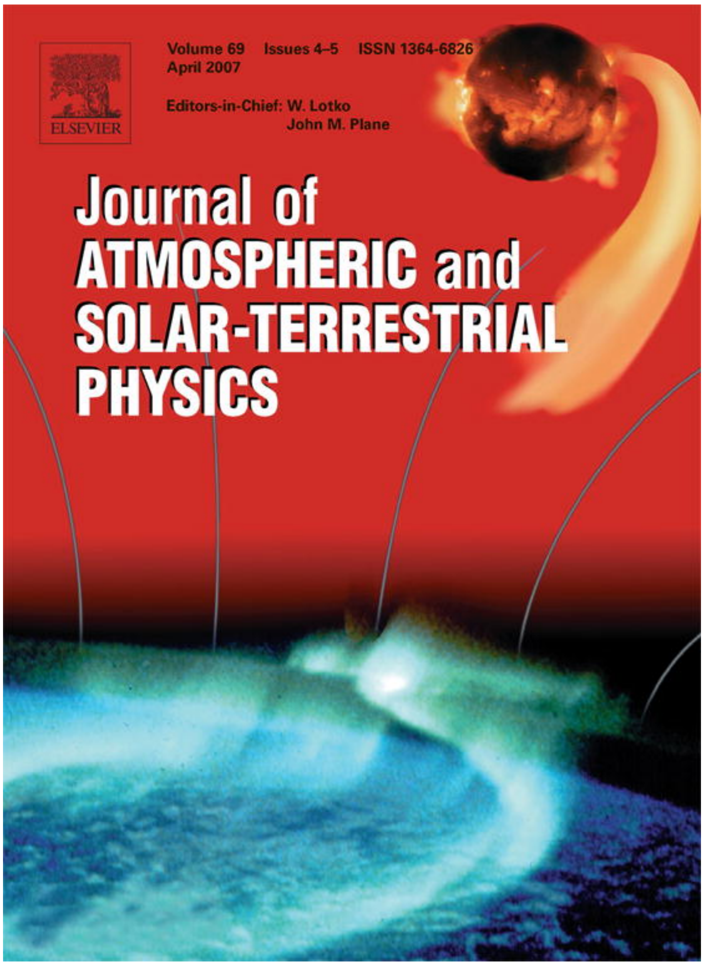
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A climatology of tides and gravity wave variance in the MLT above Rothera, Antarctica obtained by MF radar

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Abstract

A cumulative total of over 5 years of data from an MF radar situated at Rothera (67°S, 68°W) on the Antarctic Peninsula have been used to derive climatologies of periodic motions in the wind field in the mesosphere and lower thermosphere with periods less than or equal to 1 day. Strong tidal motions are observed at 24, 12 and 8 h and monthly mean climatologies are presented between 74 and 94 km altitude for comparison with the HWM-93 horizontal wind model. The 24 h tide shows a strong seasonal dependence in both the zonal and meridional components with a summertime maximum and wintertime minimum over all altitudes. The monthly mean maximum amplitude is $12(\pm 2)\,\mathrm{ms}^{-1}$ at 94 km in January and the minimum is $<1\,\mathrm{ms}^{-1}$ around 86 km in early winter. The 12 h wave shows large short-term amplitude variability with a peak in amplitude around late autumn. It reaches a minimum at high altitudes in winter and below ~80 km during summer, characteristic of a mixture of migrating and non-migrating modes. The phase of the 12 h wave is relatively constant throughout winter with a minimum mean vertical wavelength of ~75 km around equinox. The 8 h wave is predominantly a summertime high altitude phenomenon. It is seen most strongly in the winds above 85 km and reaches monthly mean amplitudes of $6(\pm 2)\,\mathrm{ms}^{-1}$ in the zonal winds at 94 km altitude. Finally, a seasonal climatology of gravity wave variances is generated by calculating the daily mean variance in the raw winds after subtracting the fitted tidal components. This index shows a strong seasonal and height dependence in both components with a wintertime peak of $\sim 2000\,\mathrm{m}^2\mathrm{s}^{-2}$ in the zonal component at the highest altitudes. This peak occurs when the stratospheric zonal jets are strongest and therefore the filtering of upward-propagating waves in the stratosphere should be greatest; implying that either a significant part of this wintertime wave activity is generated from a region above the peak stratospheric wind or that there is a strong annual variability in the source or propagation of the gravity wave activity at Rothera.

Keywords: Mesosphere and lower thermosphere; Dynamics; Tides; Gravity waves; MF radar; Antarctic

1. Introduction

The dynamics of the polar mesosphere and lower thermosphere (MLT) are dominated by waves with periods ranging between a few minutes to months. These gravity waves, tides and planetary waves interact with the mean flow, generating short-lived extreme conditions and driving the MLT to states far removed from radiative equilibrium. Understanding these interactions and how they couple the different atmospheric layers in the vertical by studying the climatological behaviour of these

