Tropical Waves, Latent Heating, and Wave-Driving of the Tropical Circulation

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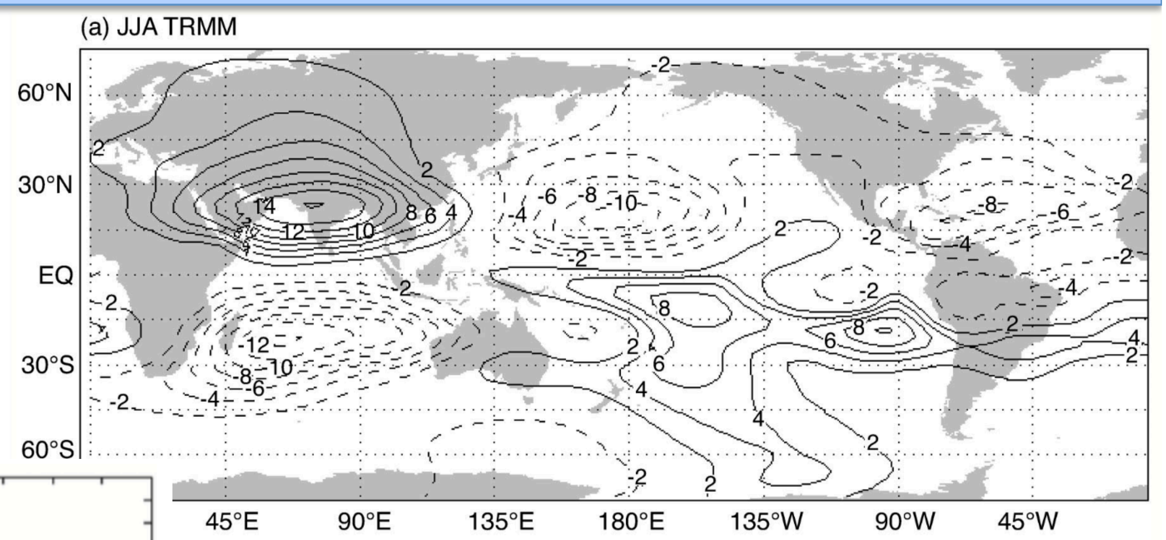
Outline

1. Introduction
2. Idealized model of tropical waves forced by realistic latent heating Q(x,y,z,t)
3. Validation of gravity waves with HIRDLS/GPS and balloon observations
4. Model results on gravity wave variations with ENSO and stratospheric drag

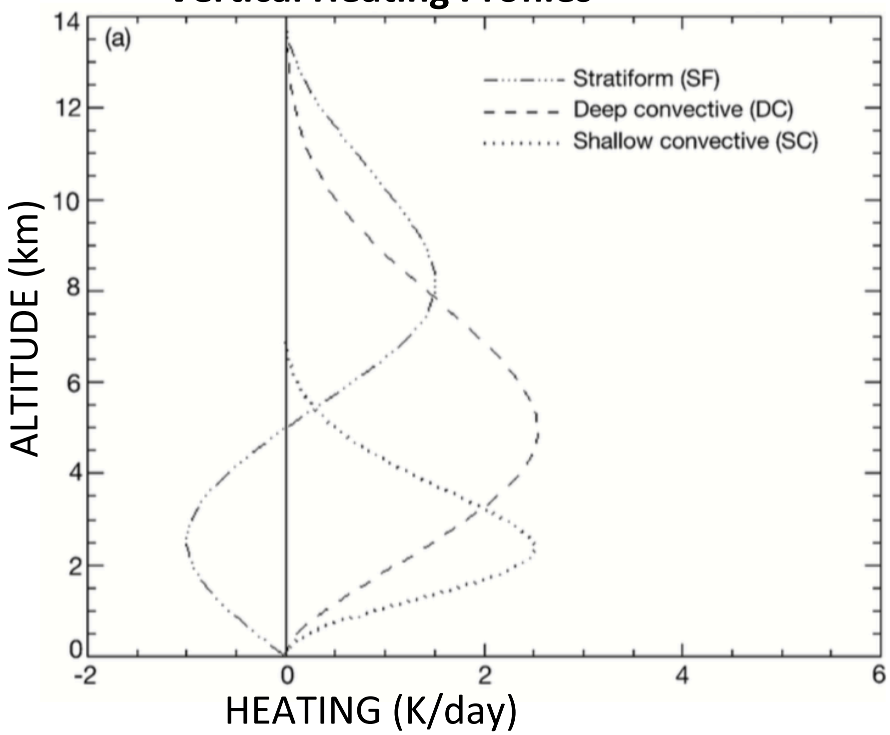
Latent Heating and Tropical Circulation

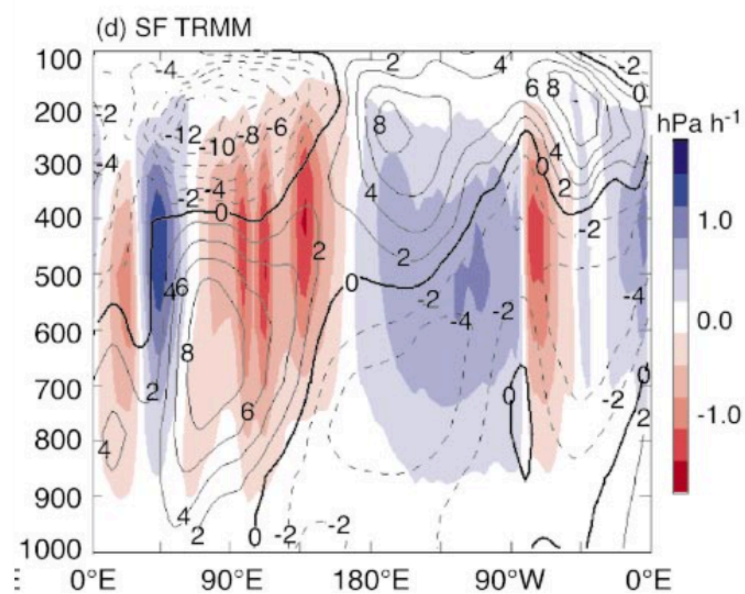
Schumacher et al. [2004]

Circulation response to seasonal-mean heating derived from TRMM precipitation includes Rossby gyres and Walker cell



Stratiform & Convective Vertical Heating Profiles

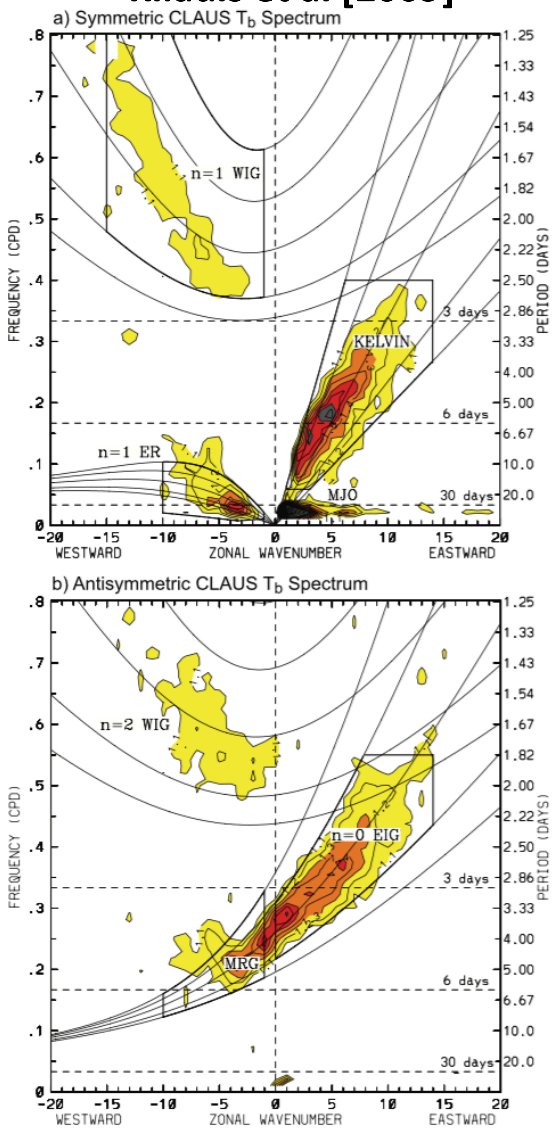




Tropical Waves & Interactions

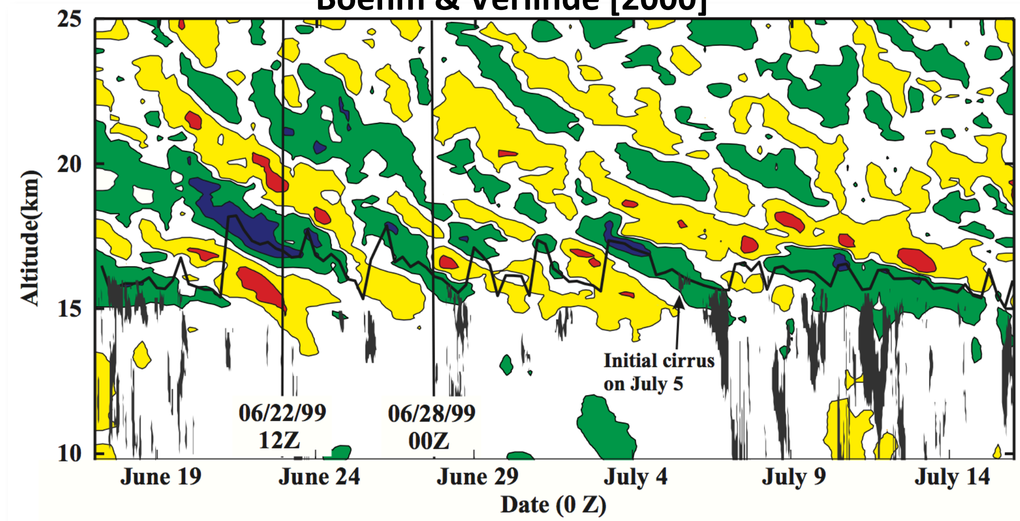
Convectively Coupled Waves

Kiladis et al [2009]



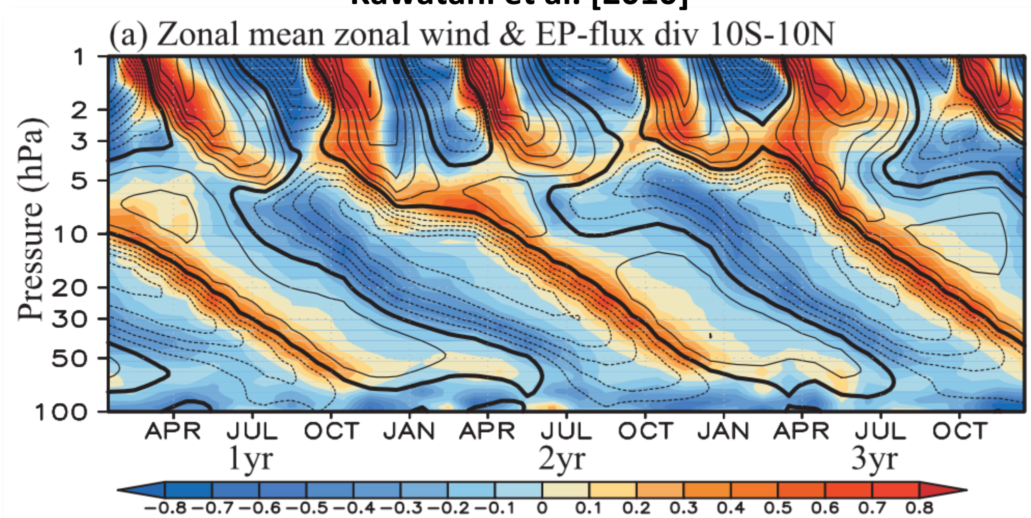
Modulation of Cirrus Clouds

Boehm & Verlinde [2000]



Momentum Forces Driving the QBO

Kawatani et al. [2010]

