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Mean winds in the MLT, the SQBO and MSAO over Ascension Island (8°S, 14°W)

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Abstract

Mean winds in the mesosphere and lower thermosphere (MLT) over Ascension Island (8° S, 14° W) have been investigated using meteor radar wind observations. The results presented in this study are from the interval October 2001 to December 2011.

There is a clear annual oscillation in the monthly-mean meridional winds. The monthly-mean meridional winds observed over Ascension Island at meteor heights are found to be southward during April-October, reaching velocities up to about -23 ms^{-1} and northward the rest of the year, reaching velocities up to about 16 ms^{-1}. The monthly-mean zonal winds are generally westward throughout most of the year, reaching velocities up to about -46 ms^{-1}. However, there are eastward winds in May-August and again in December for the lower heights which the radar observes. These winds reach a maxima at heights of about 86 km and reach velocities of up to about 36 ms^{-1} and decay quickly above and below. The Mesospheric Semi-Annual Oscillation (MSAO) is clearly observed in the monthly-mean zonal winds. The first westward phase of the winds is much stronger than the second. The westward phase of the MSAO was found to maximise at heights of about 84 km and in general, reach amplitudes of about -35 $\mathrm{m\,s}^{-1}$.

We have compared the HWM-07 empirical model to our observations. Our observed meridional winds are generally more southward than those of the model at heights of about 80 – 100 km during May – August, whereas the HWM-07 model suggested only weakly southward, or even northward winds at the lower height region. The zonal monthly-mean winds are in general agreement but somewhat less westward than observed by the radar.

Considering our observations of the zonal winds further, there were eight events in which the first westward phase of the MSAO was observed. The strongest westward winds reached about -75 $\mathrm{m\,s}^{-1}$ in 2002, which is about half the value of the mean westward winds, about -40 $\mathrm{m\,s}^{-1}$. We can explain this observation in terms of a mechanism which has been previously proposed by others. The relative phas-

ing of the Stratospheric Quasi-Biennial Oscillation (SQBO) and the MSAO allows an unusually large flux of gravity waves with large westward phase speeds to reach the mesosphere. The dissipation of the gravity waves then drives the MLT winds to large westward velocities. We demonstrate that the necessary phase relationship existed during 2002 and not during the other years observed here. This provides strong support for the suggestion that extreme zonal winds are a result of modulated gravity-wave fluxes.

1 Introduction

The equatorial stratosphere and mesosphere are host to a number of unique dynamical phenomena. These include the Stratospheric and Mesospheric Quasi-Biennial Oscillation (SQBO and MQBO), the Stratospheric and Mesospheric Semi-Annual Oscillation (SSAO and MSAO), Annual-Oscillation (AO), Kelvin waves, and various Intra-Seasonal Oscillations (ISOs). These phenomena collectively produce an environment into which waves, mostly launched from the troposphere, ascend and encounter background winds that vary significantly on intra-seasonal, seasonal and inter-annual time scales. The influence of such phenomena can be seen in the variability of the mean winds of the mesosphere, especially in the annual and inter-annual variability. The varying background winds create critical levels that can filter the field of ascending waves and in turn, modulate the momentum deposition into the middle atmosphere. The result is a strongly coupled system in which the winds of the mesosphere are strongly influenced by the winds of the stratosphere and vary on time-scales from the intra-seasonal to the inter-annual.

The background meridional and zonal mean winds at the equator in the MLT can be characterised by their seasonal cycles and are dominated by the AO and SAO. However, it has been reported that there is a large degree of inter-annual variability.

The inter-annual variability of the low latitude stratosphere is known to be dominated by the QBO. For example, Baldwin et al. (2001) made a detailed review of the stratospheric QBO. The SQBO is found to have periods of about 28 months in the equatorial stratosphere at heights of about 16 – 50 km. The SQBO consists of downward-propagating westward and eastward wind regimes. The SQBO is also evident in the distribution of chemical constituents, such as ozone, water vapour, and methane.

The seasonal variability of the equatorial mesosphere is known to be dominated by the SAO. The zonal wind amplitudes of the MSAO have been observed and reported to maximise at heights of about 80 – 85 km at latitudes of $\pm 30^{\circ}$, (e.g., Burrage et al., 1996; Garcia et al., 1997; Huang et al., 2006, 2008; Ratnam et al., 2008; Kumar et al., 2011). At the equator the MSAO is known to be influenced by the SQBO and thus the zonal winds are strongly influenced by two different low-frequency oscillations, the MSAO and the SQBO. The westward phase of the MSAO within a particular year has been observed to be of larger amplitude than the second, for example, $\sim$-80 m s^{-1} and $\sim$-40 m s^{-1}, respectively, (Garcia et al., 1997). Further, it has been suggested that the westward phase of the MSAO is itself modulated by the SQBO and that this can give rise to unusually strong westward winds. This suggests a strong coupling between the SQBO winds and the MSAO at the equator. The modulation has only been observed during the westward phase of the MSAO when the conditions are favourable for small scale gravity-waves to interact with the descent of the MSAO. The westerlies are stronger stronger during the westward phase and this may be because of enhanced gravity-waves (e.g., Hitchman and Leovy, 1988; Delisi and Dunkerton, 1988; Garcia et al., 1997). Another mechanism is that in the tropics the tropical convection of gravity-waves is greater during the westward phase, Alllen and Vincent (1995).

