Chapter 4

Gravity wave climatology

4.1 Introduction

A climatological study of gravity waves in the MLT in polar regions is presented in this chapter. Climatologies of gravity wave activity are produced for Davis and Syowa in the Antarctic, and Poker Flat and Andenes in the Arctic by averaging together all available years of MF radar wind variance data. These climatologies are investigated in terms of their seasonal and height variations, spectral characteristics and wave anisotropy.

Comparisons are made between the four locations as well as between the hemispheres. Similarities and differences are discussed such as variations in the timing and strength of various features present in the climatologies. The results of the comparisons are discussed in relation to possible sources of gravity wave activity and wave dissipation.

Hemispheric differences in gravity wave activity are expected to cause hemispheric differences in the dynamics and temperature structure of the MLT. The results presented in this chapter are discussed in relation to the results of other studies including hemispheric comparisons of phenomena such as PMCs and PMSEs. Results are also discussed in relation to the mean wind climatologies (from Chapter 3).

Results published in *Dowdy et al.* [2001] as part of this PhD research include a comparison of gravity wave activity between Poker Flat and Davis from 1999 until mid-2000. No spectral or anisotropic measurements were made, and wind variances were only shown during summer. The published results are consistent with the results presented in this chapter, with small variations as expected due to averaging over different time intervals.

4.2 Climatological overview

The MF radar wind variance data were shown previously in Figures 2.6, 2.7, 2.8 and 2.9. The data set consists of about 10 years of data from Davis, 4 years from Syowa, and 5 years from both Poker Flat and Andenes.

Variance climatologies were produced at heights from 70-100 km in the period range 20-120 minutes and also in the period range 120-480 minutes. Although the two period ranges are different in length, the variances when integrated over each period range are roughly similar in magnitude due to the $f^{\frac{5}{3}}$ nature of the gravity wave spectrum (see Figure 2.5).

Comparing the two period ranges gives a measure of the spectral content of the wave field, which can provide information about the origin of the waves and the atmosphere through which they have propagated.

Climatologies of the variances in the period range 20-120 minutes at Davis, Syowa, Poker Flat and Andenes are shown in Figures 4.1 and 4.2 for the zonal and meridional directions, respectively. They consist of variance data with a 15-day and 4-km running mean applied, averaged over all available years of data. Figures 4.3 and 4.4 are similar to Figures 4.1 and 4.2, but for longer period waves in the range 120-480 minutes.

There is considerable variation in gravity wave activity between the 4 locations. Andenes generally has lower variances than the other 3 locations. The reason for this is currently unknown, but may relate to the weaker mean winds as noted in Chapter 3.

Strong seasonal variations occur at all four locations in both period ranges, and

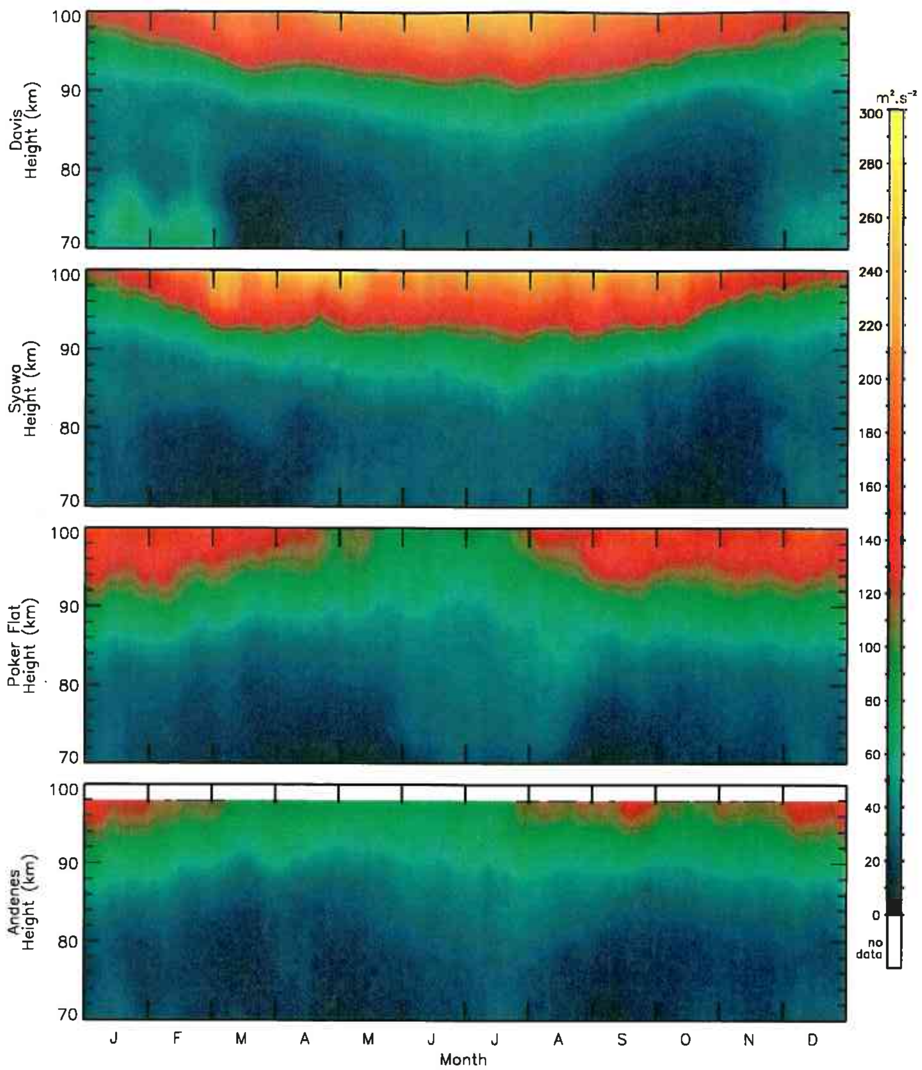

Figure 4.1: Climatologies of the zonal wind variances at Davis, Syowa, Poker Flat and Andenes in the period range 20-120 minutes. They consist of variances with a 15-day and 4-km running mean applied, averaged over all available years.

also for both horizontal components of wave motion. The timing and magnitude of the seasonal variations are investigated quantitatively in the following section using a time series analysis.

