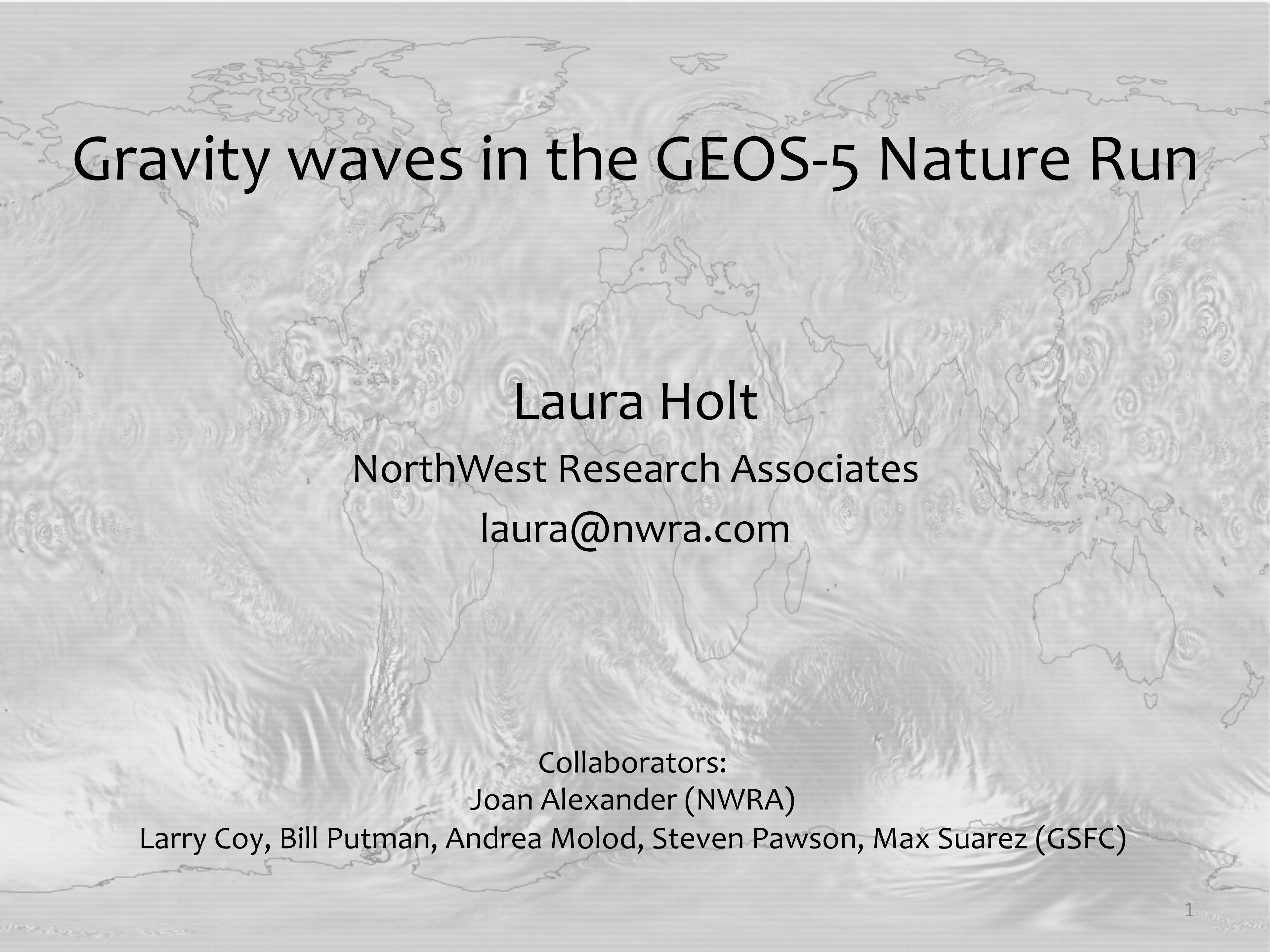

Gravity waves in the GEOS-5 Nature Run

Laura Holt

NorthWest Research Associates

laura@nwra.com

Collaborators:
Joan Alexander (NWRA)
Larry Coy, Bill Putman, Andrea Molod, Steven Pawson, Max Suarez (GSFC)

Outline

- 7-km GEOS-5 Nature Run (NR)
- Global evaluation of NR gravity waves in the stratosphere
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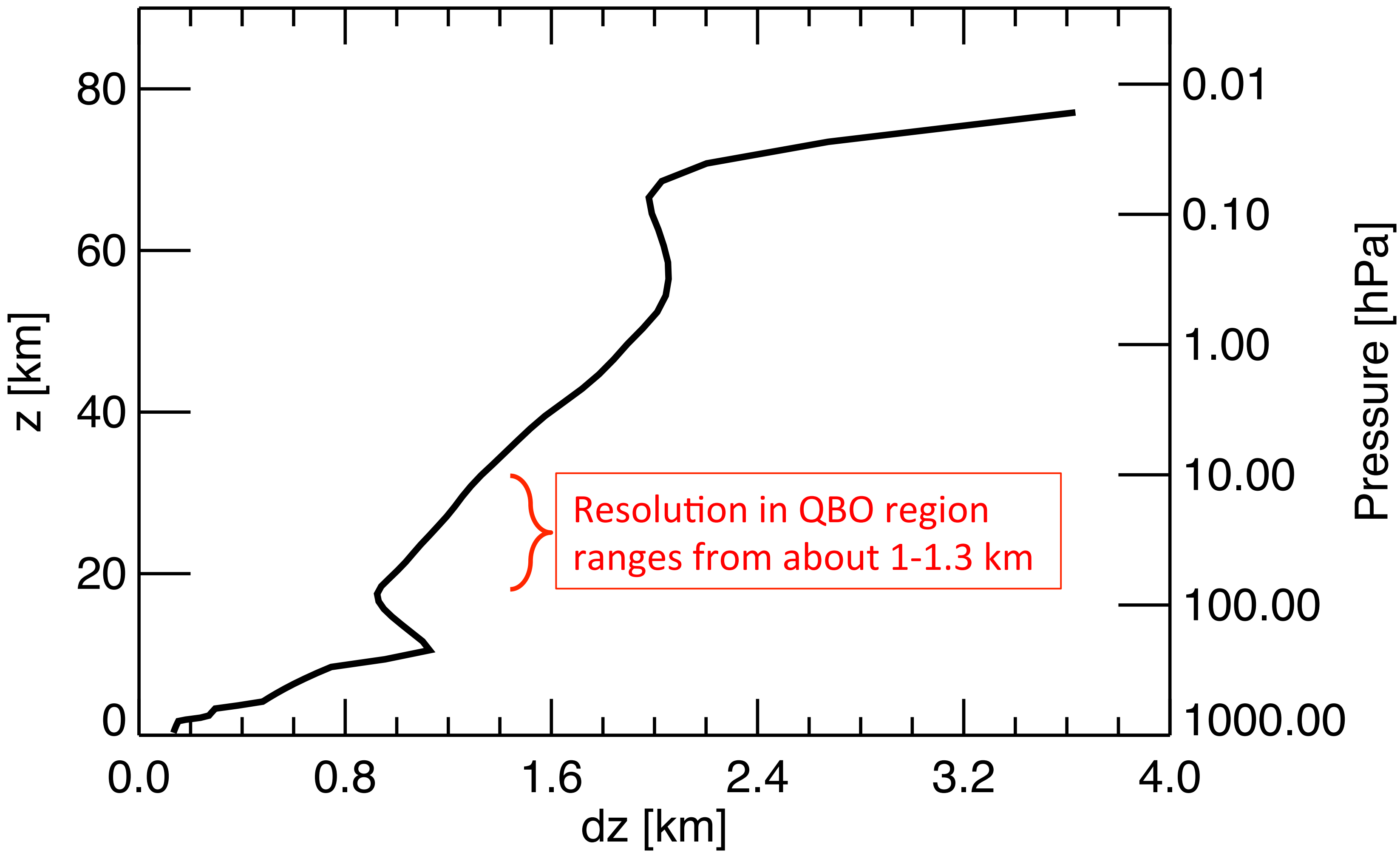
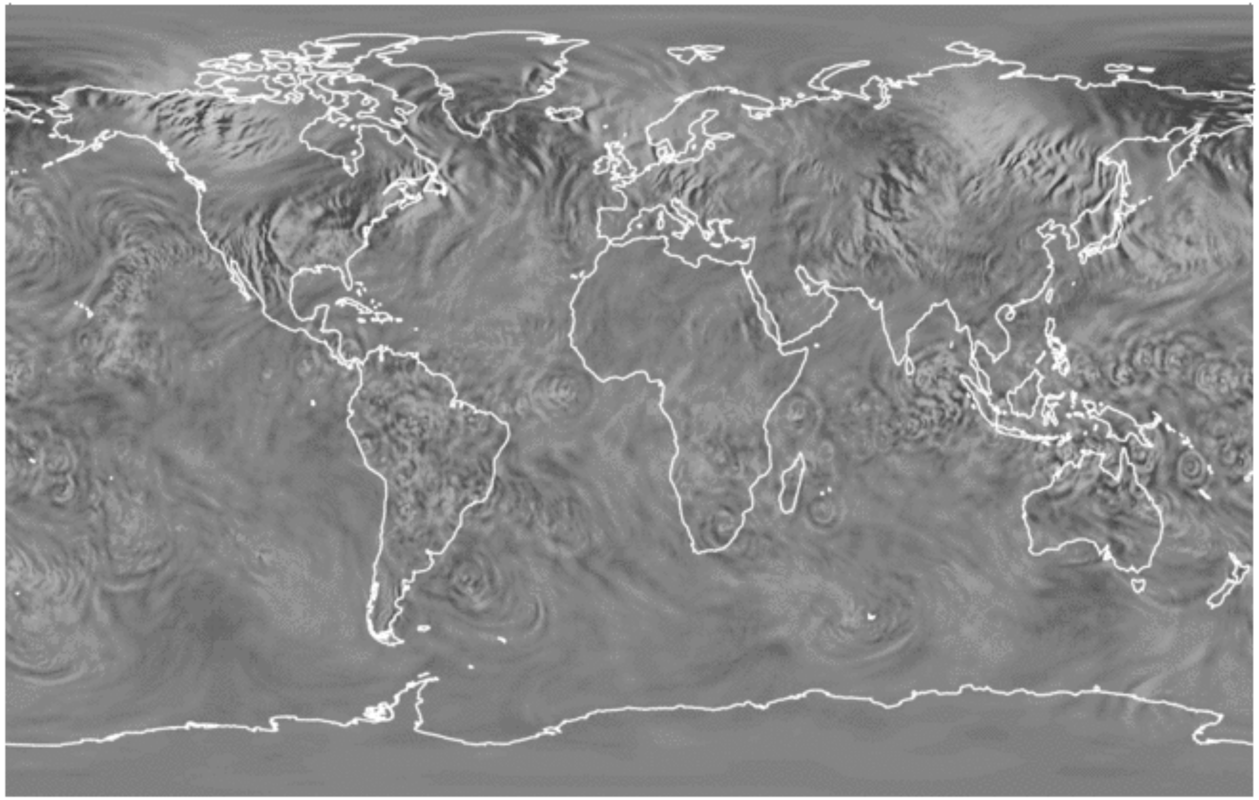
7-km GEOS-5 NR

- 2-year run produced with GEOS-5
- 7-km horizontal resolution
- Non-hydrostatic
- Cubed sphere, finite volume numerics
- Non-orographic parameterized gravity wave drag after Garcia and Boville, 1994
- 2nd order divergence damping
- Relaxed Arakawa-Schubert moist physics scheme

NR vertical resolution



NR vertical velocity on 100 hPa level



With such a high resolution model, we can study small-scale (< 1000 km) gravity waves waves, where and how they are generated, and their effects on the general circulation

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Absolute GW Momentum Flux

$$\mathbf{M}^2 = \left(1 - \frac{f^2}{\hat{\omega}^2}\right)\rho_0^2\left[\left(\overline{u'w'}\right)^2 + \left(\overline{v'w'}\right)^2\right]$$

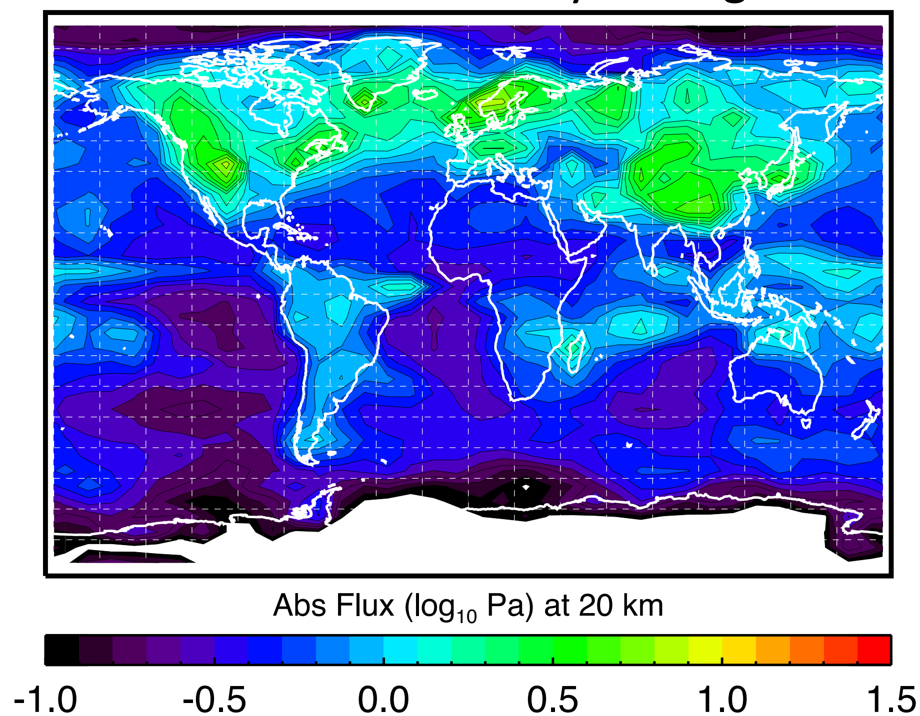
$$= \rho_0^2 w'^2 (u'^2 + v'^2)\left[1 - \frac{f^2}{\hat{\omega}^2}\right]\left[1 + \frac{f^2}{\hat{\omega}^2}\right]^{-1}, \qquad (1)$$

where $\frac{f^2}{\hat{\omega}^2} = \left(\frac{fg}{w'N^2}\right)^2\left(\frac{T'}{T_0}\right)^2.$

