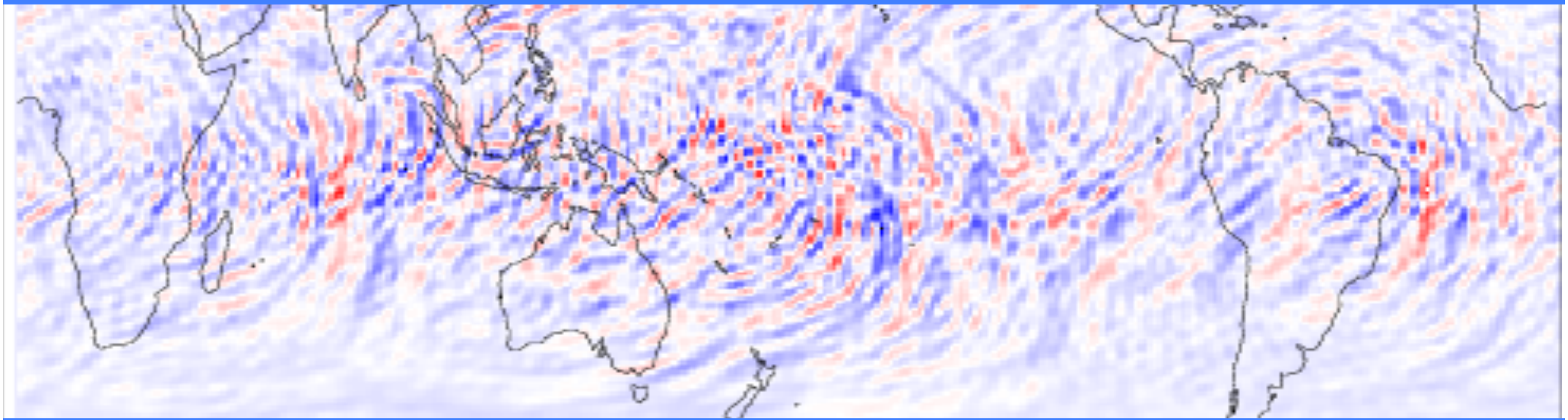
Tropical Gravity Wave Effects on Circulation and Climate



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Boulder, Colorado USA

Stratospheric Winds and Regional Climate

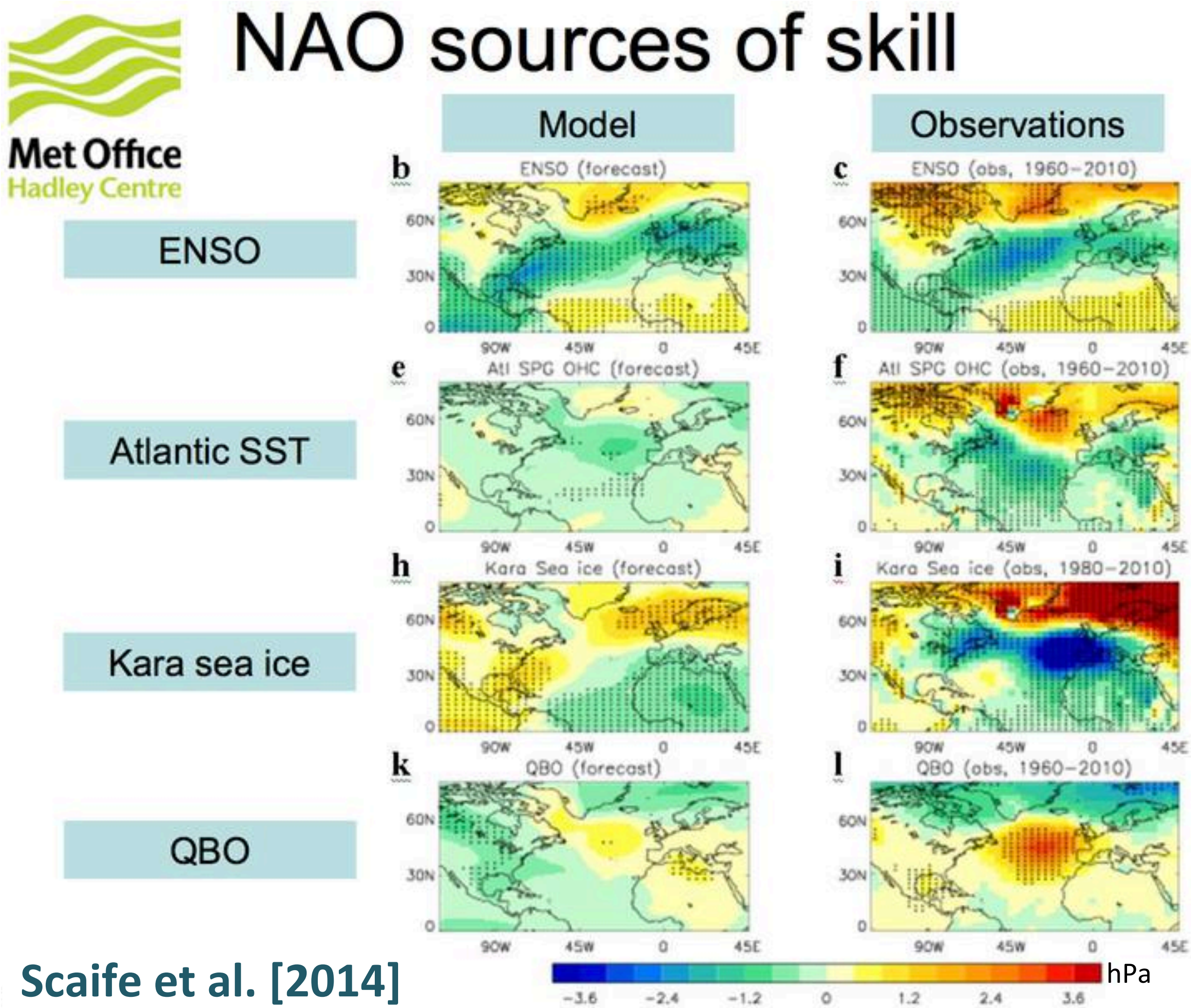
Skillful long-range prediction of the North Atlantic Oscillation

The NAO is highly predictable months ahead [Scaife et al., 2014]

Skill requires deep atmosphere coupling with ocean & sea ice.

Stratospheric Quasi-biennial Oscillation (QBO) is an important source of skill.

ENSO teleconnection has a **stratospheric pathway.**

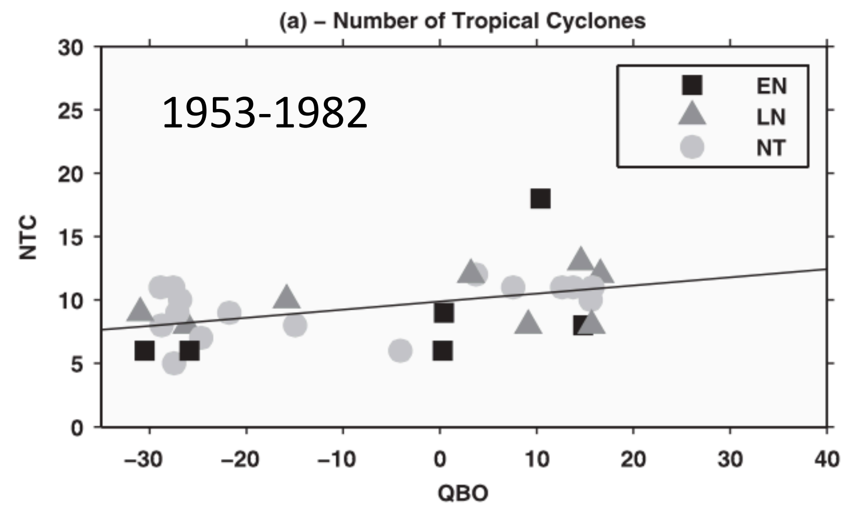


Scaife et al. [2014]

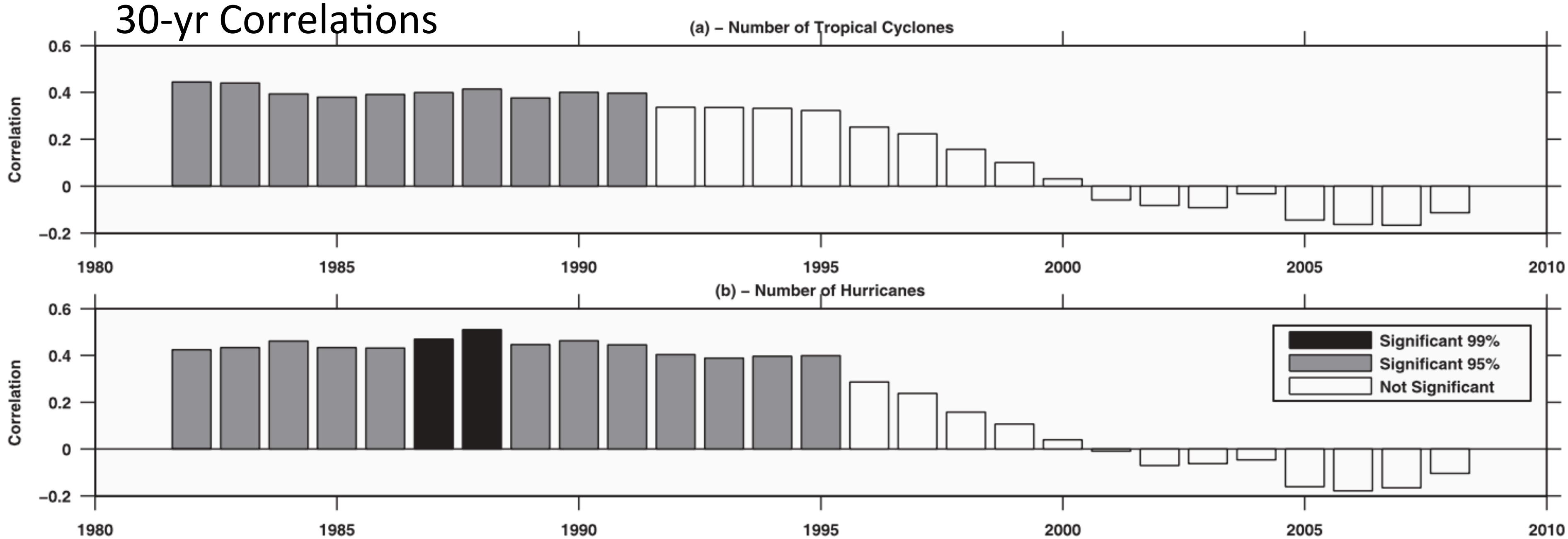
QBO & Tropical Cyclone Activity

- QBO wind correlated with Tropical Cyclones 1953-82
- Possible mechanism: tropopause wind shear disrupts cyclone intensification
- Correlation not significant in recent decades

Camargo and Sobel [2010]



