The two-day wave in the Antarctic and Arctic mesosphere and lower thermosphere

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Abstract

There have been comparatively few studies reported of the 2-day planetary wave in the middle atmosphere at polar latitudes. Here we report studies made using high-latitude meteor radars at Rothera in the Antarctic (68°S, 68°W) and Esrange in Arctic Sweden (68°N, 21°E). Observations from 2005 - 2008 are used for Rothera and from 1999 - 2008 for Esrange. Data were recorded for heights of 80 - 100 km. The radar data reveal distinct summertime and wintertime 2-day waves. The Antarctic summertime wave occurs with significant amplitudes in January – February at heights between about 88 – 100 km. Horizontal wind monthly variances associated with the wave exceed 200 m^2s^{-2} and the zonal component has larger amplitudes than the meridional. In contrast, the Arctic summertime wave occurs for a longer duration, June – August and has meridional amplitudes larger than zonal. The Arctic summertime wave is weaker than that in the Antarctic and maximum monthly variances are typically 70 m^2s^{-2}. In both hemispheres the summertime wave reaches largest amplitudes in the strongly sheared eastward zonal flow above the zero wind line and is largely absent in the westward flow below. The observed differences in the summertime wave is probably due to the differences in the background zonal winds in the two hemispheres. The Antarctic and Arctic wintertime waves have very similar behavior. The Antarctic wave has significant amplitudes in May – August and the Arctic wave in November – February. Both are evident across the full height range observed. The summertime wave is interpreted as being the classic westward propagating zonal wavenumber 3,4 wave. The wintertime wave is interpreted as being the recently reported eastward propagating zonal wavenumber 2 wave.

1 Introduction

The quasi-2-day, or 2-day, wave is a prominent feature of the mesosphere and lower thermosphere (MLT) region. It is observed each year around summer solstice. The amplitude of the wave can exceed 20 ms^{-1} near the mesopause, making it the largest amplitude planetary wave observed at mesopause heights.

First observations of the wave were reported by Muller, (1972). The wave has since been extensively studied by ground-based radar. In particular, meteor and MF radars have been used to investigate the vertical structure and climatology of the wave at middle and low latitudes (e.g., Salby and Roper, 1980; Craig *et al.*, 1983; Plumb *et al.*, 1987; Tsuda *et al.*, 1988; Harris and Vincent, 1993; Palo and Avery, 1996; Jacobi *et al.*, 1997; Thayaparan *et al.*, 1997; Jacobi *et al.*, 1998; Gurubaran *et al.*, 2001; Manson *et al.*, 2004; Pancheva *et al.*, 2004; Riggin *et al.*, 2004). Satellite observations have been used to investigate the global-scale structure of the wave (e.g., Rodgers and Prata, 1981; Wu *et al.*, 1993; Ward *et al.*, 1996; Lieberman, 1999; Limpasuvan and Wu, 2003; Smith, 2003; Jacobi *et al.*, 2004; Riggin *et al.*, 2004; Sandford *et al.*, 2008). Theoretical studies have investigated the excitation of the wave, its global-scale structure and its interaction with other waves and tides (e.g., Norton and Thuburn, 1996; Palo *et al.*, 1999; Salby and Callaghan, 2008).

These studies have led to an overall understanding of the general characteristics of the 2-day wave. Observations of the 2-day wave have revealed that its amplitude maximises around mid to low latitudes in summer (e.g., Wu *et al.*, 1996; Limpasuvan and Wu, 2003; Merzlyakov *et al.*, 2004; Limpasuvan *et al.*, 2005). At middle and low latitudes, the wave is composed primarily of westward-propagating zonal wavenumbers 3 and 4. The wave maximises in late summer at mesopause heights and attains maximum amplitude between 90–95 km in the both hemispheres. However, the amplitude maximum in the southern hemisphere exceeds that of the northern hemisphere. The southern hemisphere wave is primarily composed of zonal wavenumber 3, while the northern hemisphere wave is a mixture of wavenumbers 2, 3 and 4. The wave period also varies between the two hemispheres. In the southern hemisphere the wave period is observed to be very close to 48 hours. However, in the northern hemisphere the wave period is observed to range between 43 and 53 hours. In both hemispheres the vertical wavelength is usually observed to be very large (larger than ~70 km). Further, note that a recent study by Palo *et al.* (2007) suggested that non-linear interaction between the summertime 2-day wave and the migrating diurnal tide might generate a wavenumber 2 eastward propagating 2-day wave, which would occur simultaneously with the westward propagating modes.

Two mechanisms have been proposed for the excitation of the 2-day wave in the middle atmosphere. The first is that the 2-day wave is a manifestation of the (3,0) Rossby-gravity normal mode (Salby, 1981). The second is that the 2-day wave arises from a baroclinic instability of the summer mesospheric jet (Plumb, 1983). This latter mechanism was further developed by Pfister, (1985) in a two-dimensional stability analysis. Theoretical and observational studies have supported both the normal mode and instability interpretations, suggesting that the excitation mechanism of the 2-day wave may actually be a combination of the two. For instance, the theoretical study of Salby and Callaghan, (2001) suggested that, under solstice conditions, the Rossby-gravity mode amplifies through sympathetic interaction with the summertime mean flow. This instability forcing has little effect on the period or structure of 2-day wave.

In contrast to the situation at middle and low latitudes, there have been comparatively few studies of the 2-day wave at polar latitudes. Recent studies made using ground-based radars have investigated the summertime mesospheric polar 2-day wave and have also revealed the existence of strong 2-day wave activity around the winter solstice (Nozawa *et al*., 2003a; Nozawa *et al*., 2003b; Merzlyakov *et al*., 2004; Riggin *et al*., 2004; Nozawa *et al*., 2005; Baumgaertner *et al*., 2008; Sandford *et al*., 2008). This latter wave activity is not present at middle or low latitudes. Nozawa *et al*. (2003b) suggested that the wintertime 2-day wave might actually be an eastward propagating wavenumber-2 oscillation. Sandford *et al*. (2008) used geopotential height data from the Aura satellite to investigate the zonal structure of this wintertime wave and confirmed that it is indeed an eastward-propagating wavenumber 2, probably originating on the poleward flank of the stratospheric polar vortex and propagating up into the MLT.

In this study we present observations of summertime and wintertime polar 2-day waves in the MLT region made using meteor radars at conjugate geographical latitudes. Horizontal wind data are used in case studies to establish the general characteristics of the waves in the Antarctic and Arctic MLT region. Climatologies of the summertime and wintertime waves are determined. Inter-annual variabilities are investigated. A key focus of the work is to investigate differences between the Antarctic and Arctic regions and interactions of the waves with the general circulation.

2 Data and Analysis

The data analysed in this paper were obtained from two meteor radar located at Rothera, (68°S, 68°W) in the Antarctic and Esrange (68°N, 21°E) in Arctic Sweden. The Rothera radar has been in operation since February 2005 and the Esrange radar October 1999. Both radars have been in continuous operation for most of the time since these dates.

Both radars are commercially produced SKiYMET VHF systems that operate in an "all-sky" configuration with radiated power being largely independent of azimuth. The radars have height and time resolutions of about 1 km and about 1 hour respectively. See Hocking *et al.* (1999) and Mitchell *et al.* (2002) for details. The radars operate continuously, generating hourly values of the zonal and meridional winds at heights of ~ 80 – 100 km. This height range is split into six independent height-gates with depths of 5, 3, 3, 3, 3, 5 km. The vertical distribution of meteor echoes is peaked at a height of ~ 90 km. Therefore, for each height-gate the average meteor echo height is calculated. This yields time series of horizontal winds at heights of 80.8, 84.7, 87.5, 90.4, 93.3 and 97.1 km.

For each month of data a variance value was calculated from the bandpassed horizontal winds in each height gate. This variance is taken as a proxy for the activity of the 2-day waves in each height gate for the month in question. The result of this analysis is a time series of variance values for each month that can be used as a proxy for wave activity.

3 Results

3.1 General characteristics of the 2-day waves

The occurrence of 2-day waves in the radar time series can be investigated by the use of spectral analysis. Figure 1a,b presents a wavelet analysis of meridional winds over Rothera in 2006 and Esrange in 2007, respectively. A Morlet wavelet was used with 6 cycles of the wave contained within a Gaussian envelope. These results are for a height of 93.3 km. It can be seen from the figure that wave activity is present in strong intermittent bursts. The bursts are of relatively short duration, often lasting no more than 10 days or so. Significant wave amplitude is present at wave periods from about 1.5 to near 3 days.