Garcia and Sassi (1999) extended the above studies by modelling the atmosphere to investigate the proposed physical mechanism and therefore explain the observed relationship between the SQBO wind amplitude and the westward phase of the MSAO. They again suggested that the SQBO modulates the strength of the westward phase of the MSAO and presented evidence of this during the favourable conditions of the westward phase. The proposed mechanism involves the winds of the SQBO filtering the field of waves that ascend out of the stratosphere into the mesosphere. During these conditions when the SQBO does not filter out a significant proportion of the gravity waves with westward phase speed, they can then reach the mesosphere where they dissipate and produce anomalously strong westward accelerations of the mean flow. Support for this proposal was provided in the recent modelling study by PeñaOrtiz et al. (2010) in which they presented a change in the strength and thickness of the MSAO. There are thus strong indications that the winds of the SQBO can drive very significant variability of the low-latitude MSAO and act to strongly couple these regions of the atmosphere.

Here, we present observations of the mean winds over Ascension Island (8° S ,14° W) in the MLT. We use these winds to investigate climatological winds in the mesosphere and the interaction of the SAO and QBO in the mesosphere and stratosphere, respectively. Meteor radar wind data are considered for the eleven-year interval 2001 – 2011. These data sets allow us to make measurements of mesopause-region winds. For the climatological winds section we compare the observed monthly-mean winds with the HWM-07 empirical modelled winds over the region. This model uses assimilated ground-based and satellite data and predicts results for a specified longitude, latitude and height. More details of the model can be found in Drob et al. (2008). A particular advantage of the Ascension Island radar is that it provides the only ground-based observations of mesospheric winds available between Eastern Brazil and Southern India; we note that this is an oceanic site with no significant landmass within about 21° of longitude either east or west. This paper concentrates on climatological mean winds in the mesosphere and the coupling between the SQBO and the MSAO event of 2002.

2 Observations

The winds in the MLT over Ascension Island (8° S 14° W) were measured with an all-sky meteor radar. The radar is a Skiymet commercially produced system that was deployed on the island in 2001. The radar operates with a peak power of 12 kW and operates at a radio frequency of 43.5 MHz. Hocking et al. (2001) present a description of the Skiymet radars. The radar has operated since deployment, but operation at the site is technically difficult and there have been a number of significant interruptions in the continuity of data recording. This intermittent operation is illustrated in Fig. 1, which presents a schematic diagram of the available data from the radar. In the figure, intervals during which the radar was operating are indicated in green. As can be seen from the Figure, the radar recorded data from October 2001 to June 2011, albeit with significant gaps in recording, notably in 2004, 2007 and 2008.

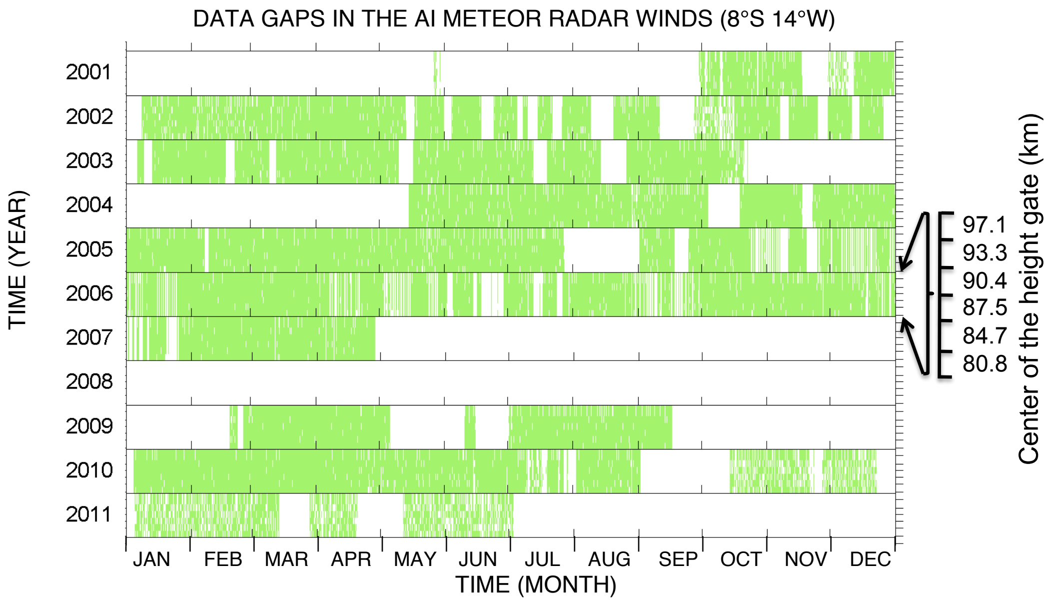

Fig. 1. A schematic showing the available data from the radar on Ascension Island from 2001 – 2011.

The radar measures horizontal winds over the approximate height range 80 – 100 km with a typical height and time resolution of $\sim$3 km and one hour, respectively. A more complete description of the analysis used to derive the winds can be found in Mitchell et al. (2002).

Monthly-mean zonal equatorial wind data at heights of $\sim$10 – 70 hPa have been used to compare the SQBO westward and eastward phase over the equator with the radar observations. The SQBO data product was obtained from Freie Univeristät Berlin (FUB). This data set has been produced from the Singapore radiosonde data, from January 1987 to December 2011.
(http://www.cdc.noaa.gov/data/correlation/qbo.data)

3 Results

To investigate the low-frequency ($\sim$60 – 500 days) components in the radar wind data over Ascension Island we present in Fig. 2 a Lomb-Scargle periodogram of these low-frequency components calculated using data for all the years available. A low-pass filter (part of the MatLab toolkit) with a frequency cut-off of 60-days was used to remove higher-frequency waves, such as gravity-waves, tides and planetary waves. From the figure it can be seen that there are a number of low-frequency oscillations evident in both the radar zonal and meridional wind observations.

