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Mean winds, temperatures and the 16- and 5-day planetary waves in the mesosphere and lower thermosphere over Bear Lake Observatory (42° N 111° W)

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Abstract

Atmospheric temperatures and winds in the mesosphere and lower thermosphere have been measured simultaneously using the Aura satellite and a meteor radar at Bear Lake Observatory (42° N, 111° W). The data presented in this study is from the interval March 2008 to July 2011.

The mean winds observed in the summer-time over Bear Lake Observatory show the meridional winds to be equatorward at all heights during April-August and to reach monthly-mean speeds of $-12\,\mathrm{ms^{-1}}$. The mean winds are closely related to temperatures in this region of the atmosphere and in the summer the coldest mesospheric temperatures occur about two weeks after the strongest equatorward meridional winds. In other seasons the meridional winds are poleward, reaching monthly-mean values of up to $12\,\mathrm{ms^{-1}}$. The zonal winds are eastward through most of the year and in the summer strong eastward zonal wind shears of up to $\sim 4.5\,\mathrm{ms^{-1}\,km^{-1}}$ are present. However, westward winds are observed at the upper heights in winter and sometimes during the equinoxes. Considerable inter-annual variability is observed in the mean winds and temperatures.

Comparisons of the observed winds with URAP and HWM-07 reveal some significant differences. Our radar zonal wind observations are generally more weakly eastward than these predicted by the URAP model zonal winds. Considering the radar meridional winds, in comparison to the HWM-07 our observations reveal equatorward flow at all heights in the summer whereas HWM-07 suggests that only weakly equatorward, or even poleward, flows occur at the lower heights. However, the zonal winds observed by the radar and modelled by HWM-07 are generally similar in structure and strength.

Signatures of the 16- and 5-day planetary waves are clearly evident in both the radar-wind data and Aura-temperature. Short-lived wave events can reach large amplitudes of up to $\sim 15\,\mathrm{ms^{-1}}$ and 8 K and $20\,\mathrm{ms^{-1}}$ and 10 K for the 16- and 5-day wave, respectively. A clear seasonal and short-term variability are observed in the 16- and 5-day planetary wave amplitudes. The 16-day wave reaches largest amplitude in winter and

is also present in summer, but with smaller amplitudes. The 5-day wave reaches largest amplitude in winter and in late summer. An inter-annual variability of the amplitude of the planetary waves are evident in the four years of observations. Some 32 episodes of large-amplitude wave occurrence are investigated and the temperature and wind amplitudes, A_T and A_W, are found to be related by, $A_T = 0.49 A_W$ and $A_T = 0.58 A_W$ for the 16- and 5-day wave, respectively.

1 Introduction

Ground-based meteor and MF radars are able to make continuous observations of winds in the Mesosphere and Lower Thermosphere (MLT) and have thus been extensively used to study the background winds and planetary waves of the MLT.

Previous ground-based observations have been made at Bear Lake Observatory (BLO) using an Imaging Doppler Instrument (IDI) to observe MLT mean winds and planetary waves. Berkey et al. (2001) presented results from February 1999 to April 2000. The mean meridional mean winds were found to be strongest at heights of ~ 90 km in mid-winter reaching ~ 15 ms^{-1}. The zonal mean winds were found to be westward in late spring to early summer, reaching speeds of ~ 25 ms^{-1}. They additionally observed planetary waves, in particular a 16- and 5–6-day wave were evident.

Jones et al. (2003) compared four months of IDI measurements with those made by a meteor wind radar at the same site. It was concluded that there was overall very good agreement between the two techniques. In addition, they noted the presence of long-period planetary waves in mid-late February. Note this meteor radar was operated at BLO for a relatively short deployment and is not the same instrument now permanently sited there.

Roper and Berkey (2011) reported observations of mean winds, gravity waves and turbulence for the year 2000 made at BLO by the IDI. It was observed that the zonal winds maximised in summer at speeds of ~ 35 ms^{-1} and reduced in the spring to speeds of ~ –10 ms^{-1}. The meridional winds were observed to be nearly continuously equatorward, expect for a very short-lived region at the upper heights in April and May.

Further studies at similar latitudes in the USA and Canada include those of Luo et al. (2002a); Manson et al. (2004a), who used MF radars to investigate the planetary-wave field in the MLT and reported a strong seasonal variability.

The Dobson-Brewer large-scale circulation of winds drives the upwelling of cold air over the northern polar region in northern summer. This circulation thus implies an intimate connection between the mean temperatures and the mean meridional winds of the MLT region. A limited number of observational studies have investigated the connection between these winds and temperatures. Further, it has been suggested that short-term perturbations in the meridional winds result in related short-term perturbations in temperature. For example, polar observations by Espy et al. (2003) revealed a clear correlation between meridional winds and temperatures over Rothera (68° S, 68° W) and Halley (76° S, 27° W) in a study made using an MF radar and OH rotational temperatures in Austral winters. Cho et al. (2011) reported meteor-radar and OH airglow observations of meridional winds and temperatures in the Arctic MLT over Resolute Bay (74° N, 95° W) and Esrange (68° N, 21° E). They observed a positive correlation between the mean meridional winds and temperatures that is consistent with the large-scale circulation.

In contrast, Jacobi et al. (2007) measured meridional winds and temperatures in the MLT over Collm (51° N, 13° E) using a meteor radar. They considered time-scales of up to one month and reported that they did not observe a correlation between the meridional winds and temperatures in the summer, but did observe a positive correlation in the winter.

Significant meridional winds have been reported in the summer-time MLT at polar latitudes (e.g., Hocking, 2001; Sandford et al., 2010), midlatitudes (e.g., Manson and Meek, 1987; Hall et al., 2008; Roper and Berkey, 2011) and equatorial latitudes (e.g., Rajaram and Gurubaran, 1998; Kishore et al., 2000; Sharma et al., 2010).

At middle latitudes the characteristics of the meridional and zonal mean winds and temperatures of the MLT have been investigated using ground-based and satellite data.

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The meridional winds of the MLT are particularly important because they play a key role in transporting air from the summer polar MLT into the winter polar stratosphere, (e.g., Plane et al., 1999; Smith, 2004). Ultimately, diabatic subsidence transports some of the meteor smoke particles carried by this circulation down into the lower stratosphere, where they may influence ozone and, potentially, climate, (e.g., Plumb et al., 2002; Curtius et al., 2005).

Planetary waves are a major feature in the dynamics of the middle atmosphere. In the MLT they can reach large amplitudes and are important because they can modulate the amplitude of atmospheric tides (e.g., Teitelbaum and Vial, 1991; Mitchell et al., 1996; Palo et al., 1999; Pancheva et al., 2004), influence the transport and photochemistry of minor species (e.g., Kulikov, 2007), modulate the fluxes of gravity-wave momentum that drives the planetary-scale 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) and cause perturbations in temperatures that then modulate the occurrence of Polar Mesospheric Clouds (e.g., Espy and Witt, 1996; Merkel et al., 2003, 2008; Nielsen et al., 2010) and Polar Mesospheric Summer Echoes (e.g., Morris et al., 2009). A major component of the planetary-wave field in the MLT is the so-called normal modes that manifest as the 2-, 5-, 10- and 16-day planetary waves (e.g., Salby, 1981a,b).

