Tropical Gravity Wave Effects on Circulation and Climate

M. Joan Alexander and David Ortland,
NorthWest Research Associates
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
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.
Richter et al. [2015]: QBO in the NCAR 60-Level CAM5 Model

20-years of winds observed at Singapore 1979-1999 showing the QBO

Tropical QBO winds in CAM5 experiment with fine Δz and parameterized gravity waves from convection.
Gravity Waves and the QBO

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

<table>
<thead>
<tr>
<th>Wind shear</th>
<th>EQWs</th>
<th>Internal inertia–gravity waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastward</td>
<td>~25%–50%</td>
<td>~50%–75%</td>
</tr>
<tr>
<td>Westward</td>
<td>Up to 10% during weak westward wind phase</td>
<td>(\lambda_x \lesssim 1000 \text{ km main wave forcing})*</td>
</tr>
</tbody>
</table>

*Some additional contribution from extratropical Rossby waves

---

**Figure 1a**: Zonal mean U & tendency of U at 30hPa, 10S-10N

**Figure 1b**: Zonal forcing at 30hPa, 10S-10N
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.
• Study of tropical gravity waves in differing ENSO conditions
• Observationally constrained model:
  - Global idealized primitive equation model
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
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
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
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**

**Distributions of Horizontal Wavelength and Momentum Flux**

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.
occur near the tropopause. Polar stratospheric clouds may also be important at polar winter latitudes. Last, the spectral window width, which is fixed for HIRDLS2 but varies with vertical wavelength for HIRDLS1, may cause errors at different latitudes in the wave retrievals near the upper and lower boundaries of the data coverage.

Zonal-mean absolute momentum fluxes versus latitude derived from the two methods HIRDLS1 and HIRDLS2 are shown in Fig. 1 with black and green lines, respectively. The left column shows January 2006, and the right column shows July 2006. The two HIRDLS methods show very similar seasonal patterns. They also show very similar interannual variability (shown later). The largest fluxes occur at Southern Hemisphere winter latitudes, maximizing just south of 50°S. Note that these are the latitudes where the HIRDLS measurement track turns toward an east–west orientation and where stratospheric zonal winds are at a maximum. Here, the zonal sampling is optimal for observing short horizontal wavelength waves propagating in the zonal direction, including mountain waves, and many waves.

**Figure 1.** Comparison of absolute gravity wave momentum fluxes at altitudes of 20, 30, 40, and 50 km derived from two different methods using HIRDLS data, one method using SABER data, and Vorcore data for (left) January and (right) July 2006. Note that the January Vorcore data are only available at 20-km altitude, and SABER data is only available at altitudes $>30$ km.

Compare to Geller et al [2013] Momentum Flux
Tropical Wave Model Description

- Dry global primitive equation model [Ortland et al. 2011]
- Waves forced by latent heating $Q(x,y,z,t)$ 30°S–30°N
- Heating derived from CMORPH rain observations [Joyce et al. 2004]
  Method of Ryu et al. [2011] includes convective and stratiform heating profiles
Tropical Wave Model Description

- **Dry global primitive equation model** [Ortland et al. 2011]
- **Waves forced by latent heating**
  \( Q(x, y, z, t) \) 30°S–30°N
- **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 \( \Delta t = 30 \text{min} \)
- **T120, \( \Delta z = 500 \text{m} \)** resolution designed to simulate waves observed with HIRDLS+GPS method

**30 minute CMORPH rainrate**

**Snapshot of Vertical Velocity at 20 km**
Model Comparisons: Dec 2006 vs Dec 2007

Yuan et al. [2013]:

<table>
<thead>
<tr>
<th></th>
<th>El Nino Mean</th>
<th>La Nina Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>QBO Period</td>
<td>= 25.0 mo</td>
<td>= 31.8 mo</td>
</tr>
<tr>
<td>QBO Amplitude</td>
<td>= 1.15</td>
<td>= 1.24</td>
</tr>
</tbody>
</table>

• 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

Geller et al. [2016] hypotheses
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
Gravity wave momentum fluxes at 20km:

<table>
<thead>
<tr>
<th>20°S—20°N</th>
<th>Model</th>
<th>GPS/HIRDLS</th>
<th>HIRDLS-only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zonal mean flux Dec 2007</td>
<td>2.6 mPa</td>
<td>3.4 mPa</td>
<td>0.8 mPa</td>
</tr>
<tr>
<td>Fraction zonal flux Dec 2007</td>
<td>76%</td>
<td>75%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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

The difference between the black and red curves show the gravity wave forcing.
Model Results: Force on the Flow

December 2007

Difference between the black and red curves show the gravity wave forcing.
Model Results: Force on the Flow

Dec 2006

Fz at 20 km, Dec 21-30 2006

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

Dec 2007

Fz at 20 km, Dec 21-30 2007
Zonal Mean Momentum Flux

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

- 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
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.