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Aura MLS observations of the westward-propagating s=1, 16-day planetary wave in the middle atmosphere: climatology and cross-equatorial propagation

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Abstract

The Microwave Limb Sounder (MLS) on the Aura satellite has been used to measure temperatures in the stratosphere, mesosphere and lower thermosphere (MLT). The data used here are from August 2004 to June 2010 and latitudes 75° S to 75° N. The temperature data reveal the persistent presence of a westward propagating 16-day planetary wave with zonal wavenumber 1. The wave amplitude maximises in winter in the stratosphere and MLT at middle to high latitudes, where monthly-mean amplitudes can be as large as ~8 K. Significant wave amplitudes are observed in the summer-time MLT and at lower stratospheric heights of up to ~20 km at middle to high latitudes. Wave amplitudes in the Northern Hemisphere approach values twice as large as those in the Southern Hemisphere. Wave amplitudes are also closely related to climatological zonal winds and are largest in regions of strongest eastward flow. There is a reduction in wave amplitudes at the stratopause. No significant wave amplitude is observed near the equator or in the strongly westward background winds of the atmosphere in summer. This behaviour is interpreted as a consequence of wave/mean-flow interactions. It has been suggested that the summer-time 16-day wave in the MLT is ducted across the equator from the winter hemisphere and that this ducting is modulated by the equatorial Quasi-Biennial Oscillation (QBO) in the westerly phase. Here we observe that the QBO modulates the 16-day wave in the polar summer-time MLT in the Northern Hemisphere as previously observed, but this modulation is not seen in the Southern Hemisphere.

1 Introduction

Planetary waves with periods of ~2–16 days are an important component in the coupling between the lower and middle atmosphere. Planetary waves play a key role in the transport of energy, momentum and chemical species, both vertically and horizontally. The waves interact very strongly with the background winds of the atmosphere

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

because the waves' horizontal phase speeds tend to be similar to the speed of the background winds, thus promoting wave/mean-flow interactions. Planetary waves are known to interact with atmospheric tides in nonlinear processes that modulate tidal amplitudes (e.g. Teitelbaum and Vial, 1991; Mitchell et al., 1996; Beard et al., 1997). Tidal interactions can also through non-linear processes generate other global-scale planetary waves (e.g. Palo et al., 2007). Planetary waves are also known to modulate the gravity-wave field of the middle atmosphere and consequently modulate the fluxes of gravity-wave energy and momentum that drive the entire global circulation of the upper middle atmosphere (e.g. Forbes et al., 1991; Miyahara and Forbes, 1991; Thayaparan et al., 1995; Nakamura et al., 1997; Manson et al., 2003). These modulated gravity-wave momentum fluxes can result in planetary-wave signatures penetrating to the thermosphere (Meyer, 1999). Temperature perturbations caused by planetary waves have been associated with modulating the occurrence of Polar Mesospheric Clouds (e.g. Espy and Witt, 1996; Merkel et al., 2003, 2008; Nielsen et al., 2010) and the associated phenomena of Polar Mesospheric Summer Echoes (Morris et al., 2009). In the stratosphere, planetary waves are a key part of the transport processes that redistribute ozone from low-latitude source regions to higher latitudes (e.g. Salby and Callaghan, 2007) and the upward flux of planetary-wave activity plays a key role in sudden stratospheric warmings (e.g. Dowdy et al., 2004; Murphy et al., 2007). The ionospheric current system of the equatorial electrojet is also believed to be modulated by planetary waves (e.g. Ramkumar et al., 2009). Studies of planetary waves are thus very important in the attempt to understand the coupling of the lower, middle and upper atmosphere.

A major class of planetary waves are the so-called normal modes, which have periods near 2, 5, 10 and 16 days (Salby, 1981a,b). These waves can be generated in the lower atmosphere and propagate from the troposphere into the stratosphere, mesosphere and lower thermosphere (MLT). However, this mechanism cannot explain the regular observation of planetary waves in the summer-time MLT. This is because the strong westward winds of the summer-time middle atmosphere prevent the propagation of planetary waves to MLT heights from the lower atmosphere (Charney and Drazin, 1961). A series of mechanisms have been proposed for the excitation of planetary waves that can explain their presence in the summer MLT. In the case of the 2- and 5-day waves, in situ generation by baroclinic or barotropic instabilities in the upper mesosphere has been suggested (e.g. Pfister, 1985; Holton, 1992; Lieberman et al., 2003). Further, ducting of planetary waves across the equator has been proposed as a mechanism to explain the observations of some planetary waves in the summer MLT and in particular the 16-day wave (e.g. Charney and Drazin, 1961; Dickinson, 1968; Salby, 1981a,b; Forbes et al., 1995; Luo et al., 2000, 2002a,b; Hibbins et al., 2009).

In this paper we will consider the 16-day planetary wave. Salby (1981a) suggested on theoretical grounds that the 16-day planetary wave is a manifestation of the gravest symmetrical wavenumber 1, westward-travelling Rossby wave. The period of the 16-day wave has, in fact, been observed to lie between about 12–20 days. The wave has been reported to have wind amplitude of up to about ∼15 $\mathrm{m\,s^{-1}}$ and temperature amplitudes reaching ∼10 K in the MLT (e.g. Forbes et al., 1995; Day and Mitchell, 2010).

Previous studies of the 16-day wave have concentrated in particular on its manifestation in the MLT region. This seems to be partly because meteor and Medium-Frequency (MF) -radars and airglow spectrometers are able to make extended campaigns of measurements at these heights (e.g. Forbes et al., 1995; Luo et al., 2002a; Lima et al., 2006). However, a number of modelling studies have suggested that the wave can reach large amplitude in the stratosphere (e.g. Miyoshi, 1999; Luo et al., 2002b; Forbes et al., 1995).

These and other studies of the 16-day wave have reported a clear seasonal cycle in wave amplitudes in the middle atmosphere at middle and low latitudes. Largest wave amplitudes generally occur in the winter-time and a secondary maximum in the summer-time MLT is also sometimes observed (e.g., Luo et al., 2000; Espy et al., 1997; Mitchell et al., 1999). Lower polar stratosphere studies of planetary-wave activity also report the 16-day wave in the winter-time with larger amplitudes in the Northern

Hemisphere than the Southern Hemisphere (e.g. Alexander and Shepherd, 2010).

In contrast, there have been only a limited number of studies of the 16-day planetary wave in the polar atmosphere (e.g. Williams and Avery, 1992; Luo et al., 2002b; Hibbins et al., 2009; Day and Mitchell, 2010). These studies also revealed a winter-time maximum in wave amplitudes and a weaker secondary maximum in summer.

The presence of the wave in winter is fully consistent with its having propagated upwards from sources in the lower atmosphere to the MLT. There are only a few reported observations of the 16-day wave in the stratosphere, (e.g. Shepherd and Tsuda, 2008; Williams and Avery, 1992) where Williams and Avery presented simultaneous observations of the wave in the lower stratosphere and the MLT.

The propagation of a planetary wave in the atmosphere is controlled by the wave's interaction with the background winds (Charney and Drazin, 1961). From Charney and Drazin theorem, in order to propagate a planetary wave must obey $0<\bar{u}-c_x<U_\mathrm{c}$, where $\bar{u}$ is the zonal wind speed, c_x is the zonal phase speed of the planetary wave at the latitude in question and U_c is the critical Rossby speed. For example, the westward-propagating $S=1$ 16-day wave at latitudes of 25, 50 and 75°, has phase speeds c_x of -26, -19 and $-8\,\mathrm{m\,s^{-1}}$, respectively. The mean zonal wind speed, $\bar{u}$, should therefore be greater than -26, -19 and $-8\,\mathrm{m\,s^{-1}}$, for these three latitudes for the wave to propagate.