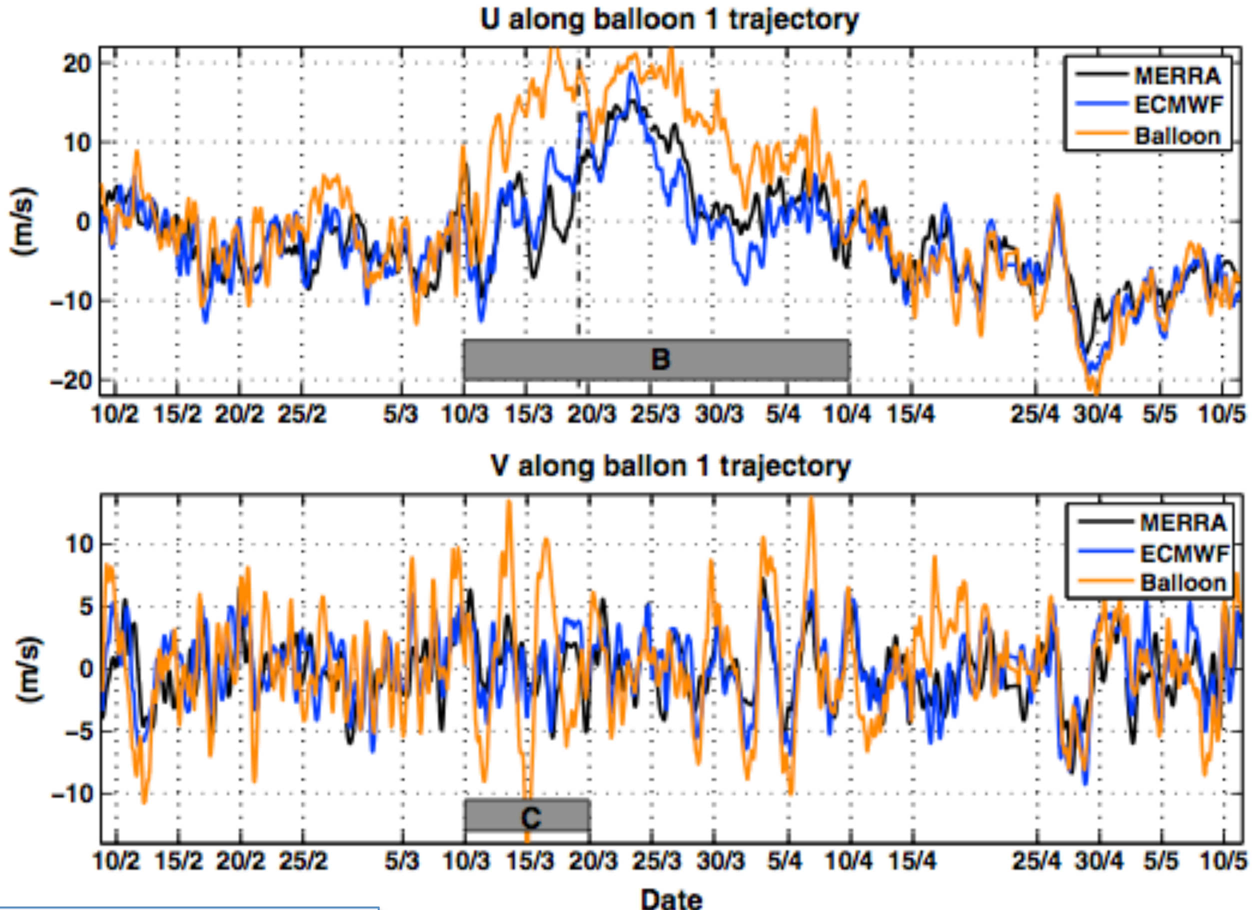


Errors in Tropical Analyzed Winds

Podglajen et al. [2014]

Large errors occur in Indian and Pacific Oceans due to lack of observations

Errors associated with missing or misrepresented large-scale Kelvin and Yanai waves

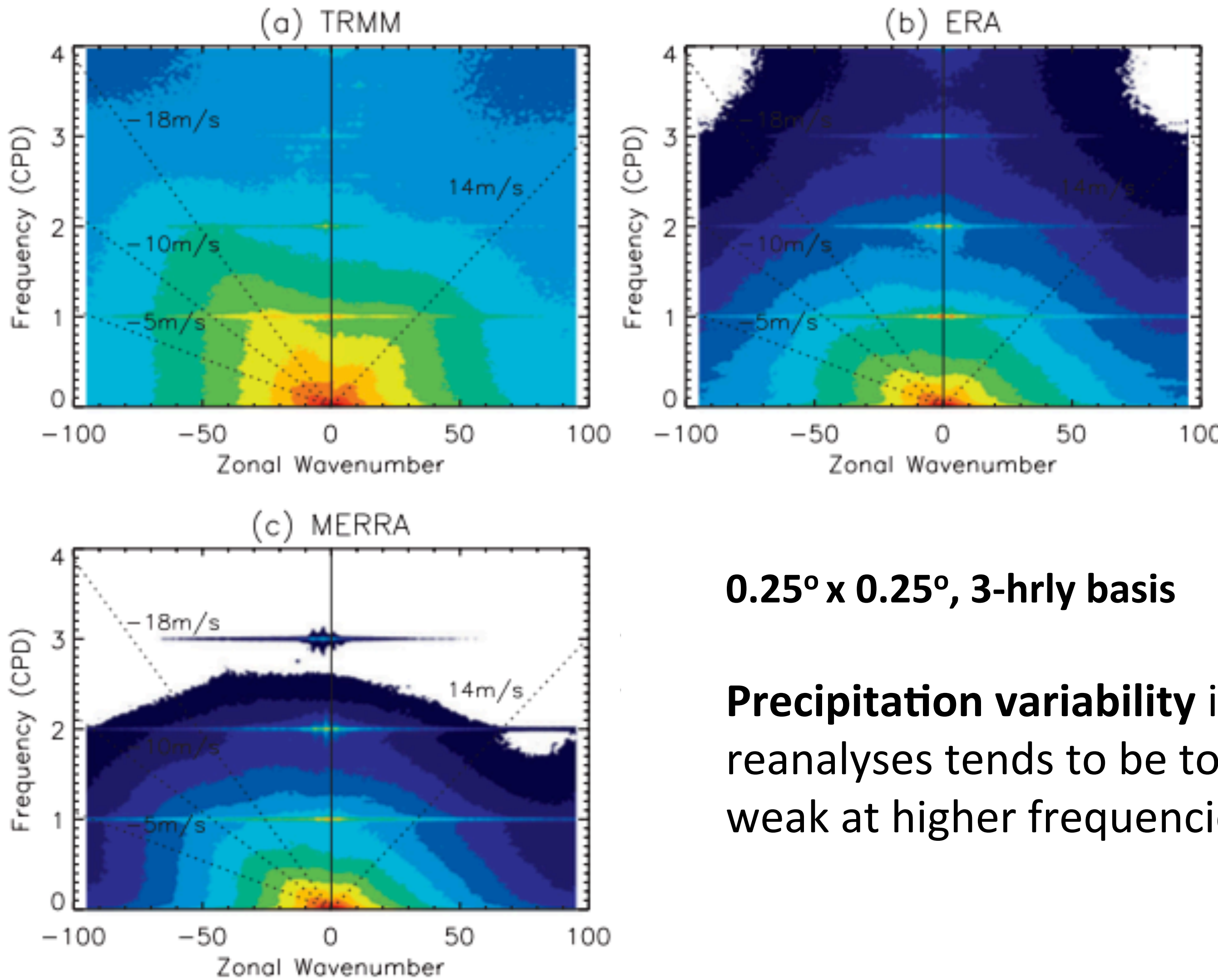


- Lack of tropical wind data
- Vertical resolution?
- Convection parameterization?

Convective Coupling at High Frequencies

Kim & Alexander [2013]

Tropical Wavenumber-Frequency Spectrum of Precipitation



0.25° x 0.25°, 3-hrly basis

Precipitation variability in reanalyses tends to be too weak at higher frequencies

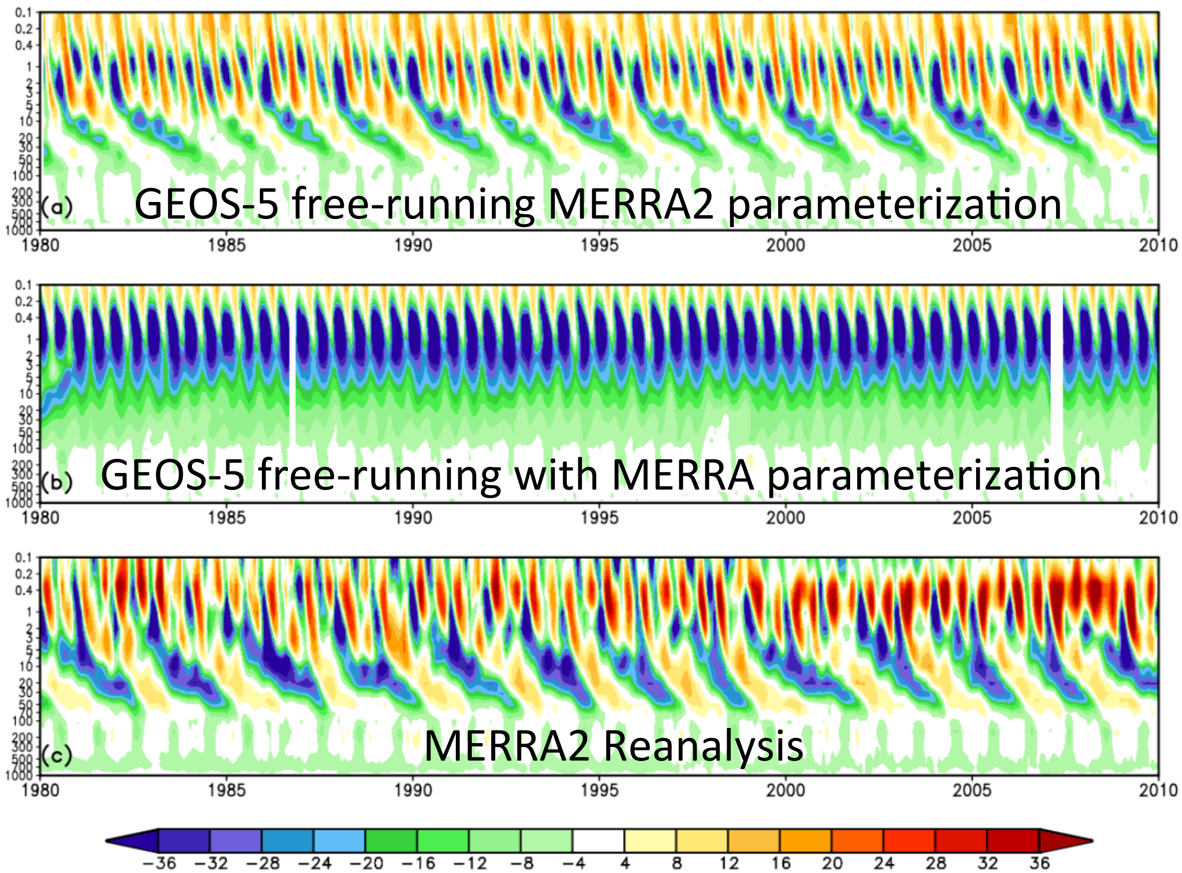
Tropical Gravity Waves in Global Models

- QBO is key factor in tropical-extratropical teleconnections
- QBO predictability for near-term climate prediction

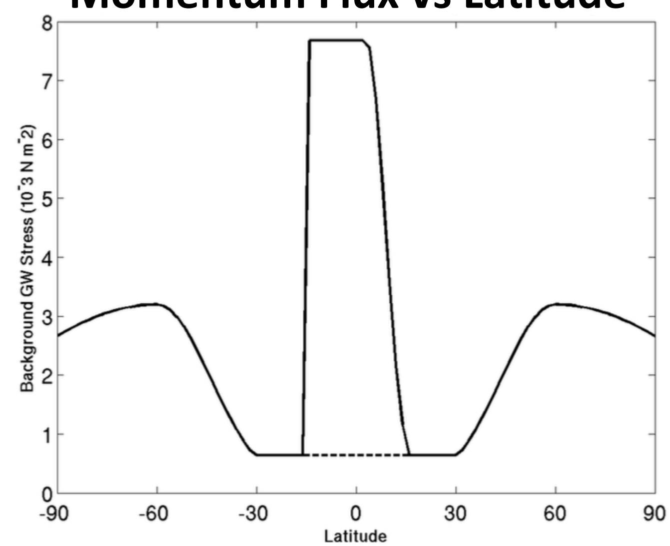
Molod et al (2015)

- GEOS-5 model for the development of MERRA2
- Gravity wave tuning to improve representation of the QBO.

