Citation for published version:
Day, KA & Mitchell, NJ 2013, 'Mean winds in the MLT, the SQBO and MSAO over Ascension Island (8° S, 14° W)', Atmospheric Chemistry and Physics, vol. 13, no. 18, pp. 9515-9523. https://doi.org/10.5194/acp-13-9515-2013

DOI:
10.5194/acp-13-9515-2013

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Link to publication

Atmos. Chem. Phys., 13, 9515–9523, 2013
www.atmos-chem-phys.net/13/9515/2013/
doi:10.5194/acp-13-9515-2013

Atmospheric Chemistry and Physics
Open Access

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

K. A. Day[1,2] **and N. J. Mitchell**[1]

[1]Centre for Space, Atmospheric and Oceanic Science, Department of Electronic and Electrical Engineering, the University of Bath, Bath, BA2 7AY, UK
[2]Met Office, Exeter, EX1 3PB, UK

Correspondence to: K. A. Day (k.a.day@bath.ac.uk)

Received: 7 January 2013 – Published in Atmos. Chem. Phys. Discuss.: 13 March 2013
Revised: 6 August 2013 – Accepted: 23 August 2013 – Published: 27 September 2013

Abstract. Mean winds in the mesosphere and lower thermosphere (MLT) over Ascension Island (8° S, 14° W) have been measured at heights of approximately 80–100 km by a meteor radar. The results presented in this study are from the interval October 2001 to December 2011. In all years, the monthly-mean meridional winds display a clear annual oscillation. Typically, these winds are found to be southward during April–October, when they reach velocities of up to about $-23\,\mathrm{m\,s^{-1}}$, and northward throughout the rest of the year, when they reach velocities up to about $16\,\mathrm{m\,s^{-1}}$. The monthly-mean zonal winds are generally westward throughout most of the year and reach velocities of up to about $-46\,\mathrm{m\,s^{-1}}$. However, eastward winds are observed in May–August and again in December at the lower heights observed. These eastward winds reach a maximum at heights of about 86 km with velocities of up to about $36\,\mathrm{m\,s^{-1}}$, but decay quickly at heights above and below that level. The mesospheric semi-annual oscillation (MSAO) is clearly apparent in the observed monthly-mean zonal winds. The winds in first westward phase of the MSAO are observed to be much stronger than in the second phase. The westward phase of the MSAO is found to maximise at heights of about 84 km with typical first-phase wind velocities reaching about $-35\,\mathrm{m\,s^{-1}}$. These meteor-radar observations have been compared to the HWM-07 empirical model. The observed meridional winds are found to be generally more southward than those of the model during May–August, when at the lower heights observed the model suggests there will be only weakly southward, or even northward, winds. The zonal monthly-mean winds are in generally good agreement, although in the model they are somewhat less westward than those observed. Throughout the observations there were eight occasions in which the first westward phase of the MSAO was observed. Strikingly, in 2002 there was an event in which the westward winds during the first phase of the MSAO were much stronger than normal and reached velocities of about $-75\,\mathrm{m\,s^{-1}}$. This event is explained in terms of a previously proposed mechanism in which the relative phasing of the stratospheric quasi-biennial oscillation (SQBO) and the MSAO allows an unusually large flux of gravity waves of large westward phase speed to reach the mesosphere. It is the dissipation of these gravity waves that then drives the MLT winds to the large westward velocities observed. It is demonstrated that the necessary SQBO–MSAO phase relationship did indeed exist during 2002, but not during the other years observed here. This demonstration provides strong support for the suggestion that extreme zonal-wind events during the MSAO result from the modulation of gravity-wave fluxes.

1 Introduction

The winds of the mesosphere and lower thermosphere (MLT) are known to be driven largely by the momentum deposited there by dissipating gravity waves launched from sources in the lower atmosphere. Further, the equatorial stratosphere and MLT host a number of unique dynamical phenomena. These include the fluctuations in wind associated with the stratospheric and mesospheric quasi-biennial oscillations (SQBO and MQBO), the stratospheric and mesospheric semi-annual oscillations (SSAO and MSAO), the mesospheric annual oscillation (MAO) and various intra-seasonal

Published by Copernicus Publications on behalf of the European Geosciences Union.

oscillations (ISOs) (e.g. Garcia and Sassi, 1999; Baldwin et al., 2001; Babu et al., 2011). Atmospheric gravity waves, propagating upwards from sources that are mostly in the troposphere, thus encounter background winds that vary significantly on the intra-seasonal, seasonal and inter-annual timescales as a result of these oscillations. The field of gravity waves that ultimately reach the MLT may thus have been significantly filtered by the winds encountered at lower heights. These filtered waves can, in turn, dissipate in the MLT where the momentum they deposit is significant in driving the mean winds. The result is that the winds and waves of the stratosphere and MLT form a strongly coupled system.

