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Gravity-wave momentum fluxes in the mesosphere over Ascension Island (8° S, 14° W) and the anomalous zonal winds of the semi-annual oscillation in 2002

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Abstract. Anomalously strong westward winds during the first phase of the equatorial mesospheric semi-annual oscillation (MSAO) have been attributed to unusual filtering conditions producing exceptional gravity-wave fluxes. We test this hypothesis using meteor-radar measurements made over Ascension Island (8° S, 14° W). An anomalous wind event in 2002 of $-85.5\,\mathrm{ms}^{-1}$ occurred simultaneously with the momentum fluxes of high-frequency gravity waves reaching the largest observed westward values of $-29\,\mathrm{m}^2\,\mathrm{s}^{-2}$ and strong westward wind accelerations of $-510\,\mathrm{ms}^{-1}\,\mathrm{day}^{-1}$. However, despite this strong wave forcing during the event, no unusual filtering conditions or significant increases in wave-excitation proxies were observed. Further, although strong westward wave-induced accelerations were also observed during the 2006 MSAO first phase, there was no corresponding simultaneous response in westward wind. We thus suggest that strong westward fluxes/accelerations of high-frequency gravity waves are not always sufficient to produce anomalous first-phase westward MSAO winds and other forcing may be significant.

Keywords. Meteorology and atmospheric dynamics (middle atmosphere dynamics; waves and tides)

1 Introduction

The general circulation and structure of the mesosphere is strongly influenced by gravity waves launched from sources at lower heights. The waves dissipate in the mesosphere and the divergence in the vertical flux of horizontal momentum carried by the waves results in a body force that accelerates the mean flow. In particular, this acts to close the mid-latitude zonal jets, force a pole-to-pole meridional circulation and reverse the solstitial meridional temperature gradients, such that the summer polar mesosphere is the coldest place on Earth, and drives a number of planetary-scale oscillations such as the stratospheric quasi-biennial oscillation (QBO) (e.g. Fritts and Alexander, 2003).

In the equatorial mesosphere, the principal mode of seasonal wind variability is the mesospheric semi-annual oscillation (MSAO). In most years, the MSAO displays the strongest westward winds at heights of near 80 km shortly before the equinoxes and the strongest eastward winds around 85 km near the solstices. This oscillation is out of phase with the stratospheric semi-annual oscillation (SSAO) (e.g. Burrage et al., 1996; Garcia et al., 1997; Huang et al., 2008; Ratnam et al., 2008; Peña-Ortiz et al., 2010; Kumar et al., 2011; Day and Mitchell, 2013).

However, despite the large amplitude of the MSAO, the details of its forcing remain unclear, although it is thought that the oscillation is entirely driven by waves. In particular, the majority of MSAO forcing appears to come from the dissipation of ascending gravity waves that have been selectively filtered by the eastward and westward winds of the SSAO. In this process, westward SSAO winds allow eastward-propagating waves to reach the mesosphere where their dissipation then forces eastward winds. Similarly, when the SSAO winds are eastward, westward-propagating waves reach the mesosphere where their dissipation results in a westward forcing of mesospheric winds, thus driving the MSAO as an oscillation that is out of phase with the SSAO (e.g. Dunkerton, 1982; Hitchman and Leovy, 1988).

The balance of forcing between high-frequency and inertia gravity waves is uncertain, although Antonita et al. (2008) used meteor radar observations of the mesosphere to conclude that high-frequency gravity waves contribute 20–70 % of the overall forcing of the MSAO over southern India. Other studies have suggested that near the solstices the MSAO receives significant additional forcing from the mean meridional advection of zonal winds and Eliassen–Palm flux divergence associated with planetary waves, in particular, the 2-day wave (Richter and Garcia, 2006). Near the equinoxes, limited additional forcing may also come from the dissipation of the migrating diurnal tide (Lieberman and Hays, 1994).

A striking feature of the MSAO is that in some years the winds of the first westward phase of the oscillation reach much larger amplitudes than normal, with westward winds as strong as $-80\,\mathrm{m\,s^{-1}}$. These events are clearly different from the usual behaviour of the MSAO (e.g. Garcia et al., 1997; Day and Mitchell, 2013).