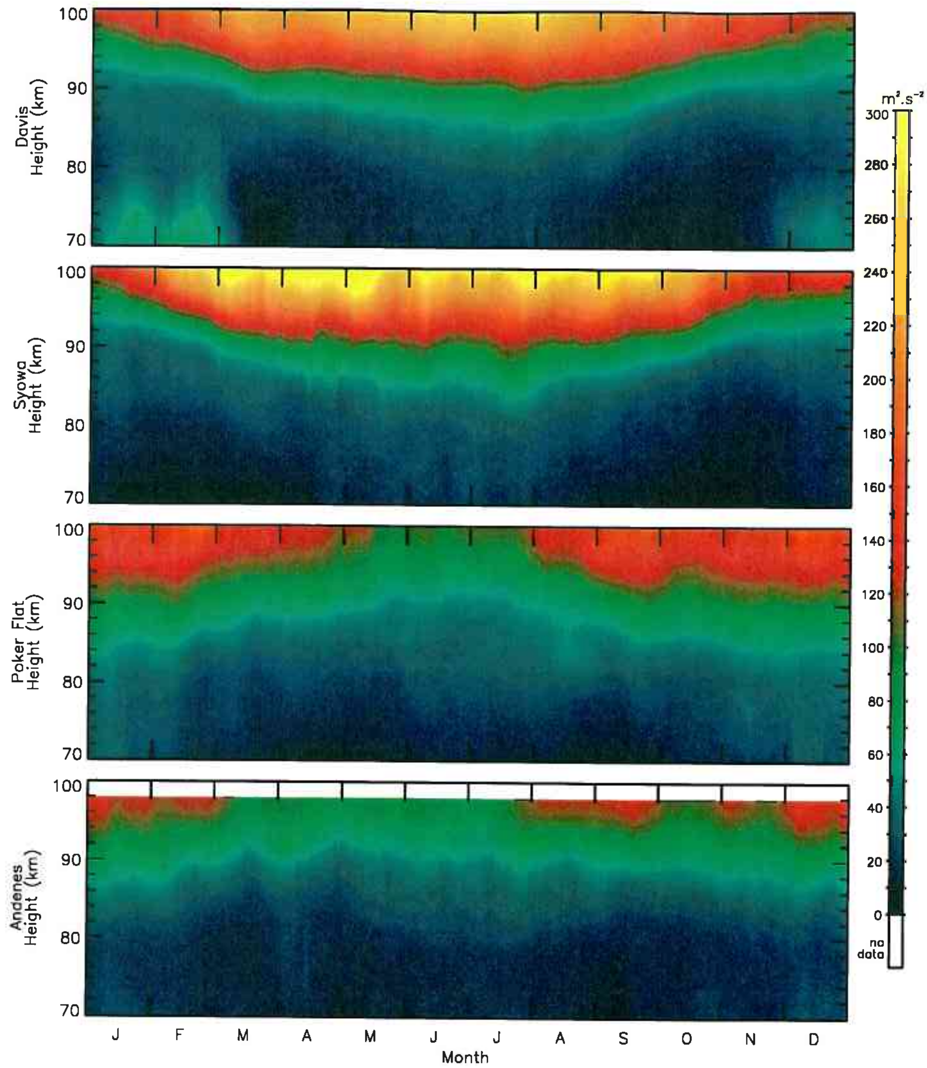

Figure 4.2: As for Figure 4.1, but for the meridional variances in the period range 20-120 minutes.

4.3 Time series analysis of wave climatologies

Time series of the zonal and meridional variances are investigated for both period ranges (20-120 minutes and 120-480 minutes) at Davis, Syowa, Poker Flat and Andenes. This is done for two height ranges, from 76-84 km (80 $\pm$ 4 km) and from 86-94 km (90 $\pm$ 4 km).