In the MLT, the seasonal variability of equatorial winds is significantly influenced by the MSAO. This oscillation usually has peak zonal wind amplitudes of about 40 m s^{-1}, and these are usually observed to maximise in the upper mesosphere at heights near 80–85 km (e.g. Burrage et al., 1996; Garcia et al., 1997; Huang et al., 2006, 2008; Ratnam et al., 2008; Kumar et al., 2011). However, an interesting property of the MSAO is that there have been a limited number of episodes reported when the westward winds of its first phase reached much larger amplitudes than those normally observed. In these anomalous events, the westward winds can reach values of the order of −80 m s^{-1}. Note that this behaviour occurs only in a minority of years, but has been reported as occurring in 1993 and 1995 (e.g. Garcia et al., 1997; Garcia and Sassi, 1999).

A number of suggestions have been made to explain this anomalous behaviour. The most persuasive explanation relies on the role of the SQBO and MSAO in filtering the field of gravity waves that reach the MLT. In particular, it is possible for a relative phasing to exist between the MSAO and SQBO that allows an increased flux of gravity waves of westward phase speeds (and thus westward momentum) to reach the upper mesosphere. The dissipation of these waves in the MLT then deposits anomalously large quantities of westward momentum into the mean flow. It is this additional westward momentum that then forces the larger observed westward winds in the MLT (e.g. Hitchman and Leovy, 1988; Delisi and Dunkerton, 1988; Garcia et al., 1997; Garcia and Sassi, 1999). Further support for this proposal was provided in the recent modelling study by Peña-Ortiz et al. (2010) in which they presented a change in the strength of the MSAO and the depth of atmosphere enhanced by the MSAO. These studies thus indicate that the variability of the MSAO is closely coupled to the relative phasing of the MSAO and SQBO.

Here, we present observations of the mean winds in the MLT over Ascension Island (8° S, 14° W) measured by a meteor radar over the interval 2001–2011. A particular advantage of observations made by the Ascension Island meteor radar is that they offer the only low-latitude ground-based observations of MLT winds available at longitudes between eastern Brazil and southern India. We use the observations to determine climatological winds in the MLT over Ascension Island, and we compare the observed monthly-mean winds with those of the HWM-07 empirical model. We also use the observations to investigate an anomalous MSAO event that was observed in 2002 and consider the role of the SQBO and MSAO in its forcing.

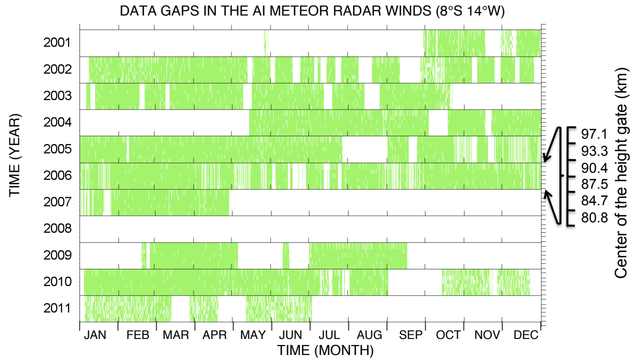

Fig. 1. A schematic showing the available data from the radar on Ascension Island from 2001 to 2011.

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.

The radar measures horizontal winds over the approximate height range 80–100 km with a typical height and time resolution of ∼3 km and 1 h, respectively. A more complete description of the analysis used to derive the winds can be found in Mitchell et al. (2002).

3 Results

To investigate the low-frequency (∼60–500 days) components in the radar wind data over Ascension Island, we present in Fig. 2 a Lomb–Scargle periodogram (Scargle, 1989) 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,

