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Key Points:

- A quasi-biennial oscillation is observed in the midlatitude MLT gravity wave momentum flux
- The QBO modulation is best explained by interhemispheric coupling to the Holton-Tan effect

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QBO modulation of the mesopause gravity wave momentum flux over Tierra del Fuego

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Abstract The interannual variability of the mesosphere and lower thermosphere (MLT) gravity wave momentum flux over southern midlatitudes (53.7°S) has been studied using more than 7 years of meteor radar observations at Río Grande, Argentina. A modulation, with periods similar to that of the equatorial stratospheric quasi-biennial oscillation (QBO), is observed in the vertical flux of zonal as well as meridional momentum. The QBO signal is largest in the zonal component during summer and is in phase with the stratospheric QBO at 50 hPa (~21 km). The relation between the stratospheric QBO and the QBO modulation in the MLT gravity wave forcing (derived from the divergence of the momentum flux) was found to be consistent with that expected from the Holton-Tan effect coupled to the interhemispheric coupling mechanism. These results provide the first observational support for the existence of the midlatitude gravity wave forcing anomalies as hypothesized in the interhemispheric coupling mechanism.

1. Introduction

Gravity waves (GWs) play a key role in coupling various atmospheric regions both through their ability to transport energy and momentum and their role in wave-mean flow interactions [e.g., *Fritts and Alexander*, 2003; *Becker*, 2011]. To describe the effect of waves on the circulation, the divergence of the Eliassen-Palm (E-P) flux is included in the transformed Eulerian mean (TEM) equations. The importance of GWs is highlighted by the presence of the GW vertical flux of horizontal momentum ($\overline{u'w'}$, $\overline{v'w'}$) in the E-P flux terms [e.g., *Ern et al.*, 2011], and at middle and high latitudes in particular the zonal component acts to drive the mesosphere and lower thermosphere (MLT) summer to winter pole residual circulation [e.g., *Becker*, 2011; *Fritts*, 2015]. Due to the presence and importance of $\overline{u'w'}$ in the E-P flux term and hence TEM equations, a deeper understanding of the processes that control $\overline{u'w'}$ are important in order to better understand the MLT circulation.

Besides their influence on the MLT circulation, GWs are among the drivers of the stratospheric quasi-biennial oscillation (QBO). The QBO is the main mode of interannual variability in the equatorial stratosphere and is most readily observed as alternating bands of downward propagating eastward and westward wind with a period of approximately 28 months [e.g., *Baldwin et al.*, 2001, and references therein]. However, the existence of quasi-biennial modulations extends this region in both latitude as well as altitude. *Holton and Tan* [1980] demonstrated that planetary waves (PWs) disturb the Northern Hemisphere (NH) winter polar vortex less when the equatorial stratospheric QBO (from now on referred to as SQBO) at 50 hPa (~21 km) is in its eastward phase, resulting in a stronger polar vortex. The effect is observed in the Southern Hemisphere (SH) as well. Here *Baldwin and Dunkerton* [1998] noted that the influence of the SQBO on the SH vortex is similar in magnitude to that of the NH, although the largest modulations occur in November during the final warming phase of the SH vortex, whereas in the NH the largest effects are observed in January.

Various satellite as well as ground-based observations have furthermore shown the existence of a QBO signal in the equatorial mesosphere [e.g., *Burrage et al.*, 1996; *Venkat Ratnam et al.*, 2001, 2008; *Li et al.*, 2012]. As with the SQBO, the mesospheric QBO (MQBO) signal is not confined to the equatorial region. Indeed, QBO effects at MLT altitudes over midlatitude and polar sites ranging from, e.g., horizontal wind [*Ford et al.*, 2009; *Murphy et al.*, 2012], PW activity [e.g., *Espy et al.*, 1997; *Hibbins et al.*, 2009], temperatures [e.g., *Espy et al.*, 2011], and tides [e.g., *Hibbins et al.*, 2007; *Xu et al.*, 2009] have been observed.