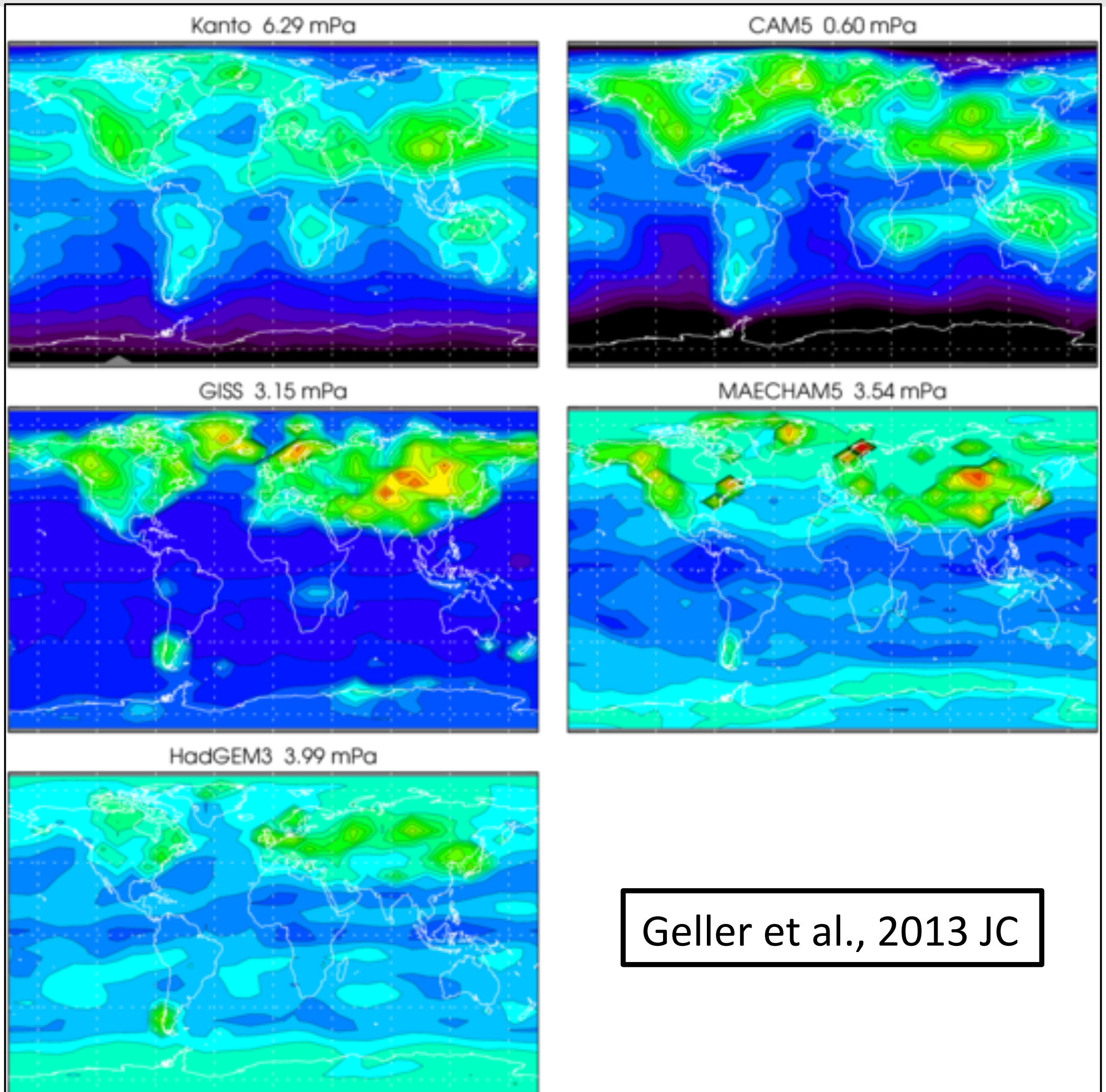
Geller et al., 2013 JC

*Primed variables < 1000 km

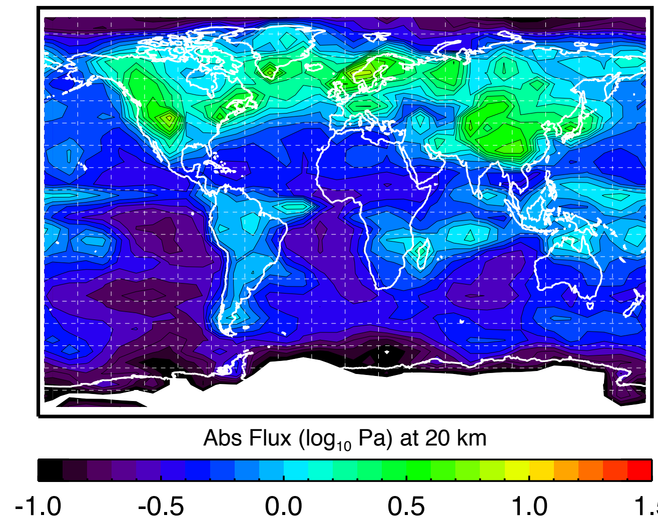
Nature Run January average



January Absolute GW Momentum Flux at 20 km

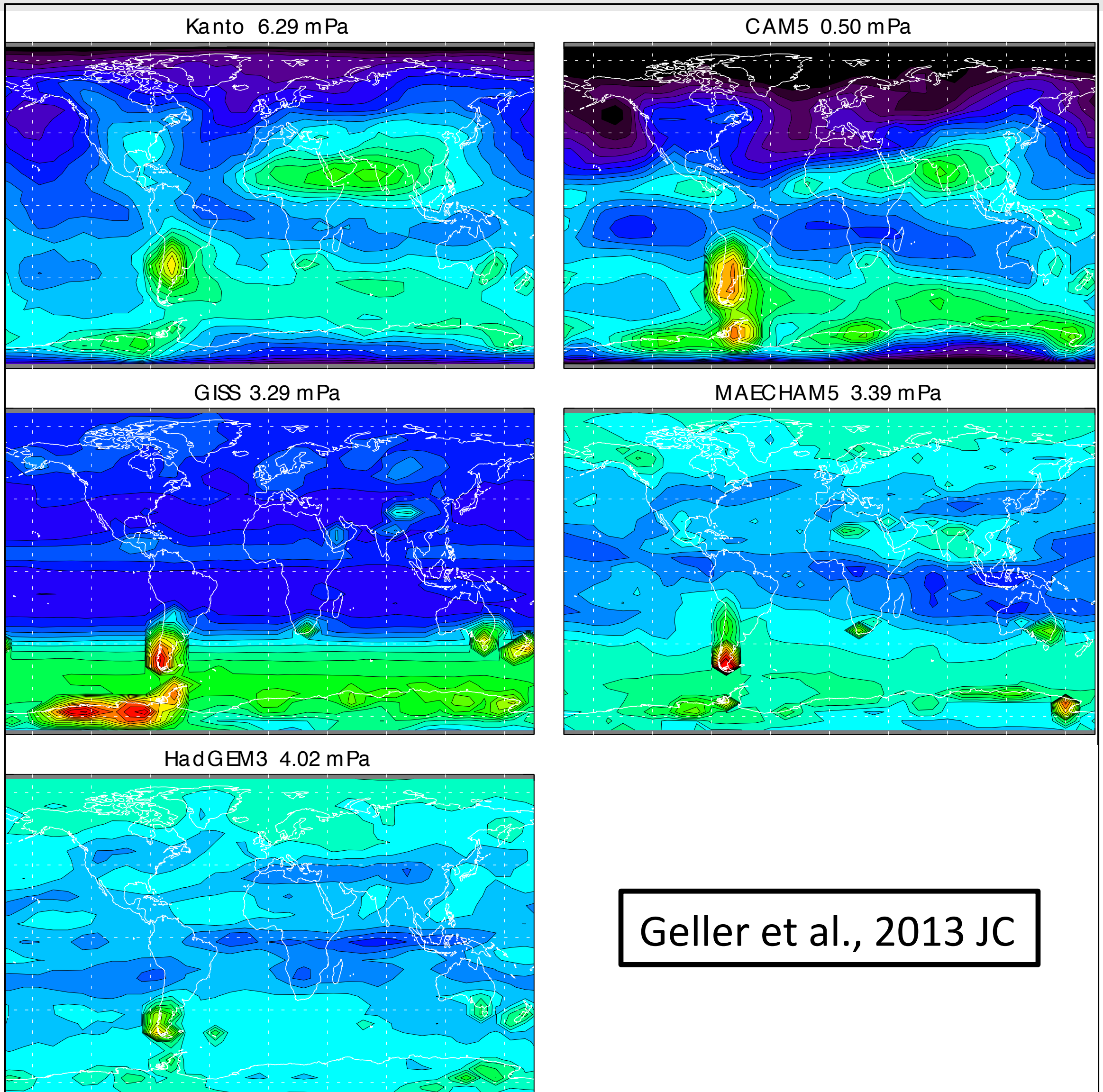


Nature Run 0.6 mPa
(Resolved GWs < 1000 km)



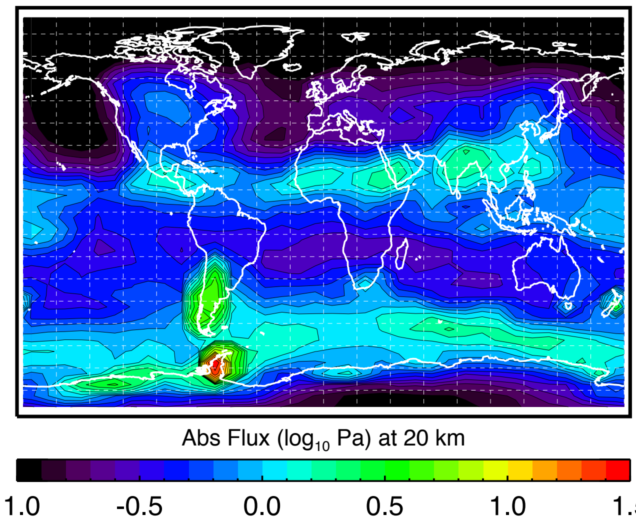
- Global variations very realistic
- Mean values on the low end (comparable to CAM5)

July Absolute GW Momentum Flux at 20 km



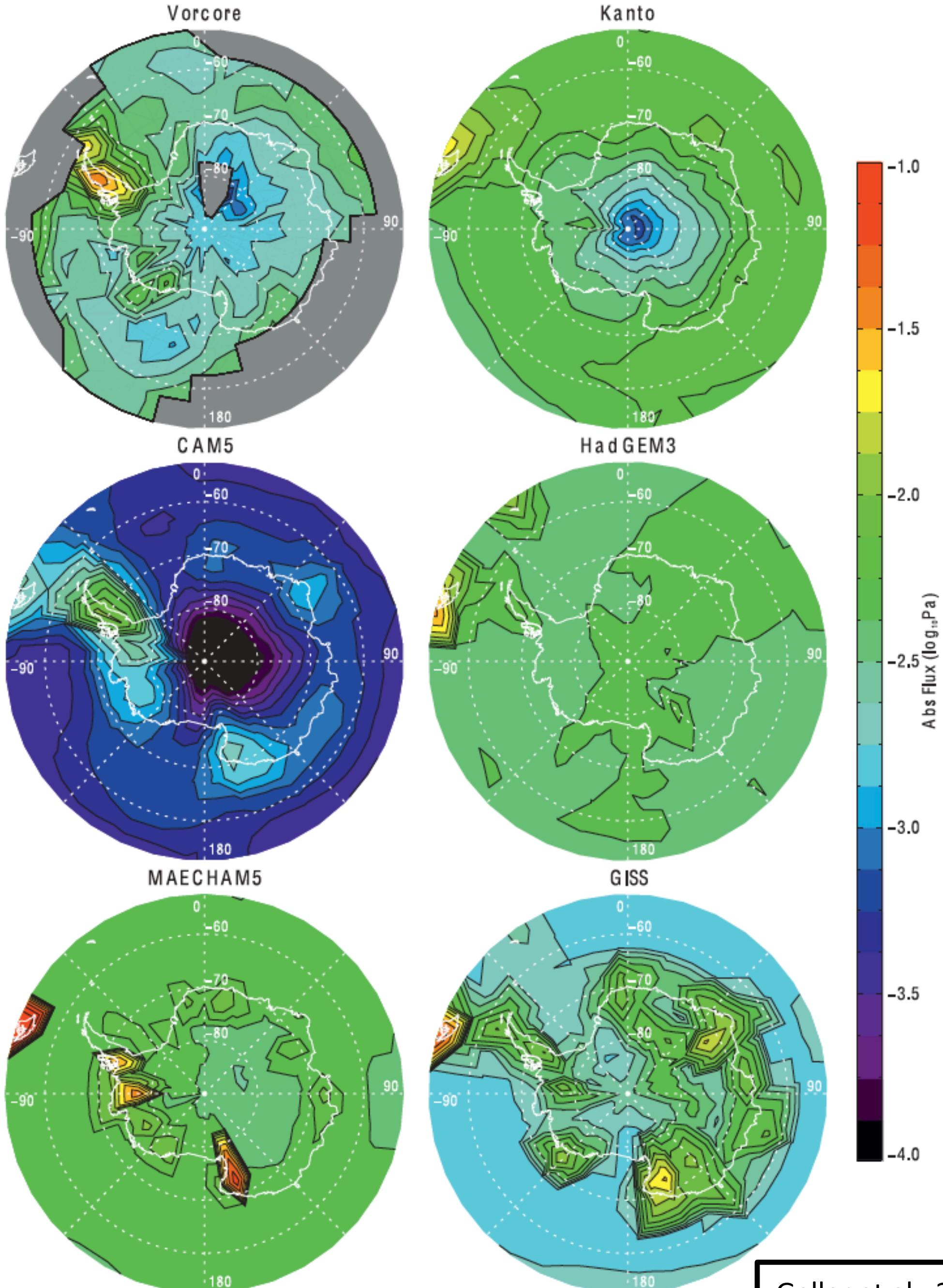
Geller et al., 2013 JC

Nature Run 0.6 mPa
(Resolved GWs < 1000 km)

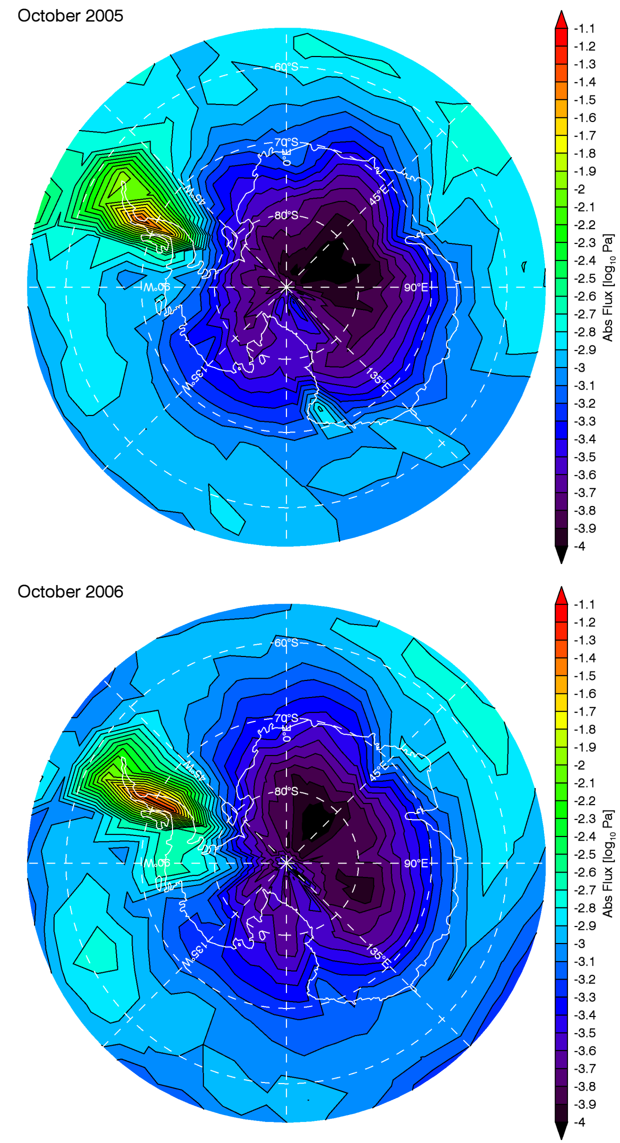


- Global variations very realistic
- Mean values on the low end (comparable to CAM5)