At lower frequencies the wind time series become dominated by the signatures of the MSAO and the AO. It is notable that in these long-term time-series the largest amplitude component in the zonal winds is the MSAO.The modulation of the amplitude of the SAO appears as a broadening of the semiannual peak, as can be seen in the zonal wind spectra shown in Fig. 2. This can be shown by statistical analysing of the side-lobe peaks and calculating the QBO period that they would be modulated by. From Fig. 2 and using the following equation: $1/\omega_1$ - $1/\omega_1$ = $1/\omega_{QBO}$. Where, ω_1 is the first lobe peak, 162 days and ω_2 is the second lobe peak, 207 days and ω_{QBO} is the period of the QBO. It was found that frequency of the modulating wave was calculated to be

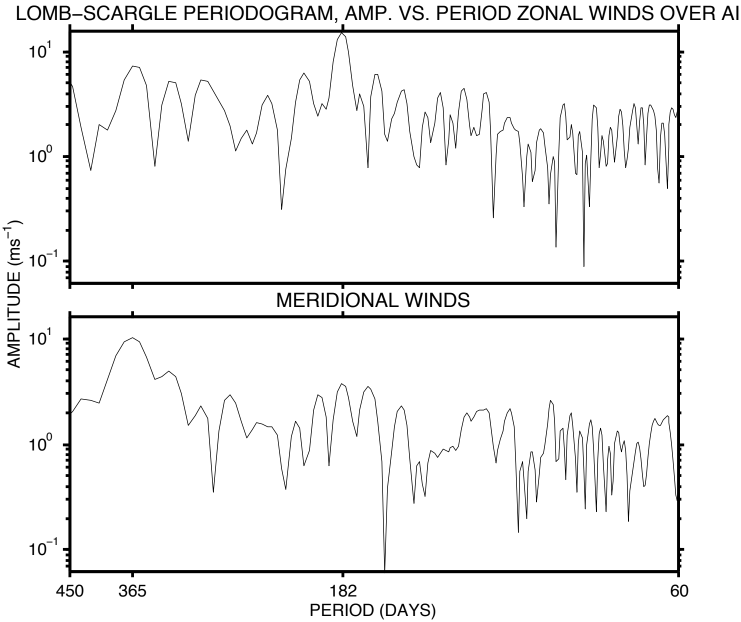

Fig. 2. A Lomb-Scargle periodogram of the zonal and meridional winds at a height of about 90 km over Ascension Island for October 2001 to December 2011.

about 25 months, approximately the QBO frequency. Therefore the QBO does seem to modulate the amplitude of the SAO as the broadening of the peak as suggested by the side-lobes either side of the SAO in the figure. In contrast, in the meridional winds the largest amplitude component is the annual cycle. We will now consider the AO and the MSAO in more detail.

3.1 Seasonal mean winds and comparisons with the HWM-07 model

This section presents a climatology of the seasonal mean winds in the MLT over Ascension Island and then compares our observations with the HWM-07 model winds for approximately the same location. Monthly-mean zonal and meridional winds were calculated for each month and height gate.

Figure 3 presents the radar observations of the monthly-mean meridional winds. The figure presents the individual years and also a composite year. Note that the monthly-mean values can mask any short-term fluctuations of less than one month.

The meridional winds in the figure reveal a clear annual cycle or oscillation. These observations agree very well with the simple concepts of the large-scale mean meridional circulation of the middle atmosphere in which in the mesosphere the meridional circulation is a pole-to-pole cell.

Here we observe the meridional winds to be generally southward (negative) from June – August and northward (positive) from December – February. From April – October the winds are observed to generally be strongest at heights of $\sim$93 km and to regularly reach velocities more negative than -12 m s^{-1} . In contrast, during November – March the winds are positive in the upper heights observed, reaching velocities of $\sim$12 m s^{-1} in most years. Two successive maxima are observed and peak in November/December at heights of $\sim$91 km and again in January at heights of $\sim$86 km. The inter-annual variability of the winds will be considered in Sect. 3.2 where we will investigate the contribution of the SQBO to the inter-annual variability of the mesospheric winds.

A similar monthly-mean wind analysis was used to produce Fig. 4, which shows the monthly-mean zonal winds for each individual year and the composite-year. The figure shows a semi-annual oscillation (SAO) of the monthly-mean zonal winds. The winds are generally westward (negative) all year except at lower heights, 83 – 93 km where the winds are eastward (positive) May – August. During June – August the winds maximise at heights of about 86 km in June and reach velocities of up to about 35 m s^{-1}. Further, there is a second occurrence of strong eastward winds in December of most years,

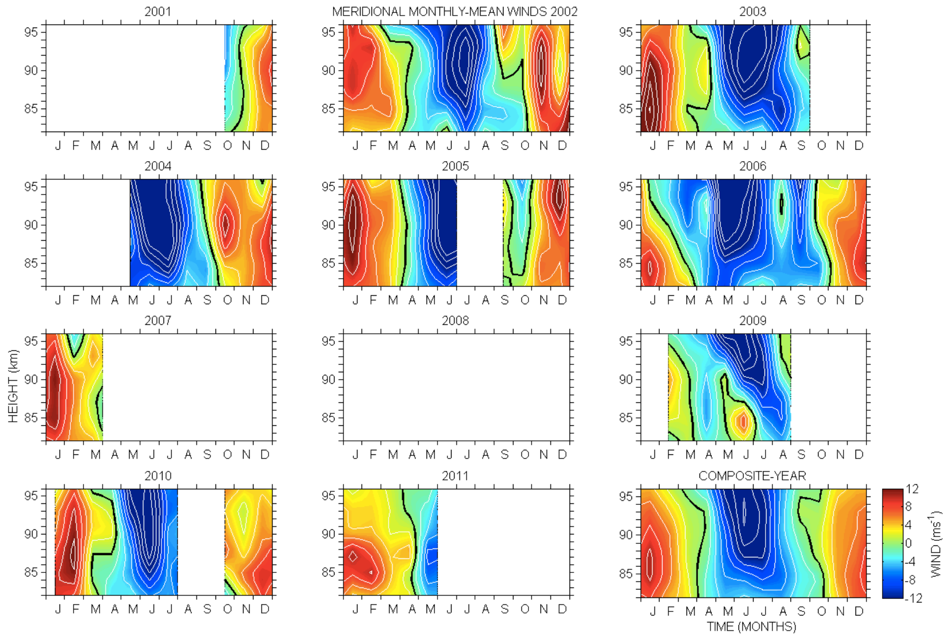

Fig. 3. Monthly-mean meridional winds over Ascension Island for the years 2001 – 2011 and the composite-years. The zero wind contour is indicated in black and the white contours are in steps of $2\,\mathrm{m\,s^{-1}}$.

