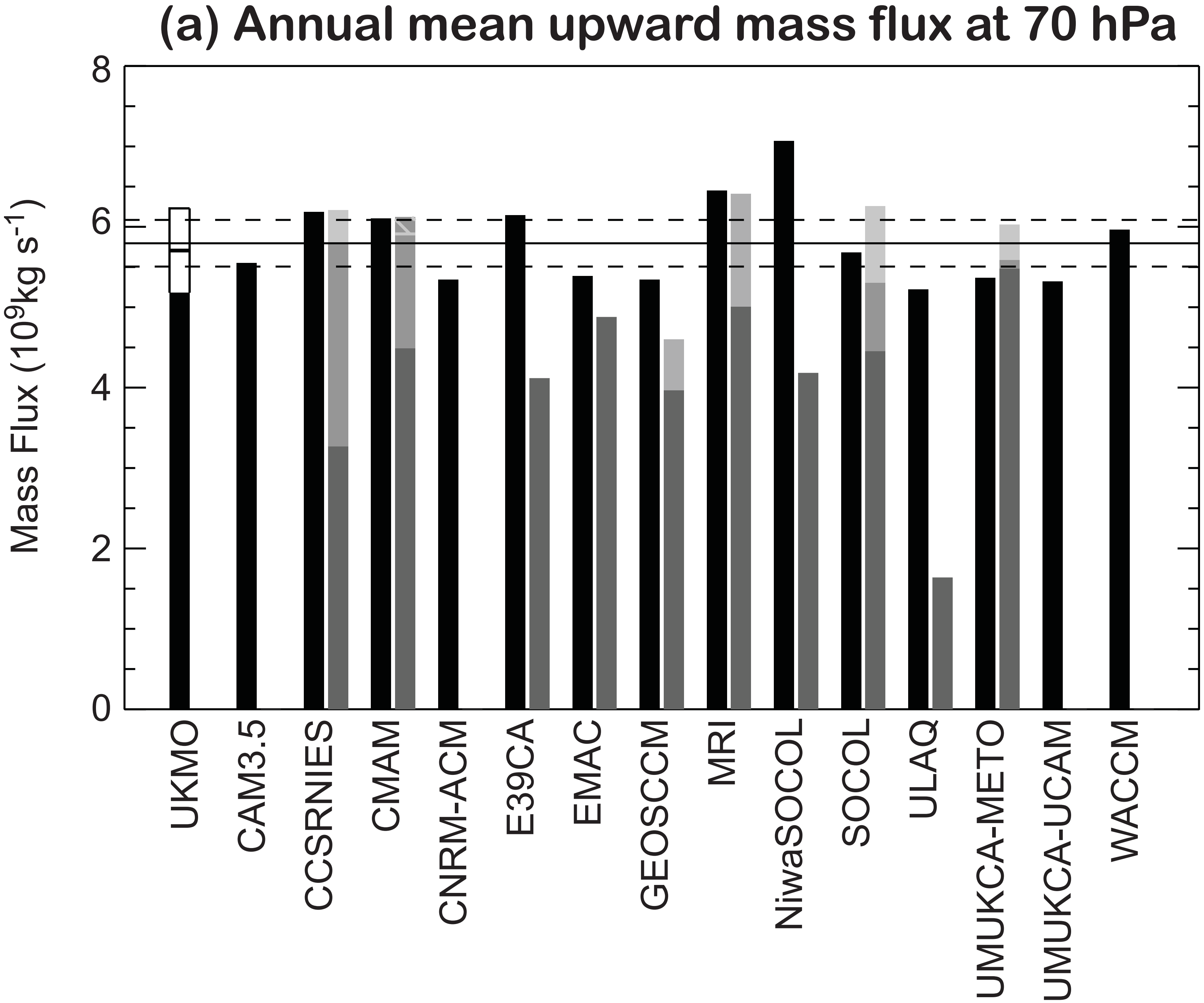


What drives the Brewer-Dobson Circulation?



total

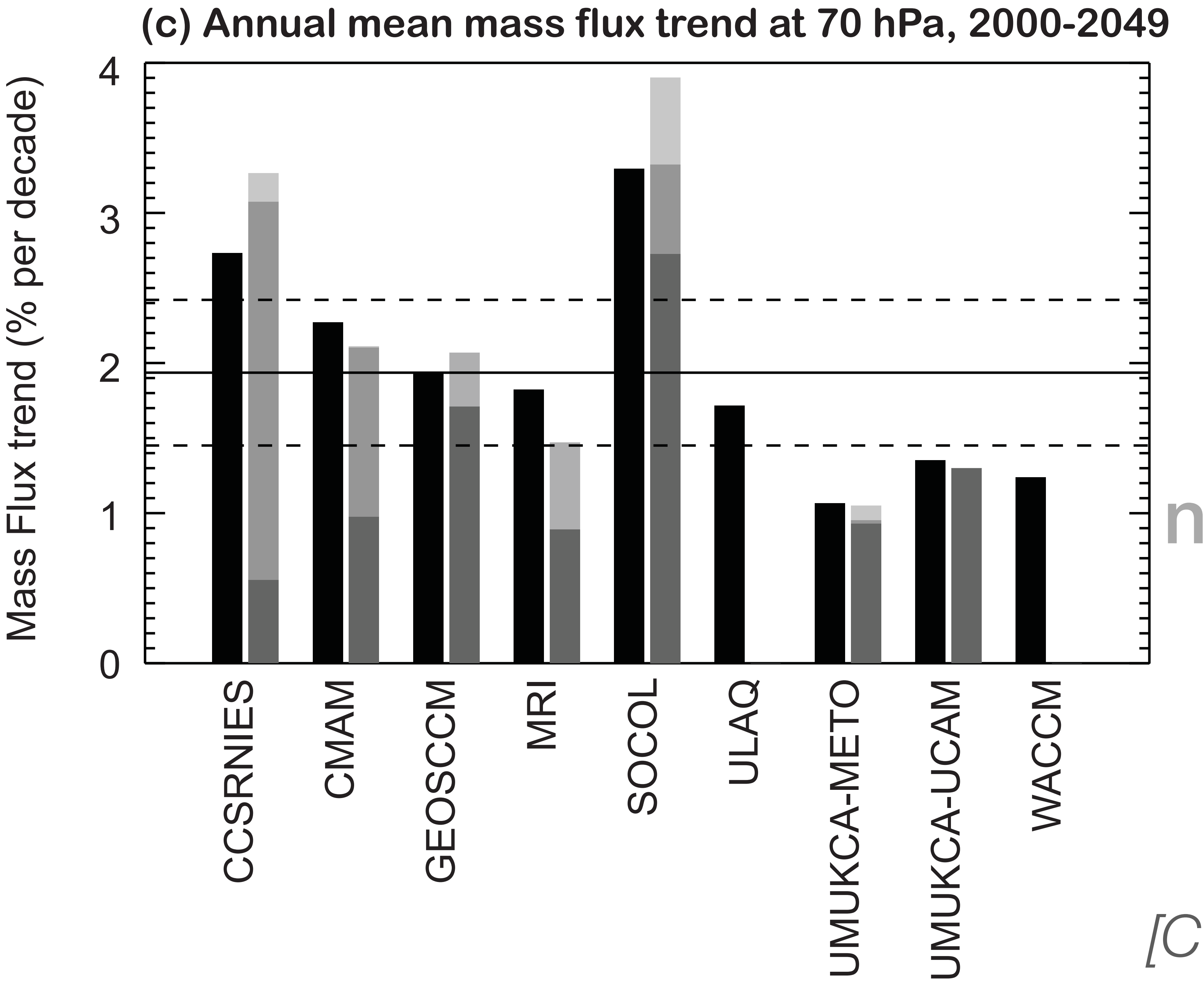
Rossby waves

orographic GW

non-orographic GW

[CCMVal2 Report, Chpt 4]

What drives change in the Brewer-Dobson Circulation?



total

Rossby waves

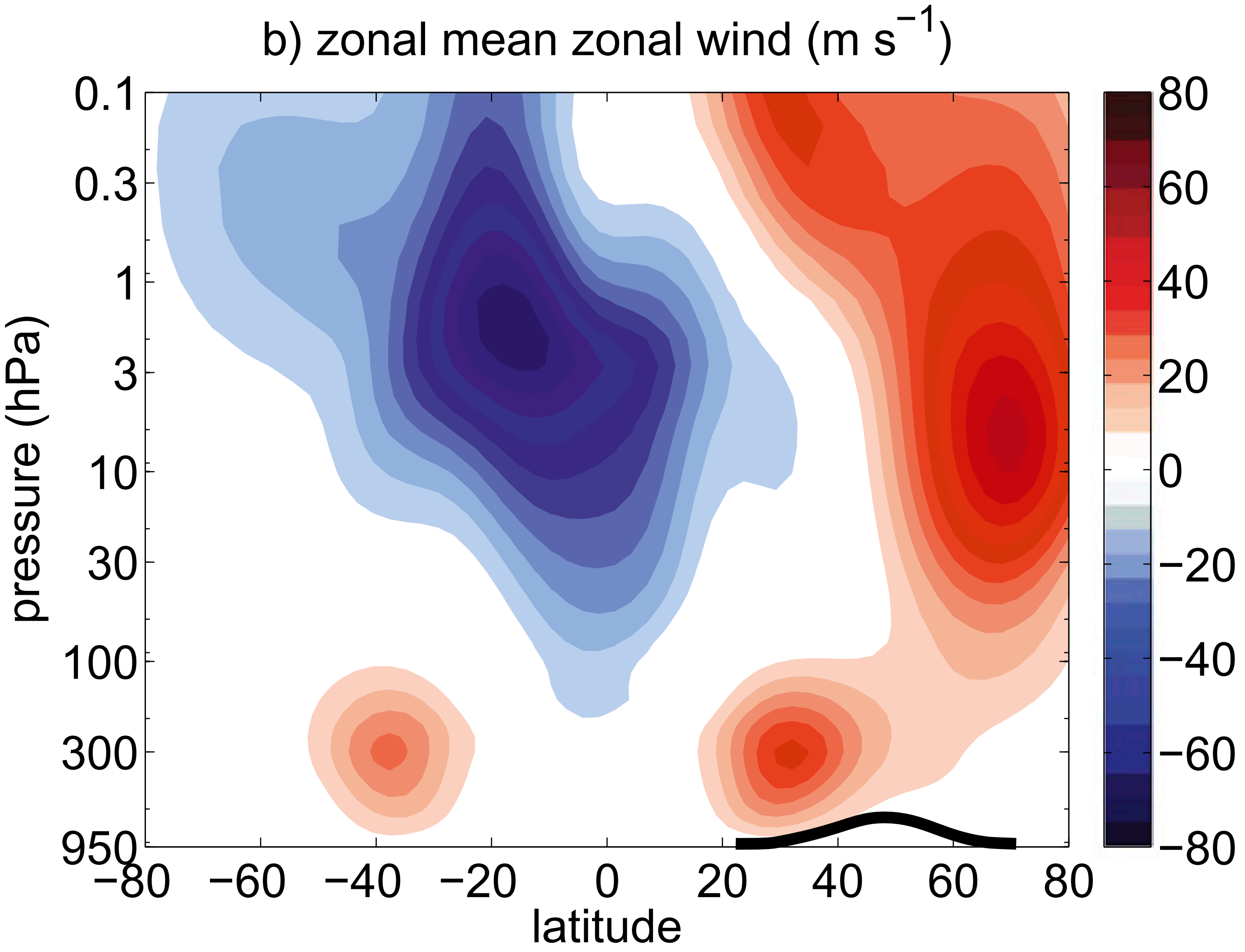
orographic GW

non-orographic GW

[CCMVal2 Report, Chpt 4]

What "drives" the BDC? Experiments with an idealized GCM

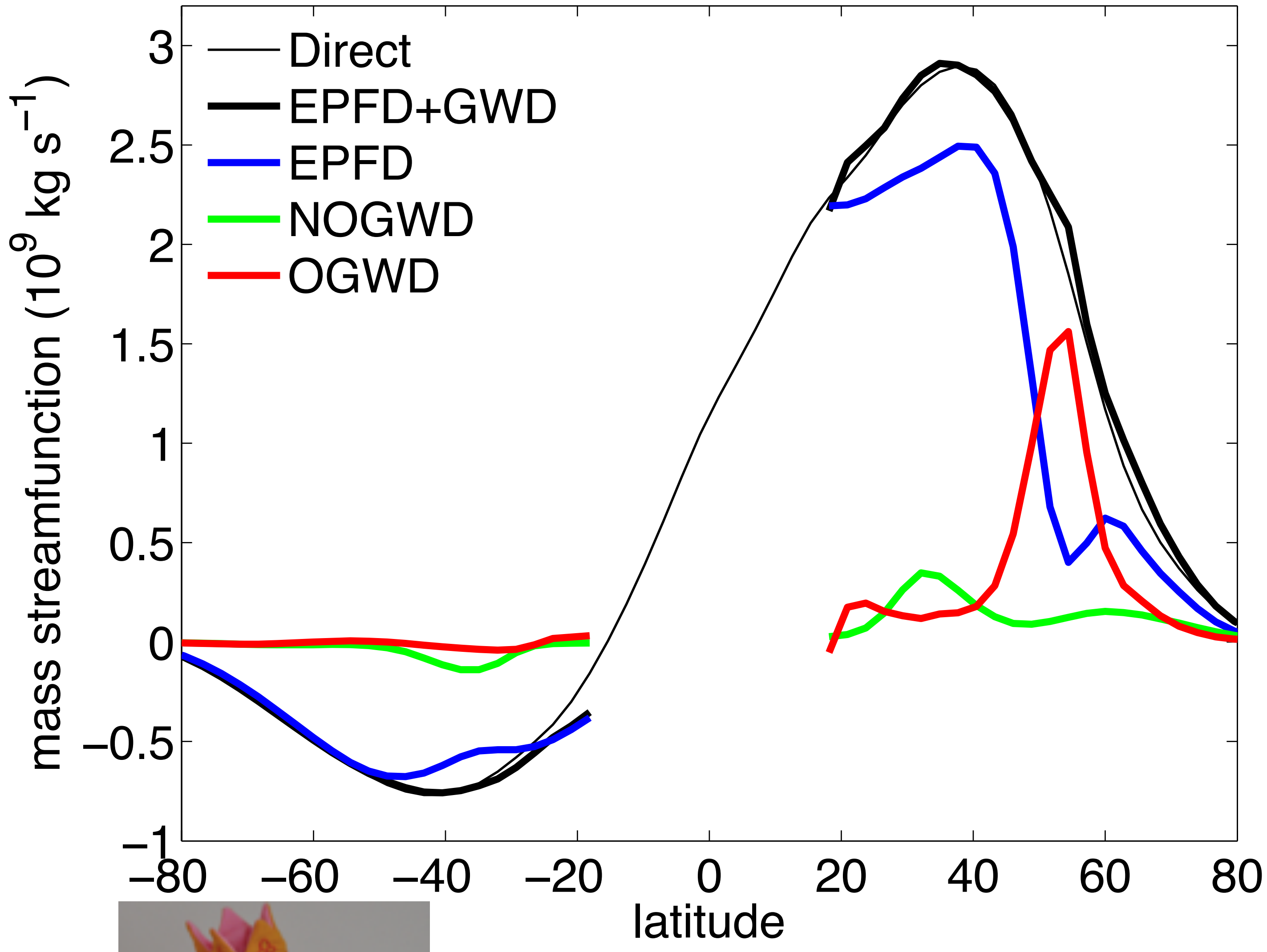
- dry primitive equations on the sphere
- Newtonian relaxation of temperature to radiative-convective equilibrium profile *[Held and Suarez 1994; Polvani and Kushner 2002]*
- Simple large scale topography *[Gerber and Polvani, 2009]*
- *Alexander and Dunkerton [1999]* non-orographic gravity wave drag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

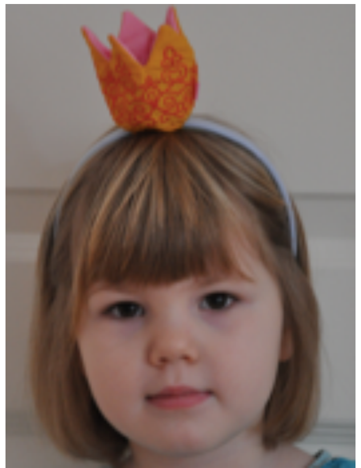


[Cohen et al. 2013]