October 2005



Nature Run Abs Mom Flux from Resolved GWs < 1000 km at 20 km



Geller et al., 2013 JC

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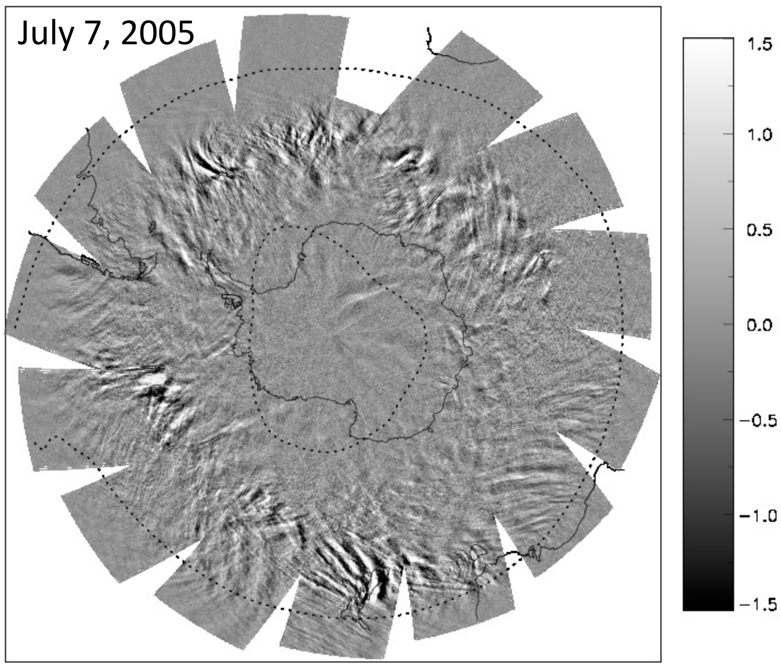
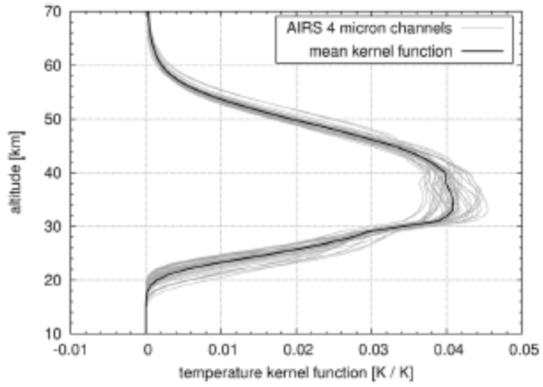
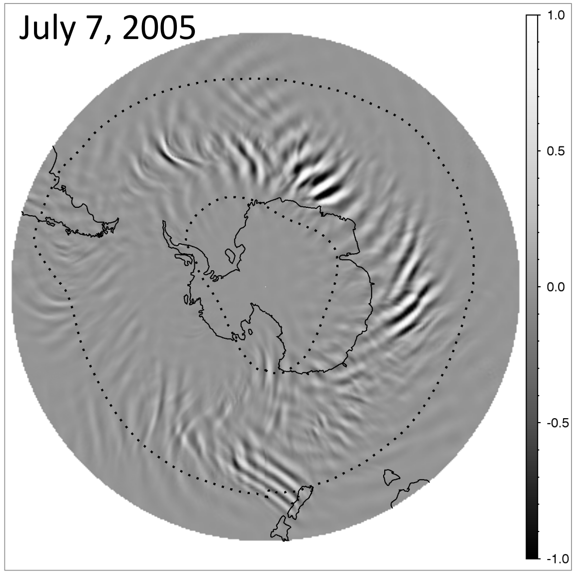
AIRS and NR brightness temperature (T_b) anomalies (< 500 km)

AIRS



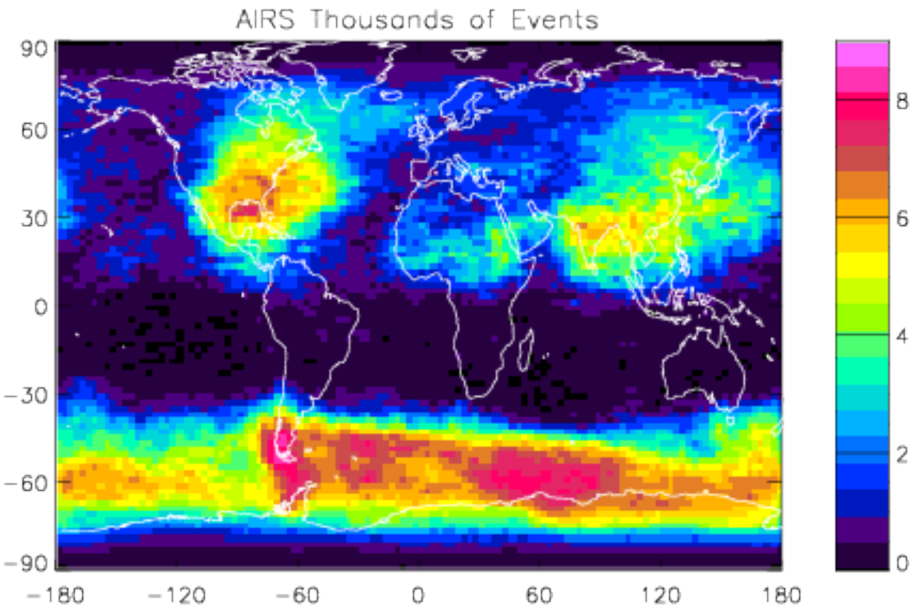


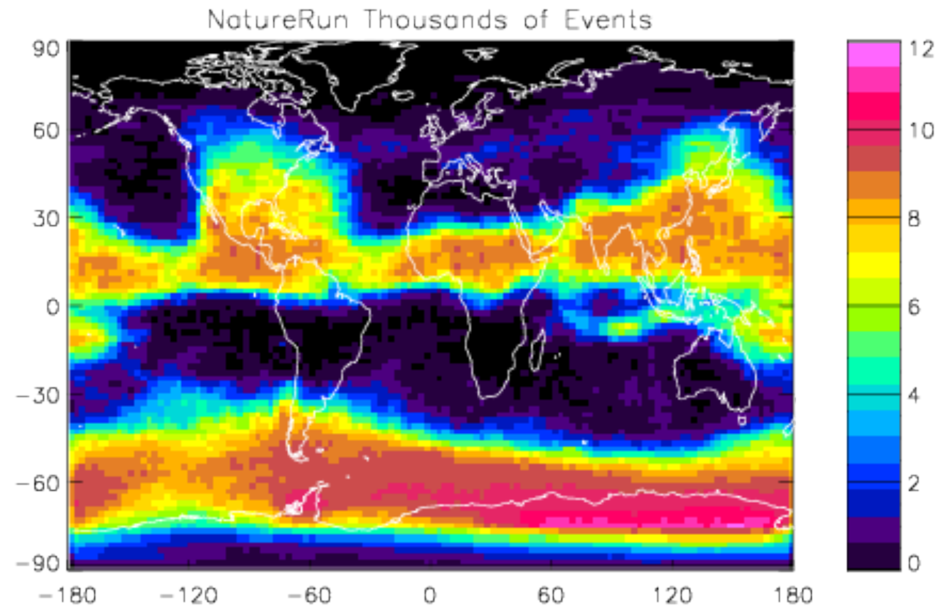
NR



Dashed lines are 40 m/s wind in lower stratosphere

AIRS & NR T_b sampled at AIRS locations: Number of events

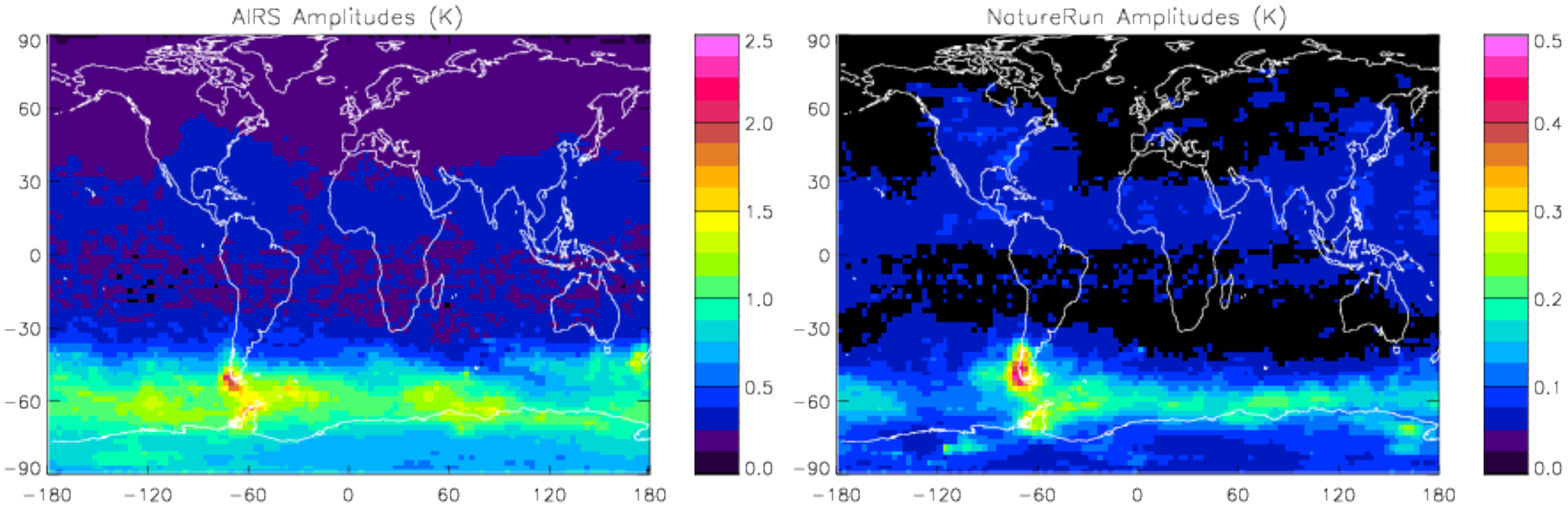




- For AIRS, events with amplitudes > 3*noise(T)
- For Nature Run, events with amplitudes > 0.02K

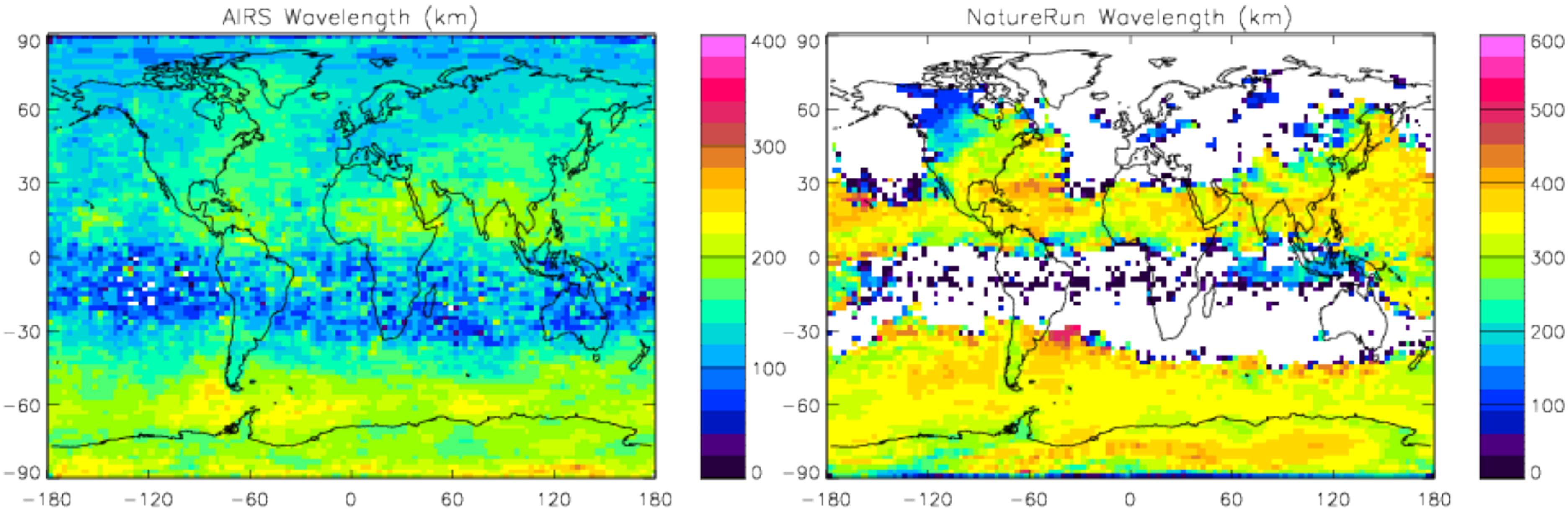
Events occur with similar global patterns

AIRS & NR T_b sampled at AIRS locations: Amplitudes



- AIRS amplitudes are about 5x larger than NR
- Global patterns are very similar

AIRS & NR T_b sampled at AIRS locations: Wavelengths

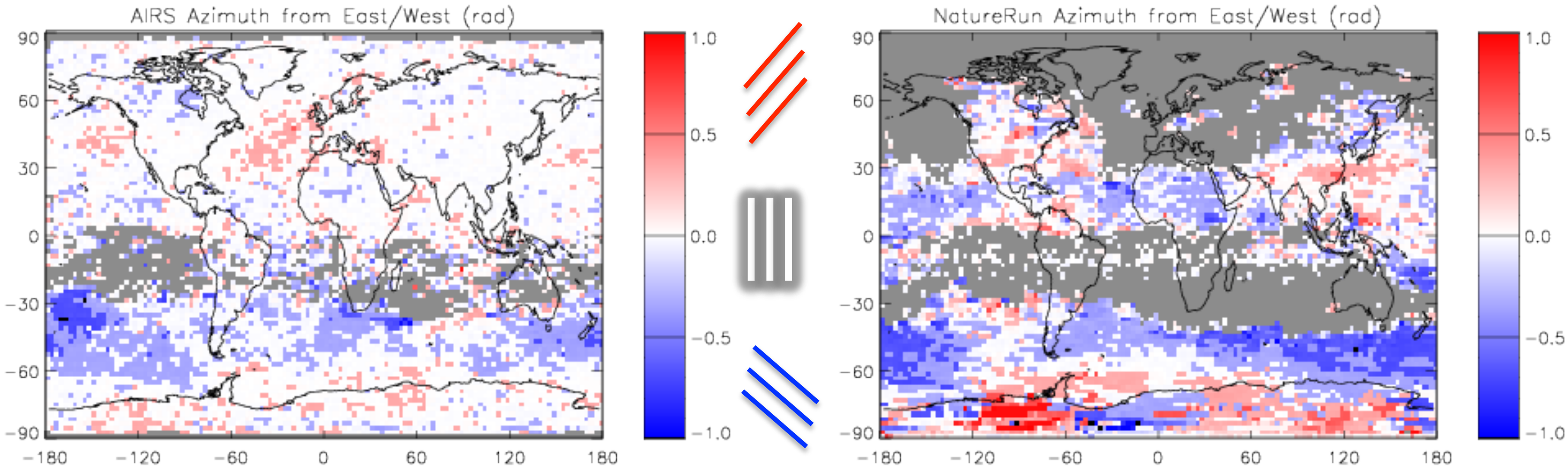


White = little or no data

AIRS Wavelengths are about 2x smaller than NR

AIRS & NR T_b sampled at AIRS locations: Propagation direction

Phase Line Orientation



Gray = little or no data

- At 30-40km altitude, AIRS sees waves propagating latitudinally into the jets (e.g. Sato et al., 2009)
- Nature run shows this even more clearly
- AIRS waves propagate mostly within +/- 30 degrees from zonal except in SH winter

Recap: GW comparisons

- Global pattern of gravity wave absolute momentum flux in NR compares well to other models but global means are on the low end
- Gravity wave absolute momentum flux in SH compares very well to Vorcore over Antarctic peninsula but is weaker on average
- NR is similar to AIRS in global pattern, but NR waves are smaller amplitude and longer wavelength

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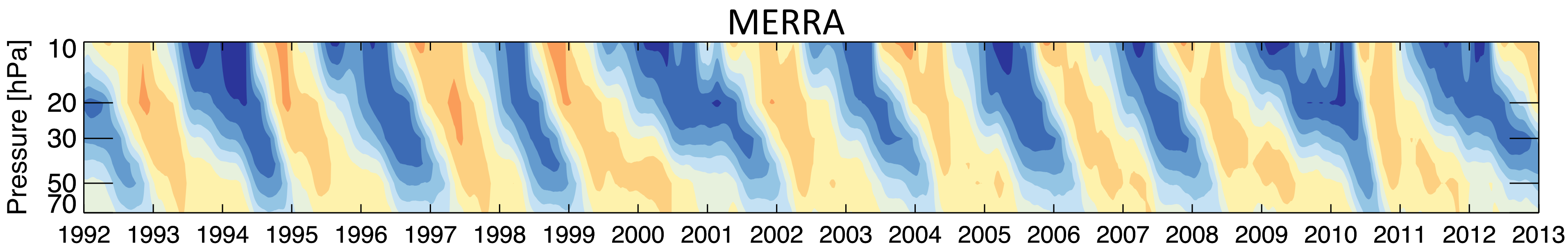
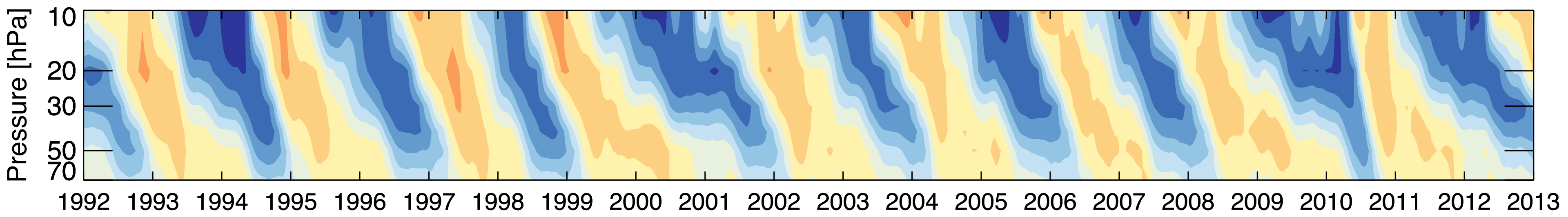
Quasi-biennial oscillation in tropical lower stratosphere winds