It has been suggested that these anomalous events occur when the relative phasing of the QBO and SSAO produces a selective filtering that allows an excess of westward-propagating gravity waves to reach the mesosphere, thus driving stronger westward winds than normal and thus modulating the MSAO. However, only the westward phase of the MSAO is modulated, due to the westward QBO winds being stronger than the eastward QBO winds and also because the Kelvin waves that drive the eastward phase of the MSAO have larger phase velocities and so are in any case less subject to filtering (e.g. Garcia et al., 1997; Garcia and Sassi, 1999).

It is thus clear that gravity waves play an important and probably dominant role in the forcing of the MSAO, and increased westward fluxes may explain the anomalous westward first-phase events. There is thus an essential need to measure gravity-wave momentum fluxes in attempts to understand the MSAO. Despite this, it is notoriously difficult to measure gravity-wave variances, momentum fluxes and accelerations in the mesosphere over the extended intervals necessary. Recently, however, techniques have been developed that allow meteor radars to make statistical measurements of gravity waves at mesospheric heights of ~ 80–100 km (e.g. Hocking, 2005; Fritts et al., 2012). Crucially, these techniques allow estimates of gravity-wave momentum fluxes and their divergence, which then allows estimates to be made of the acceleration of the mean flow by the waves. Note that this method primarily represents the fluxes of high-frequency gravity waves of periods less than ~ 2 h (Placke et al., 2015).

Here, for the first time, we apply these techniques to data recorded by a meteor radar on Ascension Island (8° S, 14° W). We use these data to investigate the relationship between the fluxes of gravity waves, their forcing of the mean flow and the winds of the MSAO. In particular, we will concentrate on the role of gravity waves in forcing an anomalous first-phase westward flow event observed in February/March of 2002. Section 2 describes the radar, data set and analysis used. Section 3 presents our observations, and Sect. 4 interprets these in terms of wave forcing of the MSAO during this particular event.

2 Data and data analysis

Measurements of mesospheric winds and high-frequency gravity-wave fluxes were made using the Ascension Island meteor radar (8° S, 14° W). The radar is a commercially produced standard Skiymet system. It operated in an all-sky configuration with a peak power of 12 kW up until 2007, after which it was switched to 6 kW. It transmits at a frequency of 43.5 MHz. The data used in this study are for the period January 2002 to December 2007. The radar operated largely uninterrupted during this interval except for a period in late 2003/early 2004.

Although not originally designed to measure momentum fluxes, standard Skiymet systems nevertheless have a proven ability to do so (e.g. Hocking, 2005; Fritts et al., 2010, 2012; Vincent et al., 2010; Andrioli et al., 2013; de Wit et al., 2014; Placke et al., 2015), albeit with a lower resolution than advanced systems specifically designed for this task (Fritts et al., 2012). The ability to estimate gravity-wave momentum fluxes ultimately relies on being able to separate the contributions to the radial velocity of each individual meteor made by gravity waves from the contributions made by background winds, tides and planetary waves. Incomplete removal of the background will thus tend to amplify the estimates of momentum flux, and so such estimates are likely to be an upper bound. A particular problem at low latitudes is that the diurnal tide can reach very large amplitudes in the mesosphere. Thus, if the diurnal tide is not fully accounted for, it will tend to lead to over-estimation of the momentum flux.

In this study, the local background wind for each meteor, including the tidal wind, was estimated and then removed by linearly interpolating the 2-hourly-mean background wind to the time and height of each meteor. The method we use here is an alternative to that of Andrioli et al. (2013), who employed a composite-day analysis to reduce the effects of tidal contamination.

Monthly-mean estimates of the zonal and meridional momentum fluxes, $<\overline{\boldsymbol{u'w'}}>$ and $<\overline{\boldsymbol{v'w'}}>$ respectively, are made in six height gates: 78–83, 83–86, 86–89, 89–92, 92–95 and 95–100 km, which are centred on 82, 85, 88, 90, 93 and 96 km respectively. A reduced number of meteors are detected in the uppermost and lowermost height gates, which makes flux estimates less reliable in these height gates. The change of the vertical flux of zonal momentum with height, z, combined with estimates of atmospheric density, ρ, from the US Standard Atmosphere (1976), thus provides an estimate of the zonal acceleration of the mean flow, $\boldsymbol{a}_{\mathrm{GW}}$, due to the dissipation of gravity waves (e.g. Fritts and Vincent, 1987) as per Eq. (1).