To investigate the period of the wave, Lomb-Scargle periodograms were used. Figure 2a,b presents a sample of Lomb-Scargle periodogram of meridional winds over Rothera and Esrange for summer and winter seasons. These results are typical of the results observed in most years. Figure 2a presents a periodogram of summertime winds at a height of 93.3 km over Rothera for the three month interval December 2005 – January 2006. During this interval there is a large peak at a period of about 48 hours. Figure 2b presents a similar analysis for the wintertime wave over Esrange in January 2008. There is a peak in the meridional component at 42 hours.

The figures show that there is a significant difference in the frequency of the wave between the 2 hemispheres. In the northern hemisphere the period is ~ 42 hours. In the southern hemisphere the wave period varies between about 48 hours and about 55 hours.

To examine the horizontal wind time series in more detail to investigate waves with periods near two days, the data were bandpassed. The filter was an elliptical type with 99% high/low cut-off frequencies corresponding to periods of 1.6 and 2.8 days. We assume that wave activity within this period band is dominated by the 2-day waves of interest (note that at the latitude of Rothera and Esrange the inertial period is approximately 12.9 hours and so there will be no significant gravity wave activity within the frequency band selected for the filter).

Figure 3a,b presents the results of this analysis in the case of meridional winds recorded over Esrange and Rothera, respectively in 2007. The figure shows that wave activity is present throughout the year in this period range, but that strong bursts of wave activity occur in winter and in late summer. For example, over Esrange wave amplitudes exceed 10 ms^{-1} in winter (December – January) and in summer (July – August). Similarly, over Rothera amplitudes exceed 10 ms^{-1} in winter (June – August) and in summer (December – January). The zonal amplitudes, not shown, reveal a similar pattern of behaviour, although the zonal amplitudes are rather smaller in the Arctic summer.

To investigate the vertical structure of the summer and winter waves, data from the six height gates was bandpassed as above and then used to produce time – height contours of zonal and meridional wind over each site. Figure 4a,b presents two examples of this analysis. Figure 4a presents contours of the summertime meridional wind over Rothera in the Antarctic for 1st December 2006 to 30th February 2007 (day numbers 335 – 59). Figure 4b presents contours of the summertime meridional wind over Esrange for 1st June 2007 to 31st August 2007 (day numbers 152 -243). These intervals are presented as being typical of summertime two-day wave activity observed over these two sites. Several distinguishing characteristics are apparent from the figures, i) the wave activity occurs in strong bursts of duration of ten to twenty days, although wave activity is present throughout the whole height time interval, ii) the phase fronts of the wave are effectively vertical, implying a long vertical wavelength, iii) the period of the wave is slightly different in the Antarctic and Arctic. In the Antarctic the period is about 1.9 days, whereas in the Arctic the period is about 2.2 days, iv) In the Antarctic the wave only reaches large amplitudes (say > 10 ms^{-1}) at heights above about 90 km. In the Arctic the wave maximises at heights 90 - 95 km.

Figure 5a,b presents similar examples of this analysis. Figure 5a presents contours of the wintertime meridional wind over Rothera for 1st June 2007 to 31st August 2007 (day numbers 152 – 243). Figure 5b presents contours of the wintertime meridional wind over Esrange for 1st December 2006 to 30th February 2007 (day numbers (335 – 59). These intervals are again presented as being typical of wintertime two-day wave activity. Several distinguishing characteristics are again apparent from the figures, i) the wave activity again occurs in bursts, although there is a suggestion that the bursts are of rather shorter duration than is the case in the summertime, ii) the phase fronts are again effectively vertical, implying a long vertical wavelength, iii) in contrast to the summertime wave the period of the wave appears to be about the same, 2.2 days, in both the Antarctic and Arctic, iv) in contrast to the summertime wave, the wave activity occurs across the whole height range observed and does not seem to maximise in a particular height range.

To examine the phase difference between the zonal and meridional components, the bandpassed winds for a seasonal period were used to derive hourly wind vectors. The trace path of the tip of the wind vector is plotted as a hodograph. For Rothera in summertime the direction of rotation was usually anti-clockwise. For Esrange in summertime it was usually clockwise. In the winter months the figures are noisy and a clear sense of rotation is not always apparent.

Hodographs can be used to investigate the amplitude/phase relationship of the zonal and meridional components of the waves. Figure 6a-d presents hodographs for Rothera and Esrange for summer and winter seasons typical of the behaviour observed in most years. Figure 6a presents a hodograph of summertime winds at a height of 93.3 km over Rothera for the three month interval December 2007 – February 2008. Figure 6b presents similar summertime winds over Esrange for June 2008 – August 2008.

The Rothera data show the rotating wind vector associated with the 2-day wave describes an ellipse, i.e, the wave is elliptically polarised. When the wave has largest amplitudes this ellipse tends to be aligned NE – SW. The Esrange data also reveal an elliptically polarised wave, but in this case the alignment is approximately N – S.

Figure 6c presents a similar analysis of the wintertime 2-day wave at a height of 84.7 km over Rothera for the three month interval June – August 2007. Figure 6d presents similar wintertime winds over Esrange for December 2003 – February 2004. The wintertime hodographs generally show little evidence of a preferred direction of polarisation. Examination of the full set of the wintertime hodographs (not shown for reasons of space) suggest that there is a higher degree of inter-annual variability of the hodographs associated with the wintertime wave than is the case in summer.

3.2 Climatology of the 2-day waves

The previous results suggest there is a seasonal cycle in 2-day wave activity. To investigate this further, monthly values of variance were calculated and used as a proxy for wave activity. The bandpassed zonal and meridional wind time series for each height gate were broken into consecutive sections of one month duration. The variance was calculated for each section yielding a single variance value for each month in each height gate.

Figure 7 presents time height contours of monthly variance at heights of ~ 80 - 100 km for zonal and meridional components measured over Rothera for April 2005 to September 2008. From the figure it can be seen that there is a seasonal cycle in 2-day wave activity with a maximum in late summer (December – February), a secondary maximum in winter (reaching largest variances in June – August) and equinoctial minima. These maxima correspond to the events described above. As suggested by the bandpassed results of figure 4, the summertime wave reaches largest amplitudes at heights above ~ 85 – 90 km. In contrast the wintertime wave can reach large amplitudes across the height range observed. A considerable degree of inter-annual variability is apparent. For example, the summertime 2-day wave is significantly stronger in 2006 compared to 2007 and 2008. This is particularly noticeable in the meridional component. The wintertime 2-day wave also exhibits significant inter-annual variability.

Figure 8 presents a similar analysis applied to data from Esrange. The seasonal behaviour is generally similar to that observed over Rothera. Again, the summertime 2-day wave tends to maximise at heights above about 88 km and the wintertime 2-day wave is present across the height range observed. Inter-annual variability is also very strong. Over Esrange the meridional variances are noticeably larger than the zonal ones in most years.

One difference evident between the results from Rothera and Esrange is that over Esrange the summertime 2-day wave has larger variances in the meridional component than in the zonal, whereas over Rothera the zonal variances are larger than the meridional variances.

To provide a clearer understanding of the seasonal behaviour of the 2-day wave, a composite year analysis ("average year") was carried out using all available data. The monthly variance data have a log-normal distribution and so the composite year cannot be produced by simply averaging the monthly variances in a particular height gate over all the years available. Instead, the variance was calculated for a given month and height gate by constructing a continuous time series of bandpassed winds for that height gate and month using data from all years. A variance was then calculated for this single time series and the procedure repeated for all other height gates and months. Figure 9 presents two examples of this analysis. Figure 9a presents time-height contours of composite-year analysis at heights of ~ 80 - 100 km for the meridional component. The monthly-mean zonal winds were similarly averaged. Contours of these mean zonal winds are also plotted on the figure as lines. Figure 9b presents a similar analysis of the composite-year analysis of the zonal component of the 2-day wave. Again, the monthly mean zonal winds are also plotted for comparison.

It can be seen from the figures that over Rothera the summertime wave has a much larger variance than the wintertime wave. The summertime wave reaches variances above 200 m^2s^{-2} at heights above ~ 90 km. In fact, the summertime wave variance maximises just above the zero wind line in both components. In contrast the wintertime wave is generally smaller than 60 m^2s^{-2} at most heights.

