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Mean winds, SAO and QBO in the stratosphere, mesosphere and lower thermosphere 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 and 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 $-23\,\mathrm{m\,s^{-1}}$ and northward the rest of the year, reaching velocities up to about $16\,\mathrm{m\,s^{-1}}$. The monthly-mean zonal winds are generally westward through most of the year, reaching velocities up to about $-46\,\mathrm{m\,s^{-1}}$. However, there are eastward winds in May–August and again in December in the lower heights that the radar observes. These winds maximises at heights of about 86 km reaching velocities up to about $36\,\mathrm{m\,s^{-1}}$ and decays 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 first westward phase of the MSAO was found to maximise at heights of about 84 km and to in general reach amplitudes of about $-35\,\mathrm{m\,s^{-1}}$.

We have compared the HWM-07 model to our observations. Our observed meridional winds are generally more southward than those of the model at meteor heights in the southern hemispheric winter, whereas HWM-07 suggests that in this season only weakly southward, or even northward flows occur at the lower heights. The zonal monthly-mean winds are in general agreement but somewhat less westward than observed by the radar.

In one of the eight events in which the first westward phase of the MSAO was observed, the strongest westward winds reached about $-75\,\mathrm{m\,s^{-1}}$, compared to the mean of about $-35\,\mathrm{m\,s^{-1}}$ for other events. We explain this observation in terms of a mechanism which has been previously proposed by others. In this the relative phasing of the Stratospheric Quasi-Biennial Oscillation (SQBO) and the MSAO allow an unusually

large flux of gravity waves with westward phase speed to reach the mesosphere. The dissipation of these waves then drives the MLT winds to large westward velocities. We demonstrate that the necessary phase relationship existed during the event we observed in 2002 and not during other times. This provides strong support for the suggestion that those extremes in zonal flow 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 (the SQBO and MQBO), the Stratospheric and Mesospheric Semi-annual Oscillation (SSAO and MSAO), 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. These varying background winds create critical levels that can filter the field of ascending waves and so, 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 at lower heights and which can display variability 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, which are dominated by the Annual Oscillation (AO) and SAO. However, it has been reported that there is also 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 QBO in the stratosphere and mesosphere. 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. A QBO signature is also evident in the mesosphere. This signal is out of phase with the SQBO at heights of 40 hPa (23 km).

The seasonal variability of the 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 ±30°, (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 dominated by two different low-frequency oscillations, the MSAO and the SQBO. The first westward phase of the MSAO within a particular year has been observed to be of larger amplitude than the second, for example, $\sim -40\,\mathrm{m\,s^{-1}}$ and $\sim -20\,\mathrm{m\,s^{-1}}$, respectively. Further, it has been suggested that the first 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.

Garcia and Sassi (1999) extended the above studies by constructing a model that investigated the correlation between the MSAO westward phase and the phase of the SQBO. They again suggested that the SQBO modulates the strength of the first westward phase of the MSAO. The proposed mechanism involves the winds of the SQBO filtering the field of waves that ascend out of the stratosphere into the mesosphere. Under conditions when the SQBO does not filter out a significant proportion of the waves with westward phase speed, these waves can 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 Peña-Ortiz et al. (2010). 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). We use these to investigate the interaction of the SAO, AO and QBO. Meteor radar wind

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data are considered for the eleven-year interval 2001–2011. These data sets allow us to make measurements of mesopause-region winds. We compare the observed winds with the HWM-07 model. 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 mean winds and the coupling between the SQBO and the MSAO.

2 Data Analysis

This study uses observations of winds in the MLT measured by a meteor radar located on Ascension Island, (8° S 14° W). The radar is a SKiYMET VHF radar system. Details of the system can be found in Day and Mitchell (2010); Day et al. (2012) and references therein. There is one noteworthy difference between the systems, this radar operates at a radio frequency of 43.5 MHz and not at the 32.5 MHz, used by the other radars used in those studies. The radar commenced operation in October 2001 and has produced measurements since that time, giving about eleven years of operation. However, operation at the site is technically difficult and so there have been a number of significant interruptions in the data continuity. Figure 1 presents a schematic showing the available data from the radar. Note that the radar did not operate for most of 2007 and all of 2008.

The radar measures horizontal winds between 80–100 km in the atmosphere. Here, the height of observation is separated into six independent height gates. Horizontal winds are calculated for each height gate is observed with a one hour time resolution. A more complete description of the radar system and the data analysis can be found in, e.g. Hocking et al. (2001); Mitchell et al. (2002).