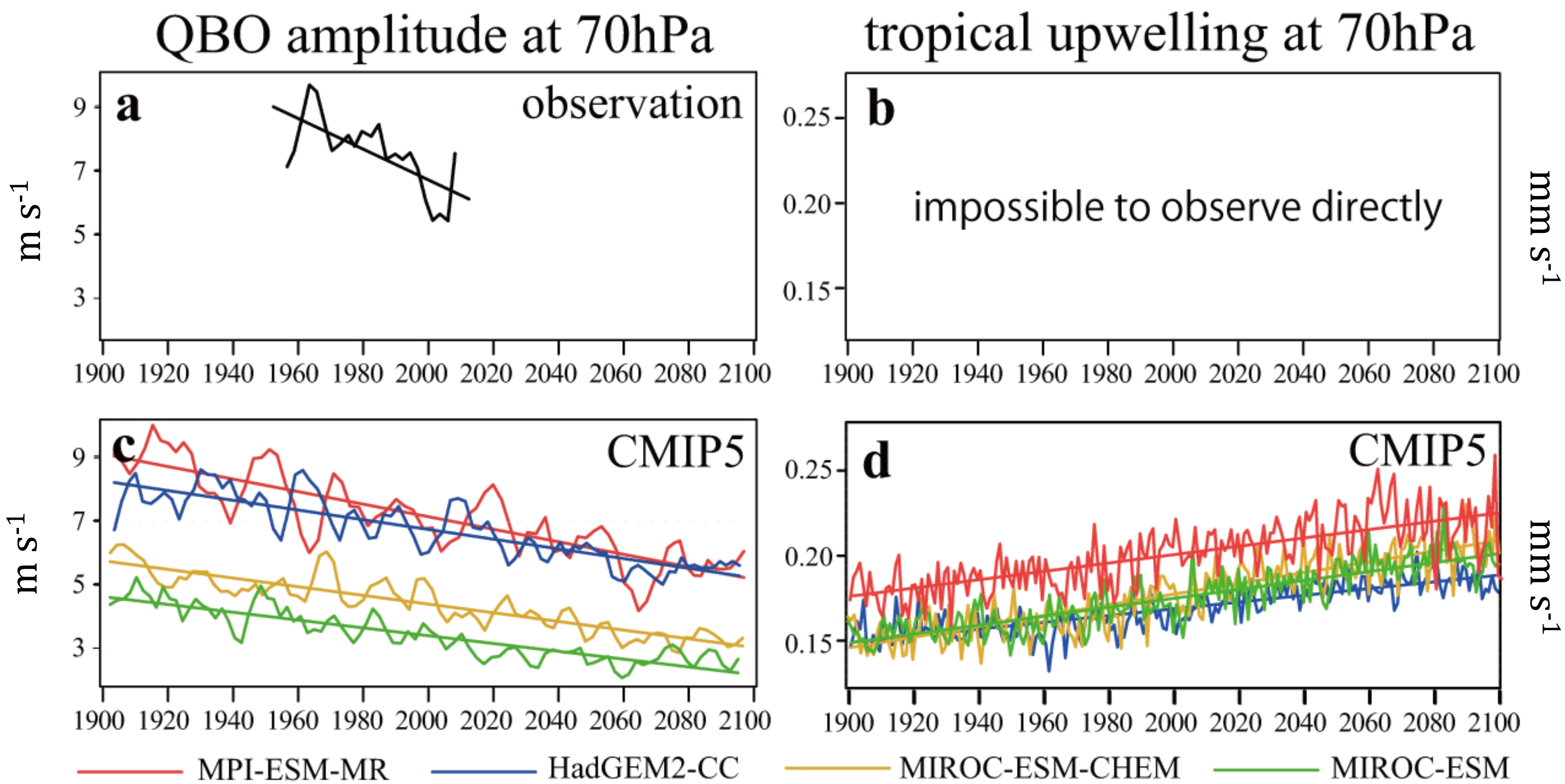
30-yr Correlations



QBO Changes with Climate?

Evidence the QBO may be changing with warming climate

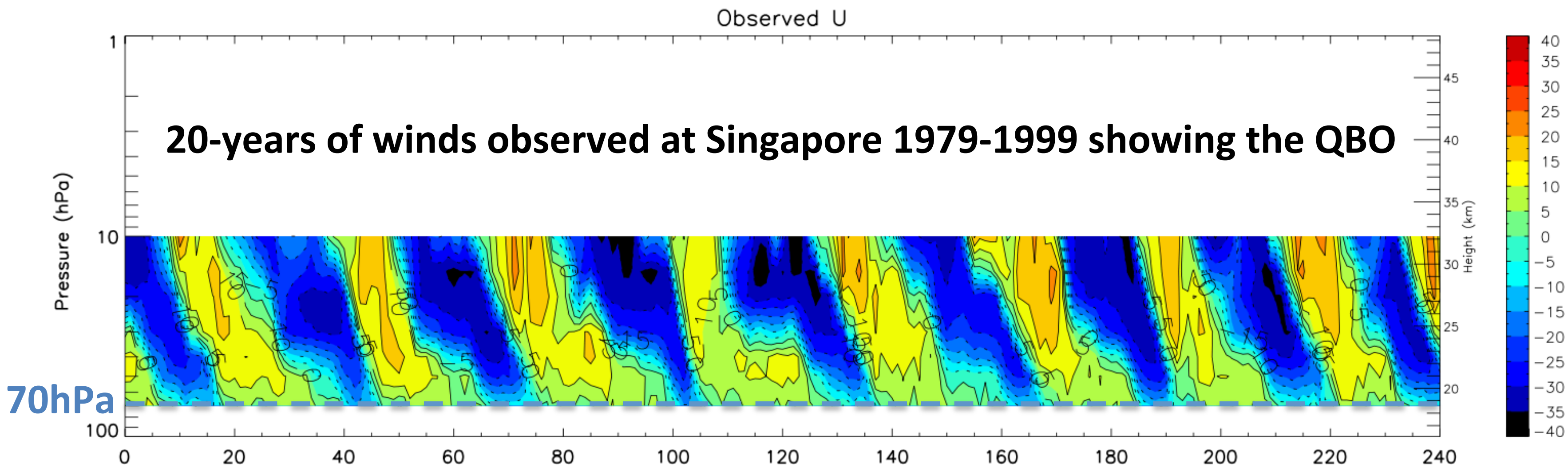
Kawatani and Hamilton [2013]:

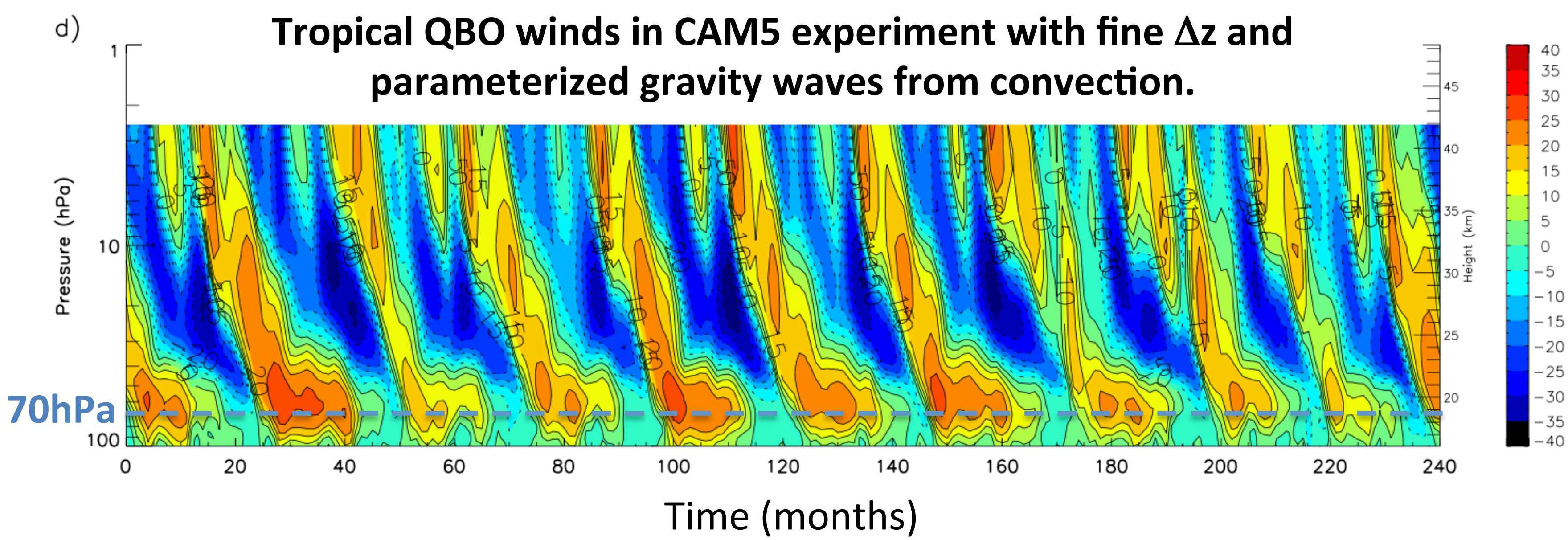


- Evidence that QBO winds near tropopause have grown weaker with time
- Consistent with model predictions that the Brewer-Dobson circulation is growing stronger, and may continue to do so in the future.
- Models also tend to predict the QBO period will get longer in the future.

QBO in Models

Richter et al [2015]: QBO in the NCAR 60-Level CAM5 Model



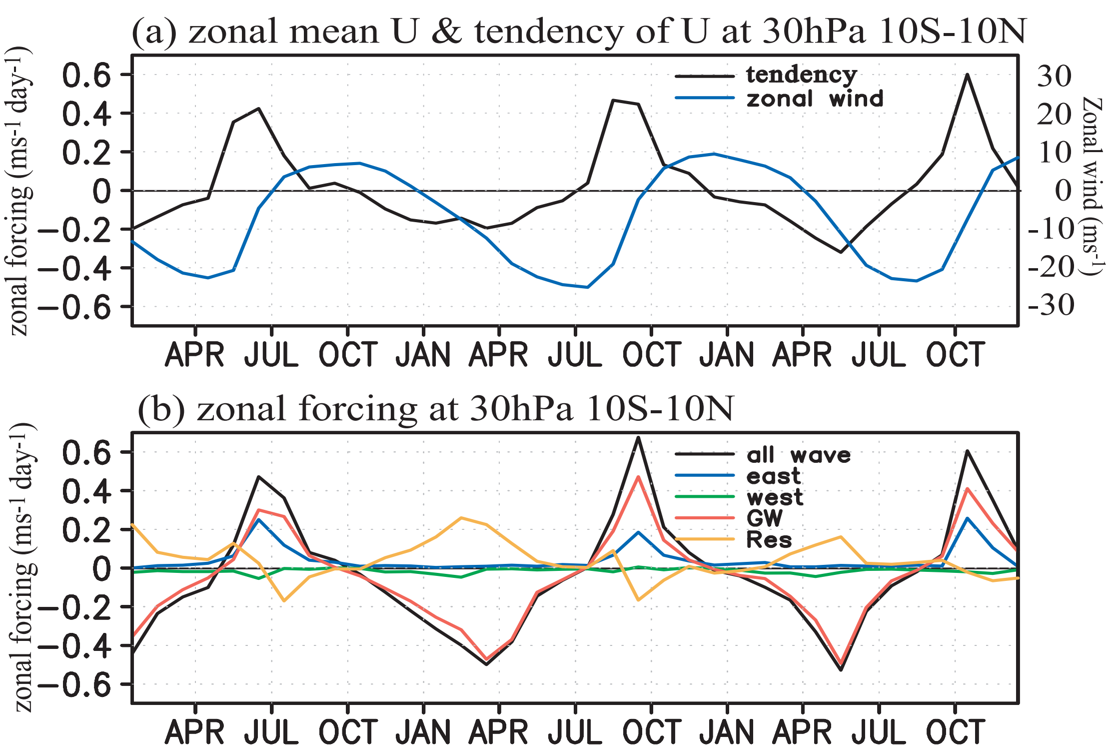


Gravity Waves and the QBO

Kawatani et al. [2010]: Analysis of T213 spectral model with 300m vertical resolution and no gravity wave parameterization

Wind shear	EQWs	Internal inertia–gravity waves
Eastward	~25%–50%	~50%–75%
Westward	Up to 10% during weak westward wind phase	$\lambda_x \lesssim 1000$ km main wave forcing*