- QBO is driven by a continuum of waves, from large-scale Kelvin and Rossy-gravity waves to small-scale gravity waves
- The details of this wave spectrum are still not understood
- More than half of the forcing is due to gravity waves that must be parameterized by GCMs in order to obtain a model QBO
- Model QBOs are very sensitive to changes to many parameters, including resolution, GW parameterization, and dynamical core

Modeling the QBO is extremely challenging

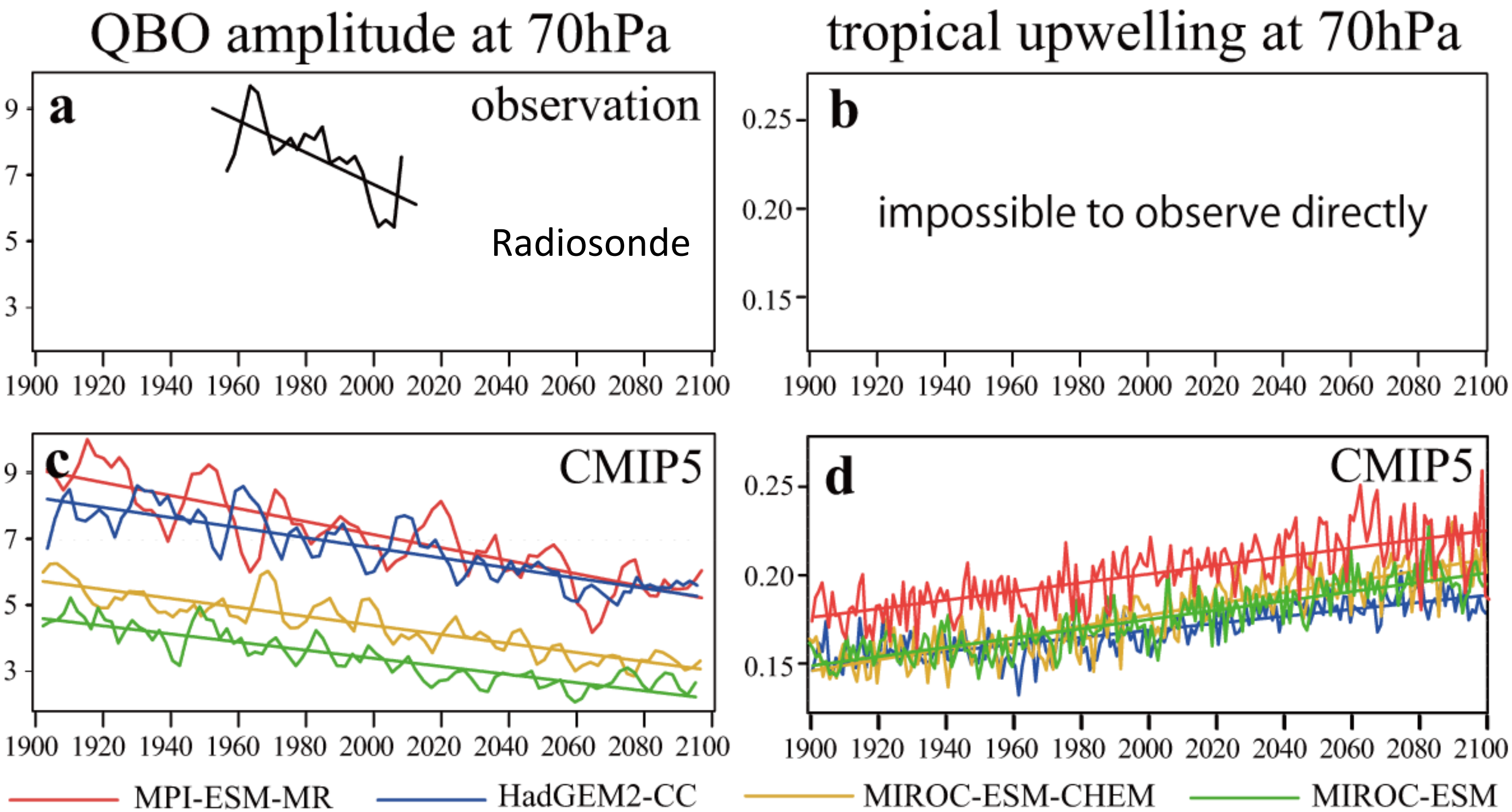
Quasi-biennial oscillation in tropical lower stratosphere winds



Why do we care about having a QBO in models (and for the right reasons)?

- Influences tropical-extratropical teleconnections and seasonal forecasts of the North Atlantic Oscillation [Scaife et al. 2014] and tropical cyclone activity (e.g. Camargo and Sobel [2010])
- Differences in wave forcing and/or QBO winds in the lowermost stratosphere could affect tropical upwelling
- How will QBO change with climate? Implications?

Evidence the QBO is changing with warming climate



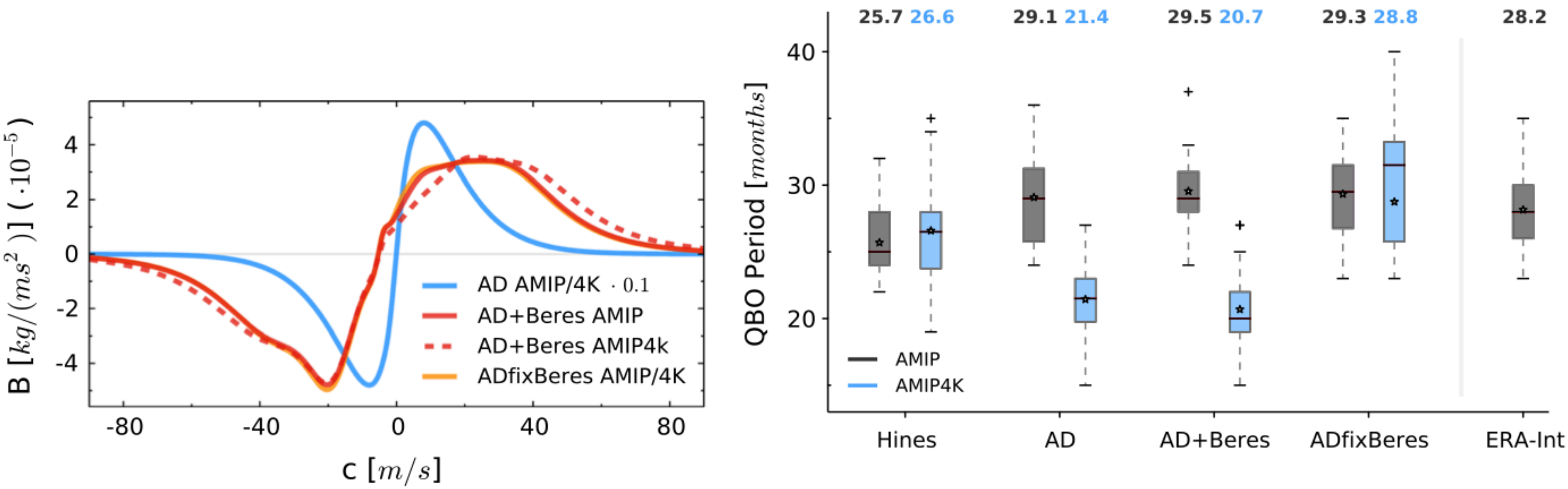
Kawatani and Hamilton, 2013 Nature

- Evidence that QBO winds near tropopause have grown weaker with time
- Consistent with model predictions that the Brewer-Dobson circulation is growing stronger, and will continue to do so in the future

The quasi-biennial oscillation in a warmer climate: sensitivity to different gravity wave parameterizations

Schirber et al [2014]

Effects of changes to the model's gravity wave scheme on the simulated QBO.



- Subtle changes in the gravity wave parameterization details gave different predictions for changes in the QBO in a warmer climate
- A previous study predicts a lengthened future QBO period, but here many experiments gave a shorter period

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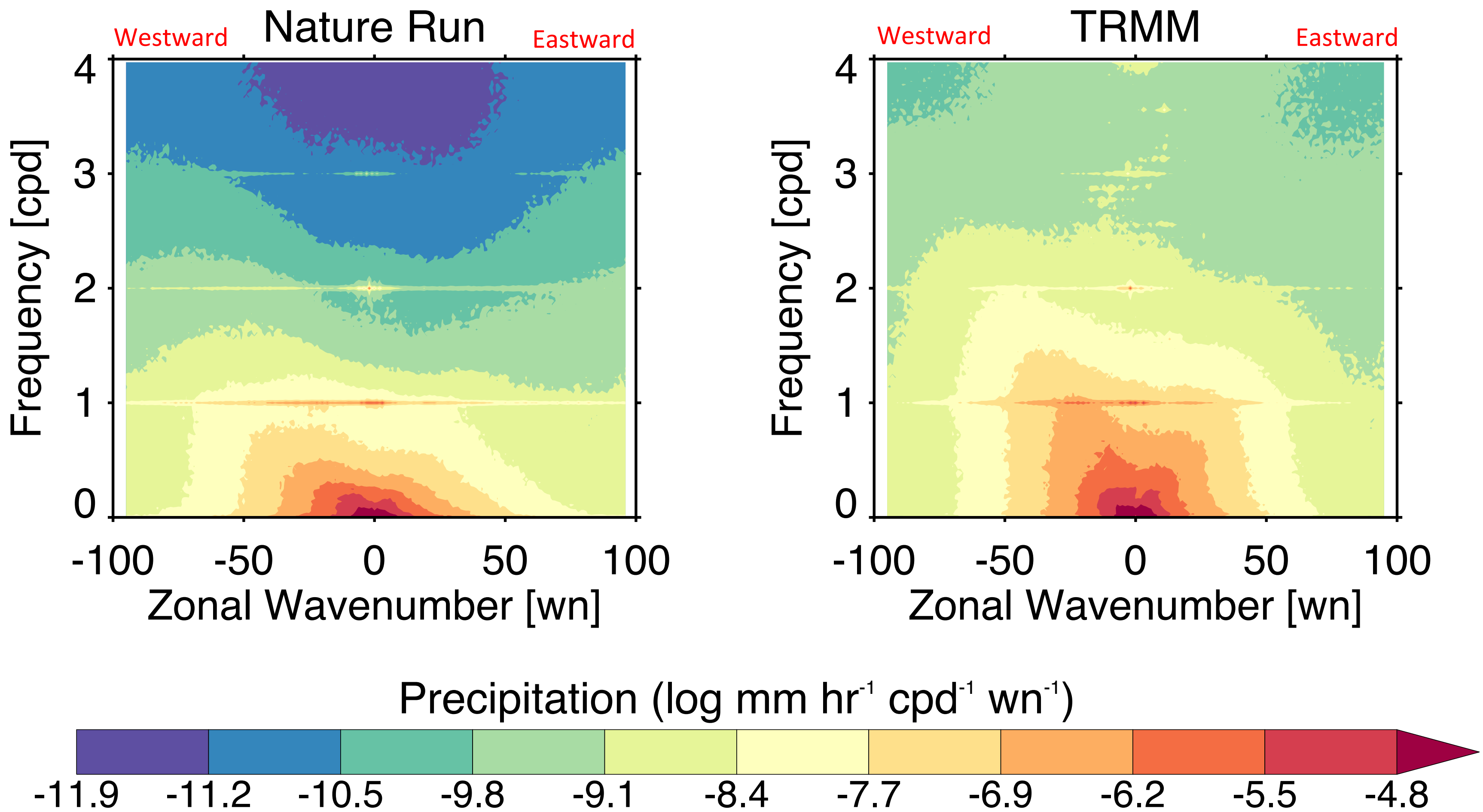
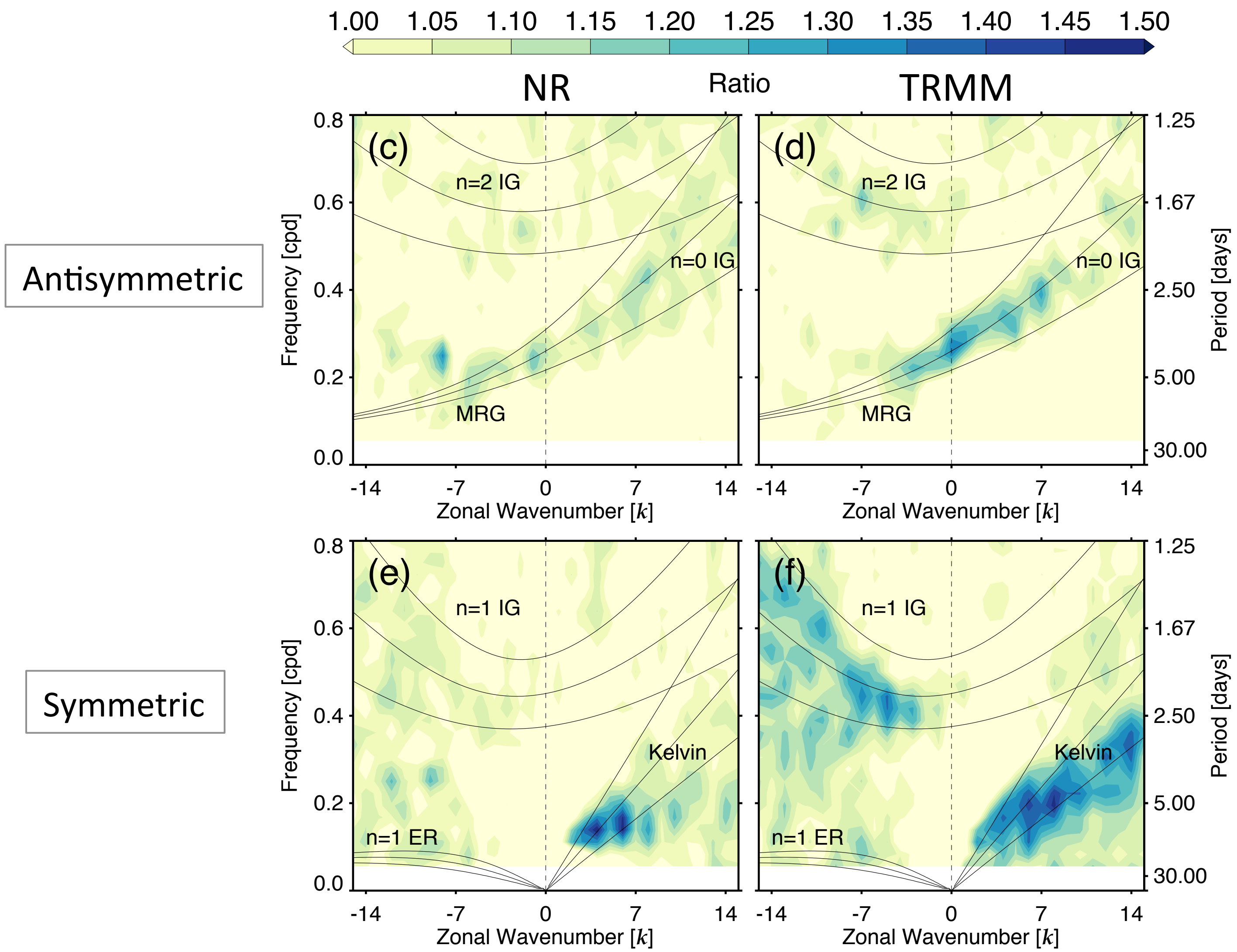
NR reproduces broad range of convectively coupled waves