Monthly-mean zonal equatorial wind data for height of ∼10–70 hPa have been used to compare the SQBO westward and eastward phase over the equator with the radar and satellite observations. The SQBO data product was obtained from Freie Univeristät

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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 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. From the figure it can be seen that there are a number of 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, the Annual Oscillation (AO) and lower frequency components associated with the MQBO. 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. However, 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

This section presents a climatology of the seasonal mean winds in the MLT over Ascension Island. Monthly-mean zonal and meridional winds were calculated for each month and height gate. Figure 3 presents these 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

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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) in the Southern Hemisphere winter (June–August) and generally northward (positive) in the Southern Hemisphere summer (December–February). The meridional winds are generally southward from April–October at all heights observed by the radar. The flow is generally strongest at heights of ~ 93 km, regularly reaching velocities more negative than $-12\,\mathrm{m\,s^{-1}}$. In contrast, the southern hemispheric summer-time flow is northward and strongest in the upper heights. The strongest northward flows are generally observed from November–March reaching velocities of $\sim 12\,\mathrm{m\,s^{-1}}$ in most years. The southern hemispheric summer-time winds sometimes display two successive maxima, peaking in November/December at heights of ~ 91 km and again in January at heights of ~ 86 km. This behaviour is evident in the southern hemispheric summers of March 2002, May 2004 and June 2005, but not in February 2001, July 2006 and November 2010.

The inter-annual variability of the winds will be considered in Sect. 3.3 where we will address 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 in the lower heights, 83–93 km where the winds are eastward (positive) in late autumn and early/mid-winter (May–August). The southern hemispheric winter-time winds maximise at heights of about 86 km in June and reach velocities of up to about $35\,\mathrm{m\,s^{-1}}$. Further, there is a second occurrence of eastward flow in December of most years, 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 flow is observed in Autumn during the month of March and reaches velocities of up to about 50 $\mathrm{m\,s^{-1}}$. 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 flow in the southern hemispheric winter months varies from year-to-year. This results in the height at which the winds reverse from eastward to westward also varying from year-to-year. For example, in 2002 the eastward flow maximises in July at heights of about 83 km, whereas in 2006 and 2009 the eastward flow maximises in June at heights of about 87 km. Further, in 2006 and 2009 the region of eastward flow 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 and also does not include 2002. The data from 2002 were not included for the following reasons; during February to April of 2002 there were unusually strong westward winds, reaching $\sim$70 $\mathrm{m\,s^{-1}}$ at a height of $\sim$84 km. The composite-year shows winds reaching $\sim$35 $\mathrm{m\,s^{-1}}$ at about the same height. The 2002 winds are considered outliers and would skew the composite-year plot if included, presenting winds reaching $\sim$42 $\mathrm{m\,s^{-1}}$ at this height. Including the zonal winds of 2002 also changed the structure of the wave in the observed height region. The zonal winds were increased by about a quarter for the months of February–April if the winds of 2002 were included in the composite-year analysis. Thus for these reasons the zonal winds of 2002 are not included in the composite-year plot. In Sect. 3.3 we will discuss this phenomena of strong westward winds in more detail and explain the importance of it for understanding the coupling of the dynamics of the atmosphere between the SQBO and the MSAO.

3.2 Comparison with HWM-07

We will now compare the climatological meridional and zonal winds observed Ascension Island by the radar with the winds predicted by the HWM-07 model. This model uses assimilated ground-based and satellite data and predicts results for a specified

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longitude, latitude and height. More details of the model can be found in Drob et al. (2008). 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 southern hemispheric summer-time winds to maximise in December–January 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 observations reveal 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.

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, the southern hemispheric winter-time 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 the autumnal equinox in the model reach about 35 $\mathrm{m\,s^{-1}}$, whereas our observations indicate winds of greater velocity, about 45 $\mathrm{m\,s^{-1}}$. More significantly, in the southern hemispheric winter-time, the eastward winds in the model reach up to $\sim 40\,\mathrm{m\,s^{-1}}$ whereas our observations indicate winds only about half that velocity.

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In summary, the HWM-07 winds are in reasonable agreement with the observations in the case of the zonal winds. However, the HWM-07 predicted peak meridional southern hemispheric winter-time southward flows are of similar velocity to those observed, but the model does not show the deep region of southward flow evident across the full range of heights observed by the radar.