*Some additional contribution from extratropical Rossby waves

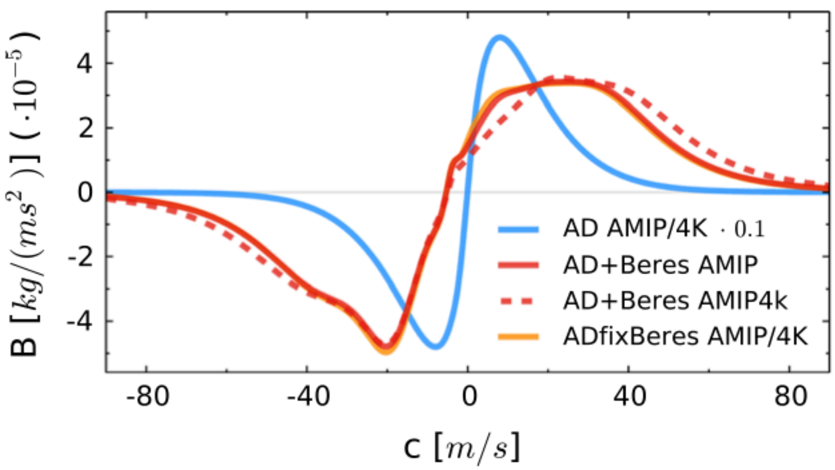


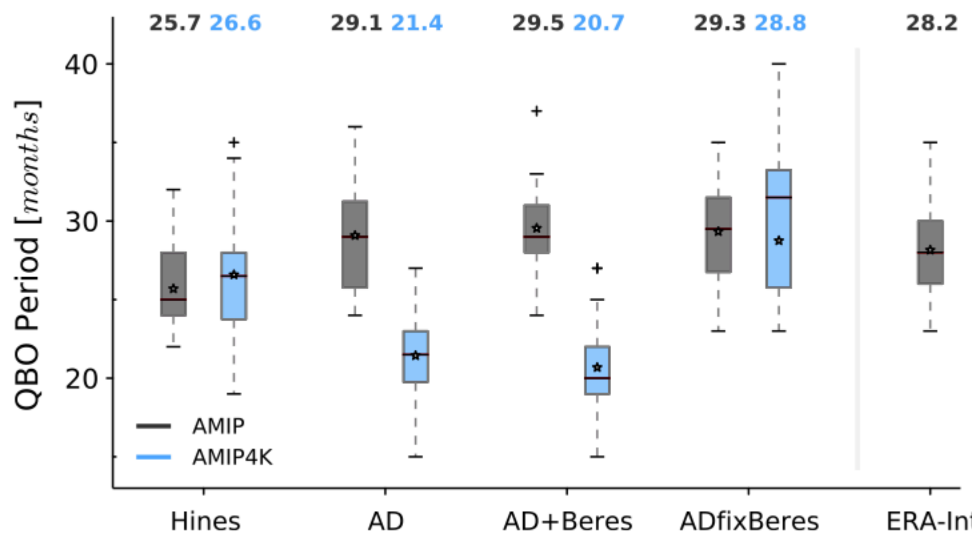
QBO Changes with Climate?

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.



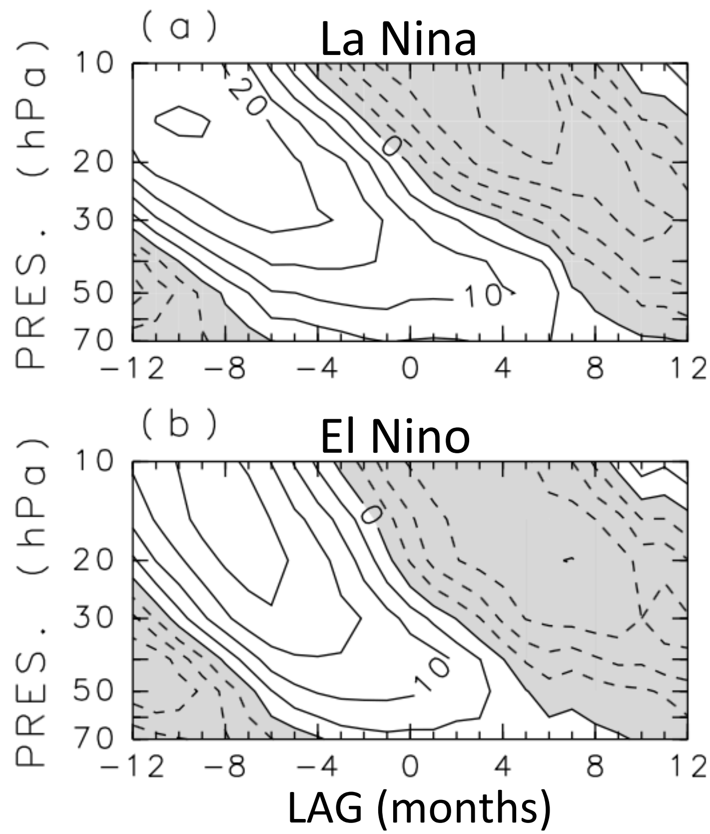


- Subtle changes in the gravity wave parameterization details gave different predictions for changes in the QBO in a warmer climate.
- Different cases have almost the same average momentum flux spectrum, but assume either frequent weak waves or intermittent stronger waves.

Observations and Speculations in the Literature

- **Taguchi [2010]:** Evidence that
  1. QBO period shorter El Nino and longer La Nina.
  2. QBO wind amplitude 10% stronger La Nina.
- **Geller et al. [2016]** suggest:
  1. GW momentum flux is higher during El Nino than La Nina, but
  2. The phase speed spectrum is broader during La Nina than El Nino.

Composites [Taguchi, 2010]



Model Study with Observational Validation

- Study of tropical gravity waves in differing ENSO conditions
- Observationally constrained model:
  - Global idealized primitive equation model

Model Study with Observational Validation

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  - **Forced with latent heating derived from observed precipitation rates**
  - Zonal mean state constrained to MERRA reanalysis
  - Validation of waves with 3-dimensional limb-sounding momentum fluxes

SOURCES

Model Study with Observational Validation

- Study of tropical gravity waves in differing ENSO conditions
- Observationally constrained model:
  - Global idealized primitive equation model
  - Forced with latent heating derived from observed precipitation rates
  - **Zonal mean winds and temperatures constrained to MERRA reanalysis**

MEAN

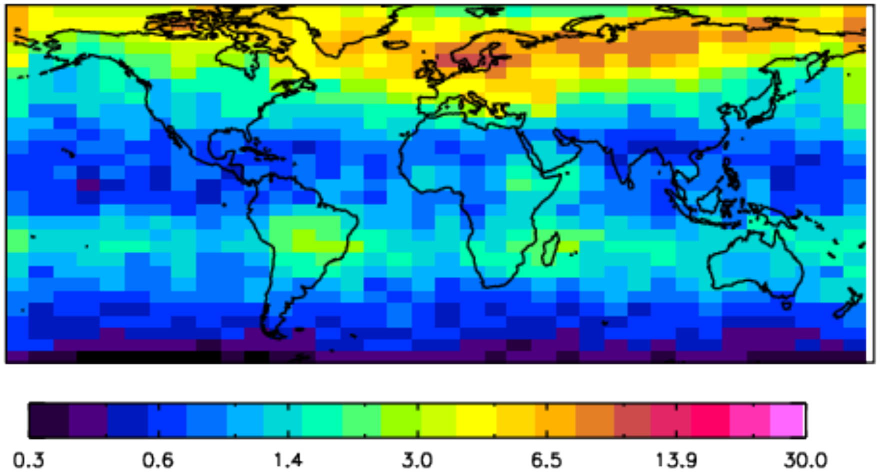
Model Study with Observational Validation

- Study of tropical gravity waves in differing ENSO conditions
- Observationally constrained model:
  - Global idealized primitive equation model
  - Forced with latent heating derived from observed precipitation rates
  - Zonal mean state constrained to MERRA reanalysis
  - **Validation of waves with 3-dimensional limb-sounding momentum fluxes**

WAVES

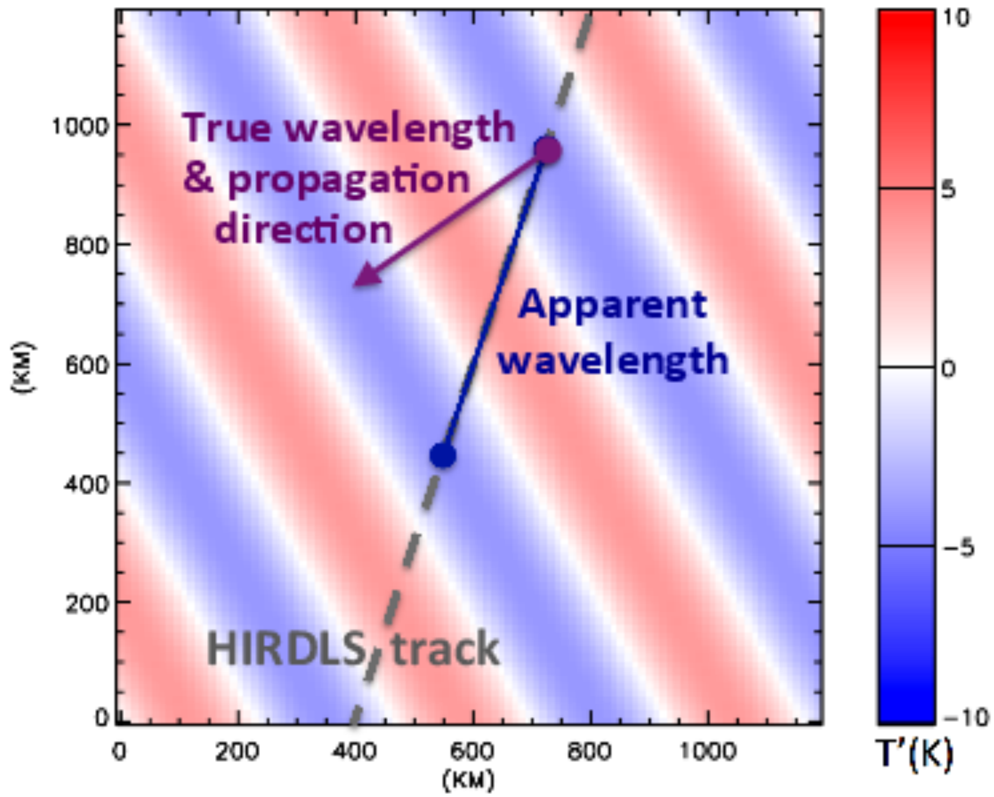
HIRDLS "2D" Gravity Wave Momentum Flux

HIRDLS "2D" Momentum Flux



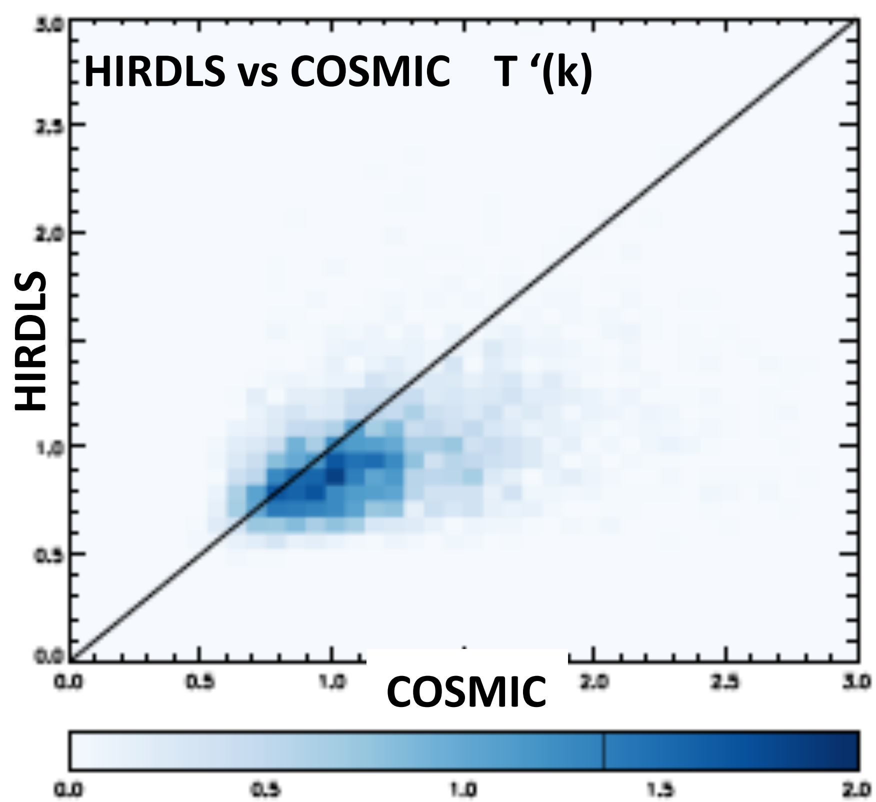
HIRDLS has best coverage and resolution in lower stratosphere. Method is limited to a "2D" approach due to the satellite sampling pattern.