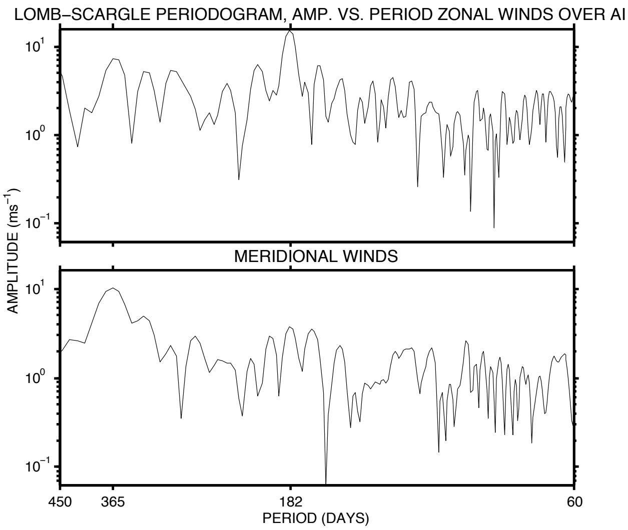

Fig. 2. A Lomb–Scargle periodogram of the zonal and meridional winds at a height of about 90 km over Ascension Island for October 2001 to December 2011.

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 analysing the side-lobe peaks and calculating the QBO period that they would be modulated by. From Fig. 2 and using the following equation, it was found that frequency of the modulating wave was calculated to be about 25 months, approximately the QBO frequency: $1/\omega_1 - 1/\omega_2 = 1/\omega_{QBO}$, 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. Therefore the QBO does seem to modulate the amplitude of the SAO as the broadening of the peak as suggested by the side lobes on 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 to August and northward (positive) from December to February. From April–October the winds are generally observed to be strongest at heights of ~ 93 km and to reach velocities more negative than $-12\,\mathrm{m\,s^{-1}}$ regularly. In contrast, during November–March the winds are positive in the upper heights observed, reaching velocities of $\sim 12\,\mathrm{m\,s^{-1}}$ in most years. Two successive maxima are observed and peak in November/December at heights of ~ 91 km and again in January at heights of ~ 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 $35\,\mathrm{m\,s^{-1}}$. Further, there is a second occurrence of strong eastward winds 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 winds were observed during March–May, and in March winds reach 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 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 were available. The composite year shows zonal winds reaching $\sim 40\,\mathrm{m\,s^{-1}}$ at about a 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

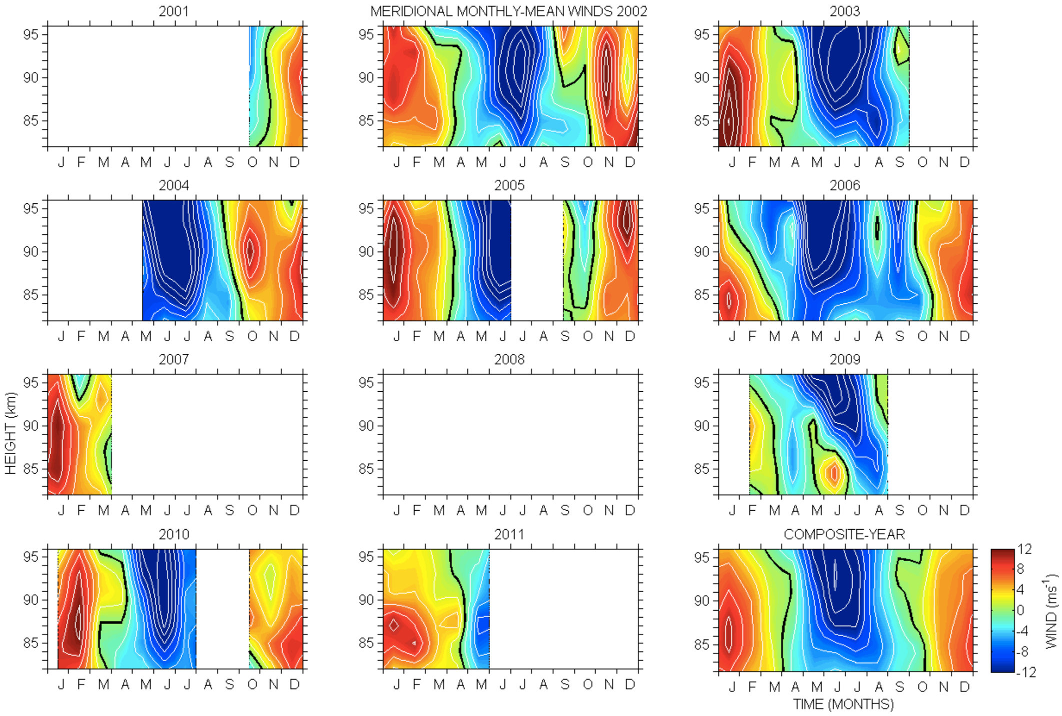

Fig. 3. Monthly-mean meridional winds over Ascension Island for the years 2001–2011 and the composite years. The zero wind contour is indicated in black, and the white contours are in steps of $2\,\mathrm{m\,s^{-1}}$.

