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Interannual variability of mesopause zonal winds over Ascension Island: Coupling to the stratospheric QBO

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[1] Zonal-wind measurements obtained between October 2001 and July 2011 with the SKiYMET meteor radar located at Ascension Island (8°S, 14°W) have been used to study the interannual variability at meteor ablation altitudes (approximately 78–100 km) and its coupling to the stratospheric quasi-biennial oscillation (QBO). An upper mesospheric QBO (MQBO) with a period of 27.5 months has been detected throughout the observational period. The MQBO is found to be out-of-phase with the stratospheric QBO (SQBO) at 15–20 hPa and in-phase compared to 70 hPa, whereas no significant zero time-lag correlation exists between the long-term mesospheric zonal winds and the SQBO at 40–50 hPa. The MQBO magnitude is found to be 4.1±0.7 m/s at 88 km. No significant change in MQBO magnitude is found throughout the altitude range under consideration. It was found that the MQBO signal is mainly carried around the March equinox, although the MQBO signal is present throughout most of the year, although less pronounced, at the lower altitudes as well. No observational evidence was found that the MQBO, between approximately 78–100 km, plays a role in the interhemispheric ducting of the quasi-16 day wave.

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1. Introduction

[2] The dominant mode of interannual variability in the equatorial stratosphere is the quasi-biennial oscillation (QBO) in the zonal wind with a period of about 28 months [e.g., *Naujokat*, 1986; *Baldwin et al.*, 2001]. Phase fronts propagate downward in time, giving the stratospheric QBO (hereafter SQBO) its characteristic westerlies (easterlies) overlaying easterlies (westerlies) structure. Maximum SQBO amplitudes are observed near 20 hPa [*Naujokat*, 1986] and over the equator [*Baldwin et al.*, 2001, and references therein]. The latitudinal distribution of the SQBO is approximately Gaussian about the equator, falling off in amplitude with a half width of about 12° [*Baldwin et al.*, 2001].

[3] Although the SQBO is confined to the equatorial region, its influence extends to extratropical regions as well. *Holton and Tan* [1980] found that the equatorial SQBO modulates the global circulation at 50 hPa, showing that the Northern Hemisphere (NH) polar vortex is stronger and less disturbed by planetary waves (PWs) when the SQBO at 50 hPa is in the westerly phase. *Baldwin and Dunkerton* [1998] showed similar behavior for the NH using 40 hPa as a reference level.

[4] The existence of the QBO signal is not limited to the stratosphere. Using around 3 years of zonal wind data obtained with the High Resolution Doppler Imager (HRDI) on board the Upper Atmosphere Research Satellite (UARS), *Burrage et al.* [1996] detected a QBO in the mesosphere (hereafter MQBO) that maximized around 85 km, with an amplitude of approximately 30 m/s. The existence of a QBO in zonal winds and temperatures at mesospheric heights has since been confirmed by multiple ground-based and satellite observations [e.g., *Ratnam et al.*, 2001; *Shepherd et al.*, 2004; *Huang et al.*, 2006; *Ratnam et al.*, 2008; *Rao et al.*, 2012].

[5] Unlike the SQBO, some studies note that the MQBO does not appear to be a constant signal that is visible throughout the year. Rather a quasi-biennial modulation of the westward phase of the mesospheric semi-annual oscillation (MSAO) during the March equinox is detected [e.g., *Sharma et al.*, 2010; *Rao et al.*, 2012]. This behavior is not only present in observations but also modeling studies have shown larger mesospheric amplitudes during the NH spring equinox [*Peña-Ortiz et al.*, 2010]. This has led *Rao et al.* [2012] to introduce the term mesospheric quasi-biennial enhancement (MQBE) since the term MQBO may not be appropriate if the wind variability is simply an enhancement of the westward winds during March. Throughout this paper, however, we will use the more conventional term "MQBO".

[6] MQBO signals have been reported outside the equatorial region as well. *Burrage et al.* [1996] noted that the

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MQBO extends to latitudes of ±30°. A study over Maui, Hawaii (20.7°N, 156.3°E) conducted by *Li et al.* [2012] using meteor radar data showed that an MQBO signal is present in the zonal wind at 81 km, in-phase with the SQBO at both the equator and at 19.5°N at 10 hPa. An extratropical study using 10 years of Middle and Upper atmosphere radar data over Shigaraki, Japan (34.9°N, 136.1°E) noted that, in the majority of years under investigation, when the SQBO at 40 hPa is in the westerly (eastward) phase, the summer mesospheric westward winds persist for longer [*Namboothiri et al.*, 1999].

[7] The extratropical influence of the MQBO not only manifests itself as a zonal mean wind signature. *Espy et al.* [1997] found that the existence of long-period PWs in the high latitude mesosphere strongly depends on the phase of the SQBO. Using OH-airglow temperatures, they found a quasi-16 day wave around 87 km in the summer mesopause over Stockholm (59.5°N, 18.2°E) during the westerly (eastward) phase of the SQBO at 10 hPa, while no quasi-16 day wave was detected during the easterly (westward) phase. *Hibbins et al.* [2007] found a quasi-biennial modulation of the semidiurnal tide in the mesosphere over Halley, Antarctica (76°S, 27°W) using 9 years of SuperDARN meteor radar wind data. They observed an increase in amplitude and a phase shift in the summer months during the westerly phase of the SQBO at 5 hPa, whereas no significant difference was observed between April and October. A subsequent study by *Hibbins et al.* [2010] concluded that the QBO dependence of the semidiurnal tide is driven by the nonmigrating $S = 1$ component, as the amplitude and phase of the migrating $S = 2$ component showed no correlation with the SQBO.