Figure 11 presents a similar superposed epoch analysis for the data from Esrange. As in Figure 9, Contours of mean zonal winds are plotted on the figure as lines. The results from Esrange are generally similar to those from Rothera. Again the summertime wave has a larger maximum variance than the wintertime wave and maximises just above the zero wind line. The summertime wave reaches a maximum of ~ 70 m^2s^{-2} at a height of ~ 94 km in the meridional component. The zonal component is rather weaker, with a maximum of ~ 50 m^2s^{-2}. The wintertime wave has a variance at most heights of about 40 m^2s^{-2}, with a minimum at about 88 km in both zonal and meridional components.

We will now compare and contrast the climatology of summertime and wintertime 2-day waves in the Antarctic and Arctic.

Firstly, we will consider the summertime 2-day wave. From figures 9 and 11, it can be seen that there are a number of key similarities and differences between the 2-day wave of the two polar regions. These are:

1. The maximum variance of the wave is larger in the Antarctic than the Arctic. This is true in both the zonal and meridional components. For example, in the Antarctic the summertime wave monthly variance reaches values larger than 160 m^2s^{-2}, whereas in the Arctic the equivalent value is only about 60 m^2s^{-2}.
2. The relative magnitude of the zonal and meridional components is different between the two hemispheres. In the Antarctic, the zonal component is larger than the meridional and the ratio of peak variance, zonal/meridional, is about 1.3 at a height of about 93 km in January. In contrast, in the Arctic the meridional component is larger than the zonal and the ratio of peak variance, zonal/meridional l, is about 0.7 at a height of about 93 km in July.
3. In both hemispheres the summertime wave maximises at a height of about 93 km. This is in the region of strongly sheared zonal flow associated with the summertime mesospheric zonal jet. The waves reach largest amplitudes above the zero wind line, but are still detectable to the lowest heights observed.
4. The duration of occurrence of the 2-day wave appears to be shorter in the Antarctic than in the Arctic. In the Antarctic, strong wave activity lasts only a little longer than a month (January), but in the Arctic strong wave activity is evident for at least three months (June-August). This appears to be connected to the duration of the strongly-sheared zonal flow occurring above the zero wind line. In the Antarctic, such strong shear above the zero wind line, with the zero wind line at a height of about 90 km or below, only occurs in January. So although there is strong zonal wind shear in December, the zero wind line occurs at heights above 95 km and there is no evidence of the wave having significant activity. In contrast, in the Arctic, strong zonal wind shears exist above the zero wind line with the zero wind line being below about 90 km throughout June-August. The wave is observed throughout this longer interval.

To investigate the duration of occurrence of the 2-day wave in more detail, figure 10a,b presents composite variances at a height of ~93 km. The variances calculated over Rothera were shifted by 6 months in order to make the seasons comparable, so the months used on the time axis are those at Esrange. Figure 10a presents the meridional mean monthly variances measured over Rothera and Esrange. Figure 10b presents a similar analysis for the zonal component. It can be seen from the figures that the summertime wave activity over the Antarctic is significantly more intense in both components. However, the Antarctic wave activity is shorter lived than that in the Arctic.

Secondly, we will consider the wintertime 2-day wave. From figures 9 and 11, it can be seen that there are again a number of key similarities and differences between the wintertime 2-day wave of the two polar regions. These are:

1. The variances appear to be very similar in both the Antarctic and Arctic. The mean variances in both hemispheres reach maximum values between ~ 50 – 70 m^2s^{-2}.
2. In both hemispheres the ratio of zonal to meridional variances is approximately one.
3. The wave is evident across the height range observed but in both hemispheres has a minimum at heights between ~ 88 – 90 km with maxima above and below this height.
4. In both hemispheres the duration of the wave appears to be very similar. The wave reaches significant variances (say, above 20 m^2s^{-2}) in May – August over Rothera and November – February over Esrange.

To investigate further the differences in the 2-day wave between the Antarctic and Arctic, a ratio of the composite years of Figures 9 and 11 was calculated. The composite monthly mean variances calculated over Rothera were shifted by 6 months in order to make the seasons comparable. Figure 12a,b presents time-height contours of these ratios. In the figure, the months used on the time axis correspond to the month at Esrange. Figure 12a presents the composite monthly mean variances for the meridional component of the 2-day wave over Rothera divided by the equivalent variance from Esrange. Figure 12b presents a similar analysis for the zonal component. Differences of the composite years of Figures 9 and 11 were also calculated for both zonal and meridional components (not shown here). The differences calculated confirmed the results in Figure 12.

The data presented in the figure show considerable inter-hemispheric differences between Rothera and Esrange. The summertime 2-day wave (June – August) is stronger over Rothera, in both the zonal and meridional components. The ratio reaches a maximum of just over 4 in the zonal component at heights of ~ 90 – 94 km, corresponding to larger wave amplitudes in the Antarctic. In contrast, in the meridional component, although the variances are larger over Rothera the ratio is only about 2.5.

If we consider the wintertime 2-day wave, there is no clear tendency for larger variances over either polar region.

4 Discussion

Nozawa *et al*. (2003b) suggested that in the mesosphere and lower thermosphere the summertime 2-day wave and the wintertime 2-day wave are actually separate phenomena, the first being the familiar wavenumber 2,3,4 westward propagating planetary wave and the latter being an eastward propagating wave of wavenumber 2. Palo *et al*. (2007), Baumgaertner *et al*. (2008) and Sandford *et al*. (2008) used satellite observations to confirm this suggestion. Palo *et al*. (2007) suggested that E2 waves of this type are generated by non-linear interaction between the summertime 2-day wave and the migrating diurnal tide. Sandford *et al*. (2008) suggested that the wintertime E2 wave originates on the poleward flank of the winter polar stratospheric vortex. Here we will consider the summertime and wintertime waves in turn.

Firstly, we will consider the summertime 2-day wave. A number of observers have investigated the 2-day wave at mid-latitudes in the northern and southern hemispheres. These studies have revealed a general pattern in which the largest amplitudes occur in the southern hemisphere (Craig *et al*., 1980; Rodgers and Prata, 1981; Craig *et al*., 1983; Limpasuvan and Wu, 2003 and others). Our observations suggest that the larger southern hemisphere amplitudes persist to high latitudes and are clearly observed in the polar regions. This inter-hemispheric difference in amplitude is probably due to the different wavenumber components comprising the 2-day wave in the two hemispheres. In particular, the southern hemisphere is known to be dominated by a westward wavenumber 3 component, whereas the northern hemisphere is known to have significant additional contributions from the westward 2 and westward 4 components (e.g., Meek *et al*., 1996; Norton and Thuburn, 1996; Lieberman, 1999; Limpasuvan and Wu, 2003; Pancheva *et al*., 2004).

Our observations also suggest that the average duration of 2-day wave activity is rather shorter in the Antarctic than the Arctic. An explanation for this behaviour might be as follows. The major W3 component of the 2-day wave is believed to have the character of the Rossby (3,0) normal mode, but can be excited by instabilities associated with the summertime mesospheric westward jet (e.g., Fritts *et al.*, 1999; Lieberman, 1999; Salby and Callaghan, 2001). We thus might expect to find strongest wave activity at times when there is strong shear in the summertime mesospheric jet.

However, the wave propagation is constrained by wave/mean-flow interactions as outlined by Charney-Drazin theorem. Thus it can only propagate within a particular range of zonal wind speeds. The Charney-Drazin theorem can be approximated as allowing propagation only for zonal mean wind speeds, $0 < \overline{u} - c_x < u_c$, where $\overline{u}$ is the zonal mean wind, c_x is the zonal phase speed of the planetary wave (~ 28 ms^{-1} for a 2-day W3 wave at a latitude of 68°) and u_c is the Rossby critical velocity [~ 36 ms^{-1} for this wave, (Charney and Drazin, 1961)]. This means that the wave should only be able to propagate for zonal wind speeds in the approximate range +28 to +64 ms^{-1} (i.e. eastward winds).

Because the zero-wind line is higher in the early months of the summer in the Antarctic, compared to the Arctic (at least in the years observed), the zonal winds are not strongly eastwards enough in the height range observed to allow the wave to propagate in the Antarctic during these early summer months. For example, over Rothera in November and December the zonal winds are almost entirely westward, whereas in the corresponding months in the Arctic (May and June) the winds become increasingly eastward above about 90 km (see figures 9 and 11). The summertime 2-day wave is thus largely absent in early Antarctic summer, but is present in early Arctic summer, leading to a reduced overall duration of occurrence in the Antarctic.

Secondly, we will consider the wintertime 2-day wave. In contrast to the summertime situation, the wintertime wave appears to have relatively small inter-hemispheric differences. In both the Antarctic and Arctic the seasonal climatology appears to be rather similar and the ratio of zonal to meridional variances is on average close to 1. The wave is present throughout the height range observed in both hemispheres and has a smaller maximum variance than the summertime wave in the climatological average.