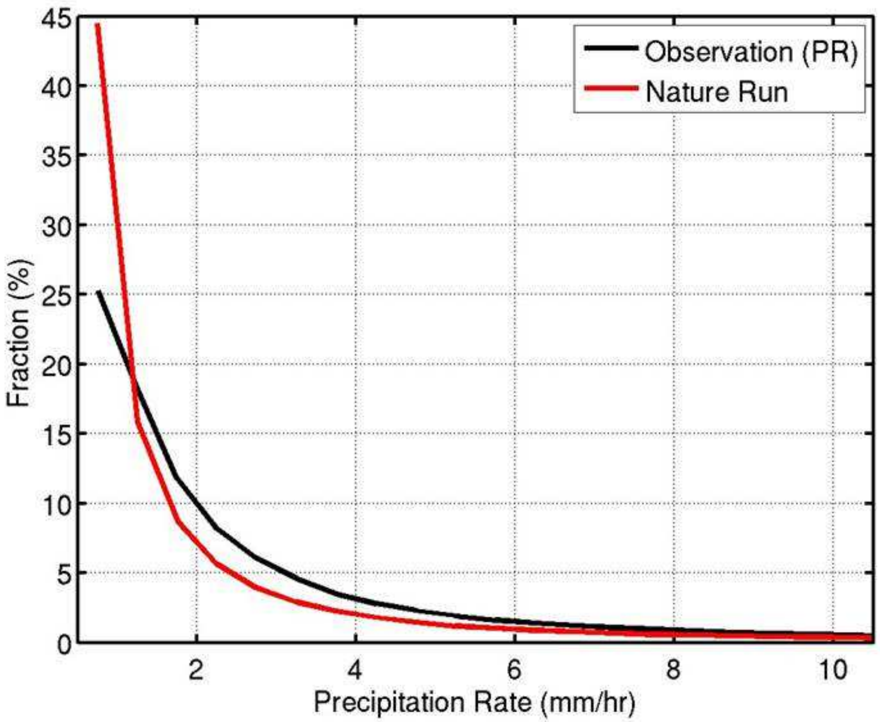
TRMM spectrum reproduced from Kim and Alexander, 2013

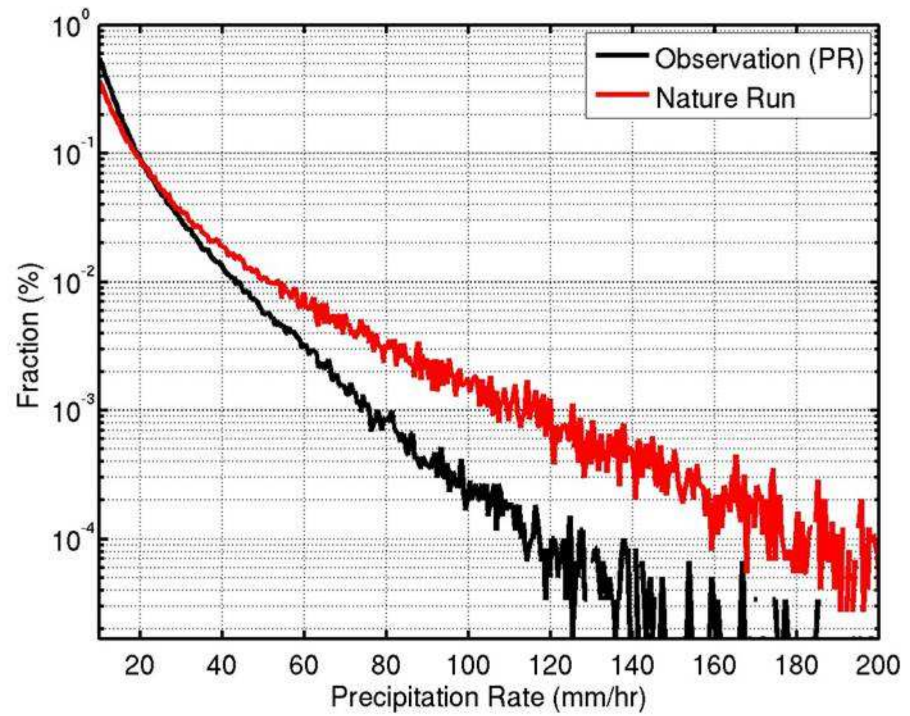
NR precipitation spectra with background removed



NR has the same preferred modes of variability as the real atmosphere

Probability distribution of surface precipitation compared to TRMM

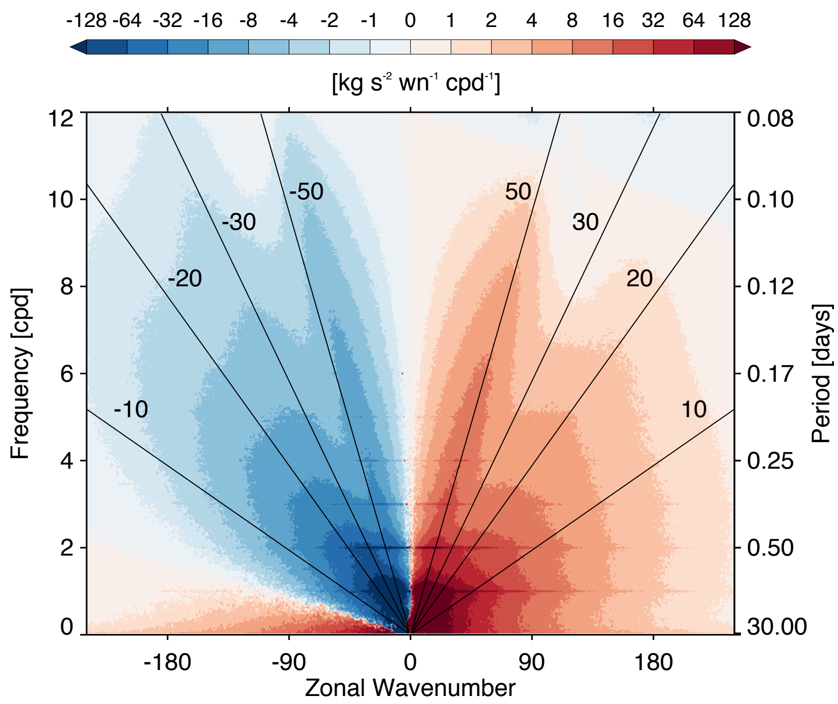




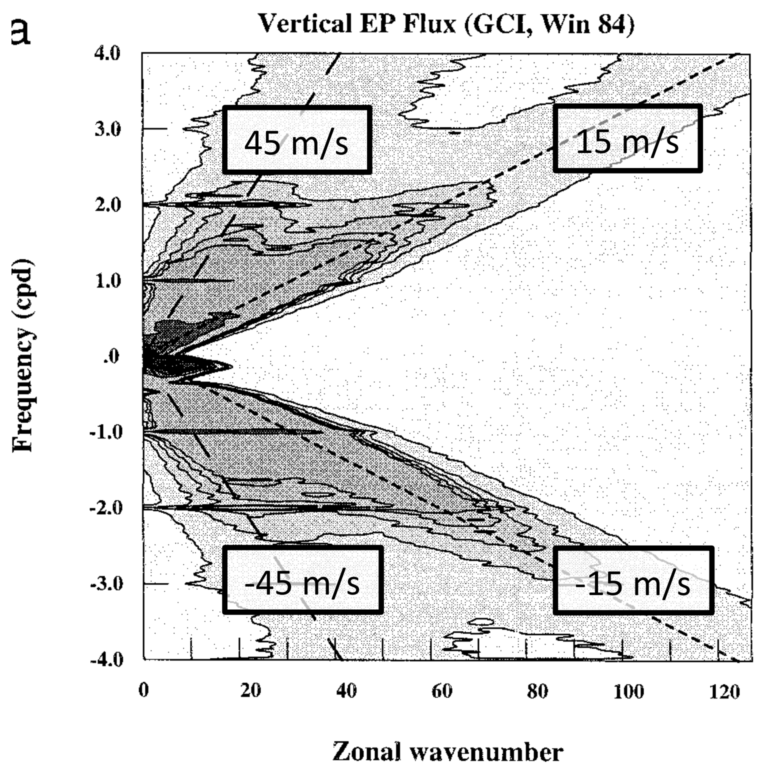
- NR > TRMM for light precipitation (<1 mm/hr) and heavy precipitation (> 20 mm/hr)
- NR < TRMM for precipitation between 1 and 20 mm/hr

NR vertical EP-Flux compared to that derived from Global Cloud Imager

NR



GCI

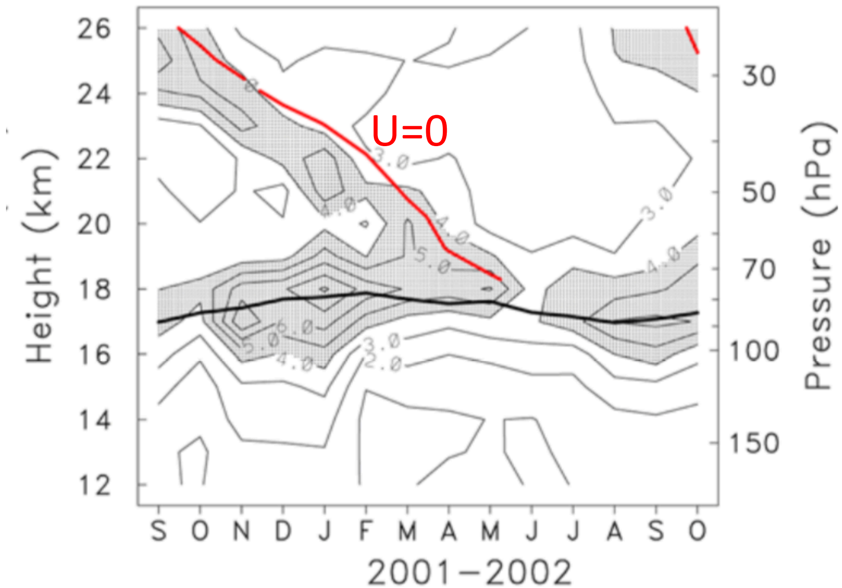


- Double lobe structure is present in NR
- NR captures the high phase speed lobe

Ricciarduli and Garcia, 2000 JAS

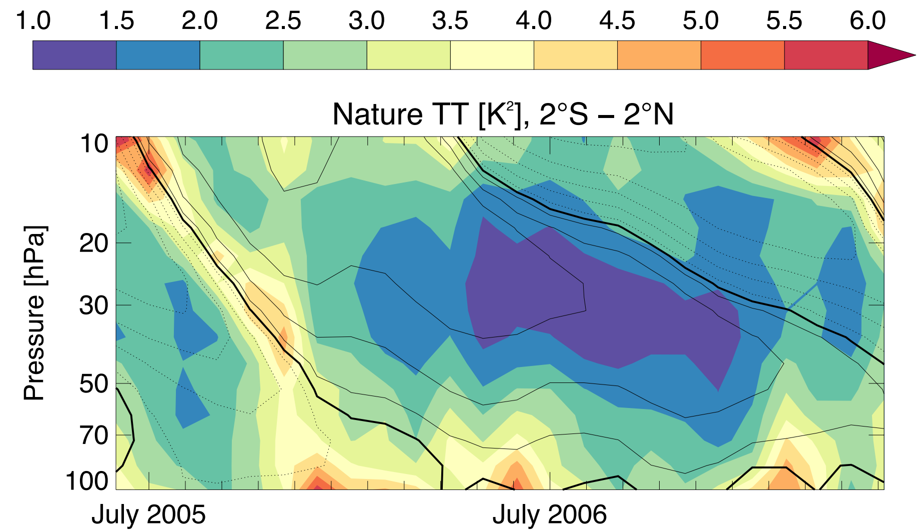
Small-scale temperature variance

GPS radio occultation T’^{2}



Randel and Wu, 2005 JGR

NR T’^{2}



- Small-scale waves drive tropopause T variance
- Interaction between small-scale waves and u=0 region

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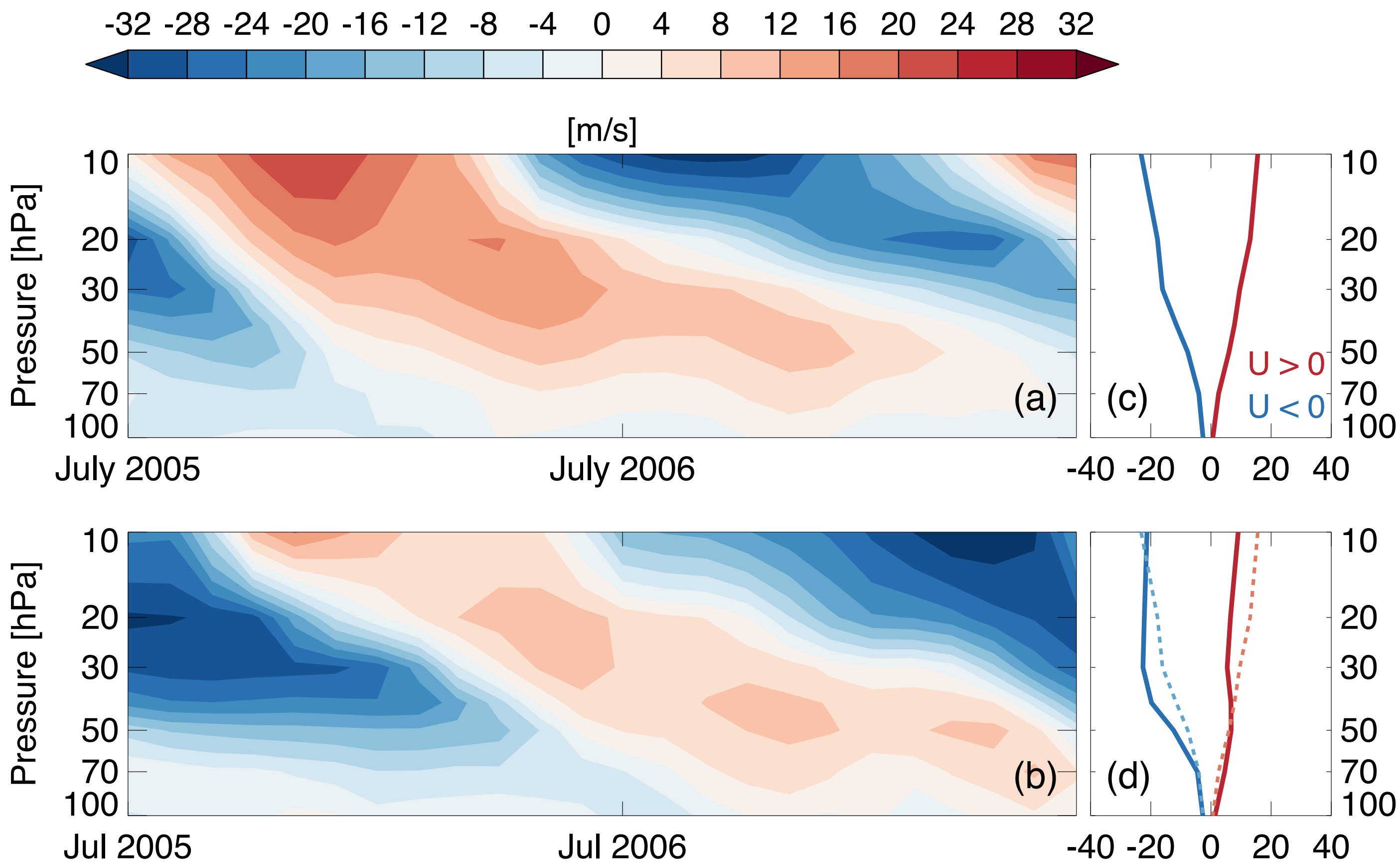
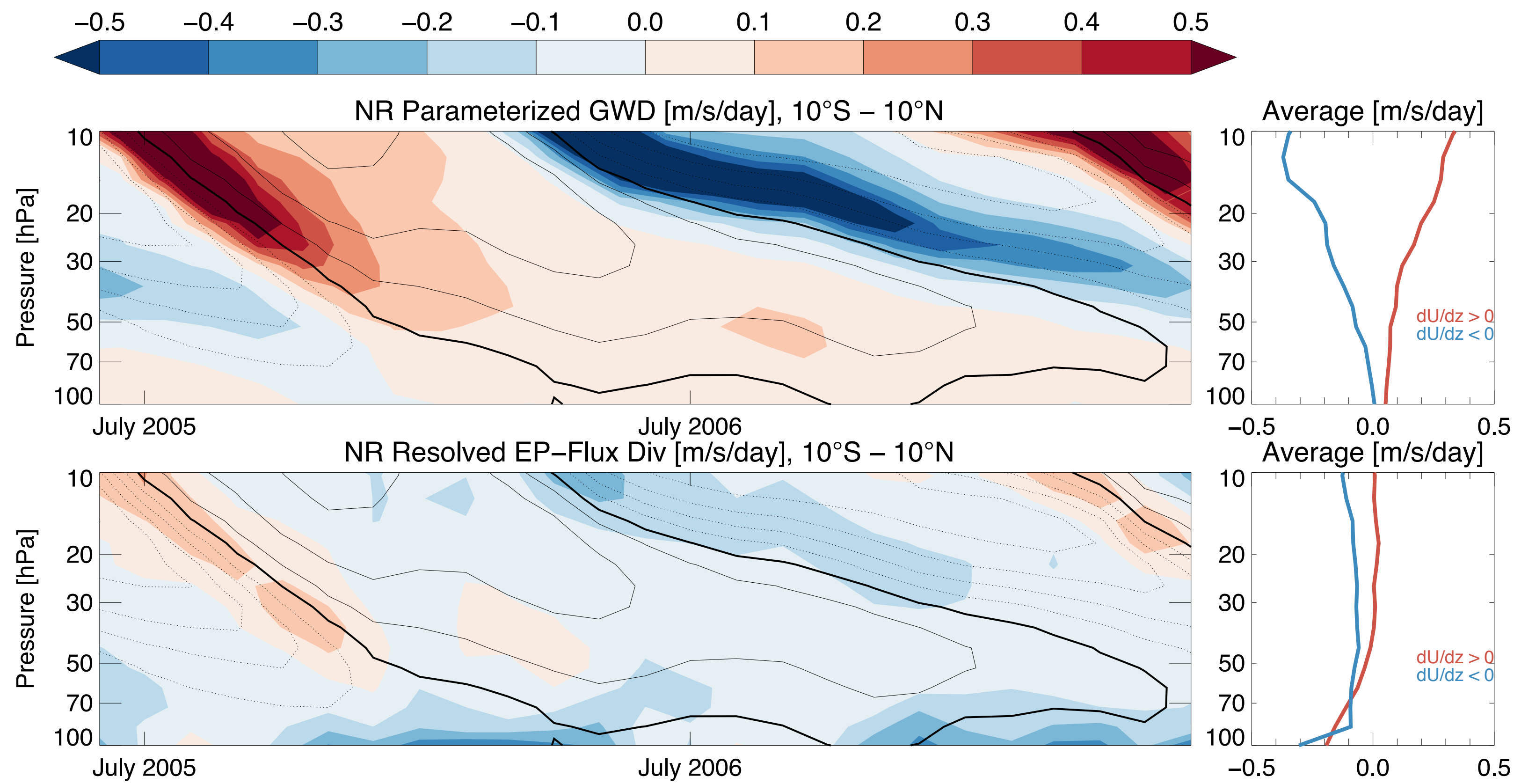
NR and MERRA-2 QBO