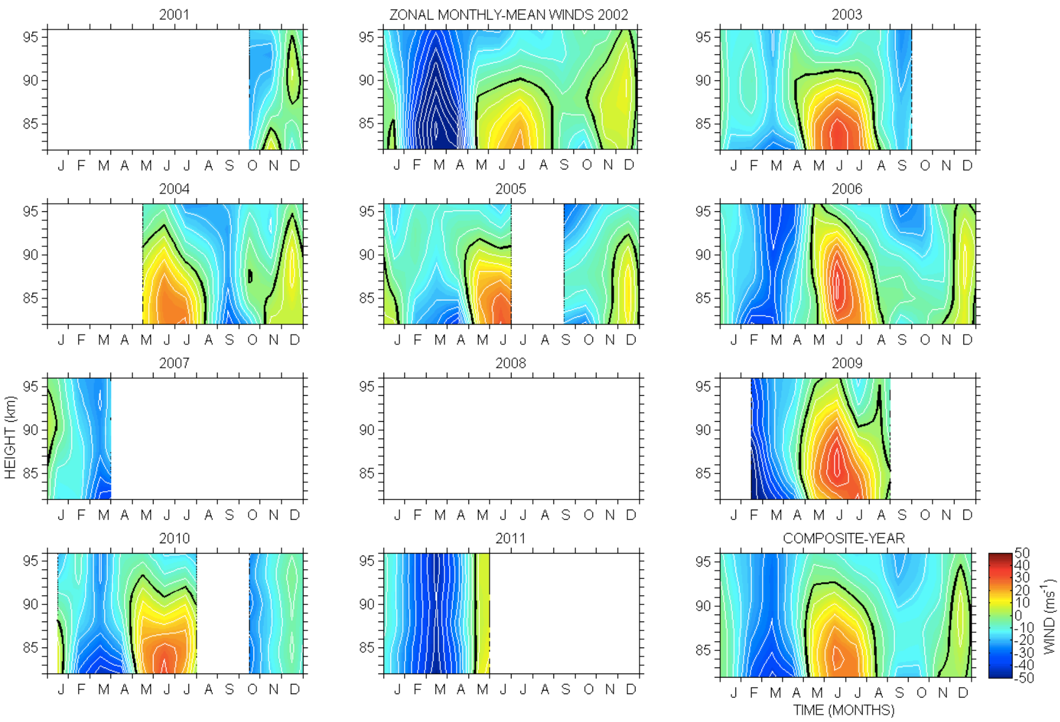

Fig. 4. Monthly-mean zonal winds over Ascension Island for the years 2001–2011 and a composite year. The zero wind contour is indicated in black, and the white contours are in steps of $5\,\mathrm{m\,s^{-1}}$.

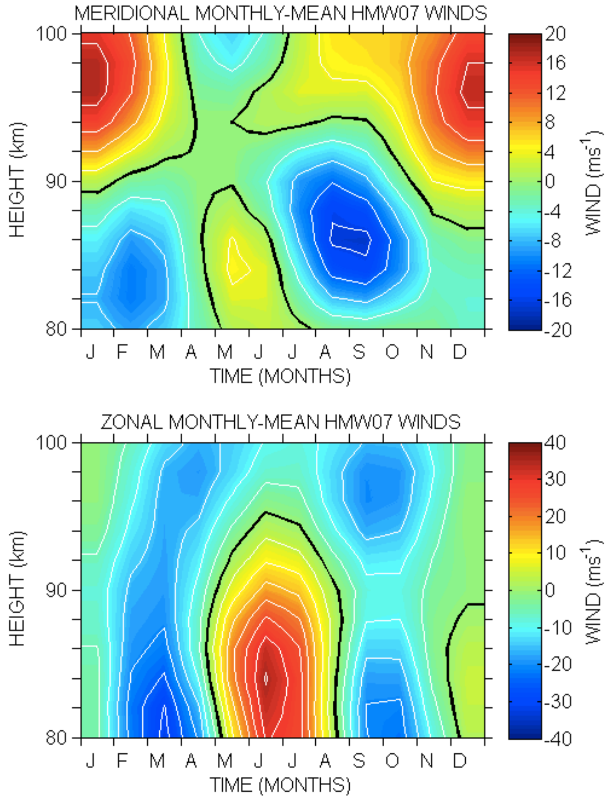

Fig. 5. Monthly-mean meridional and zonal winds over Ascension Island (7.94° S and 14.37° W), from the HWM-07 model. The zero wind line is indicated in black, and the white lines indicate 5 m s^{-1} steps.

will discuss this phenomenon 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 near 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 only to 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 to 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 to October at all heights observed and is strongest at the upper heights in June.