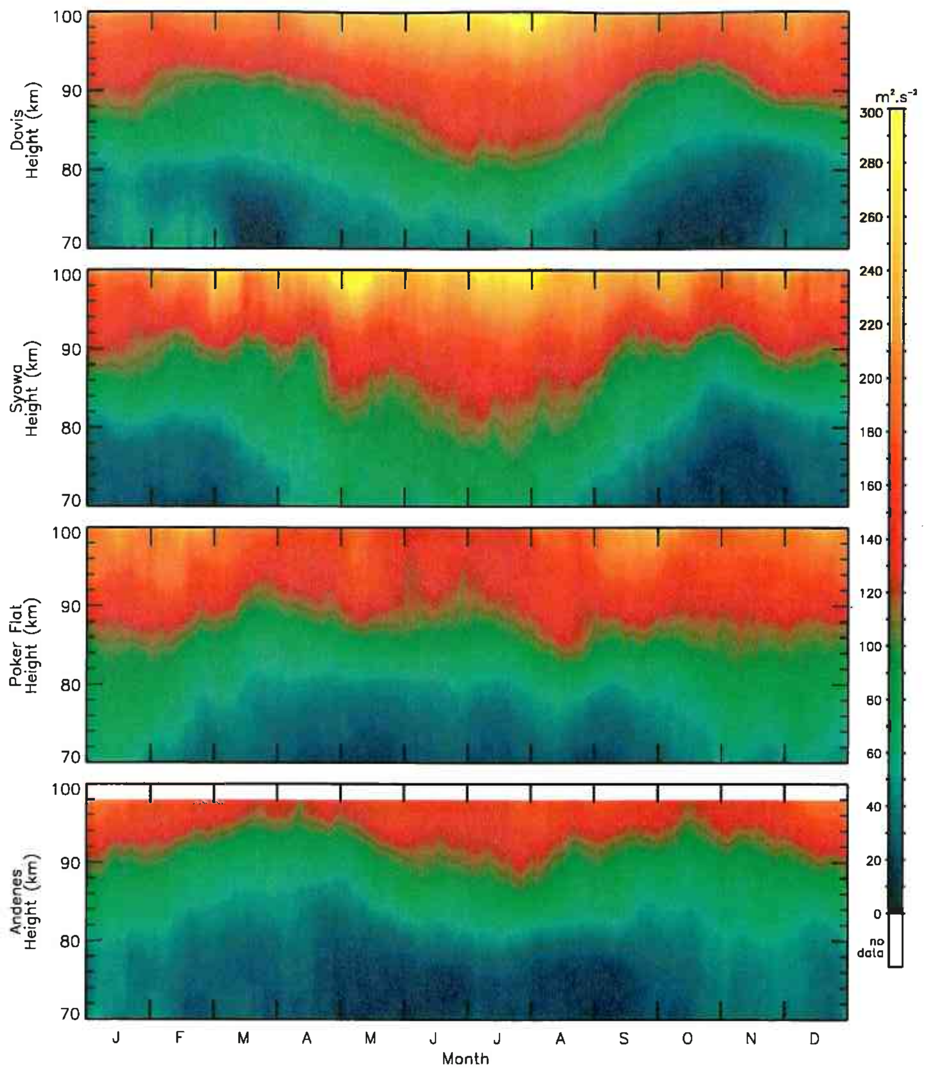

Figure 4.3: As for Figure 4.1, but for the zonal variances in the period range 120-480 minutes.

4.3.1 Time series of 20-120 minute period variances from 76-84 km

Time series of the zonal and meridional wind variances in the short period range (20-120 minutes) are shown in Figure 4.5 at a height of 80 ± 4 km (averaged from 76-84 km). Data are shown with respect to the date of the summer solstice in each hemisphere. A 7-day running mean is applied, and the data are averaged over all

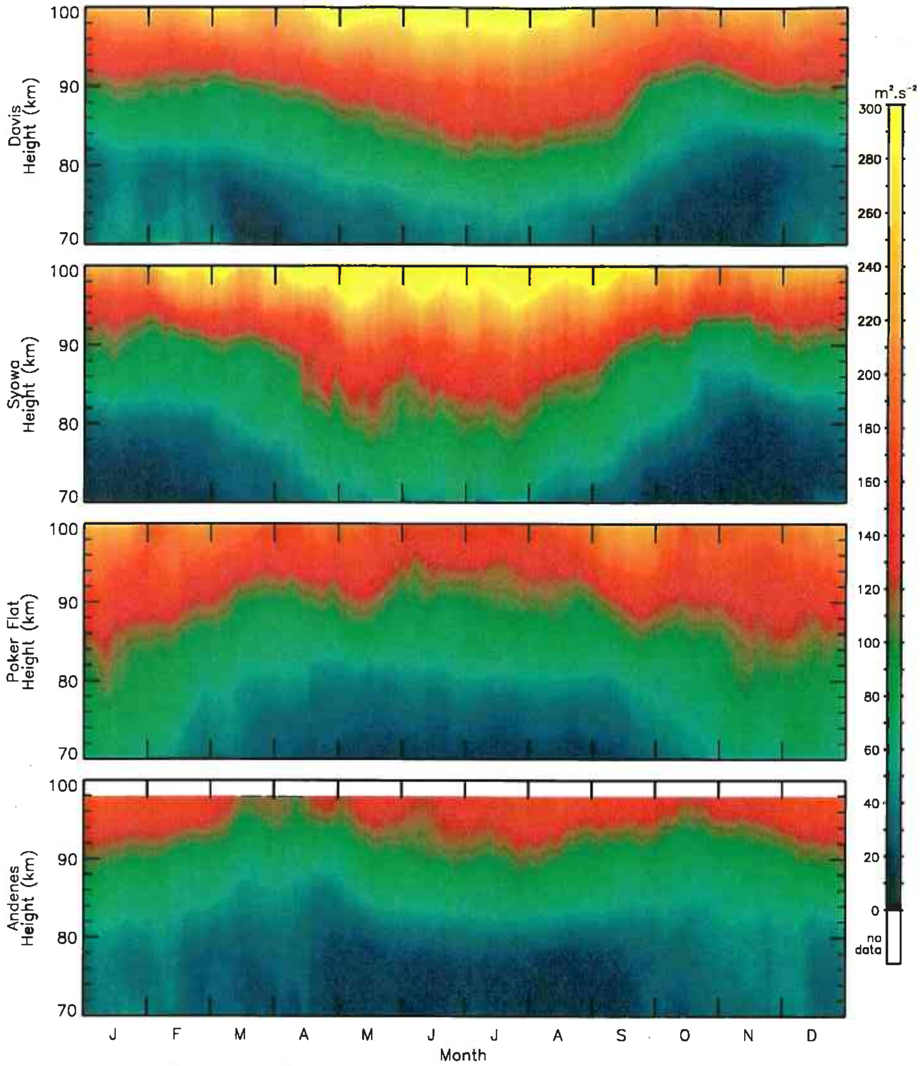

Figure 4.4: As for Figure 4.1, but for the meridional variances in the period range 120-480 minutes.

available years. The dotted lines represent a least-squares harmonic fit to the data consisting of the sum of the mean, annual, semi-annual and ter-annual components.

The zonal variances show a strong semi-annual variation at all four locations, with maxima around the solstices and minima around the equinoxes. The amplitude of the semi-annual variation is not as large for the meridional variances as for the zonal variances. This is particularly true at Syowa and Poker Flat where the seasonal variations of the meridional wind variances are more annual in nature.

	Winter maxima (days from summer solstice)	Spring minima (days from summer solstice)	Summer maxima (days from summer solstice)	Autumn minima (days from summer solstice)
Davis (z)	-162	-63	27	112
Davis (m)	-163	-50	37	115
Syowa (z)	-146	-58	13	78
Syowa (m)	-159	-48	25	51
Poker Flat (z)	181	-70	34	115
Poker Flat (m)	-180	-67	44	96
Andenes (z)	176	-72	25	104
Andenes (m)	-182	-78	18	97

Table 4.1: The timing of the seasonal variations in gravity wave activity in the period range 20-120 minutes at heights from 76-84 km (using the harmonic fits shown in Figure 4.5). Data are shown for both the zonal (z) and meridional (m) wind variances.