[8] Two possible mechanisms for the QBO modulation of the 16-day wave occurrence in the summer mesosphere are described by *Espy et al.* [1997]. The first involves the generation of the wave in the winter hemisphere which is then ducted through a corridor of eastward winds in the equatorial middle atmosphere. Alternatively, the wave is generated *in situ* via momentum deposition due to breaking gravity waves (GWs) propagating upward through the troposphere and stratosphere where they have been modulated by the stratospheric 16-day wave. *Hibbins et al.* [2009] found strong evidence for the ducting mechanism by studying PW activity over Halley, Antarctica and Þykkvibær, northern Iceland (64°N, 19°W), simultaneously. It was found that, when the SQBO above 25 hPa is in the westerly phase, wintertime PW activity in the high latitude mesosphere-lower thermosphere (MLT) is reduced, whereas summer time PW activity is increased. Hence, a decrease in PW activity was observed in the NH when activity was increased in the Southern Hemisphere and vice versa. *Hibbins et al.* [2009] noted that this strongly suggests part of the PW activity in the summer mesosphere is generated in the winter hemisphere and, if this is the case, a sufficiently strong interhemispheric duct which depends on the phase of the SQBO must exist. As the MQBO shows a dependence on the phase of the SQBO [*Burrage et al.*, 1996], the MQBO was identified as possible mechanism by which the interhemispheric propagation of the quasi-16 day PW could be modulated. It should be noted, however, that some subsequent studies have not observed a clear QBO modulation of high latitude PWs [e.g., *Day et al.*, 2011; *McDonald et al.*, 2011].

[9] In order to further examine the ducting mechanism, a better quantification of the interannual variability in the mesospheric zonal wind is required [*Hibbins et al.*, 2009]. This paper uses 11 years of meteor radar wind data obtained over Ascension Island (A.I., 8°S, 14°W) to describe the interannual variability in the equatorial MLT region. We present supporting evidence for the existence of a mesospheric QBO and describe its phase relation to the SQBO and the stability of this relation over time. Observational evidence of the principle of selective filtering of GWs by stratospheric winds is explored as a generation mechanism of the MQBO. The strength, apparent seasonal cycle, and phase relation of the MQBO are shown and are discussed in the light of the mechanism described by *Hibbins et al.* [2009].

2. A.I. Meteor Radar Data and Analysis Techniques

[10] The A. I. (8°S, 14°W) SKiYMET meteor radar has been operating since October 2001. The system operation frequency is 43.5 MHz with a peak power of 12 kW (6 kW after October 2005) [*Younger et al.*, 2009]. Hourly zonal and meridional wind data are available between 78 km and 100 km [*Sandford and Mitchell*, 2007] at height gates centered around 82, 85, 88, 91, 94, and 98 km. The meteor count rate maximizes around 90 km [*Pancheva et al.*, 2004]. Previously, A.I. meteor radar data have been used to characterize PWs in the equatorial MLT region [*Pancheva et al.*, 2004; *Younger and Mitchell*, 2006], to describe the latitudinal and seasonal variation of meteor count rates [*Younger et al.*, 2009], and to study ultra-fast Kelvin waves [*Davis et al.*, 2012] and lunar tides in the equatorial Atlantic sector [*Sandford and Mitchell*, 2007]. This study uses data recorded between October 2001 and July 2011. Some major gaps are present in the data, with data gaps longer than one calender month occurring from November 2003 up to and including April 2004, August 2005, May 2007 to January 2009, June 2009, and October 2009 to December 2009. Hence, a total of 86 full or partial months of data are used in this analysis.

[11] To study the long-term variability in the mesosphere, the annual cycle is removed from the observations. A composite day for each separate month in the data set is constructed by averaging the data for that month into hourly bins for each altitude level. The annual cycle is computed by grouping the same months together. This results in 12 (January through December) 24 h profiles showing the monthly average daily winds for the six altitude levels. After removing the annual cycle from the observations, the tide is removed by fitting a 24, 12, and 8 h wave to the composite-day data. The data points are weighted according to $\frac{1}{\sigma_c^2}$, where the standard deviation σ_c for each point is calculated from the spread in the composite-day data. The deseasonalized monthly mean wind is given by the average of the fit, and the fit error σ represents the variation in the winds unexplained by the tides. In order to determine the monthly mean zonal wind (cf. Figure 1a), the same procedure is followed without the removal of the annual cycle.

[12] The mesospheric data are divided in SQBO positive and negative phase using the Singapore (1°N, 104°E) stratospheric data obtained from the Free University of