Zonal Winds versus time (yrs) and height (hPa)

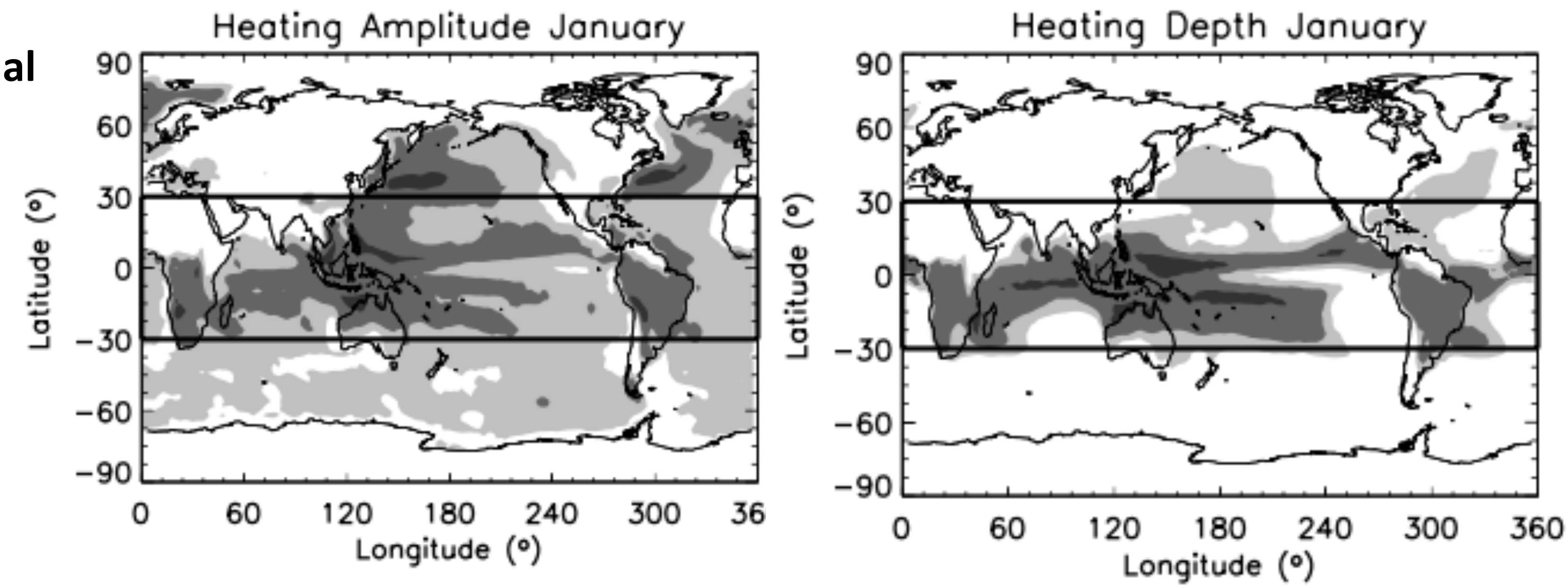


Parameterized Gravity Wave Momentum Flux vs Latitude



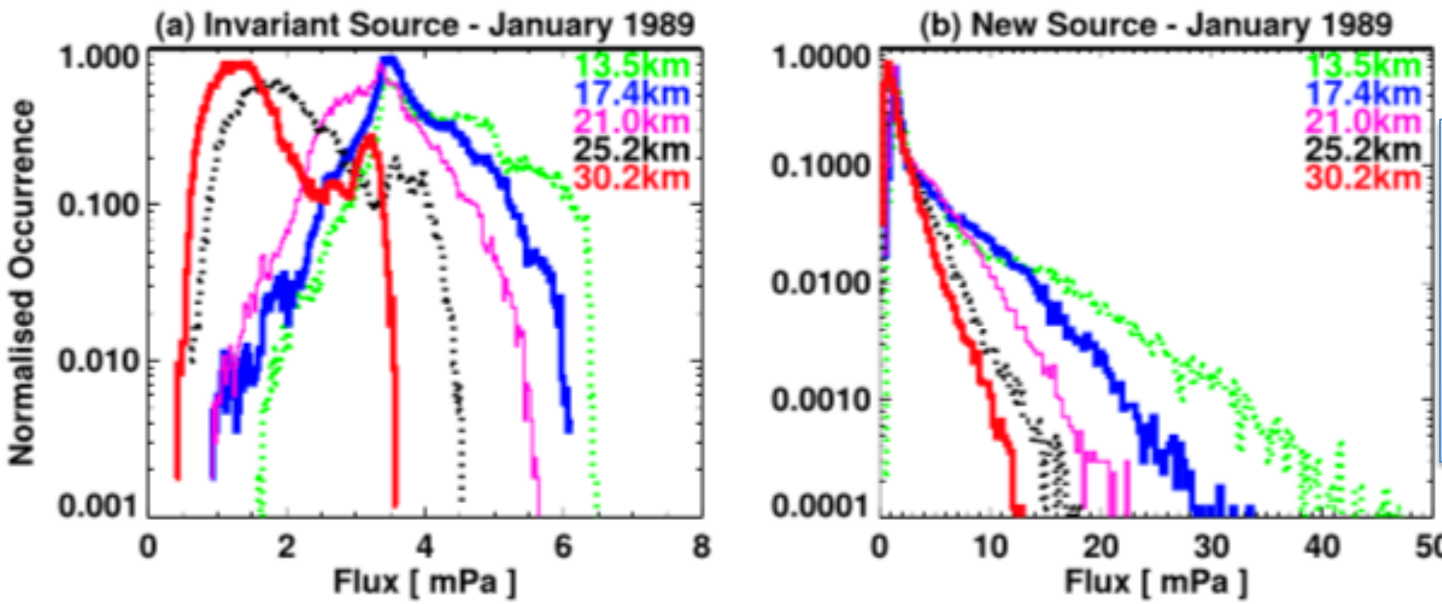
Convection Source Parameterizations

Beres et al (2005)



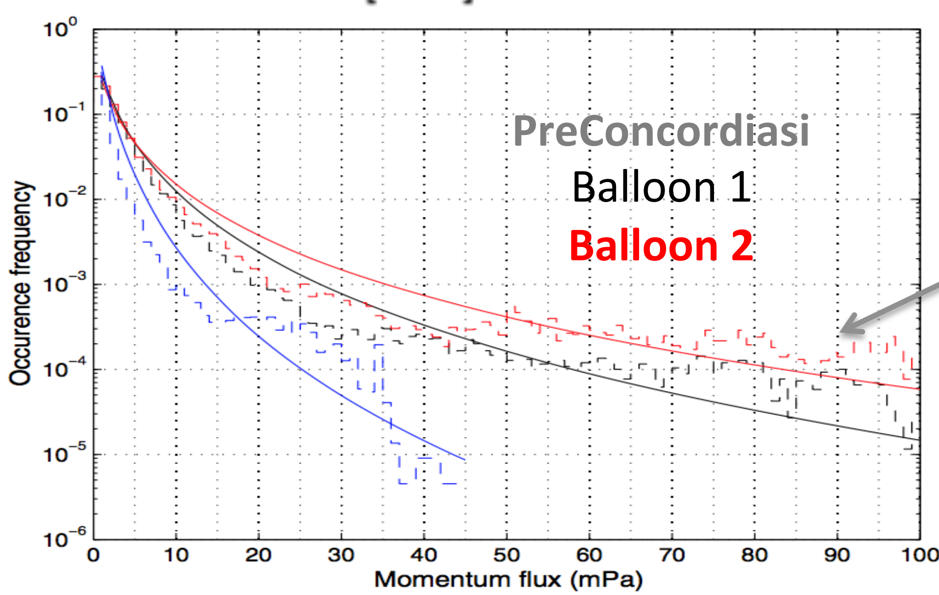
- Some models like WACCM include convective gravity wave sources
- Wave spectrum depends on strength/depth of latent heating

Intermittency in Sources



Bushell et al (2015)

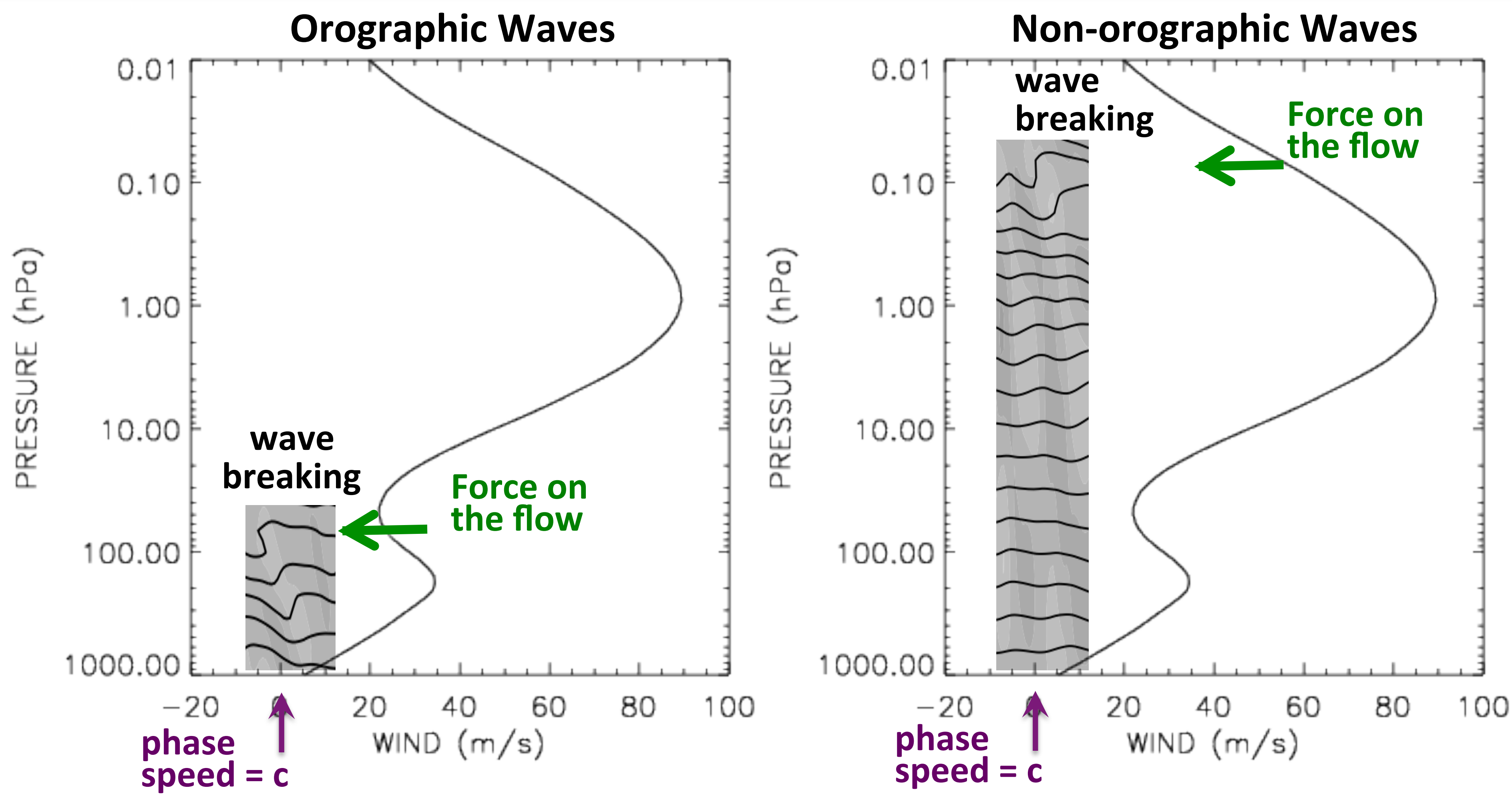
- Convective gravity wave source parameterizations give more realistic intermittency



Jewtoukoff et al (2013)

- Observed gravity waves display long distribution tails of large amplitude gravity waves.
- Common assumption is that convective waves include few large-amplitude wave events.