Salby (1981a) suggested on theoretical grounds that the 16- and 5-day planetary waves are manifestations of the gravest symmetrical wavenumber 1, westward-travelling Rossby wave. The period of the 16- and 5-day wave has, in fact, been observed to lie between about 12–20 days and 4–7 day, respectively. The 16-day wave has been reported to have wind amplitudes of up to about $\sim 15\,\mathrm{ms^{-1}}$ and temperature amplitudes reaching $\sim 10\,\mathrm{K}$ in the MLT (e.g., Williams and Avery, 1992; Forbes et al., 1995; Day and Mitchell, 2010b). The 5-day wave has been reported to have wind amplitudes of up to about $\sim 20\,\mathrm{ms^{-1}}$ and temperature amplitudes reaching $\sim 15\,\mathrm{K}$ in the MLT (e.g., Williams and Avery, 1992; Belova et al., 2008; Day and Mitchell, 2010a).

This study considers near-continuous observations of MLT winds and temperatures

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made over a 41-month interval using a meteor radar at BLO and the Aura Microwave Limb Sounder (MLS), respectively. The first focus of the study is to establish a climatology of mean winds over BLO at heights of about 80–100 km and to relate this to the seasonal variation in temperature. This is compared to the URAP and the HWM-07 models. Secondly, a representative climatology of the 16- and 5-day waves over BLO measured by simultaneous meteor radar winds and Aura MLS temperatures is presented. These data are used to investigate the relative magnitude of the wind and temperature perturbations caused by each wave. The two day wave will be the subject of a separate study. Note that here we will not consider the atmospheric tides or long-term variability of the mean winds and planetary waves. These subjects will be considered in subsequent publications.

2 Data analysis

The winds used in this study were measured by a meteor radar located at BLO, near Logan, Utah, in the USA (42° N, 111° W) installed in March 2008. The radar is a standard all-sky, SKiYMET VHF system operating at a radio frequency of 32.5 MHz, with a pulse repetition of 2144 Hz and a peak power of 6 kW. The interferometer arrangement of radars consists of six crossed-element Yagi antenna, five receiving and one transmitting. More than 95 % of meteor echoes are detected at heights between 80–100 km. The radar typically records ∼ 4000 meteors a day. Only underdense echoes are recorded. A more complete description of a very similar radar design can be found in Hocking et al. (2001).

The radar data were used to estimate zonal and meridional winds with a time step of 1 h at heights between ∼ 80–100 km. This height range was divided into six independent height-gates of depth 5, 3, 3, 3, 3, 5 km. However, the vertical distribution of meteor echoes maximises at a height near 90 km and the meteor counts decrease strongly above and below this height. To allow for this, in each height gate the average meteor echo height was calculated yielding heights of 80.8, 84.7, 87.5, 90.4, 93.3 and

97.1 km as the weighted mean height of the six height gates. The radar data set thus consists of hourly-spaced zonal and meridional winds in six height gates.

These local measurements of wind were complemented by estimates of temperature measured by Aura MLS. Aura MLS Version 2.2 Temperature Analysis was used in this study. MLS observations commenced from early August 2004 (Livesey et al., 2008). The data are recorded on 34 pressure levels, 316–0.001 hPa (∼ 10–96 km). The vertical resolution is 7–8 km at 316–100 hPa, 4 km at 31–6.8 hPa, 6 km at 1 hPa and 9 km above 0.1 hPa. For this study the pressure levels were converted to approximate heights for comparisons with the meteor radar measurements.

The standard product for temperature was taken for the Core retrieval (118 GHz only) from 316–1.41 hPa and from the Core + R2A (118 and 190 GHz) retrieval from 1–0.001 hPa. The temperature precision is ∼ ±1 K from 316–0.1 hPa and degrades to ∼ 3 K at 0.01 hPa Schwartz et al. (2008). The data are assigned a "flag" commenting on the quality of the data. The quality comment is computed from a χ^2 statistic for all the radiances that are considered to have significantly affected the retrieved species and then normalised by dividing by the number of radiances. The quality flag is simply the reciprocal of this statistic. Data that have a quality flag of "0" they are regarded as poor quality and therefore discarded.

3 Results

3.1 Seasonal mean winds and temperatures

This section presents the climatology of the mean winds and temperatures in the MLT over BLO. The climatological winds are then compared with the predicted winds from the UARS (URAP) and the HWM-07 models. To investigate the behaviour and characteristics of the background winds over BLO monthly-mean mean zonal and meridional winds were calculated for each month and height gate.

Firstly, we will consider the mean meridional winds and temperatures and examine

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how they are related. Figure 1 shows the monthly-mean meridional winds for each individual year and also a composite-year. Note that the monthly-mean values may mask any short-term perturbations. Plotted below each meridional wind plot is the corresponding temperature plot. MLS temperatures were calculated as 14-day means for the height gates centred on 81, 86, 91 and 97 km to allow a comparison with the meridional winds. The temperatures are means for a latitude/longitude "box" of 40–45° N, 90–120° W for four the height gates between on ~ 81–97 km.

The figure reveals a clear seasonal cycle in which the meridional winds are equatorward (negative) in the summer and poleward (positive) in the winter. The meridional winds are generally equatorward from April–September at all heights observed by the radar. The flow is generally strongest at heights of ~ 85 km, regularly reaching speeds of ~ $-12\,\mathrm{ms^{-1}}$. In contrast, the winter-time flow is poleward and strongest in the upper heights. The strongest poleward flows are generally observed in early–mid winter reaching speeds of ~ $12\,\mathrm{ms^{-1}}$ in most years. In the late winter the winds maximise again, but at slightly lower heights of ~ 83 km, reaching speeds of ~ $6\,\mathrm{ms^{-1}}$. However, we should note monthly-means can hide short-term fluctuations in the mean winds.

The figure also reveals a high degree of inter-annual variability. For instance, if we consider the winds in summer we find that the strongest equatorward flows occurred in May in 2008 but in June in 2009, 2010 and 2011. We also note that the strongest equatorward flows peak at heights near 85 km in all years, except in 2010 when a region of strong flow existed at heights of above 85 km in May. Further, the winter flow is not consistently poleward throughout the season, for example, in January 2011 the winds reverse and are equatorward reaching speeds of $-4\,\mathrm{ms^{-1}}$.

To compare the meridional winds with the temperatures, the temperature plots are marked with a vertical line where the strongest equatorward winds occurred (two lines are shown for 2010 because the winds had two distinct episodes of maximum flow). It can be seen that the temperature minima in most cases lag the corresponding meridional wind minima (i.e., time of strongest equatorward flow) by about two weeks. For example, in 2008 the strongest equatorward winds occur in May whereas the coldest

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temperatures occur in early June. This behaviour is also apparent in the composite-year plots of the mean winds and temperatures. However, we did not observe a link between the strength of the mean meridional winds and temperatures.

A similar mean-wind analysis was used to produce Fig. 2, which shows the monthly-mean zonal winds for each individual year, a composite year and also the composite-year URAP zonally-averaged monthly-mean zonal winds.