where the winds reach up to about $10\,\mathrm{m\,s^{-1}}$ and often extend through the height region observed. The winds are strongly westward at the equinoxes, where the strongest winds were observed during March – May and in March winds reach velocities of up to

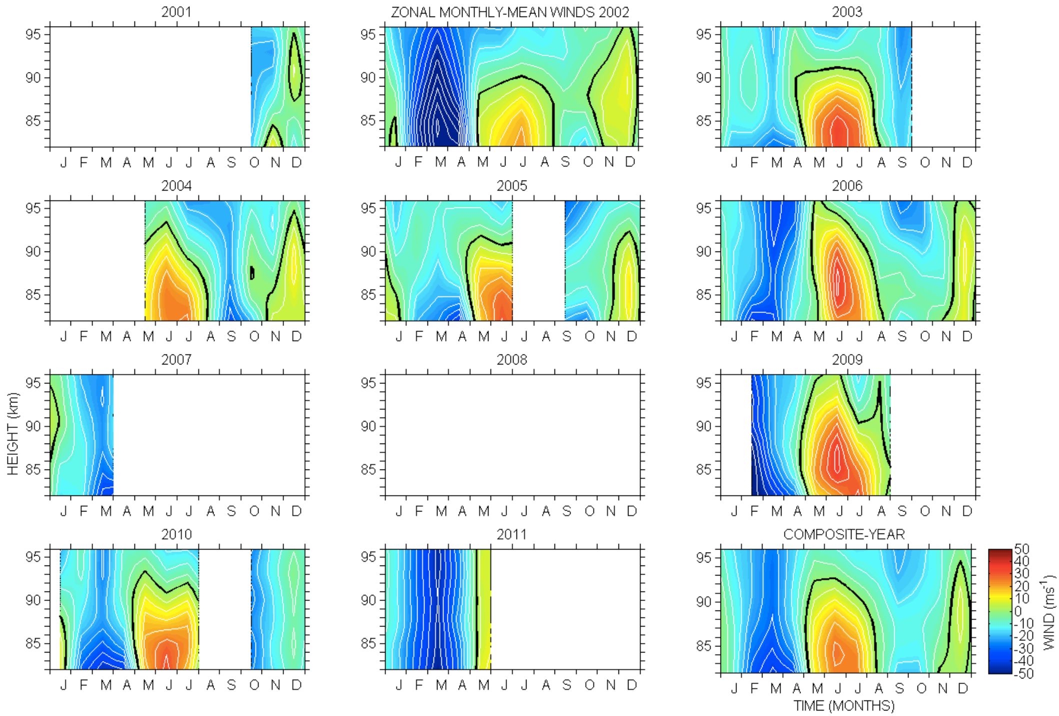

Fig. 4. Monthly-mean zonal winds over Ascension Island for the years 2001 – 2011 and a composite-year. The zero wind contour is indicated in black and the white contours are in steps of 5 m s^{-1}.

about 50 m s^{-1}. This pattern of winds is the well-known MSAO.

There is some inter-annual variability evident in the monthly-mean zonal winds. The strength of the region of eastward winds during June – August varies from year-to-year.

This results in the height at which the wind reverses from eastward to westward also varying from year-to-year. For example, in 2002 the eastward winds maximised in July at heights of about 83 km, whereas in 2006 and 2009 the eastward winds maximised in June at heights of about 87 km. Further, in 2006 and 2009 the region of eastward winds also extends throughout the height observed up to at least 96 km.

Note the composite-year plot does not include months where no data was available. The composite-year shows zonal winds reaching $\sim 40\,\mathrm{m\,s^{-1}}$ at about height of ~ 84 km during February – April. However, in 2002 the zonal winds reached $\sim 80\,\mathrm{m\,s^{-1}}$ at the same height. In Sect. 3.2 we will discuss this phenomena of strong westward winds in more detail and discuss the importance of it for understanding the coupling of the dynamics of the atmosphere between the SQBO and the MSAO.

We will now compare the climatological meridional and zonal winds observed Ascension Island by the radar with the winds predicted by the HWM-07 empirical model. Here, the HWM-07 model has been used to predict the meridional and zonal winds at 7.9°S and 14.4°W, i.e., the position of Ascension Island, for heights of 80 – 100 km.

Figure 5 presents the meridional and zonal monthly-mean winds from the HWM-07 model. Firstly, we will consider the HWM-07 meridional winds and compare them to the composite-year monthly-mean observations of Fig. 3. From the figures it can be seen that, although there are some similarities between the model and the observations, there are also a number of significant differences. In particular, the model predicts the northward December – February winds to maximise at heights of about 98 km and to only extend down to heights of about 90 km, below which the winds reverse to become southward. In contrast, our observational composite (Fig. 3, lower right-hand panel) revealed the winds to be northward from October – March at all heights observed by the radar. Further, the model predicts the southward flow to be strongest in February at heights of about 82 km, in May at heights above 100 km and again in August/September at heights of about 86 km. This behaviour is very different from the radar observations where the flow is, in general, consistently southward from April – October at all heights observed and is strongest at the upper heights in June.