However, the summer-time 16-day wave reported in the MLT cannot have propagated upwards through the stratosphere to the MLT from source regions in the troposphere and lower stratosphere. This is because the zonal phase speed of the 16-day wave is less than the zonal winds of the middle atmosphere. To illustrate this, Fig. 1 presents the zonal phase speed of a 16-day wave as a function of latitude. Note that the phase speed only decreases below $\sim 10\,\mathrm{m\,s^{-1}}$ at latitudes poleward of 70°. Figures 2 and 3 present for comparison climatological zonal winds from the UARS Reference Atmosphere Project (URAP) for the northern and Southern Hemispheres, respectively, at the tabulated latitudes of 24°, 52° and 76°. Also indicated on the figures are lines corresponding to the zonal phase speed of the 16-day wave at these latitudes. From

Figs. 2 and 3 it can be seen that the wave cannot propagate above heights of about 32, 38 and 38 km for the respective latitudes in the northern summer and about 32, 35 and 43 km for similar latitudes in the southern summer. However, the wave can again propagate at MLT heights in summer where the zonal winds have increased to values that allow the wave to propagate again. In winter the zonal winds are strongly eastward at all latitudes and so the wave can propagate vertically through the entire depth of the atmosphere.

There must therefore be a mechanism for exciting the 16-day wave in the MLT in the summer. Two principle mechanisms have been proposed for the excitation of the summer-time 16-day wave in the MLT. These are:

1. In situ excitation has been suggested by Williams and Avery (1992). In this mechanism gravity waves from the lower atmosphere propagate upwards, but are filtered by the 16-day wave in the upper troposphere and lower stratosphere, thus imposing a 16-day modulation on the field of ascending gravity waves. The gravity waves then dissipate and transfer their momentum and energy into the mean flow of the MLT, which in turn excites a 16-day wave in situ. Smith (1996) observed this in situ forcing of planetary-scale disturbances due to variations in gravity-wave drag caused by stratospheric filtering. The modelling study by Smith (2003) also showed that such a mechanism can produce significant planetary-wave amplitudes in the MLT, at least in the case of stationary planetary waves.

2. Cross-equatorial propagation has been suggested, where the winter-time MLT wave crosses the equator to the summer hemisphere at heights above the strong westward zonal mean flow of the summer-time middle atmosphere through which wave propagation is prohibited. This mechanism has been investigated using models by Miyahara et al. (1991); Forbes et al. (1995). These authors also suggested that gravity-wave stresses in the mesosphere may impeded the ducting across the equator.

Observational studies by Espy et al. (1997), Jacobi et al. (1998), Jacobi (1998) and Hibbins et al. (2009) considered the cross-equatorial propagation mechanism and attributed year-to-year fluctuations in the amplitude of the 16-day wave in the summertime MLT to a modulation of the ducting process by the equatorial QBO. These authors proposed that the amplitude of the 16-day wave was greater in the middle- to high-latitude summer MLT during the eastward (westerly) phase of the QBO. This is because when the QBO is in the negative (easterly) phase the QBO winds in the MLT reduce the winds of the background circulation yielding a more westward total wind which, through Charney-Drazin theorem, prevents the cross-equator propagation of the wave.

Here, we present observations of temperatures in the global atmosphere at heights of ~20–100 km using Aura MLS data. The data set is about 7 years long, spanning the interval from August 2004 to June 2010. In the first part of this study we present a representative climatology of the 16-day wave. We believe this is the first extended global climatology of the westward-travelling $s=1$, 16-day planetary wave. In the second part of the paper we investigate the role of the QBO in modulating the occurrence of the summer-time 16-day wave in the polar MLT. In this study we concentrate on establishing a representative seasonal climatology of the 16-day wave. The role of instabilities in the circulation of the middle atmosphere that may excite the wave will be addressed in a follow-on study.

2 Data analysis

Data from the Microwave Limb Sounder (MLS) on the NASA EOS Aura satellite is used in this study. Data have been recorded almost continuously since 15 July 2004. Aura MLS is a limb-scanning emission microwave radiometer which measures radiation in the GHz and THz frequency range (millimeter and submillimeter wavelengths). The instrument measures the vertical profile of temperatures in the middle atmosphere. Aura MLS provides daily global coverage. The satellite is in a high inclination, sunsynchronous orbit which has an orbital period of ∼100 min. It repeats the ground track every 16 days, providing atmospheric measurements over virtually the whole globe in a repeated pattern. The Limb instruments are designed to observe roughly along the orbit plane. MLS is on the front of Aura and so observes in a forward velocity direction.

MLS temperatures from the Version 2.2 Temperature Analysis are used in this study, this version has data available from 8 August 2004 (Livesey et al., 2008). The data are recorded on 34 pressure levels ranging from 316–0.001 hPa (∼10–96 km). The vertical resolution of 7–8 km from 316–100 hPa, 4 km at 31–6.8 hPa, 6 km at 1 hPa and 9 km at 0.1 hPa. We converted the pressure levels to approximate heights and will present the results as a function of this approximate height. This is done to facilitate comparisons with measurements made by ground-based radars. The standard product for temperature is taken for the Core retrieval (118 GHz only) from 316 to 1.41 hPa and from the Core+R2A (118 GHz and 190 GHz) retrieval from 1 hPa to 0.001 hPa. The temperature precision is ∼±1 K from 316–0.1 hPa. The data is assigned a "flag" to comment on the quality of the data. Quality is computed from a χ^2 statistic for all th e radiances considered to have significantly affected the retrieved species, normalised by dividing by the number of radiances. Quality is simply the reciprocal of this statistic. Here, if the data has a quality flag of "0" then it is regarded as poor quality and not used in the analysis.

The 16-day planetary wave has been observed to occur with a wide range of periods between ∼12 to 20 days, as described in Sect. 1. Here, we will consider all planetary-scale wave activity within the period range 12 to 20 day and of westward travelling wavenumber 1 to be attributable to the "16-day wave". This range of periods has also been used in the majority of studies of the 16-day wave, (e.g. Forbes et al., 1995; Miyoshi, 1999; Luo et al., 2002a; Jiang et al., 2005; Lima et al., 2006; Day and Mitchell, 2010). Our results should thus be directly comparable with these other studies.

Here, the temperature data are sorted into 10° latitude bands and a least-squares fit of a westward-propagating zonal wavenumber 1 wave is applied to the monthly data within each latitude band. The data is gridded into 31 latitude bins, in steps of 5° from

75° N to 75° S. Wave periods of 12–20 days are fitted in hourly steps. The largest amplitude signal within this period range is then identified as the 16-day wave for a particular latitude band and month. For each height and latitude bin we have thus produced a time series of the temperature amplitude of the 16-day wave.

The error in the least-squares fit amplitude was calculated using the standard deviations on the least-squares periodic fitting of the data. The error was generally found to be less than ~0.6 K. Figure 4 presents height latitude contours of this error for the example months of January and July 2007 (not all years and months are shown for reasons of space). The least-squares fit wave amplitude error was calculated using a 95% confidence level.

These data are then used to produce composite years by averaging together all similar months and height gates from the different years. This yields a composite, representative, or superposed-epoch month.

UARS Reference Atmosphere Project (URAP) data (http://database.rish.kyoto-u.ac.jp/arch/sparc/data/ref_clim/urap/wind/) have been used to produce a composite-year analysis of the monthly-mean zonal winds of the atmosphere. The monthly data are available from November 1991 to November 1999 at heights of ~0–118 km and latitudes of −80 to 80°. Note that although this data set has not overlapped in time with that from Aura MLS, it nevertheless can be used to provide a crude comparison between wave amplitudes and climatological winds.

To investigate the role of the QBO in modulating the summer-time MLT 16-day wave, we considered monthly-mean zonal winds at 10 hPa. The QBO data product was obtained from Freie Univeristät Berlin (FUB) (www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html). This data set has been produced from the Singapore radiosonde data, January 1987 to May 2009.

3 Results

3.1 Climatology

In this section we will present a representative climatology of the 16-day wave. Firstly, we will consider the variation of wave amplitudes (50–75°) from year-to-year. Figure 5 presents the monthly-mean amplitude of the wave at middle to high latitudes for the Northern and Southern Hemispheres. Figure 5a presents the amplitude averaged over heights of 65–95 km, chosen as representative of the MLT. Figure 5b presents the amplitude averaged over heights of 35–55 km chosen as representative of the stratosphere. From the figures it can be seen that there is a clear seasonal cycle in wave amplitude that approximately repeats from year to year. In particular, the wave amplitude maximises in winter and has a minimum in summer. There is significant interannual variability evident. For example, in the winter of 2009/2010 the peak Northern Hemisphere wave amplitudes were ∼6 K, but in the previous winter of 2008/2009 the wave amp litudes reached only ∼3 K. Wave amplitudes in the stratosphere and mesosphere are in general very similar in a particular hemisphere. However, wave amplitudes are generally larger in the Northern Hemisphere than the Southern. If we consider the two months of largest wave amplitude from each year, averaged over all the years observed, we find that Northern Hemisphere peak amplitudes are ∼5 K in the mesosphere and ∼6 K in the stratosphere, whereas in the Southern Hemisphere the equivalent peak amplitudes are only ∼3 K and ∼3 K.