In both hemispheres, the wintertime wave variance has a minimum at a height of around 90 km. This behaviour was also reported by Nozawa *et al.* (2005), where it was suggested that the secondary maxima in the wintertime 2-day wave amplitudes may be due to nonlinear coupling process between the 2-day wave and other waves/tides for example, the 24 and 12 hour tides.

The wave was present in all the winters observed in both hemispheres and so seems to be a persistent feature of the wintertime polar mesosphere and lower thermosphere. The satellite observations reveal this to be an E2 wave possibly originating in the lower polar stratosphere as suggested by the latter two studies (Palo *et al*., 2007; Baumgaertner *et al*., 2008; Sandford *et al*., 2008). Our observations show that despite the well known differences between the Antarctic and Arctic lower stratosphere, at MLT heights there is surprisingly little inter-hemispheric difference in the character of the wintertime 2-day wave.

The seasonal behaviour of this wave suggests it interacts with the mean winds. For an E2 2-day wave at 68° latitude, the zonal phase speed will be about 43.6 ms-1 wave will only be able to propagate in regions where the zonal wind speed lies between ~ +43.6 and +72.6 ms^{-1}. However, this is not the case in the mesosphere where the observed monthly mean wind speeds reach a maximum of +20 ms^{-1} during the winter months. This implies that the wave may not be freely propagating at mesospheric heights and may therefore be evanescent. Similar behaviour has been reported in the case of the 16 day wave by Luo *et al*. (2000) who observed significant wave activity in regions where the zonal wind was outside the range predicted by the Charney-Drezin theorem.

5 Conclusions

In this paper we have presented climatologies of the 2-day wave at Antarctic and Arctic latitudes. These were constructed from data recorded using identical meteor radars situated at the conjugate geographical latitudes of Rothera, (68°S, 68°W) and Esrange (68°N, 21°E). Inter-hemispheric comparisons can therefore be made free from the technique biases that might affect measurements if made by different techniques, such as comparisons between meteor and MF radars. This allows a robust assessment of inter-hemispheric differences between the two polar regions. The observations reveal two distinctly different waves in summer and winter in both hemispheres. We interpret the summertime wave as the polar manifestation of the classic westward midlatitude wavenumber 3 and 4 2-day wave. We interpret the wintertime wave as the polar eastward 2 wave reported in section 1.

In summer, the 2-day wave was observed in each year. A considerable degree of inter-annual variability was observed in each hemisphere. The climatological mean reveals that the wave amplitude is, on average, larger in the Antarctic than the Arctic. In the Antarctic the zonal component of the wave is stronger than the meridional (at least in the three years observed). This is in contrast to the Arctic where the meridional component dominates. The duration of strong wave activity in the Antarctic is usually shorter than in the Arctic. This shorter Antarctic duration may be due to the shorter interval of time during which a strong shear exists in eastward zonal flow above the zero wind line. The different durations of occurrence of the 2-day wave would thus be a consequence of the differences in the background flow of the two polar regions.

The wintertime wave is also a persistent feature of the polar middle atmosphere. It occurs each year. The amplitude of the wintertime wave is generally weaker than the summertime wave in both the Antarctic and Arctic. The meridional and zonal components have approximately equal amplitudes. There is little inter-annual variation in the amplitude and duration of the wave. Our observations show that the observed characteristics of the 2-day MLT wintertime wave are very similar in both hemispheres. From this we conclude that it is the same type of wave being observed in the Antarctic and Arctic (the eastward 2 described above). The similarity in behavior of the Antarctic and Arctic wintertime wave occurs despite the significant inter-hemispheric differences known to exist in the lower stratosphere.

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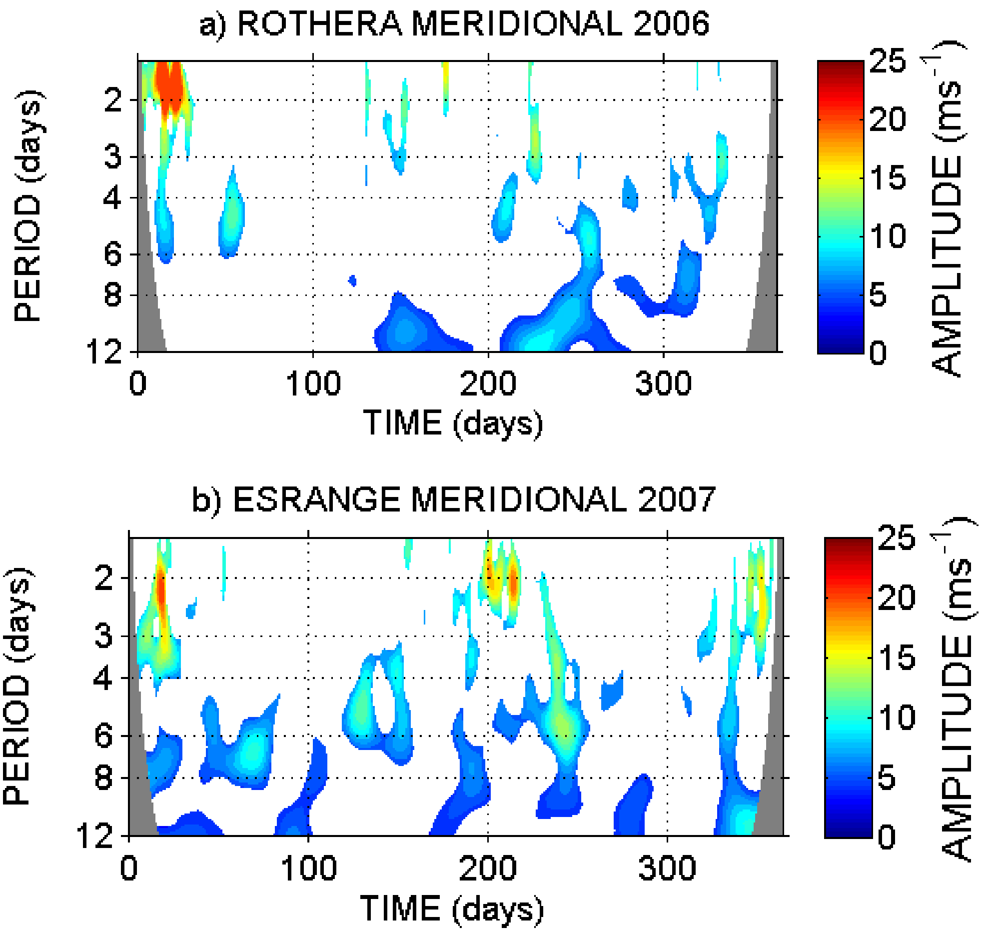


Figure 1. Wavelet analysis of meridional winds as a function of time at a height of ~ 93 km a) over Rothera in 2006, b) over Esrange in 2007. The signal is only plotted above the 95% confidence level.