$$\boldsymbol{a}_{\mathrm{GW}} = -\frac{1}{\rho}\frac{\partial(\rho < \overline{\boldsymbol{u'w'}} >)}{\partial z} \tag{1}$$

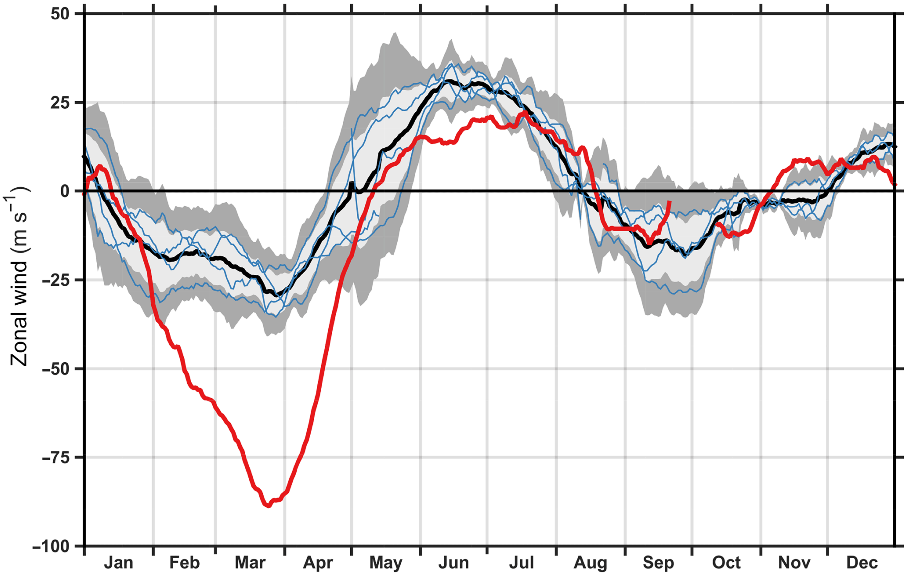

Figure 1. Monthly-mean zonal wind over Ascension Island at a height of 85 km altitude during 2002–2007. The thin blue lines are the zonal wind for each of the years 2003–2007, and the mean for this period is shown by the thick black line. The light and dark grey filled areas show 1 and 2 standard deviations from the mean respectively. The thick red line shows the zonal wind for 2002.

A significant source of error on the estimates of wind, momentum flux and acceleration values is the zenith angle. Here we estimate errors in the radar measurements as follows. We assume a 1.5° error on the zenith angle (Hocking, 2005) and add this error to individual meteor zenith angles scaled by a pseudo-random Gaussian distribution centred on zero. Likewise, the error on the radial velocity of each meteor, which is the standard deviation of the values calculated from each antenna pair, is also added to the radial velocity of each meteor. The analysis was then run independently 25 times; the standard deviation of the wind, momentum flux and acceleration at each time is used as an estimation of the error on the winds, momentum fluxes and accelerations calculated in the original analysis.

Ascension Island is a low-latitude oceanic site, so it can be assumed that most of the observed high- and mid-frequency gravity waves in the mesosphere will have been generated by convective sources within a few hundred kilometres of the island. In this study we assume that the majority of gravity waves that reach the mesosphere are from tropospheric sources rather than in situ generation (Fritts and Alexander, 2003). Here, NOAA's outgoing long-wave radiation (OLR) and NASA's 3B42 V7 derived Tropical Rainfall Measurement Mission (TRMM) data sets are used as proxies for this convective activity and rainfall, respectively, on the assumption that these will provide a crude measure of the strength of gravity-wave excitation. These data sets are frequently used for this purpose (e.g. Alexander et al., 2008; Wright and Gille, 2011; Wright et al., 2013). Lower OLR values are a consequence of low cloud-top temperatures that correspond to increased convective activity. The TRMM daily rainfall data are proportional to the latent heat release in tropospheric clouds, or, equivalently, the available energy in these convective systems.