Different pathways through which QBO signals could appear in the MLT have been suggested. In the equatorial region, the MQBO is believed to be caused by the selective filtering of gravity waves (GWs) in the SQBO winds [e.g., *Burrage et al.*, 1996; *Mayr et al.*, 1997; *de Wit et al.*, 2013]. This MQBO has been proposed to act as a gate that depending on its phase, allows or blocks the interhemispheric propagation of PWs from the winter to the summer MLT, explaining the QBO signal in both PW activity and zonal winds at high latitudes [e.g., *Jarvis*, 1996; *Hibbins et al.*, 2009; *Ford et al.*, 2009]. Furthermore, *Espy et al.* [2011] found that the observed QBO signal in summer high-latitude mesopause temperatures and winter stratospheric temperatures were correlated. The sign and phase of these correlations were consistent with coupling of the QBO modulation of the winter stratospheric vortex (through the Holton-Tan effect) to the summer mesopause through interhemispheric coupling (IHC) [*Becker and Fritts*, 2006; *Karlsson et al.*, 2009; *Körnich and Becker*, 2010]. The IHC mechanism couples PW-induced temperature perturbations in the winter stratosphere to temperature perturbations in the summer MLT region through various circulation changes. Key to the summer branch is the development of a GW forcing perturbation at midlatitudes, forcing meridional circulation changes resulting in the summer mesopause temperature anomaly.

In order to better quantify and understand the variability of MLT GW momentum flux (MF), in this study the interannual variability of MLT GW MF is presented for the first time. The SH midlatitude GW MF, derived from meteor radar observations over Tierra del Fuego, Argentina, and its relation to the SQBO is studied and discussed in light of the IHC of QBO modulations as suggested by the results of *Espy et al.* [2011] and *Murphy et al.* [2012].

2. Data and Analysis

Since May 2008 the Southern Argentina Agile Meteor Radar (SAAMER) at Río Grande on Tierra del Fuego, Argentina (53.7°S, 67.7°W) has been providing near-continuous observations, enabling the determination of a multiyear time series of MLT GW MF. SAAMER was specifically designed to enable observations of the GW MF by employing a peak transmitter power of 60 kW resulting in high meteor count rates, and an eight-transmitter array directing most of the power between ~15° and ~50° off zenith [*Hocking*, 2005; *Fritts et al.*, 2010a, 2010b]. A detailed description of the radar design and capabilities can be found in *Fritts et al.* [2010a].

The monthly mean GW MF is derived following the technique outlined in *Fritts et al.* [2010b], which is based on the *Hocking* [2005] matrix-inversion method after the removal of the background wind. As in *Fritts et al.* [2010b], the background wind, consisting of the mean and tidal winds, is derived from the S-transform [*Stockwell et al.*, 1996] fits of the diurnal and semidiurnal tides to the hourly mean winds. In addition, for this study we have also removed the terdiurnal tide prior to the GW MF determination. The monthly mean vertical flux of zonal momentum, $\overline{u'w'}$, and meridional momentum, $\overline{v'w'}$, are derived in 3 km altitude bins, centered at 81, 84, 87, 90, and 93 km.

To increase reliability, time and height intervals for which less than 5000 meteors were available for the GW MF determination were excluded from further analysis, as were months during which instrument interference problems were detected (December 2008 to January 2009, February 2010, February 2011, and June–August 2013). This resulted in 48 months of data at 81 km, and 83 months of data from 84 km to 93 km. The interannual variability is studied after removing the climatology based on a composite year. In addition, the data were linearly detrended in order to determine the Lomb-Scargle periodograms, whereas for all further analysis the nondetrended time series were used. It should be noted that all analyses have been performed using the detrended time series as well, and although exact numbers change relative to the results presented here, the conclusions remain the same when using the detrended time series.

Equatorial SQBO information is derived using the Singapore (1°N, 104°E) monthly mean radiosonde zonal winds from 100 to 10 hPa (~17–31 km) obtained from the Free University of Berlin [*Naujokat*, 1986]. For consistency with the MLT observations, the data are deseasonalized by removing a composite year prior to further analysis.