	Winter maxima (m^2s^{-2})	Spring minima (m^2s^{-2})	Summer maxima (m^2s^{-2})	Autumn minima (m^2s^{-2})
Davis (z)	37	17	40	20
Davis (m)	33	16	33	18
Syowa (z)	33	16	29	20
Syowa (m)	33	15	20	19
Poker Flat (z)	34	22	41	27
Poker Flat (m)	40	23	31	29
Andenes (z)	27	18	32	20
Andenes (m)	27	17	24	19

Table 4.2: The magnitude of the seasonal variations in gravity wave activity in the period range 20-120 minutes at heights from 76-84 km (using the harmonic fits shown in Figure 4.5). Data are shown for both the zonal (z) and meridional (m) wind variances.

The timing and magnitude of the seasonal variations are detailed in Tables 4.1 and 4.2, respectively (using the harmonic fits shown in Figure 4.5). The timing is shown as positive (negative) values corresponding to days after (before) the summer solstice in each hemisphere.

Winter maxima occur at all four locations for both the zonal and meridional variances. The maxima occur earlier (with respect to the solstice) at the Antarctic locations than at the Arctic locations. The maxima of the harmonic fits occur on average about 25 days after the winter solstice at the Antarctic locations, and about 4 days before the winter solstice at the Arctic locations (from Table 4.1), giving a hemispheric difference of about 29 days.

The spring minima are the times of weakest wave activity at all locations for both the zonal and meridional wind variances. A hemispheric difference also occurs for the timing of this feature. The spring minima occur before the summer solstice by about 55 days in the Antarctic, and by about 72 days in the Arctic.

The average change in magnitude from the winter maxima to the spring minima is about -18 m^2s^{-2} at the Antarctic locations and about -12 m^2s^{-2} at the Arctic locations. The average rate of change in variance strength from the winter maxima to the spring minima is -0.18 $m^2s^{-2}day^{-1}$ for the southern hemisphere locations and -0.11 $m^2s^{-2}day^{-1}$ for the northern hemisphere locations.

4.3.2 Time series of 120-480 minute period variances from 76-84 km

Figure 4.6 is similar to Figure 4.5, but for variances in the longer period range (120-480 minutes). A semi-annual variation is less obvious for the longer period variances than was the case for the shorter period variances in this height range (76-84 km), with a more annual variation being apparent. This is due to the summer maxima not being as pronounced for the longer period variances.

The longer period variances have maxima during winter and minima during spring. The dates and magnitudes of these extreme values are shown in Tables 4.3 and 4.4, resepctively, using the harmonic fits shown in Figure 4.6.

The winter maxima and spring minima occur significantly later at the southern hemisphere locations than at the northern hemisphere locations (as was also seen for the shorter period waves at these heights). The winter maxima occur on average ∼25 days later at the southern hemisphere locations, and the spring minima occur ∼10 days later than at the northern hemisphere locations (from Table 4.4).

	Winter maxima (days from summer solstice)	Spring minima (days from summer solstice)
Davis (z)	-160	-45
Davis (m)	-152	-37
Syowa (z)	-156	-44
Syowa (m)	182	-37
Poker Flat (z)	-178	-51
Poker Flat (m)	-182	-48
Andenes (z)	169	-53
Andenes (m)	169	-52

Table 4.3: The timing of the seasonal variations in gravity wave activity in the period range 120-480 minutes at heights from 76-84 km (using the harmonic fits shown in Figure 4.6). Data are shown for both the zonal (z) and meridional (m) wind variances.

	Winter maxima (m^2s^{-2})	Spring minima (m^2s^{-2})
Davis (z)	97	28
Davis (m)	92	24
Syowa (z)	107	31
Syowa (m)	102	24
Poker Flat (z)	88	46
Poker Flat (m)	98	42
Andenes (z)	53	29
Andenes (m)	49	28

Table 4.4: The magnitude of the seasonal variations in gravity wave activity in the period range 120-480 minutes at heights from 76-84 km (using the harmonic fits shown in Figure 4.6). Data are shown for both the zonal (z) and meridional (m) wind variances.

The winter maxima are about 97 m^2s^{-2} at the southern hemisphere locations on average, decreasing to about 27 m^2s^{-2} in spring, giving a total decrease of 70 m^2s^{-2}. A smaller decrease of 36 m^2s^{-2} is observed for the northern hemisphere locations. The average time from the winter maxima to the spring minima is about 123 days at the Antarctic locations and 137 days at the Arctic locations. This gives an average rate of change of -0.56 $m^2s^{-2}day^{-1}$ for the Antarctic locations which is about twice the rate of -0.26 $m^2s^{-2}day^{-1}$ of the Arctic locations.

4.3.3 Time series of 20-120 minute period variances from 86-94 km

Figure 4.7 is similar to Figure 4.5, but for heights around 90 km (averaged from 86-94 km) in the short period range (20-120 minutes). The dates and magnitudes of the maximum and minimum variance strengths are shown in Tables 4.5 and 4.6, resepctively, using the harmonic fits shown in Figure 4.7.

A hemispheric difference can be seen from Table 4.5 for the timing of the winter maxima. The winter maxima occur ∼37 days after the winter solstice at the southern hemisphere locations, but only ∼12 days after the winter solstice at the northern hemisphere locations.

The time series differ from what was seen at lower heights in that minima in variance strength generally occur around the time of the summer solstice. The time series at Andenes are the exception to this, where the minima occur in spring (as was the case at all locations at heights around 80 km for both period ranges).

The change in magnitude between the winter maxima and the spring/summer minima is about -61 m^2s^{-2} at the Antarctic locations and about -35 m^2s^{-2} at the Arctic locations. This gives a rate of change in variance strength of -0.38 $m^2s^{-2}day^{-1}$ for the southern hemisphere locations which is once again about twice the rate of -0.21 $m^2s^{-2}day^{-1}$ for the northern hemisphere locations.

4.3.4 Time series of 120-480 minute period variances from 86-94 km

Figure 4.8 is similar to Figure 4.5, but for variances in the longer period range (120-480 minutes) at heights around 90 km (averaged from 86-94 km). The time series shown in Figure 4.8 have winter maxima and spring minima at all four locations for both the zonal and meridional variances. There is some indication of a semi-annual variation, particularly at Davis and Andenes for the zonal variances where maxima also occur during summer with minima in autumn.