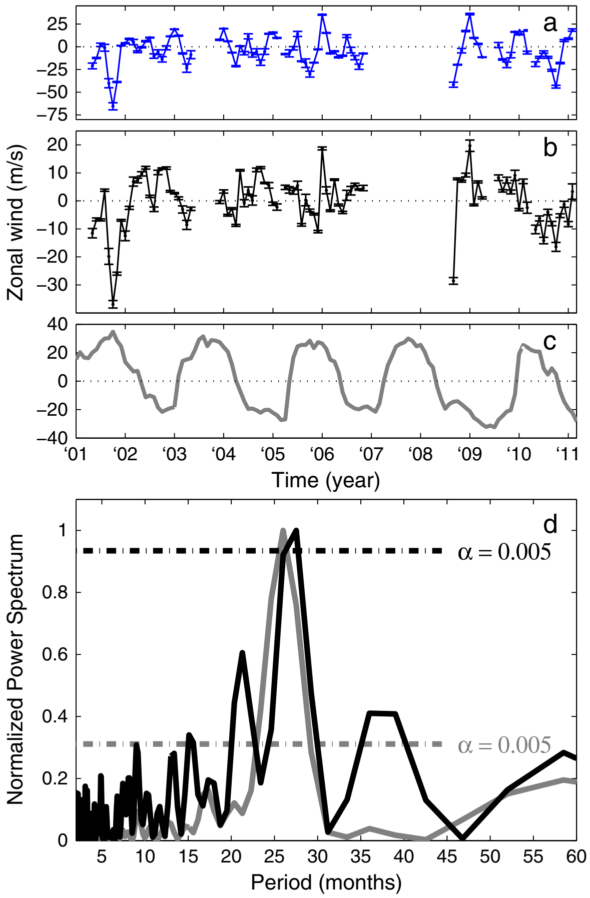

Figure 1. (a) Monthly mean zonal wind at 88 km; (b) deseasonalized monthly mean wind at 88 km; (c) as b, but for 15 hPa; and (d) Lomb-Scargle periodogram of the deseasonalized monthly mean zonal wind data at 88 km (stratosphere, 15 hPa) in black (gray) and the 99.5% confidence level denoted with a black (gray) dash-dotted line. Both power spectra have been normalized with respect to their peak power.

Berlin through http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html. This data set starts in 1987 and contains monthly mean equatorial zonal radiosonde winds from 10 to 100 hPa at 15 levels (10, 12, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, and 100 hPa). For consistency with the meteor radar winds, the data are first deseasonalized by removing the composite year obtained by using 25 years of Singapore data (January 1987 to July 2012). As the SQBO is the dominant oscillation in the equatorial stratosphere [*Baldwin et al.*, 2001; *Pascoe et al.*, 2005], care should be taken when calculating the small seasonal cycle in order to avoid a bias in the annual composite due to the incomplete removal of the QBO. Therefore, the longest possible data period is chosen in order to calculate the annual cycle. The same analysis was repeated using the same period for which the meteor wind data are available (2001 to 2011), which gave similar results (not shown).

[13] The strength of the QBO signal is calculated by separating the monthly mean mesospheric and stratospheric zonal wind into SQBO eastward ($u > 0$ m/s) and SQBO westward ($u < 0$ m/s) phases as defined at 15 hPa, as it was found that the MQBO magnitude maximizes with the use of the 15 hPa level (see section 3.3). Above 78 km, the monthly mean winds are separated according to these SQBO phases as well. The magnitude of the MQBO signal is defined as half the difference in the weighted average of the monthly mean winds in these two composites. For this region, the error is given by the weighted sample standard error of the mean. In the stratosphere, the same procedure is carried out using a nonweighted average, together with the standard error of the mean. These magnitudes represent the average deviation from the climatological mean during the two phases of the SQBO. For the remainder of this paper, we will refer to magnitudes as defined above. If the QBO signal were a perfect sine wave, then this magnitude could be converted to an equivalent sinusoidal amplitude by multiplying the magnitudes by $\frac{\pi}{2}$. However, it should be noted that the QBO signal is not best represented by a pure sine wave [*Naujokat*, 1986]. Hence, fitting a sine wave to the QBO time series will result in fitted amplitudes lower than this value.

3. Results

3.1. Quasi-Biennial Variability in the Mesopause Zonal Winds

[14] Figure 1a shows the monthly mean and deseasonalized monthly mean zonal wind at 88 km over A.I. (Figure 1b). The deseasonalized monthly mean zonal wind in the stratosphere at 15 hPa is shown in Figure 1c for comparison. In order to study the long-term (>1 year) oscillations in the stratosphere and mesosphere, a Lomb-Scargle analysis [*Scargle*, 1982] is performed on the deseasonalized data sets. The result for the stratospheric analysis (15 hPa, gray line) is presented in Figure 1d. It should be noted that the power spectrum and the confidence level have been normalized with respect to the spectrum's peak power. The dominant oscillation, significant at the 99.5% confidence level, is identified as the SQBO. This is known to have a periodicity between 22 and 34 months with an average of approximately 28 months [*Baldwin et al.*, 2001].

[15] In the same figure (Figure 1d), the normalized power spectrum of the deseasonalized monthly mean mesospheric zonal wind at 88 km is shown in black. No 12 month oscillations are visible in the spectrum, showing that the data have been successfully deseasonalized. The dominant oscillation with a period of approximately 27.5 months (again significant above the 99.5% level) is comparable to the oscillation period present in the stratosphere (the SQBO) and is identified as the MQBO over A.I.

3.2. Phase Relation Between the SQBO and MQBO

[16] In order to study the phase relation between the SQBO and the MQBO, the zonal monthly mean deseasonalized wind at all radar wind levels is correlated with the zonal mean deseasonalized wind at all available stratospheric levels. The results are presented in Figure 2. From Figure 2, it can be seen that a significant correlation at zero time-lag between the upper mesospheric and stratospheric oscillations is only present for stratospheric levels from 10 hPa to approximately 30 hPa and from 60 hPa to 80 hPa (solid lines denote the 95% confidence level). Around 15–20 hPa, the MQBO is out-of-phase with the SQBO, whereas compared to around 70 hPa, both oscillations are in-phase.