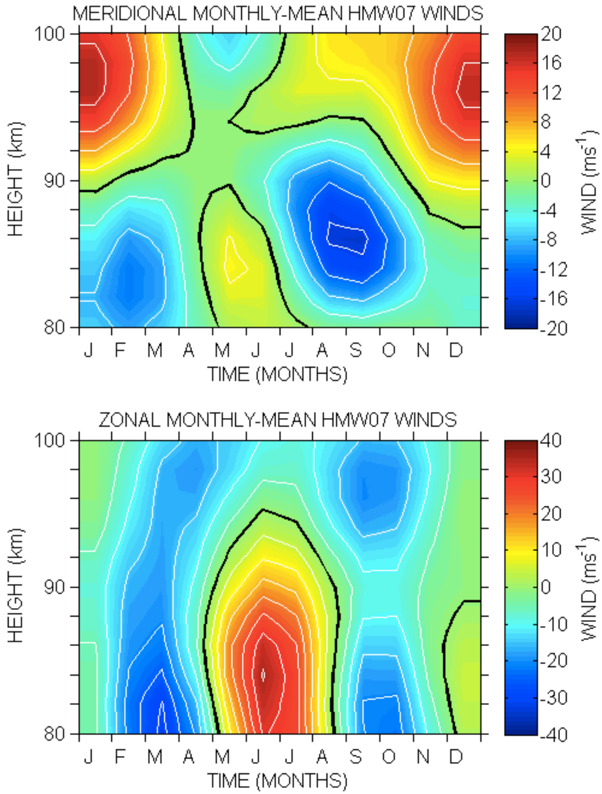

Fig. 5. Monthly-mean meridional and zonal winds over Ascension Island (7.94°S and 14.37°W), from the HWM-07 model. The zero wind line is indicated in black and the white lines indicate $5\,\mathrm{m\,s^{-1}}$ steps.

Considering the meridional winds quantitatively, it can be seen that the southern winds in our observations maximise in June at height of about 94 km reaching velocities of about - 16 m s^{-1}, whereas the model winds maximise in September at heights of about 86 km reaching velocities of about - 20 m s^{-1}. Considering the maximum northward winds, it can be seen in our observations that they maximise in January at heights of about 86 km reaching velocities of about 10 m s^{-1}, the model winds also maximise in January, but at heights of about 97 km and reaching twice the velocity of the observed winds, about 20 m s^{-1}. These differences could be because of the difference in period and instruments used infer the winds. The composite observations from the radar presented here are from an 11 year period 2001 – 2011 with one ground-based instrument, whereas the model was developed using 50 years of data from many satellite, rocket, and ground-based instruments to infer the winds from 1956 – 2005. The different locations and times may account for some of the differences in strength and location of the winds. Further, some difference can be explained by changes in the general circulation in the MLT occurring over decadal time scales. Here we are looking at only one decade, whereas the model uses multiple decades and this could mask shorter term changes in the circulation of the MLT.

Secondly, we consider the HWM-07 zonal winds and compare them to the composite-year observations of Fig. 4. From the figures, it can be seen that the model winds are generally in good agreement with our composite-year zonal wind observations. However, a number of differences are again apparent. In particular, during the months June – August the zonal winds at the lower heights are slightly stronger in HWM-07 model than we observe. For instance, at the lowest heights considered the strongest winds around March — May in the model reach about 35 m s^{-1}, whereas our observations indicate winds of greater velocity, about 45 m s^{-1}. More significantly, during June – August, the eastward winds in the model reach up to $\sim$40 ms^{-1} whereas our observations indicate winds only about half that velocity.

In summary, the HWM-07 winds are in reasonable agreement with the observations in the case of the zonal winds. However, although the HWM-07 predicted peak meridional southward winds during June – August of similar velocity to those observed here, but the model does not show the deep region of southward winds evident across the full range of heights observed by the radar.

3.2 SQBO and MSAO of the mean winds

Garcia et al. (1997) has previously investigated the link between the SQBO and the MSAO. During the westward phase of the SQBO it can modulate the MSAO in favourable conditions. Their data-set is from 1990 – 1995 and therefore pre-dates ours allowing for this link to be investigated further. Here we will now investigate whether there is evidence of such coupling in our observations made over Ascension Island, 2001 – 2011. We have used the Singapore radiosonde monthly-mean equatorial zonal winds at $\sim$10 hPa to determine the phase of the QBO in the stratosphere.

Figure 6 presents the Singapore radiosonde QBO wind data at heights of about 16 – 33 km ($\sim$100 – 10 hPa) for the years 2001 – 2011. Figure 6 shows the characteristic descending phase of the stratospheric QBO where perturbation winds regularly reach velocities of about 20 m s^{-1}.

Here we will use the vertical distribution of the amplitude of the MSAO and SQBO at the equator presented by Baldwin et al. (2001) to investigate the QBO and SAO of the stratosphere and mesosphere in more detail. Baldwin et al. (2001) based the QBO on UARS/HRDI observations and the SAO on rocket observations from Ascension Island report that they observed the SQBO from about 16 – 40 km, peaking at heights of about 25 km and reach velocities of about 20 m s^{-1}. This agrees with the observations presented in Fig 6 and for those which our data set spans. Further, the MSAO was presented by Baldwin et al. (2001) with a maximum at heights of about 75 – 85 km, peaking at 80 km and reaching velocities of about 30 m s^{-1}.