Figure 5 shows that there is latitudinal structure to the wave. To investigate this further, Fig. 6 presents the monthly-mean wave amplitude in the MLT (65–95 km) as a function of latitude for 2005. The figure reveals that wave amplitudes have an equatorial minimum in all months. Around the equinoxes the wave is simultaneously present in both hemispheres and maximises at latitudes of ∼60°. Near the solstices, the wave is largely confined to the winter hemisphere and appears much reduced in the summer hemisphere. It is notable that, despite the largest amplitudes occurring in the winter hemisphere, there is still small but significant wave activity in summer, e.g., in the

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Southern Hemisphere in December and February and in the Northern Hemisphere in August. Similar behaviour is observed for other years of data (not shown for reasons of space).

The seasonal and long-term variability suggested above can be investigated further by considering latitude-height contour plots of monthly-mean wave amplitude. An example of this analysis is presented here in Fig. 7. The month of December is presented as an example, because in all of the years there is wave amplitude present in winter and some smaller wave amplitudes are also present in the summer hemisphere. Wave activity is almost absent at equatorial latitudes in all years observed.

Considering the figure in detail, it can be seen that in winter the wave is present throughout the stratosphere and mesosphere at latitudes polewards of ~25°. In a given year, wave amplitudes are similar in the stratosphere and mesosphere, for example in 2005 wave amplitudes exceed ~6 K in both the stratosphere and mesosphere and in 2004 wave amplitudes reach ~3 K in both stratosphere and mesosphere. In the stratosphere, wave amplitudes appear to maximise at a height just above ~40 km, i.e., just below the stratopause. In the mesosphere, peak amplitudes tend to be similar to those in the stratosphere and occur at heights below ~80 km, although the wave is still evident to the greatest heights observed. In many years there is a significant amplitude minimum near the stratopause. The tendency for wave amplitudes to decrease at heights above ~80 km was also reported in the radar studies of the polar MLT 16-day wave by Day and Mitchell (2010).

The wave is largely absent from the summer hemisphere. However, some wave activity is present at heights above ~80 km at middle and high latitudes and also at heights below ~40 km at high latitudes. With regard to these observations of the 16-day wave in the lower stratosphere, we note that Williams and Avery (1992) reported significant wave amplitudes at heights below 30 km throughout most of the year.

The regular seasonal cycle revealed in Figs. 5 and 6 means that a composite-month analysis can be used to reveal a representative seasonal behaviour. Figure 8 presents the 12 composite months of the entire seasonal cycle. In each month the data from all years of observation have been averaged. Also plotted on the figure are the monthly-mean zonal winds from the URAP climatology. Note that the Aura and URAP data are not coincident in time. However, here we are making comparisons of climatological average behaviour and so the comparison is still very useful. From the figure it can be seen that:

1. Wave amplitudes are largest in the winter hemisphere and are larger in the Northern Hemisphere than the Southern Hemisphere.
2. Stratospheric wave amplitudes in winter tend to maximise at the heights and latitudes where the zonal winds are the most strongly eastward. For example, in December the strongest zonal winds of ~50 ms^{-1} occur at a latitude of ~55° N and a height of ~45 km which coincides with the largest-amplitude occurrence of the wave. Similar behaviour in the stratosphere can be seen in all months. This behaviour is less clear in the mesosphere.
3. The wave is usually less than 1 K in amplitude in regions of westward zonal wind, which accounts for the wave's absence in the summer stratosphere and lower mesosphere.
4. Throughout the year the largest wave amplitudes tend to occur at latitudes near 60°.
5. In all months the wave amplitudes are usually small at the equatorial latitudes.
6. In most months of winter, spring and autumn there is a minimum in wave amplitude around the stratopause.
7. Small but significant wave amplitudes are evident in the upper mesosphere and lower stratosphere in most summer months in both hemispheres.
8. Near the equinoxes, the wave is present in both hemispheres simultaneously. At these times the zonal winds are either eastward or weakly westward in both hemispheres.

9. In autumn in both hemispheres, as wave amplitudes begin to rise to the winter maximum, the largest amplitudes occur first in the mesosphere.

3.2 A QBO modulation of the mesopause-region wave in the summer?

One of the most interesting observations above is the presence of a summer-time 16-day wave in the MLT. As noted in Sect. 1, a number of authors have attributed the summer-time activity to the ducting of the wave from the winter hemisphere at mesospheric heights, i.e., above the region where the strong westwards winds of the summer hemisphere prevent the vertical propagation of the wave. Further, it has been demonstrated in some studies that the QBO modulates the amplitude of the wave in the summer hemisphere (see Sect. 1).

The ~7 years of Aura MLS data considered here allow us to investigate this modulation in a new and extensive data set. We investigated the relationship between the phase of the QBO and the amplitude of the 16-day wave in the summer mesosphere as follows. The 16-day wave amplitude was calculated for each month as an average within a height-latitude box covering heights of ~80–96 km and latitudes of 50–75°. A summer-time mean was then taken by averaging these amplitudes for June–August (Northern Hemisphere) and December–February (Southern Hemisphere). This yields a single amplitude representing the mesospheric 16-day wave in summer.

For each year these summer-time averages were then compared with the QBO winds. Summer-time mean QBO winds were calculated from the FUB data base. Here we present the winds from a pressure level of 10 hPa (although pressure levels between 70 and 10 hPa were considered).

Figure 9 presents the mean MLT summer-time temperature amplitudes of the 16-day wave compared to the mean summer-time QBO wind at 10 hPa. Both the Northern and Southern Hemisphere summer-time wave were considered. Correlation coefficients between the wave amplitude and the QBO wind calculated for the Northern Hemisphere were found to be 0.56. In the Southern Hemisphere the correlation coefficient was found to be found to be −0.68.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

A simplistic but clear method for testing the QBO modulation further considers the average wave amplitudes related to the phase of the QBO. The Northern Hemisphere mean amplitude is 2.0 K in the single year when the mean QBO is positive (2004) and 0.9 K in the QBO negative years. The Southern Hemisphere mean amplitude is found to be similar in both phases of the QBO (0.9 K when the QBO is positive and 1.1 K when the QBO is negative). It can be seen from these values that the wave amplitude is enhanced in the Northern Hemisphere summer-time MLT when the QBO is positive, but not enhanced in the Southern Hemisphere summer-time MLT. Note that is it not the magnitude of the 10 hPa QBO wind that is important in this figure, rather it is the phase. The summer-time MLT QBO modulation in the Northern Hemisphere agrees with the observations of Espy et al. (1997); Hibbins et al. (2009), where the QBO has a modulation effect on the amplitude of the 16-day wave, when the QBO is in the positive phase the wave is enhanced in the MLT. The Southern Hemisphere observations shown here are however, not conclusive. We should note that these conclusions are tentative because of the relatively short data set available.

4 Discussion

Our observations reveal the 16-day wave to be a significant feature of the winter stratosphere and MLT at middle and high latitudes. Wave amplitudes regularly reach or exceed 5 K in both the stratosphere and the MLT during winter. There appear to be two discrete amplitude maxima, one at a height of ~70 km and one at ~45 km, separated by an amplitude minimum at the stratopause where wave values drop to about half the peak amplitudes. Wave amplitudes are very small equatorwards of about 25° latitude, peak at latitudes near 60° and then reduce towards the pole. The wave is largely absent in summer and this is almost certainly a consequence of wave propagation being prevented by the westward winds of the summer middle atmosphere (Charney-Drazin theorem).