The OLR data set used provides daily values of OLR on a 2.5° × 2.5° latitude–longitude grid that has been preprocessed to fill any gaps using temporal and spatial interpolation (Liebmann and Smith, 1996). The TRMM data set gives daily mean rainfall on a 0.25° × 0.25° grid between 50° N and 50° S (Huffman et al., 2007). In this study a local time series of both OLR and daily rainfall is calculated by taking the average daily value of the data within a 5° × 5° latitude–longitude box centred on Ascension Island. For comparison, a zonal mean time series of OLR and daily rainfall is also calculated around a 5° latitude band centred on Ascension Island. The typical monthly-mean uncertainties, estimated using the standard error on the mean, are 0.13 and 0.01 $\mathrm{W\,m^{-2}}$ on OLR values and 0.006 and 0.025 $\mathrm{mm\,day^{-1}}$ on daily rainfall values for local and zonal conditions, respectively.

To investigate the zonal wind structure of the stratosphere we use European Centre for Medium-Range Weather Forecasting (ECMWF) operational analysis data. The data used are from the 1.125° resolution data set, available from 2000 to present. Data are available up to 64 km until February 2006, when the model was extended to 80 km. It should be noted that limited observational data are available above 40 km, and thus the ECMWF data set is less reliable above this height. However, on the monthly timescales used here, these ECMWF data provide a good estimate of the underlying wave-filtering local to Ascension Island. A detailed description of this data set can be found in Dee et al. (2011).

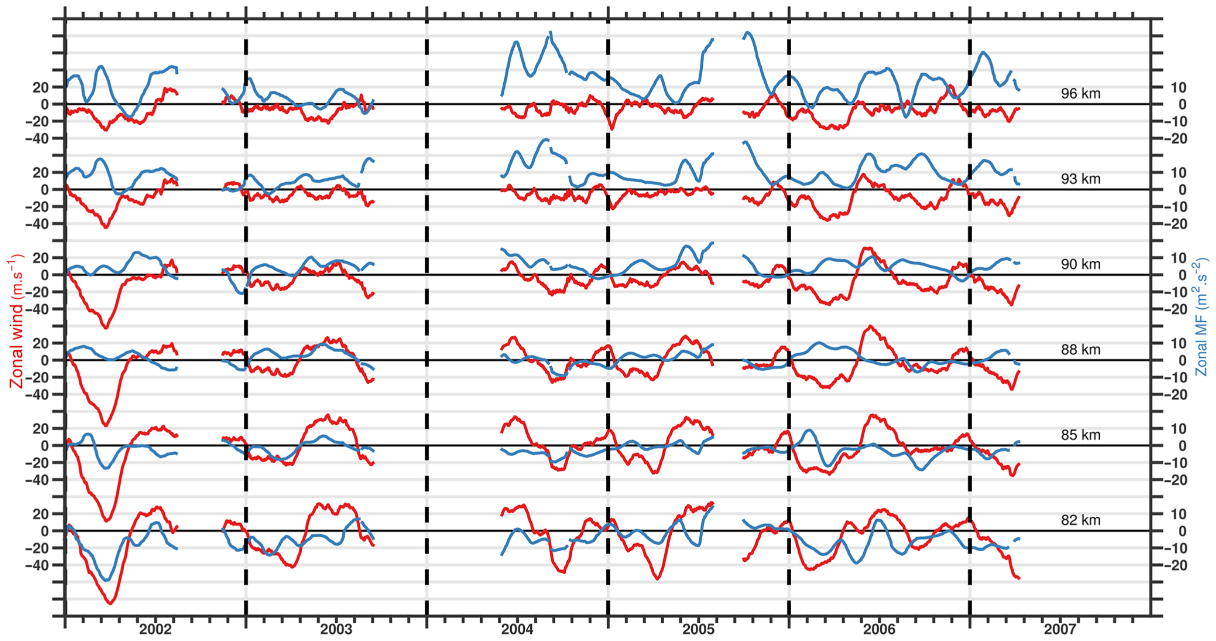

Figure 2. Monthly-mean zonal wind (red) and zonal momentum flux (blue) for 2002–2007 in six height gates. The horizontal black line is the $0\,\mathrm{m\,s^{-1}}$ (left y axis) and $0\,\mathrm{m^2\,s^{-2}}$ (right y axis) line for each height gate. The average height is shown above the zero line for each height gate.