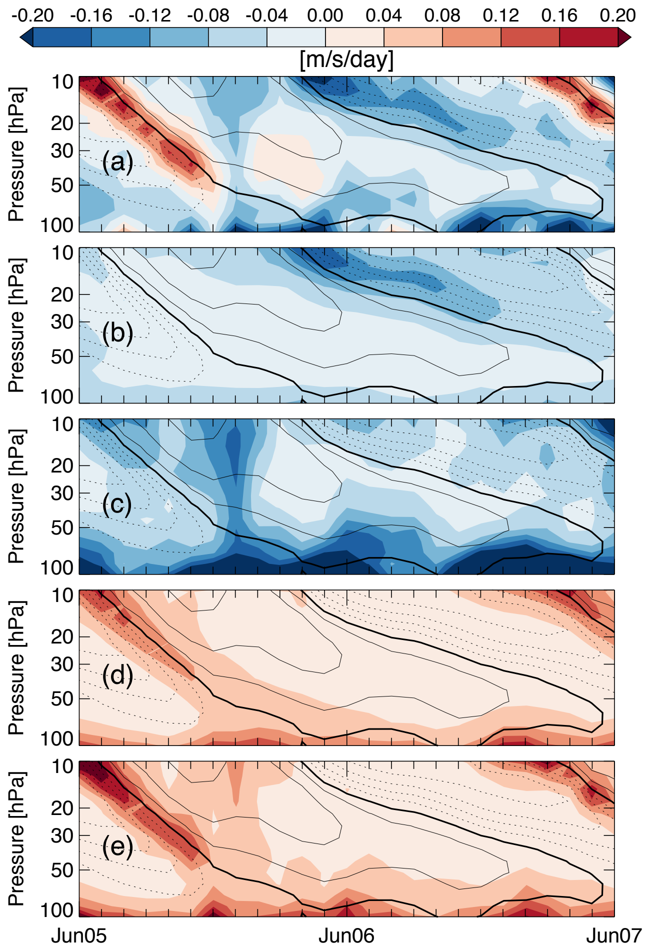
Holt et al., 2016 JAS, under review

NR parameterized GWD and resolved EP-flux divergence



Resolved EP-Flux divergence < 25 % of parameterized GWD

NR vertical EP-Flux divergence from different wavenumber-frequency bins



Total EP flux divergence

Westward small-scale waves

Westward large-scale waves

Eastward small-scale waves

Eastward large-scale waves

Small-scale

$|k| \geq 12$

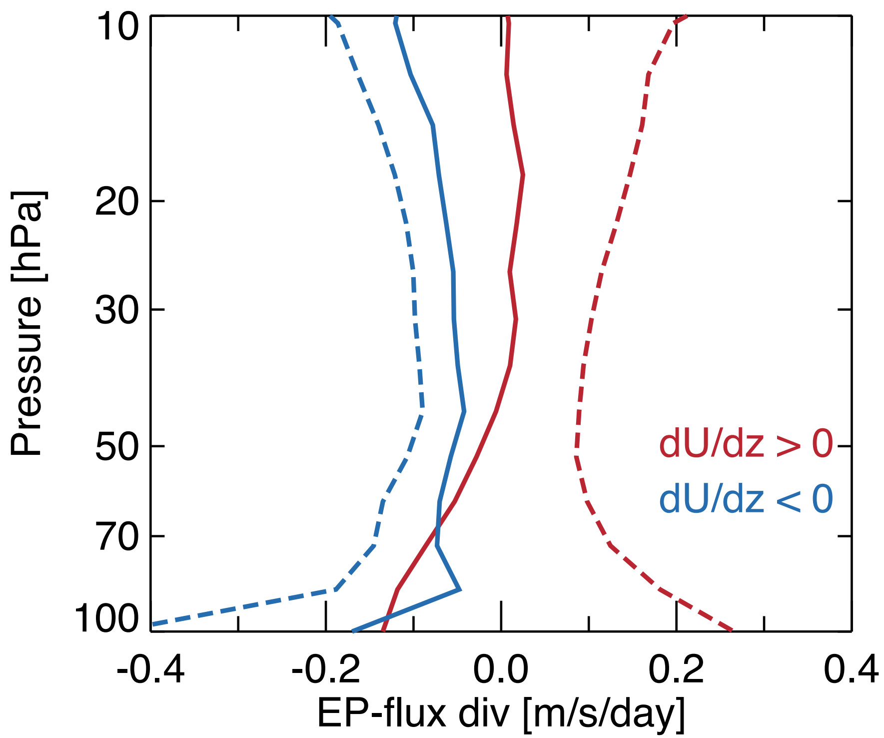
Large-scale

$1 \leq |k| \leq 11$ ($\lambda_x \approx 3600$ km)

$\omega < 1.0$ cpd

- High-frequency, small scale GWs dominate during westward shear phase
- Kelvin waves provide half of the forcing in eastward shear phase
- In agreement with previous studies (e.g. Kawatani et al., 2010)

NR EP-flux divergence averaged over shear zones



Solid lines = Total EP flux divergence in eastward shear (red) and westward shear (blue) zones

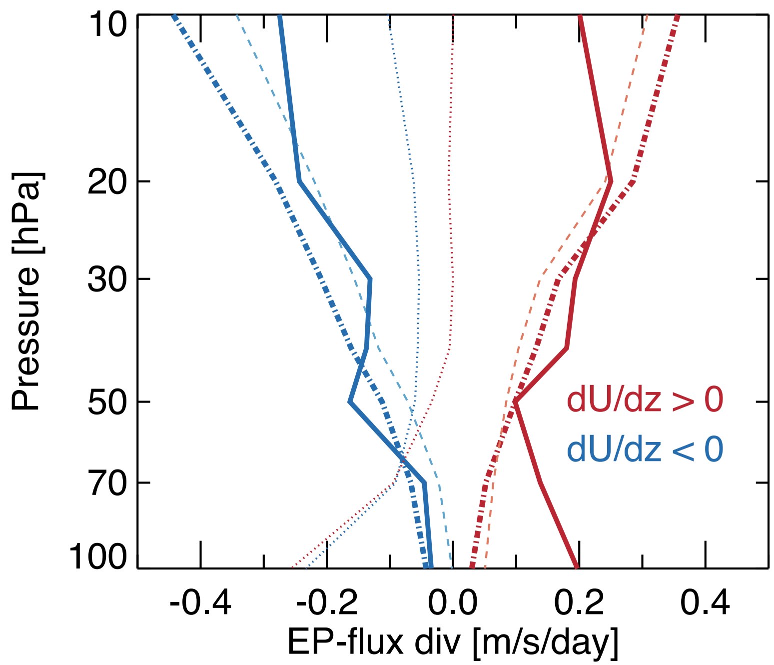
Dashed lines = Only eastward (westward) EP flux divergence in eastward (westward) shear zones

Large amount of cancelation in both shear zones and especially in westerly shear zones

NR vertical EP-flux div compared to MERRA-2 total zonal forcing

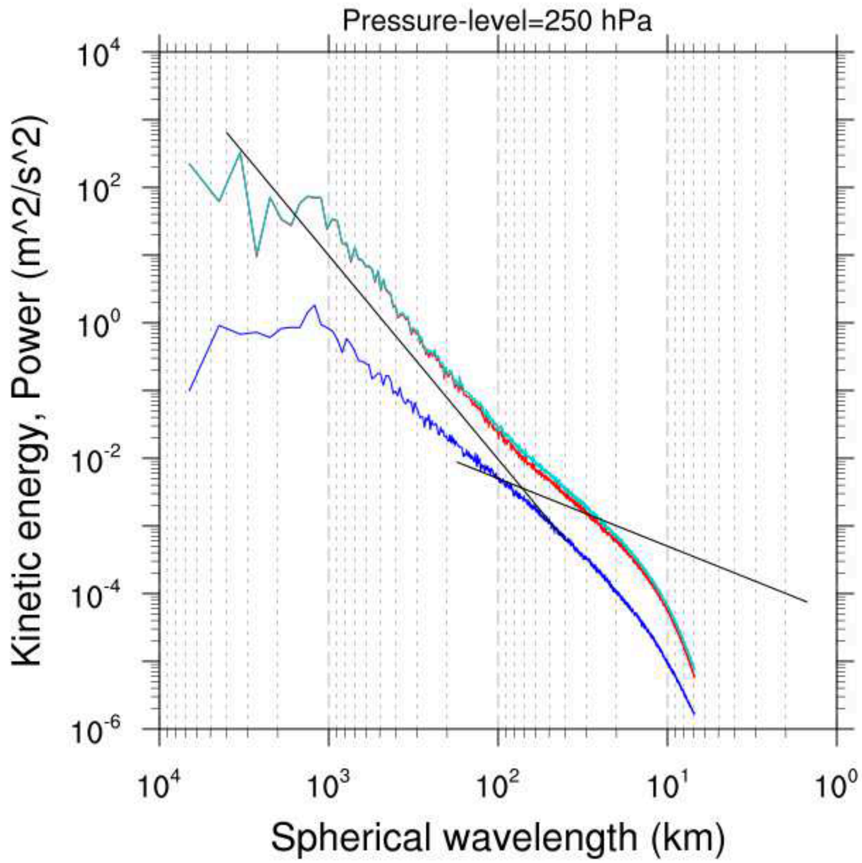
$$\frac{\partial \bar{U}}{\partial t} + \bar{w}^* \frac{\partial \bar{U}}{\partial z} = \bar{X} + \left(\rho_0 a \cos\phi\right)^{-1} \vec{\nabla} \cdot \vec{F}$$

1	2	3
solid	dashed	dot-dash



Without large amount of cancelation perhaps the parameterized GWD could be tuned down

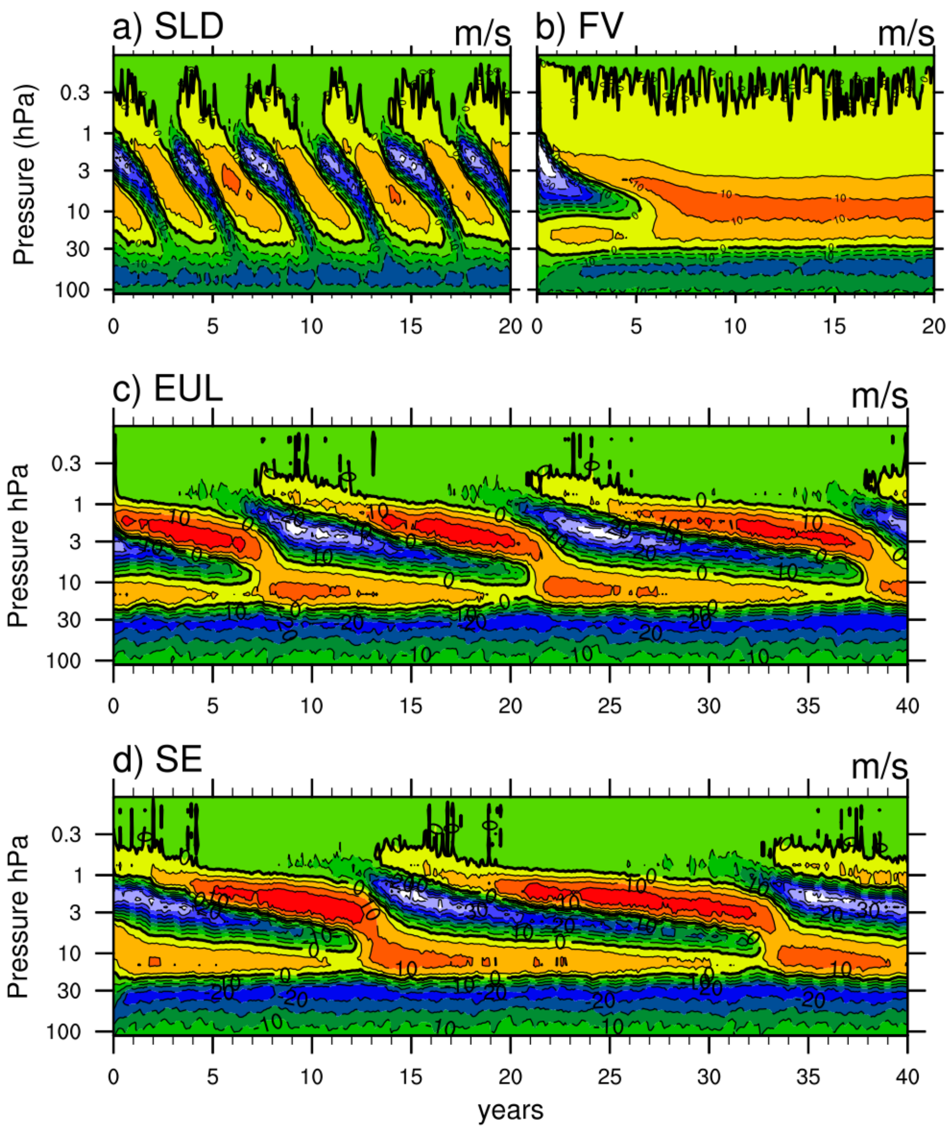
Too much dissipation?