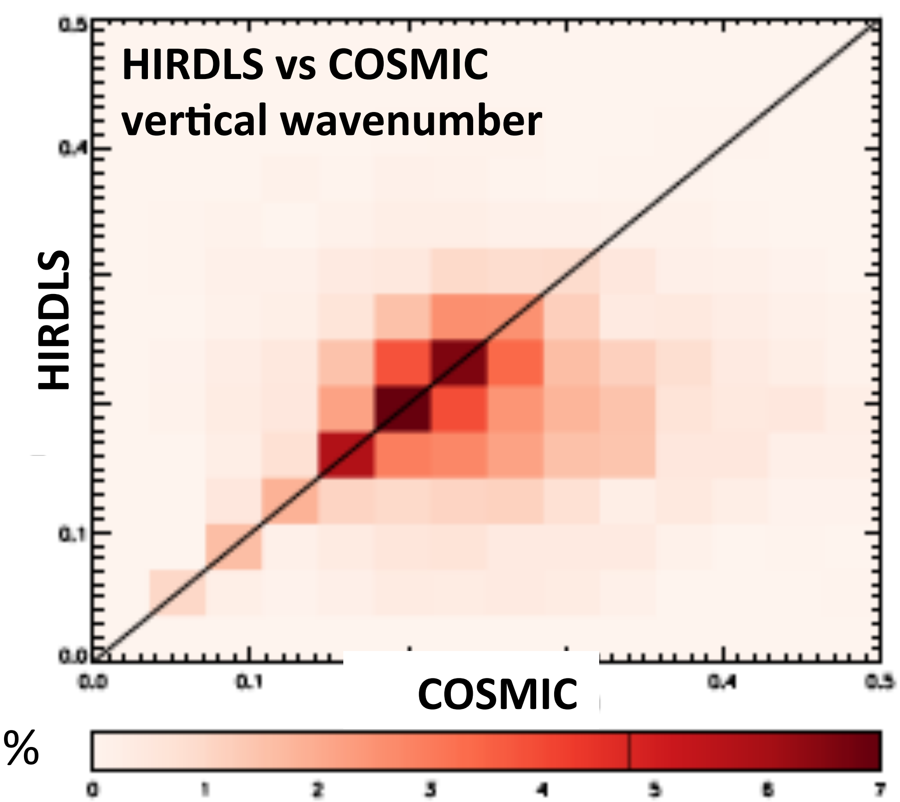
Need "3D" information off the measurement track to correct the major known bias in these momentum fluxes



3D Method: Combines GPS 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.



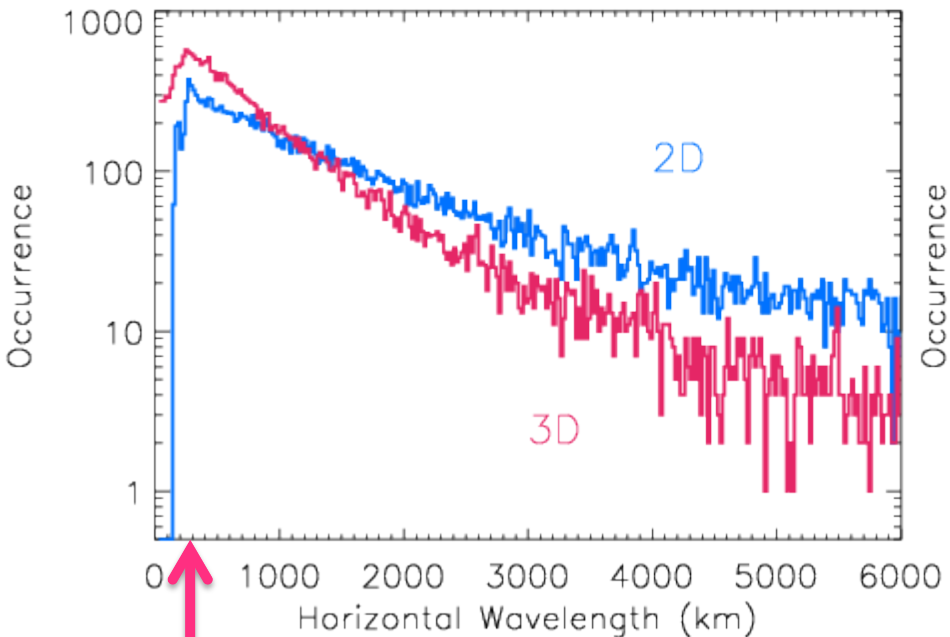


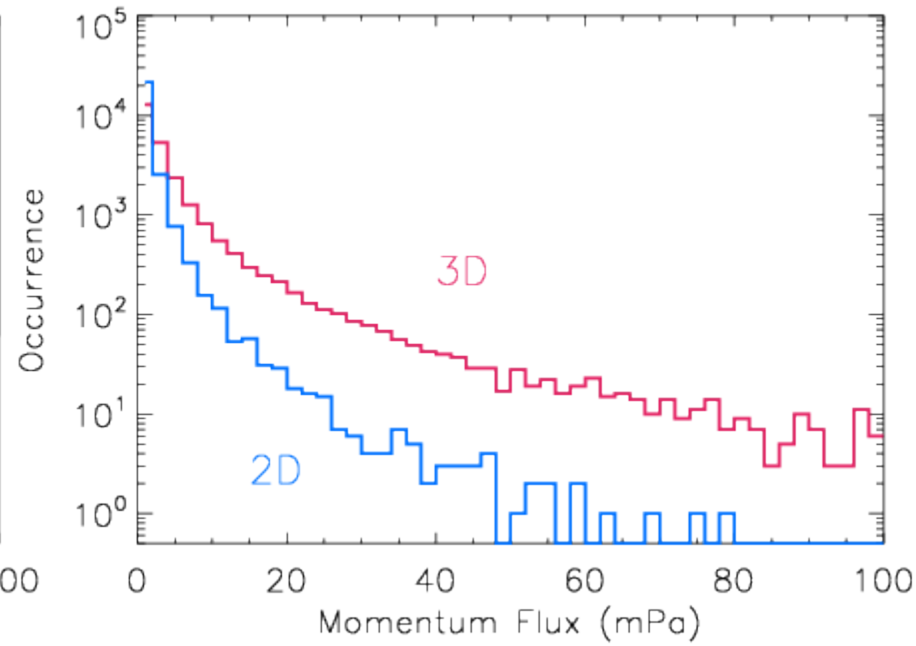
%

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:

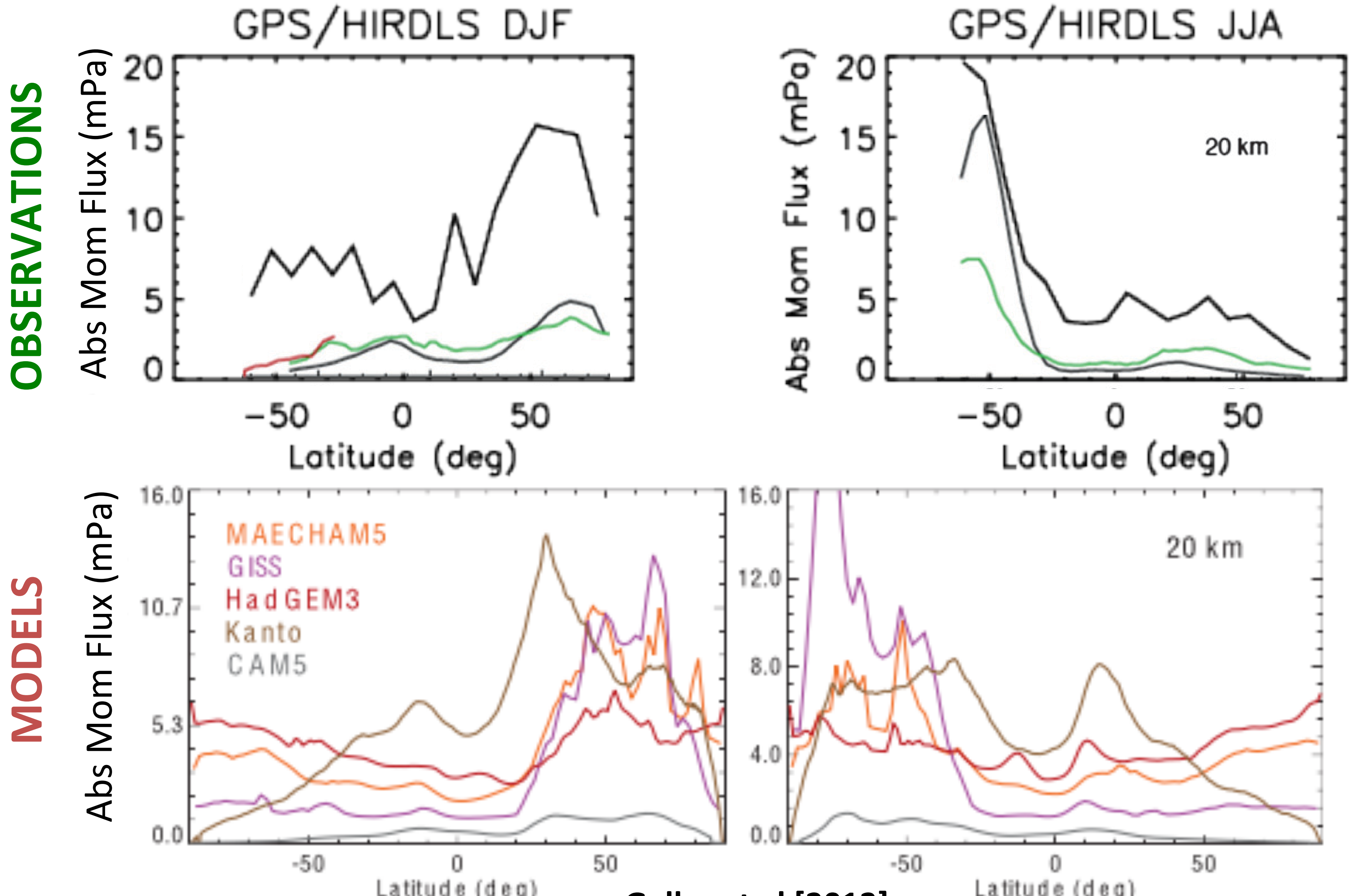
888 km → 354 km

Mean absolute momentum flux increases by a factor of 3.7:

1.7 mPa → 6.4 mPa

- Amplitudes display long large-amplitude tails.