A broadly similar seasonal behaviour has been reported in ground-based studies of the 16-day waves in the mesosphere (e.g. Williams and Avery, 1992; Espy and Witt, 1996; Jacobi, 1998; Mitchell et al., 1999; Luo et al., 2000, 2002a,b; Hibbins et al., 2009; Day and Mitchell, 2010). Only some of these studies measured temperatures, including Espy and Witt (1996) and Espy et al. (1997) who used a Michelson interferometer to measure OH rotational temperatures near the mesopause over Stockholm (60° N). They observed the 16-day wave and reported mesospheric temperatures amplitudes of up to 5 K. Day and Mitchell (2010) used a meteor radar to measure temperatures in the polar mesosphere over Esrange (68° N) and Rothera (68° S). They reported instantaneous temperature amplitudes of up to 10 K in winter and 5 K in summer. These reported summer-time temperature amplitudes are larger than those presented here measured by Aura MLS. How ever, this difference is very likely because these studies reported temperature amplitude related to short-lived maxima, whereas our results here are based on monthly means.

A number of modelling studies have examined the 16-day wave in the middle atmosphere. Forbes et al. (1995); Miyoshi (1999); Luo et al. (2002b) used a variety of different models and reported significant wave amplitudes present in both the stratosphere and mesosphere of the winter hemisphere. None of these model results reproduce the stratopause-level minimum in wave amplitude reported here. However, all show a similar latitudinal structure with maximum amplitudes occurring at middle to high latitudes. Wave activity is either absent or significantly reduced in the summer in all three models (see below for further discussion).

As noted earlier, the 16-day wave is largely absent (less than 1 K in amplitude) from the summer-time middle atmosphere. However, there are two relatively restricted regions of the summer-time atmosphere where wave activity is nevertheless present in our observations.

The first of these is in the lower stratosphere at middle and high latitudes. Here, the zonal background winds are less than the zonal phase speed for a particular latitude and the wave is thus trapped below this height, but free to propagate below. Similar behaviour is observed in the Northern Hemisphere in June–August. The ground-based observations of Williams and Avery (1992) made by a Mesosphere-Stratosphere-Tropsphere (MST) radar at Poker Flat (65° N) reported significant wave activity around the summer tropopause, reinforcing the suggestion that the wave is present in the lower stratosphere in summer. The models of Forbes et al. (1995); Miyoshi (1999) also indicate small but significant wave activity in the high-latitude summer-time lower stratosphere. This wave activity most likely arises because the zonal winds of this region of the atmosphere are not sufficiently strong to prevent the wave from propagating.

The second region where the wave is observed in summer is in the MLT at heights above those where the zonal wind speed is greater than the zonal phase speed. For example, in December it can be seen that the wave is only present at the very top of the heights observed where the zonal winds increase again to ∼$-10\,\mathrm{ms}^{-1}$. At middle latitudes the wave appears at slightly lower heights in the atmosphere, probably because it is not inhibited by such a high zonal wind speed. At ∼25° S the wave is observed at heights as low as ∼80 km, where the winds are ∼$-20\,\mathrm{ms}^{-1}$, this compares to a zonal phase speed at this latitude of ∼$-19\,\mathrm{ms}^{-1}$. Again, this suggests that the wave is limited in where it can occur by wave/mean-flow interactions.

As discussed above, the 16-day summer-time wave cannot have propagated upward through the atmosphere to the MLT where we observe it due to blocking by the zonal background wind. To explain the observations of a summer MLT 16-day wave it has been hypothesised that the wave must have been cross-equatorially ducted because it is observed to have its amplitude modulated by the phase of the QBO (e.g. Espy et al., 1997; Jacobi, 1998; Luo et al., 2000; Hibbins et al., 2009). Such a modulation would not be likely if the wave in the MLT was being excited by modulated gravity-wave fluxes originating in the lower atmosphere of the summer hemisphere. Observations of a QBO modulation of 16-day wave amplitudes in the summer MLT (as reported here) thus support the suggestion that this wave has been ducted from the winter hemisphere.

However, Luo et al. (2000) observed the presence of the 16-day wave in the summer-time MLT and suggested that the wave may have leaked from the winter-hemisphere by a duct. They showed that the wave activity appeared to be modulated by the QBO mechanism, but only in some years and only in some months. This suggests that any QBO modulation of a hypothetical inter-hemispheric ducting may be intermittent in nature.

In this context we note that our observations only suggest a QBO modulation of the polar summer-time MLT wave in the Northern Hemisphere, but not in the Southern Hemisphere. This maybe because this process is intermittent in nature as suggested by Luo et al. (2000).

Possible explanations for the differences in these studies are that the various data sets employed were sometimes from different years. If any modulation is intermittent then some studies may thus observe a modulation and some not. Further, our data are from a solar-minimum period, which has been suggested to dampen the QBO phase mechanism effect, e.g., Jacobi (1998).

Finally we should note that the in situ mechanism proposed by e.g., Williams and Avery (1992), Forbes et al. (1995), Miyoshi (1999) would not require the summer-time wave to cross through the region of strong QBO wave amplitudes at low latitudes and so could result in a sumer-time MLT wave that displayed no QBO modulation at all.

The sources of the 16-day summer-time wave in the MLT is thus still an open question and further studies are needed to determine its origin.

5 Conclusions

The 16-day wave is a persistent, large-amplitude feature of the winter stratosphere and MLT – at least in the seven years of observations reported here. Monthly-mean wave amplitudes exceed 6 K in most northern winters and 4 K in most southern winters. Wave activity is confined to latitudes poleward of ~25°. Some wave activity is observed nevertheless in both hemispheres in the summer months, where it reaches ~3 K. The summer-time wave activity is restricted to regions where the monthly-mean zonal winds are greater than the zonal phase speed for a given latitude. Thus, summer-time wave activity is observed at heights up to ∼30 km in the lower stratosphere and again at heights above ∼70 km in the MLT. This behaviour is interpreted as a consequence of wave/mean-flow interactions. The wave in the summer-time MLT can therefore not have propagated from below.

Our observations suggest that the QBO may modulate the amplitude of the wave in the polar summer-time MLT. However, we only observe this behaviour in the Northern Hemisphere.The absence of such a modulation in the Southern Hemisphere maybe a consequence of our comparatively short data set and an intermittency in the modulation. Nevertheless, the observation of modulation supports the suggestion that the 16-day wave observed in the summer MLT has been duct across the equator from the winter hemisphere and that the modulation took place in the low-latitude atmosphere where the wave and QBO interacted.

References

Alexander, S. P. and Shepherd, M. G.: Planetary wave activity in the polar lower stratosphere, Atmos. Chem. Phys., 10, 707–718, doi:10.5194/acp-10-707-2010, 2010. 23201

Beard, A. G., Mitchell, N. J., Williams, P. J. S., Jones, W., and Muller, H. G.: Mesopause-region tidal variability observed by meteor radar, Adv. Space Res., 20, 1237–1240, 1997. 23199

Charney, J. G. and Drazin, P. G.: Propagation of planetary-scale disturbances from lower into the upper atmosphere, J. Geophys. Res., 66, 83–109, 1961. 23200, 23201

Day, K. A. and Mitchell, N. J.: The 16-day wave in the Arctic and Antarctic mesosphere and lower thermosphere, Atmos. Chem. Phys., 10, 1461–1472, doi:10.5194/acp-10-1461-2010, 2010. 23200, 23201, 23204, 23207, 23211

Dickinson, R. E.: Planetary Rossby waves propagating vertically through weak westerly wind wave guides, J. Atmos. Sci., 25, 984–1002, 1968. 23200

Dowdy, A. J., Vincent, R. A., Murphy, D. J., Tsutsumi, M., Riggin, D. M., and Jarvis, J. M.: The large-scale dynamics of the mesosphere – lower thermosphere during the Southern Hemisphere stratospheric warming of 2002, Geophys. Res. Lett., 31, doi:10.1029/2004GL020282, 2004. 23199

Espy, P. J. and Witt, G.: Observation of a quasi 16-day oscillation in the polar summer mesospheric temperature, Geophys. Res. Lett., 23, 1071–1074, 1996. 23199, 23211