3.3 SQBO and MSAO of the mean winds

As discussed earlier, it has been suggested that there is a link between the SQBO and the MSAO such that westerlies (eastward winds) occur through a deep height region of the stratosphere, the SQBO, and will modulate the MSAO in its first westward phase (e.g. Burrage et al., 1996; Garcia et al., 1997; Huang et al., 2006, 2008; Ratnam et al., 2008; Kumar et al., 2011). We will now investigate whether there is evidence of such coupling in our observations made over Ascension Island. We have used the Singapore radiosonde monthly-mean equatorial zonal winds at ~ 10 hPa to determine the phase of the QBO.

Figure 6 presents the Singapore radiosonde QBO wind data at heights of about 16–33 km (~ 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 $\mathrm{m\,s^{-1}}$.

Here we will use the vertical distribution of the amplitude of the MQBO, MSAO, SSAO, SQBO, and AO 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 MQBO on UARS/HRDI observations, the SAO on rocket observations from Ascension Island, and the AO from COSPAR International Reference Atmosphere.

We have investigated the suggestion by Baldwin et al. (2001) (as describe above) using our observational data and the SQBO winds to try to explain the coupling suggested by Baldwin et al. (2001).

Figure 7 compares the lowpassed radar zonal mesospheric winds at heights of about 84 km for the years 2004–2011 (filtered using a lowpass limit of 15 months). Also shown on the figure are the maximum eastward and westward 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 first 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 $\sim -90\,\mathrm{m\,s^{-1}}$). In fact, the MSAO winds at this time were more 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 no westward component.

To clarify this relationship, Fig. 8 shows the relationship between the maximum westward and eastward SQBO monthly-mean zonal winds, at heights of about 84 km and the zonal mean MSAO winds, 25–30 km, over Ascension Island for monthly-mean values of February to April, 2001–2011. The MSAO zonal wind height of about 84 km was chosen as this is where the winds were shown to maximise, as represented in Fig. 4 and compared with the maximum wind velocities of the SQBO at height of about 25–30 km. In the year 2002 the zonal mesospheric winds are much greater than the other years and the difference between the maximum wind speeds in the SQBO is much smaller than the other years. In 2002 we observed the strongest westward zonal winds, therefore during the first phase of the westward MSAO the atmosphere was observed to be modulated by the SQBO.

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Figure 9 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. With the data available we observed the link between the first westward phase of the MSAO in the zonal winds and the westward dominated SQBO winds.

Figure 10 shows a schematic of the proposed filtering mechanism for the westward winds in the first phase of the MSAO.

Considering all of the years of SQBO wind data available (1987–2011) it can be seen by the figure that the winds were favourable in 1993 and 1995.

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 et al., 2011). We observed the winds to reach velocities of greater than $\pm 12\,\mathrm{m\,s^{-1}}$, (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 $10\,\mathrm{m\,s^{-1}}$.

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 first 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 first westward phase of the SAO. Compared to those reported by Babu et al. (2011) the eastward winds maximise at heights of about 86 km during June and decrease rapidly above and below this height.

Babu et al. (2011) also reported on the zonal winds over Thumba (8.5° N, 77° E) at heights of about 82–98 km for March 2006–2009. They reported a clear SAO in the zonal winds that maximised in late northern hemispheric winter at the lower height and in the northern hemispheric summer at all heights. They observed the zonal winds to maximise at height of about 82 km. They reported winds to reach between about 20 and $-30\,\mathrm{m\,s^{-1}}$. The SAO of the winds is very similar to that which we observed. However, we observed the zonal winds, in general, to be stronger, specifically in 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. The zonal winds from the model show the SAO, but they are generally stronger during June and weaker in 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 the first westward phase of the MSAO to be modulated to large amplitudes by a strong eastward (westerly, positive) SQBO. This 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; Peña-Ortiz 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 first phase of the westward MSAO we would expect to observe modulations in the years 1993 and 1995, as shown

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in Fig. 9. 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 first 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. 9 and 10 we would expect to observe MSAO modulations in the first 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 why the eastward phase of the MSAO is unaffected by the SQBO; the stratospheric zonal winds during a eastward phase are far less than the previous stated phases speeds and the eastward MSAO phase being faster than the westward the SQBO can only modulate the westward spectrum of vertically-propagating equatorial waves. However, they noted the inter-annual variability of wave forcing in the real atmosphere was not accounted for in their model and this could explain the differences.