	Time of maxima (days from summer solstice)	Time of minima (days from summer solstice)
Davis (z)	-151	26
Davis (m)	-146	20
Syowa (z)	-140	5
Syowa (m)	-145	9
Poker Flat (z)	-166	4
Poker Flat (m)	-170	8
Andenes (z)	-171	-60
Andenes (m)	-172	-47

Table 4.5: The timing of the seasonal variations in gravity wave activity in the period range 20-120 minutes at heights from 86-94 km (using the harmonic fits shown in Figure 4.7). Data are shown for both the zonal (z) and meridional (m) wind variances.

	Maxima (m^2s^{-2})	Minima (m^2s^{-2})
Davis (z)	103	48
Davis (m)	107	42
Syowa (z)	90	41
Syowa (m)	108	35
Poker Flat (z)	90	53
Poker Flat (m)	95	47
Andenes (z)	74	47
Andenes (m)	76	47

Table 4.6: The magnitude of the seasonal variations in gravity wave activity in the period range 20-120 minutes at heights from 86-94 km (using the harmonic fits shown in Figure 4.7). Data are shown for both the zonal (z) and meridional (m) wind variances.

The dates and magnitudes of the winter maxima and spring minima in variance strengths are shown in Tables 4.7 and 4.8, respectively, using the harmonic fits shown in Figure 4.8. The winter maxima occur 9 days later on average at the southern hemisphere locations, with the spring minima occurring 20 days later than at the northern hemisphere locations.

The change in magnitude between the winter maxima and the spring minima is -87 m^2s^{-2} at the Antarctic locations compared with -42 m^2s^{-2} at the Arctic locations.

	Time of maxima (days from summer solstice)	Time of minima (days from summer solstice)
Davis (z)	-153	-64
Davis (m)	-153	-53
Syowa (z)	-155	-59
Syowa (m)	-159	-50
Poker Flat (z)	-158	-80
Poker Flat (m)	-162	-74
Andenes (z)	-171	-78
Andenes (m)	-166	-77

Table 4.7: The timing of the seasonal variations in gravity wave activity in the period range 120-480 minutes at heights from 86-94 km (using the harmonic fits shown in Figure 4.8). Data are shown for both the zonal (z) and meridional (m) wind variances.

	Winter maxima (m^2s^{-2})	Spring minima (m^2s^{-2})
Davis (z)	171	88
Davis (m)	180	92
Syowa (z)	168	98
Syowa (m)	187	81
Poker Flat (z)	150	113
Poker Flat (m)	150	100
Andenes (z)	110	67
Andenes (m)	106	69

Table 4.8: The magnitude of the seasonal variations in gravity wave activity in the period range 120-480 minutes at heights from 86-94 km (using the harmonic fits shown in Figure 4.8). Data are shown for both the zonal (z) and meridional (m) wind variances.

This gives a rate of change in variance strength of -0.88 $m^2s^{-2}day^{-1}$ for the southern hemisphere locations and -0.48 $m^2s^{-2}day^{-1}$ for the northern hemisphere locations.

4.3.5 Time series anaylsis summary

Table 4.9 summarises the results of the time series analysis. Many of the results are common between the different height and period ranges.

The winter maxima occur later (by about 21 days on average) at the Antarctic

	Variance period (minutes)	Height (km)	Maxima (days from summer solstice)	Minima (days from summer solstice)	Δ magnitude (m^2s^{-2})	Rate of change ($m^2s^{-2}day^{-1}$)
SH	20-120	80	-158	-55	-18	-0.18
NH	20-120	80	-184	-72	-12	-0.11
SH	120-480	80	-163	-41	-70	-0.56
NH	120-480	80	-188	-51	-36	-0.26
SH	20-120	90	-146	+15	-61	-0.38
NH	20-120	90	-170	-24	-35	-0.24
SH	120-480	90	-155	-57	-87	-0.88
NH	120-480	90	-164	-77	-42	-0.48

Table 4.9: The timing of the winter maxima and spring/summer minima (summarising Tables 4.1-4.8). The change in magnitude and the rate of change between the maxima and minima are also shown.

locations than at the Arctic locations in both period ranges and both height ranges. The minima also occur later at the Antarctic locations in all cases (with an average difference of about 22 days).

The magnitude of the change from the maxima to the minima is 90% larger (28 m^2s^{-2}) on average at the Antarctic locations than at the Arctic locations in both period ranges and both height ranges. The average rate of change is also larger in magnitude at the Antarctic locations in all cases than at the Arctic locations.

The seasonal variation in gravity wave activity is normally dominated by an annual component, although a semi-annual component is strong at heights around 80 km for the short period zonal variances at all four locations. It is interesting that the summer maxima relating to this semi-annual variation are not seen around 90 km in this period range (see Figure 4.7). One interpretation of this is that waves in the 20-120 minutes period range are being strongly dissipated around the summer mesopause region. There is also a possibility that during summer values above 90 km could be contaminated by total reflections, although this is unlikely as it should not influence one hemisphere differently to the other.

The summer maxima at heights around 80 km for the short period zonal variances occur on average about 4 days earlier in the Antarctic than in the Arctic (from Table 4.1). The minima in wave activity following the summer maxima occur about ∼14 days earlier in the Antarctic than in the Arctic.

These hemisperic timing delays are similar to what is observed for the equatorward jet around the summer mesopause. The jet reaches peak values about 4 days later and persist for about 13 days longer in the Arctic than in the Antarctic (see Table 3.4).

4.4 Height profiles of wave activity

4.4.1 Height profiles for the period range 20-120 minutes

Height profiles of the variance climatologies in the period range 20-120 minutes are shown in Figure 4.9 averaged during summer and winter. Summer (winter) values are defined here as the mean value during December and January (June and July) in the southern hemisphere and June and July (December and January) in the northern hemisphere.