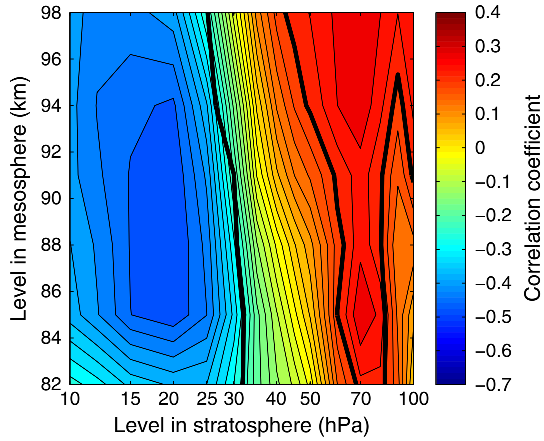

Figure 2. Correlation between the deseasonalized monthly mean zonal wind in the stratosphere and mesosphere. Colored shading shows the correlation coefficient. Thick black lines denote the 95% confidence level.

[17] Figure 1 shows the periods of the SQBO and MQBO are comparable, and no phase drift is present in both the SQBO and MQBO over the observed time period as only one significant peak is identified in the Lomb-Scargle analyses. From Figure 2, it is concluded that the SQBO at 15 hPa and the MQBO at 88 km are anticorrelated, with a correlation coefficient of –0.46 at zero time-lag and a probability of random association < 0.1%. The out-of-phase relationship between the zonal wind at 88 km and 15 hPa can be seen to be present throughout the entire time period (Figures 1b and 1c), suggesting that the MQBO signal is a stable feature over the observed time series.

3.3. Strength and Seasonality of the MQBO

[18] As mentioned, in order to define the strength of the MQBO, the meteor wind data have been separated with respect to the phase of the stratospheric QBO. From Figure 2, it can be seen that the deseasonalized zonal winds at 88 km and the stratospheric winds show maximum (anti)correlation at 15–20 hPa. We find that the MQBO magnitude calculated when compositing the mesospheric data with respect to the SQBO maximizes when comparing to 15 hPa, hence this level has been used throughout the rest of this paper when referring to MQBO magnitude.

[19] The result of this analysis is shown in Figure 3. As expected from Figure 2, the SQBO and MQBO are 180° out-of-phase. Hence, when the SQBO at 15 hPa is eastward (westward), the MQBO is westward (eastward). The analysis leads to an SQBO magnitude of $\pm$19.5$\pm$0.7 m/s at 15 hPa, compared to an MQBO of $\mp$4.1$\pm$0.7 m/s at 88 km, equivalent to an MQBO sinusoidal amplitude of 6.5$\pm$1.1 m/s. Even though the strength of the QBO in the mesopause region is smaller than that in the stratosphere, the signal is statistically significantly different from zero for all six radar wind levels from 82 to 98 km. Furthermore, unlike in the stratosphere, the vertical shear in the zonal wind is much smaller in the mesopause. In the stratosphere, the zonal wind reverses over a vertical range of approximately 10 km, whereas the radar winds are not statistically significantly different over approximately the same altitude span.

[20] Some observational studies have identified the MQBO signal to be strongest during the March equinox, when the MSAO is in its strongest westward phase [*Sridharan et al.*, 2003; *Rao et al.*, 2012], a discussion of this phenomenon can be found in *Rao et al.* [2012]. In order to check for this phenomenon, the composite analysis is performed for all months separately. The data used are treated in the same way as described in section 2 (Data section), except that the annual cycle has not been removed to highlight the influence of the MSAO. The result is shown in Figure 4.

[21] From Figure 4, it can be seen that at the highest level (98 km) a statistically significant signal is present only around the March equinox. Looking at the lower altitudes, it follows that although the MQBO signal is mainly carried around the March equinox, an MQBO signal becomes increasingly present at other times during the year as one moves toward lower levels. This is particularly evident in December below 91 km (Figure 4, top panels).

4. Discussion

4.1. General MQBO Characteristics

[22] The A.I. meteor radar zonal winds exhibit an interannual variability with a dominant period of about 27.5 months at 88 km (see Figure 1), and this oscillation has been identified as the MQBO over A.I. Our observed period is within the range of previously reported MQBO periods that vary from approximately 2 years using data from November 1991 to March 1995 at 85 km [*Burrage et al.*, 1996] to around 28 months between 1977 and 2006 at 72.5 and 77.5 km [*Ratnam et al.*, 2008]. For convenience, the complete set of previous observational studies discussed here and their MQBO parameters are summarized in Table 1.

[23] The MQBO over A.I. is 180° out-of-phase with the SQBO at 15–20 hPa, and in-phase with the SQBO at 70 hPa, while no statistically significant zero time-lag relation is present between the MQBO and SQBO around approximately 40–50 hPa (Figure 2). Such an in-phase/out-of-phase

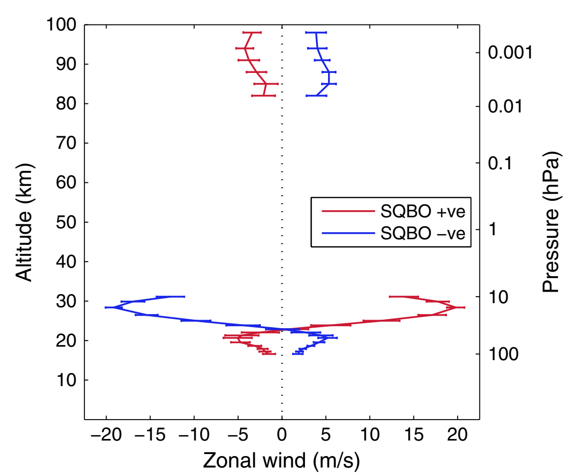

Figure 3. Vertical profiles of composite zonal wind anomalies for SQBO eastward (red) phase and westward (blue) phase at 15 hPa. Error bars for the stratospheric (mesospheric) levels denote the (weighted) standard error of the mean.