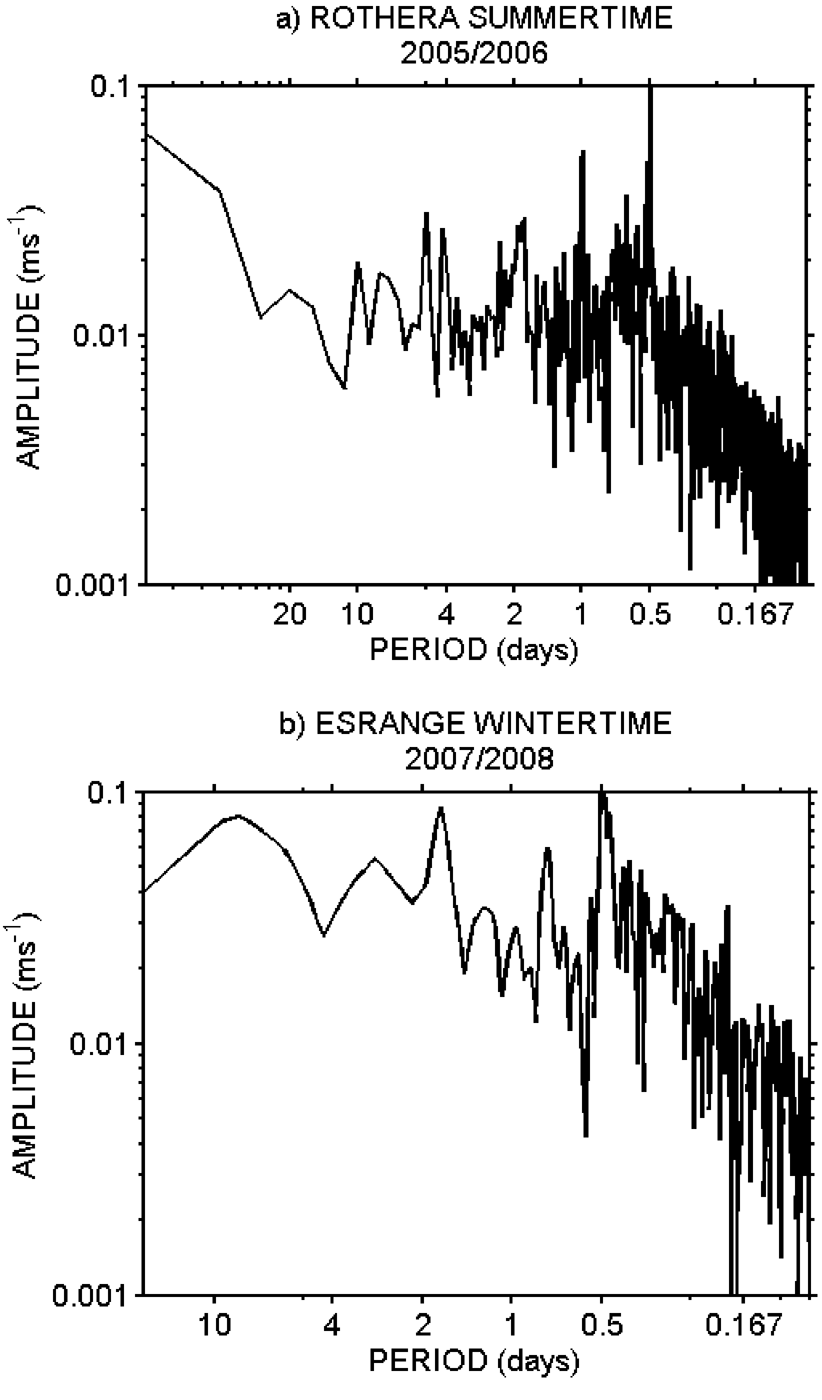


Figure 2. Lomb-Scargle analyses of meridional winds at a height of ~ 93.3 km a) over Rothera in summertime for the three month interval December 2005 – February 2006, b) Esrange wintertime in January 2008.

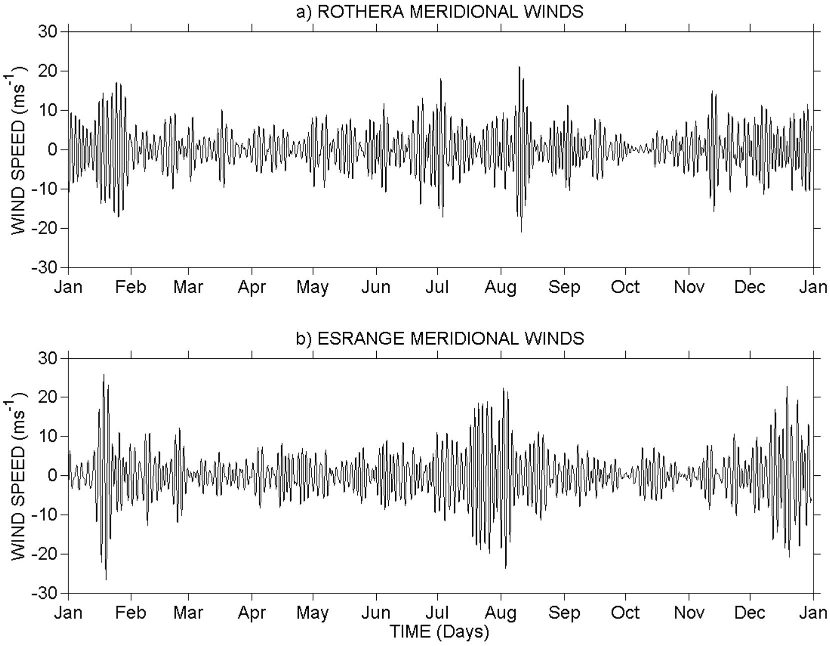


Figure 3. Bandpassed meridional winds as a function of time at a height of ~ 93 km, for 2007, a) over Rothera, b) over Esrange. The data have been bandpassed between periods of 1.6 and 2.8 days.

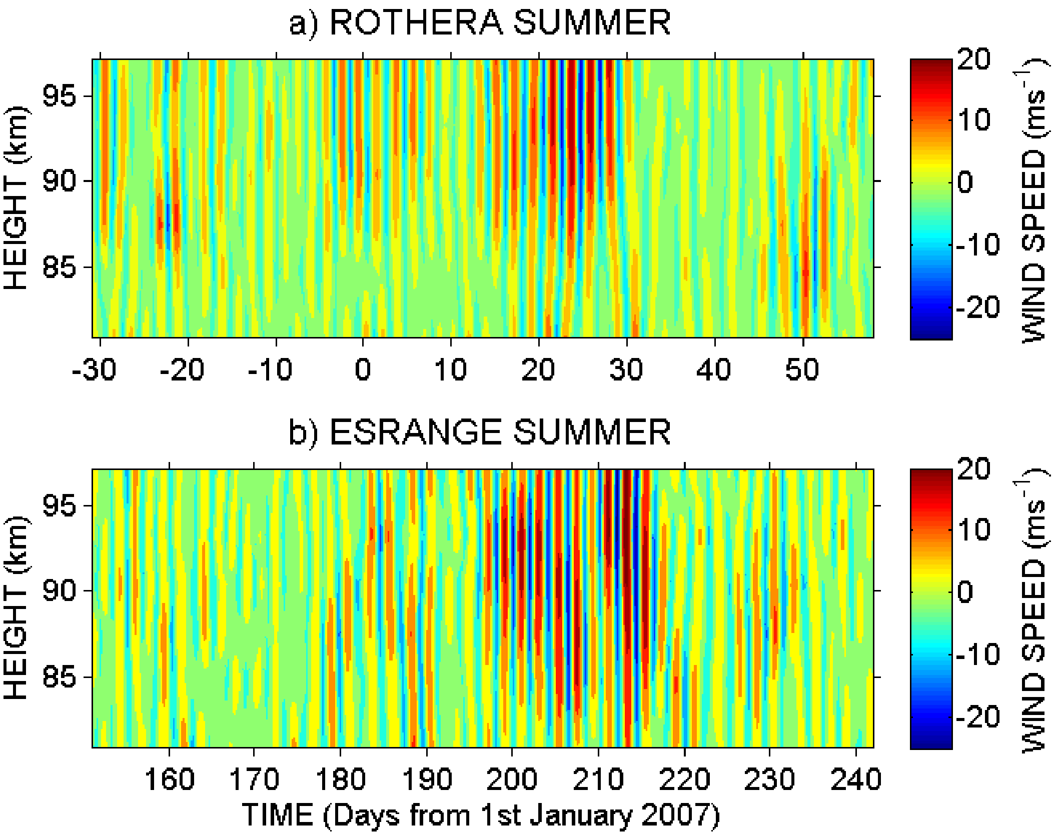


Figure 4. Bandpassed meridional winds as a function of time and height during summertime 2007, for heights of ~ 80 - 97 km, a) over Rothera, b) over Esrange. The data were bandpassed between periods of 1.6 and 2.8 days.