3 Results

To illustrate the intra-annual variability of the mesospheric winds, Fig. 1 shows the annual time series of monthly-mean zonal wind at 85 km for each of the years used in this study. This monthly smoothing is applied to suppress the variation of the wind due to tides and planetary waves. The mean and standard deviation of the winds are indicated by the black line and grey filled areas, while the individual years (2003–2007) are shown by the blue lines. There is a clear MSAO present, with maximum amplitudes of $\approx 30\,\mathrm{ms^{-1}}$ in both the eastward and westward phases. The MSAO is seen to have a larger amplitude during the first half of the year, in agreement with previous studies (e.g. Garcia et al., 1997).

The red line shows the monthly-mean zonal wind for 2002. From February to June the zonal wind is dramatically more westward than the other years considered. In particular, during this westward phase of the MSAO, peak zonal wind values reach $\approx -85\,\mathrm{ms^{-1}}$. This is more than twice the magnitude of any other year in the data set and far exceeds the typical variability indicated by the grey shading. This figure highlights the anomalous zonal winds during the first westward phase of the MSAO in 2002.

Figure 2 shows the monthly-mean zonal wind and zonal momentum flux for each of the height gates. The MSAO is the dominant signal in the zonal wind time series in the lower height gates, but it becomes less significant with increasing height; this is seen as westward minima (maxima) peaking during March/April and September/October (June/July and December/January). This decrease in amplitude with height is particularly noticeable during 2002, where the magnitude of the westward zonal wind steadily changes from $\approx -85\,\mathrm{ms^{-1}}$ in the lowest height gate to $\approx -30\,\mathrm{ms^{-1}}$ in the uppermost height gate. This decrease can be observed during other years for the MSAO first-phase westward maximum and also for the 2004 MSAO second-phase westward maximum. In all years except 2002 and 2006 the MSAO signal becomes indistinguishable from the background above ≈ 90 km.

Momentum fluxes are mostly in the range -10 to $+20\,\mathrm{m^2\,s^{-2}}$. Typical uncertainties on momentum flux estimates, not shown for reasons of clarity, range from approximately $\pm 2\,\mathrm{m^2\,s^{-2}}$ in the middle height gates to approximately $\pm 7\,\mathrm{m^2\,s^{-2}}$ in the uppermost and lowermost height gates where the meteor count rates are lower. These fluxes are consistent with those reported in other studies using meteor radars (e.g. Hocking, 2005; Antonita et al., 2008; Fritts et al., 2010; Vincent et al., 2010; de Wit et al., 2014; Placke et al., 2015). Zonal momentum flux becomes more eastward with increasing height in the mesosphere, suggesting a general transfer of westward momentum from the gravity waves to the mean flow. This is particularly evident at the time of the 2002 event in the lowest height gate.

Application of Eq. (1) to the momentum fluxes in successive height gates allows an estimation of the acceleration of the winds due to the dissipation of gravity waves. Figure 3a shows monthly wave-induced zonal accelerations calculated between the height gates centred on 85 and 88 km and the