Gravity Wave Parameterization Paradigm



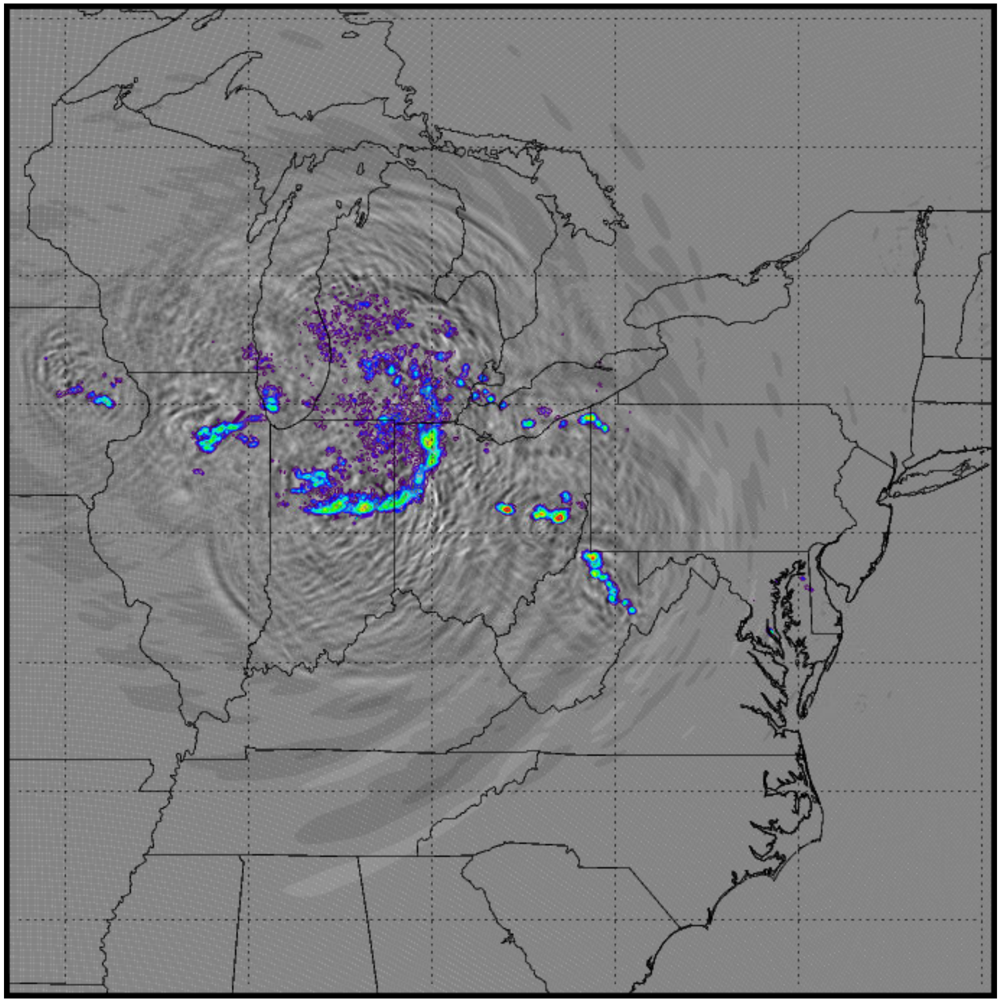
The Paradigm: Orographic = big amplitude waves, break lower
Non-orographic = small amplitude waves, break higher

Gravity Waves from Convection

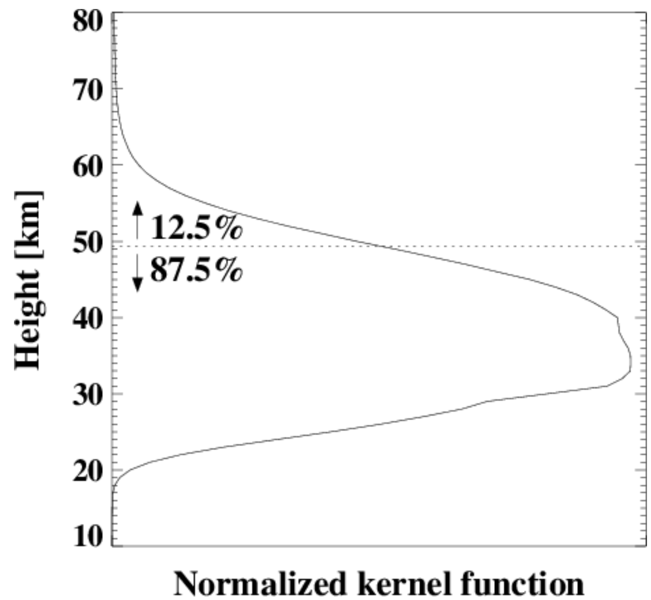
Stephan & Alexander [2015]

Idealized Gravity Wave Model

Forced with heating derived from algorithm based on Radar-observed Precipitation

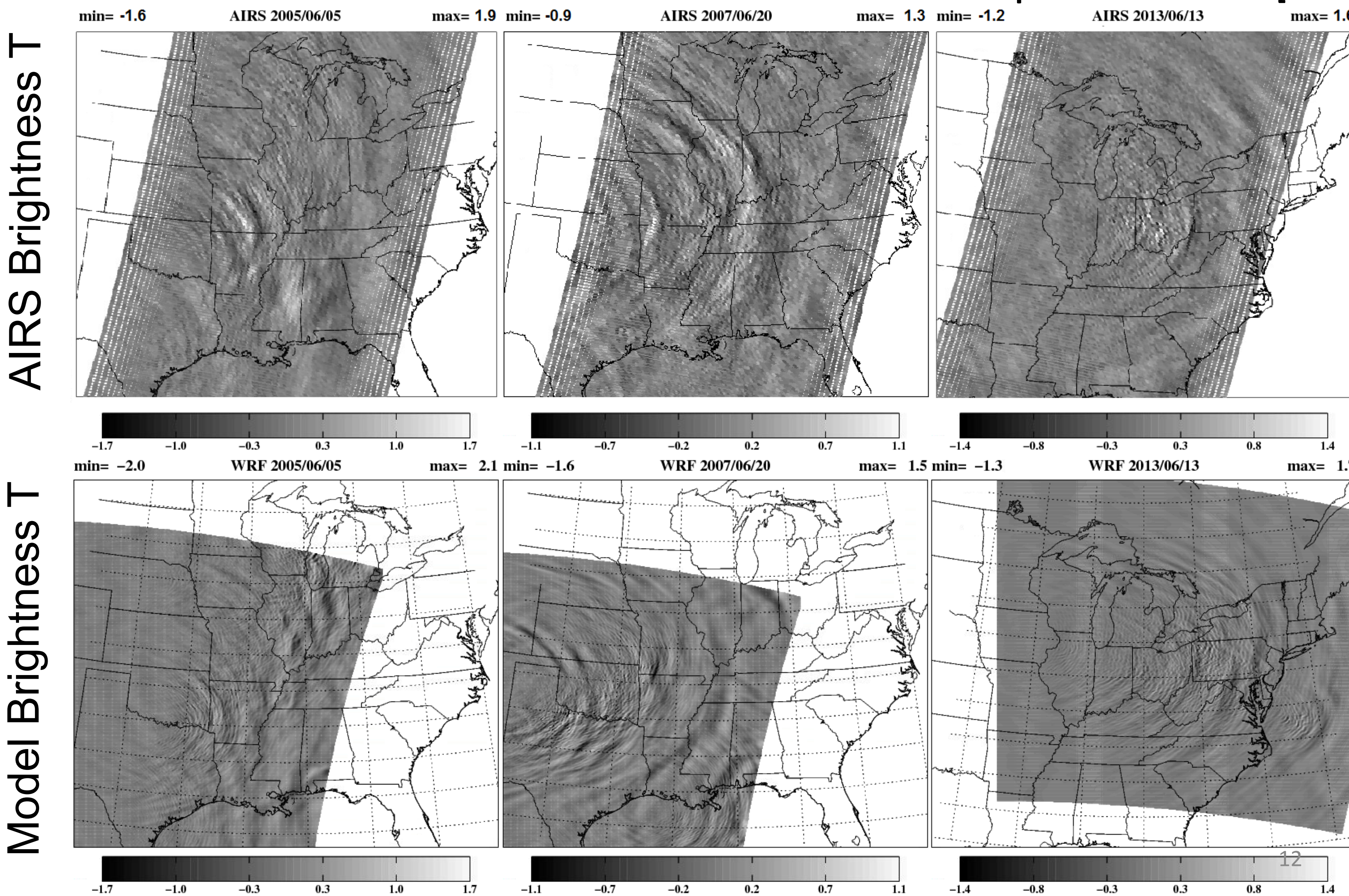


Sample with AIRS weighting function for validation of the gravity wave amplitudes



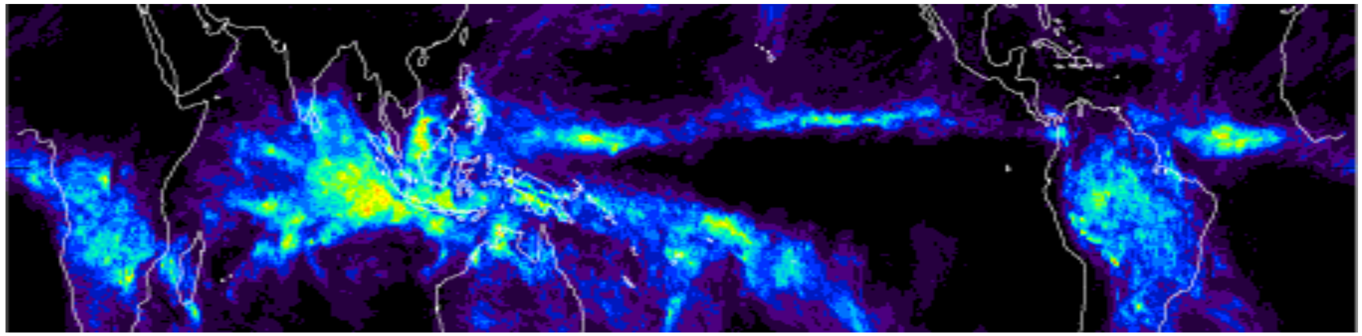
Quantitative Comparison to Observed Waves

Stephan & Alexander [2015]



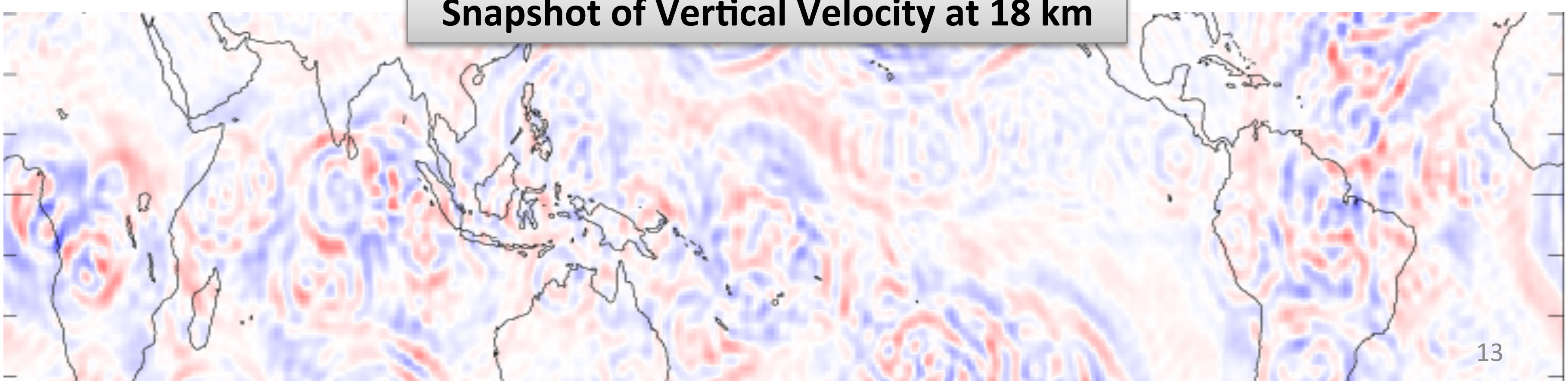
Gravity Waves Forced by Tropical Heating