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 to infer the winds. The composite observations from the radar presented here are from the 11-year period of 2001–2011 with one ground-based instrument, whereas the model was developed using 50 yr of data from many satellite, rocket, and ground-based instruments to infer the winds from 1956 to 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 timescales. 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 the 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, the model does not show the deep region of southward winds evident across the full range of heights observed by the radar.

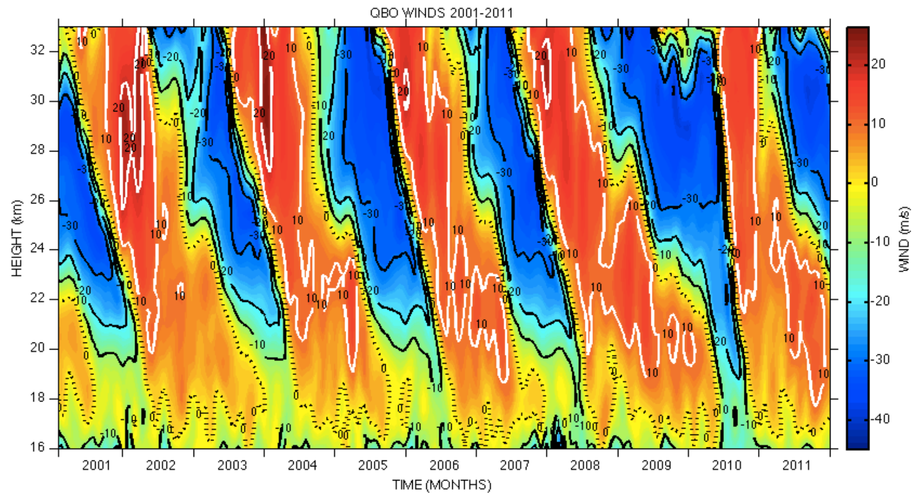

Fig. 6. The Singapore radiosonde QBO wind data from 2001 to 2011, with the contours steps of 10 m s^{-1} (http://www.cdc.noaa.gov/data/correlation/qbo.data).

3.2 SQBO and MSAO of the mean winds

Garcia et al. (1997) have 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 to 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 ∼ 10 hPa to determine the phase of the QBO in the stratosphere.

Monthly-mean zonal equatorial wind data at heights of ∼ 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).

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 m s^{-1}.

Baldwin et al. (2001) presented the vertical distribution amplitude of the MSAO and SQBO at the Equator. Here we will use the peak amplitude heights presented by Baldwin to investigate the MSAO and SQBO further. Baldwin et al. (2001) used observations from over Ascension Island and reported the SQBO to be observed from about 16 to 40 km and to peak at heights of about 25 km reaching velocities of about 20 m s^{-1}. This agrees with the observations presented in Fig. 6 and with 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 were low-pass filtered with a cut-off frequency of 60 days, for reasons presented previously. Figure 7 presents the low-pass filtered data for the years 2001–2011. Also shown in 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.

Now we will consider the stratospheric winds at times when simultaneous mesospheric winds were recorded. It can be seen that westward monthly-mean equatorial stratospheric winds were very weak (actually near-zero) only in 2002, during the westward phase of the MSAO. During this interval, February–April 2002, the stratospheric winds had no significant westward component and were simultaneously accompanied by the strongest westward mesospheric winds observed in the entire set of meteor radar observations (speeds of ∼ −90 m s^{-1}). In fact, the MSAO winds during 2002 were more than twice as strong as the winds observed during any other time of the westward phase of the MSAO. In other words, for those times when the radar data were available, the strongest westward MSAO winds occurred only 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 allow 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