- NR KE spectrum follows n^{-3} law for large scales
- NR KE spectrum falls off sharply as horizontal wavelength approaches smaller scales

Characteristic of unrealistically large dissipation at the smallest resolved model scales

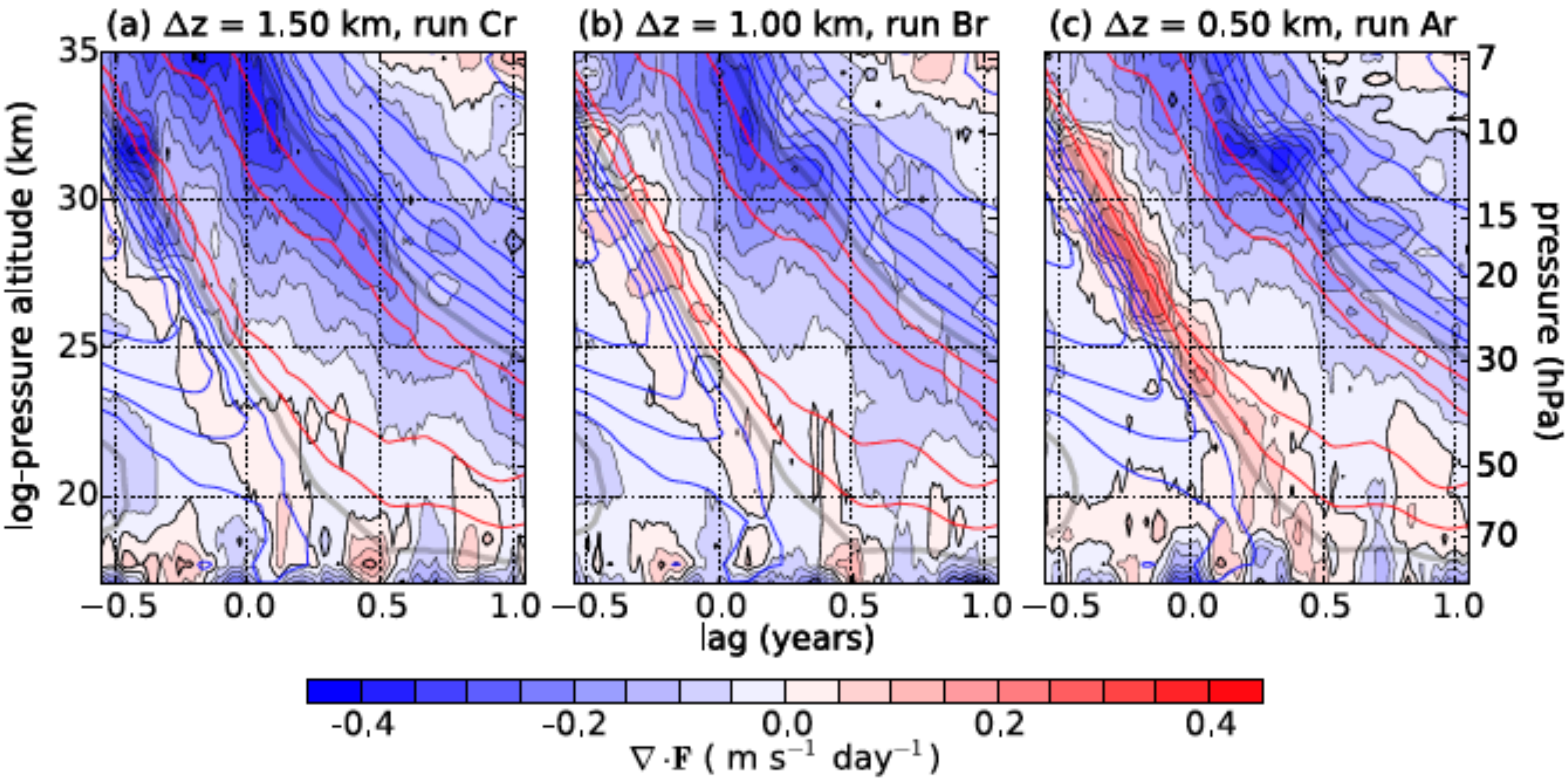
Influence of dynamical core choice?



- Dry GCM dynamical cores
- QBO-like oscillations in all but FV
- Measures of wave activity much lower in FV

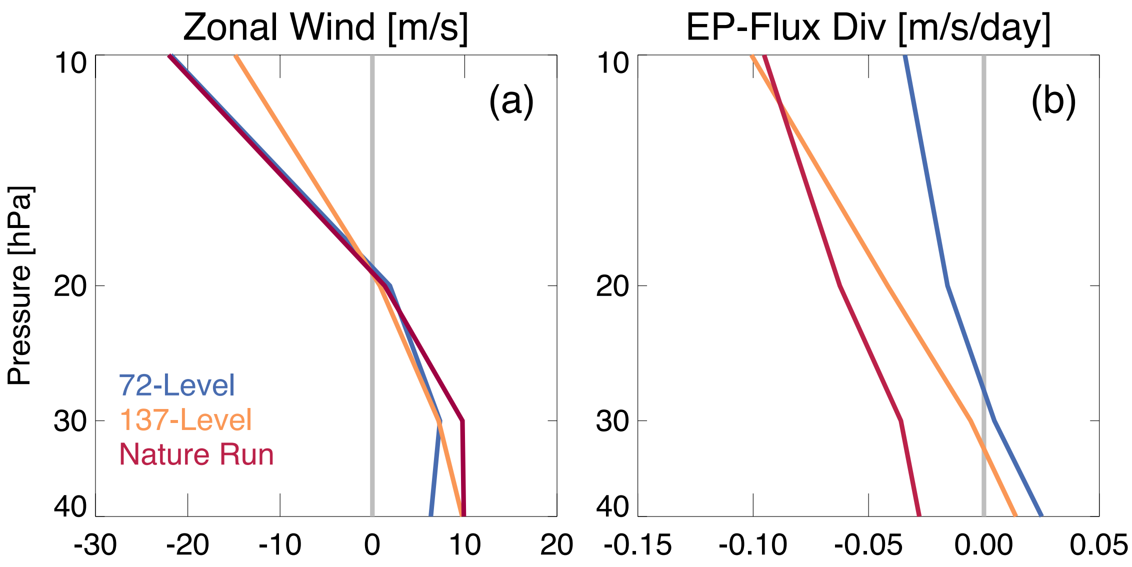
Yao and Jablonowski, 2015 JAS

Vertical resolution?



Anstey et al., 2016 JAS

Vertical resolution?



Control—1° horizontal resolution

Doubled vertical resolution

Horizontal resolution increase to 0.0625°

- Increasing the horizontal resolution by 16x leads to 4x larger EP flux divergence near 0 m/s wind line
- Doubling vertical resolution leads to 2x larger EP flux divergence near 0 m/s wind line

Recap: NR QBO

- Resolved small-scale waves in NR are well-represented and behaving realistically
- Resolved waves in NR contribute about 25% of zonal force for QBO
- Still need parameterized GWs to get QBO
  - Vertical resolution?
  - Too much dissipation/damping? Dynamical core?

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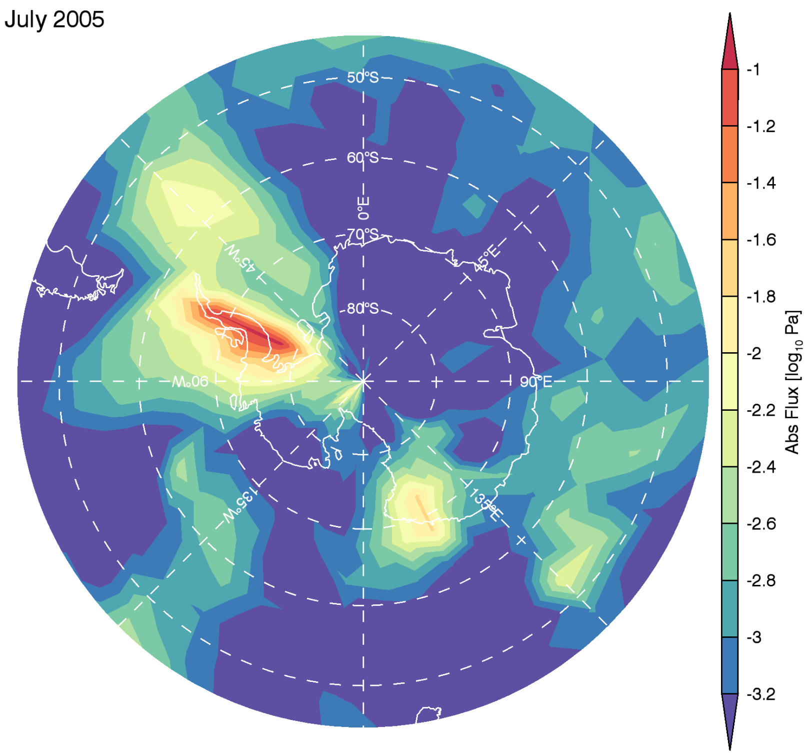
GW sources in the SH

GW (<1000 km) Abs Mom Flux at 15 km



Binned to 10° lon x 5° lat

Can we relate large-scale diagnostics of convection, fronts, and geostrophic adjustment in the troposphere to the GW momentum flux in the lower stratosphere?

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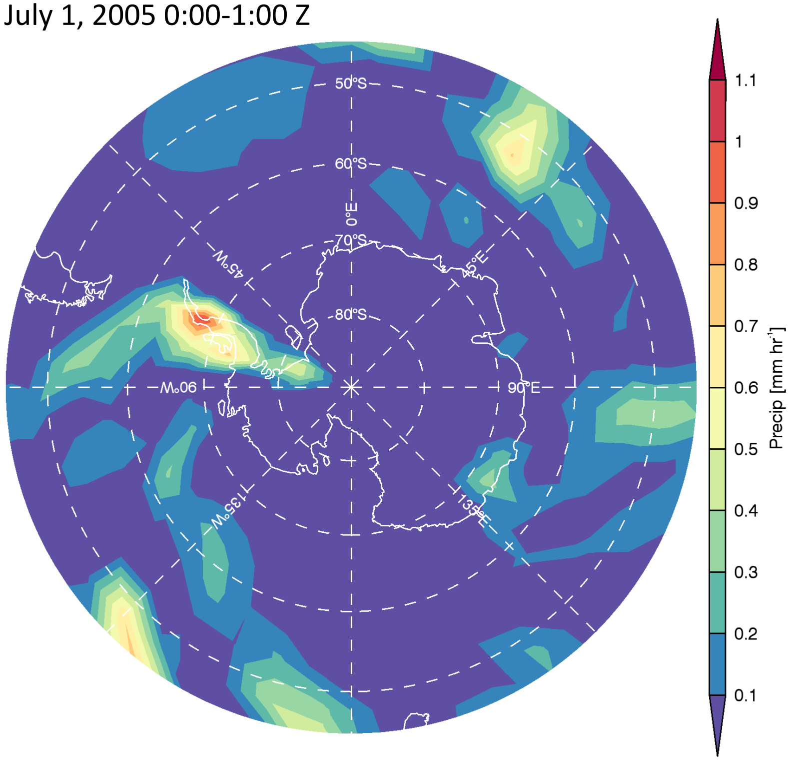
Convection

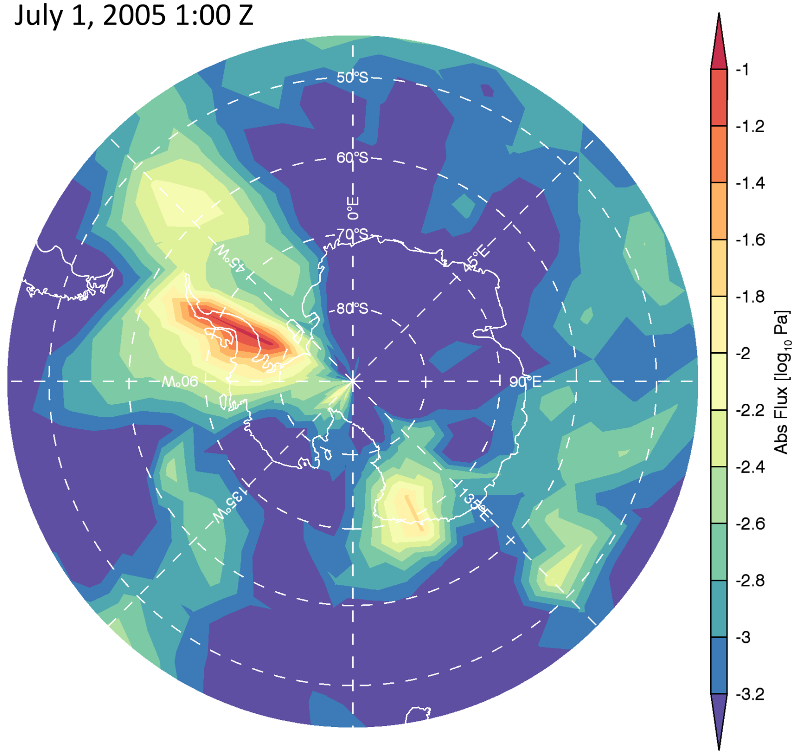
July 1, 2005 Precipitation (hourly average)

GW (<1000 km) Abs Mom Flux at 15 km

July 1, 2005 0:00-1:00 Z



July 1, 2005 1:00 Z



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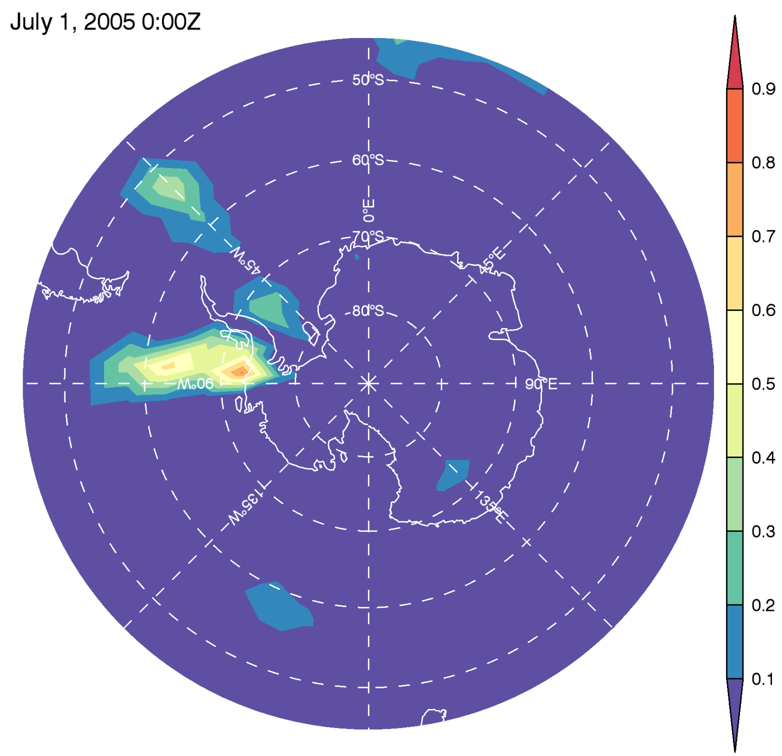
Frontogenesis function

$$\frac{1}{2}\frac{D|\nabla\theta|^2}{Dt} = -\left(\frac{1}{a\cos\phi}\frac{\partial\theta}{\partial\lambda}\right)^2\left[\frac{1}{a\cos\phi}\frac{\partial u}{\partial\lambda} - \frac{v\tan\phi}{a}\right]$$
$$-\left(\frac{1}{a}\frac{\partial\theta}{\partial\phi}\right)^2\left[\frac{1}{a}\frac{\partial v}{\partial\phi}\right] - \left(\frac{1}{a\cos\phi}\frac{\partial\theta}{\partial\lambda}\right)\left(\frac{1}{a}\frac{\partial\theta}{\partial\phi}\right)$$
$$\times\left[\frac{1}{a\cos\phi}\frac{\partial v}{\partial\lambda} + \frac{1}{a}\frac{\partial u}{\partial\phi} + \frac{u\tan\phi}{a}\right] \quad (2.1)$$