Compare to Geller et al [2013] Momentum Flux

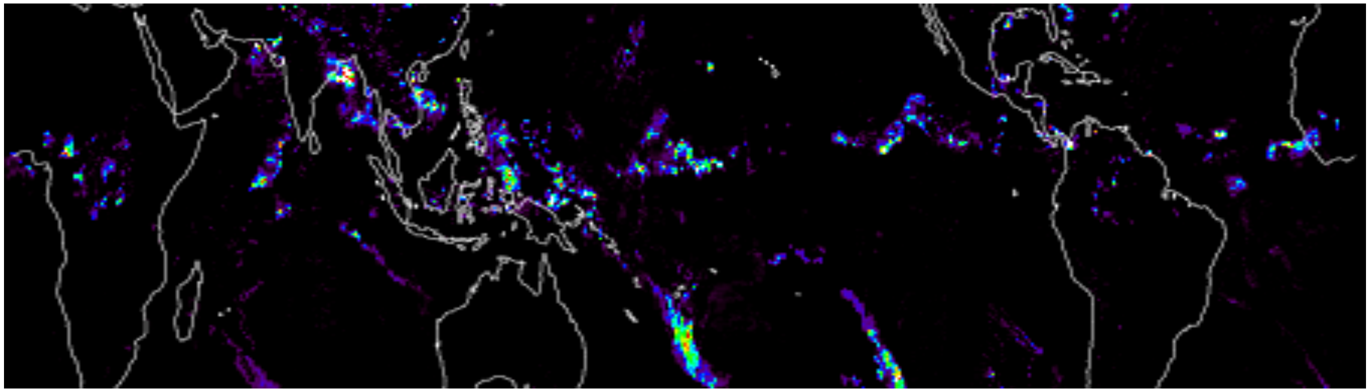


Geller et al [2013]

Tropical Wave Model Description

- Dry global primitive equation model [Ortland et al 2011]
- **Waves forced by latent heating** Q(x,y,z,t) 30^{o}S–30^{o}N

30 minute CMORPH rainrate



- **Heating derived from CMORPH rain observations** [Joyce et al. 2004]
  Method of Ryu et al. [2011] includes convective and stratiform heating profiles

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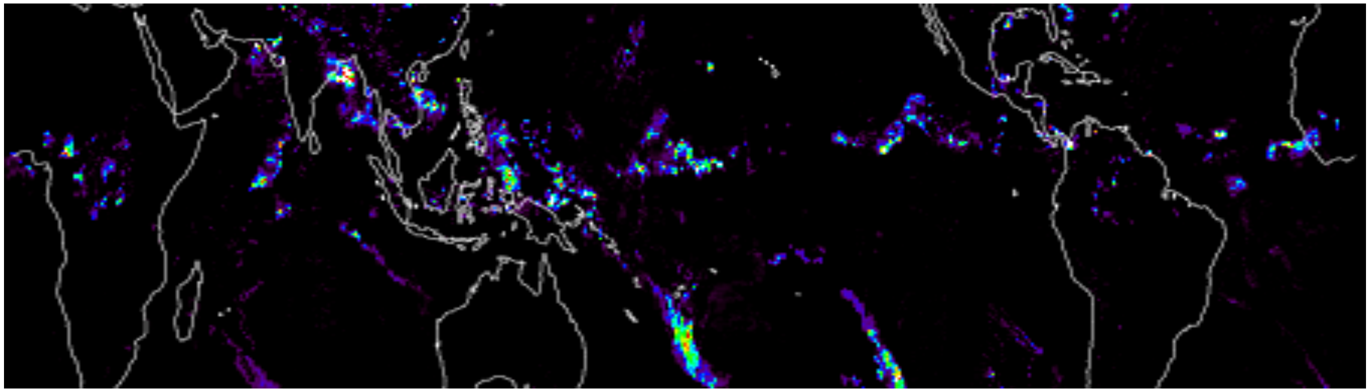
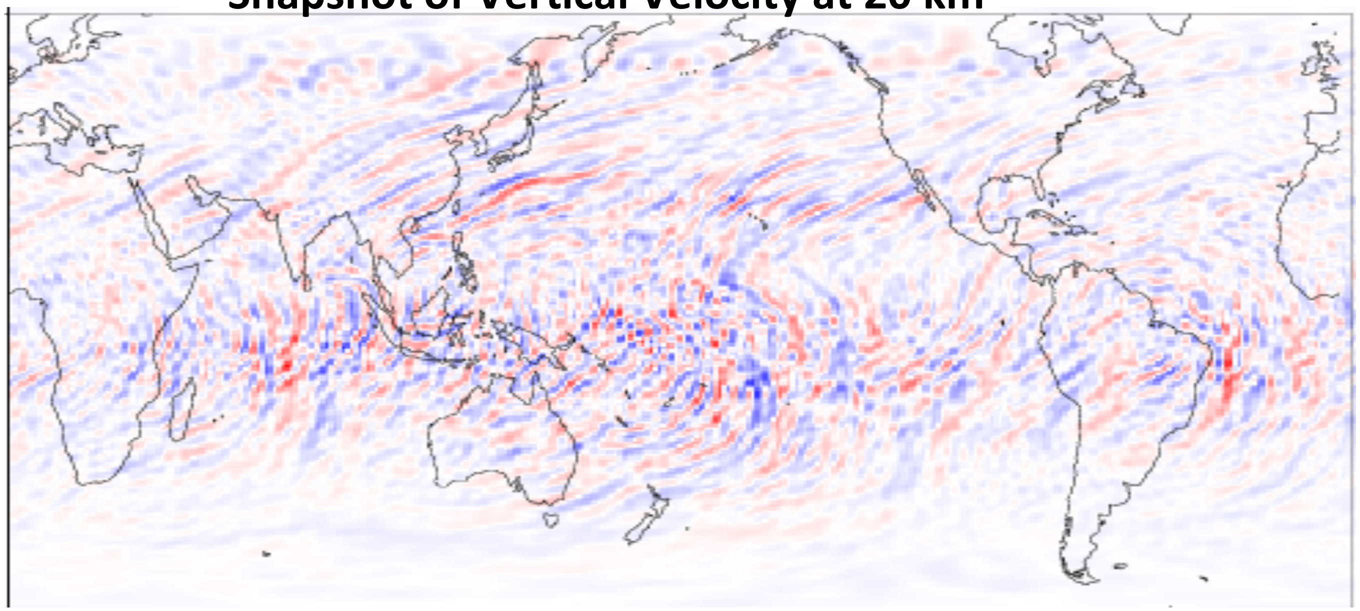


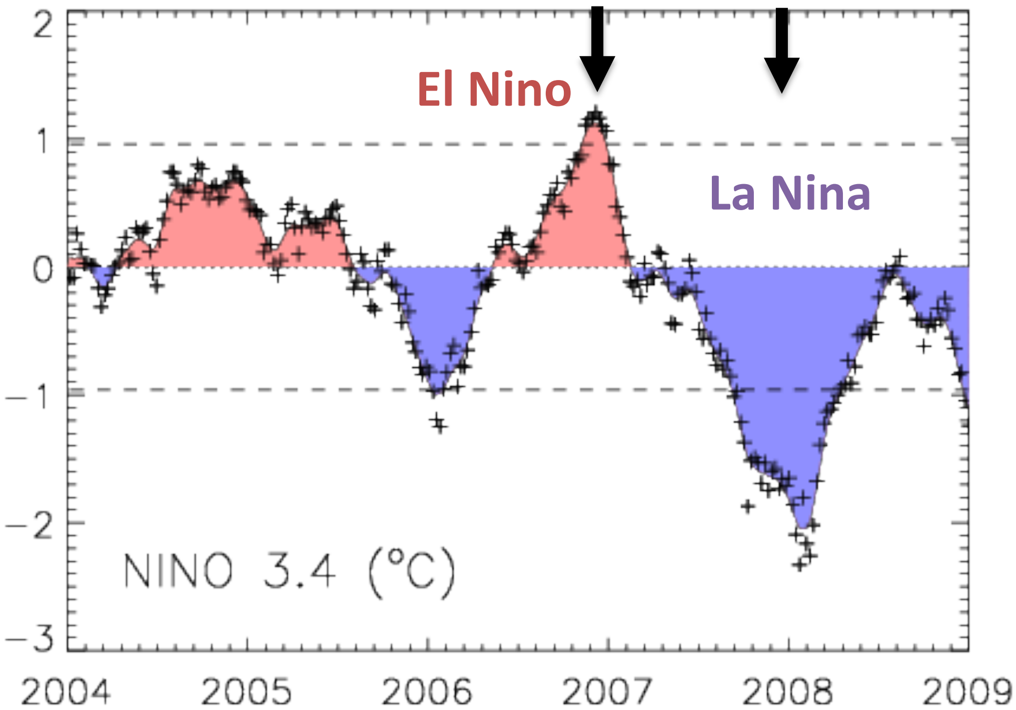
- **Heating derived from CMORPH rain observations** [Joyce et al. 2004]
  Method of Ryu et al. [2011] includes convective and stratiform heating profiles

- Variable heating: resolution Δt=30min
- T120, Δz=500m resolution designed to simulate waves observed with HIRDLS+GPS method

Snapshot of Vertical Velocity at 20 km



Model Comparisons: Dec 2006 vs Dec 2007



Yuan et al. [2013]:

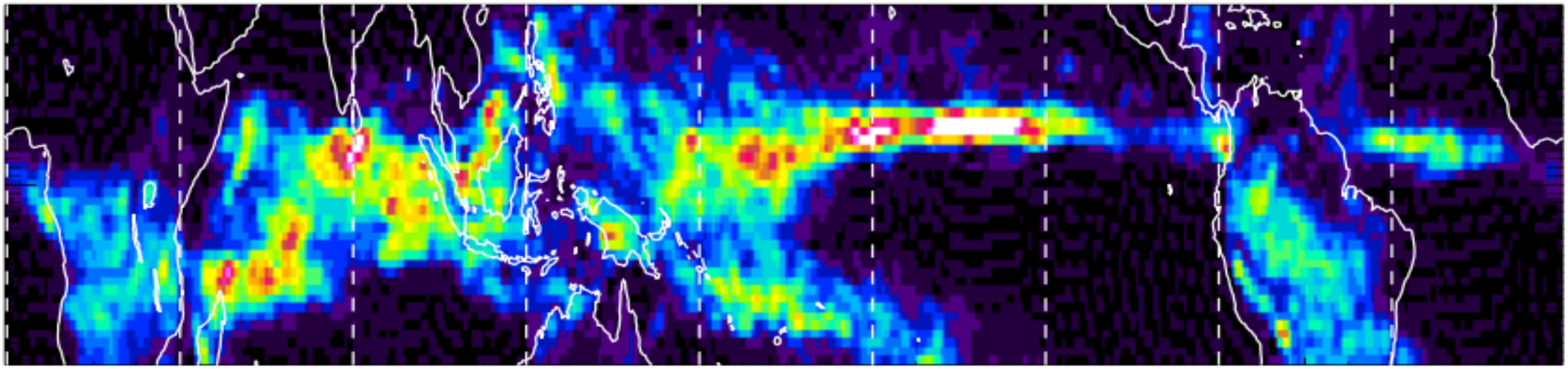
El Nino Mean	La Nina Mean
QBO Period = 25.0 mo	QBO Period = 31.8 mo
QBO Amplitude = 1.15	QBO Amplitude = 1.24

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

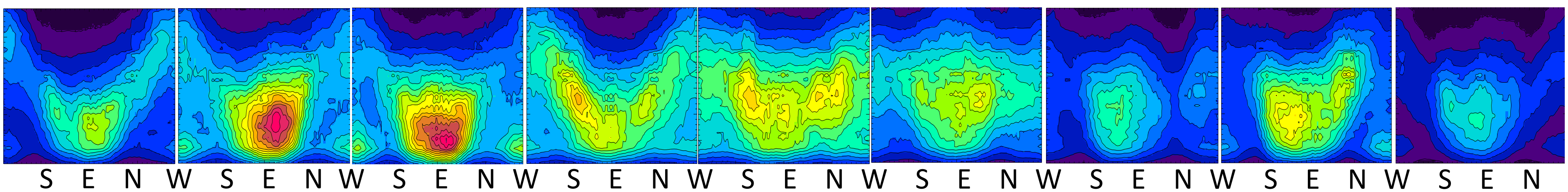
→ Geller et al. [2016] hypotheses

- The **El Nino** year has significantly shorter QBO period
  → larger gravity wave fluxes
- The **La Nina** year has significantly larger QBO amplitude
  → broader phase speed spectrum