Espy, P. J., Stegman, J., and Witt, G.: Interannual variations of the quasi-16-day oscillation in the polar summer mesospheric temperature, J. Geophys. Res., 102, 1983–1990, 1997. 23200, 23203, 23210, 23211, 23212

Forbes, J. M., Jun, G., and Miyahara, S.: On the interactions between gravity waves and the diurnal propagating tides, Planet. Space Sci., 39, 1249–1257, 1991. 23199

Forbes, J. M., Hagan, M. E., Miyahara, S., Vial, F., Mason, A. H., Meek, C. E., and Portnyagin, Y. I.: Quasi 16-day oscillation in the mesosphere and lower thermosphere, J. Geophys. Res., 100, 9149–9163, 1995. 23200, 23202, 23204, 23211, 23212, 23213

Hibbins, R. E., Jarvis, J. M., and Ford, E. A. K.: Quasi-biennial oscillation influence on long-period planetary waves in the Antarctic upper mesosphere, J. Geophys. Res., 114, doi:10.1029/2008JD011174, 2009. 23200, 23201, 23203, 23210, 23211, 23212

Holton, J. R.: An introduction to dynamic meteorology, in: International Geophysics Series, vol. 48, 3rd edn., Academic Press, 1992. 23200

Jacobi, C.: The Quasi 16-day Wave in the Summer Midlatitude Mesopause Region and its Dependence on the Equatorial Quasi-Biennial Oscillation, Report of the LIM and the IFT9, Leipzig, 117–129, 1998. 23203, 23211, 23212, 23213

Jacobi, C., Schminder, R., and Kürschner, D.: Long-period (12–25 days) oscillations in the summer mesopause region as measured at Collm (52° N, 15° E) and their dependence on the equatorial quasi-biennial oscillation, Atmos. Phys., 1, 461–464, 1998. 23203

Jiang, G.-Y., Xiong, J.-G., Wan, W.-X., Ning, B.-Q., Liu, L.-B., Vincent, R. A. and Reid, I.: The 16-day waves in the mesosphere and lower thermosphere over Wuhan (30.6° N, 114.5° E) and Adelaide (35° S, 138° E), Adv. Space Res., 35, 2005–2010, 2005. 23204

Lieberman, R. S., Riggin, D. M., Franke, S. J., Manson, A. H., Meek, C., Nakamura, T., Tsuda, T., Vincent, R. A., and Reid, I.: The 6.5-day wave in the mesosphere and lower thermosphere: evidence for baroclinic/barotropic instability, J. Geophys. Res., 108, doi:10.1029/2002JD003349, 2003. 23200

Lima, L. M., Batista, P. P., Clemasha, B. R., and Takahashi, H.: 16-day wave observed in the meteor winds at low latitudes in the Southern Hemisphere, Adv. Space Res., 38, 2615–2620, 2006. 23200, 23204

Livesey, N., Filipiak, M., Froidevaux, L., Read, W., Lambert, A., Santee, M., Jiang, J., Pumphrey, H., Waters, J., Cofield, R., Cuddy, D., Daffer, W., Drouin, B., Fuller, R., Jarnot, R., Jiang, Y., Knosp, B., Li, Q., Perun, V., Schwartz, M., Snyder, W., Stek, P., Thurstans, R., Wagner, P., Avery, M., Browell, E., Cammas, J.-P., Christensen, L., Diskin, G., Gao, R.-S., Jost, H.-J., Loewenstein, M., Lopez, J., Nedelec, P., Osterman, G., Sachse, G., and Webster, C.: Validation of aura microwave limb sounder O_3 and CO observations in the upper troposphere and lower stratosphere, J. Geophys. Res., 113, doi:10.1029/2007JD008805, 2008. 23204

Luo, Y., Manson, A. H., Meek, C. E., Meyer, C. K., and Forbes, J. M.: The quasi 16-day oscillation in the mesosphere and lower thermosphere at Saskatoon (52° N, 107° W), 1980–1996, J. Geophys. Res., 195, 2125–2138, 2000. 23200, 23211, 23212, 23213

Luo, Y., Manson, A. H., Meek, C. E., Thayaparan, T., MacDougall, J., and Hocking, W. K.: The 16-day wave in the mesosphere and the lower thermosphere: simultaneous observations at Saskatoon (52° N, 107° W), London (43° N, 81° W), Canada, J. Atmos. Sol.-Terr. Phys., 64, 1287–1307, 2002a. 23200, 23204, 23211

Luo, Y., Manson, A. H., Meek, C. E., Meyer, C. K., Burrage, M. D., Fritts, D. C., Hall, C. M., Hocking, W. K., MacDougall, J., Riggin, D. M., and Vincent, R. A.: The 16-day planetary waves: multi-MF radar observations from the arctic to equator and comparisons with the HRDI measurements and the GSWM modelling results, Ann. Geophys., 20, 691–709, doi:10.5194/angeo-20-691-2002, 2002b. 23200, 23201, 23211

Manson, A. H., Meek, C. E., Luo, Y., Hocking, W. H., MacDougall, J., Riggin, D. M., Fritts, D. C., and Vincent, R. A.: Modulation of gravity waves by planetary waves (2 and 16 d): observations with the North American-Pacifc MLT-MFR radar network, J. Atmos. Sol.-Terr. Phys., 65, 85–104, 2003. 23199

Merkel, A. W., Thomas, G. E., Palo, S. E., and Bailey, S. M.: Observations of the 5-day planetary wave in PMC measurements from the Student Nitric Oxide Explorer Satellite, Geophys. Res. Lett., 30, 1196, doi:10.1029/2002GL016524, 2003. 23199

Merkel, A. W., Garcia, R. R., Bailey, S. M., and Russell III, J. M.: Observational studies of planetary waves in PMCs and mesospheric temperature measured by SNOE and SABER, J. Geophys. Res., D14202, doi:10.1029/2007JD009396, 2008. 23199

Meyer, C. K.: Gravity wave interactions with mesospheric planetary waves: a mechanism for penetration into the thermosphere-ionosphere system, J. Geophys. Res.-Space Phys., 104, 28181–28196, 1999. 23199

Mitchell, N. J., William, P. J. S., Beard, A. G., Buesnel, G. R., and Muller, H. G.: Non-linear planetary tidal wave interactions in the lower thermosphere observed by meteor radar, Ann. Geophys.-Atm. Hydr., 14, 364–366, 1996. 23199

Mitchell, N. J., Middleton, H. R., Beard, A. G., Williams, P. J. S., and Muller, H. G.: The 16-day planetary wave in the mesosphere and lower thermosphere, Ann. Geophys., 17, 1447–1456, doi:10.1007/s00585-999-1447-9, 1999. 23200, 23211

Miyahara, S. and Forbes, M.: Interactions between gravity waves and the diurnal tide in the mesosphere and lower thermosphere, J. Meteorol. Soc. Jpn., 69, 523–531, 1991. 23199

Miyahara, S., Portnyagin, Y. I., Forbes, J. M., and Solovjeva, T. V.: Mean zonal acceleration and heating of the 70- to 100-km region, J. Geophys. Res., 96, 1225–1238, 1991b. 23202

Miyoshi, Y.: Numerical simulations of the 5-day and 16-day waves in the mesopause region, Earth Planets Space, 51, 763–772, 1999. 23200, 23204, 23211, 23212, 23213

Morris, R. J., Klekociuk, A. R., and Holdsworth, D. A.: Low latitude 2-day planetary wave impact on austral polar mesopause temperatures: revealed by a January diminution in PMSE above Davis, Antarctica, Geophys. Res. Lett., 36, doi:10.1029/2009GL037817, 2009. 23199

Morris, R. J., Murphy, D. J., French, W. J. R., and Vincent, R. A.: Long-period planetary waves in the mesosphere and lower thermosphere above Davis, Antarctica, J. Atmos. Sol.-Terr. Phys., 69, 2118–2138, 2007. 23199

Nakamura, T., Fritts, D. C., Isler, J. R., Tsuda, T., Vincent, R. A., and Reid, M.: Short-period fluctuations of the diurnal tide observed with low-latitude MF and meteor radars during CADRE: evidence for gravity wave/tidal interactions, J. Geophys. Res.-Atmos., 102, 26225–26238, 1997. 23199