Mean Heating December 2007

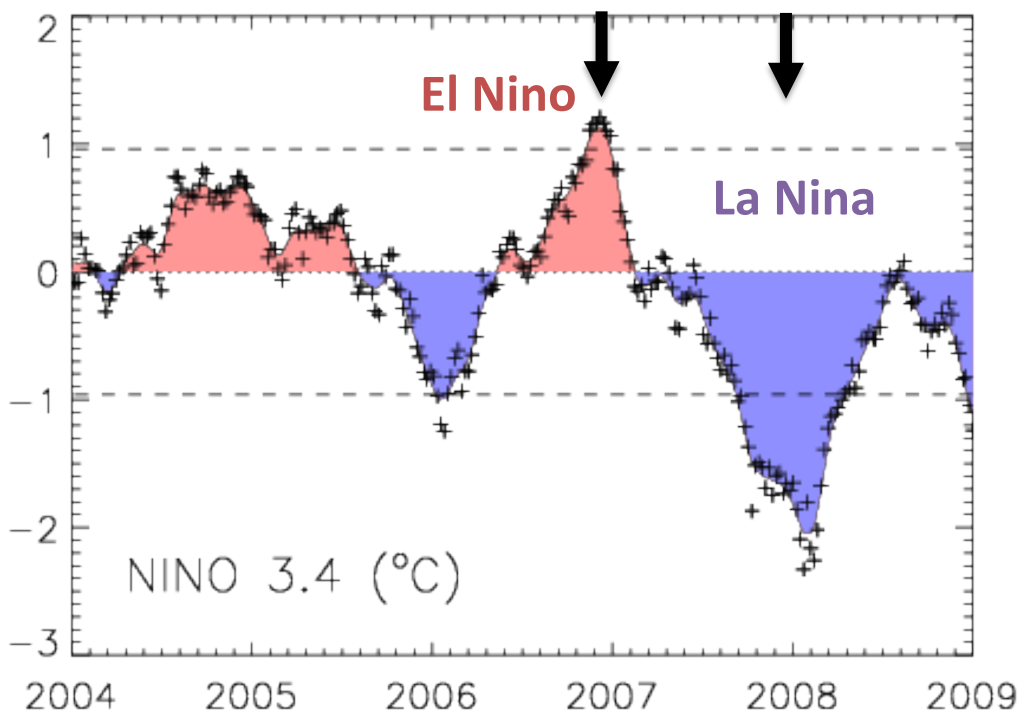


- **Waves forced by latent heating** Q(x,y,z,t) $30^oS–30^oN$
- Variable heating at 0.25^o; Δt=30min
- **Heating derived from global rain observations** (e.g. CMORPH, Joyce et al. 2004) Method of Ryu et al. [2011] includes convective and stratiform heating profiles
- Idealized model T120, Δz=500m resolution designed to simulate waves observed with HIRDLS+GPS method

Snapshot of Vertical Velocity at 18 km



Model Comparisons: Dec 2006 vs Dec 2007



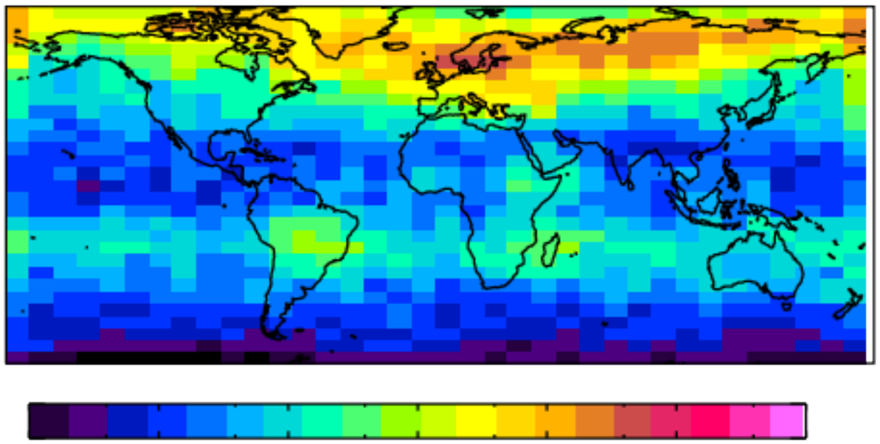
HIRDLS data available
for wave validation

El Nino Case Dec 2006	La Nina Case Dec 2007
QBO Period = 20.9 mo	QBO Period = 25.1 mo
QBO Amplitude = 0.90	QBO Amplitude = 1.49

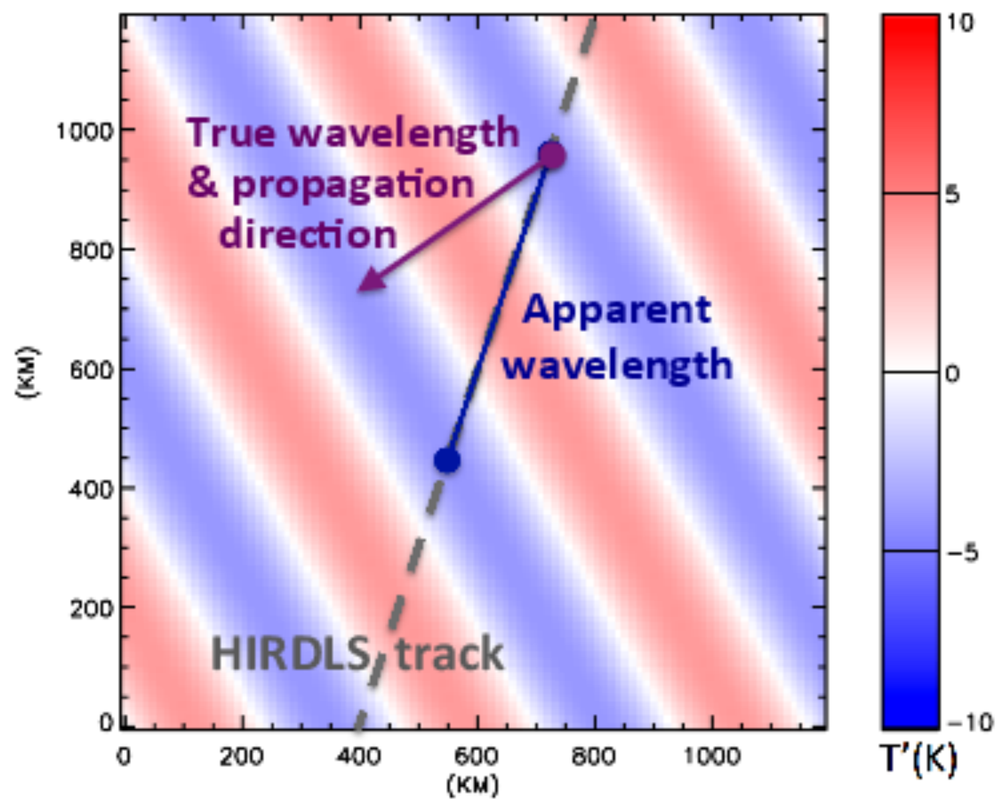
Yuan et al. [2013]

Gravity Wave Validation: HIRDLS 2005-08

HIRDLS "2D" Momentum Flux



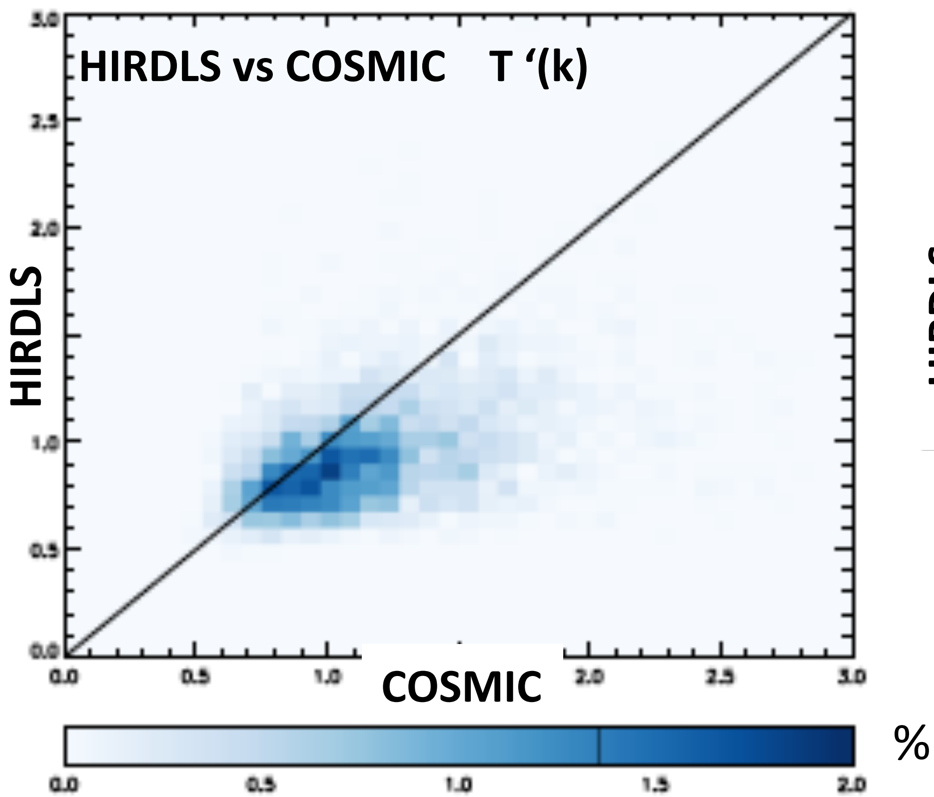
HIRDLS has best coverage and resolution in lower stratosphere. Method is limited to a "2D" approach due to the satellite sampling pattern.

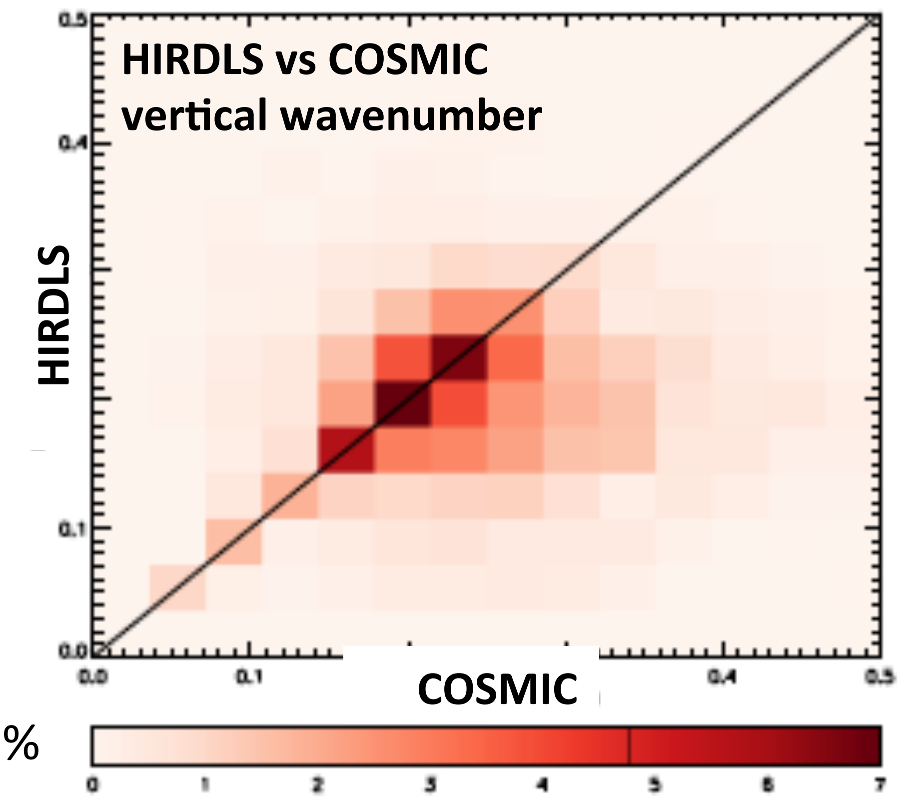


Need "3D" information off the measurement track to correct the major known bias in these momentum fluxes