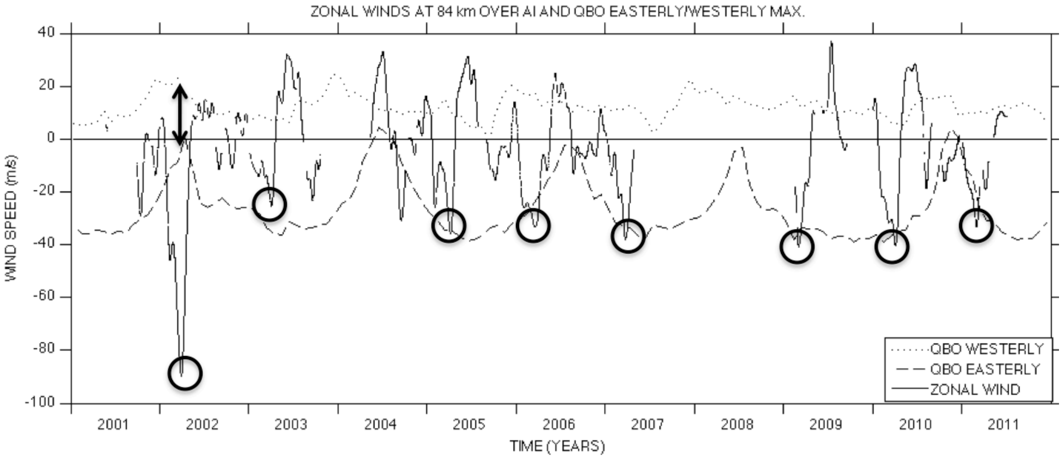

Fig. 7. Comparison of monthly zonal low-passed (60-day cut-off) radar winds over Ascension Island at 84 km (solid line) with the strongest eastward (short-dashed) and westward (long-dashed) QBO wind data at 25–30 km for February to April from 2001 to 2011. The double-headed arrow shows the small difference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

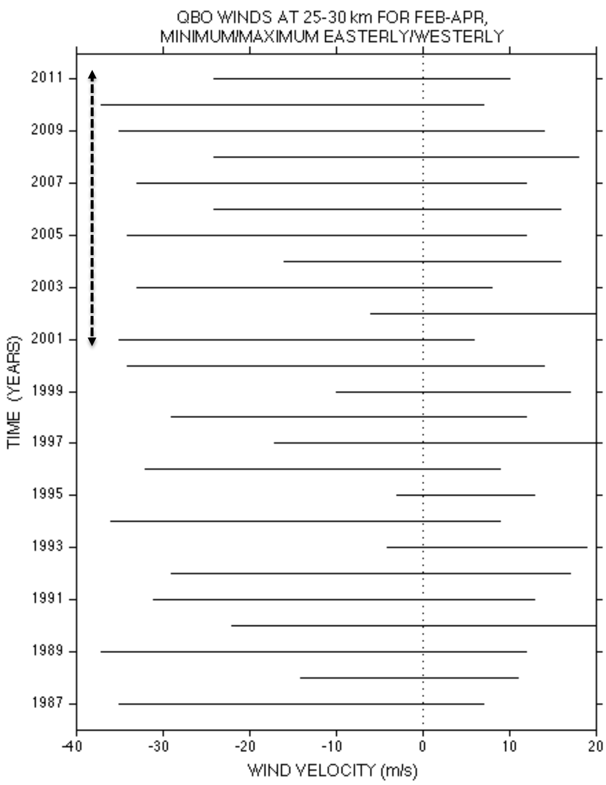

Fig. 8. The strongest eastward and westward QBO wind data at 25–30 km for February to April from 1987 to 2011 for the months of February–April. The dashed line shows duration of the zonal winds observed by the Ascension Island radar.

2002. Note that in other years (e.g. 2004) the winds may seem favourable. 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. The radiosonde data from 1897 to 2011 have 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 to 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. 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. 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; Peña-Ortiz et al., 2010). Our observations of this dramatic and very unusual event support the hypothesis of the strong coupling of the SQBO and MSAO. This is one of a handful of observations and adds support to the reports by Garcia et al. (1997).

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

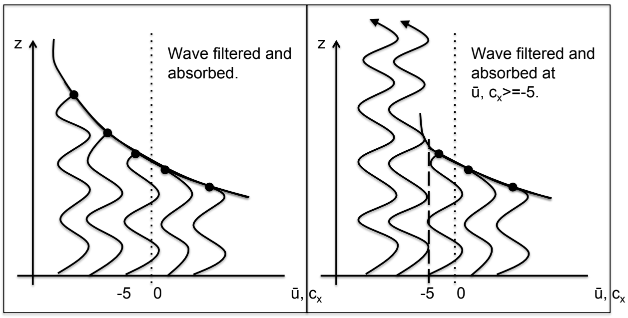

Fig. 9. A schematic diagram of the mechanism proposed by Garcia and Sassi (1999) for the filtering of gravity wave by the westward winds of the MSAO. The upward oscillations show wave propagating in the atmosphere, where the circle-ended waves are filtered and absorbed by the background flow and the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

right-hand panel shows the waves being allowed to propagate upwards freely. Free upward propagation can occur when the background flow is less than the critical phase speed. Thus the gravity waves can reach the mesosphere and modulate the MSAO. This was observed here during February to April of 2002 and in 1993 and 1995 by Garcia et al. (1997).