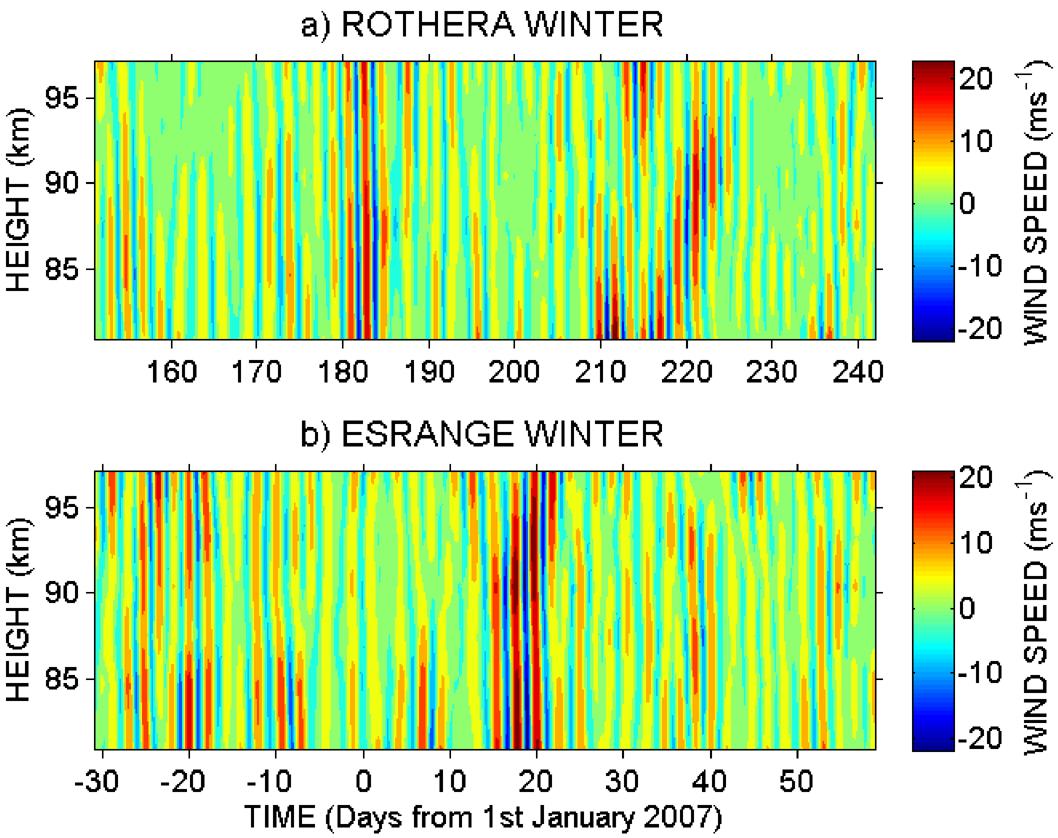
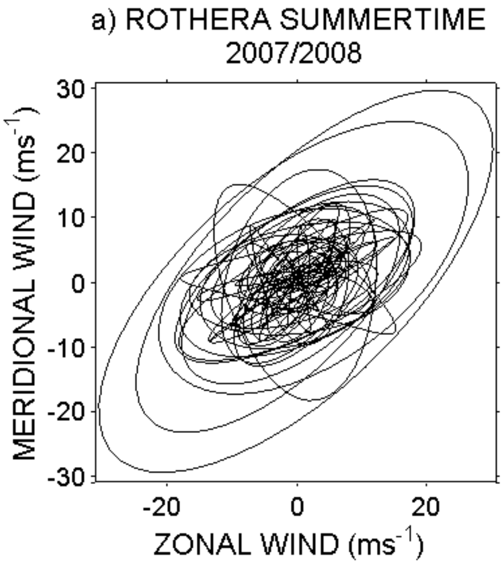
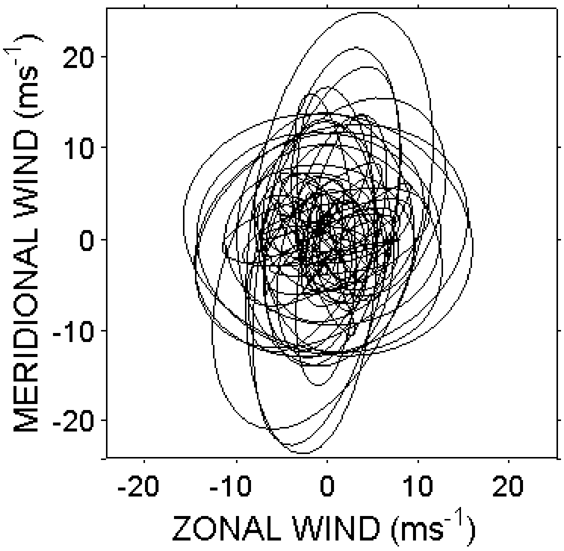


Figure 5. Bandpassed meridional winds as a function of time and height during wintertime 2007, for heights of ~ 80 - 97 km, a) over Rothera, b) over Esrange. The data were bandpassed between periods of 1.6 and 2.8 days.



b) ESRANGE SUMMERTIME
2008



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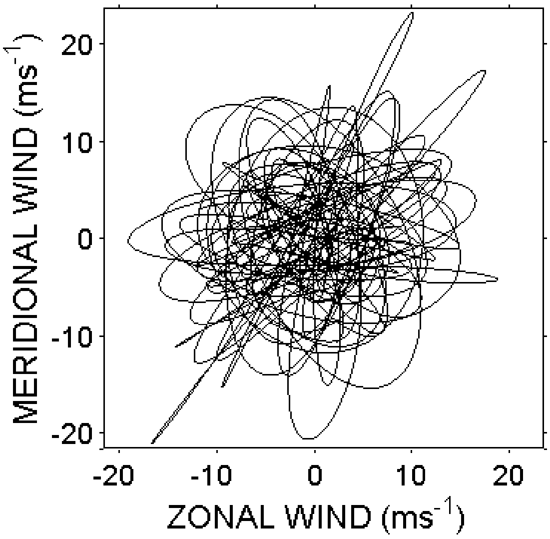
c) ROTHERA WINTERTIME
2007



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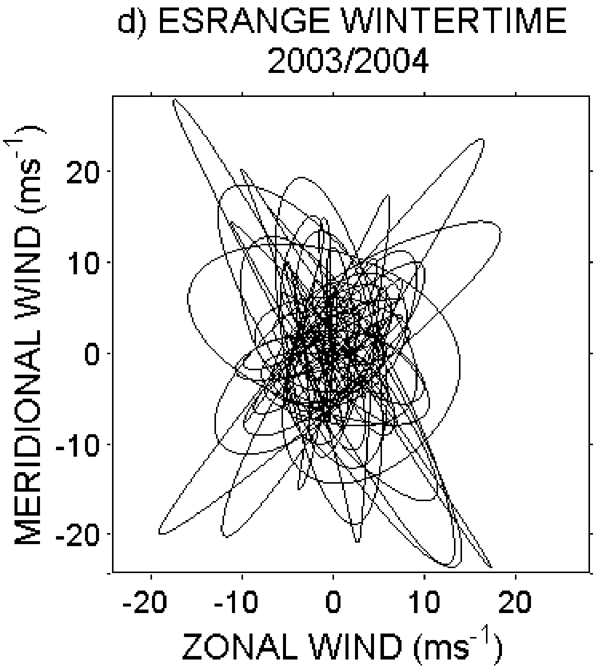


Figure 6. Hodograph analyses of a 48-hour period wave in summer at a height of ~ 93 km, during a) December 2007 – February 2008 over Rothera, b) June 2008 – August 2008 over Esrange. Hodograph analyses of a 48-hour period wave in winter at a height of ~ 84.7 km during c) June – August 2007 over Rothera and d) December 2003 – February 2004 over Esrange.

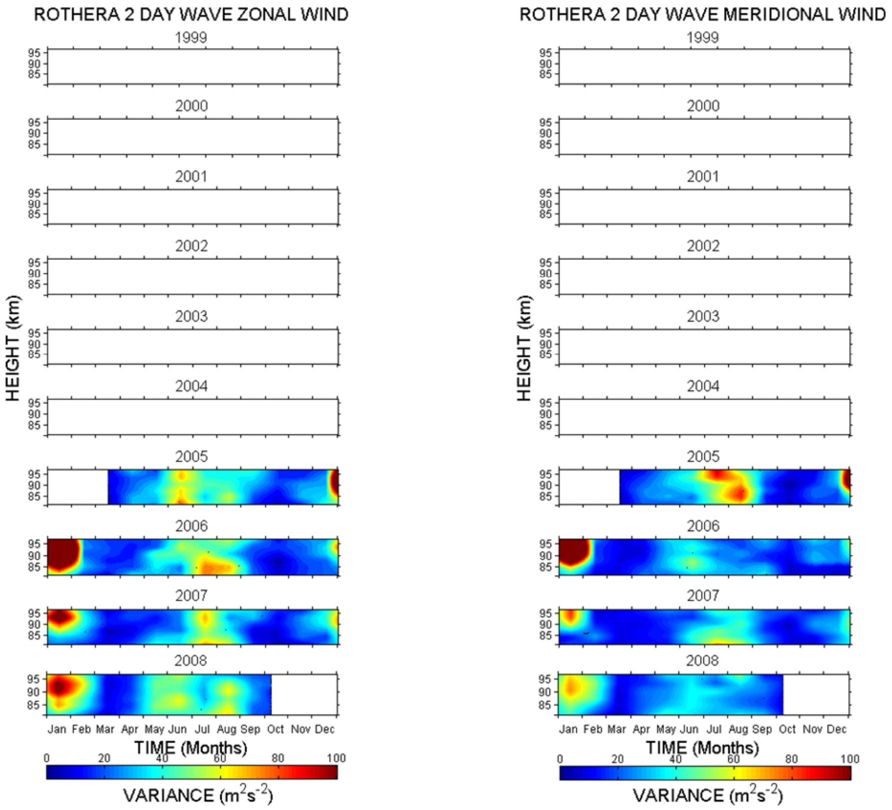


Figure 7. Time-height contours of the monthly variance of bandpassed horizontal winds over Rothera in the Antarctic between April 2005 - September 2008. The bandpass is between periods of 1.6 and 2.8 days.