3. Results

Figures 1a and 1c show the deseasonalized time series of MLT $\overline{u'w'}$ and $\overline{v'w'}$, whereas Figure 1b shows the deseasonalized equatorial stratospheric wind at 50 hPa. The stacked Lomb-Scargle periodograms of the detrended and deseasonalized time series can be found in Figure 1d. Here colored solid (dash-dotted) lines denote the zonal (meridional) component of the MLT GW MF, and the black periodogram at the bottom corresponds to the equatorial stratospheric wind shown in Figure 1b. The 29.3 month dominant oscillation of

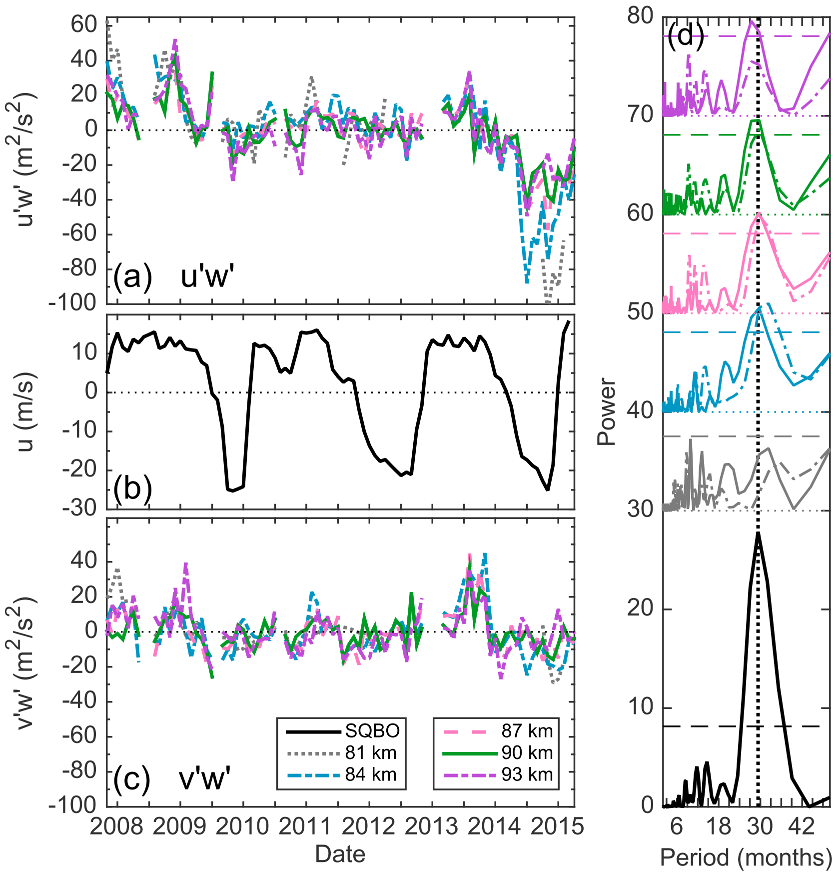

Figure 1. Deseasonalized (a) $\overline{u'w'}$ and (c) $\overline{v'w'}$ at 81 km (gray), 84 km (blue), 87 km (pink), 90 km (green), and 93 km (purple). For comparison, (b) the equatorial stratospheric zonal wind (at 50 hPa) is included. (d) The stacked Lomb-Scargle periodograms of the zonal (solid line) and meridional (dashed line) GW MF at the five altitude levels together with that of the 50 hPa SQBO time series (black, bottom). The dominant period of the SQBO is highlighted by the vertical black dotted line. The 95% confidence levels are indicated by dashed lines.

the equatorial winds during the time period under consideration is identified as the SQBO, which falls well within the previously reported spectrum of QBO periods that range from 22 to 34 months with an average of approximately 28 months [e.g., *Baldwin et al.*, 2001]. Except at the 81 km altitude level, the periodograms of $\overline{u'w'}$ and $\overline{v'w'}$ show peaks at periods comparable to that of the SQBO. These oscillations are significant above the 95% confidence level in the zonal as well as meridional direction with the exception of $\overline{v'w'}$ at the top-most level and suggest the existence of a QBO signal in the mesopause GW MF over Tierra del Fuego. As the signal is most prominent in the zonal direction, the remainder of this paper will focus on the $\overline{u'w'}$ component.