In contrast, 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° N, 76.9° E). They reported that on an average, ∼20–60 % and ∼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 height of below 90 km with wind velocities of about $20\,\mathrm{m\,s^{-1}}$ in the first cycle and about $5\,\mathrm{m\,s^{-1}}$ 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. They also used a co-located OH all-sky imager to observe the zonal momentum flux of short-period gravity waves at heights of about

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87 km. They found the westward phase in southern hemispheric winter and summer to correspond to the eastward phase of the MSAO, and eastward phase in spring and fall to correspond to the westward phase of the MSAO.

Finally, the results we have presented highlight the importance of wave/mean-flow interactions in modulating the momentum flux of gravity-waves in the stratosphere reaching the mesosphere.

5 Conclusions

The meridional winds are dominated by a AO where the winds are southward from April to October in most years observed. 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 modulated the MSAO in the zonal winds during the first westward phase when the SQBO winds also meet the criteria and were therefore not filter. The winds are required to be westward dominated, this allows the winds to propagate through the atmosphere to the mesosphere. This was shown in our observations or the year 2002 and previously observed 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 mesosphere in the first phase when the phase of the stratospheric QBO allows gravity waves of westward phase speed to reach the mesosphere.

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Low frequency dynamics over Ascension Island

K. A. Day and N. J. Mitchell

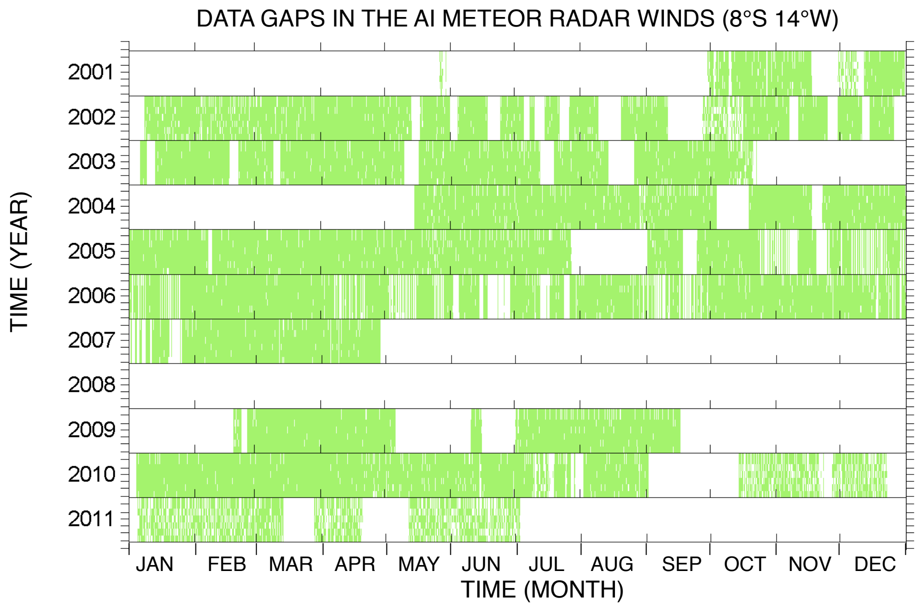

Fig. 1. A schematic showing the available data from the radar on Ascension Island from 2001–2011.