The figure shows a well-defined seasonal cycle in monthly-mean zonal winds. Eastward flow occurs throughout the summer and through most of the winter except at the uppermost heights observed in winter and during late spring/early summer. The summer-time zonal winds maximise at heights of ~ 93 km with wind speeds reaching up to ~ 40 ms^{-1}. Above and below these heights the wind speeds decrease. In the winter the zonal winds generally maximise at the lowest heights observed, at ~ 83 km with winds reaching up to ~ 30 ms^{-1}. There is a minimum observed at the equinoxes. In two of the four years (2009 and 2010) the winds actually reverse at all heights near the spring equinox.

Some inter-annual variability is evident from the figure. Considering the winds in summer, we find that the strongest eastward flows occurred every June and peak at heights of ~ 93 km. However, the duration of these strongly eastward winds varies from year-to-year. For example, in 2008, 2009 and 2011 the winds are strongly eastward from May–August and reach speeds of ~ 35 ms^{-1}, whereas in 2010 the winds are strongly eastward from May–July and reach rather stronger speeds of ~ 45 ms^{-1}. The spring equinoctial flow in 2009 and 2010 is strongly westward at all heights observed, reaching speeds of ~ –20 ms^{-1}. In contrast, in 2008 and 2011 the westward flow is significantly weaker or even absent around the spring equinox. In these two years the strongest winds reach only speeds of –5 ms^{-1} and are restricted to the lower heights, below ~ 85 km.

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3.2 Comparison with URAP and HWM-07

The URAP model uses measurements from the Upper Atmosphere Research Satellite (UARS), the High Resolution Doppler Instrument (HRDI) and the UK Met Office Stratospheric data assimilation system. See Swinbank and Ortland (2003) for more details. The data have been used to produce a composite-year analysis of the monthly-mean zonally-averaged zonal winds. The monthly data are available from November 1991 to November 1999 at heights of ~0–118 km and at latitudes of −80–80°. Note that although this data set does not overlap in time with that of the radar and uses zonal rather than local averages, it nevertheless can be used to provide a useful comparison. The URAP model is used as it is an empirical model of global coverage.

Comparing the zonal wind composite-year from our radar with the URAP model reveals some significant differences. The zonal winds are generally stronger in the URAP model. A striking difference is that the deep region of westward flow following the spring equinox is not well represented in the URAP model. Further, the winds in winter are significantly stronger in URAP than those observed and do not reverse at any height, whereas our observations suggest the winter zonal winds often reverse at heights between 90–95 km. We will consider possible explanations for this in Sect. 4. Considering the difference years observed by the radar and the composite-year URAP monthly-mean zonal winds we see that they are most similar in the years 2008 and 2011, where for example, there is no spring equinox reversal observed across the entire height range.

The HWM-07 model predicts both meridional and zonal winds using assimilated ground-based and satellite data. Full details of the model can be found in Drob et al. (2008). The model predicts results for specified longitude, latitude and height. Here, the HWM-07 model has been used to estimate the meridional and zonal winds at 41.9° N and 111.4° W, i.e., over BLO, for heights of 80–100 km.

Figure 3 presents the meridional and zonal monthly-mean winds from the HWM-07 model. Considering the meridional winds, a comparison with the composite-year radar

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results of Fig. 1 reveals a general similarity in that the strongest equatorward winds occur in summer. However, there are a number of notable differences. In particular, the model shows equatorward winds present, at least at some heights, throughout the year (although some poleward flow does occur) whereas our observations show a clear seasonal reversal in meridional winds such that equatorward flow occurs at all heights from about April–August. Further, the model predicts poleward flows in winter of generally less than 2 ms^{-1}, whereas our observations suggest rather faster flows of up to ~8 ms^{-1}. Finally, the model suggests the summer-time equatorward flow actually reverses heights below ~80 km, whereas our observation show that the flow is strongly equatorward even at the lowest heights observed.

Considering the zonal winds from the HWM-07 model, it can be seen that they are generally in good agreement with our composite-year zonal winds. However, a number of differences are again apparent. In particular, the winter-time zonal winds at the lower heights are much stronger in HWM-07 model than we observe. For instance, at the lowest heights considered the strongest winter-time winds reach almost 50 ms^{-1}, whereas our observations indicate winds only about half that speed. In the summer-time, the eastward winds in the model reach up to ~50 ms^{-1} compared to our observations in which they reach up to ~40 ms^{-1}.

In summary we see that both the URAP and HWM-07 models predict stronger zonal winds in the winter than we observe at the lower heights. Further, although HWM-07 model predicts summer-time equatorward flows of similar speed to those observed, it does not show the deep region of poleward flow evident over BLO.

3.3 16- and 5-day planetary waves

This section presents observations of the 16- and 5-day planetary waves over BLO. A particular focus will be observations of the waves made simultaneously in winds and temperatures.

The time-series of daily radar winds and MLS temperatures were first examined for oscillations that might be caused by planetary waves. Figure 4 presents an example of

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the winds and temperatures from the interval 1 September 2009 to 31 January 2010. It is evident from the figure that there are a number of intermittent oscillations in wind and temperature with periods of several days or more. Successive wind (top axis) and temperature (bottom axis) maxima are marked on the figure to highlight the oscillations. For example, there is an oscillation with the period of ~6 days and amplitude of order ~10 $\mathrm{m\,s^{-1}}$ and 5 K in September (the period lengthening to ~8 days in October). There is also an oscillation of period ~16 days and amplitudes of order ~15 $\mathrm{m\,s^{-1}}$ and 10 K in December and January, similarly marked on the figure. These periods are consistent with those reported for the "5-day wave" and the "16-day wave", respectively (e.g., Espy and Witt, 1996; Espy et al., 1997; Luo et al., 2002b; Lieberman et al., 2003; Riggin et al., 2006; Day and Mitchell, 2010a,b; Day et al., 2011).

To examine the evolution of these oscillations throughout the wind data, a wavelet analysis of the zonal-wind time-series at a height of ~90 km was performed and the results of this analysis are presented in Fig. 5. The analysis used a Morlet wavelet of non-dimensional wavenumber 6. The figure shows "bursts" of wave activity occurring at different wave periods throughout the data set in a similar manner to those reported in observations of MLT winds (e.g., Manson et al., 2004b).

Wave amplitudes in the wavelet analysis can reach peak values of more than 20 $\mathrm{m\,s^{-1}}$. Particularly large-amplitude bursts include the 5- and 16-day wave bursts described above, i.e., in September–October 2009 (wave period ~6–8 days) and December 2009 (wave period ~16 days) which have amplitudes of ~13 $\mathrm{m\,s^{-1}}$ and 10 $\mathrm{m\,s^{-1}}$, respectively. Note that the 5-day wave appears to be occur in bursts throughout the year in every year, whereas the 16-day wave is mainly present during the solstice.

To investigate the seasonal variability of the 16- and 5-day waves, the horizontal wind variance has been used as a proxy for wave activity. In this analysis, the band-passed winds in each height gate for each month are used to calculate a variance value for the meridional and zonal components of the winds. The time-series where band-passed between period limits of 12–20 days and 4–7 days, corresponding to the period ranges of the 16- and 5-day waves, respectively. These limits were chosen on the basis of the results presented above and because they are commonly used in studies of these two particular planetary waves.