4 Discussion

The monthly-mean zonal and meridional winds we observed over Ascension Island are generally similar to those reported from other low-latitude sites across a wide range of differing longitudes. In particular, the seasonal cycle in meridional and zonal winds resulting from the superposition of MAO and SAO appears to be a common feature of observations of the equatorial MLT (e.g. Hitchman and Leovy, 1988; Delisi and Dunkerton, 1988; Allen and Vincent, 1995; Burrage et al., 1996; Garcia et al., 1997; Garcia and Sassi, 1999; Baldwin et al., 2001; Huang et al., 2006; Antonita et al., 2008; Huang et al., 2008; Ratnam et al., 2008; Babu et al., 2011; Kumar et al., 2011; Li et al., 2012). Setting aside the anomalous zonal-wind events of the sort described above and discussed below, the relatively small differences between these various observations probably result from a combination of inter-annual variability when observations are made in different years and measurement biases between different techniques, such as meteor radar and medium-frequency radar.

The zonal winds of the HWM-07 model are in reasonable agreement with our radar observations. However, the model indicates zonal wind speeds to be larger than we observed in June and then smaller throughout the rest of the year. In contrast, the HWM-07 meridional model winds do not reproduce the clear seasonal changes observed by the radar, where the winds are southward from April to October and northward for the rest of the year. Further, the model's northward flows are generally stronger and maximise at heights of about 97 km, whereas the observed northward flows maximise somewhat lower, at heights of about 86 km, and persist northward through the height region observed.

The most unusual event in our observations is the increased amplitude of the MSAO during March 2002 when, during the MSAO's first westward phase, the winds reached speeds more than twice as large as in the other years observed. The relative phasing of the winds of the SQBO and MSAO during this event indicates that it is similar in character to those reported in a number of earlier studies and proposed to originate during times when the stratospheric winds at low latitudes do not have strong westward velocities at any height. These winds then allow a large flux of westward-propagating gravity waves to reach the mesosphere, where their dissipation then deposits westward momentum into the mean flow and so drives the large westward winds observed in the MLT (e.g. Burrage et al., 1996; Garcia et al., 1997; Garcia and Sassi, 1999; Huang et al., 2008; Peña-Ortiz et al., 2010). This phenomenon is a striking demonstration of the importance of gravity waves in driving the winds of the mesosphere.

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 are found to be dominated by an annual oscillation in which during most years the winds are southward from April to October and northward at other times. In contrast, the zonal winds are found to be dominated by a semi-annual oscillation in which the winds are westward around the equinoxes but eastward at other times. We have compared our observed meridional and zonal winds to the HWM-07 model. The model generally predicts the meridional winds to be more northward than observed. Further, the well-defined alternating southward/northward pattern of the observed winter/summer winds is not well represented in the model. The zonal winds of the model are generally more similar to the observed winds, although they tend to be rather more eastward than observed.

A striking event in 2002, during which the westward winds of the first phase of the MSAO were observed to be much stronger than normal, has been explained in terms of a modulation by the winds of the SQBO of the field of gravity waves reaching and then dissipating in the mesosphere (a mechanism first proposed by Garcia et al. (1997)). The SQBO winds appear to allow a strong flux of gravity waves with westward phase speeds to reach the mesosphere. When these waves then dissipate, the westward momentum they deposit into the mean flow drives the large westward flow observed. The particular SQBO phasing required did indeed occur during 2002, and our observations thus provide strong support for the mechanism proposed by Garcia et al. (1997) and indicate a strong coupling between the winds of the mesosphere and the SQBO.

Acknowledgements. We would acknowledge and thank NERC for funding the project. We would also like to thank and acknowledge editor and referees for their support and advice with the publication of the paper.

Edited by: T. von Clarmann

References

Allen, S. J. and Vincent, R. A.: Gravity wave activity in the lower atmosphere: Seasonal and latitudinal variations, J. Geophys. Res., 100, 1327–1350, 1995.

Antonita, T. M., Ramkumar, G., Kumar, K. K., and Deepa, V.: Meteor wind radar observations of gravity wave momentum fluxes and their forcing toward the Mesospheric Semiannual Oscillation, J. Geophys. Res., 113, p. 12, doi:10.1029/2007JD009089, 2008.