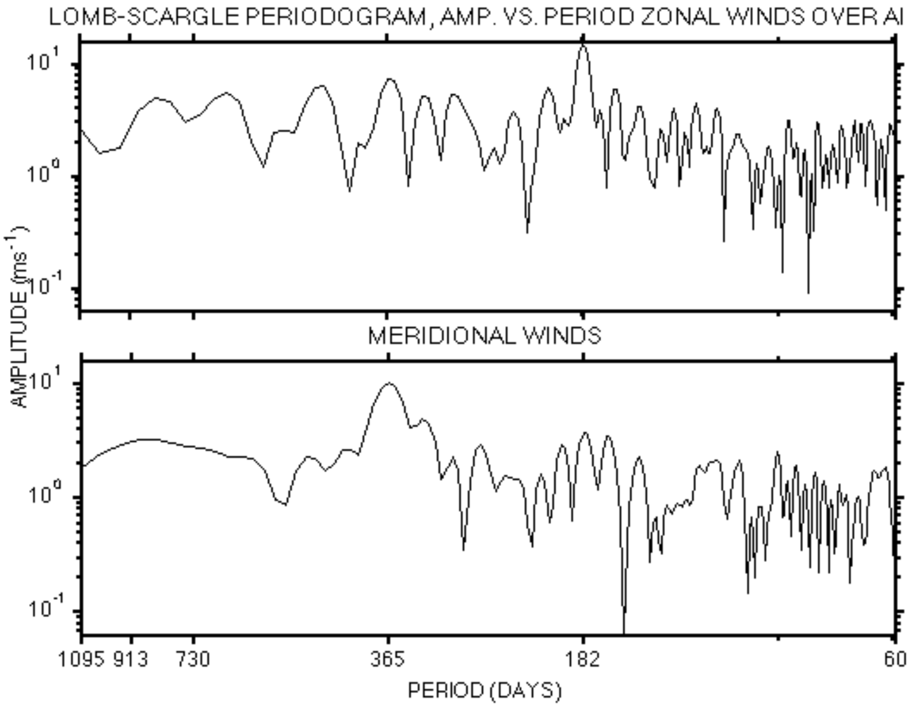

Fig. 2. A lomb-Scargle periodogram of the zonal and meridional winds at a height of about 90 km over Ascension Island for October 2001 to December 2011.

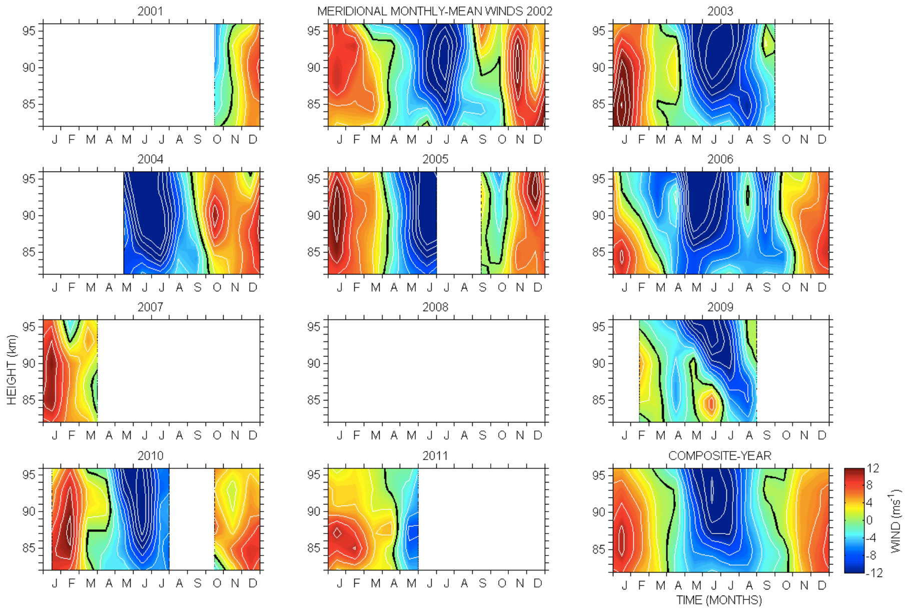

Fig. 3. Monthly-mean meridional winds over Ascension Island for the years 2001–2011 and the composite-years. The zero wind contour is indicated in black and the white contours are in steps of 2 m s^{-1}.