Nielsen, K., Siskind, D. E., Eckermann, S. D., Hoppel, K. W., McCormack, J. P., Benze, S., Randall, C. E., and Hervig, M. E.: Seasonal variation of the quasi 5-day planetary wave: causes and consequences for polar mesospheric cloud variability in 2007, J. Geophys. Res., 115, D18111, doi:10.1029/2009JD012676, 2010. 23199

Palo, S. E., Forbes, J. M., Zhang, X., Russell III, J. M., and Mlynczak, M. G.: An eastward propagating two-day wave: Evidence for nonlinear planetary wave and tidal coupling in the mesosphere and lower thermosphere, Geophys. Res. Lett., 34, doi:10.1029/2006GL027728, 2007. 23199

Pfister, L.: Baroclinic instability of easterly jets with application to the summer mesosphere, J. Atmos. Sci., 42, 313–330, 1985. 23200

Ramkumar, T. K., Gurubaran, S., and Rajaram, R.: Mesospheric planetary wave signatures in the equatorial electrojet, J. Geophys. Res.-Space Phys., 114, doi:10.1029/2007JA012935, 2009. 23199

Salby, M. L.: Rossby normal modes in nonuniform background configurations. Part I: simple fields, J. Atmos. Sci., 38, 1803–1826, 1981a. 23199, 23200

Salby, M. L.: Rossby normal modes in nonuniform background configurations. Part II: equinox and solstice conditions, J. Atmos. Sci., 38, 1827–1840, 1981b. 23199, 23200

Salby, M. L. and Callaghan, P. F.: Influence of planetary wave activity on the stratospheric final warming and spring ozone, J. Geophys. Res., 112, doi:10.1029/2006JD007, 2007. 23199

Shepherd, M. G. and Tsuda, T.: Large-scale planetary disturbances in stratospheric temperature at high-latitudes in the southern summer hemisphere, Atmos. Chem. Phys., 8, 7557–7570, doi:10.5194/acp-8-7557-2008, 2008. 23201

Smith, A. K.: Longitudinal variations in mesospheric winds: evidence for gravity wave filtering by planetary waves, J. Atmos. Sci., 53, 1156–1173, 1996. 23202

Smith, A. K.: The Origins of Stationary Planetary Waves in the Upper Mesosphere, American Meteorological Society, 3033–3041, 2003. 23202

Teitelbaum, H. and Vial, F.: On tidal variability induced by nonlinear interaction with planetary waves, J. Geophys. Res., 96, 14169–14178, 1991. 23199

Thayaparan, T., Hocking, W. H., and MacDougall, J.: Observational evidence of tidal/gravity wave interactions using the UWO 2 MHz radar, Geophys. Res. Lett., 22, 373–376, 1995. 23199

Williams, C. R. and Avery, S. K.: Analysis of long-period waves using the mesosphere-stratosphere-troposphere radar at poker flats, Alaska, J. Geophys. Res., 97, 20855–20861, 1992. 23201, 23202, 23207, 23211, 23212, 23213

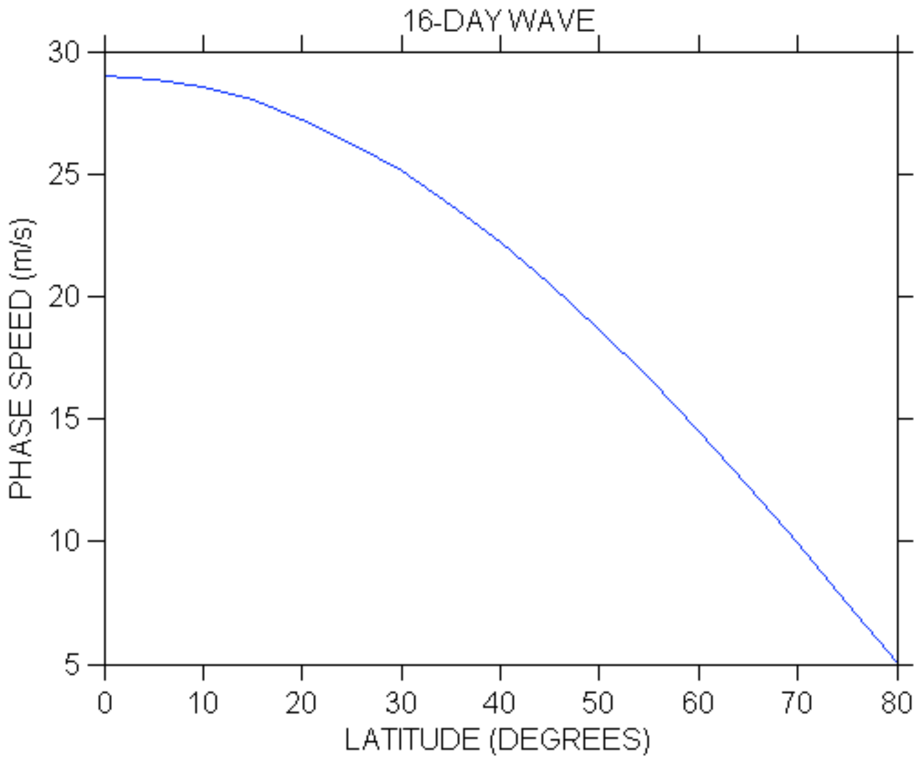

Fig. 1. Zonal phase speed as a function of latitude for a 16-day wave of zonal wavenumber 1.

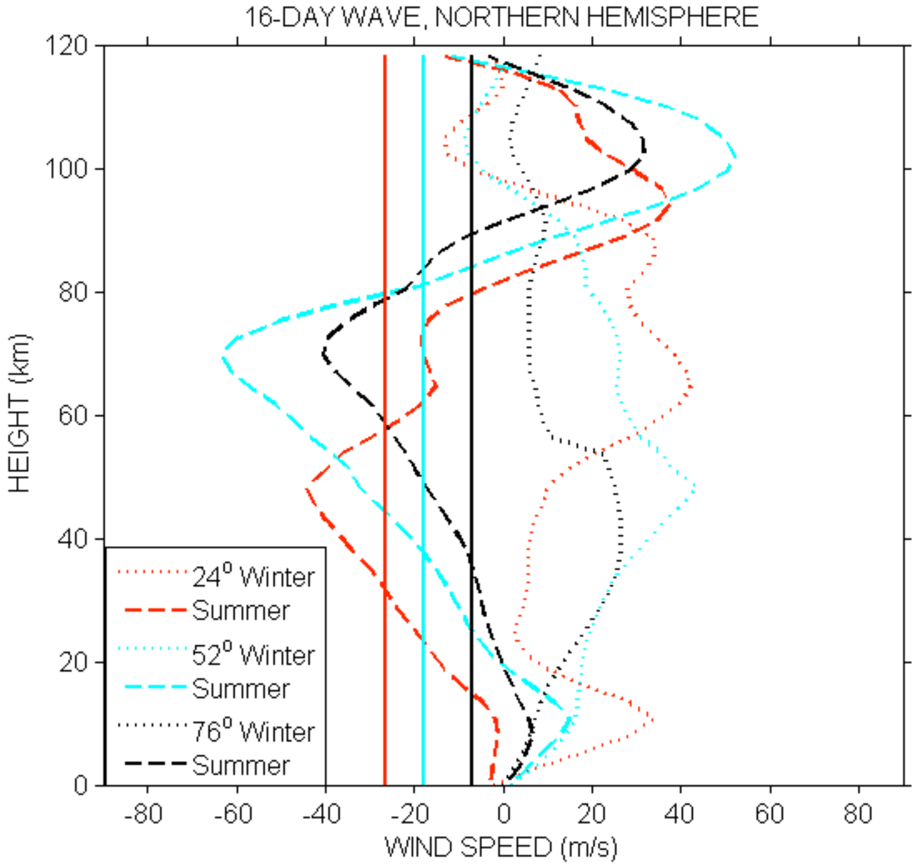

Fig. 2. URAP winds for latitudes of 24, 52 and 76° for both winter (January) and summer (July) in the Northern Hemisphere. Also plotted are the zonal phase speeds of the 16-day wave for these latitudes.