To examine the phase relation between the SQBO and the QBO in the GW MF, the zero-lag correlation between the SQBO at all available stratospheric levels and the deseasonalized GW MF above 81 km is shown in Figure 2. Correlations significant at the 99% level between $\overline{u'w'}$ and the SQBO are present. For the highest stratospheric altitude levels between 10 and 12 hPa (~31–29 km) the parameters are negatively correlated (out of phase). In the lower stratosphere between 30 and 70 hPa (~24–19 km) the SQBO and $\overline{u'w'}$ are positively correlated (in phase). The correlations can be seen to maximize for stratospheric levels around ~50 hPa (~21 km), with a maximum correlation coefficient R of 0.52 between the SQBO and the MLT GW MF at 90 km. The correlation pattern is similar for all MLT levels under consideration, suggesting that the phase of the modulation remains the same throughout the observational MLT altitude interval.

In Figure 3 the amplitude as well as stability of the QBO signal in GW MF throughout the year is explored by stratifying the MLT time series relative to the SQBO positive and negative phase during summer (defined as December, January, and February: DJF), autumn (March, April, May: MAM), winter (June, July, August: JJA), and

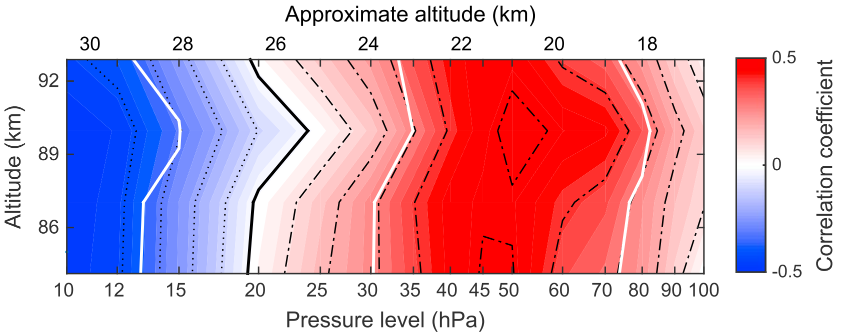

Figure 2. Correlation between $\overline{u'w'}$ and SQBO for all available stratospheric pressure levels. Dotted (negative) and dash-dotted (positive) correlation coefficient contour intervals are 0.1, and the solid black line indicates the zero-correlation contour. The 99% confidence level is highlighted with a solid white line.

spring (September, October, November: SON). Here the SQBO phase is defined relative to the 50 hPa reference level, for which the highest correlation coefficient was found (Figure 2).

As expected from the correlation results, which showed that the GW MF and SQBO at 50 hPa are in phase, the GW MF anomaly is generally positive (negative) during the eastward (westward) phase of the SQBO, except during spring (SON) when no signal is present. Although a QBO modulation in $\overline{u'w'}$ appears to be present throughout all other seasons, the signal generally does not exceed 20 m^2/s^2 during autumn and winter (with the exception of the 84 km level during the MAM period). The signal is largest during summer (DJF), where the difference in $\overline{u'w'}$ between SQBO positive and negative phase becomes as large as ~50 m^2/s^2 at 84 km.