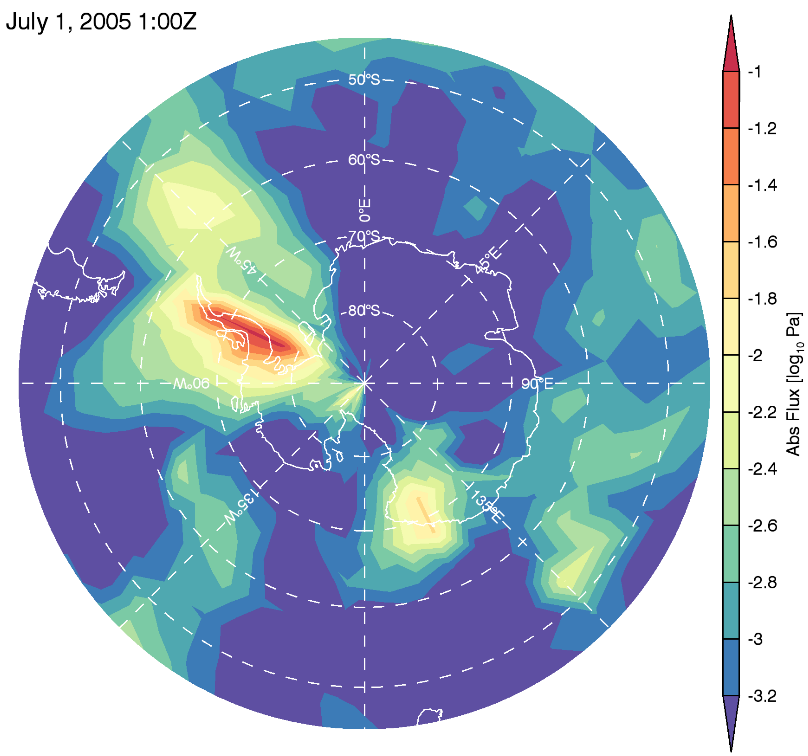
Charron and Manzini, 2002 JAS

Frontogenesis function

Frontogenesis function at 600 mbar



GW (<1000 km) Abs Mom Flux at 15 km



Outline

- 7-km GEOS-5 Nature Run (NR)
- Global evaluation of NR gravity waves in the stratosphere
- Tropical waves and the QBO in NR
- GW sources in the SH in NR
  - Convection
  - Fronts
  - Geostrophic adjustment
- Conclusions

Geostrophic adjustment

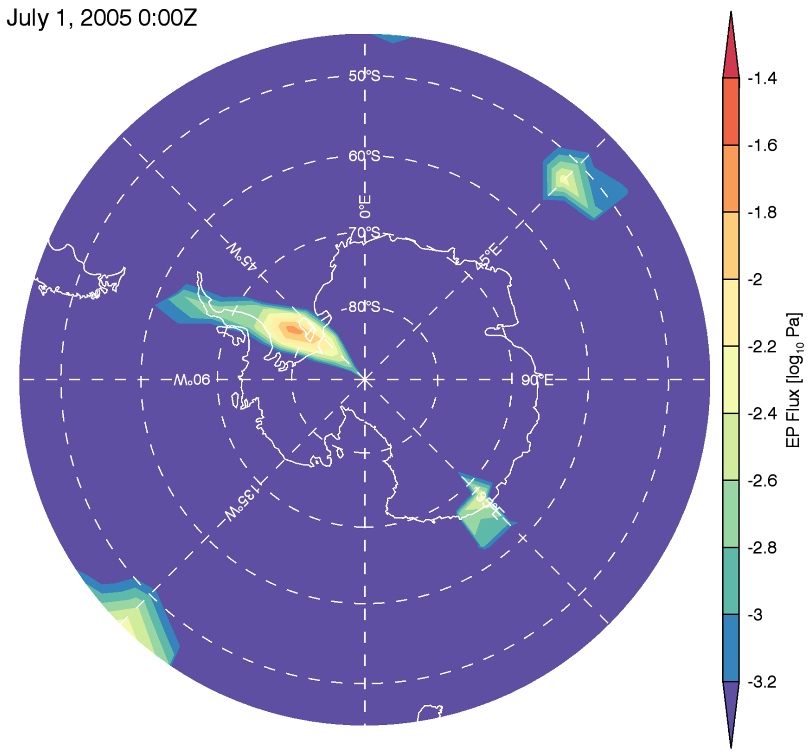
Spontaneous emission of gravity waves from PV anomalies in a vertical shear produce a gravity wave EP-flux given by:

$$F = \frac{F_0}{4} e^{-\pi\sqrt{J}}$$

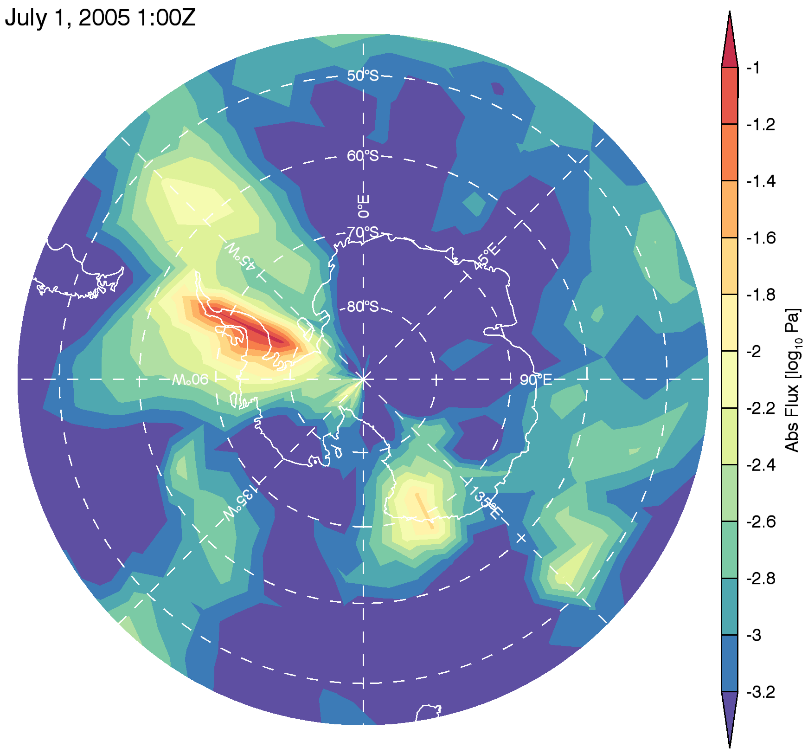
J=Richardson number

Lott et al., 2010 JAS

Estimate of EP-flux due to PV anomalies



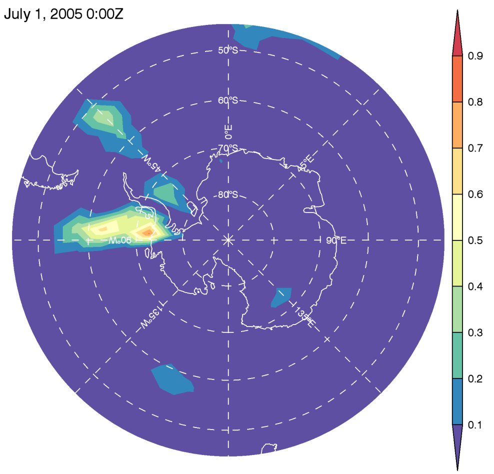
EP-Flux due to GW launched from PV anomalies near tropopause



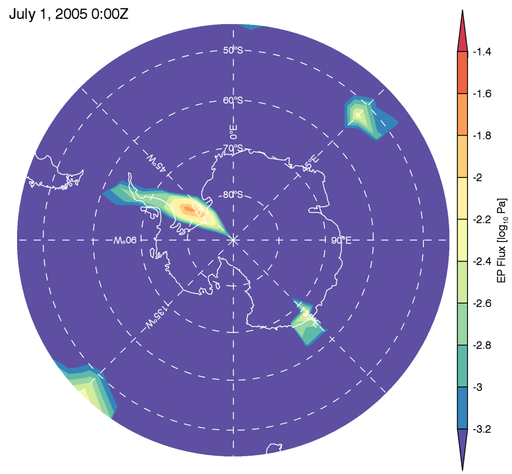
GW (<1000 km) Abs Mom Flux at 15 km

SH gravity wave sources

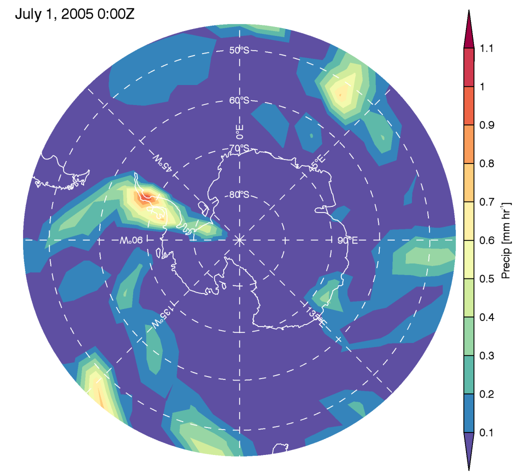
Frontogenesis



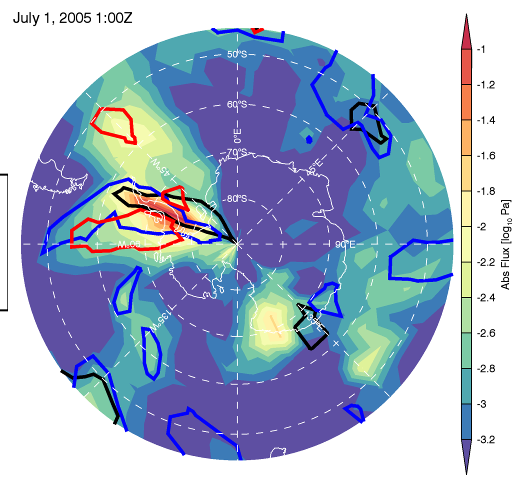
PV



Precipitation



GW (<1000 km) Abs Mom Flux at 15 km



Precipitation

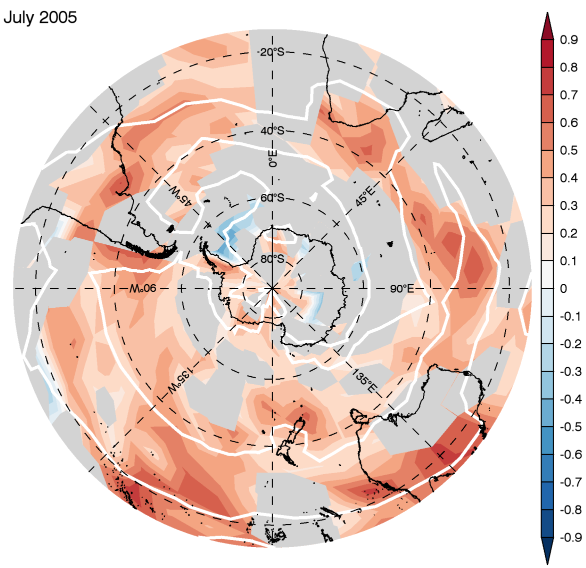
PV

Fronts

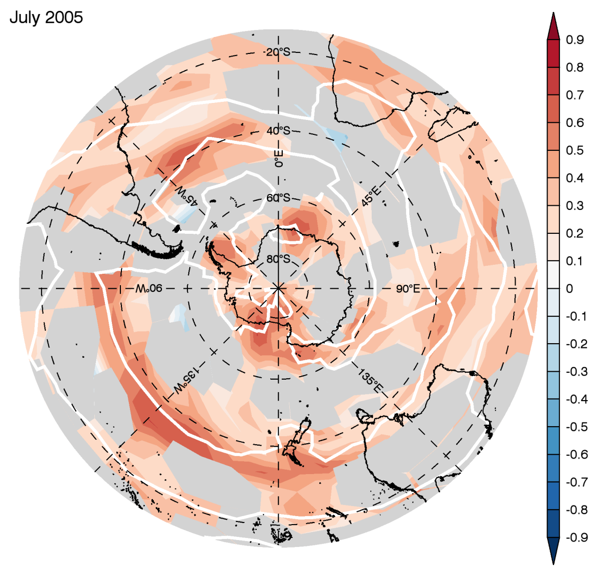
SH gravity wave sources

Spearman rank correlation with GW momentum flux for July

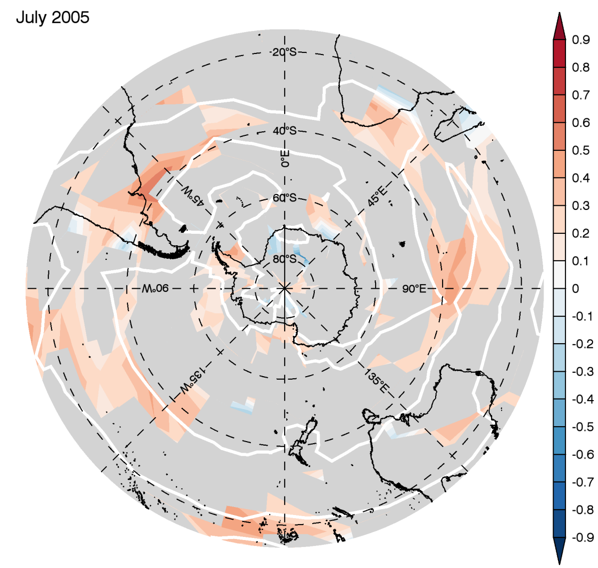
Precipitation



PV



Fronts



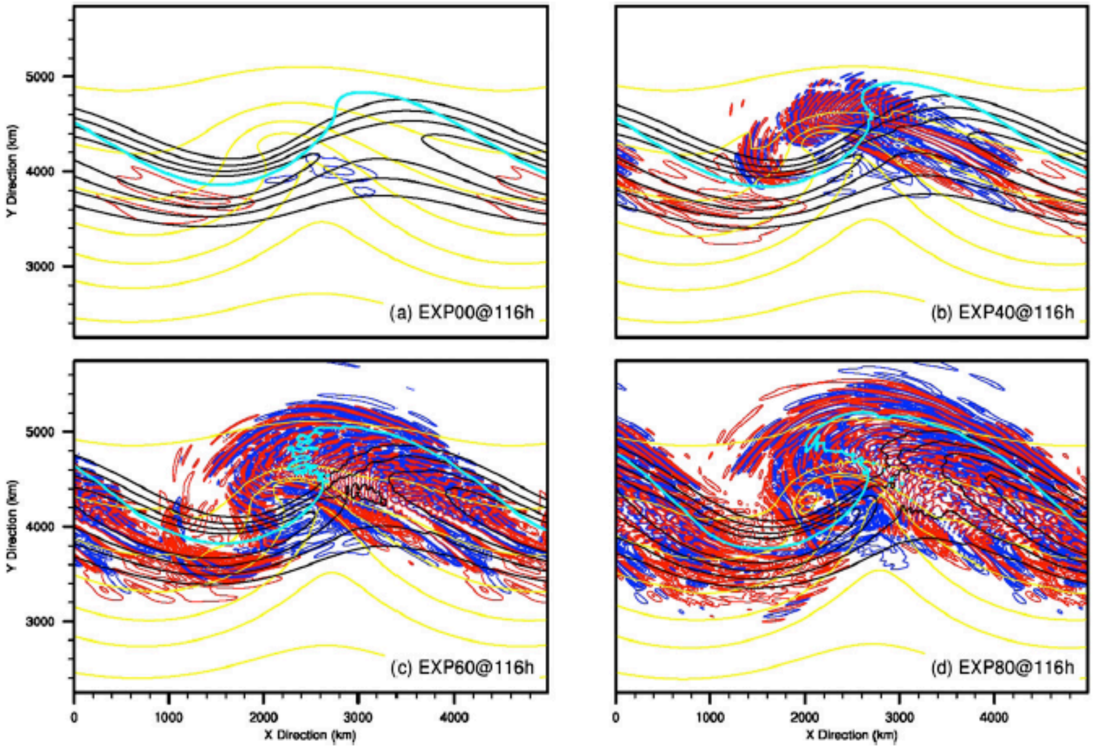
Convection is an important source of GWs in the SH

Importance of moisture

More intense GW emission with higher moisture in idealized baroclinic jet

0% RH

40% RH



60% RH

80% RH

Wei and Zhang, 2014 JAS

Recap: SH gravity wave sources in NR

- We looked at SH sources of gravity waves by relating large-scale diagnostics like precipitation, PV anomalies, and frontogenesis to GW momentum flux
- Precipitation and PV anomalies show strongest correlations with GW momentum flux for month of July, highlighting the importance of convection as a source

Conclusions

- Global pattern of gravity wave absolute momentum flux in NR compares well to other models but global mean values are on the lower end
- Gravity wave absolute momentum flux in SH compares very well to Vorcore over Antarctic peninsula but is weaker on average
- NR is similar to AIRS in global pattern but NR waves have smaller amplitude and longer wavelength
- Resolved small-scale waves in tropics are well-represented and behaving realistically in NR
- Resolved waves in NR contribute about 25% of zonal force for QBO
- Still need parameterized GWs to get QBO
- A look at SH sources highlights the importance of convection as a source

Thank You