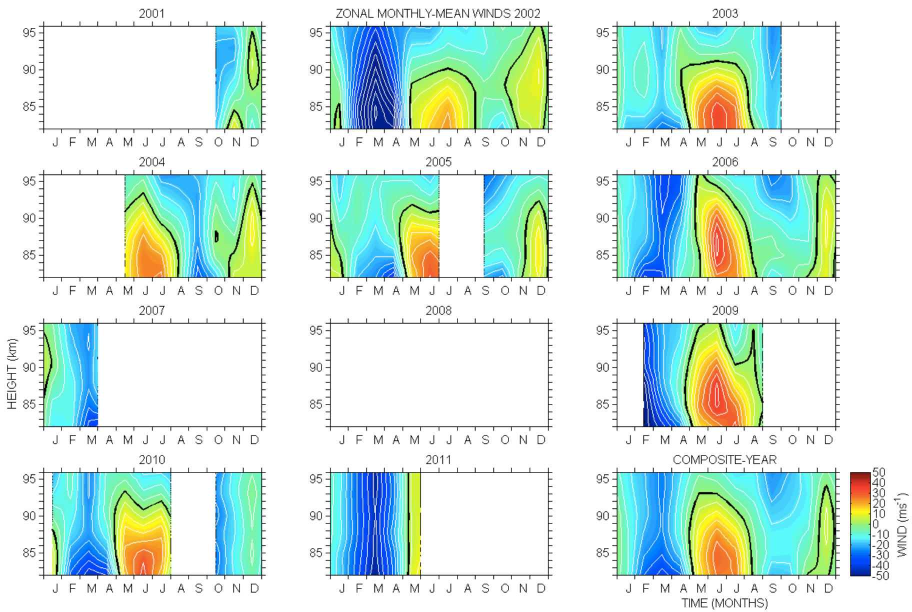

Fig. 4. Monthly-mean zonal winds over Ascension Island for the years 2001–2011 and a composite-year. The zero wind contour is indicated in black and the white contours are in steps of $5\,\mathrm{m\,s^{-1}}$.

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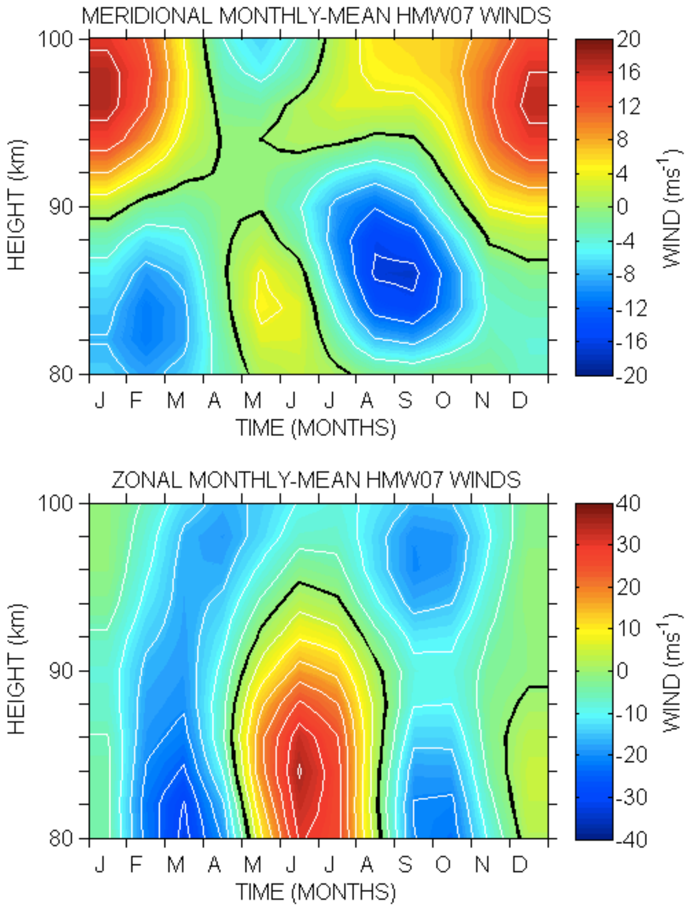

Fig. 5. Monthly-mean meridional and zonal winds over Ascension Island (7.94° S and 14.37° W), from the HWM-07 model. The zero wind line is indicated in black and the white lines indicate 5 $m\,s^{-1}$ steps.

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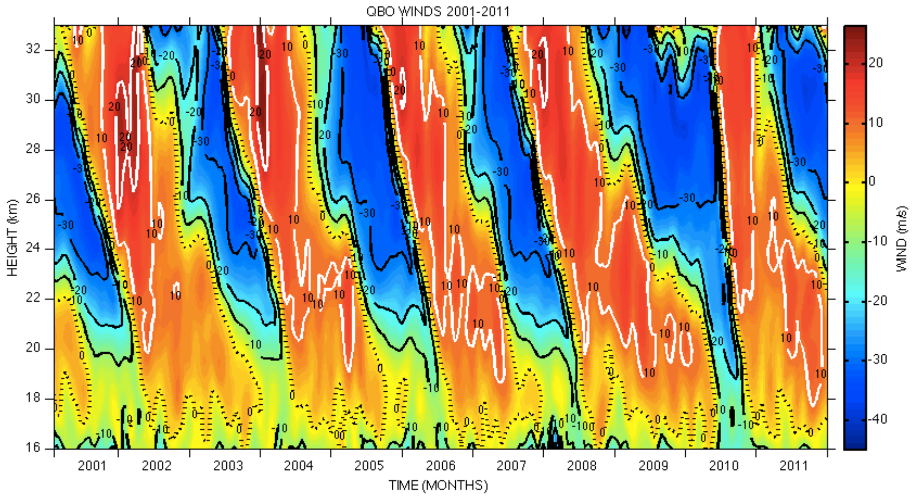

Fig. 6. The Singapore radiosonde QBO wind data from 2001 to 2011, with the contours steps of $10\,\mathrm{m\,s^{-1}}$.