4. Discussion

The most dominant features in the $\overline{u'w'}$ time series (Figure 1a) are the outbursts of GW MF at the beginning and end of the time series. The cause of these outbursts is currently under investigation and will be the topic of a future publication. However, it should be noted that the observed QBO signal in the MLT GW MF is not an artifact of these features. First, the spectral analysis of the $\overline{v'w'}$ time series shows that the same period oscillation is present in the meridional component, although $\overline{v'w'}$ does not exhibit clear GW MF outbursts. Second, a Lomb-Scargle analysis of the GW MF after discarding the outburst time periods shows that the QBO signal is still present (not shown). It should be noted, however, that removal of those periods results in a shortened data set in which only two full QBO cycles are present. Longer time series are crucial to properly

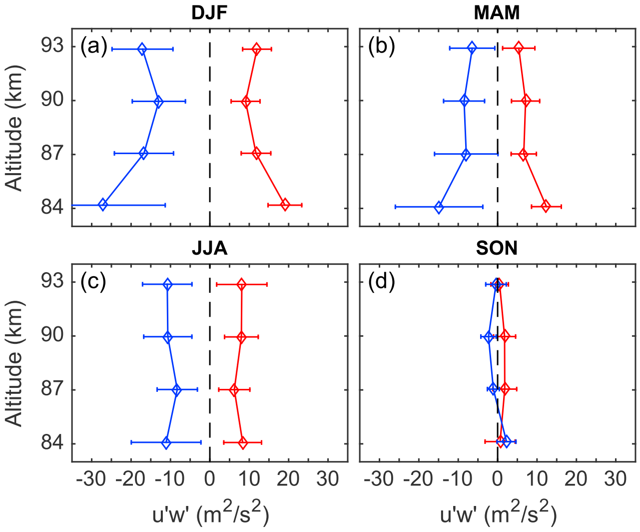

Figure 3. The GW MF stratified relative to SQBO eastward (red) and westward (blue) phase at 50 hPa for (a) December, January, and February; (b) March, April, and May; (c) June, July, and August; and (d) September, October, and November. Error bars denote the standard error of the mean, based on the variability in the composite.

quantify the QBO modulations, which is why it was decided to use the entire available time series for the analyses.

QBO modulations of various measurements of GW activity have previously been reported. *Ern et al.* [2014] studied, using High Resolution Dynamics Limb Sounder (HIRLDS) and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) satellite observations, the contribution of GWs to the SQBO in the equatorial stratosphere. Also in the subtropical stratosphere, SABER/TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) satellite observations of absolute GW MF have been shown to exhibit QBO modulations [*Ern et al.*, 2011], and *Krebsbach and Preusse* [2007] observed a biennial signal in the midlatitude lower mesospheric GW variance. However, a QBO signal in the MLT GW MF as presented in this work has, to the best of the authors' knowledge, never been directly observed.

Various theories exist to explain the presence of a QBO in the MLT. In the equatorial region, the MQBO is readily explained by selective filtering of vertically propagating GWs by the stratospheric QBO winds [e.g., *Mayr et al.*, 1997; *de Wit et al.*, 2013]. As the stratospheric vortices located at higher latitudes have also been shown to be modulated by the QBO [e.g., *Holton and Tan*, 1980; *Baldwin and Dunkerton*, 1998], the possibility exists that QBO periodicities in the extratropical MLT GW MF are similarly driven by modulated GW filtering in the vortex winds.

However, *Baldwin and Dunkerton* [1998] and *Naito* [2002] found the largest QBO effect on the SH stratospheric vortex to be in November. Comparison with the current results which show the largest QBO effect to be present in the SH MLT during DJF (while no QBO effect was found in SON) suggests that the QBO modulation of the SH stratospheric vortex is unlikely to be the source of the MLT QBO GW modulation. Stratifying Modern-Era Retrospective analysis for Research and Applications (MERRA) stratospheric zonal winds at the grid point closest to Tierra del Fuego relative to SQBO positive and negative phase (following the method used to derive Figure 3) indeed confirms that the largest stratospheric vortex modulations occur during the SON period (not shown). Furthermore, *Baldwin and Dunkerton* [1998] and *Naito* [2002] found the influence of the QBO on the SH vortex to maximize using SQBO reference levels around 20–30 hPa (~26–24 km), whereas little effect was seen when using 40–50 hPa (~22–21 km). This is in contrast to the situation in the NH where the QBO signal maximizes when compared to SQBO pressure levels around 40–50 hPa [*Naito*, 2002, and references therein]. As Figure 2 shows that the SH MLT $\overline{u'w'}$ signal maximizes using the SQBO winds at 50 hPa (and as the maximum modulation in the MLT $\overline{u'w'}'$ signal occurs during the SH summer), this implies that modulation of the NH stratospheric winter vortex could be key to understanding the current observations.