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waves is vital in attempting to quantify the main contribution to the energy and momentum budgets of the MLT. Rothera station is ideally situated for such studies on the Antarctic Peninsula, often within the wintertime polar vortex and at a similar latitude to several northern and southern hemisphere stations where long-term monitoring of the dynamics of the MLT is being undertaken. Several climatological studies over the past few years have been made from Rothera. Lübken et al. (1999, 2004) and Müllemann and Lübken (2005) used a series of rocket-launched falling sphere observations to study the temperature, density and horizontal winds between ~30 and 90 km in January and February 1998. They found that in the mesosphere the southern hemisphere January temperatures and zonal winds were very similar to temperatures recorded at equivalent summertime northern hemisphere latitudes, contrary to that predicted by the CIRA-86 model reference atmosphere and expectations based on PMSE observations (Balsley et al., 1995). They also found that the temperature in the mesosphere rose more rapidly from January to February in the Southern hemisphere compared to equivalent northern hemisphere observations suggesting that, at least in 1998, the transition from summer to autumn conditions in the mesosphere occurred much more quickly in the southern hemisphere. Hibbins et al. (2005) combined the zonal wind climatology from these falling sphere data with several years of data from a co-located MF radar and a series of radiosonde balloon launches to derive a zonal wind climatology for Rothera. They found that the summertime westward maximum in the zonal wind occurred much lower and earlier in the season than that observed at latitudinally similar northern and southern hemisphere sites. Chu et al. (2004) used a lidar based at Rothera to compare the height of polar mesospheric clouds with those observed at South Pole. They concluded that the January mesopause region temperatures are warmer than at South Pole and the corresponding Rothera cloud heights are ~1.3 km lower than at South Pole, but approximately 1 km higher than those recorded at northern hemisphere sites at similar latitudes. In addition Espy et al. (2003, 2005) observed strong 43 day planetary wave activity in both the meridional winds and OH rotational temperatures in the MLT above Rothera over the winter of 2002 prior to the southern hemisphere stratospheric warming, and Diettrich et al. (2006) generated a climatology of sporadic iron layers and showed evidence for tidal modulation of the layers and layer destruction, apparently due to gravity wave breaking. Several other studies from Rothera have concentrated on characterising the gravity wave activity in the MLT: Jones et al. (2004) first showed that seasonal enhancements in the signal-to-noise ratio observed by the MF radar were likely to be due to breaking gravity waves, and Diettrich et al. (2005) combined lidar and airglow imager studies to derive the intrinsic properties of high frequency atmospheric gravity waves over Rothera. Finally Espy et al. (2006) have shown how the vertical flux of horizontal momentum carried by high frequency gravity waves during the wintertime is approximately five times greater at Rothera than at Halley station (76°S, 27°W).

Despite this work, only two studies have looked specifically at tidal periods from Rothera and both have used limited data sets. Riggin et al. (2003) observed the semi-diurnal tide from Rothera between 1997 and 1998 together with other high latitude northern and southern hemisphere sites. They observed a strong autumn enhancement in the amplitude of the tide in the northern hemisphere, but weaker enhancements from the southern hemisphere sites. This enhancement was accompanied by a dramatic shortening of the vertical scale of the tide which was explained by refraction of the migrating tide in the large zonal wind shears. Murphy et al. (2003) compared the semidiurnal tide from Rothera observed between 1997 and 1998 with that observed at the southern hemisphere stations Syowa (69°S, 40°E) and Davis (69°S, 78°E) in order to separate migrating from non-migrating components. By vector differencing the observed tides they concluded that a significant contribution to the summertime semidiurnal tide was due to the non-migrating westward-propagating wave number one 12 h wave seen to dominate the wind field over South Pole.

Since its initial period of operation between 1997 and 1998 the Rothera MF radar was refurbished in 2002 and has since been running with limited interruption. This paper summarises the tidal and gravity wave data recorded with the Rothera MF radar between 1997 and 2005 by presenting a climatological study of periodic motions between 74 and 94 km altitude with periods less than or equal to one day.

2. Data analysis

The MF profiler radar at Rothera (Jarvis et al., 1999) is a coherent spaced-sensor radar system used for measuring horizontal winds in the mesosphere and lower thermosphere through the observation and analysis of D-region partial reflection echoes. The radar employs a single broad-beam transmit antenna and three spaced receive antennas in a triangular array. The radar operates at a frequency of 1.98 MHz with a transmitter power of 25 kW and full-width half-maximum pulse width of 25 μs. This corresponds to a height resolution of ~4 km sampled at 2 km height intervals between 50 and 100 km. Data used in this study are restricted to altitudes below 94 km as several authors have observed that MF radars tend to underestimate wind speeds compared to those observed by meteor radars above this altitude (e.g. Manson et al., 2004; Portnyagin et al., 2004). These radars are also susceptible to group retardation (Namboothiri et al., 1993) and E-region echo contamination (Hocking, 1997) in summertime above ~95 km. In addition, Iimura (2006) has observed weaker semidiurnal oscillations from harmonic fits to the Rothera MF radar data recorded during 2005 than those derived from a co-located meteor radar across the common altitude range of the two instruments. The system utilises a full-correlation analysis (Briggs, 1984; Holdsworth and Reid, 1995) to determine the wind field across the range of observations. A total of 1757 full or partial days of data recorded between February 23, 1997 and December 31, 2005 are included in this study. Fig. 1 summarises the data coverage showing the two main periods of operation of the MF radar. Despite the lack of continuity in the data set, any given day of the year has data recorded from at least three different years of operation.