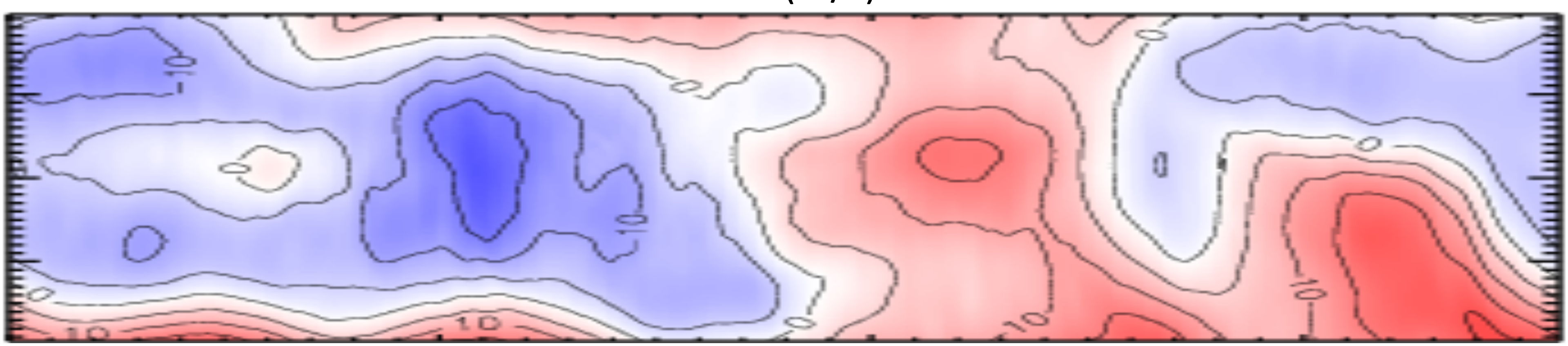
Total heating Dec06



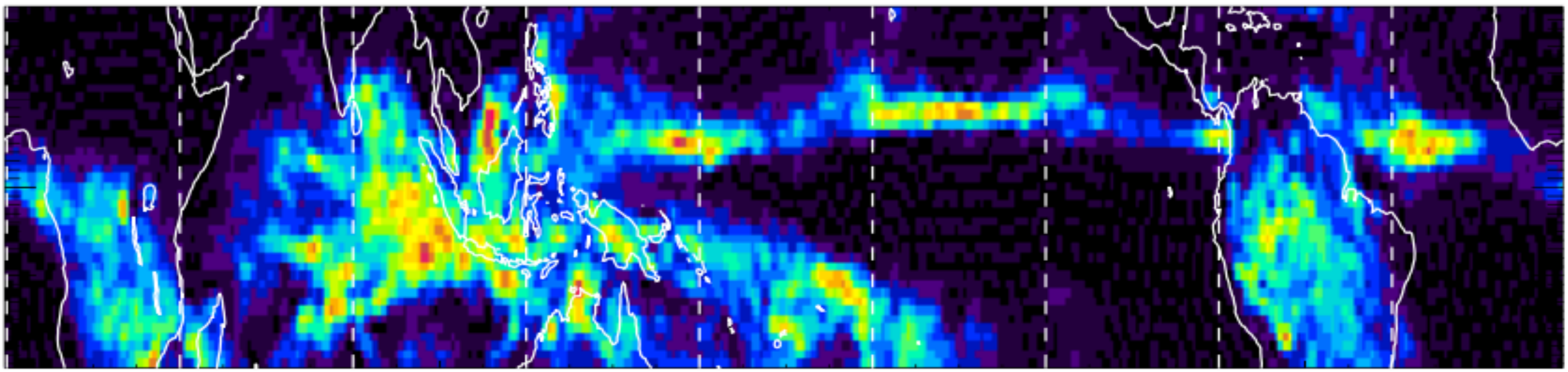
Flux at 17 km: Azimuth (W-S-E-N-W)/ Phase Speed (0-32 m/s)



Mean Zonal Wind (m/s) at 95 hPa



Total heating Dec07



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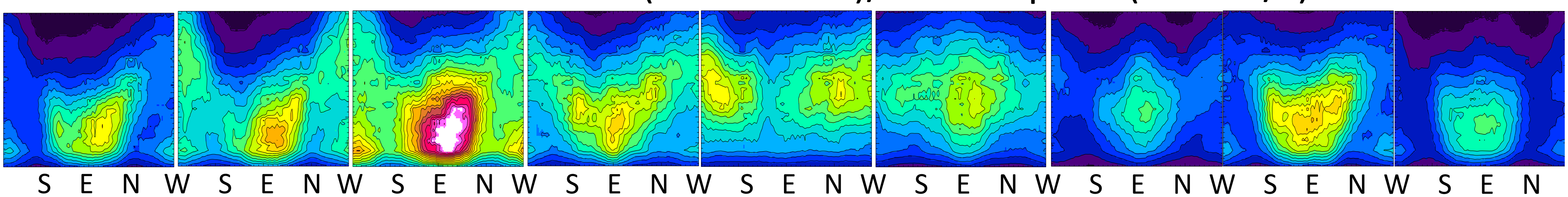

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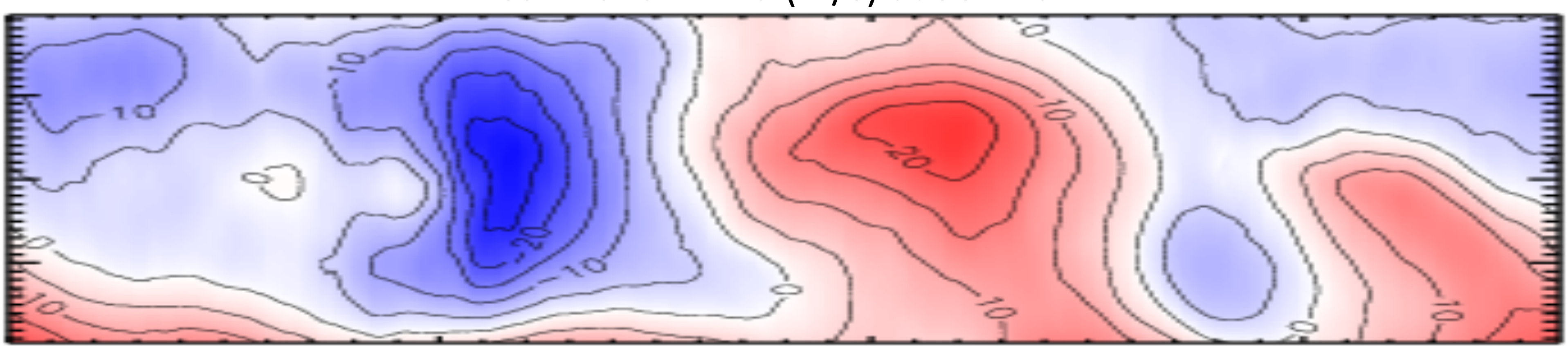


Compare Model & Observations

Gravity wave momentum fluxes at 20km:

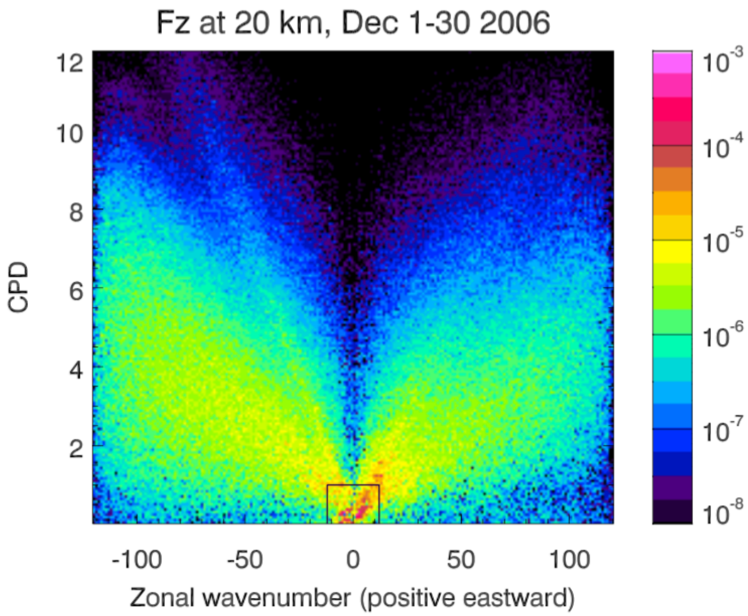
20°S—20°N	Model	GPS/HIRDLS	HIRDLS-only
Zonal mean flux Dec 2007	2.6 mPa	3.4 mPa	0.8 mPa
Fraction zonal flux Dec 2007	76%	75%	N/A

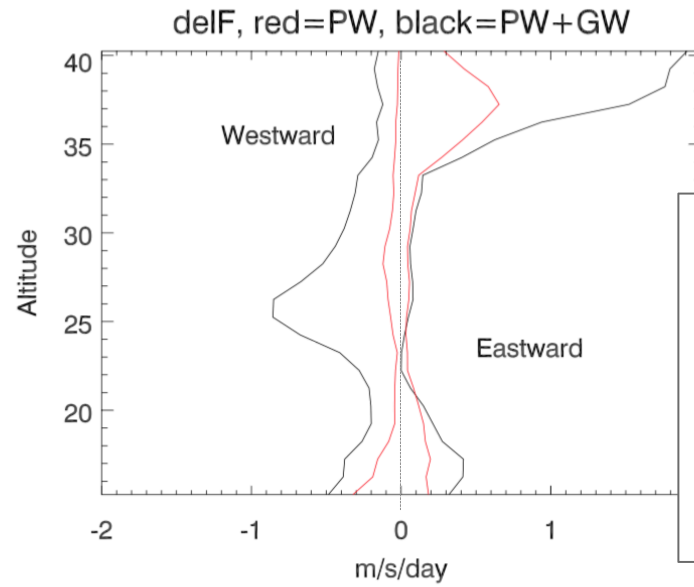
Zonal mean flux Mar-May 2010 PreConcordiasi balloons: 3.9 – 5.4 mPa*
(balloons include a broader spectrum of waves)

*[Jewtoukoff et al., 2013]