Interestingly, the summer MLT has been shown to be coupled to the winter stratosphere through dynamical interactions involving zonal wind, GW forcing, and temperature anomalies [*Becker and Fritts*, 2006; *Karlsson et al.*, 2009; *Körnich and Becker*, 2010], and strong observational evidence has been presented suggesting this IHC mechanism is modulated by the QBO [*Espy et al.*, 2011; *Murphy et al.*, 2012]. *Espy et al.* [2011] found an out-of-phase relation between the SQBO at altitudes below 15 hPa (below about 28 km, the lower stratosphere) and summer high-latitude MLT temperatures, and suggested a combination of the Holton-Tan and IHC mechanisms could explain these results. When the SQBO is in its westward phase, the Holton-Tan mechanism causes the stratospheric vortex to be more perturbed by PWs, resulting in a weaker vortex. This, in turn, leads to a weaker winter MLT GW forcing, and a cooling of the winter MLT. The subsequent reduced meridional circulation causes the equatorial MLT to warm. An interplay between circulation changes and GWs results in an increase in GW forcing in the summer midlatitude MLT, causing a decrease in the summer MLT meridional circulation and a warming of the summer high-latitude mesopause [*Espy et al.*, 2011]. Hence, the phase relation between SQBO wind and summer mesopause temperature (westward winds and higher temperatures, and vice versa) found by *Espy et al.* [2011] supports this explanation. Using MLT meridional wind observations over Davis (68.8°S), *Murphy et al.* [2012] furthermore showed that the winds become more poleward for the westward phase of the QBO, in agreement with the higher summer mesopause temperatures found during this phase, showing observational evidence linking the meridional circulation changes to the temperature anomaly.

The cause of these summer hemisphere meridional circulation changes in the IHC mechanism, however, are GW forcing anomalies in the midlatitude SH summer MLT. Using the technique outlined in *de Wit et al.* [2014], the $\overline{u'w'}$ anomalies at 87 and 90 km are used to determine the GW forcing at mesopause heights for the four seasons. In summer, the GW forcing was found to be 260 ± 167 m/s/d during the SQBO eastward phase, and −370 ± 329 m/s/d during the westward phase. During all other seasons, no statistically significant

QBO-driven GW forcing anomalies were found. In the SH, a westward (eastward) GW forcing anomaly (seen to develop during the westward (eastward) phase of the QBO) is expected to result in a poleward (equatorward) wind anomaly, and higher (lower) mesopause temperatures, consistent with IHC theory and the results of *Espy et al.* [2011] and *Murphy et al.* [2012]. Besides providing support for the QBO modulation of IHC as discussed in *Espy et al.* [2011] and *Murphy et al.* [2012], these observations provide the first observational evidence for the existence of the summer hemisphere midlatitude GW forcing anomalies as hypothesized in the IHC mechanism.

5. Summary

Due to their importance in driving the MLT, a deeper understanding of GWs and the GW MF is key. In this study, the interannual variability of MLT GW MF was studied, using more than 7 years of Tierra del Fuego (53.7°S, 67.7°W) meteor radar observations. Periodogram analysis showed that both $\overline{u'w'}$ and $\overline{v'w'}$ exhibit periods around 29.3 months, similar to that of the SQBO over the same time period. The QBO modulation is strongest in the zonal component and is in phase with the SQBO at 50 hPa, and seasonal composites of $\overline{u'w'}$ relative to SQBO phase at this level furthermore show that the signal is largest during SH summer. The phase relation between the SQBO and GW forcing anomaly was found to be consistent with that expected by the Holton-Tan effect coupled to the IHC mechanism and to provide the first observational support for the existence of the midlatitude GW forcing anomalies as hypothesized in the IHC mechanism.

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