What “drives” the BDC?
Experiments with an idealized GCM

Residual Mean Streamfunction at 70 hPa



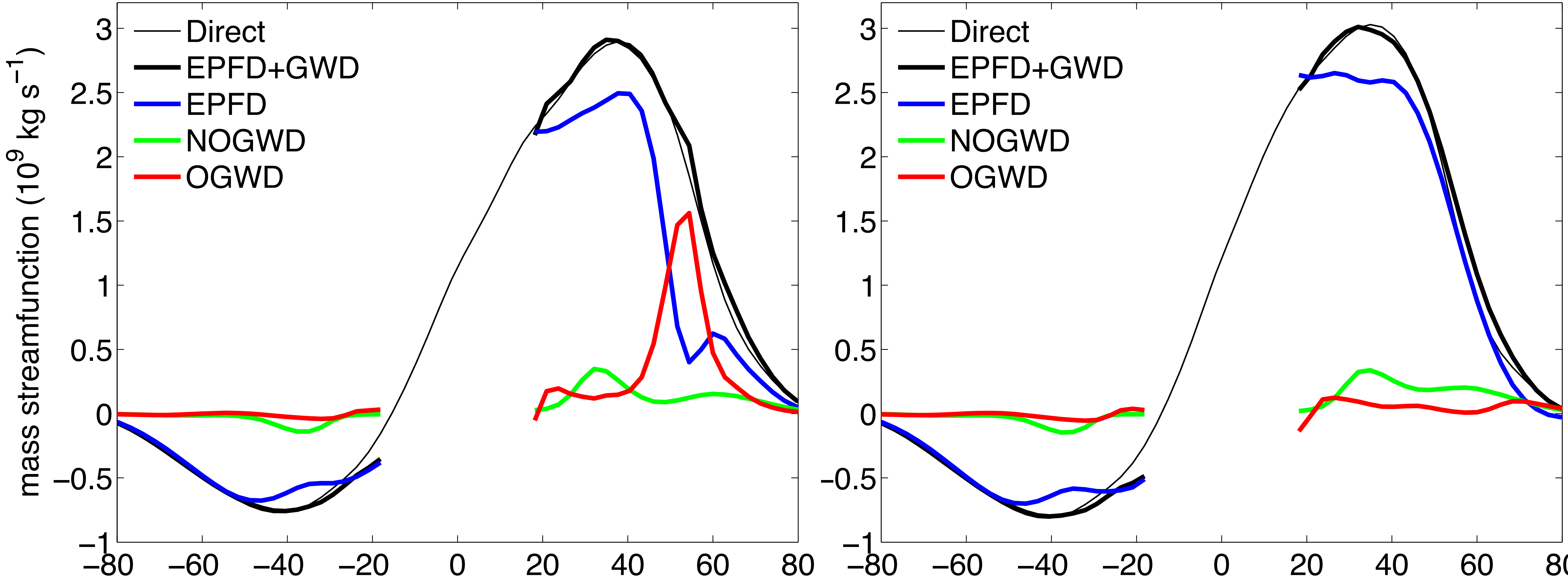


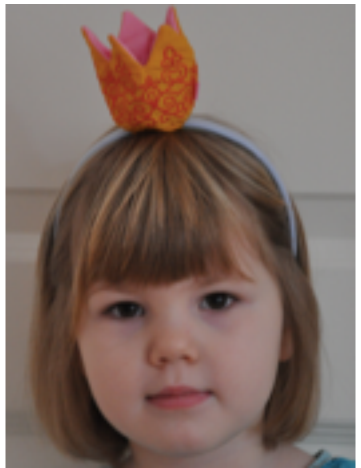
Model A

[Cohen et al. 2013]

What “drives” the BDC?
Experiments with an idealized GCM

Residual Mean Streamfunction at 70 hPa





Model A

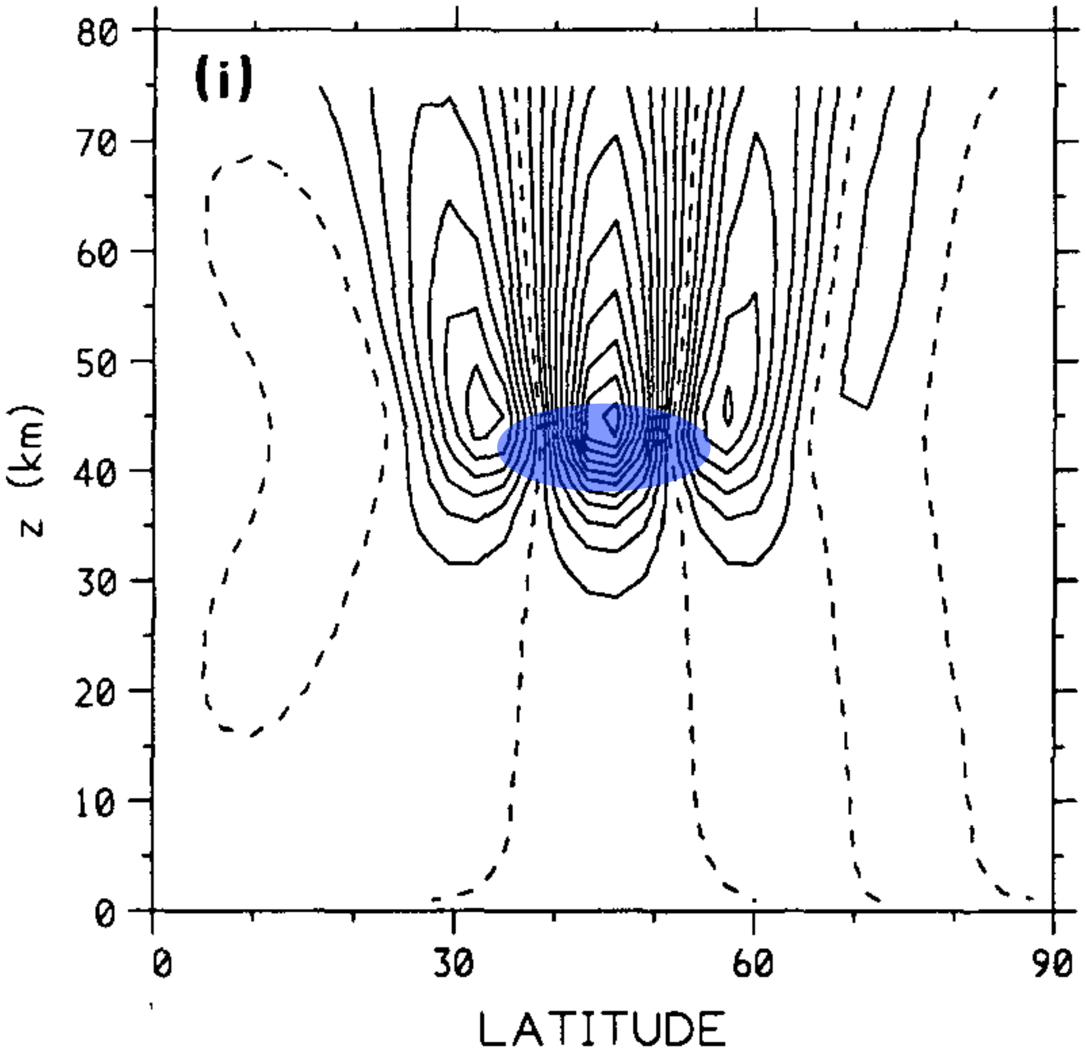
Model B

[Cohen et al. 2013]

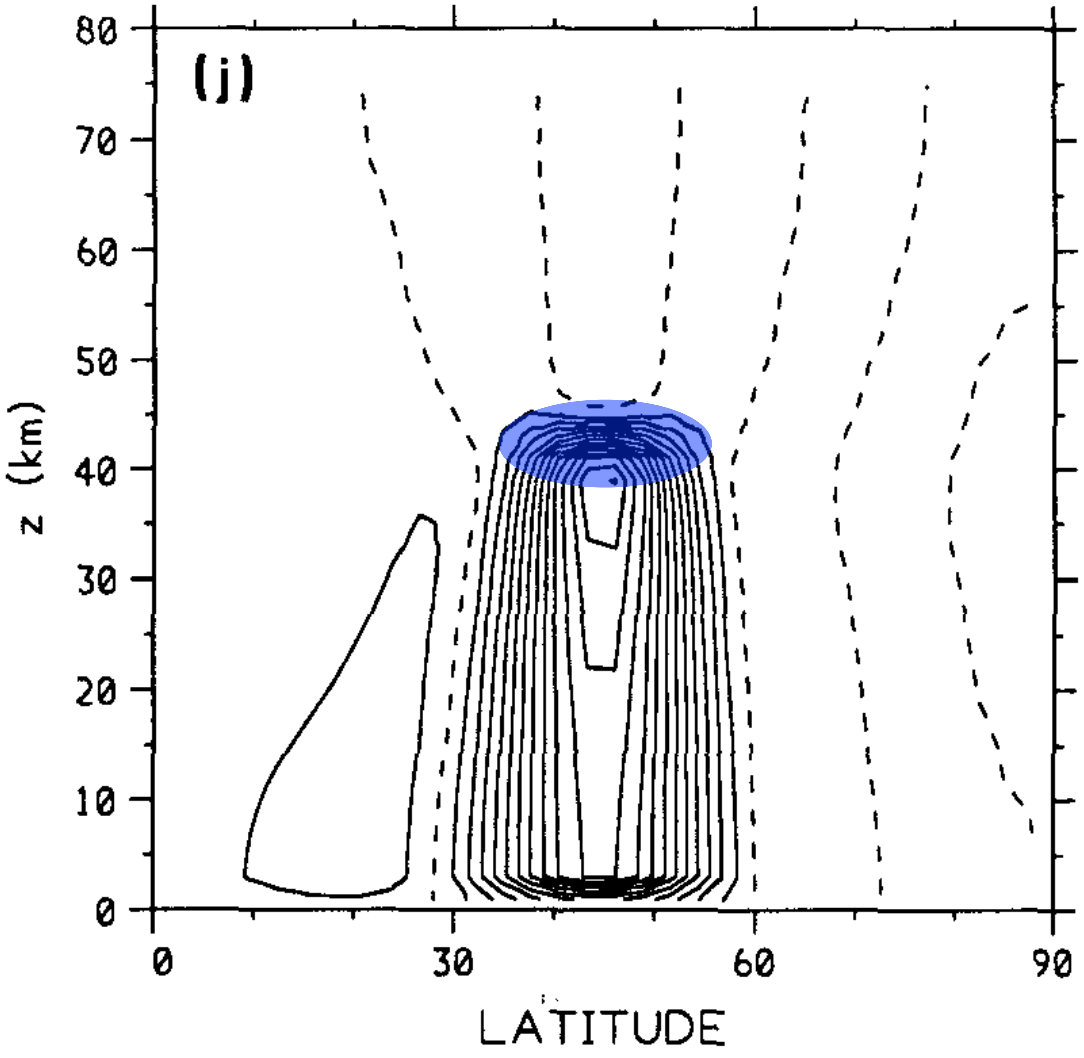
What is going on here?

Back to Basics: Haynes et al. 1991
(Near) steady response to a localized torque

zonal wind



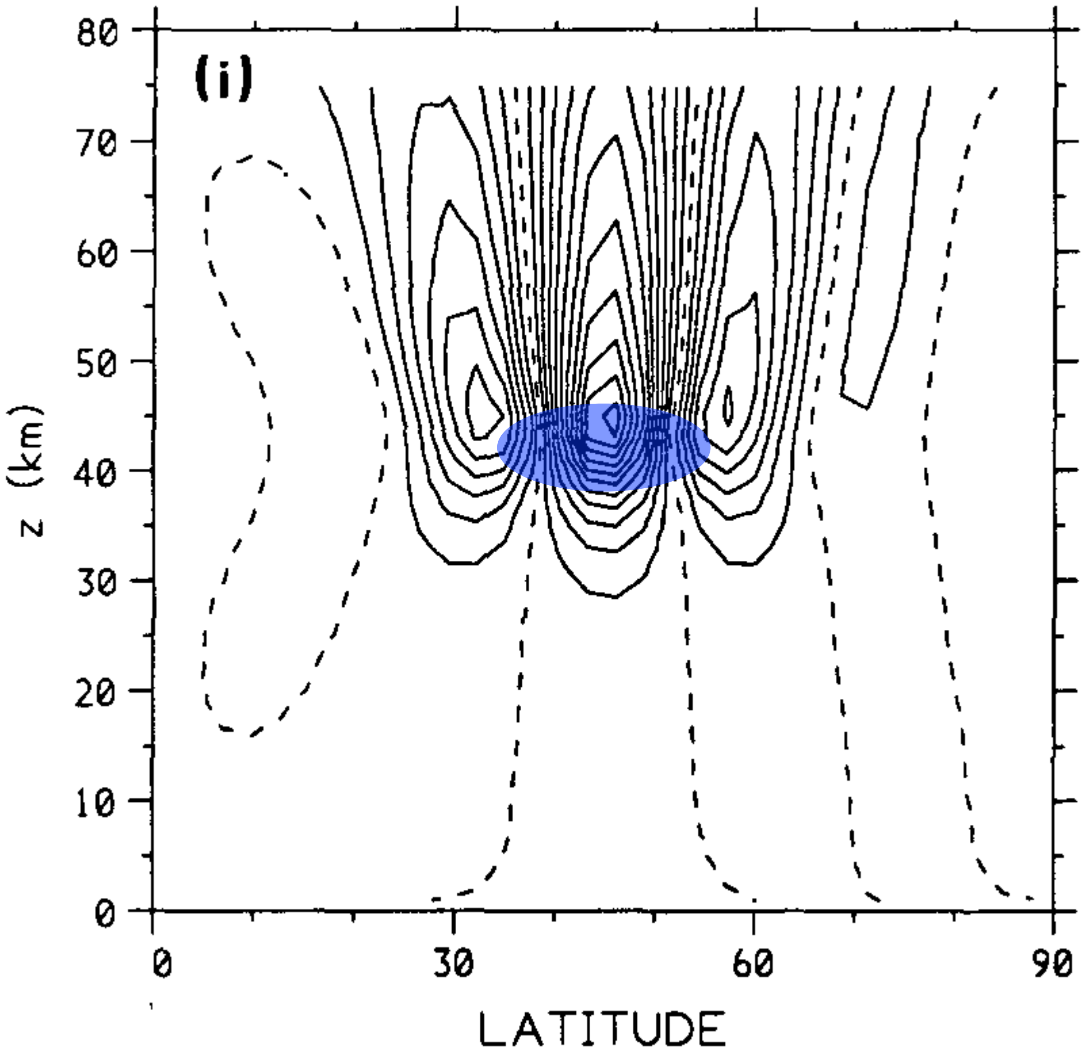
streamfunction ψ



For what torques is the circulation reasonable?