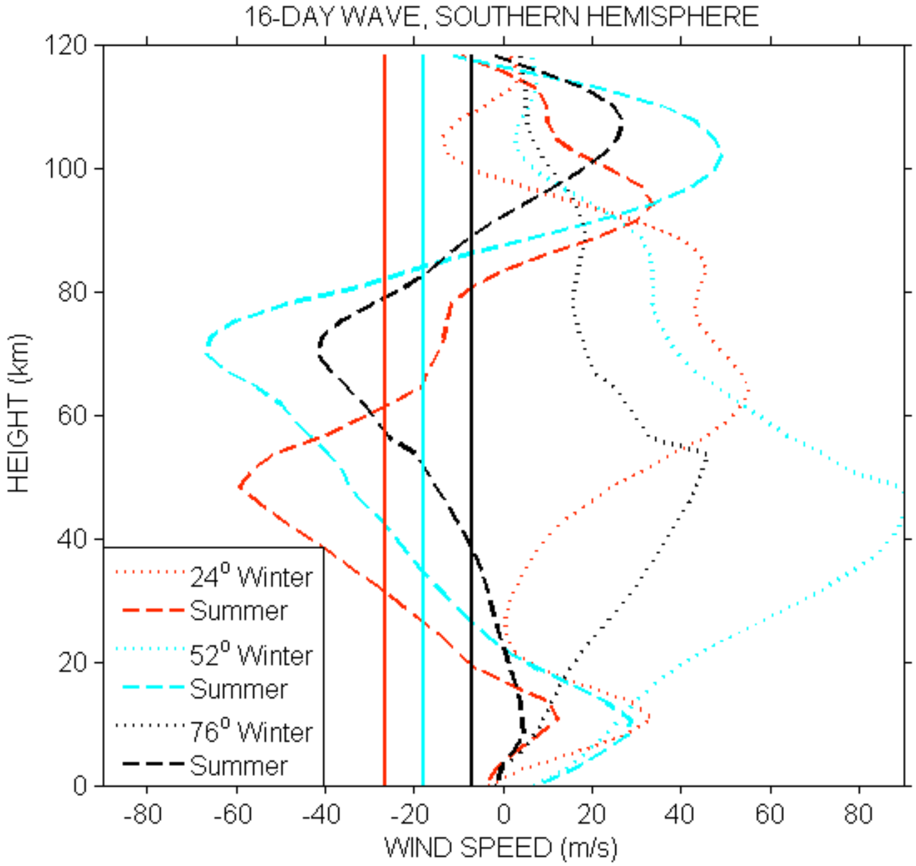

Fig. 3. URAP winds for latitudes of 24, 52 and 76° for both winter (July) and summer (January) in the Southern Hemisphere. Also plotted are the zonal phase speeds of the 16-day wave for these latitudes.

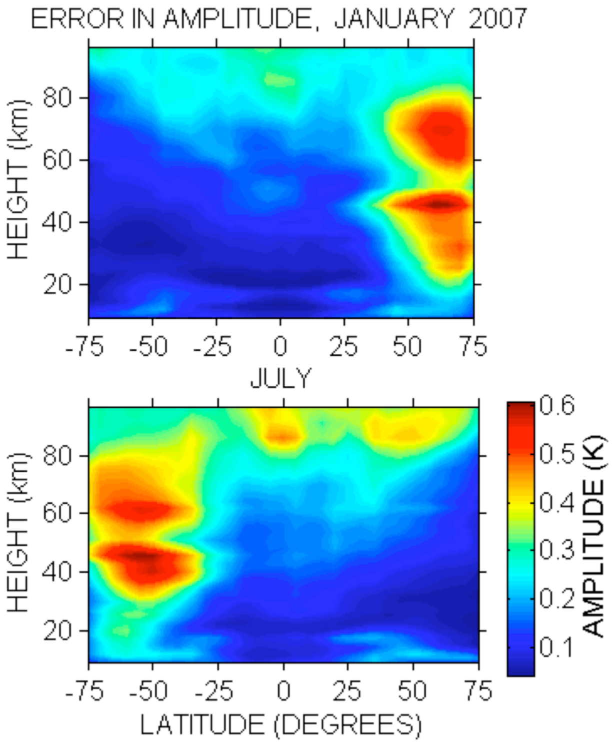

Fig. 4. Least-squares fit error in the wave amplitudes for January and July 2007 using a 95% confidence level.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮ ▶▮
◀ ▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

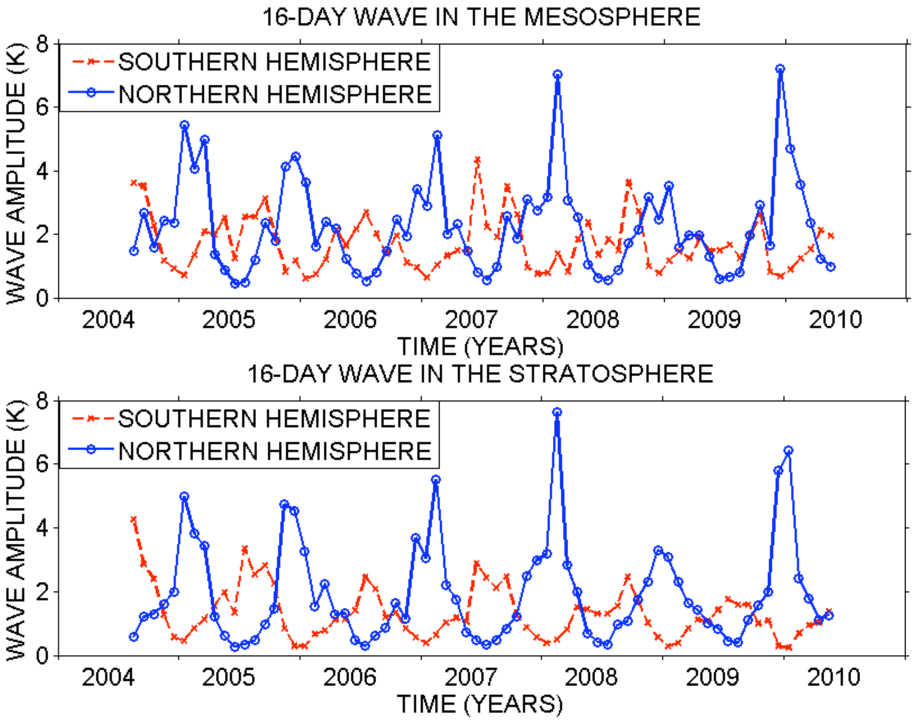

Fig. 5. Time series of monthly-mean temperature amplitudes for the 16-day wave in the MLT at 65–95 km (top) and stratosphere at 35–55 km (bottom). Both for latitudes of 50–75°.

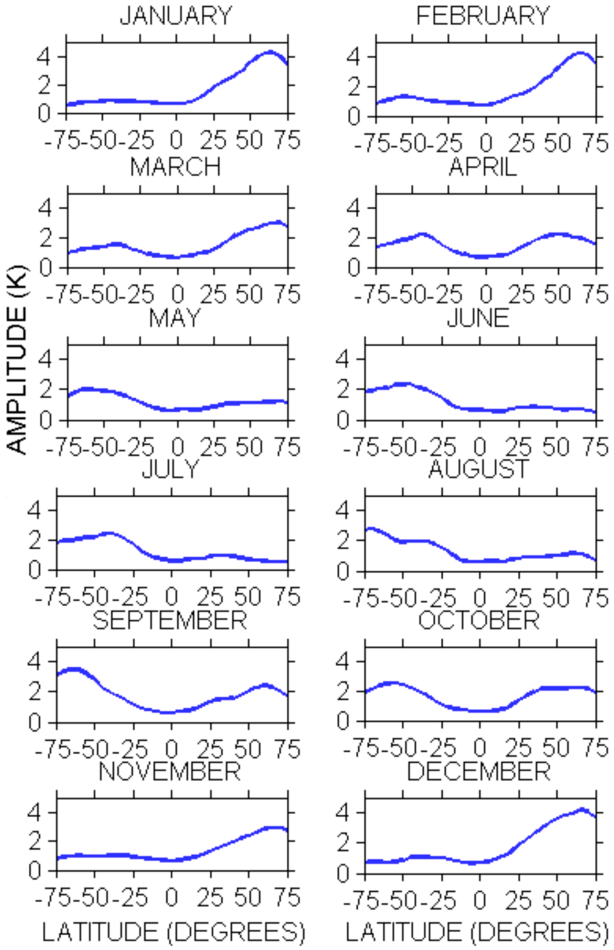

Fig. 6. The monthly-mean temperature amplitude of the 16-day wave as a function of latitude at heights of ~65–95 km for 2005.