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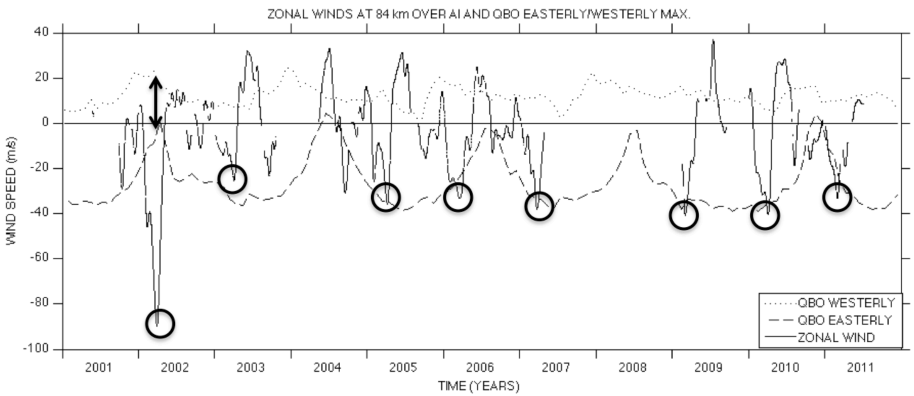

Fig. 7. Comparison of monthly zonal lowpassed radar winds over Ascension Island at 84 km (solid line) with the strongest eastward (short-dashed) and westward (long-dashed) QBO wind data at 25–30 km for February to April from 2001–2011. The double headed arrow shows the small difference between the mesospheric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

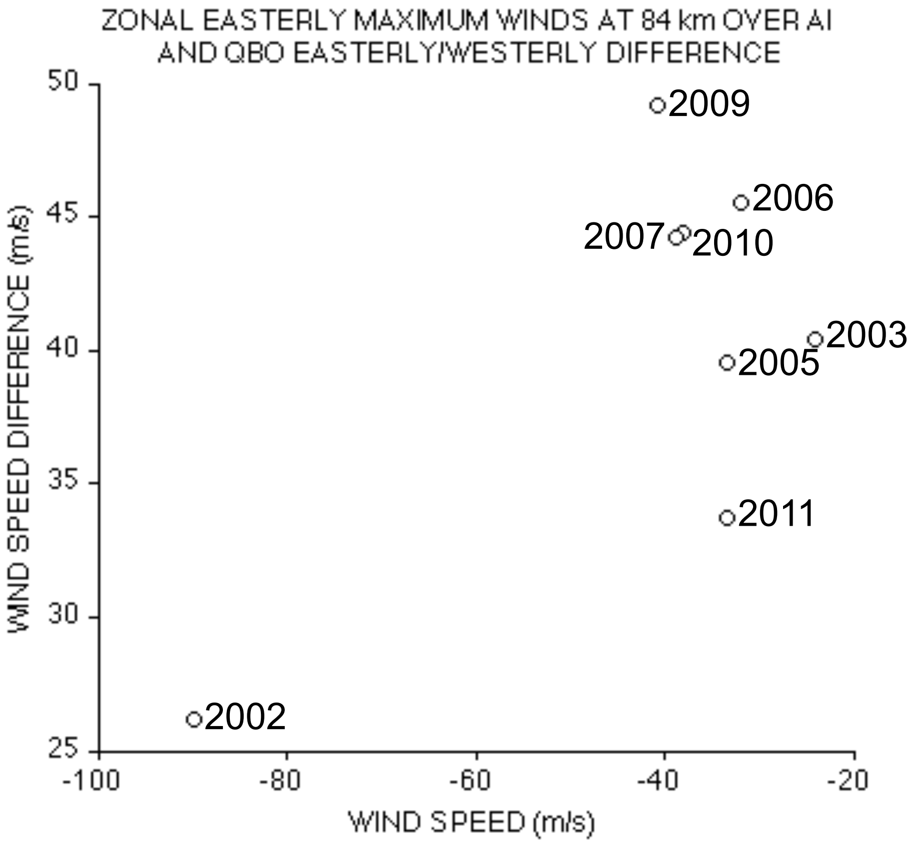

Fig. 8. Scatter of the zonal lowpassed radar winds over Ascension Island at 84 km for the first cycle of the SAO with the difference of the strongest eastward and westward QBO wind data at heights of about 25–30 km and from 2001–2011 for the months of February–April.