The dotted lines in Figure 4.9 are an estimate of the expected height profiles if wave energy was being conserved. They consist of the variance strength at 70 km, $\overline{u'^2(70)}$ (or $\overline{v'^2(70)}$), multiplied by an exponential term as such:

$$\overline{u'^2(z)} = \overline{u'^2(70)} e^{\frac{z}{2H_\rho}}$$

where $H_\rho = 5$ km, is used as the density scale height (based on July values at 69°N [*Lübken*, 1999]). The density scale height will vary with location and season, however a constant value is sufficient here since it is only used qualitatively in this section.

Some differences are evident between the four locations, with Andenes showing less difference between the summer and winter variance climatologies than can be seen at the other three locations. Another difference is that a minima in wave variance occurs at Davis at heights around 80 km during summer. This was also noted in *Dowdy et al.* [2001] using the sum of the zonal and meridional variances in the period range 20-480 minutes.

At the higher altitudes, variances are larger during winter than summer. It is therefore interesting that at the lower heights there is little or no difference in magnitude between summer and winter. An interpretation of this is that more wave saturation is occurring during summer than during winter.

The variances are similar in magnitude between all four locations at heights beneath about 90 km. The variances at the higher altitudes are stronger at the southern hemisphere locations than at the northern hemisphere locations. This is true in summer and winter for both horizontal components of the wave motions. Above about ∼90 km in summer and about ∼80 km in winter the variances at the Antarctic locations increase at a rate faster (and more similar to what would be expected for conservation of wave energy) than the rate of increase at the Arctic locations.

4.4.2 Height profiles in the period range 120-480 minutes

Figure 4.10 is similar to Figure 4.9, but for the longer period range variances (120-480 minutes).

The height profiles in Figure 4.10 show that the variances during winter are larger than the variances during summer at the higher altitudes (as was seen for the shorter period range). The winter variances are also generally larger than the summer values at lower heights (in contrast to what was seen for the shorter period variances).

There is some evidence of apparent saturation taking place at Davis and Syowa during summer at heights of up to about 80 km, but none during winter. This is different to the behaviour of the shorter period variances, where the waves appeared to be strongly saturated up to heights of about ∼90 km in summer and ∼80 km in winter.

A similarity between the two period ranges is that the variances at high altitudes at the southern hemisphere locations are significantly stronger than at the northern hemisphere locations, but similar at lower heights. This is true in summer and winter, and also for both horizontal components of the wave motions. Both the zonal and meridional variances increase with height less rapidly at the northern hemisphere locations than at the southern hemisphere locations where the height profiles more closely resemble what would be expected if wave energy was being conserved.

4.5 Wave orientation

The difference, D, between the zonal and meridional variances is defined here (using the notation of *Vincent & Fritts* [1987]) as:

$$D = \overline{u'^2} - \overline{v'^2}$$

This quantity is investigated and used in this section, along with the covariance of the zonal and meridional winds, ($\overline{u'v'}$), to measure the degree of polarisation and orientation of the wave field.

4.5.1 Wave anisotropy in the period range 20-120 minutes

Figure 4.11 shows the quantity D (using the data shown in Figures 4.1 and 4.2) at Davis, Syowa, Poker Flat and Andenes in the period range 20-120 minutes.

It can be seen from Figure 4.11 that significant regions of horizontal anisotropy are evident at all four locations. The value of D is generally positive up to heights of about ~94 km in summer at all four locations. Some hemispheric differences occur during winter, with the average value of D being positive up to about 80 km at the southern hemisphere locations, positive but relatively weak in magnitude at Andenes and negative at Poker Flat.

The seasonal variation is generally annual in nature at all locations, with maxima in summer and minima in winter. The exception to this occurs at Davis, where a semi-annual variation is observed at heights up to about ~90 km.

It is interesting that regions where D is positive are generally lower in height than regions where D is negative at any time of year at all four locations. A possible interpretation of this is that the zonally oriented waves would be expected to produce more wave drag in the MLT since they appear to be dissipated more than the meridionally oriented waves in this region.

4.5.2 Wave anisotropy in the period range 120-480 minutes

Figure 4.12 is similar to Figure 4.11, but for the longer period range (120-480 minutes). The seasonal and height variations of D show some similarities as well as some differences to what was observed for the shorter period variances.

As was seen for the shorter period variances, an annual variation occurs at all locations with the exception of Davis where the seasonal variation appears to be more semi-annual in nature at heights up to about ~90 km. One difference between the two period ranges occurs at Andenes, where the value of D in the longer period range is generally positive at all heights.

4.5.3 Covariance climatologies

The covariance of the zonal and meridional winds, $\overline{u'v'}$, are presented in this section. They provide another means of investigating the gravity wave fields in the MLT region from the available MF radar data, as well as being necessary for calculating the degree and angle of polarisation of the wave fields (as is done in Section 4.5.4). When $\overline{u'v'} > 0$, the wave field is oriented more in a north-east/south-west direction, and a more north-west/south-east direction when $\overline{u'v'} < 0$.

4.5.3.1 20-120 minute covariance climatologies

Figure 4.13 shows $\overline{u'v'}$ at Davis, Syowa, Poker Flat and Andenes for the period range 20-120 minutes. A 15-day and 4-km running mean is applied to the covariances which are averaged over all available years of data.

The covariances at the four locations show large differences to each other. The covariances at Poker Flat are generally slightly positive in the lower thermosphere throughout the year, with an annual variation apparent at lower heights that is positive in winter and negative in summer on average.

The covariances are slightly positive during summer at Andenes throughout the MLT region, but at other times of the year they generally show no significant variation with height or season.

At Syowa, the covariances are generally negative, except from a period between about March to November at heights up to about ∼80 km where they are slightly positive on average.

The covariances at Davis are very different to the other three locations. There is a well defined boundary between positive and negative covariance, with strong positive values at higher altitudes. This boundary shows an annual variation with height, ranging from ∼90 km in summer to ∼80 km in winter. A semi-annual variation is also apparent at heights up to about 80 km, with negative covariances around the times of the solstices and positive values around the times of the equinoxes.

The differences between the covariances at Davis and Syowa is somewhat surprising considering that Davis and Syowa are relatively close geographically. The strong similarities of the 2 MF radars and the data analysis techniques used suggest that this is real, indicating that gravity wave activity can vary significantly on a climatological scale over relatively small spatial scales.