Combining GPS-RO and HIRDLS

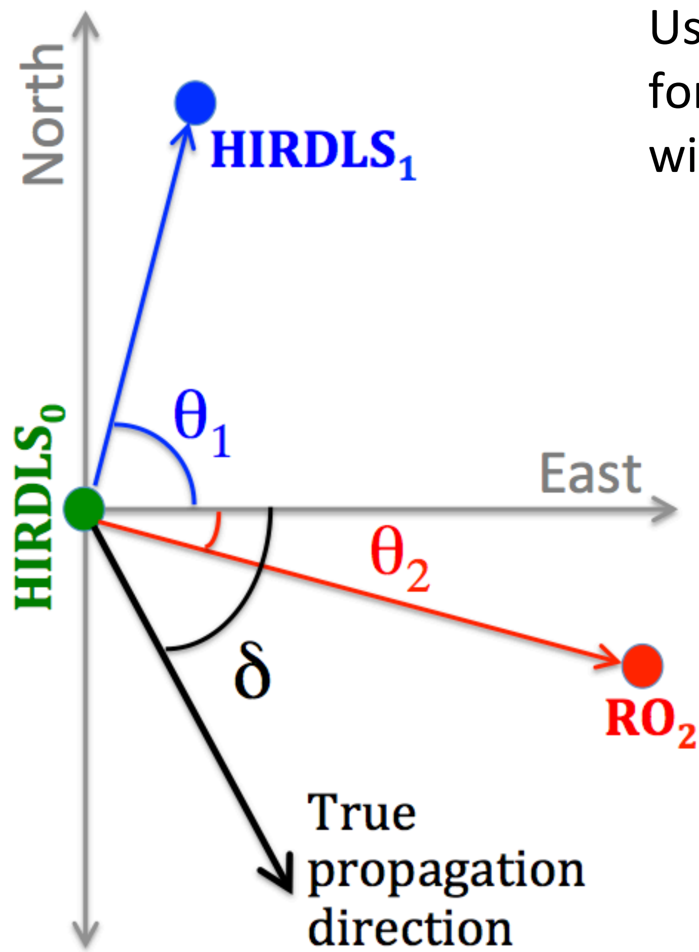
- Previous analysis compared amplitudes of largest wave components of co-located profiles, suggested HIRDLS & COSMIC RO temperatures have approximately same vertical resolution [Gille et al 2008; Barnett et al 2008].
- **Wright et al. (2011)**: HIRDLS resolution = 1 km, COSMIC slightly better, and COSMIC amplitudes slightly larger.





Combining GPS-RO and HIRDLS

Alexander [2015]



Used neighboring profile triads to solve for the true direction of propagation δ with method in Evan & Alexander [2008]:

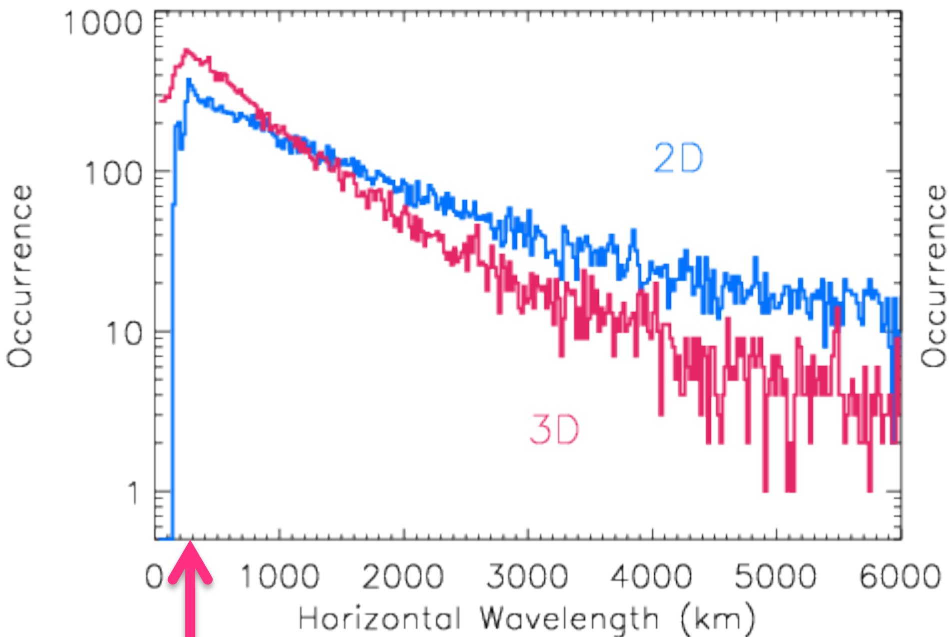
$$\delta = \arctan\left(\frac{\lambda_2 \cos\theta_2 - \lambda_1 \cos\theta_1}{\lambda_1 \sin\theta_1 - \lambda_2 \sin\theta_2}\right)$$

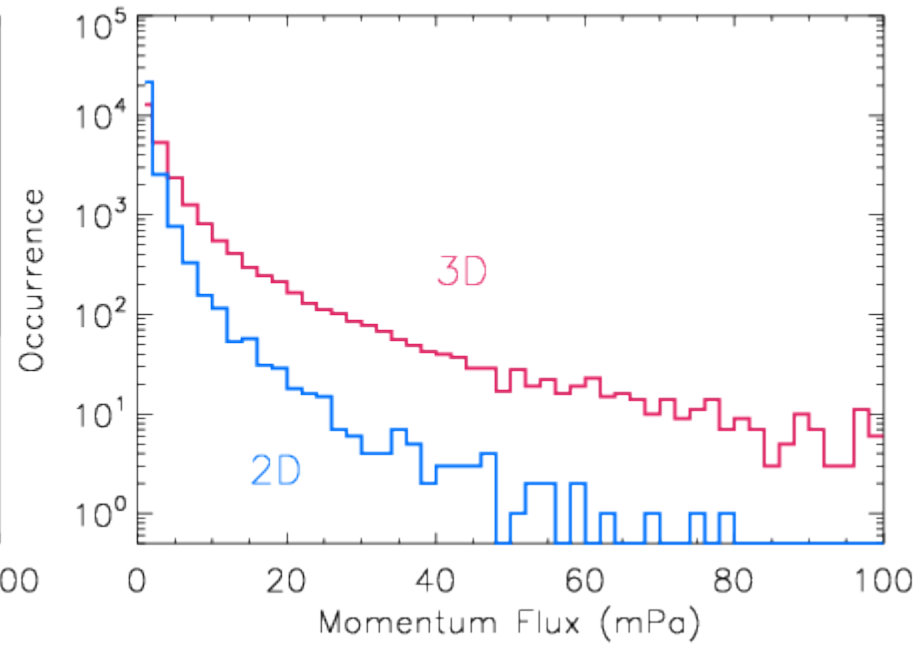
- Will show results 17-22km in lower stratosphere as input to the stratosphere.

Combined GPS and HIRDLS Alexander [2015]

Distributions of Horizontal Wavelength and Momentum Flux

2D = HIRDLS-only 3D = HIRDLS+COSMIC





Median horizontal wavelength change is small:

270 km → 250 km

Mean wavelength decreases substantially:

888 km → 354 km

Mean absolute momentum flux increases by a factor of 3.7:

1.7 mPa → 6.4 mPa

- Amplitudes display long large-amplitude tails.

Validation: Compare Model & Observations

Monthly-mean analysis results (18-22 km):

20^oS—20^oN	Model	GPS/HIRDLS	HIRDLS-only
Zonal mean flux Dec 2007	4.0 mPa	3.8 mPa	0.8 mPa
Fraction zonal flux Dec 2007	65%	81%	N/A
Zonal mean flux Dec 2006	4.0 mPa	3.1 mPa	0.8 mPa
Fraction zonal flux Dec 2006	64%	79%	N/A

At 20 km:

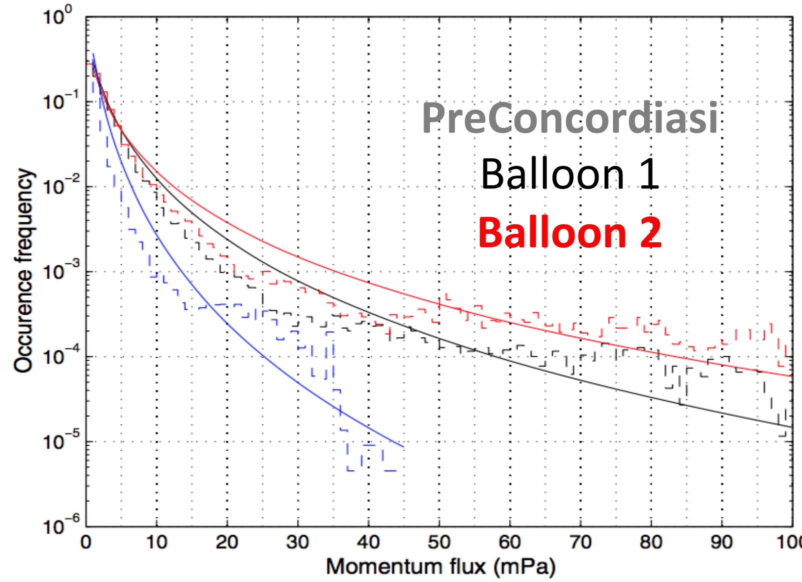
Zonal mean flux Mar-May 2010 PreConcordiasi balloons: 3.9 – 5.4 mPa

(balloons include a broader spectrum of waves)

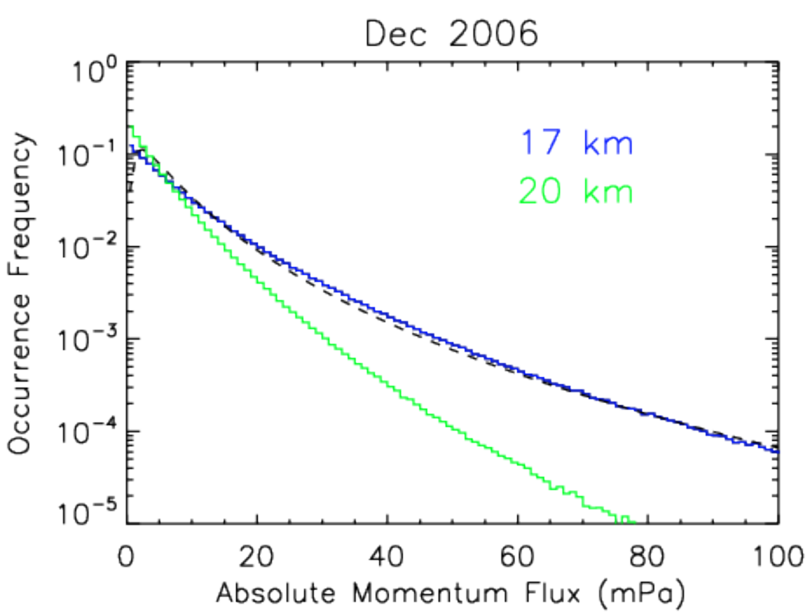
Model zonal mean fluxes at 20km: 3.3 – 3.4 mPa

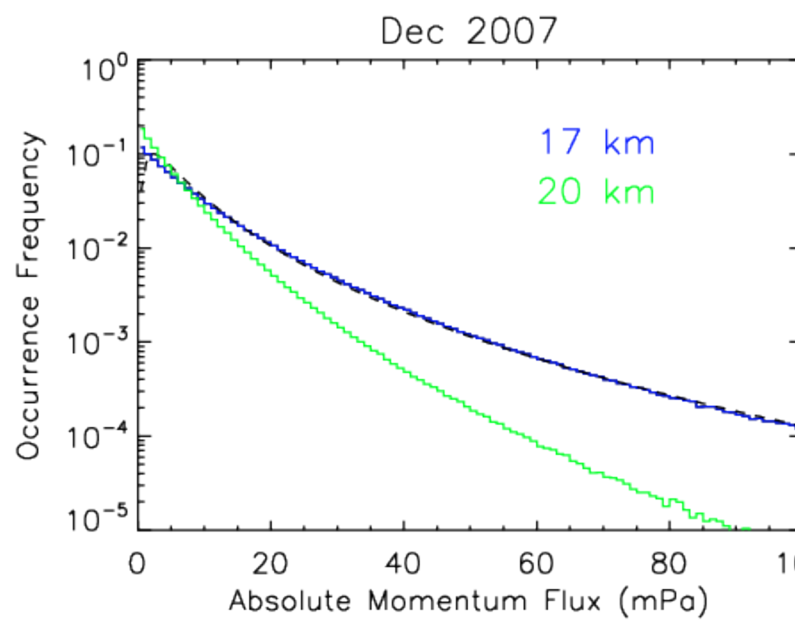
Validation: Momentum Flux Distributions

- Long duration balloon observations in the tropics (red and black)