---

zonal wind

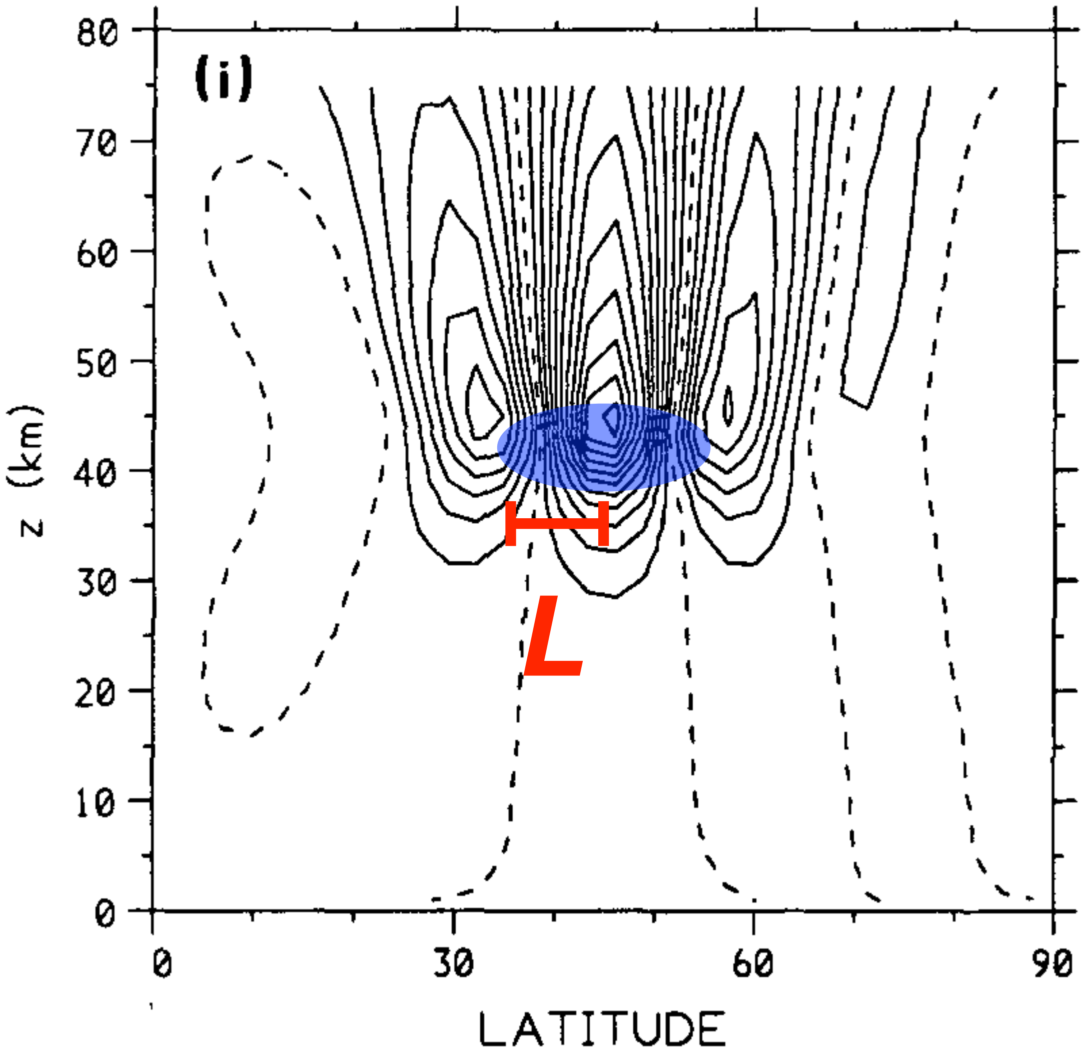


QG Potential Vorticity

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

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

zonal wind



amplitude *A*,
meridional scale *L*

QG Potential Vorticity

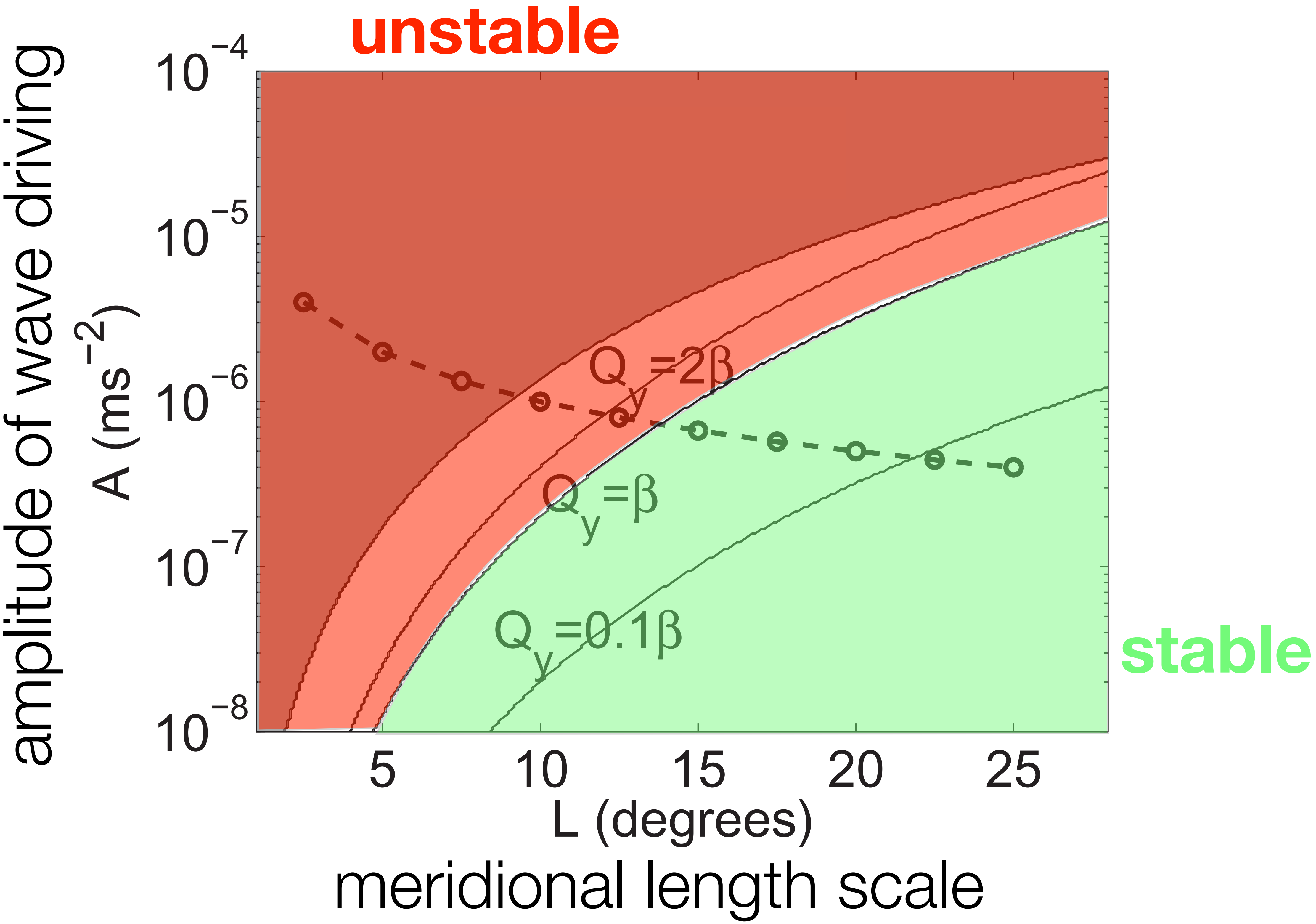
$$\overline{q}_y = \beta - \overline{u}_{yy} + f\,\frac{\overline{\theta}_y}{\overline{\theta}_p}$$

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

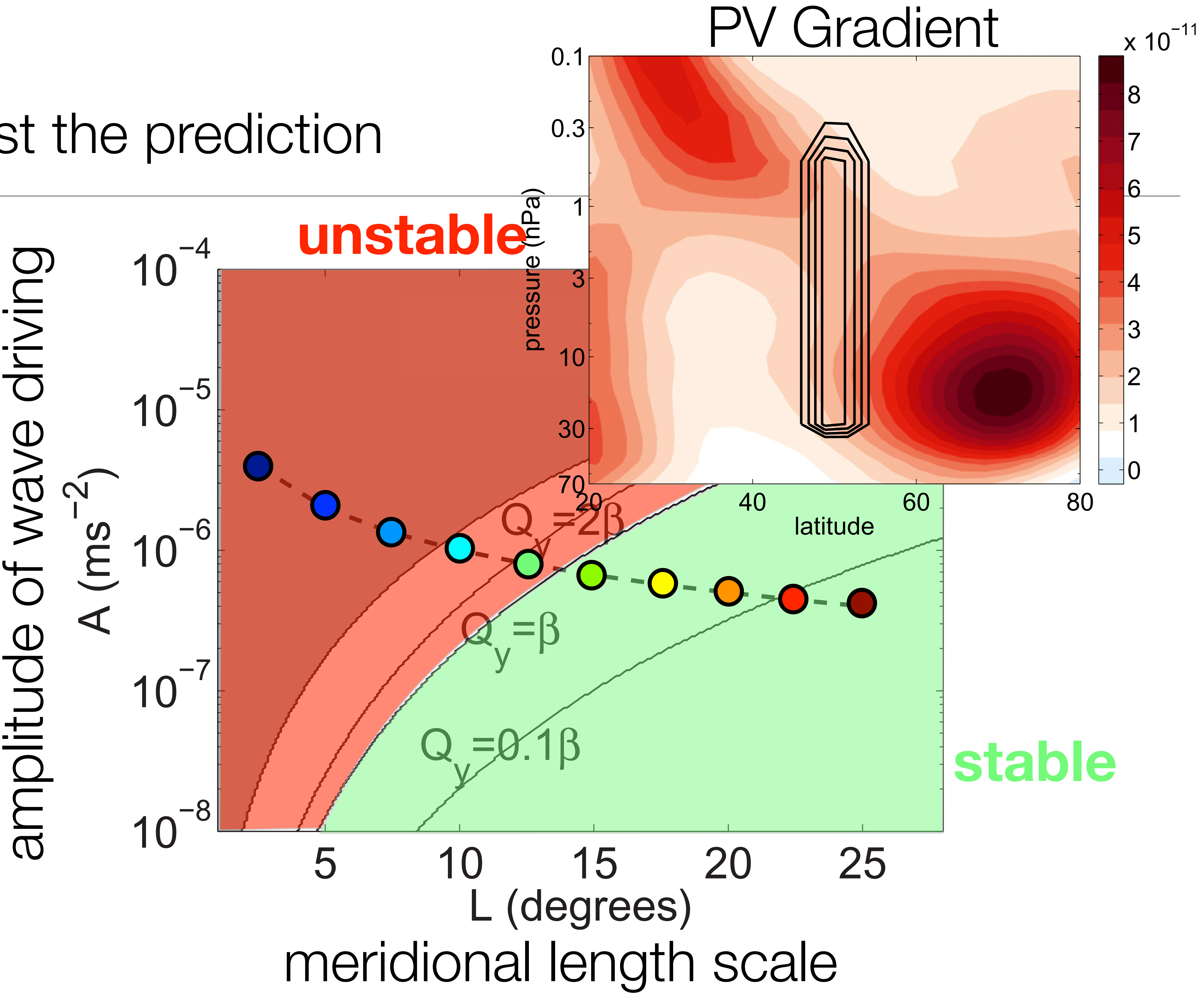
For $L << L_R$

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

Stability of the circulation for a compact torque



Test the prediction



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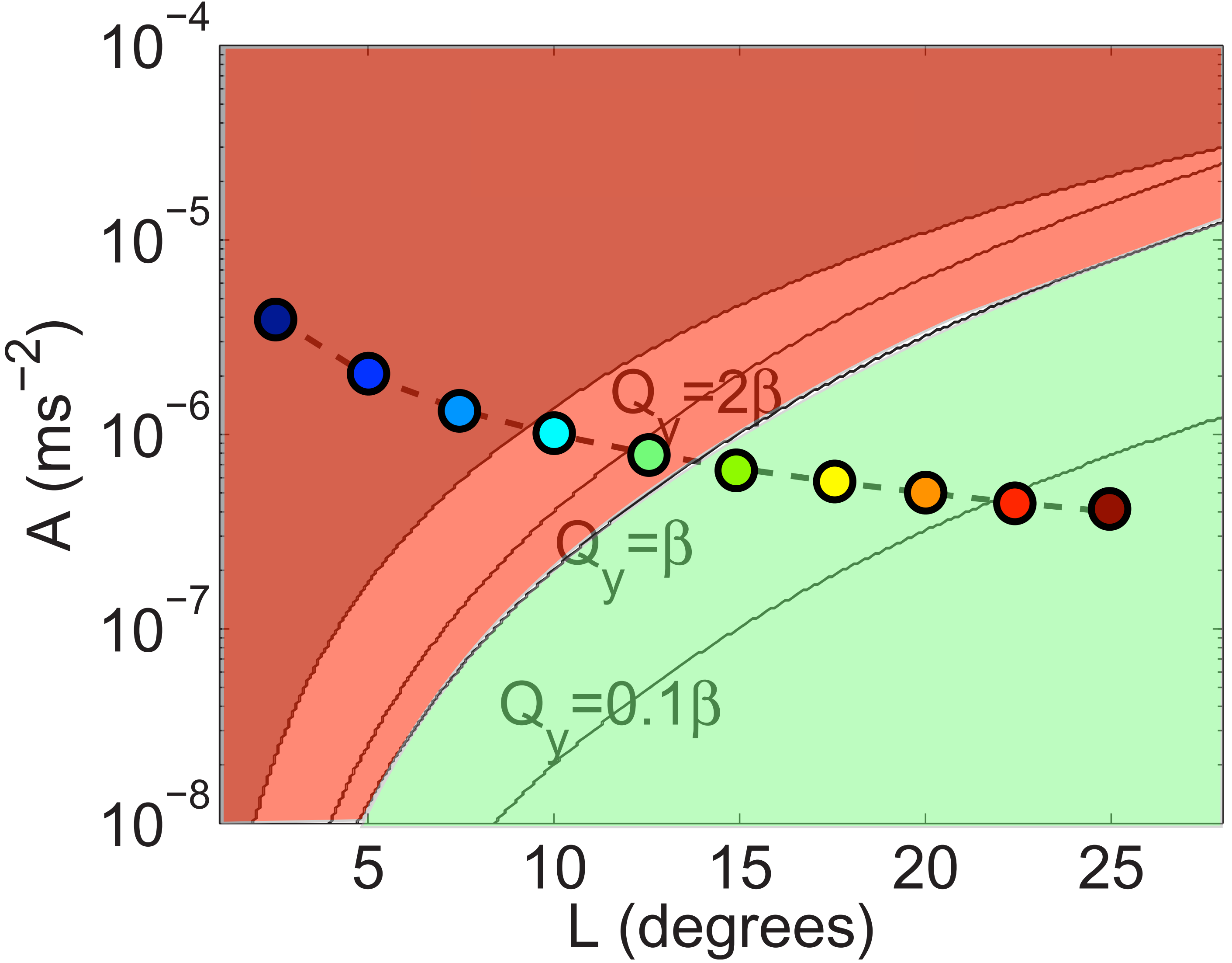
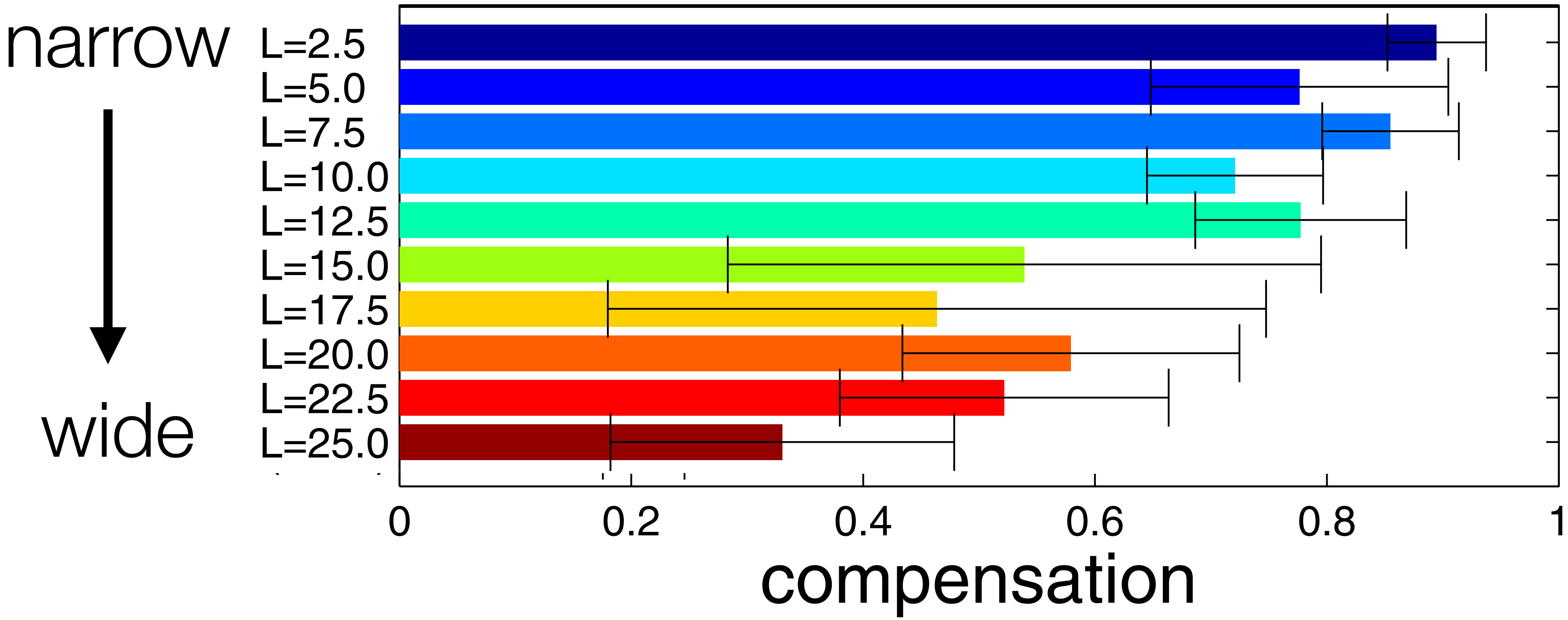
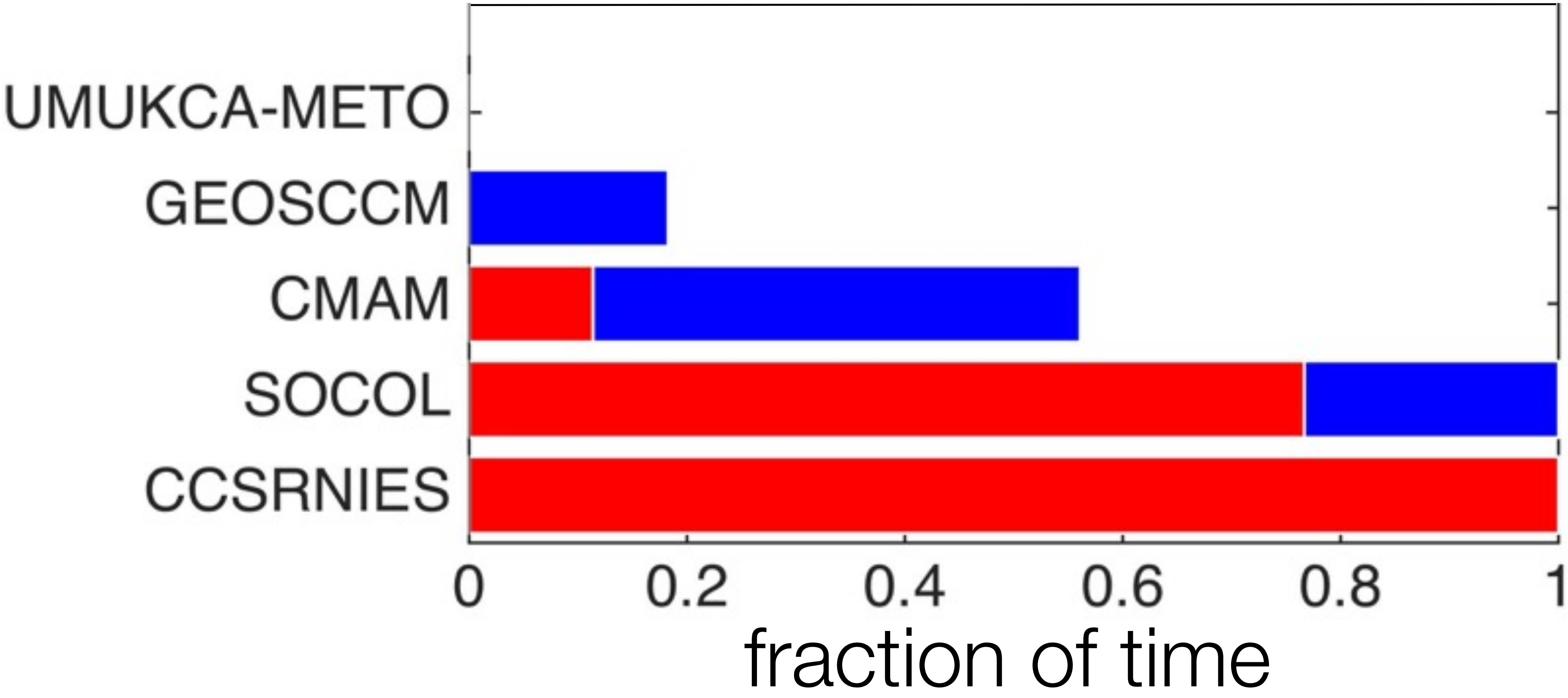