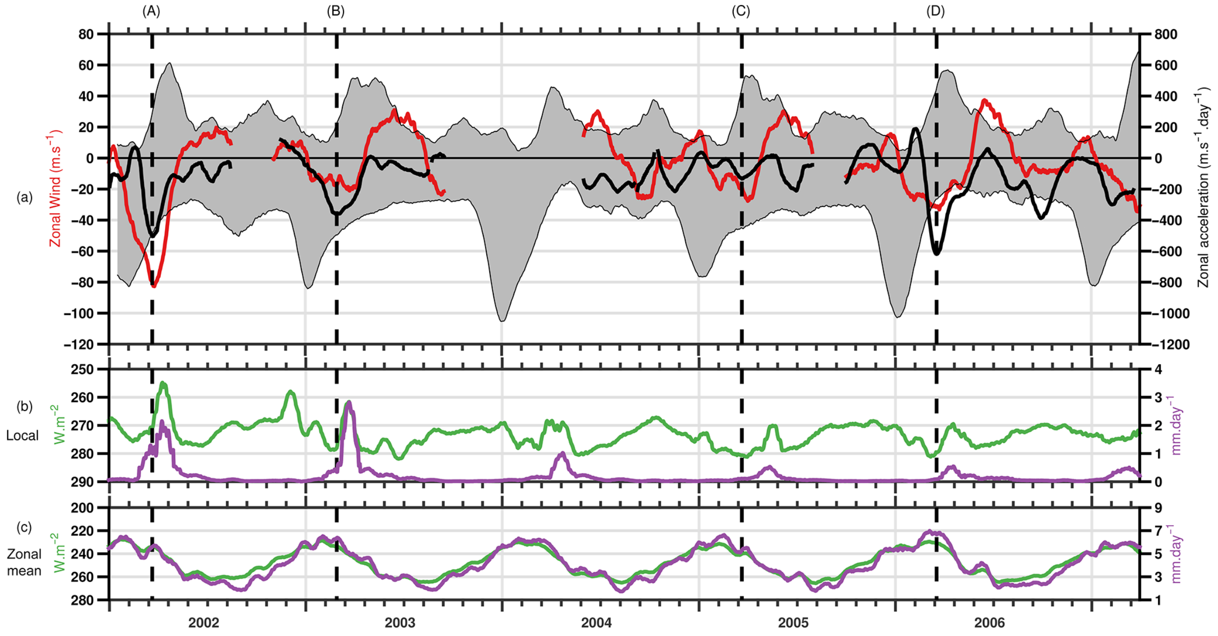

Figure 3. Panel **(a)** shows monthly-mean zonal acceleration (black) calculated between height gates centred at 85 and 88 km and corresponding monthly-mean zonal wind (red) for the period 2002–2007. Grey shading marks the ECMWF maximum and minimum monthly-mean zonal winds between 0 and 64 km. Panels **(b)** and **(c)** show monthly-mean OLR (green) and monthly-mean rainfall (purple) data for the same period averaged in **(b)** a local 5° × 5° latitude–longitude box and **(c)** a zonal band of 5° latitude. In both panels **(b)** and **(c)** the region is centred on Ascension Island. Dashed lines A–D specify the time of peak westward accelerations during the first phase of the MSAO.

corresponding zonal wind. The times of the maximum westward wave-induced acceleration occurring during the first westward phase of the MSAO are highlighted by the black vertical dashed lines in each year (labelled A–D).

Strong westward wave-induced accelerations during the first westward phase of the MSAO are observed in 2002 (A), 2003 (B) and 2006 (D). Peak accelerations are -510 ± 76, -360 ± 81, -130 ± 45 and $-620 \pm 57\,\mathrm{ms^{-1}\,day^{-1}}$ in a–d, respectively. At most other times the magnitude of accelerations is typically less than $300\,\mathrm{ms^{-1}\,day^{-1}}$. While wave-induced accelerations of hundreds of $\mathrm{ms^{-1}\,day^{-1}}$ appear large, a number of other studies have reported similar values in the mesosphere. For example, de Wit et al. (2014) reported peak 10-day moving average accelerations between -240 and $+140\,\mathrm{ms^{-1}\,day^{-1}}$ using data from the Trondheim (63.4° N, 10.5° E) meteor radar during a major sudden stratospheric warming in January 2013. Similarly, Kovalam et al. (2006) used a combination of medium-frequency radar observations and model data at Christmas Island (2° N, 157° W) to estimate accelerations as large as $200\,\mathrm{ms^{-1}\,day^{-1}}$.

Note that while the peak in the westward wave-induced acceleration during 2002 coincides well with the strongest westward winds, it is noticeable that even stronger accelerations occur at this height in 2006, but no similar response is observed in the winds. Finally, we note that a small but significant increase in gravity-wave variance measured by the meteor radar occurred during the 2002 event (not shown for reasons of space). For example, at a height of 85 km, zonal variances increased to $\sim 220\,\mathrm{m^2\,s^2}$ compared to typical values at this height of $\sim 160\,\mathrm{m^2\,s^2}$.