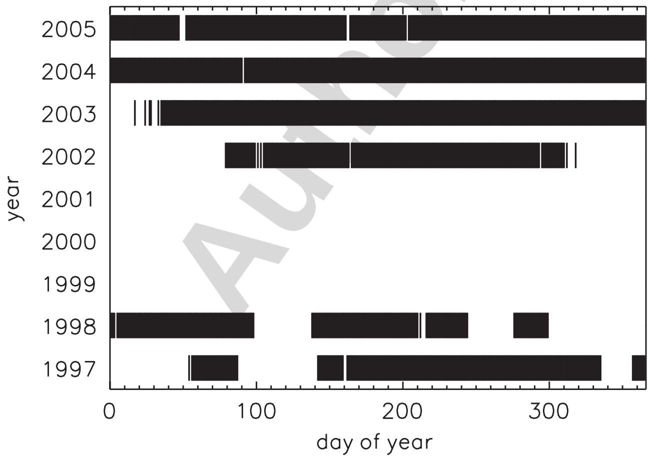

Fig. 1. Coverage of MF radar data recorded at Rothera and used in this study.

To determine which periodic components are the strongest in the data set, a Lomb–Scargle periodogram (Scargle, 1982) was employed using the near full year of data recorded in 2005. Hourly means of meridional winds were generated for the selected year of operation and the periodogram was performed on the 94 km height bin. The results are shown in Fig. 2 from which it can be seen that the three strongest peaks above the 99% confidence level (based on 1000 white noise simulations) occur at 8, 12 and 24 h. The 24 h component is actually split into 2 peaks centred on 24 h but separated by ~8 min suggesting modulation of the 24 h component by a wave with a period close to 1 year. At altitudes lower than 94 km, the 8 h wave is only significant at the 99% level above 90 km, whereas the 12 and 24 h components, although varying in strength with height, are significant at all altitudes above 74 km. Between 75 and 85 km the periodicity of the 12 h wave is centred at 12 h but is seen to vary by up to 3% either side of this maximum suggesting a less consistent phase with respect to time at these heights.

To further study these three strongest periodicities a 24 h superposed epoch was generated for each 2 km height bin between 74 and 94 km for each calendar month of zonal and meridional wind data. A mean bias together with a 24 , 12 and 8 h sine wave was then fitted to these superposed epochs to separate the mean wind from the periodic motions representative of the diurnal, semidiurnal and terdiurnal tides. Each hourly mean was weighted

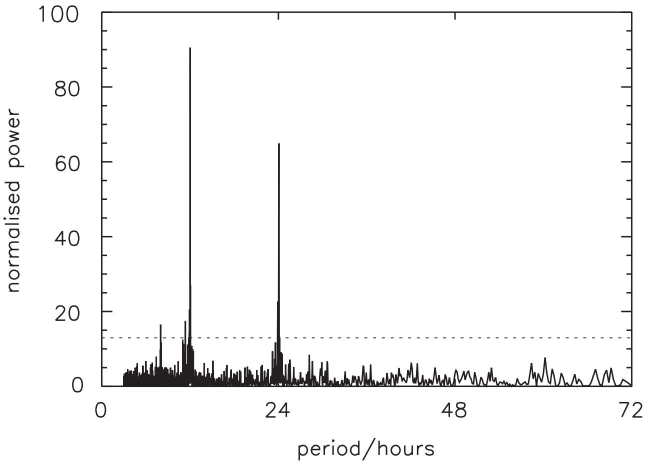

Fig. 2. Lomb–Scargle periodogram of hourly mean meridional wind data recorded during 2005 at 94 km altitude. The horizontal dotted line represents the 99% significance level based on 1000 white noise simulations. The three strongest peaks occur at the tidal periods 8, 12 and 24 h.

in the least squares fitting routine by the inverse of the square of the standard deviation of the individual data points used to calculate the mean.

For comparison, monthly 24 h superposed epochs of hourly zonal and meridional winds were derived from the empirical Horizontal Wind Model, HWM-93 (Hedin et al., 1996) at 67°S, 68°W and subjected to the identical least squares fitting procedure outlined above.

Finally the variance due to gravity waves was estimated by subtracting the fitted bias and tidal components from the raw 2 min data for each day that fits were undertaken. The variance was then calculated from these tidal-subtracted data and averaged by calendar month for each individual height bin between 74 and 94 km.

3. Results/discussion

Contour plots of the amplitudes of the zonal and meridional components of the 24 , 12 and 8 h fitted waves between 74 and 94 km altitude are reproduced in Fig. 3. Fig. 4 shows monthly line plots of the amplitudes and phases (as measured by the local time of maximum northwards or eastwards wind) of the fitted tides for comparison with those derived from the HWM-93 model atmosphere.

In common with other high latitude southern hemisphere sites (e.g. Hibbins et al., 2006; Fraser et al., 1995; Forbes et al., 1999; Riggin et al., 1999) Fig. 4a shows the 24 h wave to be strong, with amplitudes $>12(\pm 2)\,\mathrm{ms}^{-1}$ at 94 km, and largely evanescent in summertime and equinox. This behaviour is typical of the high latitude migrating diurnal tide (e.g. Pancheva et al., 2002). The wave then decreases to almost negligible amplitudes of $<1\,\mathrm{ms}^{-1}$ in midwinter when solar insolation is at a minimum. In summertime the zonal amplitudes go through a minimum around 88 km where the zonal mean wind shear is at a maximum of approximately $3\times10^{-3}\,\mathrm{s}^{-1}$ (Hibbins et al., 2005), coincident with the rapid phase change with altitude of the zonal component of the 24 h wave, indicative of a pronounced shortening of its vertical wavelength. Between October and March this shortening of the vertical wavelength is the only aspect of the HWM-93 model tides not reproduced in the observed phases of the diurnal tides. In the winter months the phases agree less well with the model, especially in the meridional component where the fitted tidal amplitudes are at a minimum. In general the summertime zonal 24 h tidal amplitudes are greater than those predicted by the model whereas the meridional amplitudes are better represented by the model.