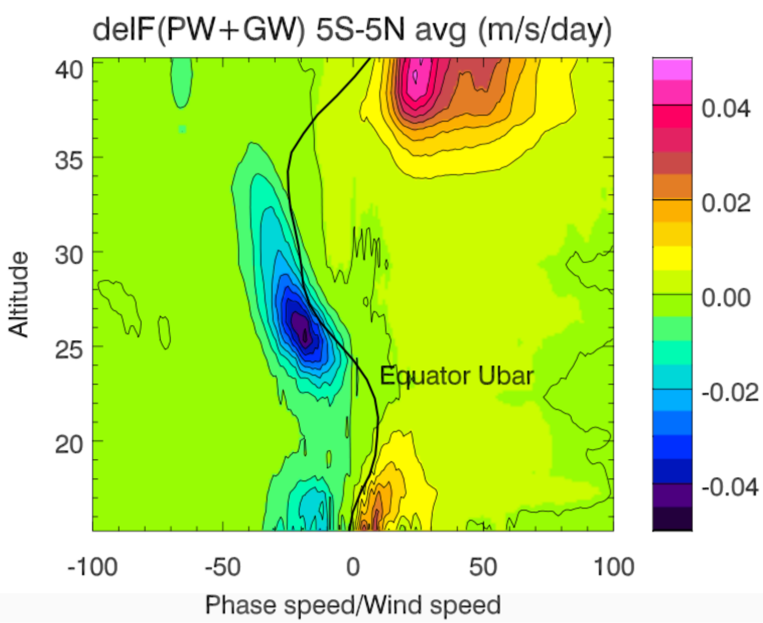
Model Results: Force on the Flow

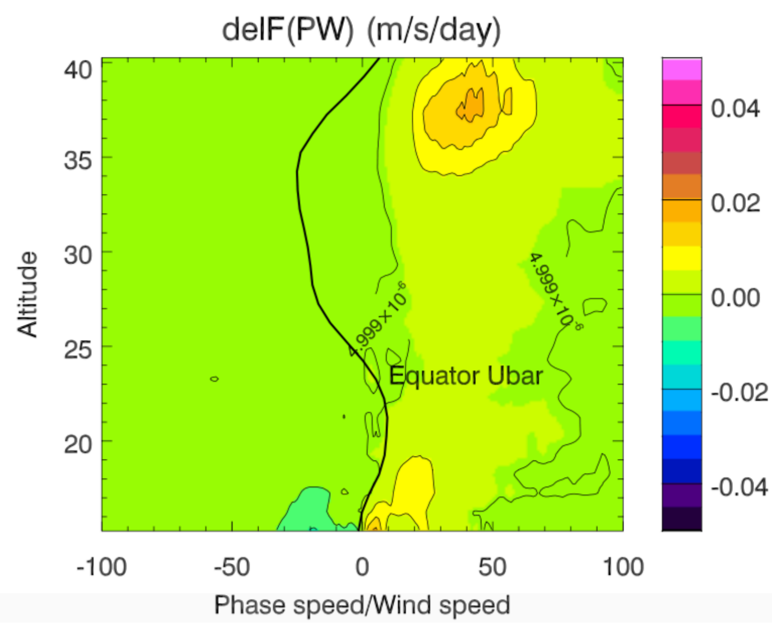
December 2006





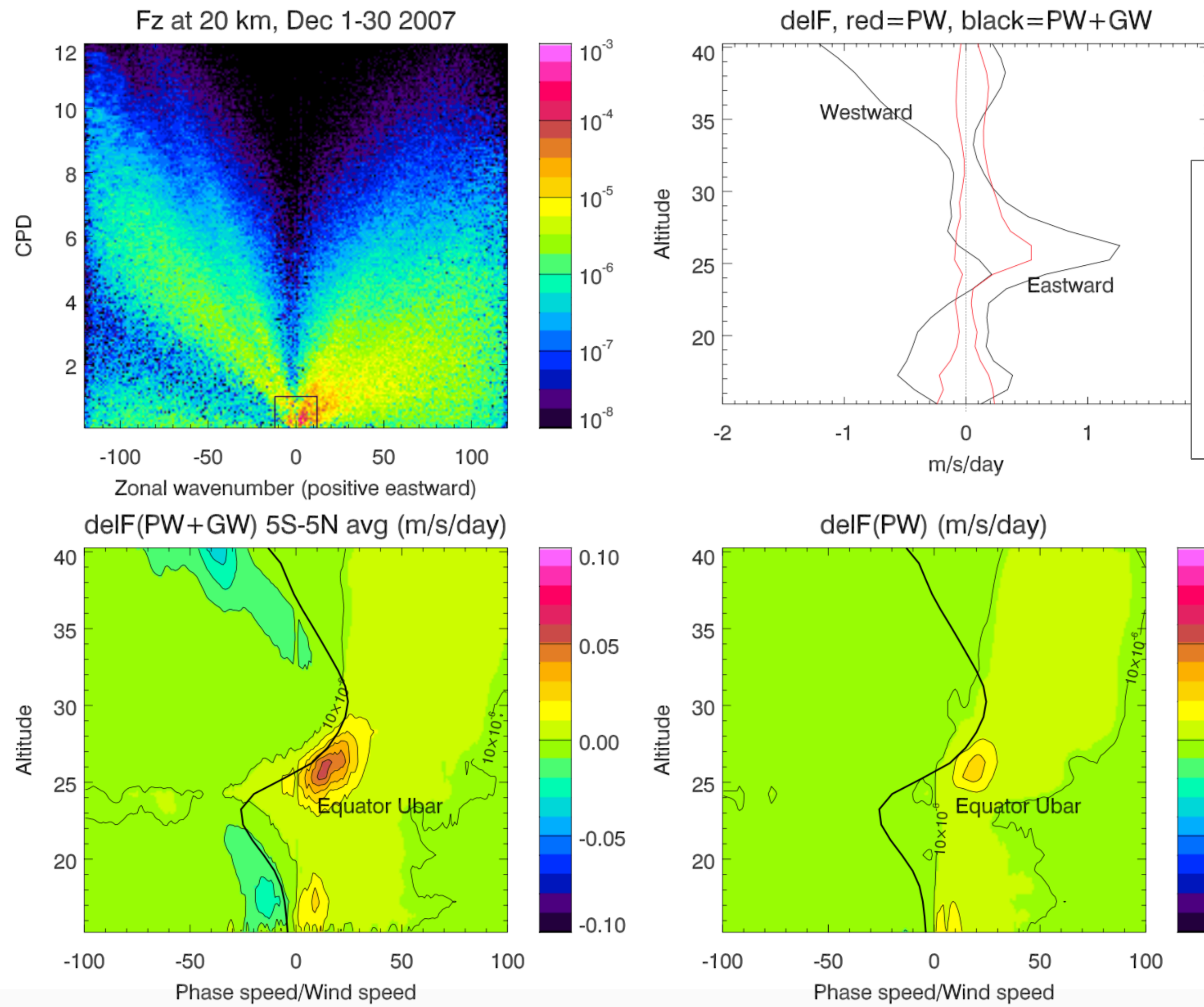
Difference between the black and red curves show the gravity wave forcing





Model Results: Force on the Flow

December 2007



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Model Results: Force on the Flow

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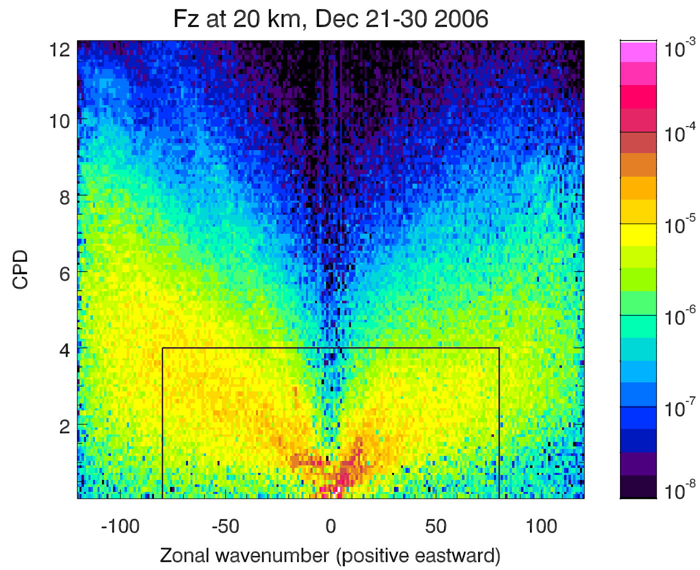

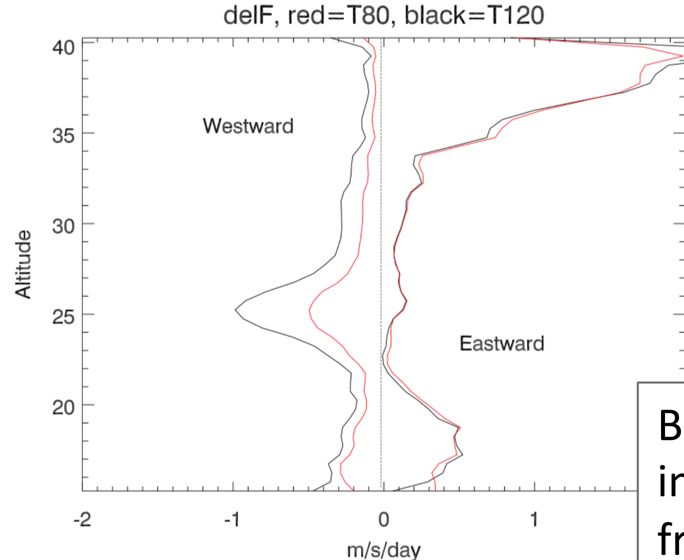

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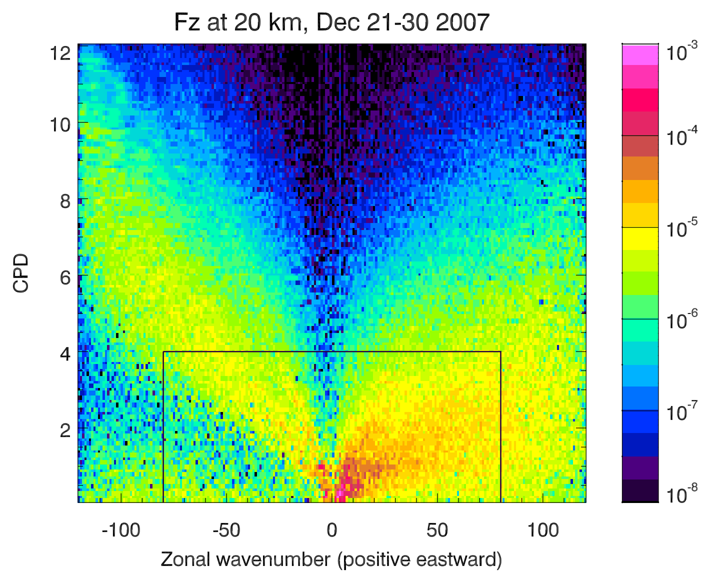
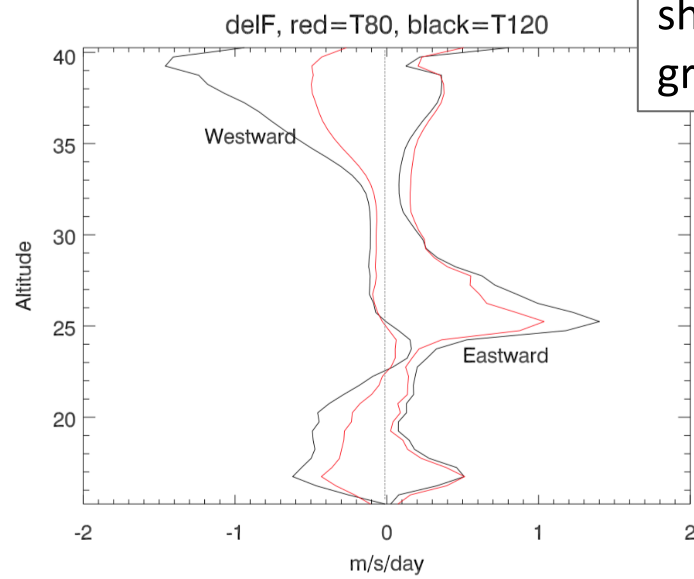