4.5.3.2 120-480 minute covariance climatologies

Figure 4.14 is similar to Figure 4.13, but for the longer period covariances in the range 120-480 minutes. The patterns in the covariance climatologies for the longer period range show some similarities as well as some differences to what was observed for the shorter period range.

A seasonal or height dependent variation of the longer period covariances is not obvious at the northern hemisphere locations. The longer period covariances at Syowa show a similar height and seasonal variation to what was observed for the shorter period range, the exception being that positive values occur above ∼90 km during summer.

The covariances at Davis are remarkably different to the covariances at the other three locations. At heights above about ~ 84 km the covariances are strongly positive at all times. At lower heights the boundary between the regions of positive or negative covariance is similar to what was observed for the shorter period covariances with more positive values at higher altitudes, however the difference is that this boundary occurs about 5-10 km lower than was the case for the shorter period covariances.

4.5.4 Stokes parameters

It was seen in the previous section that the gravity wave fields are partially polarised at all four locations. The Stokes parameters are a set of parameters that can be used to analyse partially polarised electromagnetic waves (e.g., *Born & Wolf* [1964]). They require the intensities of any two mutually orthogonal components of a wave vector and the correlation between them to determine the degree and angle of polarisation of a wave field.

The Stokes parameters can be used to analyse gravity wave motions, as is done in this section. The degree and angle of wave polarisations are determined using the Stokes parameters following the methodology of *Vincent & Fritts* [1987], and *Eckermann & Vincent* [1989].

The degree of polarisation of a wave field, d, can be estimated by:

$$d \approx \frac{\left(D^2 + P^2\right)^{\frac{1}{2}}}{I} \tag{4.1}$$

where: $D = \overline{u'^2} - \overline{v'^2}$

$P = 2\overline{u'v'}$

and $I = \overline{u'^2} + \overline{v'^2}$.

The orientation (north of east), θ, of the major axis of the elliptical gravity wave motions can be found from:

$$tan2\theta = \frac{P}{D} \tag{4.2}$$

Note that the there is a 180 degree ambiguity in θ in Equation 4.2.

4.5.4.1 Polarisation of 20-120 minutes period waves

Figure 4.15 shows the degree and angle of polarisation of the wave fields during summer and winter. Summer (winter) values are defined here as the mean value during December and January (June and July) in the southern hemisphere and June and July (December and January) in the northern hemisphere.

The waves are generally more strongly polarised in summer than in winter at heights below about 70 km (with some exceptions such as at heights from about 70-74 km at Davis). The angle of polarisation at the lower heights is generally slightly south of east at the southern hemisphere locations, and slightly north of east at the northern hemisphere locations. It can also be seen that the waves are more strongly polarised on average at the southern hemisphere locations than at the northern hemisphere locations.

The polarisation generally changes in direction with increasing height from the east at the lower heights to the north at higher altitudes at all locations. This is true for both winter and summer, with the exception of Poker Flat during winter where a northward orientation occurs throughout the MLT region.

4.5.4.2 Polarisation of 120-480 minutes period waves

Figure 4.16 is similar to Figure 4.15, but for the longer period gravity wave motions (120-480 minutes). The waves are generally more strongly polarised during summer than during winter at all locations. The waves are also generally more strongly polarised at the southern hemisphere locations than at the northern hemisphere locations during both winter and summer (as was also the case for the shorter period waves).

The angle of wave polarisation is similar to what was observed for the shorter period range, with a change occurring from an eastward orientation at lower heights to a more northward orientation at higher altitudes. Exceptions to this occur at Andenes where the orientation is slightly north of east in general at all heights in summer and winter, and at Poker Flat during winter where the waves are oriented more towards the north at lower altitudes.

At the southern hemisphere locations, the angle of polarisation changes from being slightly south of east in the mesosphere towards a more north-east orientation at thermospheric heights (as was seen for the shorter period variances). This occurs at about ∼80 km in summer and about ∼70 km in winter, in contrast to the shorter period range where this change occurs at about ∼90 km in summer and about ∼80 km in winter. It is interesting to note that these heights are similar to the heights where the variances begin increasing rapidly for each period range (see Figures 4.9 and 4.10).

4.6 Critical level filtering

Figures 4.17 and 4.18 show the zonal and meridional winds, respectively, from the ground up to 100 km. The data from the ground up to 0.3 hPa (∼56 km) are obtained from the United Kingdom Meteorological Office (UKMO) assimilated data set (see *Lorenc et al.* [2000] for details) averaged from 1999-2002, with MF radar data shown from 58-100 km averaged over all available years of data.

Average height profiles of the mean winds during summer and winter taken from Figures 4.17 and 4.18 are shown in Figure 4.19. For the southern hemisphere, summer is defined here as being from the start of December until the end of January and winter being from the start of June until the end of July, with the opposite being the case for the northern hemisphere.

Critical level filtering results in gravity waves within a range of phase speeds being filtered out by the background mean winds (see Equation 1.29). The phase speeds forbidden by the wind profiles shown in Figure 4.19 are shown as exclusion circles in Figure 4.20 for both the UKMO winds and the MF radar winds.

The exclusion circles show that the winds would preferentially filter out westward propagating winds during summer and eastward propagating winds during winter. There is little bias in the meridional direction with the exception of the Arctic locations during winter where the excluded phase speeds are more southward at Poker Flat and northward at Andenes.

It was seen from Figures 4.15 and 4.16 that the waves entering the MLT region are generally oriented in a eastward (or westward) direction. This is true in summer and winter at all locations for both period ranges, with the only exception being at Poker Flat during winter where the waves are more northward (or southward) in direction.

The exclusion circles (Figure 4.20) can be applied to help remove some of the 180° ambiguity present in the direction of polarisation. During summer at all four locations, the waves which reach the mesosphere from lower altitudes would be expected to be oriented towards the east, or have very large westward phase speeds. During winter the waves would be expected to have westward (or strongly eastward) phase speeds at Davis, Syowa and Andenes, and northward (or stongly southward) phase speeds at Poker Flat.