Fig. 4b shows the seasonal dependence of the monthly mean amplitude of the 12 h wave which shows maxima of ~7 $(\pm 1)\,\mathrm{ms}^{-1}$ in late autumn in

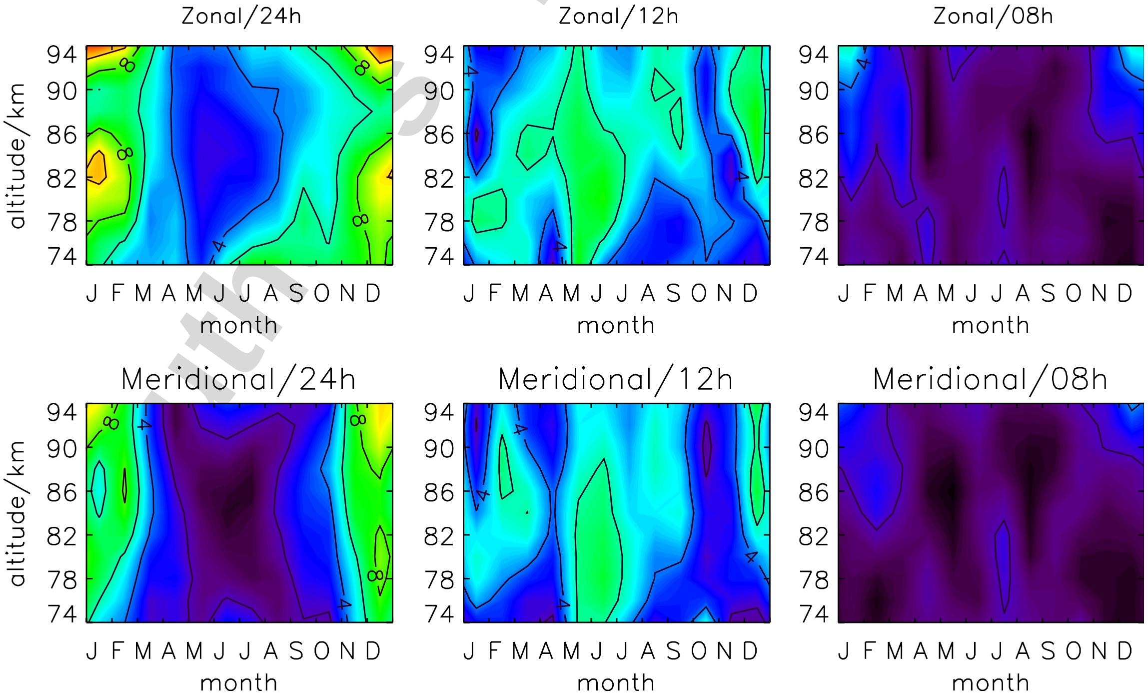

Fig. 3. Monthly mean amplitudes of the 24, 12 and 8 h waves. Contours are plotted at $2\,\mathrm{ms}^{-1}$ intervals.