Is the circulation really going unstable?

Is the circulation really going unstable?

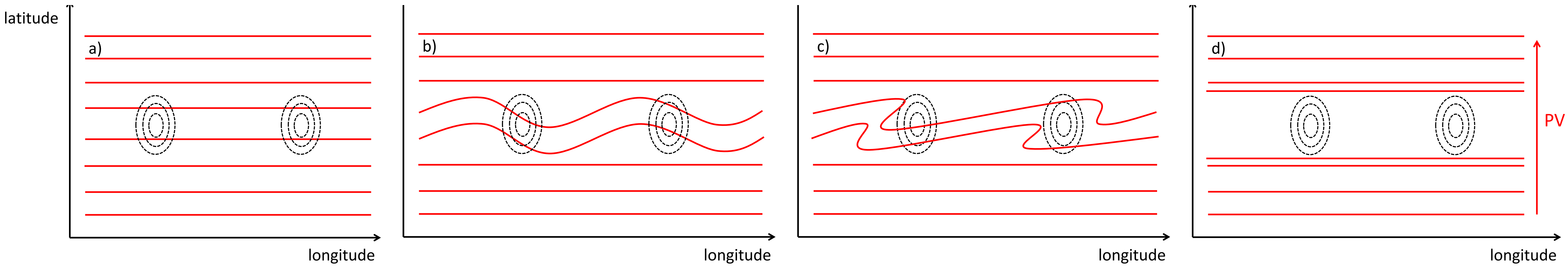
Yes (at least in some models)



$\bar{q}_y < 0 \text{ and } \nabla \cdot F > 0$

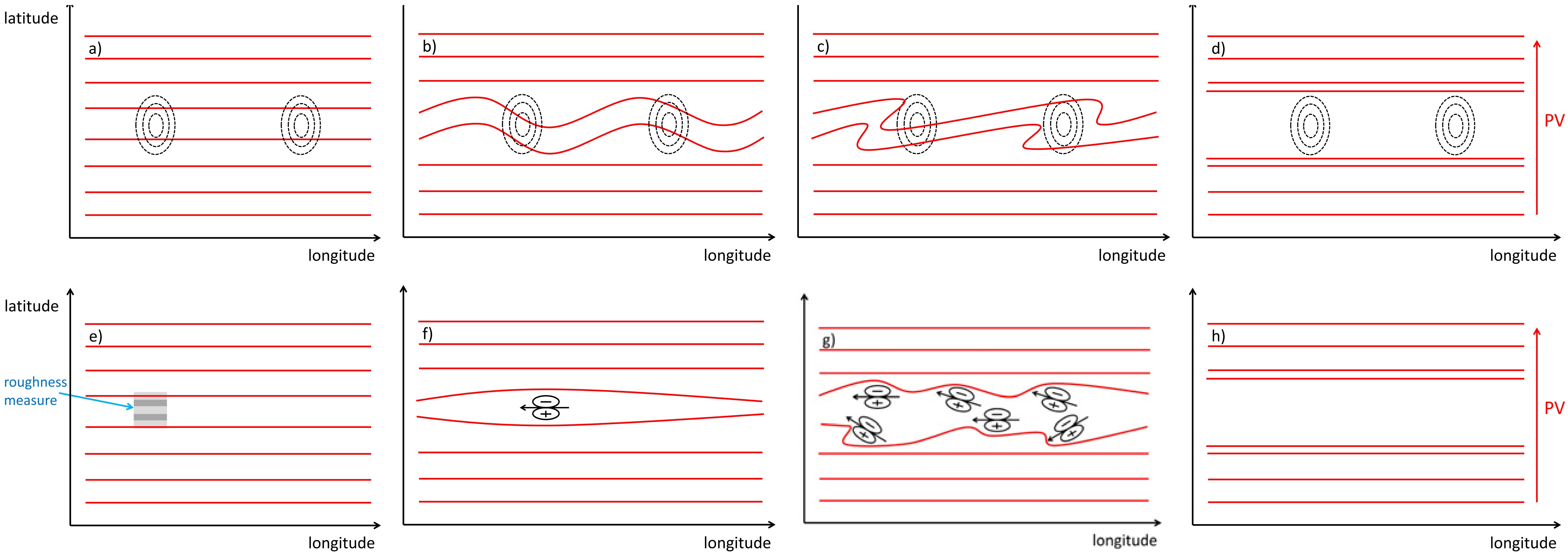
$\bar{q}_y < 0$

But it doesn’t have to…



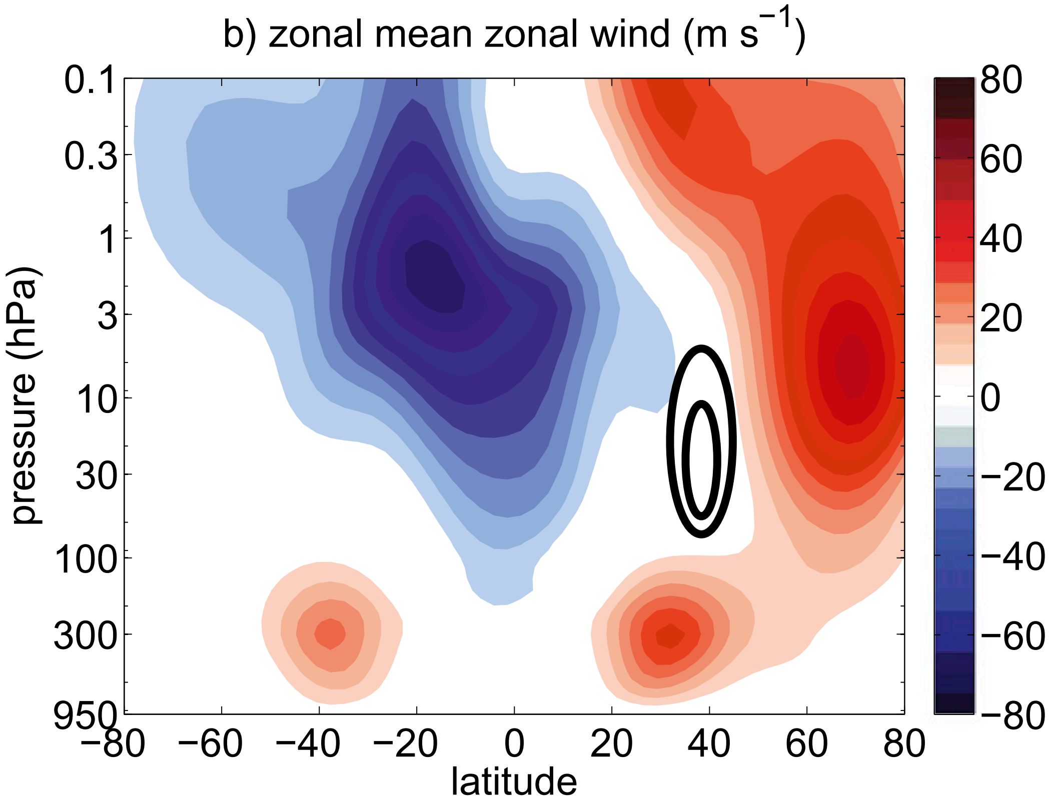
[McIntyre and Palmer, 1983]

But it doesn’t have to…

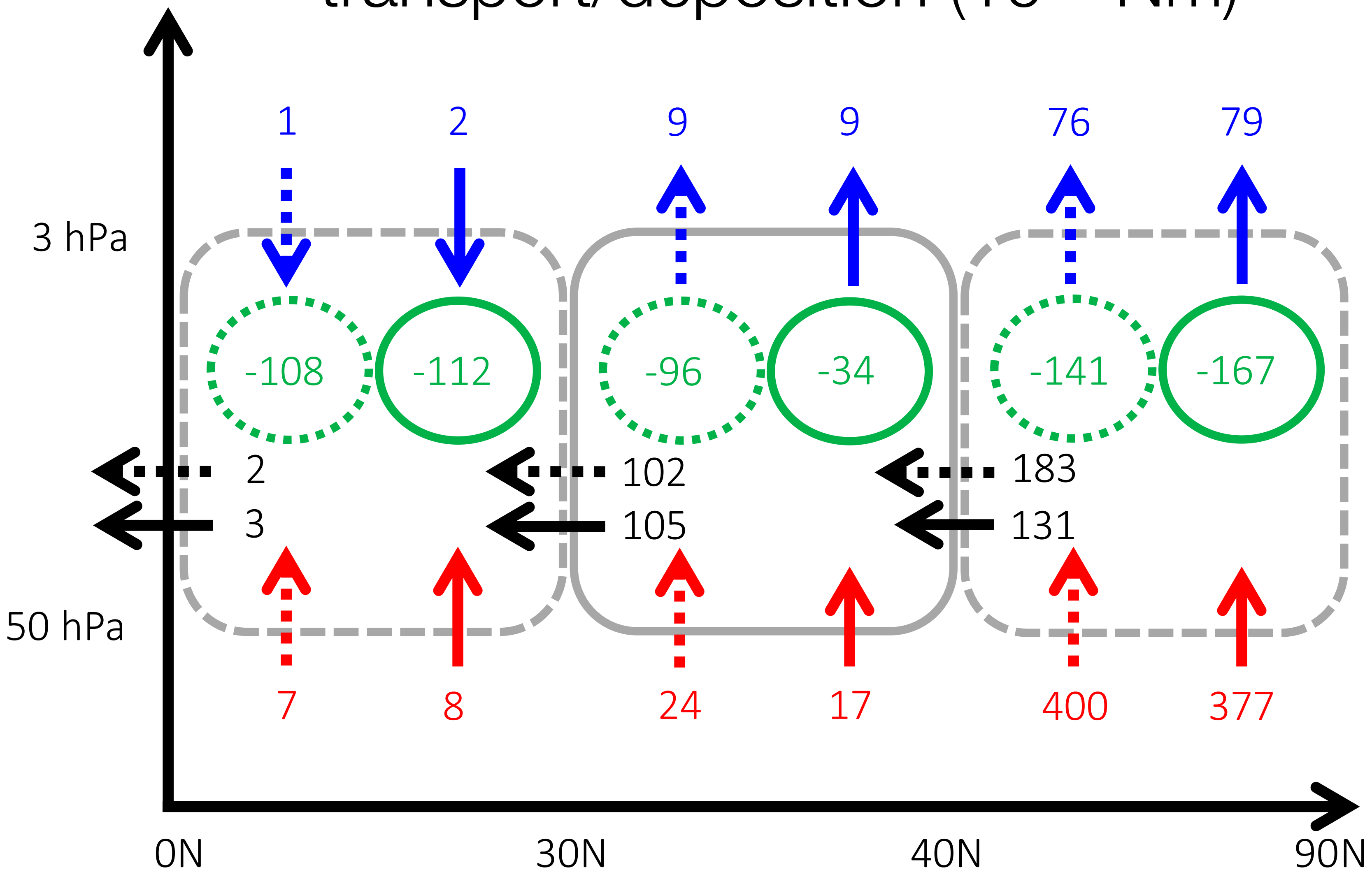


[McIntyre and Palmer, 1983]

A remote response to localized torque



b) zonal mean zonal wind (m s^{-1})

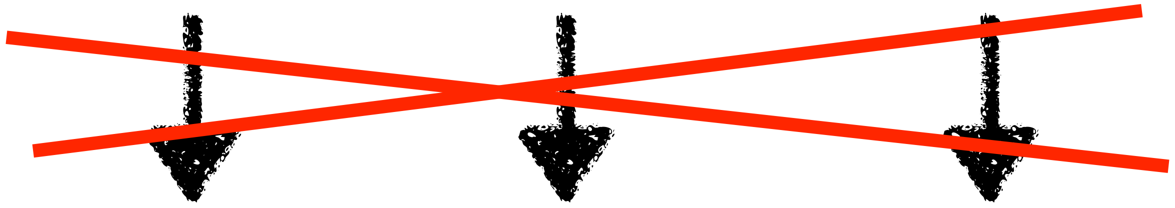


net angular momentum transport/deposition (10^{16} Nm)

[Cohen et al. 2014]