By examining these variances as a function of height and time the seasonal and inter-annual variability of the 16- and 5-day waves can be investigated. A similar analysis has been used in the the studies of the 16-day and 5-day planetary waves at polar latitudes (e.g., Day and Mitchell, 2010a,b). Note that for a constant amplitude oscillation, amplitude is equal to the square root of twice the variance. For example, a variance of $10\,m^2\,s^{-2}$ corresponds to a wave amplitude of $4.5\,ms^{-1}$, a variance of $50\,m^2\,s^{-2}$ corresponds to a wave amplitude of $10\,ms^{-1}$ and a variance of $100\,m^2\,s^{-2}$ corresponds to a wave amplitude of $14.1\,ms^{-1}$ etc.

Time-height contours of meridional and zonal monthly variances for all of the years of data available over BLO are presented in Fig. 6. The monthly-mean zonal winds for each year have been plotted over the top of the figure for that specific year to enable a comparison of the background winds and the level of 16- and 5-day wave variances.

Figure 6 shows the 16-day wave generally maximises in winter-time throughout the height region observed, where it reaches variances of up to $\sim 100\,m^2\,s^{-2}$. In contrast, in summer-time the variances are much smaller, reaching only up to $\sim 30\,m^2\,s^{-2}$ in 2009 and 2010 and $70\,m^2\,s^{-2}$ in 2008. The summer-time 5-day wave is observed to be short-lived and localised in height, whereas the winter-time wave is generally longer-lived and occurs through the whole height region observed. The 5-day wave reaches maximum variances of up to $\sim 100\,m^2\,s^{-2}$ in both summer-time and winter-time. Both waves usually display smaller variances around the equinoxes. The figure reveals a significant inter-annual variability of the waves in both the zonal and the meridional components.

We will now compare these radar observations of the waves with observations of the waves in MLS temperature data. Figures 7 and 8 present data from December and September 2009 as examples of the wave signatures in Hovmöller diagrams. Other months showed similar wave signatures and are not shown here for reasons of space. Figures 7 and 8 also present the bandpassed zonal winds, using the same bandpass

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limits as used for Fig. 6. On each Hovmöller diagram a line indicating the longitude of BLO is shown.

Considering Fig. 7, the 16-day wave can be clearly seen in both the wind and temperature data. The wind amplitudes appear to be $\sim 10\,\mathrm{ms^{-1}}$ and temperature amplitudes at the longitude of BLO appear to be $\sim 5\,\mathrm{K}$. Considering Fig. 8, the 5-day can similarly be clearly seen wave in wind and temperature data. The wind amplitudes appear to be $\sim 15\,\mathrm{ms^{-1}}$ and temperature amplitudes at the longitude of BLO appear to be $\sim 6\,\mathrm{K}$.

To examine the planetary waves in more detail temperature and zonal wind time series were band-passed as previously described. The zonal winds were used because of the larger variances evident in Fig. 6. The results of this analysis are presented in Fig. 9. Note on the figure the temperatures have been multiplied by a factor of 3 to facilitate a simple by-eye comparison with the winds.

Considering both Figs. 6 and 9, the inter-annual variability of the waves are clearly evident. The winter-time 16-day wave maximises in January/February of the years 2008 and 2010. In 2009 there was a major Sudden Stratospheric Warming (SSW) event. SSWs are known to dampen planetary-wave amplitudes and this is clearly observed in this particular case.

Further, the 5-day wave is known to have large amplitudes in the summer-time, but to be highly influenced by the background winds (e.g., Riggin et al., 2006; Belova et al., 2008; Day and Mitchell, 2010a). This may, in part, account for the inter-annual variability evident in our results. For example, in the summers of 2008 and 2009 the wave maximises at the middle and upper heights observed. In contrast, in the summer of 2010 the wave appears to extend to lower heights observed and maximises approximately one month earlier in the season.

Considering the band-passed winds and temperatures of Fig. 9 in more detail, generally, larger wind perturbations correspond to larger temperature perturbations in the case of both the 16- and 5-day waves. For each wave the correlation between the wind and temperature time series was calculated as a function of lag. In the case of the 16-day wave the correlation coefficient reached a maximum of 0.40 at a lag of 5 days with

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the winds leading the temperatures. This means for the 16-day wave that the coldest temperatures occur when the winds are zero and reversing from eastward to westward. In the case of the 5-day wave the correlation coefficient reached a maximum of 0.22 at a lag of 2 days with the winds leading the temperatures.

To quantify the relationship between the wind and the temperature perturbation of the two waves we considered episodes where the waves displayed large amplitude bursts. The bursts have been arbitrarily defined as a continuous event in which the wind amplitude exceeded 5 ms^{-1} for a duration of more than one cycle. Bursts were only used if a Student T-test showed them to be statistically related above a 90 % confidence level. Figure 10 presents the results of this analysis for both waves. A least-squares straight-line fit forced through zero to these data suggests that the temperature and wind amplitudes, A_T and A_W, respectively are related by $A_T = 0.49 A_W$ for the 16-day wave and $A_T = 0.58 A_W$ for the 5-day wave (i.e., for the 16-day wave a 1 ms^{-1} wind amplitude corresponds to a temperature perturbation amplitude of 0.49 K).

Finally, we analysed the Aura MLS temperatures using the method of Wu et al. (1995), which yields the zonal-mean amplitude and phase of particular zonal wavenumbers within a height-latitude band. Here, we have used this analysis to determine the temperature amplitudes of the 16- and 5-day waves within a latitude band of 35–45° N, assuming both waves to be westward-propagating zonal-wavenumber 1 features. In each case, the zonally-averaged amplitudes were calculated as monthly means.

Figure 11 presents the zonal-mean monthly wave temperature amplitudes calculated by this analysis. The monthly analysis was used to reduce the uncertainty in the results. Figure 11 reveals the same general seasonal cycle for the 16- and 5-day waves observed in winds over BLO in the upper mesosphere (Fig. 6).

Figure 11 reveals that the 16-day wave reaches largest amplitudes of ~ 4 K in winter at heights near ~ 80 km but also has a second maximum at ~ 45 km. This was also observed by e.g., Day et al. (2011) when considering the 16-day wave. Figure 11 also shows the 5-day wave to maximise in winter and late summer with amplitudes of up to ~ 4 K at heights of ~ 90 km. A winter-time maximum is also observed near the

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stratopause with amplitudes of up to ∼3 K at heights of ∼45 km.

Comparing these satellite observations with our radar observations, the winter-time and summer-time signatures for the 16- and 5-day waves, respectively, can be seen to be clearly represented in both the satellite and radar observations. However, the satellite observations of Fig. 11 reveal that the summer-time 5-day wave only reaches significant amplitudes at heights above ∼70 km and so does not extend to heights much lower than those observed by the radar. Figure 11 also shows that the 16-day wave does not reach amplitudes of greater than 1 K in summer.

4 Discussion

The seasonal pattern of zonal and meridional winds we report here is in good general agreement with earlier observations made at BLO (e.g., Berkey et al., 2001; Jones et al., 2003; Roper and Berkey, 2011) and other mid-latitude Northern Hemisphere observations (e.g., Manson et al., 2004a). However, some differences are apparent. The meridional mean winds reported here are stronger than those reported for the year 2000 in the IDI study of Roper and Berkey (2011) and they did not observe the equinoctial reversals evident in Fig. 1. These differences observed may be a consequence of the different years of observation or may result from instrument biases between meteor radar and IDI.