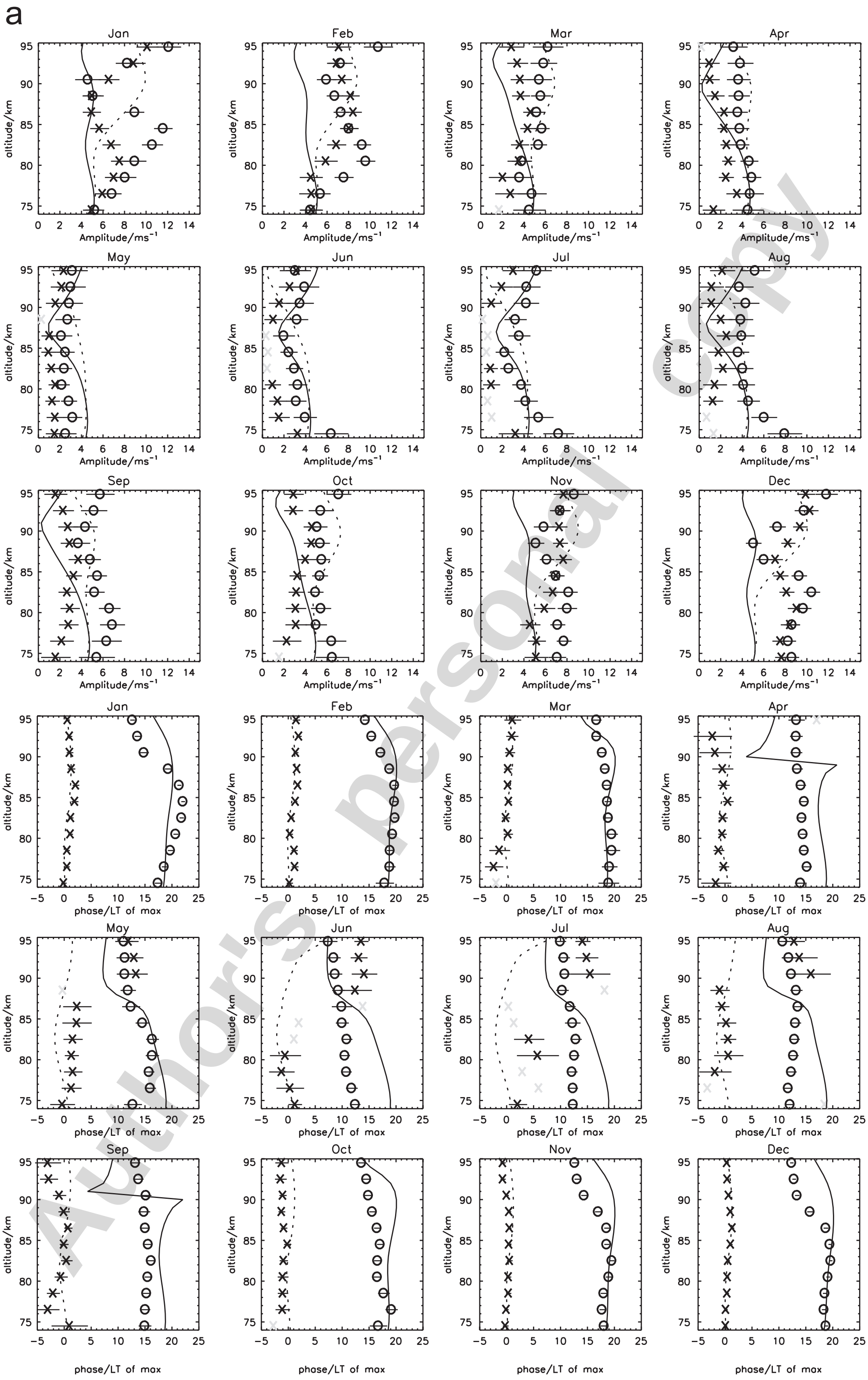

Fig. 4. (a) Monthly mean amplitude and phase (local time of maximum northward or eastward winds) for the 24 h wave recorded at Rothera plotted as a function of height; zonal component, "○"; meridional component, " × ". 2σ error bars on the fitted components are included on the plots. Amplitudes and phases derived from fits where the amplitude was smaller than 2σ are plotted in pale gray without error bars. For comparison, the amplitudes and phases of the 24 h wave derived from HWM-93 winds are included; zonal component, solid line; meridional component, dotted line. (b) As for Fig. 4a, but for the 12 h wave. (c) As for Fig. 4a, but for the 8 h wave. No significant 8 h component is seen in the HWM-93 model winds and is therefore omitted from these plots.