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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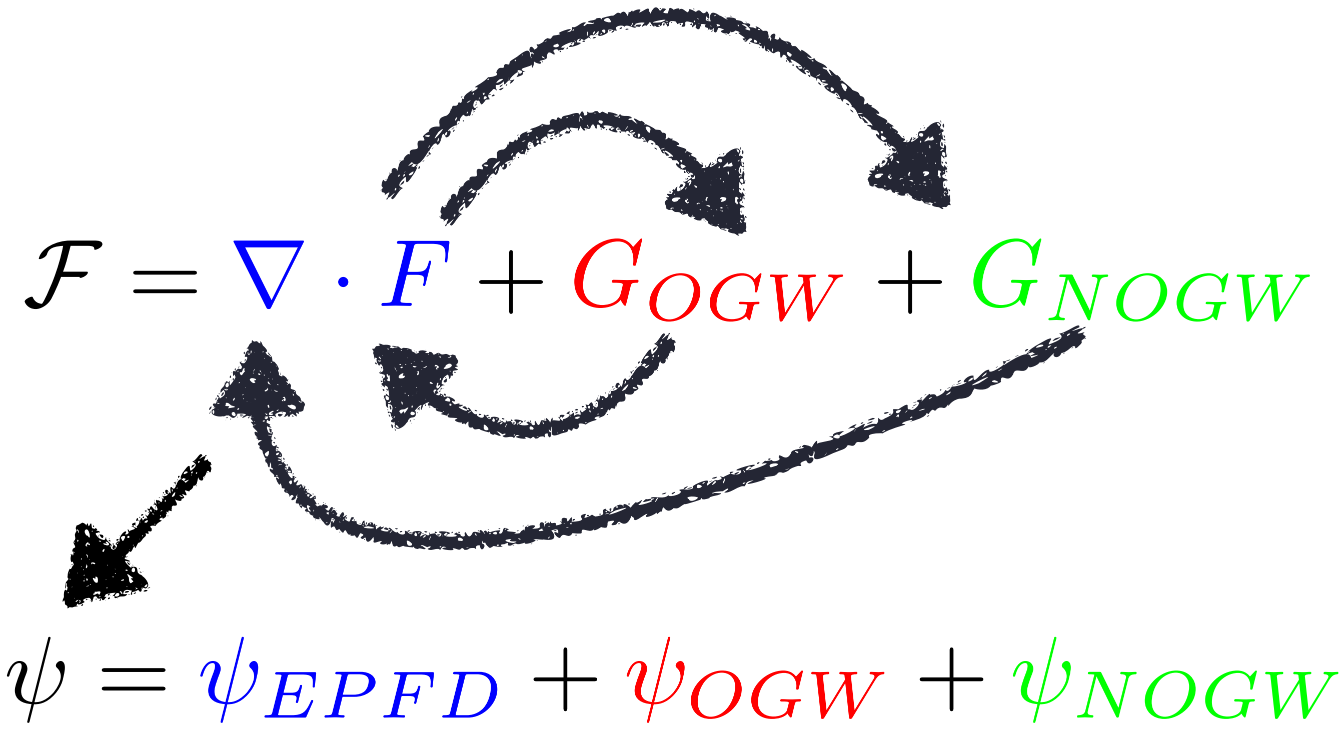
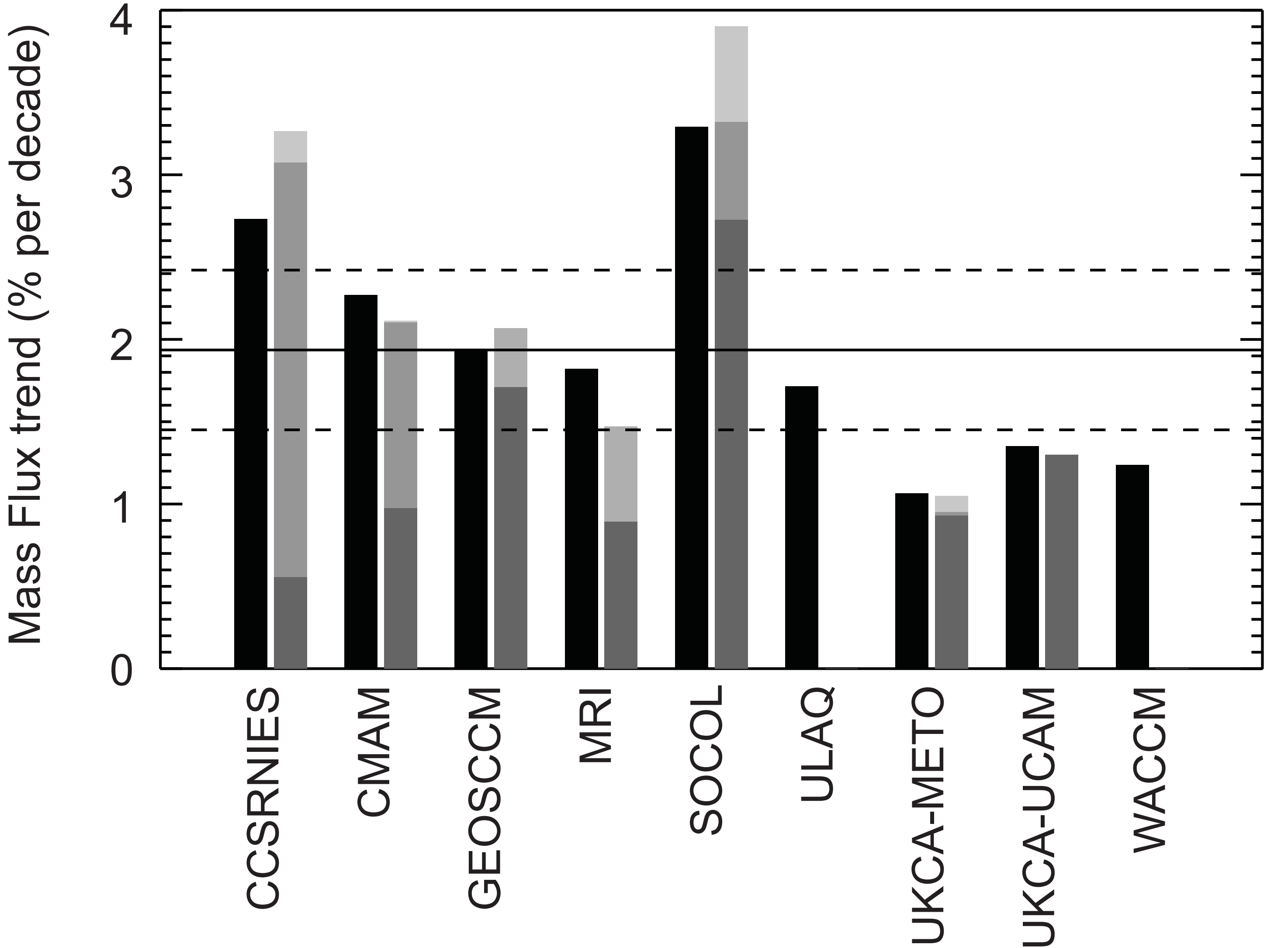


$$\mathcal{F} = \nabla \cdot F + G_{OGW} + G_{NOGW}$$

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

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

- 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?


(c) Annual mean mass flux trend at 70 hPa, 2000-2049

total

Rossby waves

orographic GW

non-orographic GW

[CCMVal2 Report]

Contributions of Anthropogenic and Natural Forcing to Recent Tropopause Height Changes

B. D. Santer,[1*] M. F. Wehner,[2] T. M. L. Wigley,[3] R. Sausen,[4]
G. A. Meehl,[3] K. E. Taylor,[1] C. Ammann,[3] J. Arblaster,[3]
W. M. Washington,[3] J. S. Boyle,[1] W. Brüggemann[5]

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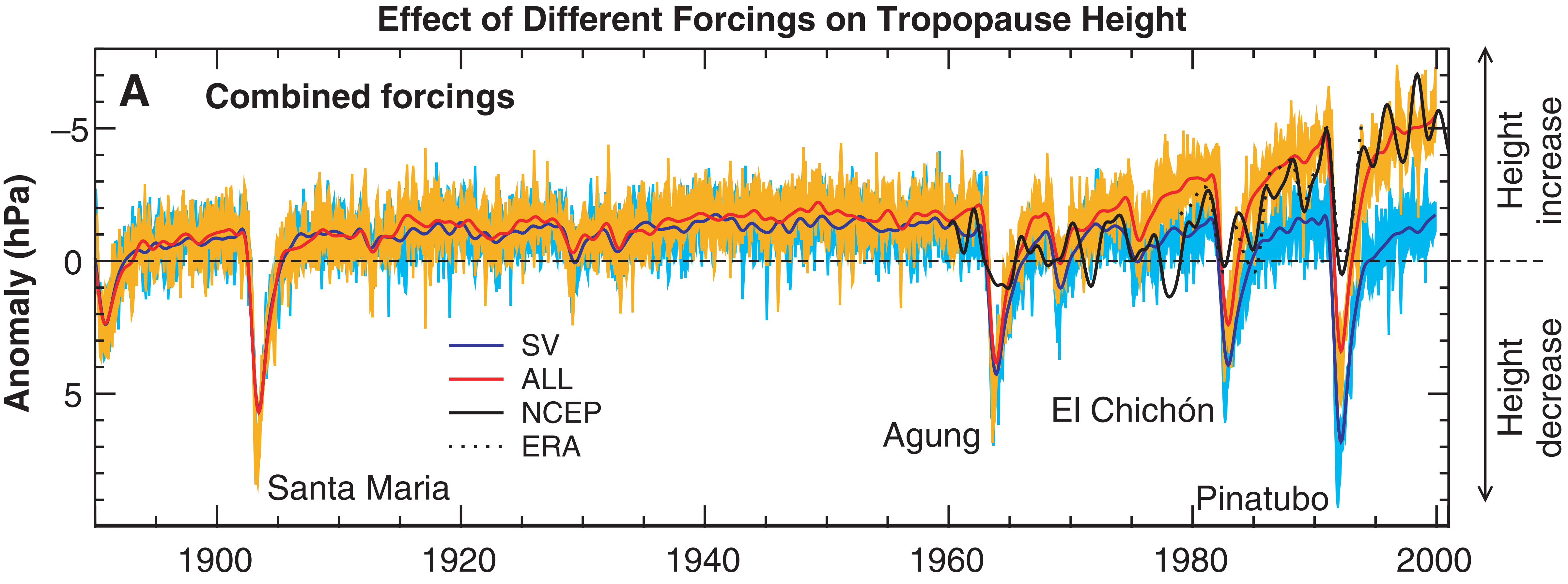
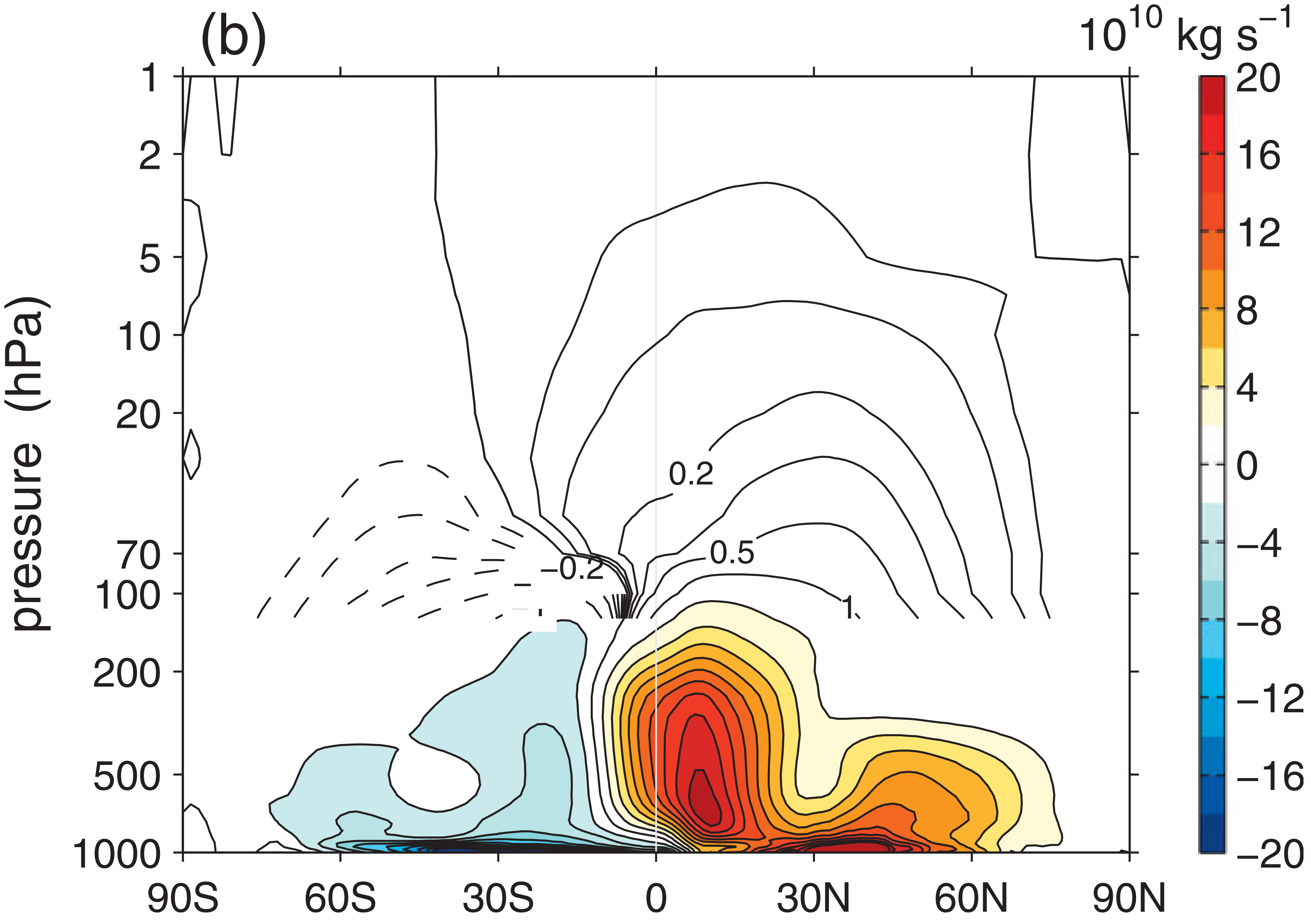


Effect of Different Forcings on Tropopause Height

Meridional overturning of the atmosphere decays rapidly from the troposphere to stratosphere



residual mean streamfunction, ERA-I (DJF)

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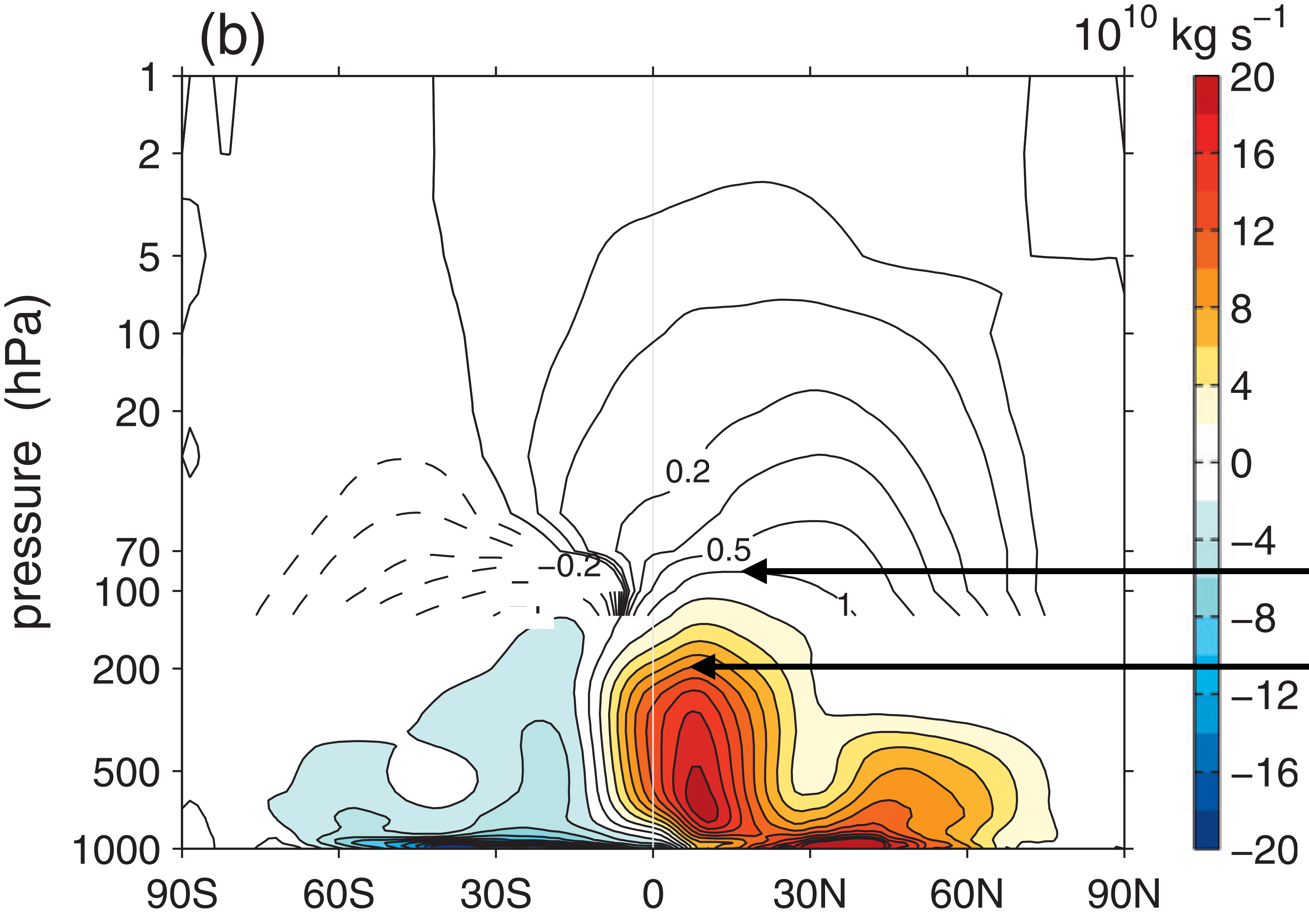


residual mean streamfunction, ERA-I (DJF)