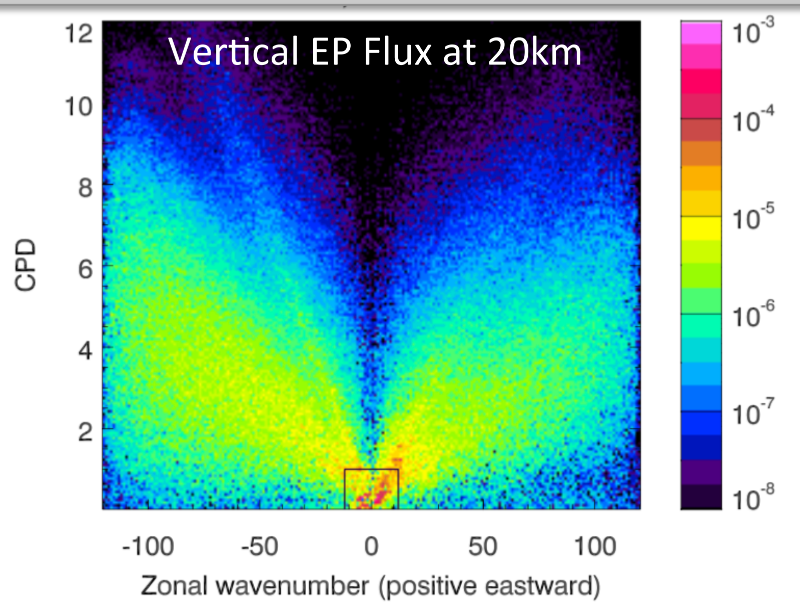
- Model gravity wave fluxes (below) display same log-normal shape, although fewer large values near the balloon altitude (20km).

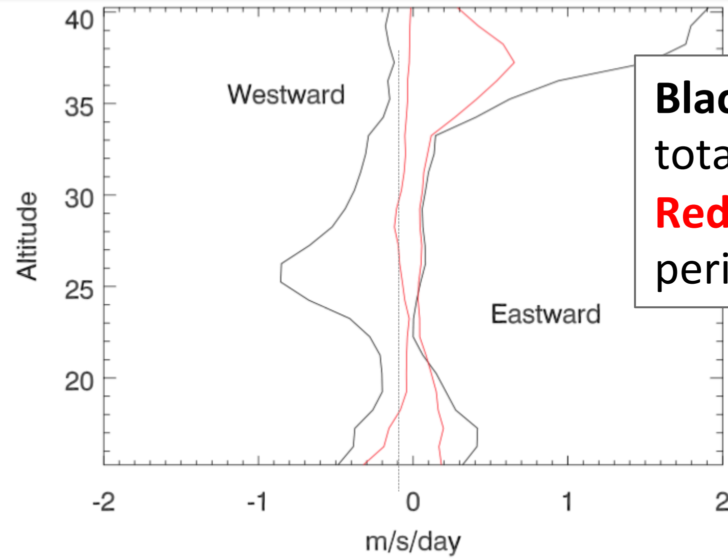




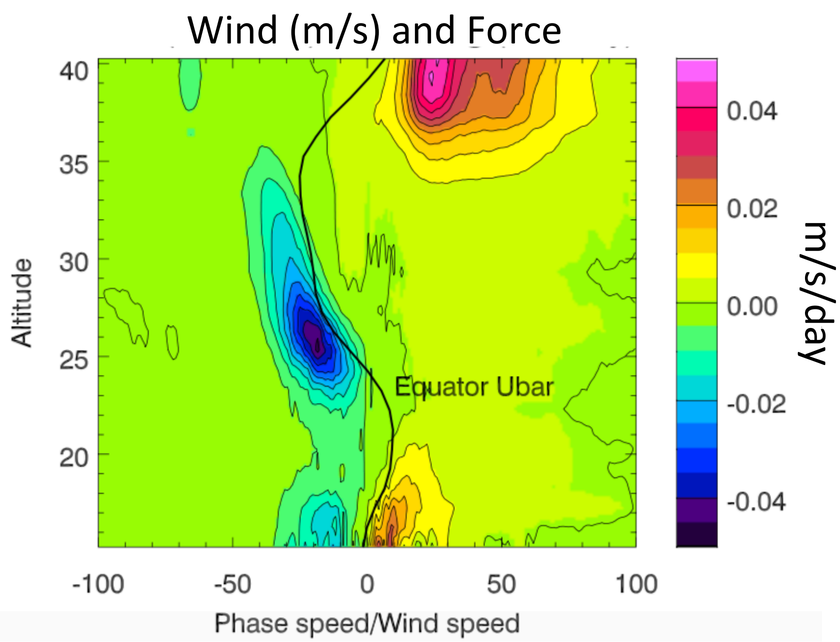
Model Results: Tropical Forcing

December 2006





Black curve is total wave force. **Red** is wn<12 and periods>1d

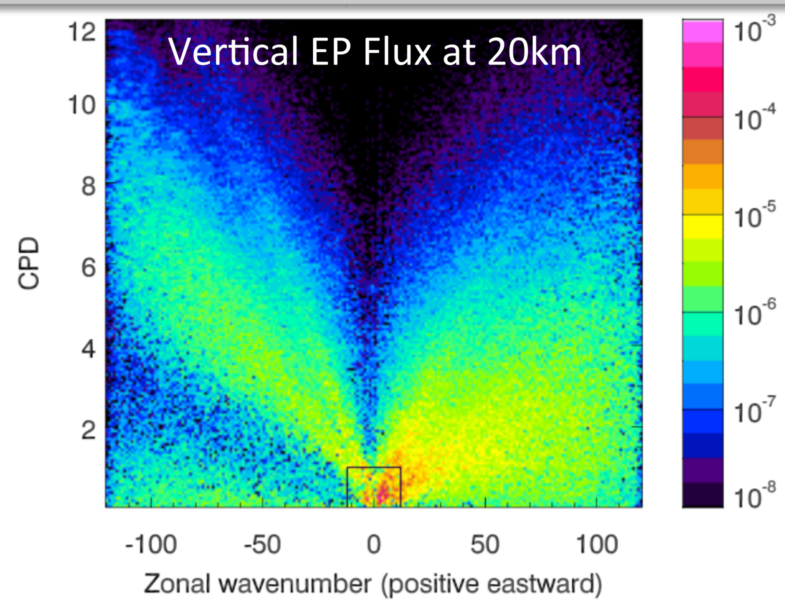


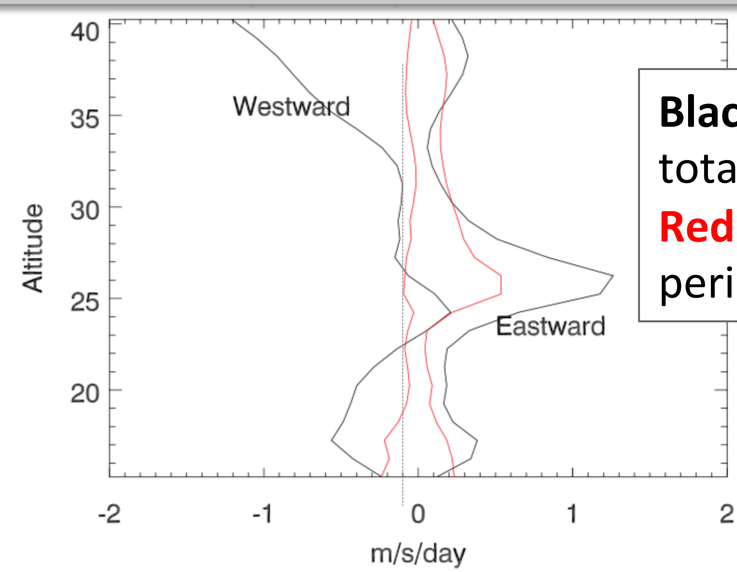
Gravity waves:

- Provide most of the QBO westward force
- Provide half or more of the eastward force
- Contributions are large even in the lowermost stratosphere

Model Results: Tropical Forcing

December 2007





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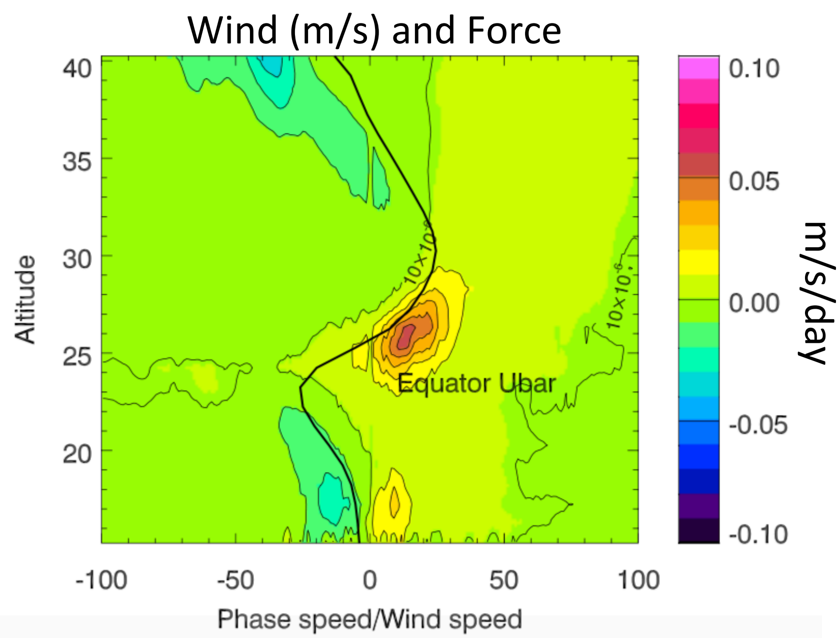

Gravity waves:

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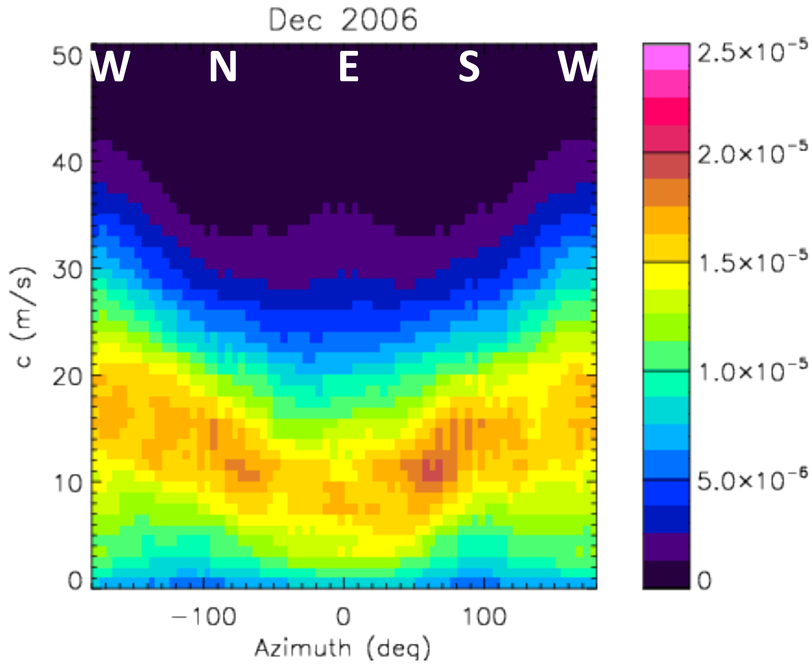
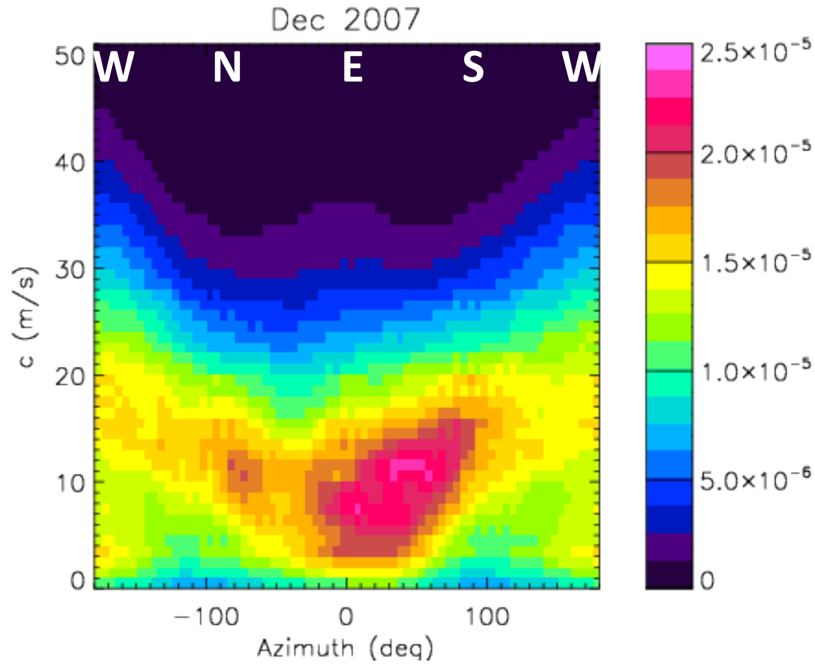
Zonal-mean Momentum Flux

Average of all longitudes, and altitudes 15-18 km
Wavelengths < 3000 km, Periods < 1 day

El Nino Case



La Nina Case

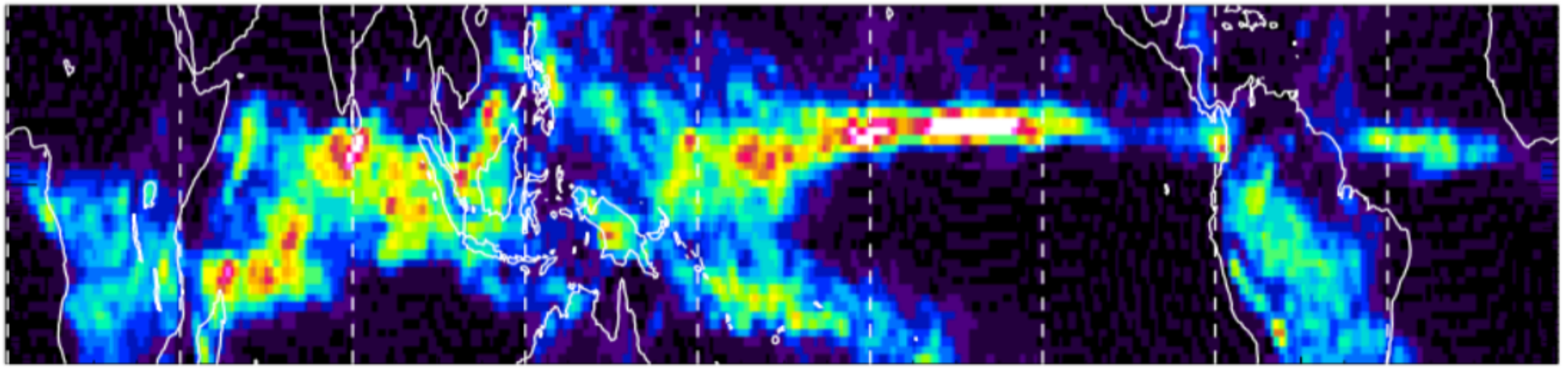


- **La Nina** Flux > **El Nino** Flux
- No obvious differences in spectral widths

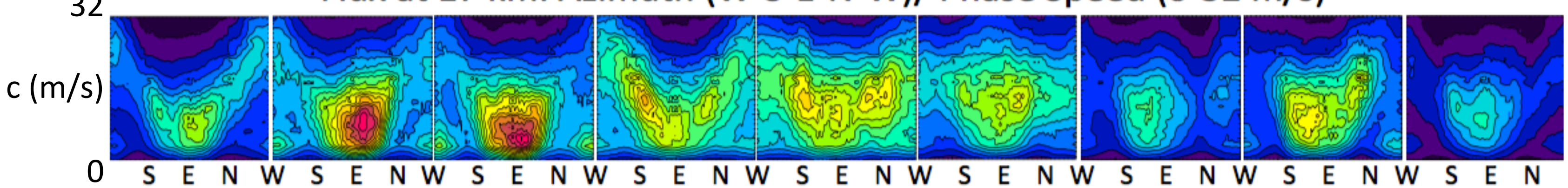
Model Results: Regional Wave Spectra

December 2006

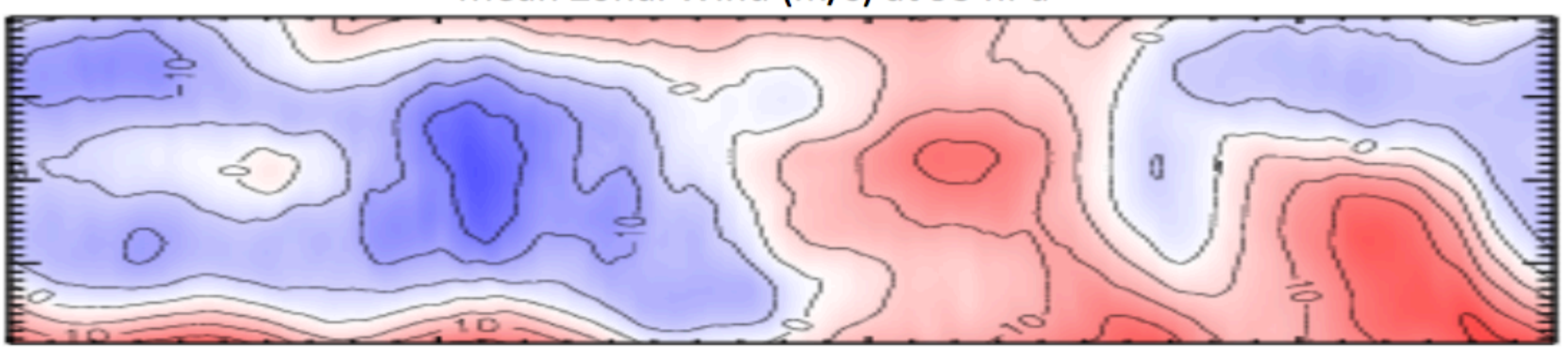
Mean Heating Pattern



Flux at 17 km: Azimuth (W-S-E-N-W)/ Phase Speed (0-32 m/s)



Mean Zonal Wind (m/s) at 95 hPa



Model Results: Regional Wave Spectra

December 2007

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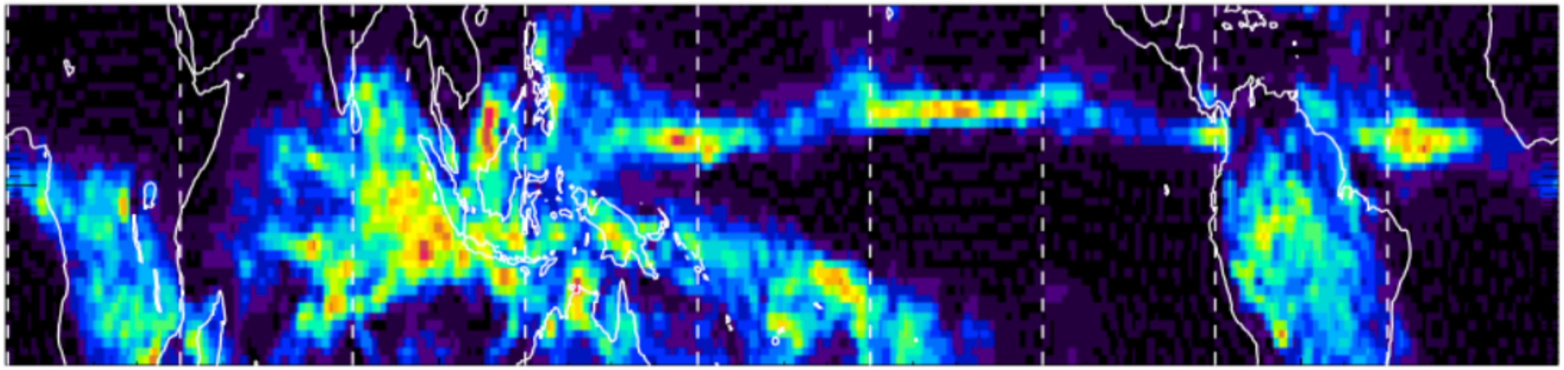

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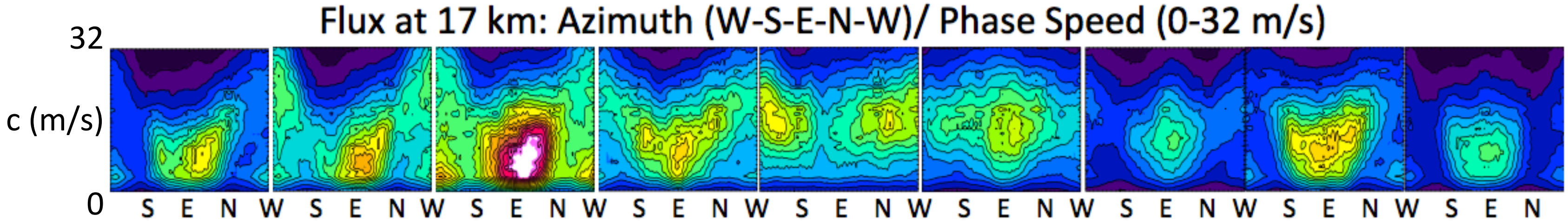

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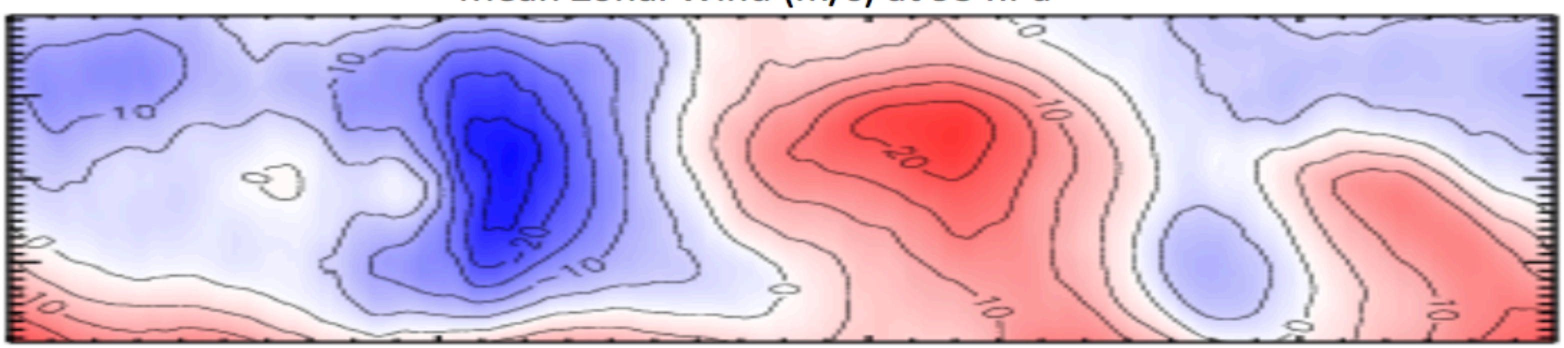

Summary & Conclusion

- **Convective latent heat release as gravity wave source**
  – waves forced with realistic Q(x,y,z,t) in idealized *nonlinear* models validated with observations
- **Convective waves with realistic strong amplitudes drive circulation changes in the lowermost stratosphere**
  – even realistic convective source parameterizations under-estimate larger amplitude gravity waves and drag