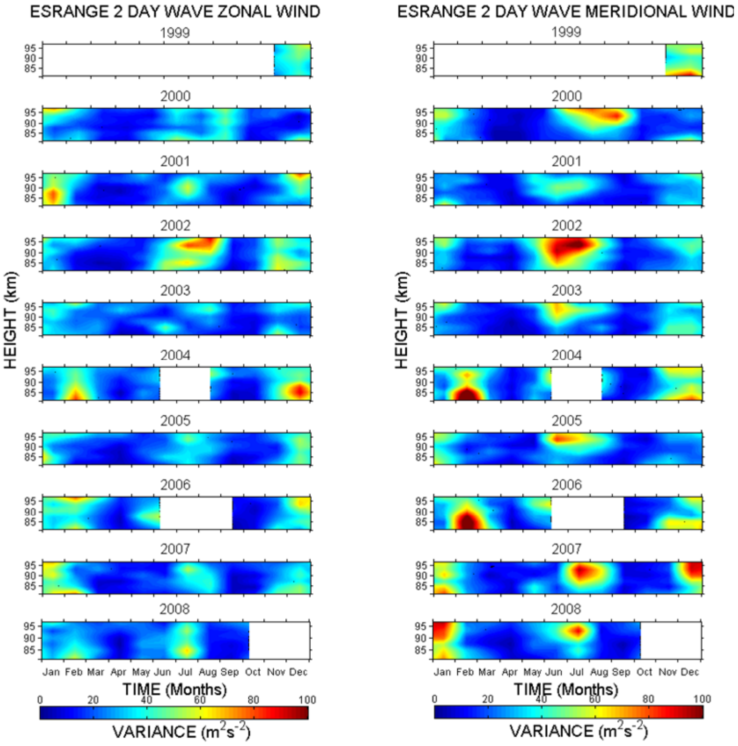


Figure 8. Time-height contours of the monthly variance of bandpassed horizontal winds over Esrange in the Arctic between October 1999 – September 2008. The bandpass is between periods of 1.6 and 2.8 days.

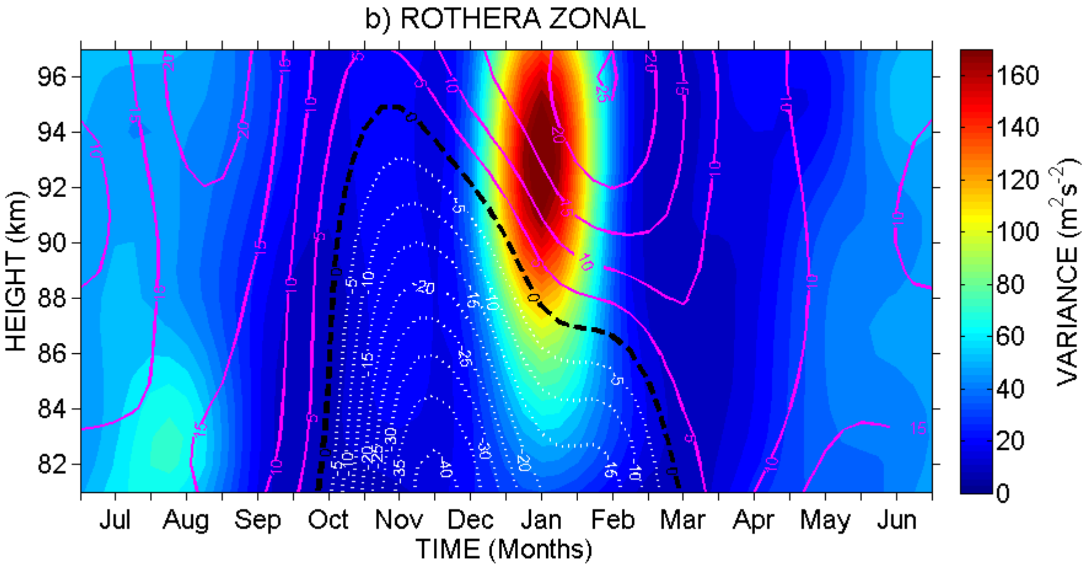
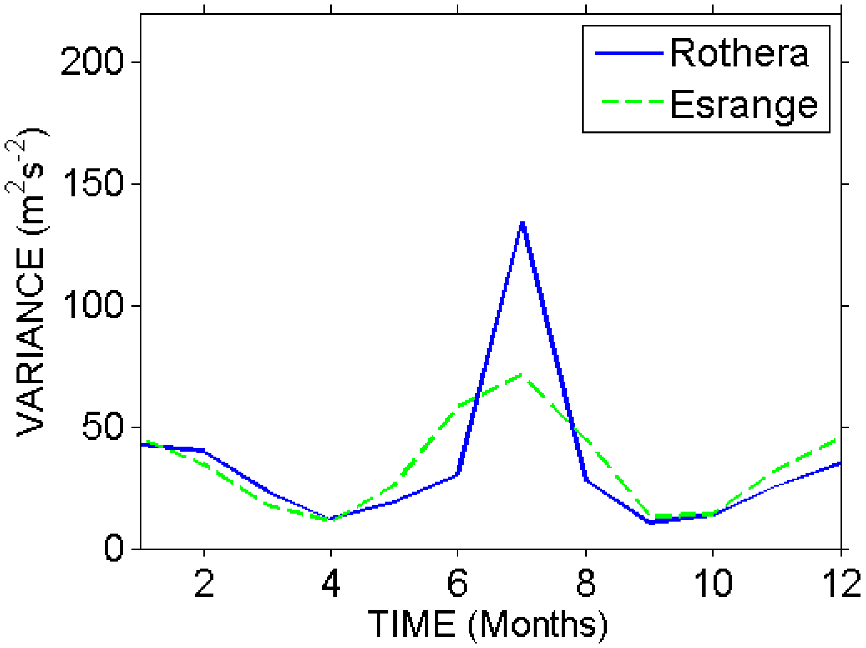


Figure 9. A composite-year analysis of the Rothera (Antarctic) variance data from Figure 6 for a) the meridional component and b) the zonal component (filled colour contours). Also plotted are monthly mean zonal winds (open contours). The zero wind contour is indicated by the heavy dashed black line. Note that the time axis is shifted by 6 months to allow easy comparison with Figure 10.

a) MERIDIONAL VARIANCES



b) ZONAL VARIANCES

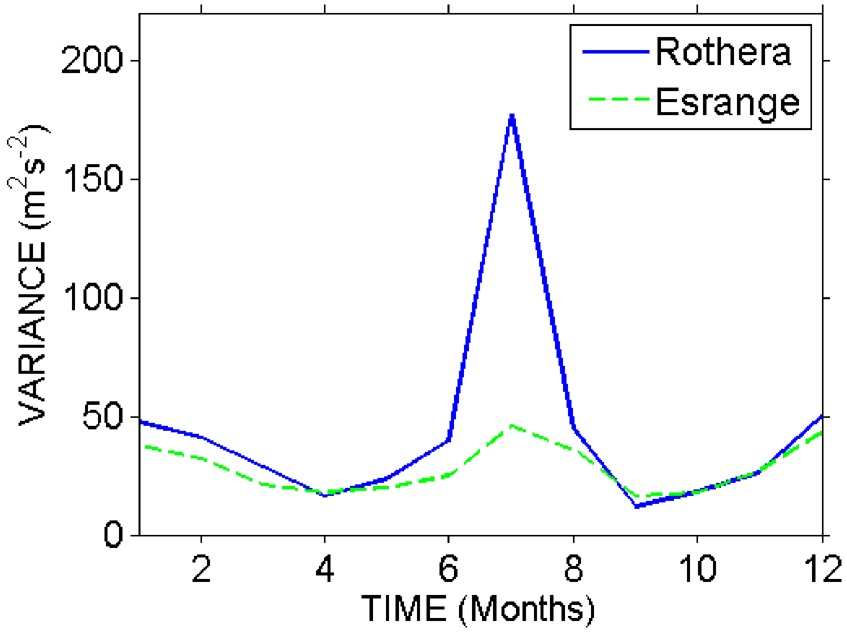


Figure 10. A composite year analysis of variances at a height of ~ 93 km, corresponding to the data shown in figures 7 and 8 for a) the meridional component and b) the zonal component.