In order to compare annual variability of the zonal mesospheric winds, radar data at heights of about 84 km was low-pass filtered with a cut-off frequency of 60 days, for reasons presented previously. Figure **??** presents the low-pass filtered data for the years 2001 – 2011. Also shown on the figure are the maximum eastward and westward

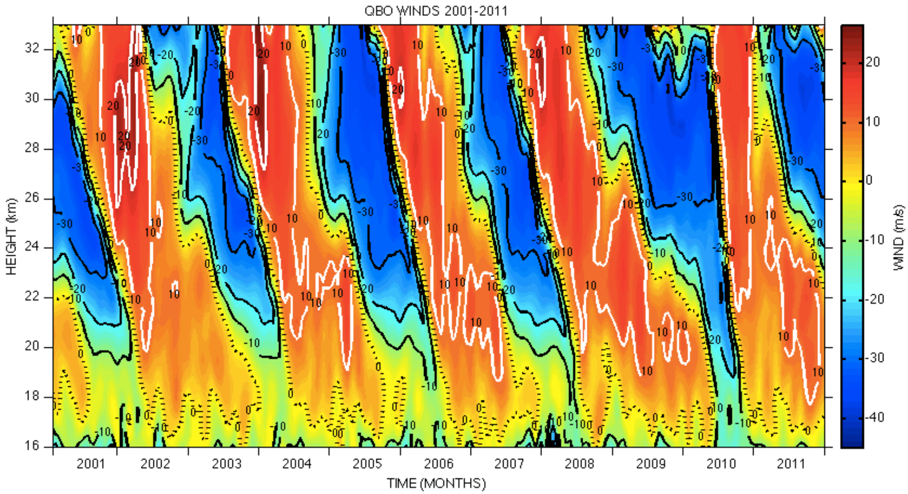

Fig. 6. The Singapore radiosonde QBO wind data from 2001 to 2011, with the contours steps of 10 m s^{-1} (http://www.cdc.noaa.gov/data/correlation/qbo.data).

monthly-mean equatorial stratospheric winds present anywhere in the height range of 25 – 30 km at a particular time. The height of 25 – 30 km was chosen as it is the height at which the SQBO has greatest wind amplitudes.

If we consider the stratospheric winds at times when simultaneous mesospheric winds were recorded, it can be seen that in just one year, 2002, there were only very weak (actually near-zero) westward monthly-mean equatorial stratospheric winds during the time of the westward phase of the MSAO. This interval in which the stratospheric winds had no significant westward component was simultaneously accompanied by the strongest westward mesospheric winds observed in the entire set of meteor radar observations (speeds of $\sim$ - 90 m s^{-1}). In fact, the MSAO winds at this time were more

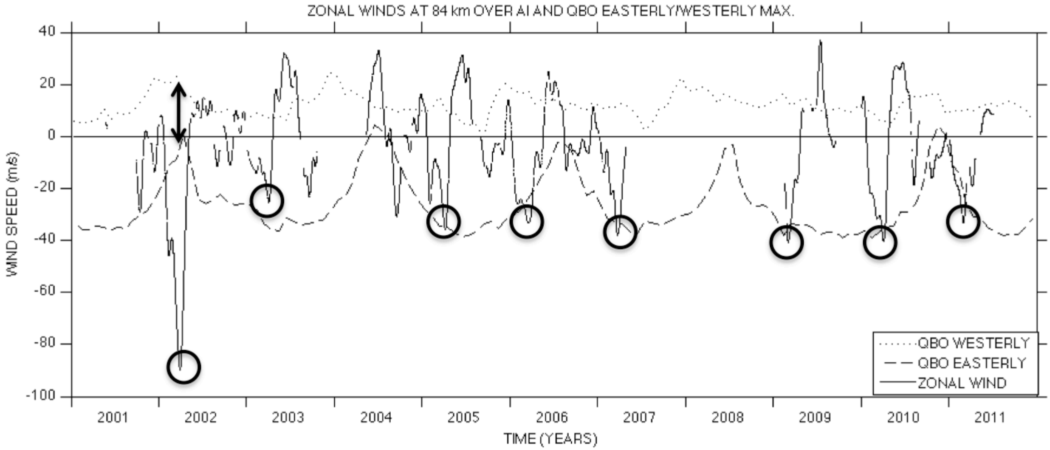

Fig. 7. Comparison of monthly zonal lowpassed (60-day cutoff) radar winds over Ascension Island at 84 km (solid line) with the strongest eastward (short-dashed) and westward (long-dashed) QBO wind data at 25 – 30 km for February to April from 2001 – 2011. The double headed arrow shows the small difference between the mesospheric and stratospheric winds. The circles identify the westward phase of the MSAO.

than twice as strong as those observed during any of the other westward phases of the MSAO. In other words, for those times when radar data were available, the strongest westward MSAO winds occurred during the only time when the stratospheric QBO winds had a very small, almost zero westward wind component.

Figure 8 presents the data by considering the critical phase speed that would allow waves to propagate and to therefore the SQBO to modulate the MSAO. Gravity waves have been modelled by Garcia et al. (1997) to show a modulation of the SQBO to the MSAO. Comparing the years 2001 – 2011 we can see that the winds were most favourable in the year 2002. Note, other years, for example 2004 may seem favourable

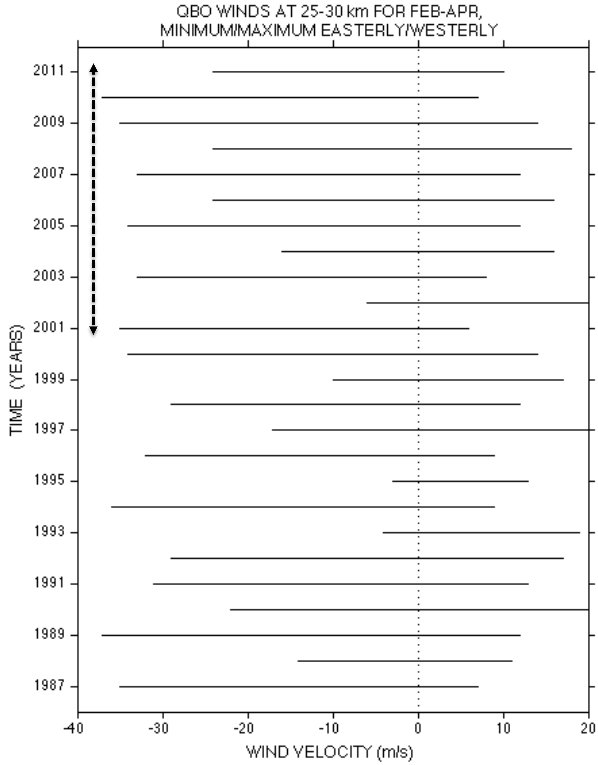

Fig. 8. The strongest eastward and westward QBO wind data at 25 – 30 km for February to April from 1987 – 2011 for the months of February–April. The dashed line shows duration of the zonal winds observed by the Ascension Island radar.