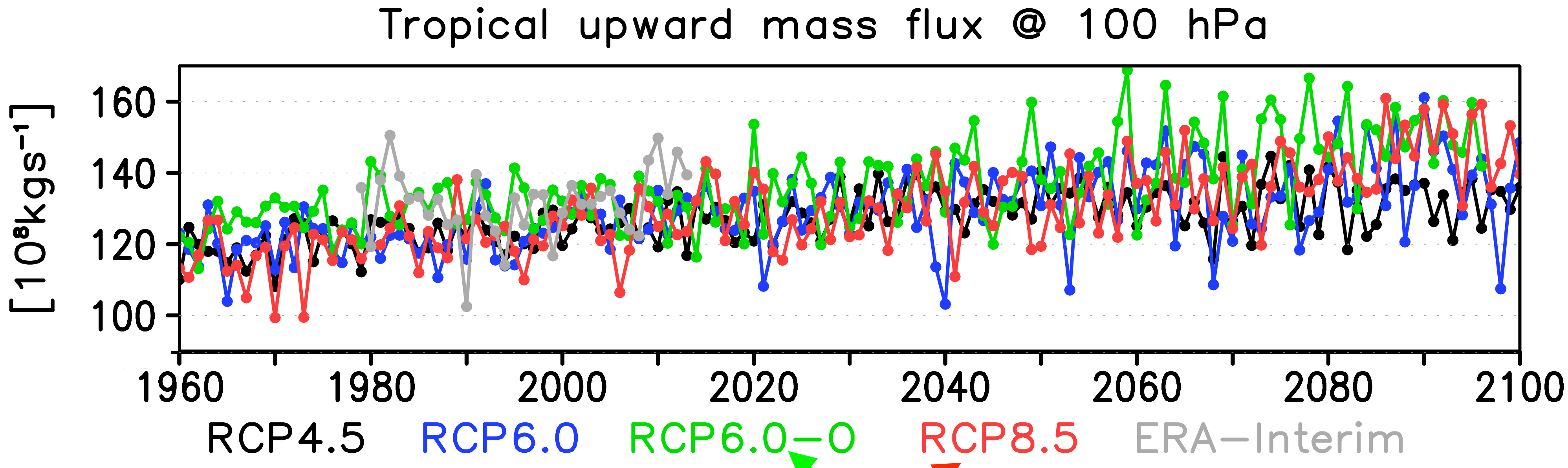
10^9 kg/s

10^{11} kg/s

only 1/5 of the mass upwelling at 100 hPa makes it to 70 hPa!

Experiments with the Free University Climate Model

(EMAC = **E**CHAM **M**ESSy **A**tmospheric **C**hemistry)

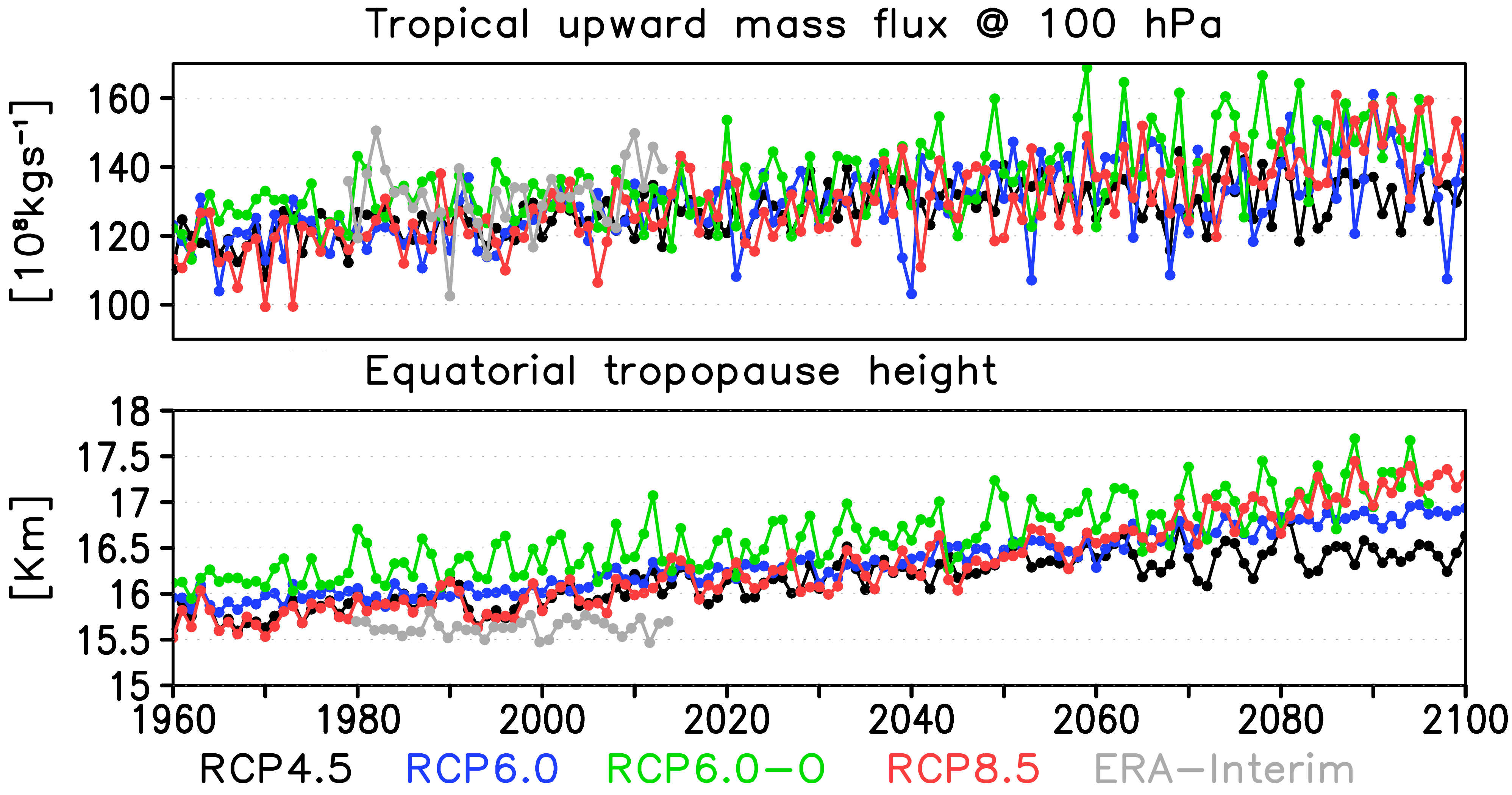


atmosphere only integrations, SSTs from coupled model with 4.5, 6.0, and 8.5 Wm^{-2} greenhouse gas forcing scenario

coupled integration w/ MPI-O ocean model, 6.0 Wm^{-2} scenario

Experiments with the Free University Climate Model

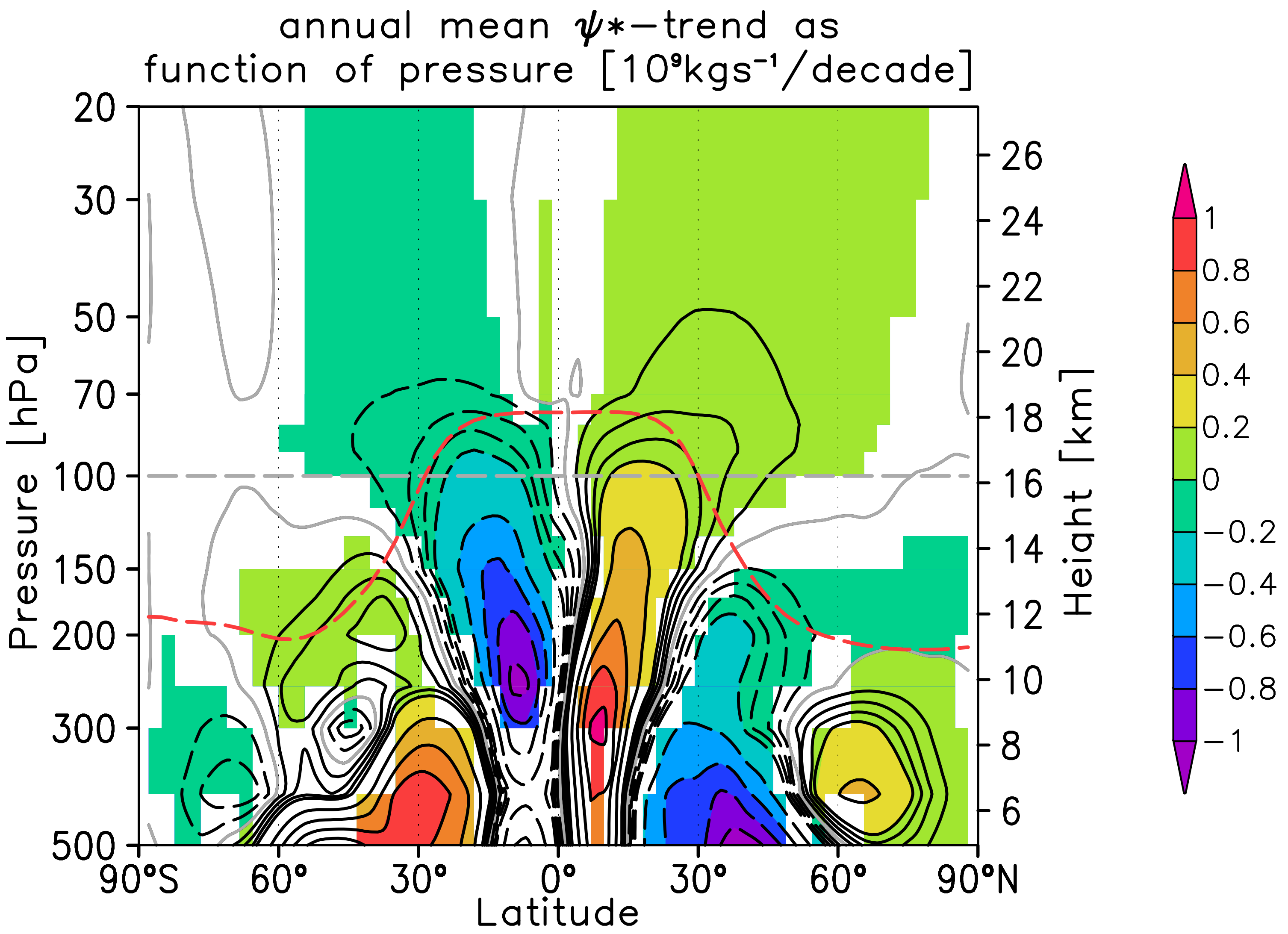
(EMAC = **E**CHAM **M**ESSy **A**tmospheric **C**hemistry)



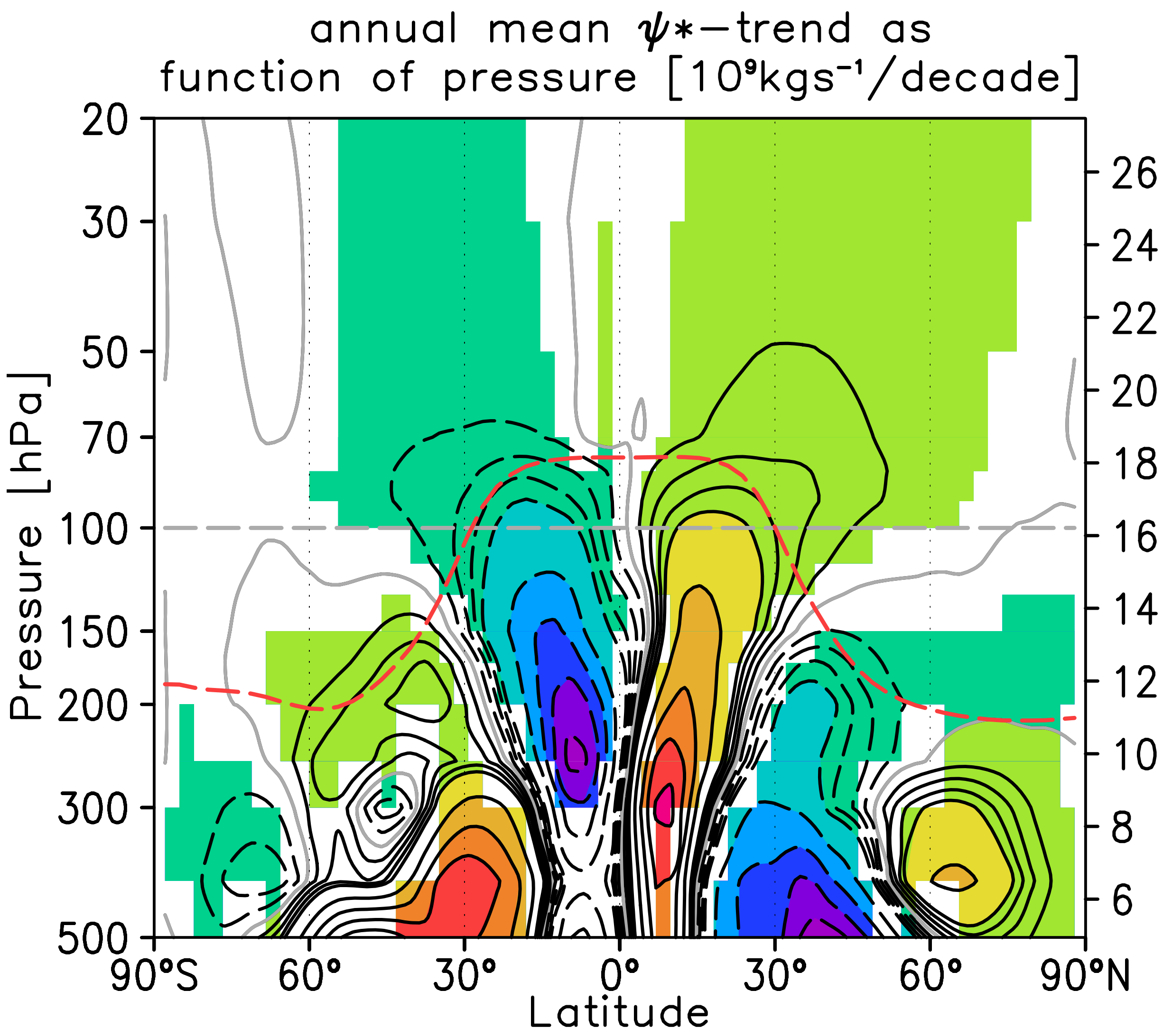
residual circulation increases and tropopause rises in all simulations: more forcing, more increase