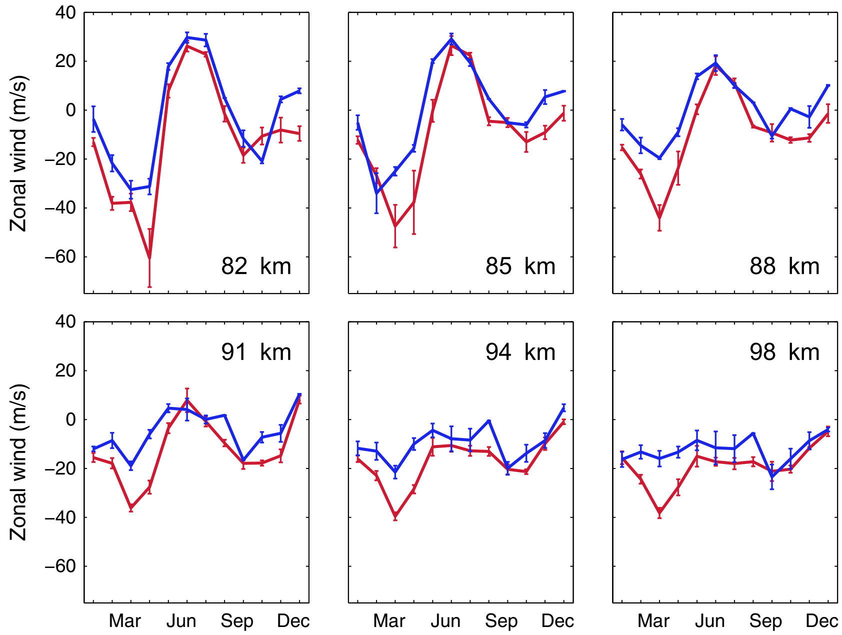

Figure 4. Monthly mean mesospheric zonal wind composited sorted by SQBO positive (red) and negative (blue) phase at 15 hPa for all months, (top panels) for 82, 85, and 88 km and (bottom panels) 91, 94, and 98 km. Error bars denote the weighted standard error of the mean.

relationship compared to different stratospheric levels is expected, due to the change in phase with altitude of the SQBO [e.g., *Naujokat*, 1986]. It should be noted that composites of the mesospheric winds made with respect to the SQBO phase measured at 40 or 50 hPa would not produce significant MQBO signals. These levels are often the pressure levels used to define the phase of the SQBO [e.g., *Holton and Tan*, 1980; *Baldwin and Dunkerton*, 1991]. Hence, care should be taken to choose a reference level that is appropriate for the process under investigation.

[24] The observed phase relation differs from that shown in *Baldwin et al.* [2001] (their Plate 2), where the MQBO is shown to be in the same phase as the SQBO in the upper stratosphere above 10 hPa. Comparing deseasonalized zonal winds at 81 km over Maui, Hawaii to deseasonalized monthly mean European Centre for Medium-Range Weather Forecasts zonal winds at the equator and 19.5°N, *Li et al.* [2012] found an in-phase relationship between the 81 km winds and 10 hPa, and an out-of-phase relationship when using 1 hPa. This also contradicts our findings, but the reason for this discrepancy could be the difference in latitude between the stations. However, the observations of *Burrage et al.* [1996] indicate no-phase shift in the MQBO between ±35° on either side of the equator. A modeling study by *Peña-Ortiz et al.* [2010] shows an in-phase relationship between the SQBO at 10 hPa and the zonal winds at 0.01–0.001 hPa (roughly the lower and upper bound of our observations). However, *Smith* [2012] has noted the

Table 1. Overview of Current State of Observed Zonal Wind MQBO Parameters[a]

Study	Location	Technique	Time	Period	Phase Shift (Comparison Level)	Amplitude (m/s) (Altitude)
Current study	8°S, 14°W	meteor radar	October 2001– July 2011	27 months	180° (20 hPa)	4.1±0.7 (88 km)
Kumar et al. [2011]	8.5°N, 77°E	meteor radar	2004–2007	n/a	180° (30 km)	3.5 (91 km)
Li et al. [2012]	20.7°N 156.3°W	meteor radar	May 2002– June 2007	n/a	0° (10 hPa) 180° (1 hPa)	5 (80 km)
Rao et al. [2012]	±22° (7 sites)	meteor and MF radar	1990–2002 (different time periods for different radars)	n/a	180° (10 hPa)	n/a
Sridharan et al. [2003]	8.7°N, 77.8°E	MF radar	1993–1997	n/a	180° (86 km, 30 hPa)	n/a
Ratnam et al. [2008]	8.5 and 13.5°N, 77 and 79.2°E	rocketsondes, meteor radar, HRDI/UARS	1977–2006	28 months	180° (30 hPa)	6 m/s (72.5 km, 77.5 km)
Burrage et al. [1996]	n/a	UARS/HRDI satellite	November 1991– March 1995	∼ 2 years (85 km)	180° (upper strat)	30

[a]When the study also included other parameters, only the parameters and observational techniques corresponding to zonal-wind observations are included.

difficulty in comparing observations made on pressure levels with altitude levels. Above and below 0.01–0.001 hPa, the phase relation is the same as that observed here, indicating that a small shift in vertical coordinate would lead to the same phase relationship in both studies.