The seasonal variability of the mean winds and temperatures presented in this study agree very well with the simple concepts of the Dobson-Brewer circulation. In particular, the seasonal reversal of the meridional winds in summer to an equatorward flow is accompanied by a decline towards the lowest temperatures and the lowest temperatures of all occur a few weeks after the strongest equatorward winds have been established in the MLT. The strongest shears in the zonal winds occur at the same time as the strongest equatorward winds. This general pattern agrees well with other ground-based observations made by radar and/or lidar at middle latitudes in the Northern Hemisphere, (e.g., Manson and Meek, 1987; Portnyagin et al., 2004; Jacobi et al.,

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2007; Hall et al., 2008; Roper and Berkey, 2011).

A particularly interesting comparison can be made between our results and the composite-year results reported by Yuan et al. (2008). Yuan et al. (2008) used a Na lidar at the nearby site of Fort Collins, Colorado (41° N, 105° W) to measure winds and temperatures in the MLT from 2002–2006. They observed slightly stronger equatorward meridional winds in summer peaking, at a speed of $\sim -17\,\mathrm{ms}^{-1}$ compared to the $\sim -12\,\mathrm{ms}^{-1}$ that we observed. However, the height at which the strongest equatorward flow occurs is in remarkable agreement being ∼ 84 km in our study and ∼ 86 km in theirs. Yuan et al. (2008) observed the late summer reversal to poleward winds occurred later in the season at greater heights in their lidar data, whereas our observations show the reversal to occurs almost simultaneously at all heights.

The seasonal pattern of temperatures reported by Yuan et al. (2008) are very similar to that reported here. For example, in the summer-time they observed temperatures to be ∼ 167 K at heights of ∼ 84 km, our observations are similar, 173 K at ∼ 81 km and 167 K at ∼ 86 km. The seasonal pattern they report for the zonal winds is in remarkably good argument with ours, with regards with the timing of the wind reveals and the winds speeds, generally agreeing to within $10\,\mathrm{ms}^{-1}$. The observed lag of about two weeks between the strongest mean meridional winds and the lowest mean temperatures is also evident in the lidar radar observations of Yuan et al. (2008). The relatively small differences in the composite winds observed in the two studies may result from either measurement biases between the Na lidar and the meteor radar techniques or inter-annual variability.

Comparing the radar winds with the URAP and the HWM-07 models reveals a number of notable differences. Specifically, URAP presents zonal winds as being much more eastwards than in our observations for all months at all heights except for heights of 82–85 km in June–August, where URAP presents them as being weaker.

An explanation for these differences maybe that that the URAP winds were modelled using data from 1991–1999 and therefore there may be some differences that can be explained by changes in the general circulation in the MLT occurring over decadal time

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scales. Further, URAP presents zonally-averaged zonal winds and so any longitudinal structure in the winds may cause differences when comparisons are made with localised ground-based measurements. Such structure may be caused by stationary planetary waves. Finally, differences may also arise from measurement biases existing between the meteor radar and the satellite instrument used in the model, (the High Resolution Doppler Imager, HRDI).

HWM-07 models the equatorward (negative) meridional winds in the summer-time to be weaker than we observed and to occupy a smaller height range. In contrast, the zonal winds predicted by the model are in quite good agreement with our observations. These differences may arise for similar reasons to those suggested in the case of URAP.

The observations of the 16- and 5-day waves reveal that both waves have a winter maximaa nd equinoctial minima. In winter, both waves can be present throughout the height range observed by the radar. This observation is consistent with the simple interpretation that the waves have ascended from sources in the lower atmosphere of the winter hemisphere, through the eastward winds of the winter stratosphere, to the MLT. In the case of both waves, the observed amplitudes are broadly consistent with those reported in other studies made at middle latitudes (e.g., Luo et al., 2000; Lieberman et al., 2003; Mitchell et al., 1999; Day et al., 2011).

Further, in the radar observations, both the 16- and 5-day planetary waves display secondary maxima in the summer at heights above the regions of strong westward wind in the mesosphere, which would prevent the waves from having propagated there directly through the underlying lower atmosphere (Charney and Drazin, 1961). Note that the summer maximum of the 16-day wave is not evident in the satellite observations, probably because its amplitude is too small.

In the case of the 16-day wave, the presence of the wave in the summer-time MLT has been reported in a number of studies made at middle and high latitudes (e.g., Williams and Avery, 1992; Luo et al., 2000; Espy et al., 1997; Mitchell et al., 1999; Day and Mitchell, 2010b; Day et al., 2011). Two mechanisms have been advanced to

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explain these observations.

In the first mechanism, the 16-day wave in the summer-time lower stratosphere is proposed to modulate the field of ascending gravity waves such that when they dissipate at MLT heights the resulting modulated momentum flux and zonal wind acceleration excites the wave in situ (Williams and Avery, 1992). Modelling support for this hypothesis is provided by the study of Smith (2003), who reported that significant planetary-wave amplitudes were excited in the MLT by this process, at least in the case of stationary planetary waves.

The second mechanism proposes that the 16-day wave is ducted across the equator from the winter hemisphere, above the heights where the strong westerly winds of the summer hemisphere prohibit propagation. The plausibility of this mechanism has been demonstrated in modelling studies (e.g., Miyahara and Forbes, 1991; Forbes et al., 1995) and experimental studies have sought to determine if any such equator-crossing wave is modulated in amplitude by the Quasi-Biennial Oscillation – although with sometimes contradictory conclusions (e.g., Espy et al., 1997; Jacobi et al., 1998; Jacobi, 1998; Hibbins et al., 2009; Day et al., 2011).

We should note that the 16-day wave in the summer MLT is observed to be generally confined to high latitudes and so the small amplitudes observed over BLO in summer may also be a consequence of this sites location towards the equatorward edge of the region of significant wave amplitude (e.g., Day et al., 2011).

In the case of the 5-day wave, the wave amplitudes in summer are slightly larger than those of the 16-day wave. Riggin et al. (2006) observed a particularly strong 5-day wave event using TIMED/SABER data and suggested that this wave was ducted from the winter hemisphere to the summer hemisphere, where it is then amplified by baroclinic instability. Belova et al. (2008) considered satellite and ground-based observations to suggest that upward propagation from the stratosphere in the summer-hemisphere, cross-equator propagation from the winter hemisphere or in-situ excitation as a result of the baroclinic instability may all be capable of exciting the 5-day wave in the summertime MLT. It thus seems that cross-equatorial ducting may well explain the

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5-day planetary wave observed over BLO in summer, but that other mechanisms may also contribute.

Throughout the period of observation, both in summer and winter, the two planetary waves display a high degree of intermittency, with significant fluctuations in both amplitude and period occurring on time scales of a few days (e.g., Fig. 5). These fluctuations appear to be a universal feature of planetary waves in the MLT, regardless of year or season (e.g., Luo et al., 2002a,b; Manson et al., 2004b; Day and Mitchell, 2010b). The origin of such intermittency has been suggested to lie in the sensitivity of planetary-wave propagation to the relative magnitudes of the zonal jets in the summer and winter hemispheres, which can vary on relatively short timescales (e.g., Hagan et al., 1993). This intermittency leads to a high degree inter-annual variability observed in the waves.