To provide a crude estimate of the strength of excitation of gravity waves near Ascension Island, two wave-generation proxies for convectively generated gravity waves are considered. These are OLR (cloud-top temperature) and rainfall. Figure 3b shows monthly smoothed OLR and daily rainfall data averaged over a 5° × 5° latitude–longitude box centred on Ascension Island. Both a minimum in OLR and a maximum in daily rainfall is observed at about the same times as the MSAO events a–d, indicative of a maximum in convective activity. However, in all events, extrema in rainfall and OLR appear to lag the extrema in monthly-mean mesospheric zonal wind and momentum flux/mean-flow acceleration, indicating that the latter are not a response to the OLR/precipitation fluctuations. Figure 3c shows the zonal-mean OLR and daily rainfall time series, calculated as a zonal mean around a 5° latitude band centred on Ascension Island. In contrast to the local OLR and daily rainfall, there is a clear regular annual cycle present with less inter-annual variability compared to the local time series. These results show that there is not a clear increase in the proxy for local gravity-wave excitation occurring at the time of any of the first-phase MSAO events.

As mentioned in Sect. 1, the filtering of gravity waves by stratospheric winds has been proposed to play an important role in the inter-annual variability of the MSAO (Garcia et al., 1997). To investigate the significance of this wave filtering to event A in 2002, the grey shaded area in Fig. 3a shows the range of zonal winds encountered by an ascending wave from the surface to a height of 64 km, estimated from ECMWF observational analyses data averaged over a 5° × 5° latitude–longitude box centred on Ascension Island. The driving of the MSAO by gravity waves will be influenced by the fraction of those waves filtered out by these winds.

Lines A–D in Fig. 3a highlight the times of maximum westward wave-induced accelerations during the first phase of the MSAO in each year. Using the ECMWF reanalysis data, the minimum/maximum zonal winds encountered by ascending gravity waves at A–D are $-49/+28$, $-50/+22$, $-45/+44$ and $-26/+44\,\mathrm{ms}^{-1}$, respectively. This is significant because it suggests that, at least for waves ascending to 64 km, there is no significant difference in the filtering from the winds during events A–D when the full range of heights are considered. In other words, the anomalous winds in event A in 2002 are probably not the result of a reduced wave filtering in comparison to other years (i.e. in disagreement to the proposed mechanism of Garcia and Sassi, 1999).

Vertical profiles of monthly-mean mesospheric zonal wind and wave-induced acceleration at the times specified by lines A–D in Fig. 3 are shown in Fig. 4. The figure shows that there is a general tendency for accelerations and winds to become more eastward with height in all years. This is particularly evident in 2002, when the change in zonal wind and acceleration between the lowest and highest height gate is $> 30\,\mathrm{ms}^{-1}$ and $> 600\,\mathrm{ms}^{-1}\,\mathrm{day}^{-1}$, respectively. In addition, the enhanced westward acceleration observed in Fig. 3 in 2006 appears to have occurred at a particular altitude and not at multiple heights as in 2002. These results highlight the connection between strong westward accelerations and strong westward winds during event A in 2002.

4 Discussion and conclusions

For the first time, measurements from the Ascension Island meteor radar are used to calculate zonal momentum fluxes and zonal-wind accelerations due to high-frequency mesospheric gravity waves. Considering the first phase of the MSAO in 2002, we note the following:

1. Anomalous and strong westward winds were observed.
2. An increase in westward momentum fluxes and westward acceleration due to high-frequency gravity waves is observed to accompany the anomalous zonal winds, strongly suggesting that these waves are responsible for the anomalous winds, in agreement with the proposed selective filtering mechanism of Garcia and Sassi (1999).
3. However, the ECMWF reanalysis data (0–64 km) suggest that the winds encountered by ascending waves in 2002 were actually no more favourable for propagation to the mesosphere than in other years, which is not in agreement with the selective filtering mechanism.
4. Further, in 2002 no indication of anomalous gravity-wave excitation is provided by the OLR/precipitation proxies.