[25] Our phase observations are in agreement with *Burrage et al.* [1996], *Sridharan et al.* [2003], and *Ratnam et al.* [2008], who showed an out-of-phase relationship between the SQBO at 30 hPa (all using the Singapore data) and 85 km [*Burrage et al.*, 1996], 86 km [*Sridharan et al.*, 2003], and 77.5 km [*Ratnam et al.*, 2008]. However, it should be noted that although our data show an out-of-phase relation between the mesosphere and 30 hPa, the relation is not statistically significant at the 95% confidence level for altitudes above 86 km. Rather, we see a clearer and more significant anticorrelation if we select a pressure level around 15–20 hPa to define the phase of the SQBO. *Rao et al.* [2012] report westward enhancements between 80 and 98 km during the eastward phase of the SQBO except for two occasions for which the wind above 30 hPa was westward and eastward below. The general behavior is in agreement with our observations, although the two exceptional cases are the reverse of our observations. *Kumar et al.* [2011] showed the QBO in the upper stratosphere at 30 km (approximately 10 hPa) to be out-of-phase with the MQBO at 98 km over Thumba (8.5°N, 77°E), again in agreement with our results.

[26] Selective filtering by the stratospheric zonal winds of a symmetrical distribution of upward propagating GWs centered on zero phase speed, and consecutive breaking and momentum deposition of the nonfiltered waves (with phase speeds opposite of the stratospheric winds) in the mesosphere can explain the 180° phase shift in QBO winds between the stratosphere and mesosphere [*Mayr et al.*, 1997]. This principle is illustrated in Figure 3, which shows the composites of monthly mean zonal mesospheric and stratospheric winds for the SQBO in the positive (red) and negative (blue) phase at 15 hPa. It can be seen that the MQBO winds are strongest eastward (westward) when the SQBO winds are strongest westward (eastward).

[27] In Figure 5, we estimate the net zonal wind experienced by a symmetric distribution of upward propagating GWs in the stratosphere. We define the net zonal wind as the average of the most positive zonal wind and the most negative zonal wind in the vertical stratospheric profile between 100 and 10 hPa during the deseasonalized QBO positive phase. As shown in Figure 3, for the QBO phase defined at 15 hPa, these wind extremes can be found around 15 hPa and 50 hPa. This mean wind is a measure for the asymmetry of the stratospheric wind field, which in turn relates to the opacity of the stratosphere to upward propagating GWs. This GW opacity between 100 and 10 hPa during the positive phase of the SQBO is shown in Figure 5 (gray line) as a function of the stratospheric level used to define the phase of the SQBO. The corresponding MQBO response at 91 km is shown in black. It can be seen that when the net zonal wind through the stratosphere is negative, more upward propagating GWs with negative phase speeds are filtered, resulting in a net GW momentum flux at 91 km that is positive. That is, when the maximum negative zonal wind between 100 and 10 hPa is larger than the maximum positive zonal wind, more negative upward propagating GWs are filtered, and the net mesospheric response is positive. The opposite is observed when the net zonal wind is positive, and the stratosphere is more opaque to westerly upward propagating GWs. In this case, more GWs with negative phase speeds can propagate up to the mesosphere and deposit their momentum (see Figure 5).

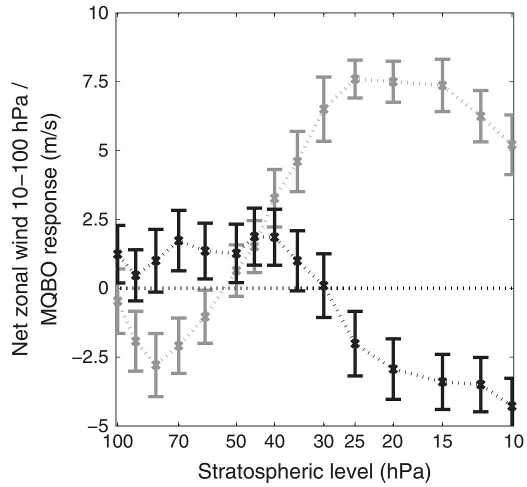

Figure 5. Net wind a uniform spectrum of upward propagating GWs would encounter between 100 and 10 hPa (gray) and the mesospheric response at 91 km (black) for the positive phase of the SQBO at the available stratospheric levels. Note that the MQBO signal maximizes when the mean winds in the stratosphere are most eastward. Error bars as in Figure 3.

[28] It is interesting to note that the observed correlation between the stratosphere and mesosphere as shown in Figure 2 can be largely explained with the help of the simple selective filtering mechanism shown in Figure 5. If the QBO phase is defined by the wind direction in the region around 25–15 hPa, then the positive phase of the SQBO maximizes the selective filtering of GWs with negative phase speeds. This would then explain the maximum negative response of the MQBO when comparing to the SQBO positive phase around 15 hPa. At the same time, when the QBO phase is defined by the wind direction near 40 hPa, the net stratospheric winds are not predominantly positive or negative. Thus, the GW filtering would be symmetrical and there would be no net forcing of the mesospheric winds. Hence, no statistically significant MQBO signal would be observed in the zonal winds. Although a more thorough analysis of the selective filtering of GWs would include both the generation and filtering of waves from the ground to 78 km altitude, this simple analysis strongly supports the selective filtering of GWs by the SQBO winds as an important contributor to the generation of the MQBO.

[29] From Figures 2 and 3, it can be noted that the phase relation with the SQBO is the same for all altitudes between 82 and 98 km, indicating that no significant downward phase propagation takes place. This is in contrast to the situation in the stratosphere. This result is supported by the analysis of *Burrage et al.* [1996], which suggests a constant phase for the MQBO between 80 and 100 km and a downward phase propagation in time at lower altitudes. Although *Ratnam et al.* [2008] showed a downward phase propagation between

77.5 and 72.5 km, our results are in good agreement with *Rao et al.* [2012] who, over the same altitude range used in this study, observed a constant phase with height.