Black curves include high-frequency, short-scale gravity waves

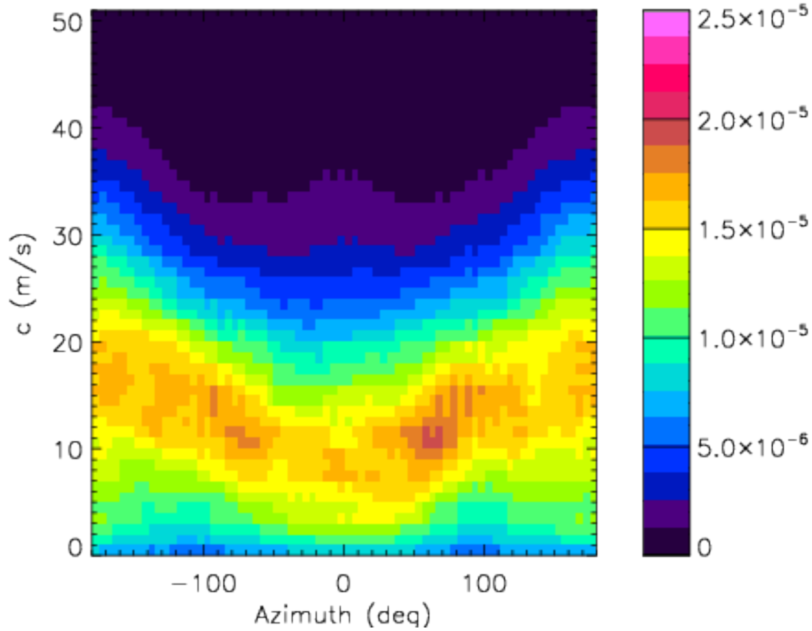
Zonal Mean Momentum Flux

Average of all longitudes, and altitudes 15-18 km

Wavelengths < 3000 km, Periods < 1 day

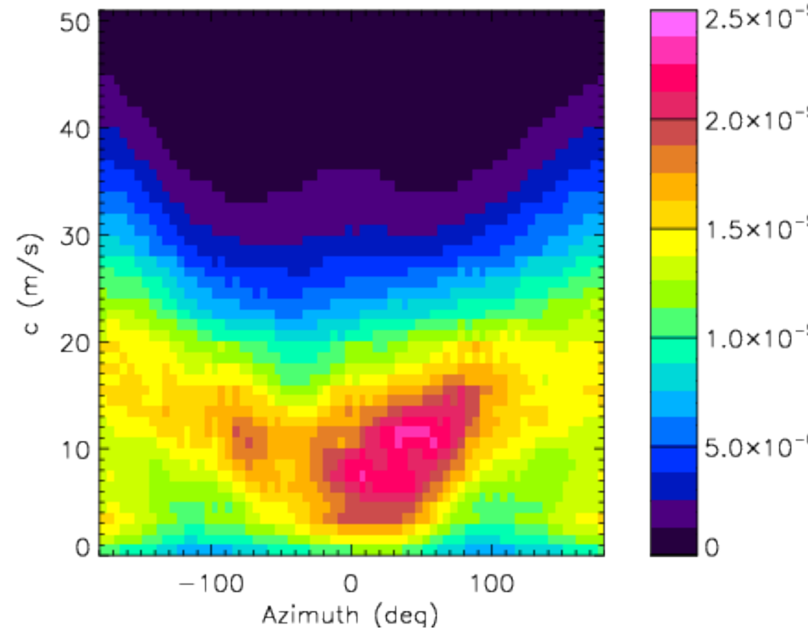
El Nino Case

Dec 2006



La Nina Case

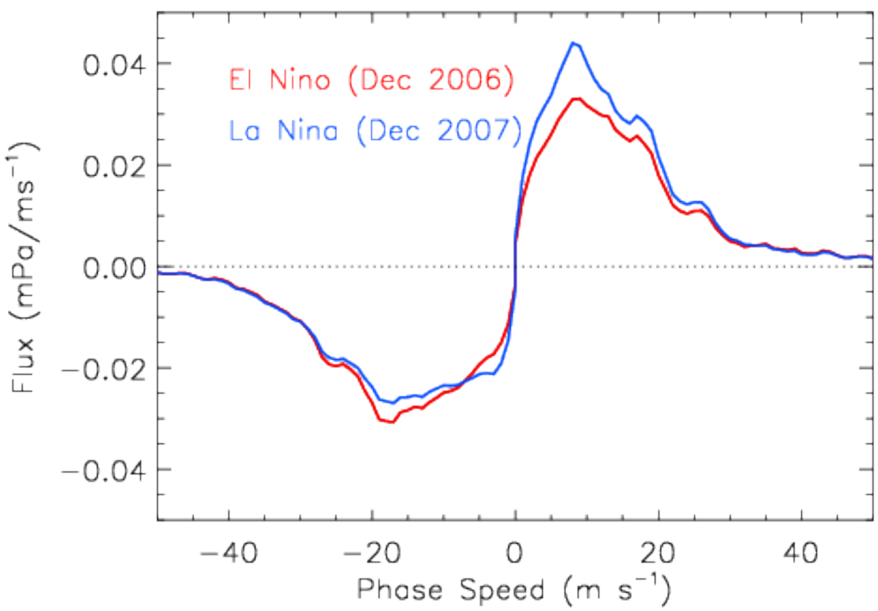
Dec 2007

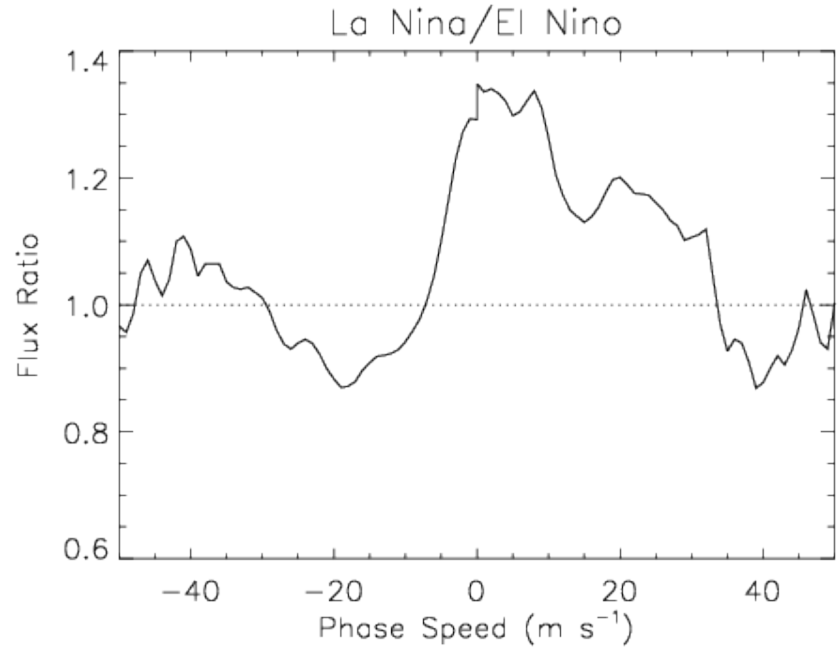


- **La Nina** Flux > **El Nino** Flux
- No obvious differences in spectral widths
- No confirmation of Geller et al [2016] hypothesis

Zonal Flux Comparison

Average of all the longitudes, at z=16 km





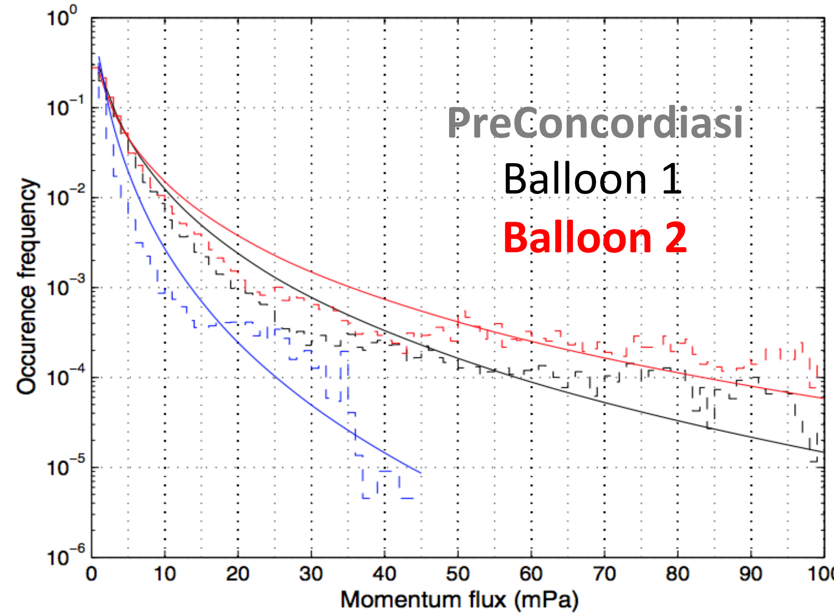
Notes on these results:

- Zonal mean fluxes are 8.5mPa (El Nino), 9.4mPa (La Nina)
- El Nino year fluxes are 10-20% larger only for westward waves -5 to -30m/s and for eastward waves with phase speeds >35 m/s.
- La Nina fluxes are 15-30% larger for eastward phase speeds < 30 m/s and 10% larger for westward waves < -40m/s.

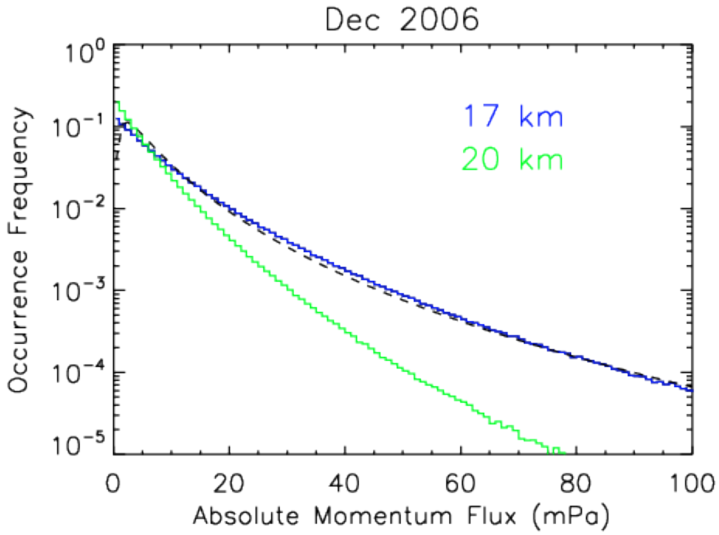
→ *Overall, this limited sample does not support the Geller et al. [2016] hypothesis.*

Momentum Flux Distributions

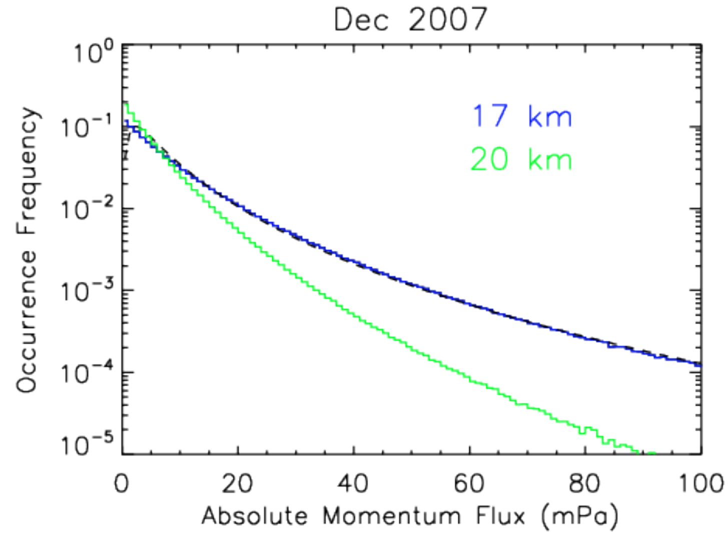
- Long duration balloon observations in the tropics (red and black) show log-normal distributions →
- Model fluxes display same lognormal shape, although fewer large values near the balloon altitude (20km).
- **2007 La Nina** > **2006 El Nino**



2006 El Nino



2007 La Nina



Conclusions

- **Combined HIRDLS + COSMIC give 3D momentum flux corrections ~ 5x in the tropics.** Sampling pattern of HIRDLS combined with wave propagation directions means traditional 2D methods have large errors in tropics.
- Observationally constrained model study comparing Dec 2006 (El Nino) to Dec 2007 (La Nina) conditions does not confirm previously hypothesized differences in the gravity wave spectrum.
- **Gravity waves in climate models are too uniform:** Missing large amplitude waves that will break in the lower stratosphere affecting QBO wind shears including lower levels most important for weather and climate effects.