Babu, V. S., Kumar, K. K., John, S. R., Subrahmanyam, K. V., and Ramkumar, G.: Meteor radar observations of short-term variability of quasi 2 day waves and their interaction with tides and planetary waves in the mesosphere–lower thermosphere region over Thumba (8.5° N, 77° E), J. Geophys. Res., 116, doi:10.1029/2010JD015390, 15 pp., 2011.

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., Holton, J. R., Alexander, M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Kinnersley, J. S., Marquardt, C., Sato, K., and Takahashi, M.: The quasi-biennial oscillation, Rev. Geophys., 39, 179–229, 2001.

Burrage, M. D., Vincent, R. A., Mayr, H., Skinner, W. R., Arnold, N. F., and Hays, P. B.: Long-term variability in the equatorial middle atmopshere zonal wind, J. Geophys. Res., 101, 12847–12854, 1996.

Delisi, D. and Dunkerton, T.: Equatorial semiannual oscillation in zonally averaged temperature observedby the Nimbus 7 SAMS and LIMS, J. Geophys. Res., 93, 3899– 3904, 1988.

Garcia, R. R. and Sassi, F.: Modulation of the mesospheric semiannual oscillation by the quasibiennail oscillation, Earth Planets Space, 51, 563–569, 1999.

Garcia, R. R., Dunkerton, T. J., Lieberman, R. S., and Vincent, R. A.: Climatology of the semiannual oscillation of the tropical middle atmopshere, J. Geophys. Res., 102, 26019–26032, 1997.

Hitchman, M. H. and Leovy, C. B.: Estimation of the Kelvin wave contribution to the Semiannual Oscillation, J. Atmos. Sci., 45, 1462–1475, 1988.

Hocking, W. K., Fuller, B., and Vandepeer, B.: Real-time determination of meteor-related parameters utilizing modem digital technology, J. Atmos. and Solar- Terr. Phys., 63, 155–160, 2001.

Huang, F. T., Mayr, H. G., Reber, C. A., Russell, J. M., Mlynczak, M., and Mengel, J. G.: Stratospheric and mesospheric temperature variations for the quasi-biennial and semiannual (QBO and SAO) oscillations based on measurements from SABER (TIMED) and MLS (UARS), Ann. Geophys., 24, 2131–2149, doi:10.5194/angeo-24-2131-2006, 2006.

Huang, F. T., Mayr, H., Reber, C. A., Russell III, J. M., Mlynczak, M. G., and Mengel, J. G.: Ozone quasi-biennial oscillations (QBO), semiannual oscillations (SAO), and correlations with temperature in the mesosphere, lower thermosphere, and stratosphere, based on measurements from SABER on TIMED and MLS on UARS, J. Geophys. Res., 113, 15 pp., doi:10.1029/2007JA012634, 2008.

Kumar, K. K., Swain, D., John, S. R., and Ramkumar, G.: Simultaneous observations of SAO and QBO in winds, temperature and ozone in the tropical middle atmosphere over Thumba (8.5° N, 77° E), Clim. Dynam., 37, 1961–1973, 2011.

Li, T., Liu, A. Z., Lu, X., Li, Z., Franke, S. J., Swenson, G. R., and Dou, X.: Meteor-radar observed mesospheric semi-annual oscillation (SAO) and quasi-biennial oscillation (QBO) over Maui, Hawaii, J. Geophys. Res., 117, doi:10.1029/2011JD016123, 9 pp., 2012.

Mitchell, N. J., Pancheva, D., Middleton, H. R., and Hagan, M. E.: Mean winds and tides in the Artic mesosphere and lower thermosphere, J. Geophys. Res.-Space Phys., 107, 14 pp., 2002.

Peña-Ortiz, C., Schmidt, H., Giorgetta, M. A., and Keller, M.: QBO modulation of the semiannual oscillation in MAECHAM5 and HAMMONIA, J. Geophys. Res., 115, 19 pp., doi:10.1029/2010JD013898, 2010.

Ratnam, M. V., Kumar, G. K., Murthy, B. V. K., Patra, A. K., Rao, V. V. M. J., Rao, S. V. B., Kumar, K. K., and Ramkumar, G.: Long-term variability of the low latitude mesospheric SAO and QBO and their relation with stratospheric QBO, Geophys. Res. Lett., 35, 5 pp., doi:10.1029/2008GL035390, 2008.

Scargle, J. D.: Studies in astronomical time series analysis. III. Fourier transforms, autocorrelation and cross-correlation functions of unevenly spaced data, Astrophys. J., 343, 874–887, 1989.