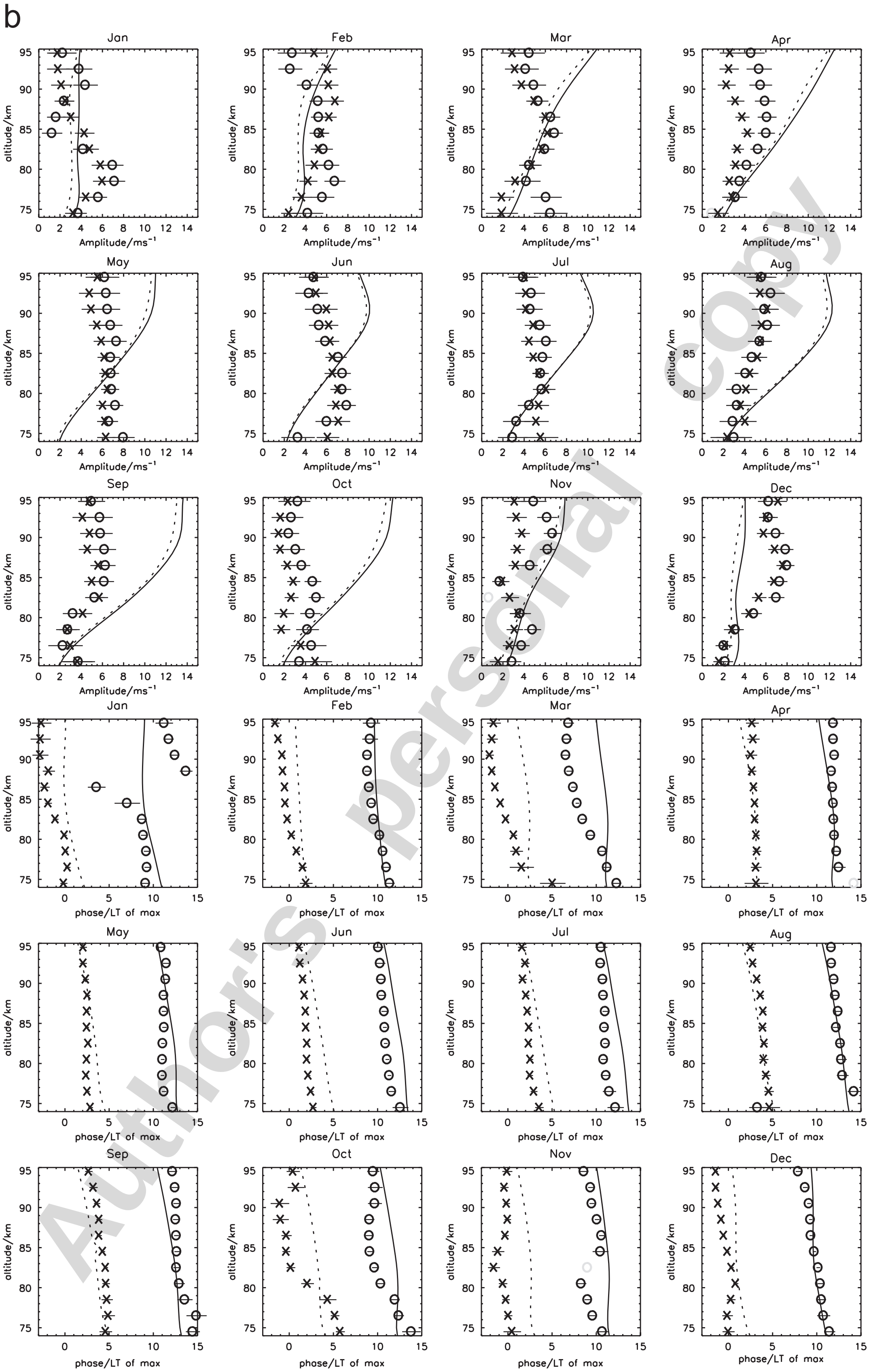

Fig. 4. (*Continued*)

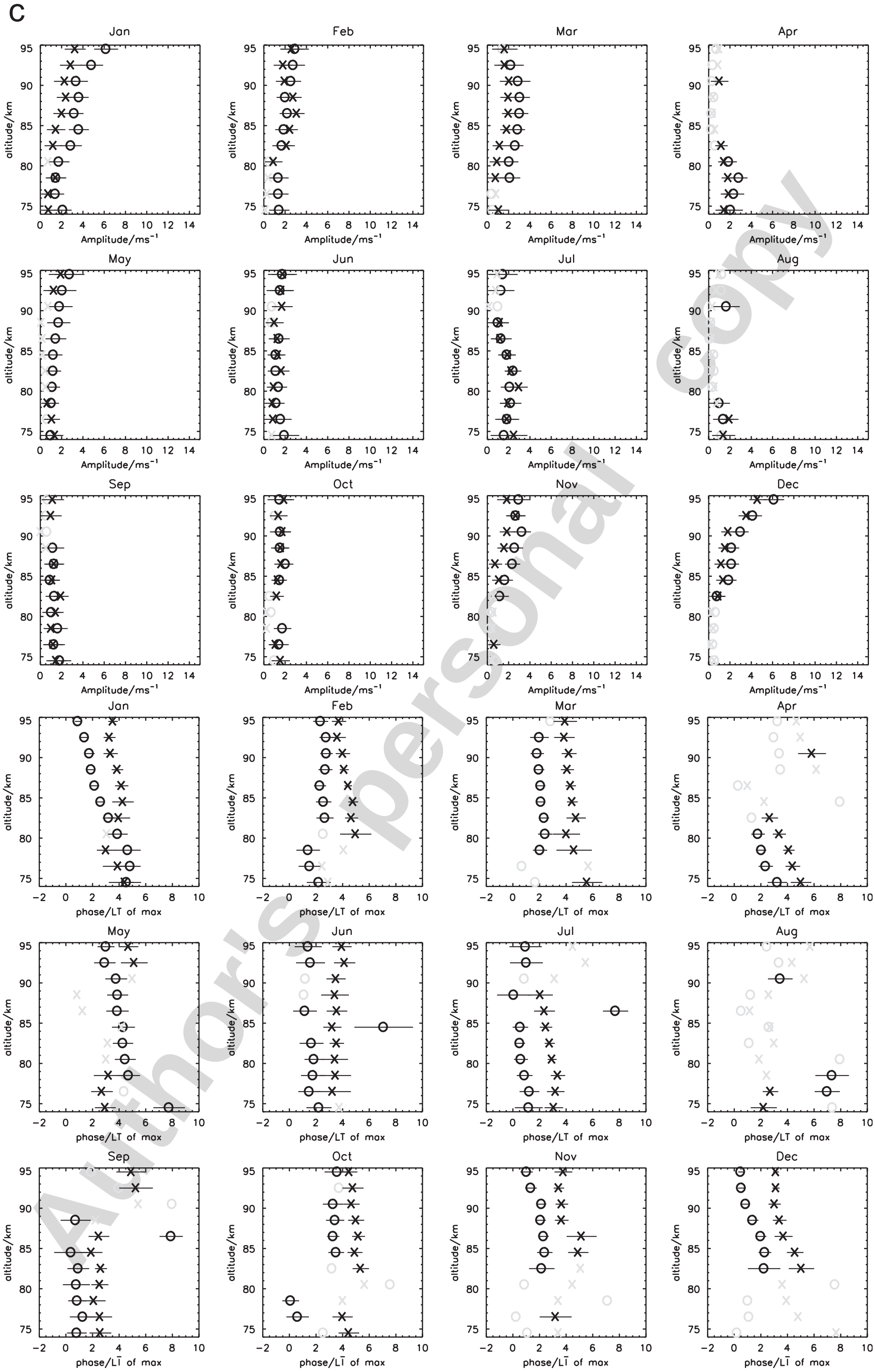

Fig. 4. (*Continued*)