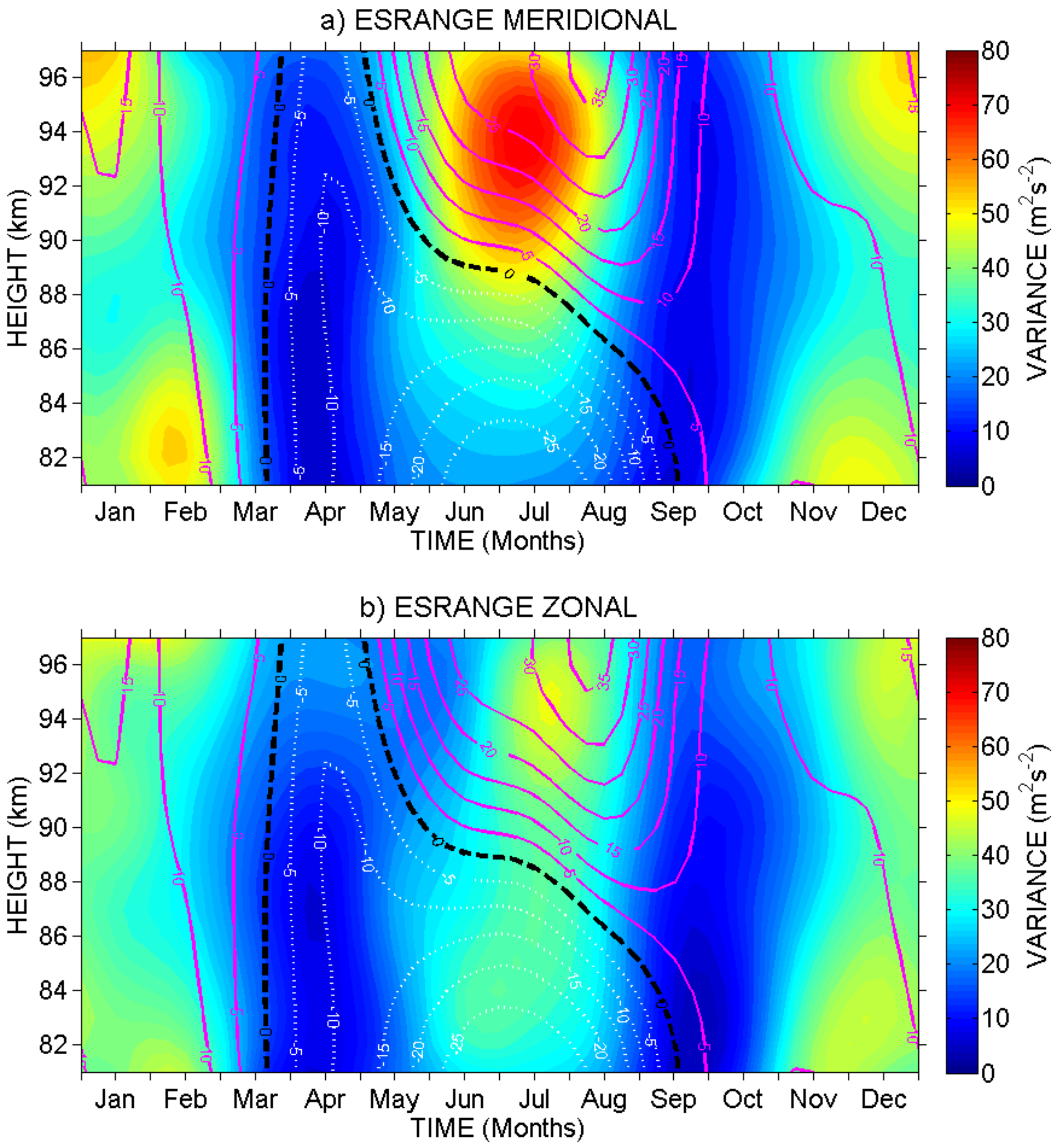


Figure 11. A composite-year analysis of the Esrange (Arctic) variance data from Figure 7 for a) the meridional component and b) the zonal component (filled colour contours). Also plotted are monthly mean zonal winds (open contours). The zero wind contour is indicated by the heavy dashed black line.

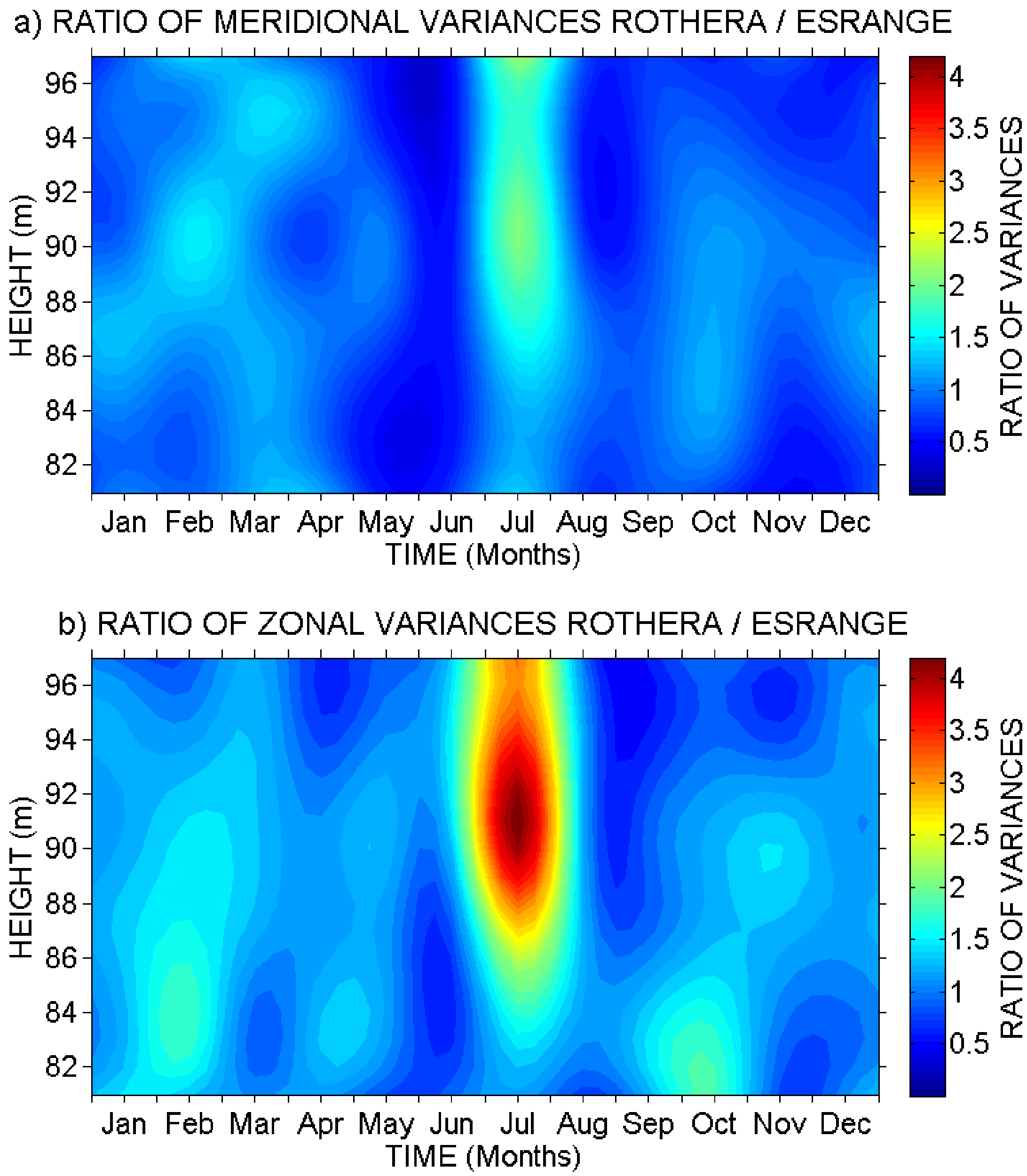


Figure 12. A ratio of the composite year analyses from Figures 9 and 11 for a) the meridional component and b) the zonal component. In each case the ratio is the variance at Rothera divided by the variance at Esrange.