5 Conclusions

The monthly-mean mean zonal and meridional winds over BLO in the MLT reveals a clear seasonal cycle. The mean meridional wind is usually poleward throughout the year except for a region of strong equatorward flow occurring in the summer. The coldest temperatures generally occur about two weeks after the time at which the equatorward winds of the summer-time are at their strongest. The mean zonal winds are eastward throughout much of the year but do display some westward flow in winter and around the equinoxes. The observed eastward winds in winter are significantly weaker than those suggest by the URAP and the HWM-07 models. This maybe a result of measurement biases or, more likely, stationary planetary waves in the winter MLT.

The 16- and 5-day planetary waves reach large amplitudes in winter and are present in summer. The planetary wave amplitudes are evident in both wind and temperature and the largest amplitudes in wind and temperature generally occur simultaneously. The amplitudes display a high degree of intermittence and therefore inter-annual variability which is probably dependant on fluctuations of the background winds. The presence of the waves in summer requires that they have either an in situ source or have

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been ducted across the equator from the winter hemisphere.

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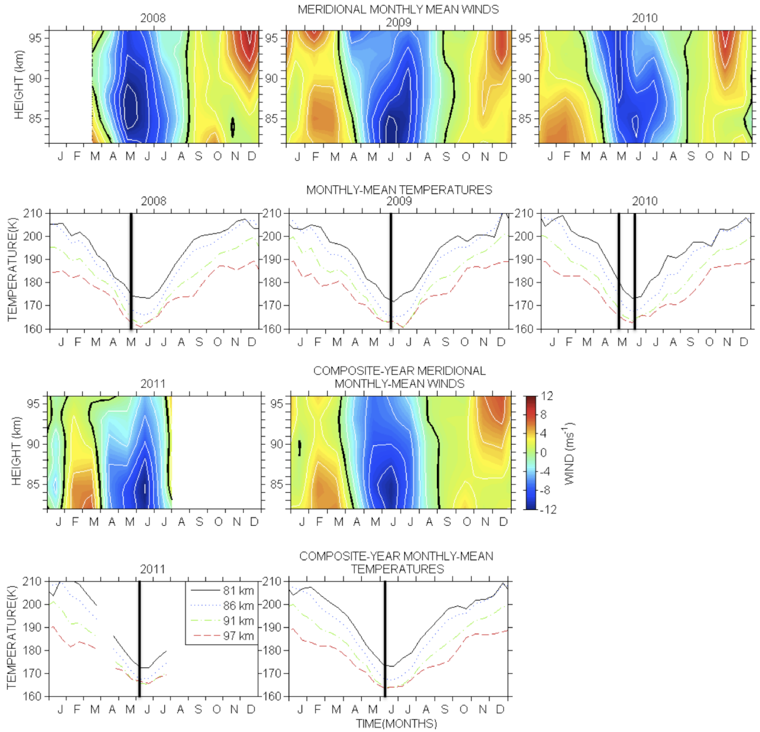

Fig. 1. Monthly-mean meridional winds over BLO and 14 day Aura MLS temperatures. The zero wind contour is indicated in black and the white contours are in steps of 2 ms^{-1}. The temperatures are means for a latitude/longitude "box" of 40–45° N, 90–120° W for four height gates between on ~81–97 km. The black vertical lines on the temperature plots indicate time of minimum meridional winds.

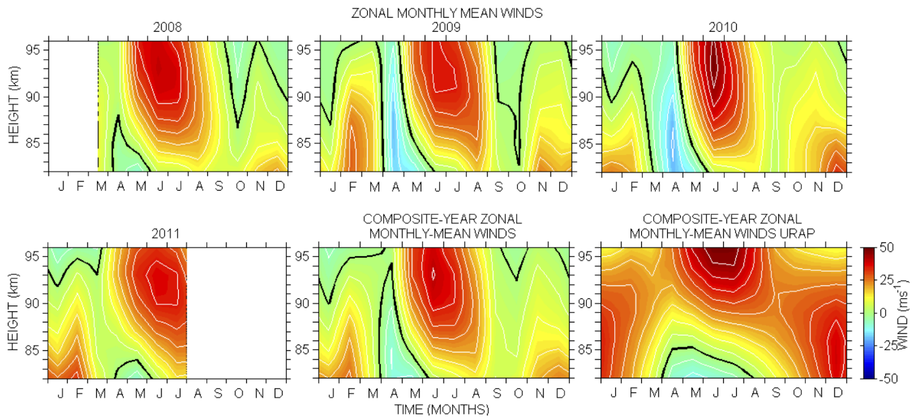

Fig. 2. Monthly-mean zonal winds and the zonally averaged composite-year monthly-mean zonal URAP winds over BLO. The zero wind contour is indicated in black and the white contours are in steps of 5 ms^{-1}.

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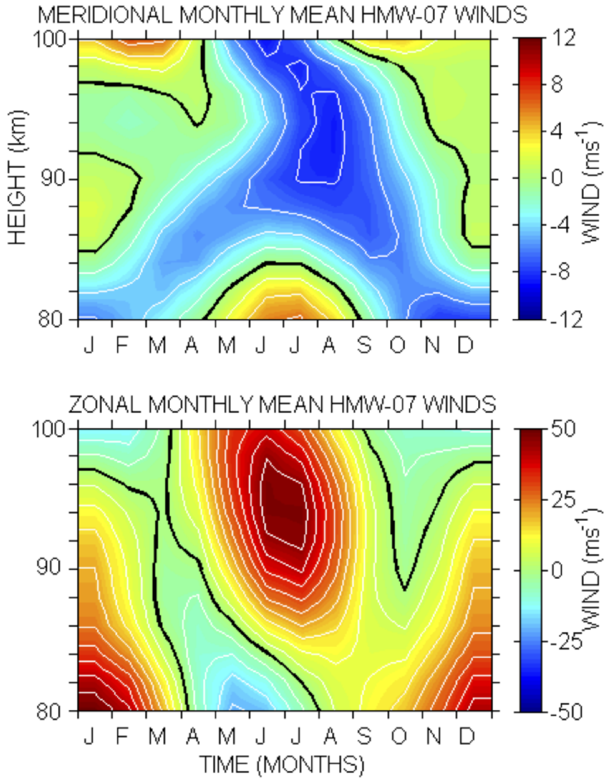

Fig. 3. Monthly-mean meridional and zonal winds over BLO (41.9° N and 111.4° W), from the HWM-07 model. The zero wind line is indicated in black and the white lines indicate 5 ms^{-1} steps.

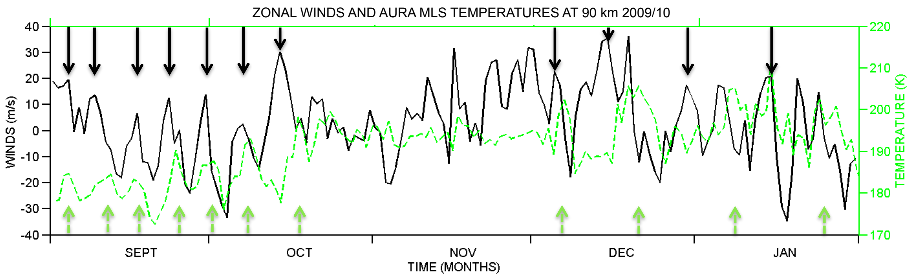

Fig. 4. The daily zonal winds and MLS temperatures at ~ 90 km measured over BLO for the interval September 2009–January 2010. Wind maxima occurring at planetary wave periods (~ 5 and 16 days) are indicated by the arrows, wind on the top axis and temperature on the bottom axis.