[30] A statistically significant MQBO magnitude of 4.1±0.7 m/s at 88 km has been derived. This falls within the range of previous ground-based observations, e.g., 6 m/s at 72.5 and 77.5 km [*Ratnam et al.*, 2008], 5 m/s at 81 km over Maui [*Li et al.*, 2012], and approximately 3.5 m/s at 98 km over Thumba [*Kumar et al.*, 2011, Figure 9c]. By contrast, *Burrage et al.* [1996] observe an approximate MQBO amplitude of 30 m/s, nearly 10 times that of the ground-based measurements, around 80–100 km altitude. It has been noted that HRDI winds are usually large when compared to the ground-based measurements at the equator and low latitudes [*Burrage et al.*, 1996; *Ratnam et al.*, 2001]. This is the only realistic explanation of the discrepancy between the HRDI satellite observations and the aforementioned ground-based measurements, some of which use data recorded at the same time as the data presented in *Burrage et al.* [1996].

[31] *Rao et al.* [2012] noted a decrease in MQBO amplitude after 2002, whereas *Sridharan et al.* [2003] found a decrease after 1999 and *Ratnam et al.* [2008] after 1996. We note that our data set does not go back far enough to confirm this. However, even though the strength might have decreased, a signal, out-of-phase with the SQBO at 15 hPa, is present throughout the entire observational period as can be seen in Figure 1. Other studies, however, have shown the phase relationship to break down during certain years prior to 2001 [*Ratnam et al.*, 2008; *Sridharan et al.*, 2003]. It has been suggested that this is related to long and strong SQBO periods [*Ratnam et al.*, 2008]. An inspection of Figure 1 suggests no such SQBO cycle was present during 2001–2011, which could explain the absence of phase shifts in our data.

4.2. Seasonal Variability in the MQBO Signal

[32] Figure 4 shows the monthly mean zonal wind composited for SQBO phase westerly (red) and easterly (blue) for all months. Starting by examining the upper level (98 km) in Figure 4, it is apparent that a statistically significant MQBO signal is only present around the March equinox, from February until April. Inspection of the other panels reveals the signal is mainly present around the March equinox at the lower altitudes as well. This is in agreement with the results of *Rao et al.* [2012], who observed interannual variability with a period of 2–3 years in the mesospheric zonal winds only during the March equinox, which led them to call this phenomena a mesospheric quasi-biennial enhancement rather than an MQBO. A similar pattern is visible in mesospheric temperatures, with strong cold anomalies during the March equinox of 1993 and 1995 [*Shepherd et al.*, 2005].

[33] A study with a simple equatorial beta-plane model by *Garcia and Sassi* [1999] showed that the decreased zonal winds in the westward MSAO phase during the easterly phase of the SQBO can be explained by a reduction in westward upward propagating inertia-gravity waves reaching the mesosphere as these have been filtered out by the easterly QBO winds in the stratosphere. The asymmetry between the phases of the SQBO, with weaker westerly winds [*Naujokat*, 1986] providing less filtering, and the finding that the waves that drive the MSAO westerly phase are faster than the ones driving the easterly phase explain why the QBO is only capable of modulating the easterly winds [*Garcia and Sassi*, 1999]. A modeling study by *Peña-Ortiz et al.* [2010] illustrates this principle, showing an MQBO signal in both April and October, but no significant signal during the solstices when the MSAO is in the eastward phase.

[34] Interestingly, a significant MQBO signal stands out in the A.I. data in December below 91 km as well, when the MSAO is in the eastward phase (Figure 4). From the explanation put forward by *Garcia and Sassi* [1999], one would only expect to see an MQBO signal during the westward phase.

[35] In order to investigate if the presence of the signal in December is genuine, the mesospheric and stratospheric time series were examined in more detail. It was checked that no spurious signal was introduced by an uneven distribution of positive and negative composite years. It was found that the positive composite included December 2001, 2005, and 2010, and the negative composite consisted of December 2002, 2004, and 2006, ruling out this possibility. Furthermore, it was concluded that the SQBO at 15 hPa during the previously mentioned Decembers was in a well-defined phase, and no phase transitions took place, suggesting the signal is genuine.

[36] Upon closer inspection of Figure 4, it appears a more general quasi-biennial modulation is increasingly present at other times during the year as one moves toward lower levels, in addition to the March equinox and December enhancements as discussed previously. The occurrence of the MQBO signal below 91 km in December can be interpreted in the light of this general presence of an MQBO signal in most months at the lower levels. The presence of the MQBO signal throughout the year resembles what would be expected from the simple GW filtering mechanism that was discussed earlier (Figure 5), as proposed by *Mayr et al.* [1997]. It is in agreement with the findings of *Burrage et al.* [1996] (their Figure 6), who observed the MQBO signal at 85 km to be present throughout the year although the strongest signal is carried around March.

4.3. Interhemispheric Duct

[37] The role of the MQBO in selectively filtering the interhemispheric propagation of planetary waves at MLT altitudes [*Hibbins et al.*, 2009] can now be discussed in the light of these new equatorial observations.

[38] The critical level for a westward propagating S = 1 16-day wave occurs in a background zonal wind of –29 m/s at the equator. Any process that forces the zonal wind more westward (eastward) than this will block (allow) the interhemispheric propagation of a 16-day S = 1 planetary wave. If the presence of this wave in the summer MLT is dependent on interhemispheric propagation through the equatorial MLT, then an equatorial MLT wind more (less) westward than –29 m/s will reduce (increase) the amplitude of the wave in the summer MLT. Thus, in order for the mechanism proposed in *Hibbins et al.* [2009] to be correct, a clear eastward enhancement of the solstice MLT winds over the equator would be required during the positive phase of the SQBO.