both the zonal and meridional components and a minimum around November. In general the HWM-93 model significantly overestimates the amplitude of the 12 h wave above ~80 km between April and October. The wintertime phases of the 12 h wave are very stable, varying by less than 1 h between April and September with typical vertical wavelengths between 100 and 200 km, slightly larger than those predicted by the HWM-93 model. During this time the wave remains in phase quadrature with the eastward maximum leading the northward by three hours. In March and October the phase change with height increases below 85 km giving vertical wavelengths as low as ~30 km in transition from wintertime to summertime conditions. In summer the phases of both components are around 3 h earlier than the mean wintertime conditions. In common with the 24 h tide the vertical wavelength of the zonal component of the 12 h wave shortens between 84 and 90 km in the strong zonal wind shear.

Riggin et al. (2003) have looked at the seasonal variability of the 12 h wave at northern and southern hemisphere high latitudes including some early limited data from the Rothera MF radar. They report a strong, repeatable autumn enhancement in the wave amplitudes in the northern hemisphere localised at around 86 km which was less apparent in the southern hemisphere during 1997–1998. This autumn enhancement was associated with a shortening of the vertical scale of the 12 h wave consistent with refraction of the wave in the background horizontal flow. This enhancement was also observed in satellite data (Burrage et al., 1995) at northern and southern hemisphere latitudes greater than 40° from which it can be unambiguously assigned to the $s = 2$ migrating semidiurnal tide. This more extensive climatology shows some evidence of an enhancement of the 12 h wave in late autumn at Rothera similar to the northern hemisphere data and a shortened vertical wavelength around equinox below 85 km. At latitudes higher than Rothera the 12 h wave is seen to be dominated by the non-migrating $s = 1$ component, especially in summertime when the 12 h wave is strongly enhanced (see e.g. Forbes et al., 1995, 1999; Riggin et al., 1999; Hibbins et al., 2006). Murphy et al. (2003) have observed a non-zero component in the vector difference between the summertime 12 h wave observed at Rothera and other similar latitude sites suggesting at least a contribution to the summertime 12 h wave from a non-migrating component at Rothera latitudes. It is therefore likely that the 12 h wave at Rothera is a complex mixture of migrating and non-migrating tidal modes.

The 8 h wave at Rothera between 74 and 94 km is essentially a summertime high altitude phenomenon with monthly mean amplitudes of ~6(±2) $\mathrm{ms^{-1}}$ in the zonal component at 94 km. The Lomb–Scargle periodogram reveals a peak at 8 h that is significant at the 99% level only above 90 km, and this is borne out by the least squares fitting procedures outlined above and summarised in Fig. 4c. Although there is some evidence for a slight enhancement to the amplitude below 85 km altitude in April and July, during the non-summer months the amplitude is typically below 2 $\mathrm{ms^{-1}}$ and commensurate with the noise estimates. Younger et al. (2002) have observed the 8 h wave between 80 and 97 km from a similar latitude northern hemisphere site at Esrange (68°N, 21°E) using a VHF meteor radar. The amplitude of the wave is seen to increase with altitude, and a pronounced maximum in the monthly mean amplitudes of $>6\,\mathrm{ms^{-1}}$ is observed at the highest altitudes around the autumn equinox. However, the summertime enhancement observed at Rothera is not seen. Smith (2000) also sees an autumn/winter enhancement in the 8 h tide at 95 km at mid latitudes from satellite observations of horizontal winds, in agreement with MF radar observations from London, Canada (43°N, 81°W) (Thayaparan, 1997). Although the seasonal behaviour of the 8 h wave observed from Rothera differs from that observed in the northern hemisphere and at lower latitudes, the maximum amplitudes are observed in the wave when both the 24 and 12 h waves are also strongest. This supports the idea that the 8 h wave is the result of a non-linear interaction between the 12 and 24 h waves (see e.g. Thayaparan, 1997), though the limited altitude range through which the wave is clearly observed makes it impossible to confirm this through accurate estimates of the vertical wavelength. The HWM-93 model atmosphere shows no significant 8 h component to the zonal or meridional wind field between 74 and 94 km at Rothera latitudes and is therefore omitted from Fig. 4c.

The fitted tidal components and mean wind were subtracted from each component of the raw data for each day of operation. The variance in the raw data (sampled at ~2 min resolution) was then calculated for each day of operation and averaged by calendar month. The resulting variance in the data can be considered to be due largely to gravity waves with periods between the Brunt–Väisälä and inertial periods, with small contributions from the system noise, shorter-period planetary waves and tidal overtones with periods shorter than 8 h. The system noise was estimated from the full day of data with the lowest variance and subtracted from the monthly mean climatological variance.