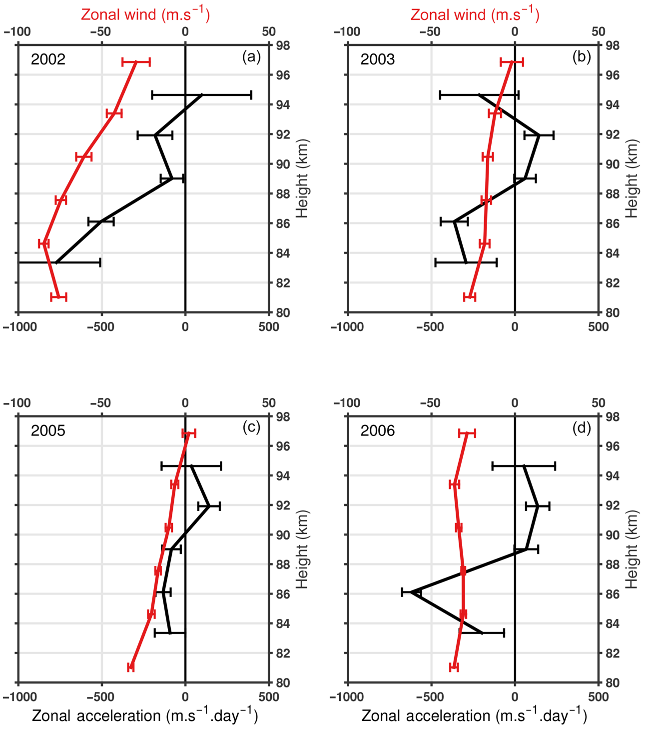

Figure 4. Variation of monthly-mean zonal wind (red) and monthly-mean zonal acceleration (black) with height at the time of maximum acceleration during the first westward phase of the MSAO for **(a)** 2002, **(b)** 2003, **(c)** 2004 and **(d)** 2005. The errors on wind values have been multiplied by 10 to make them more visible here.

Collectively, these observations do not support the selective filtering mechanism of Garcia and Sassi (1999) for the 2002 anomalous event because the strong winds, fluxes and wave-induced accelerations do not appear to result from unusual filtering conditions. We note that the winds considered here cover a greater height range than those considered by Garcia et al. (1997), Garcia and Sassi (1999) and Day and Mitchell (2013), i.e. 0–64 km here (cf. 0–32 km in the earlier studies), and it is only when this greater height range is considered that the filtering conditions in 2002 are seen to be not significantly different from the other years. In addition, the winds we consider are also geographically located over Ascension Island and, in combination with the increased range of heights considered, hence, represent a more realistic view of the winds encountered by ascending waves. Our observations thus do not provide a clear indication as to the origin of the increased gravity-wave fluxes associated with the 2002 event.

The first-phase MSAO event in 2006 was accompanied by strong gravity-wave accelerations but did not display the anomalous westward winds observed in 2002. Again, there is no clear indication the propagation environment was significantly different during this event. It is worth noting that the strong acceleration in 2006 is only observed at a single altitude and not at multiple heights as in 2002.

The evidence here thus suggests that episodes of strong westward fluxes/accelerations from high-frequency gravity waves can occur in the equatorial mesosphere without the need for obviously unusual wind filtering conditions in the underlying atmosphere. Further, the 2006 event demonstrates that strong westward fluxes/accelerations do not necessarily produce anomalous westward winds. This latter phenomenon may indicate a significant role from other waves not detected by the meteor radar. These waves might include low- and medium-frequency gravity waves not detected by the radar analysis, planetary waves (including Kelvin waves) and tides. Further, we note that 2002 saw the only stratospheric warming to be observed in the Southern Hemisphere, albeit later in the year it has been suggested to be the result of anomalous planetary wave activity during 2002.

A plausible explanation is that Kelvin-wave-induced accelerations may inhibit the accelerations due to gravity waves in years such as 2006. However, only ultra-fast Kelvin waves have significant amplitudes in the mesosphere and these are observed to have much smaller accelerations than the gravity-wave accelerations we observe (Chen and Miyahara, 2012; Davis et al., 2012). For example, Davis et al. (2012) observed peak 5-day mean ultra-fast Kelvin wave accelerations of $4\,\mathrm{ms^{-1}\,day^{-1}}$ using the Ascension Island meteor radar and Chen and Miyahara (2012) found the range of accelerations in a year to be between 0.5 and $8\,\mathrm{ms^{-1}\,day^{-1}}$ using the Kyushu University Middle Atmosphere General Circulation Model. Thus, it is unlikely that Kelvin-wave-induced accelerations are responsible for the absent strong winds in 2006.

The observations presented here highlight the importance of gravity waves in the equatorial mesosphere. Our results indicate that gravity-wave fluxes/accelerations are closely associated with anomalous MSAO wind events, but the relationship between wave excitation, propagation and dissipation and the zonal winds is complex and includes many uncertainties – highlighting the need for further observations able to address a wide range of wave parameters.

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