[39] We have shown the MQBO above A.I. to be correlated with the SQBO. However, our data show mesopause region winds to be more westward when the SQBO in the middle to upper stratosphere is in the positive (westerly)

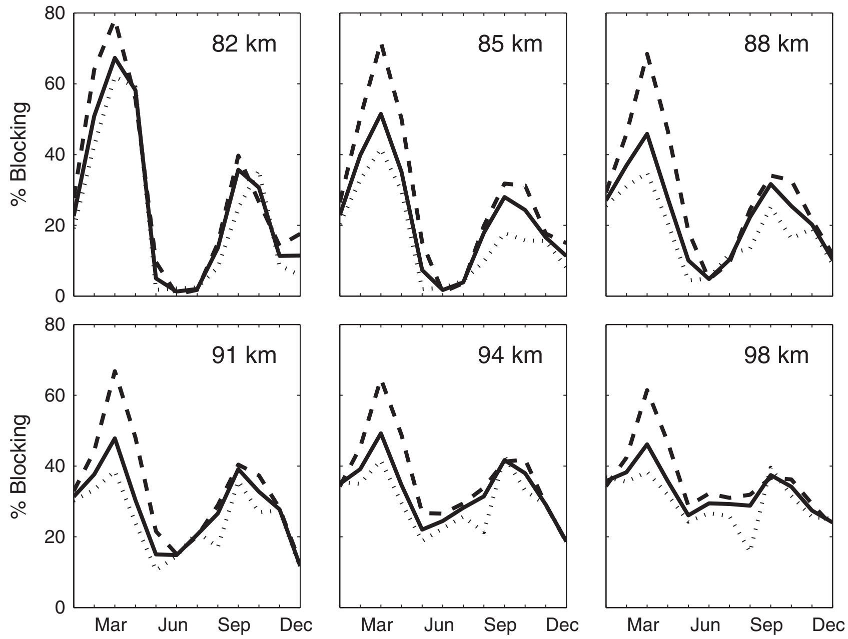

Figure 6. Climatologies of the percentage of hourly zonal winds with $u < -29$ m/s for (top panels) 82, 85, and 88 km and (bottom panels) 91, 94, and 98 km (solid line). The dotted and dashed lines represent the equivalent climatologies generated from data recorded when the SQBO is in either its negative (westward) or positive (eastward) phase at 15 hPa, respectively.

phase. In addition, we see the strongest MQBO signal around March. During the NH summer months, we see some evidence for a significant MQBO signal below around 90 km altitude, but in the opposite sense to that required to gate the interhemispheric propagation of a westward propagating planetary wave.

[40] To illustrate this point further, the raw hourly meteor wind data for all meteor radar wind levels are composited according to SQBO eastward and westward phases at 15 hPa. For both groups, the percentage of the time for which the hourly mean zonal wind $u < -29$ m/s is calculated in order to study the effect of the MQBO on the blocking of the 16-day wave. Results for the blocking analysis are shown in Figure 6. It can be seen that climatologically blocking occurs most frequently during February, March, and April, with a secondary maximum around August, September, and October. These blocking maxima coincide with the equinoxes when the MSAO is known to be in the westward phase [*Garcia et al.*, 1997] and can be understood to originate due to the stronger westward winds during this phase. During the first maximum, an effect of the QBO is present at all levels with an increase in blocking during the positive phase of the SQBO. During the second maximum, the effect is more pronounced during August for the upper levels with an effect during August, September, and October for the lower levels. During the eastward phase of the SQBO (hence westward phase of MQBO, see Figure 3), more blocking occurs than during the SQBO westward (MQBO eastward) phase. This behavior is present at all levels between 82 and 98 km, however, it should be noted that the seasonal (MSAO) variability in blocking decreases for the upper levels. Thus, the data presented here provide no strong evidence that the MQBO plays a crucial role in the gating of the interhemispheric propagation of long-period planetary waves.

5. Summary

[41] A quasi-biennial modulation of the zonal winds was found in the mesopause region over A.I. with a period of approximately 27.5 months, which is comparable to the SQBO period over Singapore. This MQBO appears to be present over the entire observational period.

[42] The MQBO at all meteor radar wind levels is out-of-phase compared to the SQBO at 15–20 hPa and in-phase at 70 hPa. Around 40 hPa, the stratospheric and meteor radar zonal winds are not correlated at zero time-lag. It has been shown that this observed phase relation with the stratosphere is consistent with the selective filtering of GWs by the stratospheric QBO winds and subsequent momentum deposition in the mesosphere.

[43] The MQBO magnitude is 4.1 ± 0.7 m/s at 88 km and is fairly constant for all mesospheric altitudes observed here. No strong change of phase with height is observed in the mesosphere, unlike the situation in the stratosphere. It has been shown that the MQBO signal is mainly carried around the March equinox, although the MQBO signal is present throughout most of the year, although less pronounced, below 98 km as well.

[44] We find no clear evidence to support the hypothesis that the MQBO plays a role in gating the interhemispheric propagation of the quasi-16 day wave through a duct between 78 and 100 km in altitude. However, it should be noted that this mechanism for QBO modulation of the interhemispheric propagation of the 16-day wave may still be valid through an equatorial duct at lower altitudes than the meteor radar can observe [e.g., *Espy et al.*, 1997].

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