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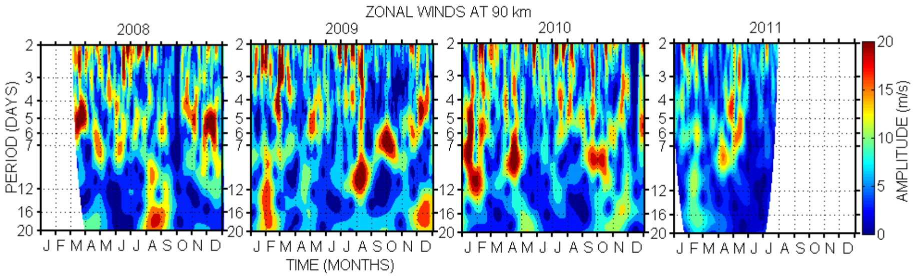

Fig. 5. A Wavelet analysis of hourly zonal wind amplitudes at heights of ∼ 90 km, over BLO from March 2008 to July 2011.

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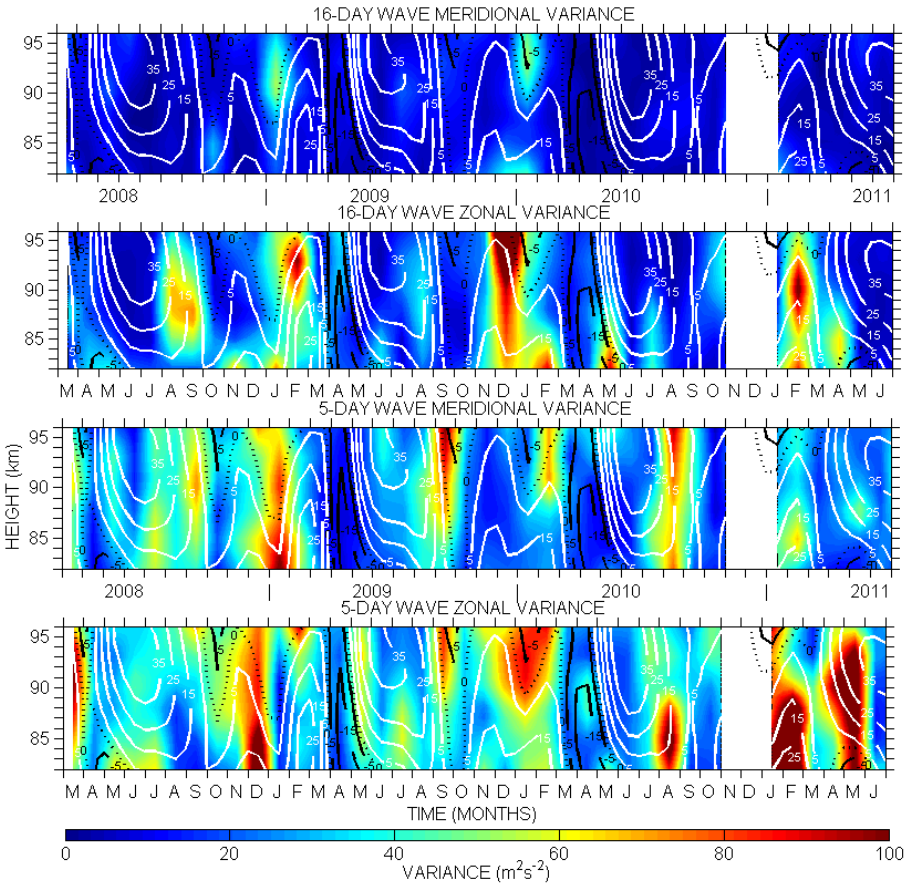

Fig. 6. Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 12–20 and 4–7 days for the 16- and 5-day wave, respectively. Over BLO for both meridional and zonal components, 2008–2011. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line.

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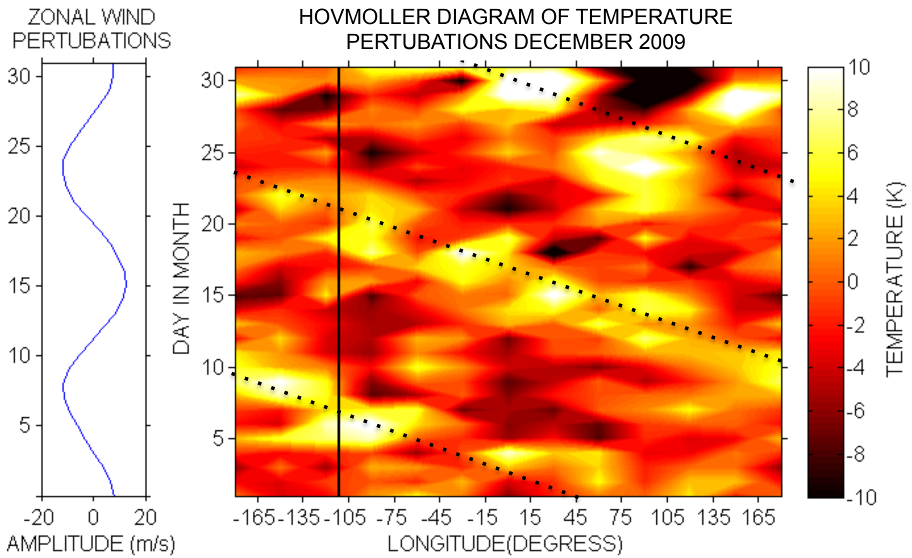

Fig. 7. On the right of the figure is the Hovmöller diagram of the Aura MLS data in 30° longitude bands for the month of December in 2009, at 40–45° N and ~90 km. The black line shows the approximate location of BLO and the dashed line the wave fronts. On the left is the band-passed 16-day wave radar zonal winds for the same time and approximate height.

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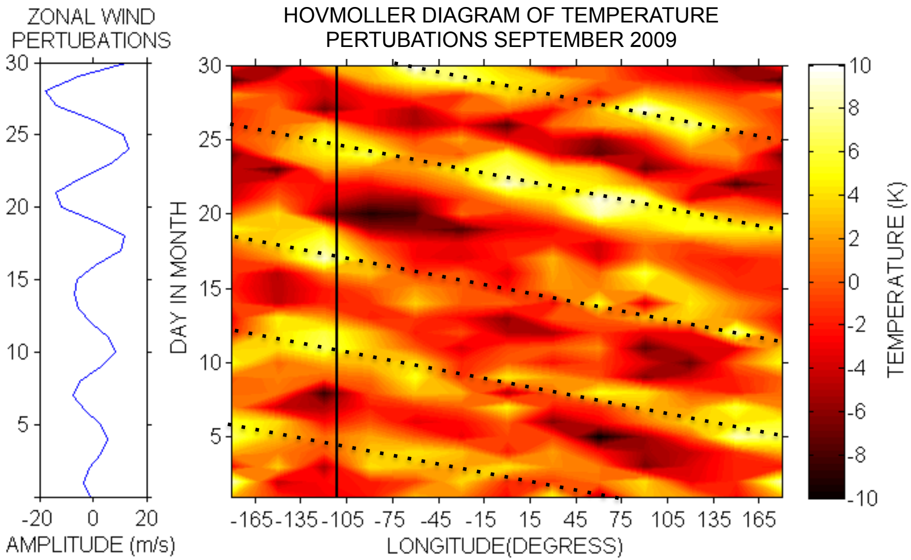

Fig. 8. On the right of the figure is the Hovmöller diagram of the Aura MLS data in 30° longitude bands for the month of September in 2009, at 40–45° N and ∼90 km. The black line shows the approximate location of BLO and the dashed line the wave fronts. On the left is the band-passed 5-day wave radar zonal winds for the same time and approximate height.