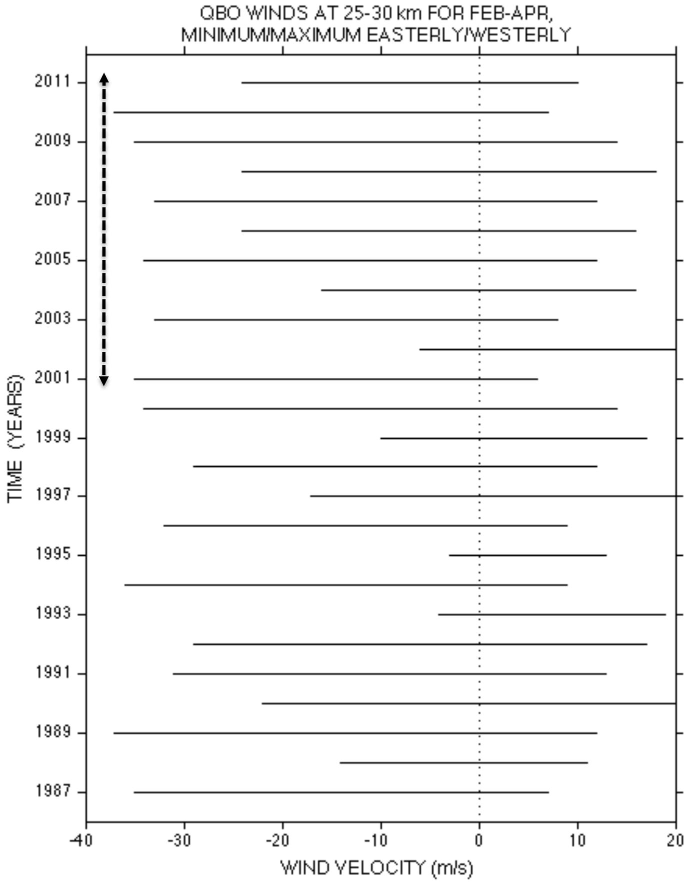

Fig. 9. The strongest eastward and westward QBO wind data at 25–30 km for February to April from 1987–2011 for the months of February–April. The dashed line shows duration of the zonal winds observed by the Ascension Island radar.

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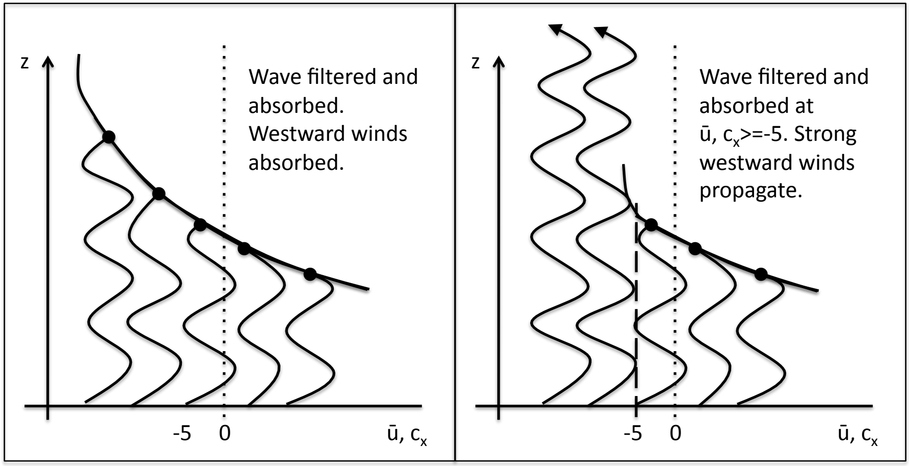

Fig. 10. A schematic diagram of the mechanism proposed by Garcia and Sassi (1999) for the filtering of gravity-wave by the westward winds in the first phase of the MSAO. The upward oscillations show wave propagating in the atmosphere, were the circle ended waves are filter and absorbed by the background flow and the arrow ended wave propagate into the atmosphere. The dashed line at −5 shows the critical wave velocity.

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