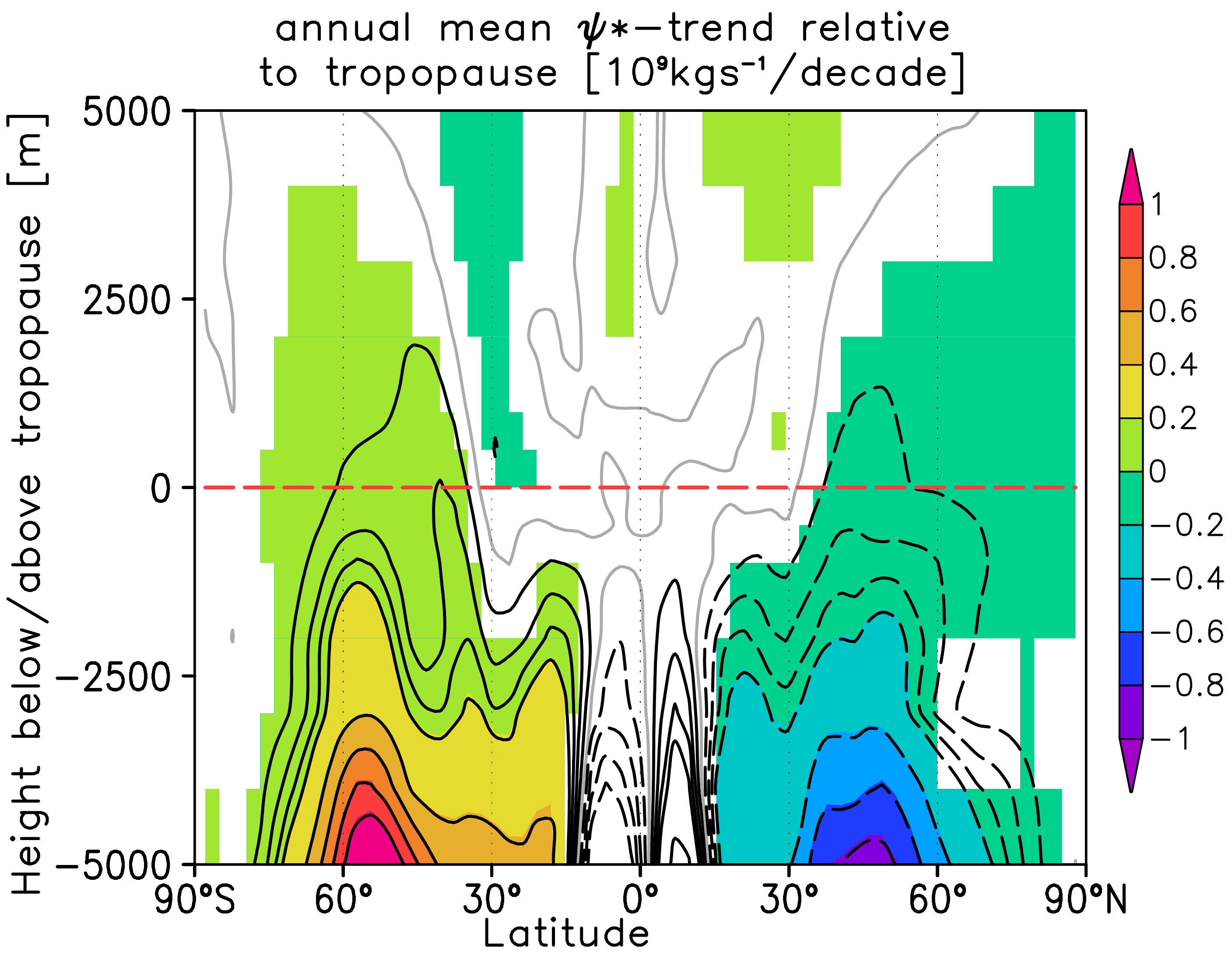
The importance of how we average:

on pressure levels

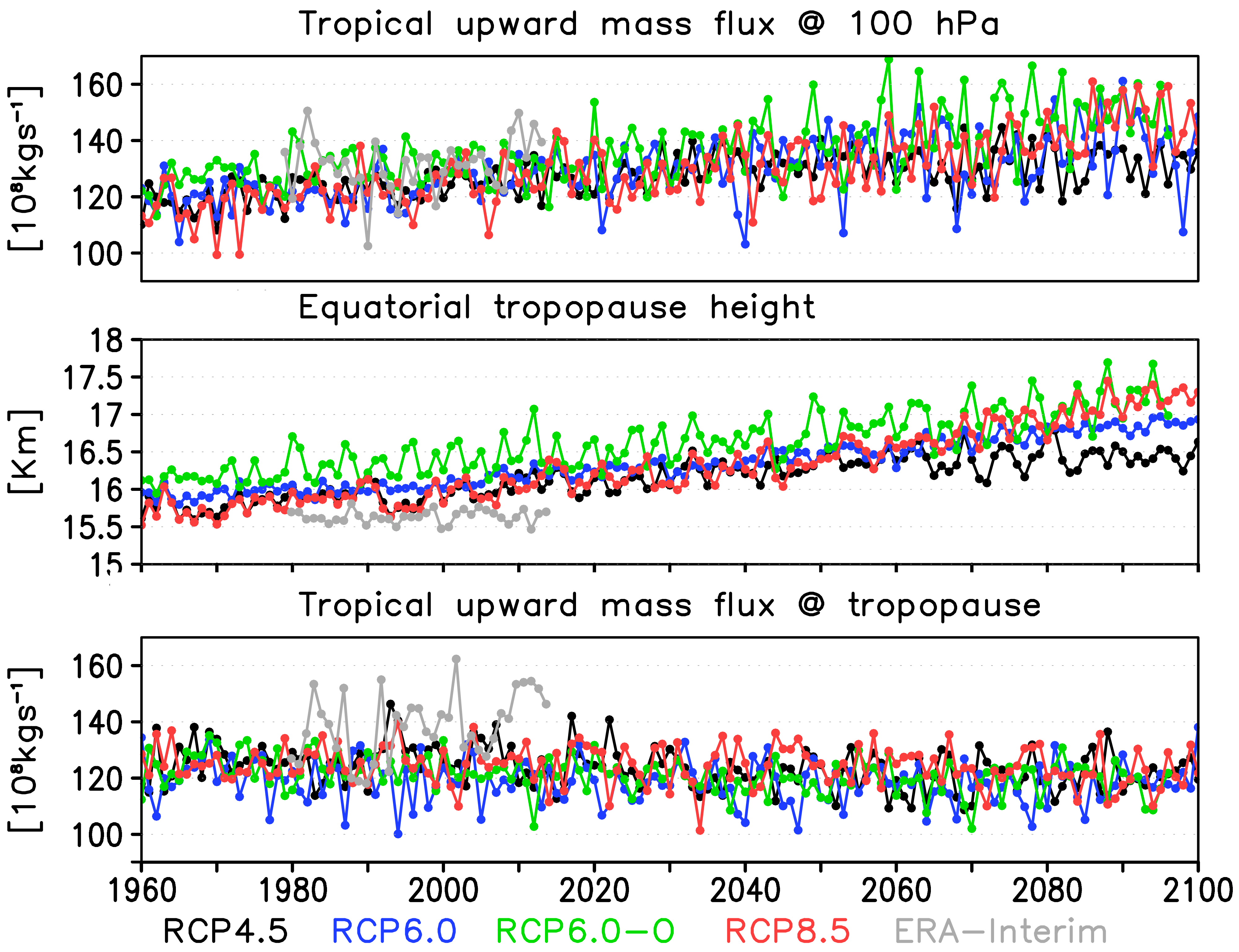


The importance of how we average:
on pressure levels or relative to tropopause


annual mean $\psi*$−trend as function of pressure [10^9kgs^{-1}/decade]


annual mean $\psi*$−trend relative to tropopause [10^9kgs^{-1}/decade]

Different averaging: mass flux across tropopause



Quantifying the impact of the rise in the circulation on the mass flux at a pressure level (i.e. 100 hPa)

$$\Delta F_{trop} = \Delta F_{shift} + \Delta F_{struct}$$

change in mass flux

change associated w/ shift

other “structural” changes

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change in mass flux

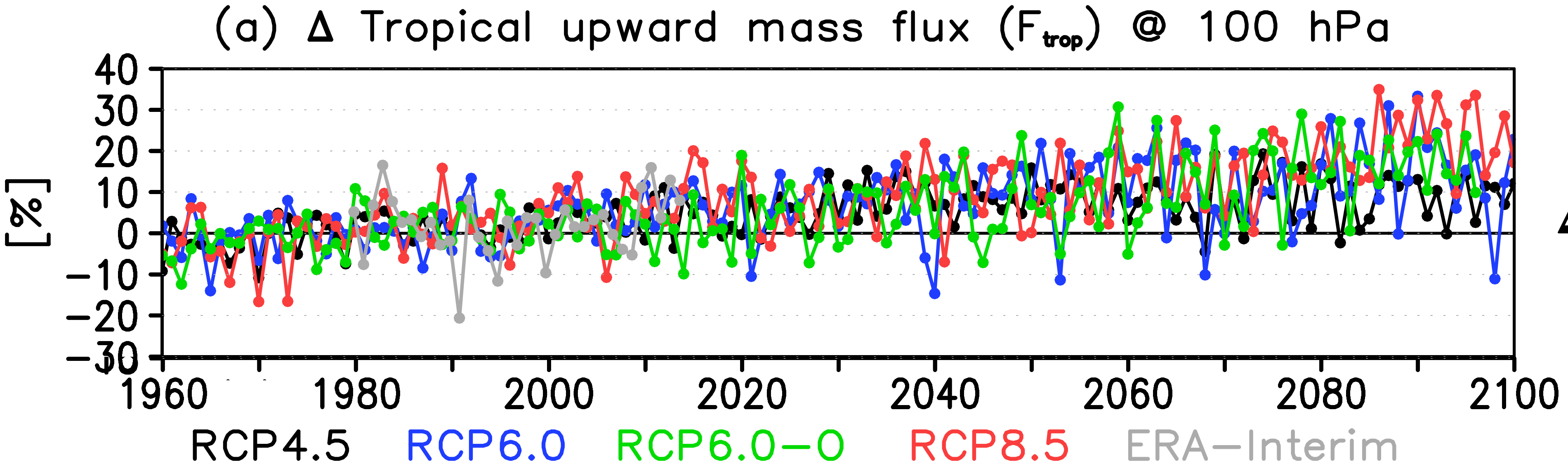
change associated w/ shift

other “structural” changes

$$\Delta F_{shift} = -\left.\frac{\partial F_{trop}}{\partial p}\right|_{past} \cdot \Delta p_T$$

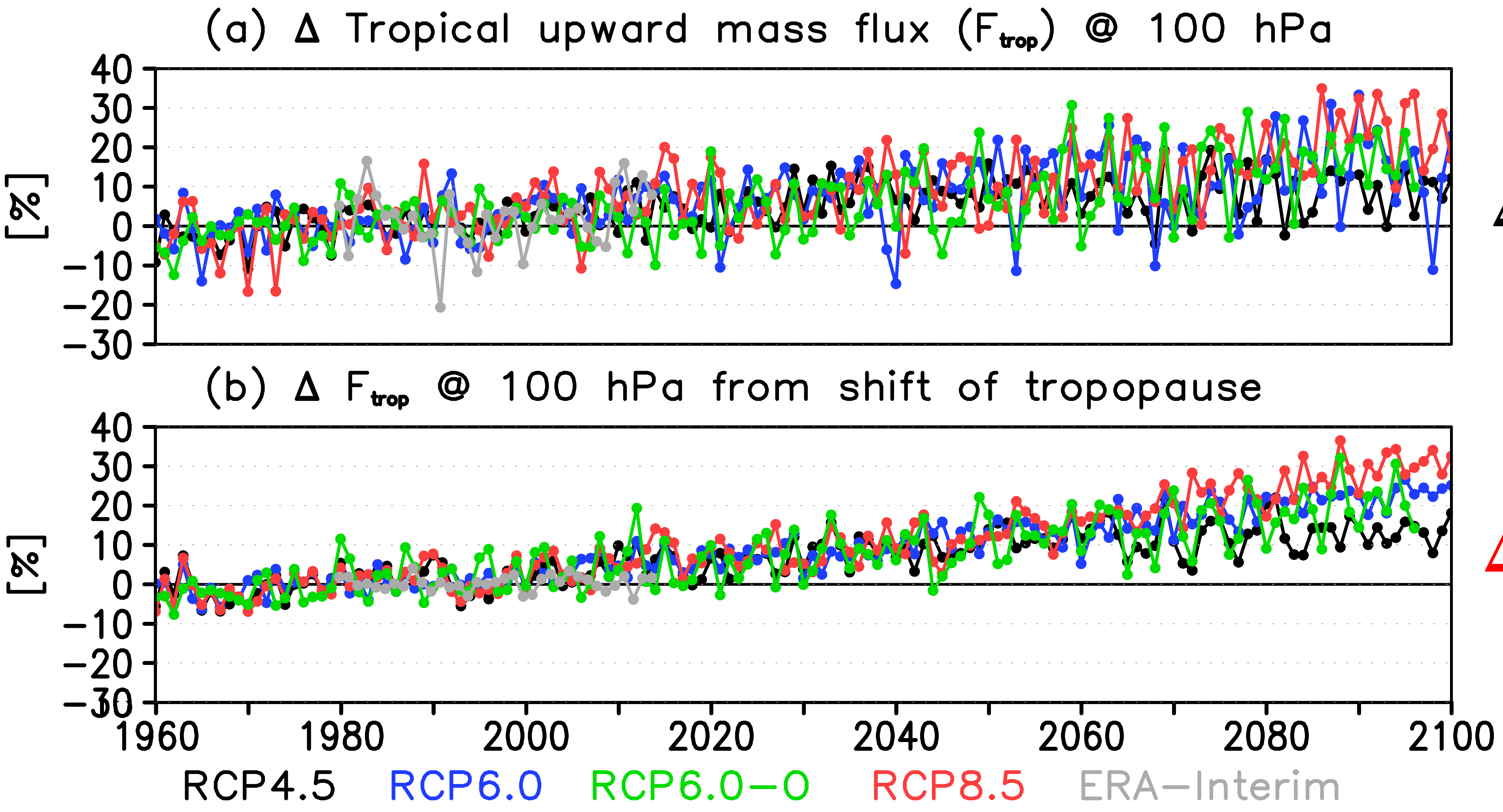
change in tropopause pressure

Partitioning the increase in the residual circulation at 100 hPa in EMAC



ΔF_{trop}

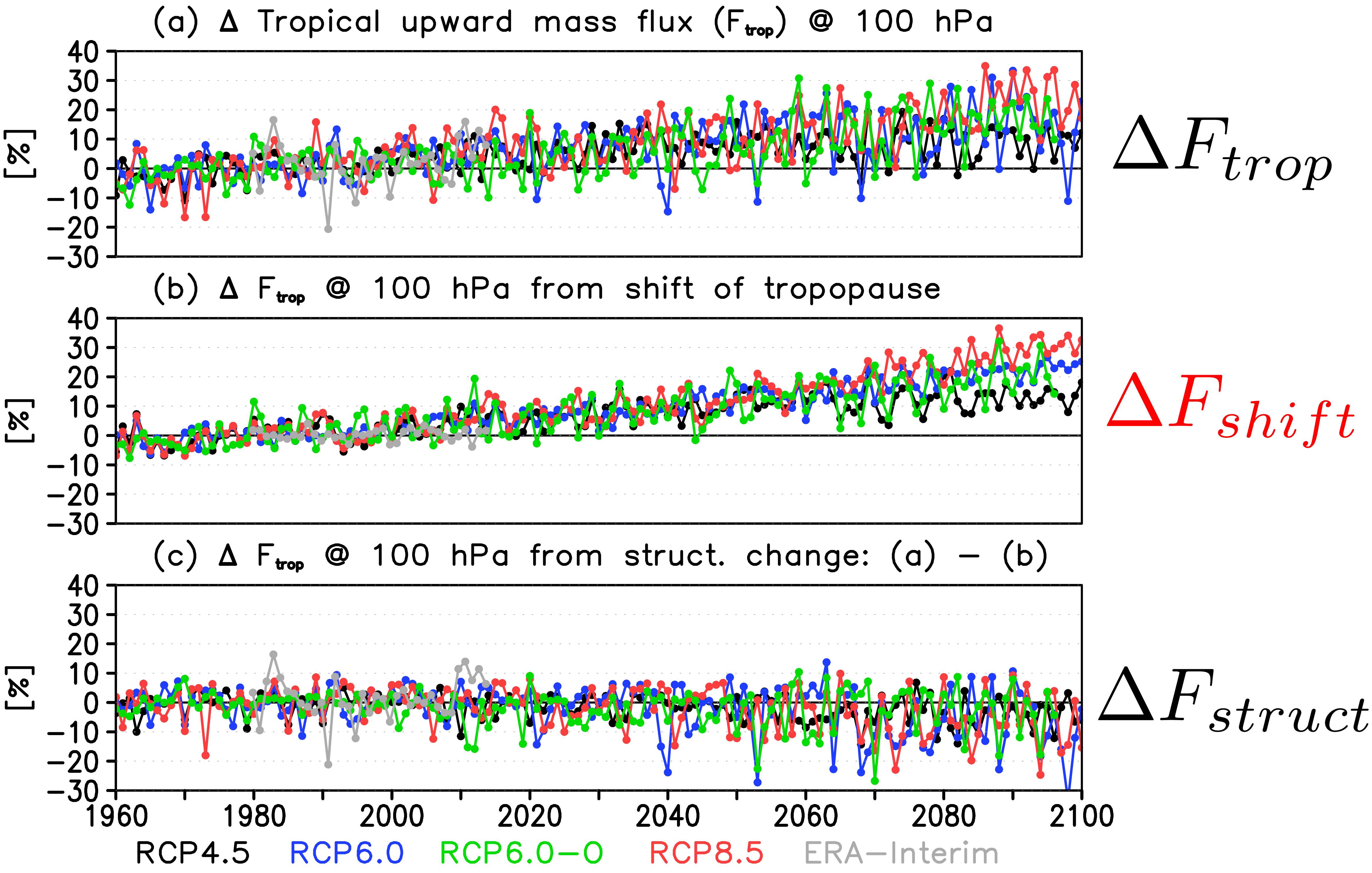
Partitioning the increase in the residual circulation at 100 hPa in EMAC