however, the minimum westward winds are strong enough to filter the wave from propagating to the mesosphere. Using the QBO wind data available from the Singapore radiosonde we observed the link between the westward phase of the MSAO in the zonal winds and the westward dominated SQBO winds. Considering all of the years of SQBO wind data available (1987 – 2011) it can be seen from Fig. 8 that the winds were favourable in 1993, 1995 and 2002. The radiosonde data from 1897 – 2011 has been presented here to allow us to compare them with our observations here and the results presented by Garcia et al. (1997). They presented radar winds at 84 km from over Christmas Island from 1990 — 1995. During this time they observed strong MSAO easterly cycles during the years 1993 and 1995, these were periods of deep QBO westerlies as can also be seen from Figure 8. This supports the suggestion that deep QBO westerlies provide favourable conditions for the MSAO easterly cycle to be observed. Our observations of the 2002 apparent coupling support the findings of Garcia et al. (1997) and add another example where the atmosphere behaves as predicted and modelled (Garcia and Sassi, 1999; Baldwin et al., 2001; PeñaOrtiz et al., 2010). Our observations of this dramatic and very unusual event support the theory of the strong coupling of the SQBO and MSAO. This is one of a handful of observations and adds support to the reports by **?**.

Figure 9 shows a schematic of the proposed filtering mechanism for the westward winds in the MSAO. From the left-hand panel of the figure it can be seen that when the background flow is greater than the critical phase speed then gravity-waves are absorbed by the background flow. This acts as a filtering mechanism on the gravity-wave propagation. The right-hand panel shows the waves being allowed to propagate upwards freely. This can occur when the background flow is less than the critical phase speed. Thus the gravity-waves can reach the mesosphere and the MSAO is clearly observed during February to April.

4 Discussion

The annual oscillation (season pattern) of the MLT meridional winds observed in this study generally agreed well with previous reports of the equatorial region (e.g., Babu

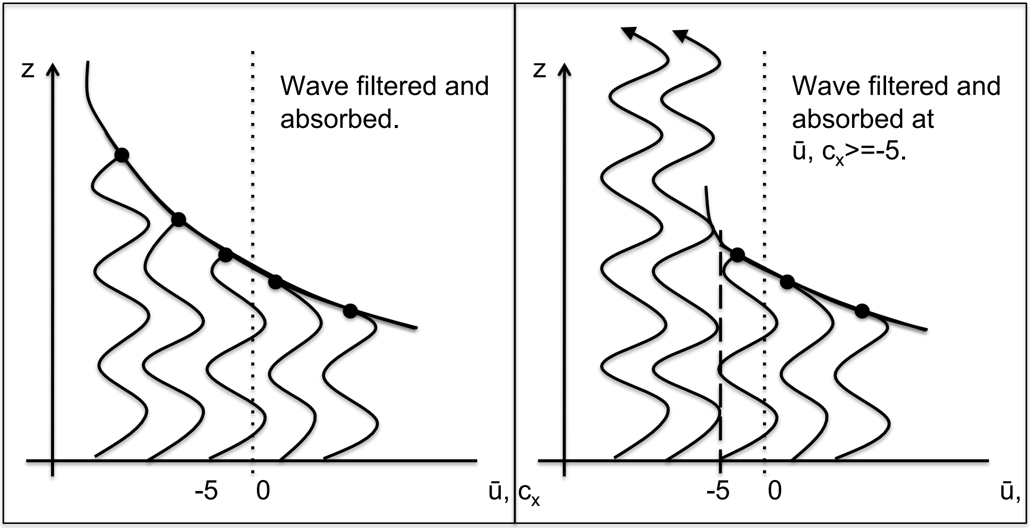

Fig. 9. A schematic diagram of the mechanism proposed by Garcia and Sassi (1999) for the filtering of gravity-wave by the westward winds of the MSAO. The upward oscillations show wave propagating in the atmosphere, were the circle ended waves are filter and absorbed by the background flow and the arrow ended wave propagate into the atmosphere. The dashed line at - 5 shows the critical wave velocity.

et al., 2011). We observed the winds to reach velocities of greater than $\pm 12\,\mathrm{ms}^{-1}$, (southward) in the southern hemispheric winter, from April–October and to be northward for the rest of the year. The winds were, in general, the same strength across the height region observed ($\sim 80-100$ km). For comparison Babu et al. (2011) observed the meridional winds using a SKiYMET Meteor Wind Radar over Thumba (8.5° N, 77° E) at heights of about 82 – 98 km for March 2006 – 2009. They report the meridional winds to be similar in strength to the southward winds observed in this paper but, weaker northward winds, where they observed winds to only reach up to about $10\,\mathrm{ms}^{-1}$.

Our observations of the zonal winds in the MLT reveal a clear SAO and present the year-to-year variability of the winds. One specific event of large variability is in part explained later in the detailed analysis of the westward phase of the SAO at heights of about 84 km. However, in general the winds are weakly westward in the top height gates observed and the westward winds are generally stronger during the westward phase of the SAO. Compared to those reported by Babu et al. (2011) the eastward winds maximise at heights of about 86km during June and decrease rapidly above and below this height.