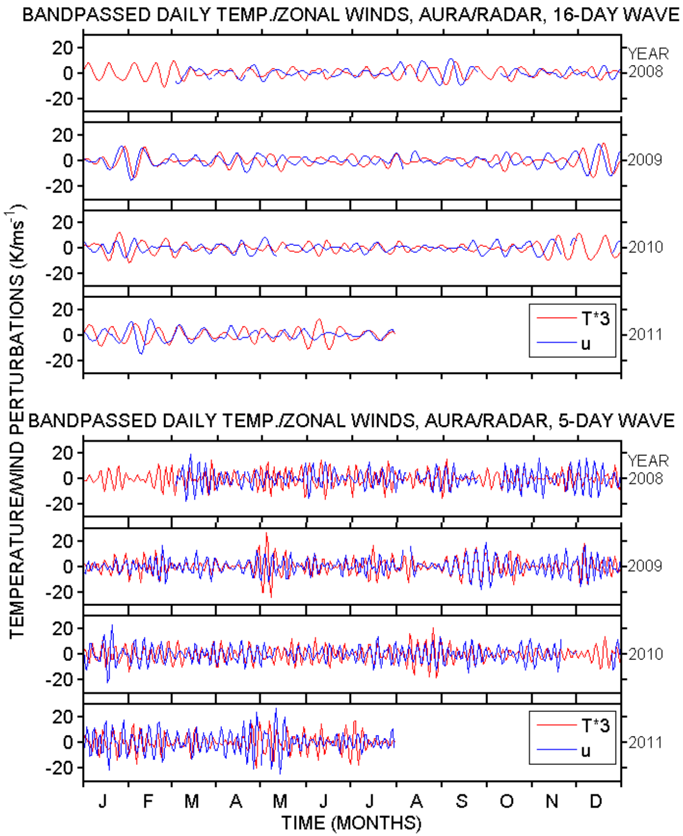

Fig. 9. Band-passed radar winds and Aura daily temperatures over BLO ~ 90 km, for the years 2008–2011. Band-pass limits are for the wave periods of 12–20 days and 4–7 days for the 16- and 5-day wave, respectively. The Aura MLS data is from 40–45° N and 90–120° W. Note the temperatures have been multiplied by a factor of 3 for a by eye comparison with the winds.

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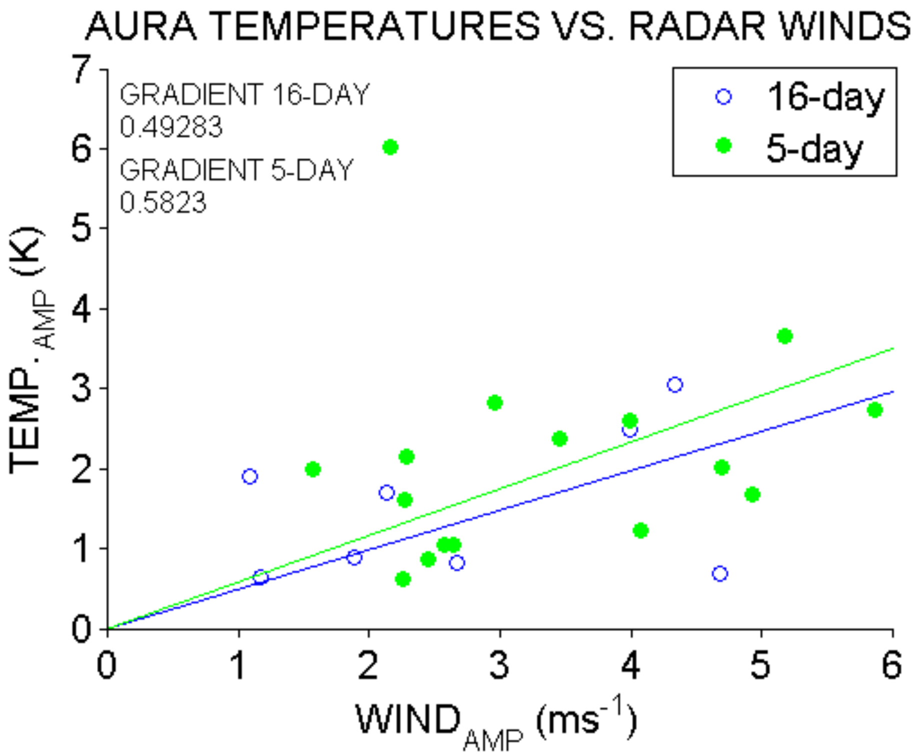

Fig. 10. A least-square fit of radar winds versus Aura temperature amplitudes at heights of ∼ 90 km, for the 16- and 5-day waves for "bursts" of temperature amplitudes over BLO. Bursts are identified as, waves that are greater than 5 ms^{-1}, that last for longer than 1 cycle and pass the Student T-test 90 % confidence level.

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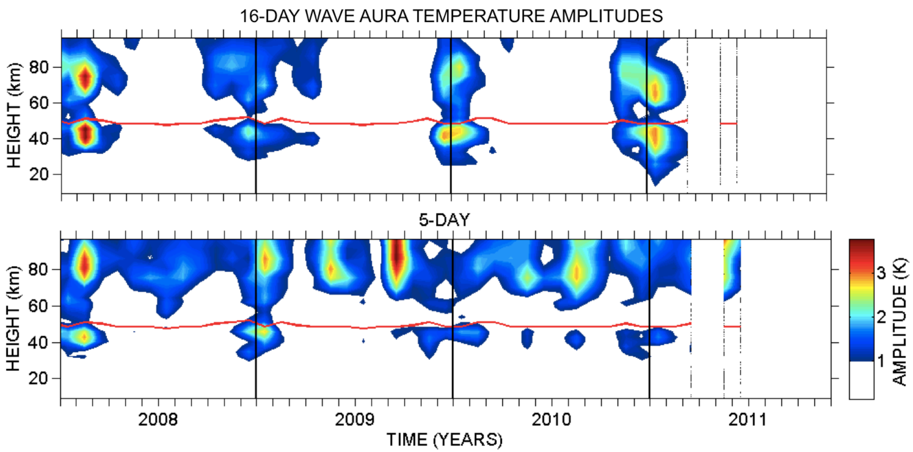

Fig. 11. Time-series of monthly-mean temperature amplitudes from 2008–2011 for the 16- and 5-day wave at a latitude 35–45° N. Also plotted is the stratopause height as a red contour line.

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