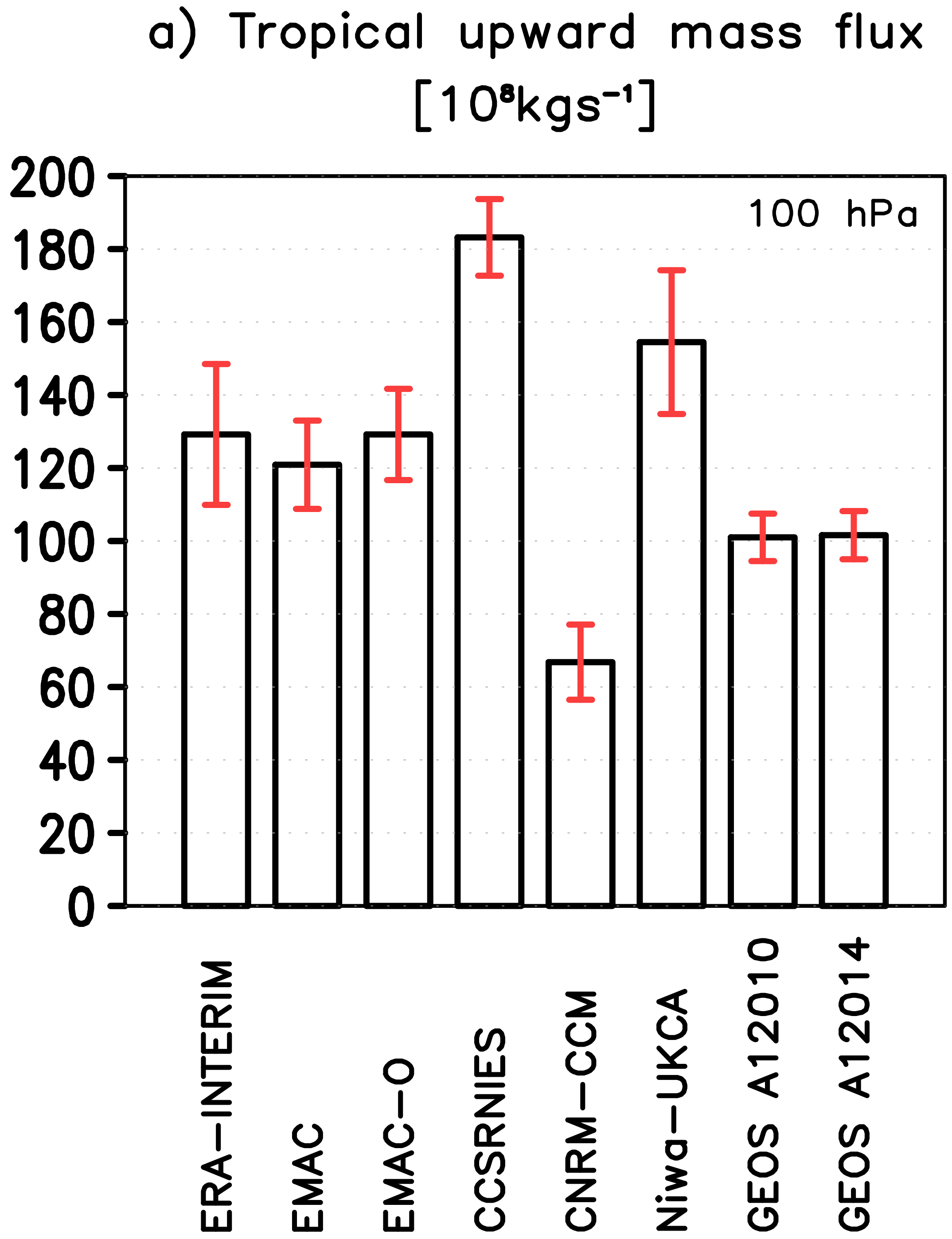
ΔF_{trop}

ΔF_{shift}

Partitioning the increase in the residual circulation at 100 hPa in EMAC



Results are consistent in other CCMI atmospheric models (all RCP6.0 integrations)



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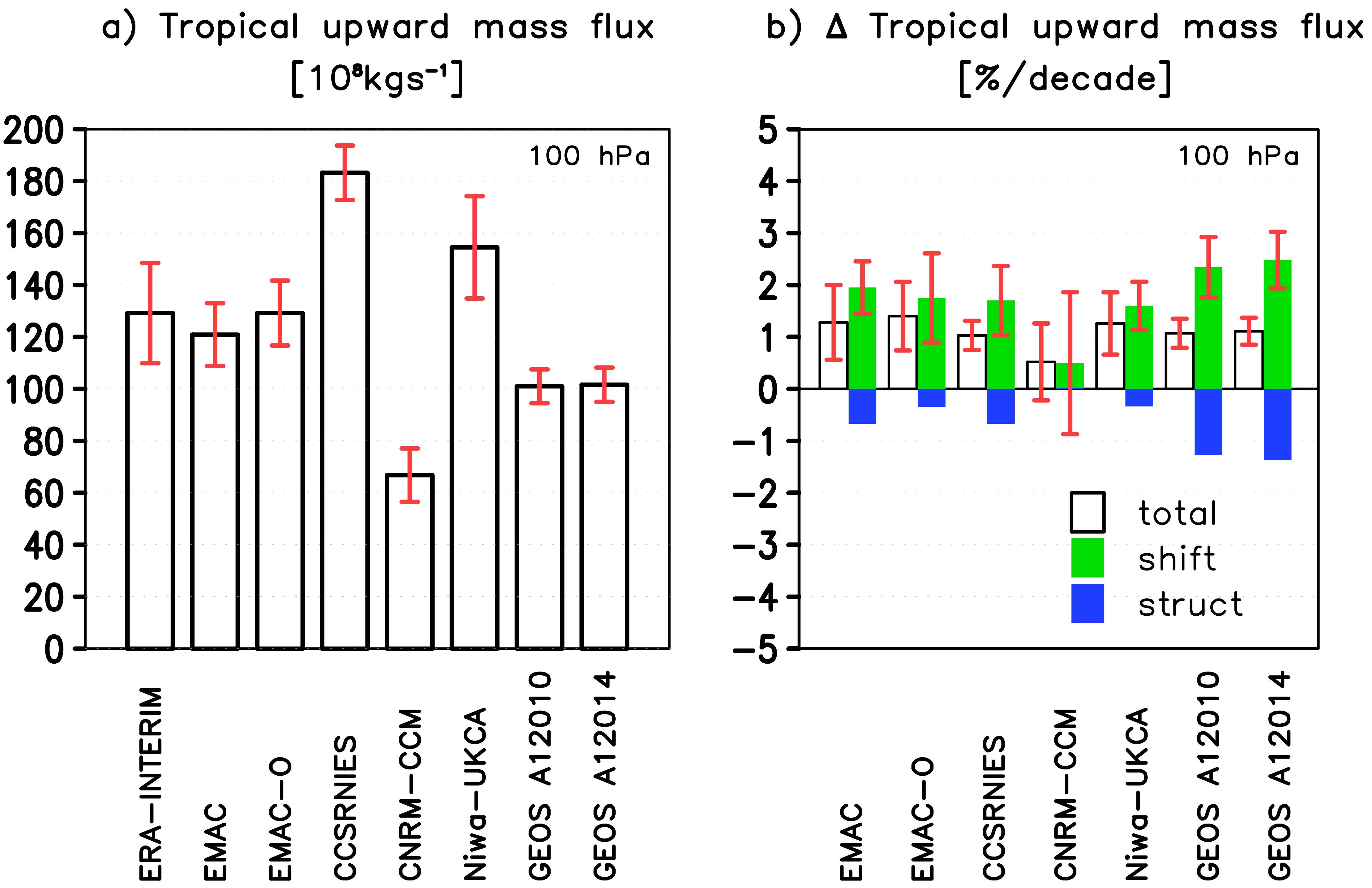

Conclusions

- What drives the Brewer-Dobson Circulation?

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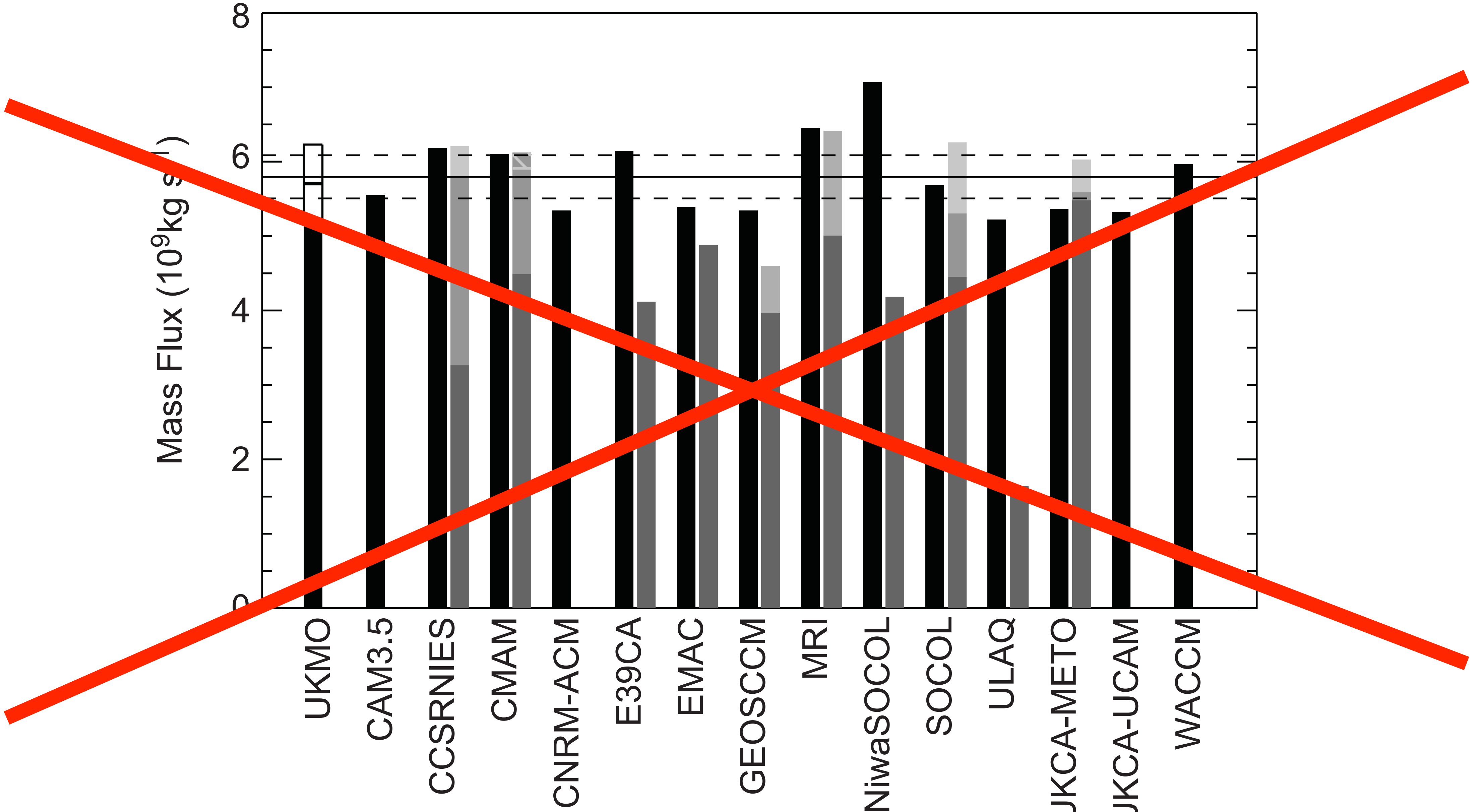
Downward control can be misleading.


(a) Annual mean upward mass flux at 70 hPa

Conclusions

- What drives the Brewer-Dobson Circulation?

Downward control can be misleading.

To move forward

- focus on gravity wave momentum drag itself [DynVarMIP]
- connect models with observations through data assimilation

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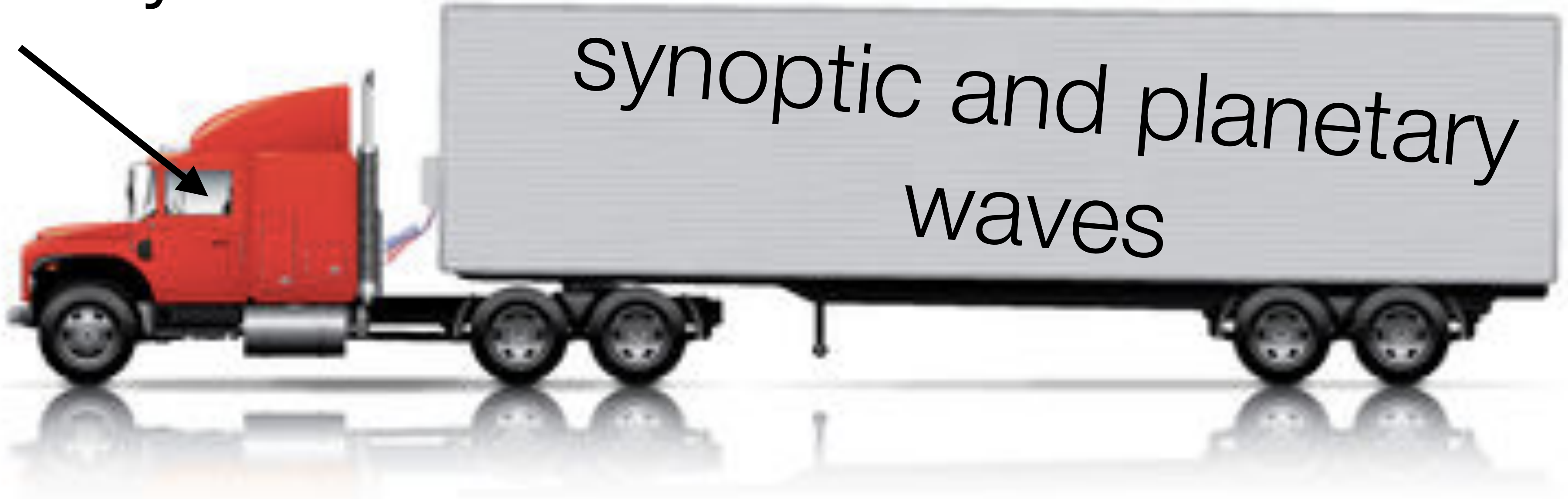
Downward control can be misleading.

To move forward

- focus on gravity wave momentum drag itself [DynVarMIP];
- connect models with observations through data assimilation.

Gravity waves key role is to steer Rossby waves.



Conclusions

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

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The Brewer-Dobson Circulation is rising with the rest of the circulation

- explains robustness of *the increase at a given pressure level* across GCMs with varying representation of the stratosphere
- complements focus on rising critical levels by Shepherd and McLandress (2011), emphasizing that mechanism depends primarily on tropospheric response to greenhouse gases
- inter-model differences in wave driving likely reflect tuning and limitations of current gravity wave parameterizations, but not fundamental gap in our understanding

Conclusions

- Parameterized gravity waves strongly interact with the resolved circulation
    - compensation (mixing and instability)
    - nonlinear impacts through index of refraction
- Downward control analysis can be misleading
    - strong and/or narrow forcings, particular in the surf zone, are likely to be compensated: *think OGW (as they are parameterized in GCMs)*
    - weak and/or diffuse forcing can have strong indirect impact: *NOGW*
- The Brewer-Dobson Circulation is rising with the rest of the circulation
    - explains robustness of *the increase at a given pressure level* across a range of GCMs with varying representation of the stratosphere
    - a fundamental response of the atmosphere to greenhouse gas forcing
    - inter-model differences in wave driving likely reflect tuning and limitations of current gravity wave parameterizations, but not fundamental gap in our understanding