These data are presented in Fig. 5 and show a clear seasonal and altitude dependence in both the zonal and meridional components with the greatest variance observed at the highest altitudes in wintertime. For example, in June the variance in the zonal component of the wind increases from ~500 (±200) m^2s^{-2} at 74 km to ~2000 (±150) m^2s^{-2} at 94 km and in December the corresponding variances are ~100 (±25) m^2s^{-2} and 600 (±100) m^2s^{-2}. This is consistent with the amplitudes of the short-period oscillations increasing as they propagate upwards in the atmosphere. Dowdy et al. (2001) report variances with periods between 20 min and 8 h recorded around the summer solstice at Davis between 70 and 100 km with an MF radar. Here, total combined zonal and meridional horizontal wind variances are around 200 m^2s^{-2} at 70 km, go through a minimum of ~100 m^2s^{-2} around 80 km altitude, and then increase to ~800 m^2s^{-2} at 100 km. These values are substantially less than the Rothera total variances for December suggesting either that there is a substantial contribution to the Rothera variances from waves with periods shorter than 20 min and/or longer than 8 h, or that the total summertime gravity-wave activity at Rothera is greater than at Davis. Espy et al. (2006) have previously shown that the wintertime vertical flux of horizontal momentum due to breaking gravity waves at ~90 km above Rothera is a factor of 4–5 times greater than that observed at Halley station. Comparison of the observed differences in the height and extent of the maximum of the westwards summertime zonal jet, which at Davis is stronger and higher (−55 ms^{-1} and 80 km, Dowdy et al., 2001) than at Rothera (−45 ms^{-1} and 65 km, Hibbins et al., 2005) also suggests that there is less eastward drag due to summertime breaking gravity waves at mesospheric altitudes above Davis, and therefore significant zonal inhomogeneity in the gravity wave activity around 68° latitude in the southern hemisphere.

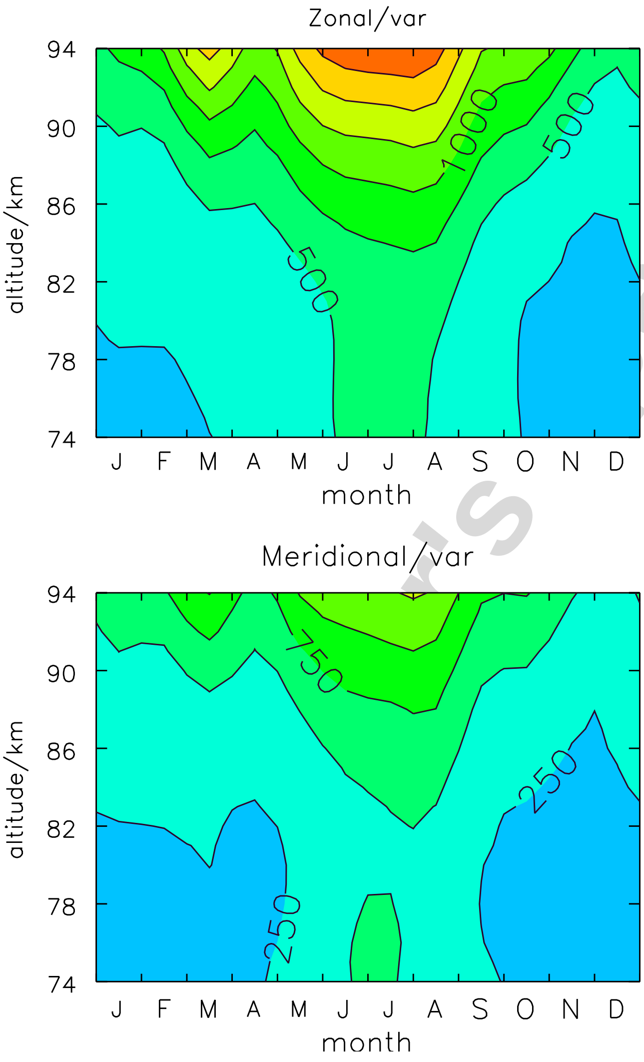

Fig. 5. Monthly mean variance of the raw winds after subtracting tidal components and system noise. Contours are plotted at 250 m^2s^{-2} intervals.

A clear seasonal dependence on the strength of the variances is observed with a wintertime maximum and summertime minimum. In the MLT a large proportion of the tropospherically-generated upward propagating waves are filtered either by the strong eastwards wintertime stratospheric jet or by the westwards summertime winds in the lower mesosphere. It would therefore be expected that a uniform spectrum of gravity waves launched from below the stratosphere would most favourably propagate up to the upper mesosphere around the equinoxes when the underlying wind fields are at a minimum. Although there is some evidence for a slight autumn enhancement in the measured variances, the gravity wave activity at these altitudes maximises at exactly the time when the filtering due to the stratospheric winds should be greatest. This implies that either the tropospheric source of the gravity wave activity observed in the MLT above Rothera varies considerably throughout the year, or that a significant proportion of the gravity wave activity is generated from a region above the peak of the wintertime stratospheric jet.

4. Summary

Climatologies of the 8, 12 and 24 h waves generated from MF radar data recorded at Rothera station on the Antarctic Peninsula have revealed the seasonal behaviour of these tidal components in the mesosphere and lower thermosphere above this unique observational site. The 8 h wave, though weak, shows a seasonal dependence different from a similar northern hemisphere site. At Rothera, it reaches a maximum in summertime at the highest altitudes where the combined 12 and 24 h wave amplitudes are greatest, suggesting an origin due to non-linear interaction between these two components. The 12 h wave has a complex structure with characteristics of both the migrating and non-migrating components seen at lower and higher latitudes respectively. Finally, after removal of these tidal components the seasonal behaviour of the horizontal wind variance due to gravity waves suggests that Rothera lies within a region of enhanced gravity wave activity.

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