Babu et al. (2011) also reported on the zonal winds over Thumba (8.5 $^\circ$ N, 77 $^\circ$ E) at heights of about 82 – 98 km for March 2006 – 2009. They reported a clear SAO signature in the zonal winds observed, which peaked in February at the lower height and again during the months June – August at all heights. They observed the zonal winds to maximise at height of about 82 km and to reach velocities of about 20 and - 30 ms^{-1}. The SAO of the winds that they observed are very similar to the observations presented here. However, we observed the zonal winds, in general, have larger amplitudes and this was observed specifically during the equinoctial westward winds.

Comparing the radar winds with the HWM-07 model we find that they are generally in good agreement in the case of the zonal winds. However, the modelled zonal winds are generally larger amplitude during June and smaller amplitude for the rest of the year. In contrast, the meridional model winds reveal a number of notable differences. They do not reveal the clear seasonal change observed by the radar, where the winds are southward from April–October and northward winds for the rest of the year. Further, the modelled northward flows are generally stronger and maximises at heights of about 97 km, whereas the observed northward flow maximises at heights of about 86 km and persist northward through the height region observed.

We observed larger amplitudes of the MSAO during March 2002 when the west westward pause was larger, which may have been modulated by a strong eastward (westerly, positive) SQBO which was present during this time in the stratosphere. Figure 8 supports this suggestion that very strong MSAO westward phases appear to occur at times when westward winds in the stratosphere are especially weak. This suggestion agrees with the observations and modelling studies of (e.g., Burrage et al., 1996; Garcia et al., 1997; Garcia and Sassi, 1999; Huang et al., 2008; PeñaOrtiz et al., 2010) and references therein.

The schematic that we have used to describe the mechanism for the filtering of gravity-waves by the SQBO which, in turn, results in a modulation of the MSAO supports the observations of Garcia et al. (1997). Considering our schematic description of the mechanism for filtering the SQBO modulation of the westward phase of the MSAO we would expect to observe modulations in the years 1993 and 1995, as shown in Fig. 8. Garcia et al. (1997) showed HRDI and radar observations of zonal winds in the mesosphere for the years 1990 – 1995 over Christmas Island (2°N). They showed the westward phase of the MSAO to be modulated in the years 1993 and 1995 reaching zonal wind velocities of about -85 $\mathrm{m\,s^{-1}}$ and -65 $\mathrm{m\,s^{-1}}$, respectively. Thus our schematic description of the filtering mechanism is supported by the observations here and by Garcia et al. (1997) and for all the years where we would expect to observe modulations using the SQBO at 25 – 30 km for February to April. From Figs. 8 and 9 we would expect to observe MSAO modulations in the westward phase for the years 1993, 1995 and 2002. These are the years that the SQBO modulating the MSAO are observed.

Garcia and Sassi (1999) suggested an explanation for the SQBO and MSAO coupling using their model. They showed how the SQBO wind could modulate the strength of the westward phase of the MSAO. They suggested that the eastward phase of the MSAO would be unaffected by the SQBO when the stratospheric zonal winds are far less than the phase velocities in the mesosphere and stratosphere. Further, the eastward MSAO phase is faster than the westward the SQBO and therefore can only modulate the westward spectrum of vertically-propagating equatorial waves. However, they also noted that the inter-annual variability of wave forcing in the real atmosphere was not accounted for in their model and this could explain the differences between their model and observations.

A gravity-wave influence of the MSAO modulation was proposed by Antonita et al. (2008). They used meteor radar observations of gravity wave momentum fluxes over Trivandrum (8.5 $^\circ$ N, 76.9 $^\circ$ E). They reported that on an average, $\sim$20 – 60 % and $\sim$30 – 70 % of the forcing toward the eastward and westward phases of MSAO, respectively, was from gravity waves.

Li et al. (2012) used a meteor radar in Maui, Hawaii from May 2002 to June 2007 to observe horizontal wind profiles in the mesopause region. They observed the MSAO at heights of about 90 km with wind velocities of about 20 m s^{-1} in the first cycle and about 5 m s^{-1} in the second cycle. They observed a modulation of the MSAO westward phase by the SQBO. The strength of the MSAO westward phase corresponded to the phase of the SQBO at heights of about 32 km.

Finally, the results we have presented here are a climatology of mean winds over Ascension Island and highlighted the importance of wave/mean-flow interactions in modulating the momentum flux of gravity-waves in the stratosphere reaching the mesosphere adding support to report by others of this rare dramatic phenomena of coupling of the SQBO and MSAO because of the specific atmospheric conditions that need to occur for the gravity-waves not to be filtered by the background winds.

5 Conclusions

Zonal and meridional winds in the MLT have been observed by meteor radar over Ascension Island in the interval 2001 – 2011. The meridional winds in the MLT over Ascension Island are found to be dominated by an annual oscillation in which the winds are southward from April to October in most of the years. The zonal winds are dominated by an SAO where the winds are westward during the equinoxes.

The meridional and zonal radar winds were compared to the HWM-07 model. The model predicted the winds to be more northward than the observations. Further, the well defined structure of the observed southern hemispheric summer-time southward and winter-time northward winds were not well represented by the model. The zonal winds in the model were similar but more eastward than the observed atmosphere.

It was observed that the SQBO can modulate the MSAO zonal winds during the westward phase when the SQBO background winds are greater than the critical phase speed required for that location. These two criteria need to be meet for the gravity-waves to propagate to the mesosphere and not filtered by the background winds. This was shown in our observations for the year 2002 and previous observes shown and discussed by Garcia et al. (1997) during the years 1993 and 1995. In summary, this modulation takes the form of greatly increased westward winds in the MSAO when the phase of the stratospheric QBO allows gravity-waves of westward phase speed to reach the mesosphere.

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