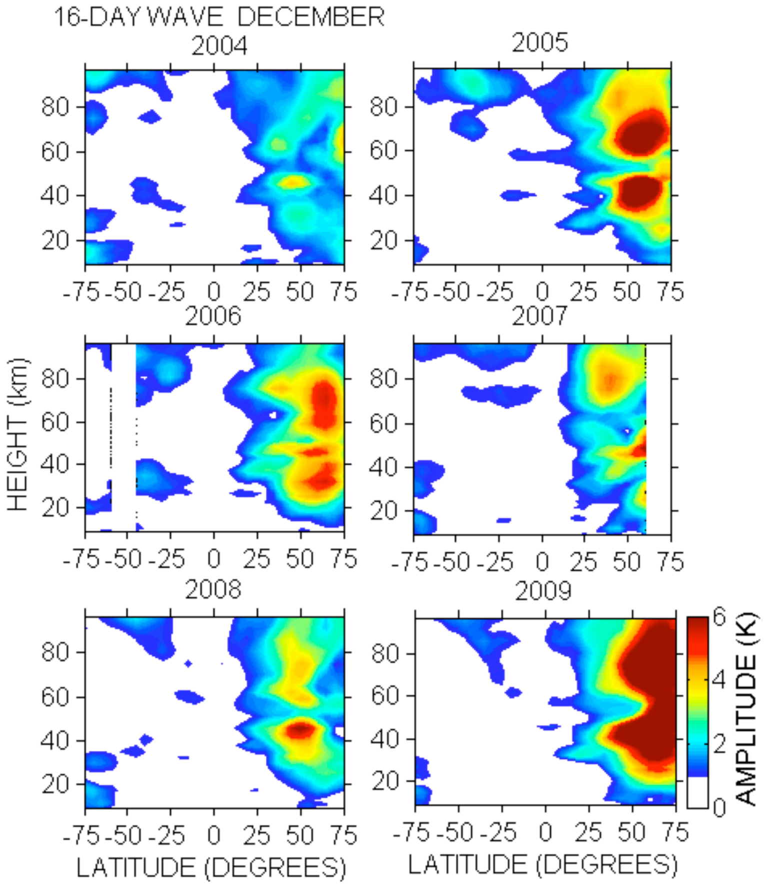

Fig. 7. Temperature amplitudes of the 16-day wave for the month of December for the years 2004–2009.

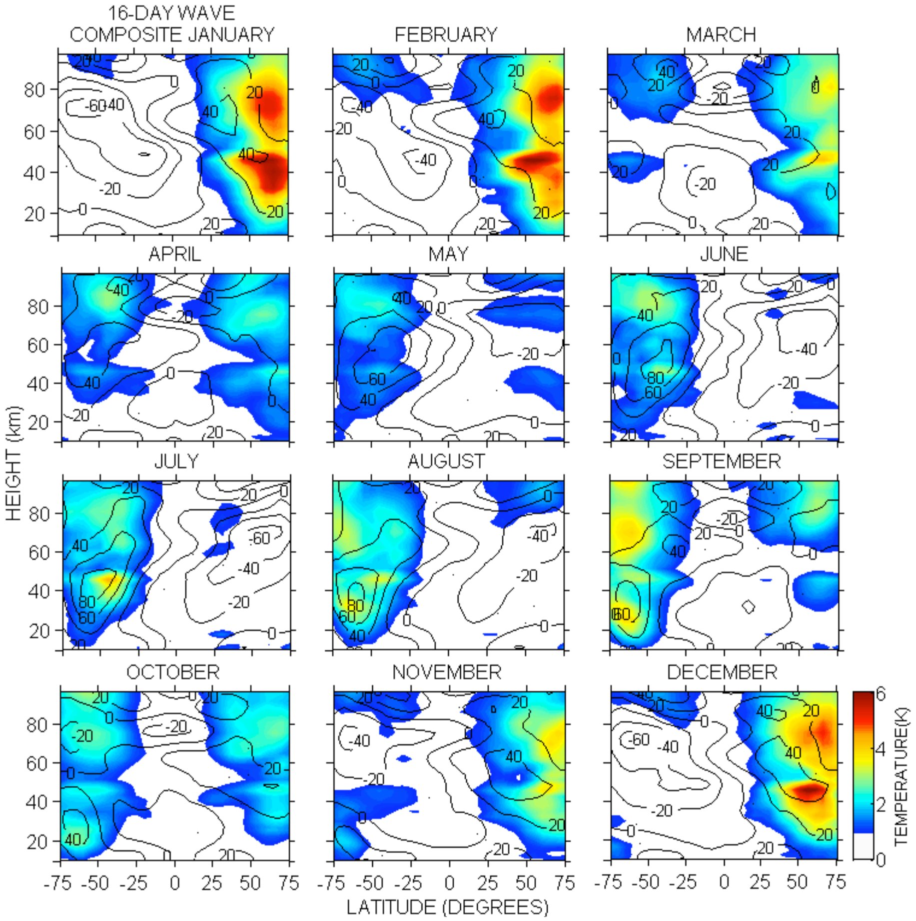

Fig. 8. Composite-month temperature amplitudes for the 16-day wave in each month of the year, August 2004–May 2010. Also plotted are the UARS composite monthly-mean zonal winds (ms^{-1}) as contour lines.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀|
|▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

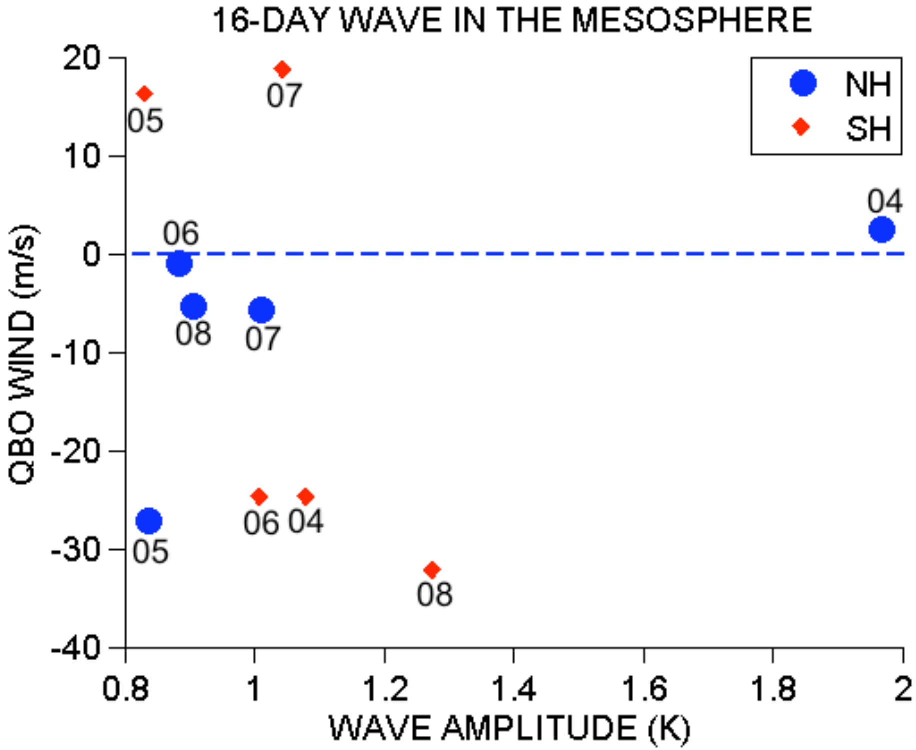

Fig. 9. Mean summer-time temperature amplitudes of the 16-day wave in the mesosphere at heights from 80–96 km and latitudes of 50–75°, as a function of QBO zonal winds at 10 hPa.