Figure 4.19 shows that the zonal winds during summer reach their largest magnitude at heights around 80 km at all four locations creating the largest exclusion circles at this height. It is interesting that above this height the zonal winds decrease in strength, reaching zero magnitude at about ∼90 km, since it is in this region that the variances begin increasing rapidly (see Figures 4.9 and 4.10). One possibile interpretation of this is that relatively little critical level filtering is occuring above about 90 km due to the weak zonal winds in this region.

4.7 Discussion and summary

Gravity waves were investigated in the MLT at Davis, Syowa, Poker Flat and Andenes using the zonal and meridional wind variances in the period ranges 20-120 minutes and 120-480 minutes. The gravity wave motions were found to be far from random in nature, with regular seasonal variations occuring in magnitude, spectral content and polarisation.

The results presented in this chapter are relatively consistent with the results of other studies. For example, annual and semi-annual variations in gravity wave activity have also been observed previously in the MLT. *Vincent* [1994] describe a semi-annual variation in wave activity, with maxima in summer and winter at Mawson, observed using the Davis MF radar before it was moved in 1994.

Mesospheric wind variances obtained from MST radars at Adelaide (35°S, 138°E) and Saskatoon (52°N, 107°W) also show semi-annual seasonal variations with maxima near both solstices [*Vincent & Fritts*, 1987; *Manson & Meek*, 1986]. An annual variation is also reported, with the winter maximum being larger than the summer one.

Wilson et al. [1991] also report a semi-annual variation in gravity wave activity from Rayleigh lidar measurements in the height range 30-75 km. The semi-annual component was found superimposed on the annual cycle of gravity wave activity at heights above 60 km. They conclude that the semi-annual variation was due to seasonal variations in the wave saturation height.

Waves of low intrinsic phase speeds and short vertical scales are expected to be subject to strong turbulent and/or radiative dissipation, whereas larger phase speed waves are expected to be able to propagate through stronger winds therefore reaching higher altitudes [*Schoeberl & Strobel*, 1984; *Matsuno*, 1982]. Many of the features in the gravity wave climatologies tha were investigated in this chapter could be explained by variations in the phase speeds of the waves reaching the MLT region.

It is assumed that the majority of gravity wave activity present in the MLT has propagated up from source regions at lower altitudes. The waves which reach the mesosphere are generally oriented in an eastward (or westward, due to a 180° ambiguity) direction. This is true in summer and winter at all locations for both period ranges, with the only exception being Poker Flat during winter where the waves are more northward (or southward) in direction.

Critical level filtering by the mean winds in the stratosphere was modelled to try to remove some of this 180° ambiguity in wave orientation. The results suggest that during summer the waves are oriented either towards the east, or have very large phase speeds in the westward direction. During winter the waves would be expected to have westward (or strongly eastward) phase speeds at Davis, Syowa and Andenes, and northward (or stongly southward) phase speeds at Poker Flat.

At higher altitudes the direction of wave orientation is more northward (or southward) at all four locations, with the exception of the longer period variances at Andenes which are generally eastward (or westward), at all heights. This means that regions of eastward (or westward) orientation are lower than regions of northward (or southward) orientation in all cases, suggesting an anisotropic difference in wave saturation.

The degree of polarisation is generally larger during summer than during winter at all locations, and also generally larger in the Antarctic than in the Arctic.

The seasonal variations in the magnitude of gravity wave activity are generally a combination of an annual component (with maxima in winter and minima in summer) and a semi-annual component (with maxima around the times of both solstices and minima around the times of the equinoxes). Maxima in wave activity occur in winter and minima in spring or summer. This is true for both period ranges and also for both the zonal and meridional directions at all four locations.

The winter maxima occur about 21 days later at the southern hemisphere locations than at the northern hemisphere locations. The hemispheric timing difference for the spring or summer minima is about 22 days, occurring later at the southern hemisphere locations. Another hemispheric difference is that the change from the winter maxima to the spring minima is about 90% larger in magnitude and at a faster rate in the

Antarctic than in the Arctic.

At the lower altitudes (80 ± 4 km), a maxima in wave activity occurs during summer for the shorter period range (20-120 minutes) that is particularly strong in the zonal direction at all four locations. This maxima is not observed at higher altitudes (∼90 km) where minima occur, suggesting that shorter period zonally oriented waves are might be strongly dissipated near the summer mesopause. This was not observed for the longer period wave motions.

The summer maxima at heights around 80 km for the short period zonal variances occur on average ∼4 days later in the Arctic than in the Antarctic (from Table 4.1 with respect to the summer solstices), with the minima in wave activity following the summer maxima occurring about ∼14 days later in the Arctic. These hemispheric timing delays are similar in magnitude to what was observed for the equatorward jet around the summer mesopause. The equatorward jet was found to reach peak values about ∼4 days later in the Arctic, and persist for about ∼13 days longer than in the Antarctic (from Table 3.4 with respect to the summer solstices). The similarity in hemispheric timing differences between the gravity wave activity and the equatorward jet gives some strength to the hypothesis (proposed in the previous chapter) that the meridional wind can be used as a proxy for gravity wave driving near the summer mesopause.

Other observations also suggest that the short period zonal waves may be causing significant wave drag. Height profiles of wave activity suggest that the shorter period waves are highly saturated up to about ∼90 km in summer, and also up to about ∼80 km during winter. There is often little or no difference between the winter and summer magnitudes at heights below about ∼90 km, although at higher altitudes the magnitude during winter is significantly larger than during summer. This was not the case for the longer period waves where the winter values are generally larger than the summer values at all heights in the mesosphere.

A hemispheric difference in wave saturation may also exist. At heights up to about 80 km the wave activity (in both period ranges) is relatively similar in magnitude at all four locations. Above about 90 km, the variances are stronger at the southern hemisphere locations than at the northern hemisphere locations. This is true in summer and winter for both the zonal and meridional directions.

The variances at the Antarctic locations increase with height at a rate faster (and more similar to what would be expected if wave energy was being conserved) than the rate of increase at the Arctic locations. A possible interpretation of this is that more wave saturation, and consequent wave drag, is occurring in the Arctic than in the Antarctic. This interpretation is consistent with the mean wind climatologies presented in the previous chapter which suggest that the Arctic MLT may be further from radiative equilibrium than the Antarctic MLT.

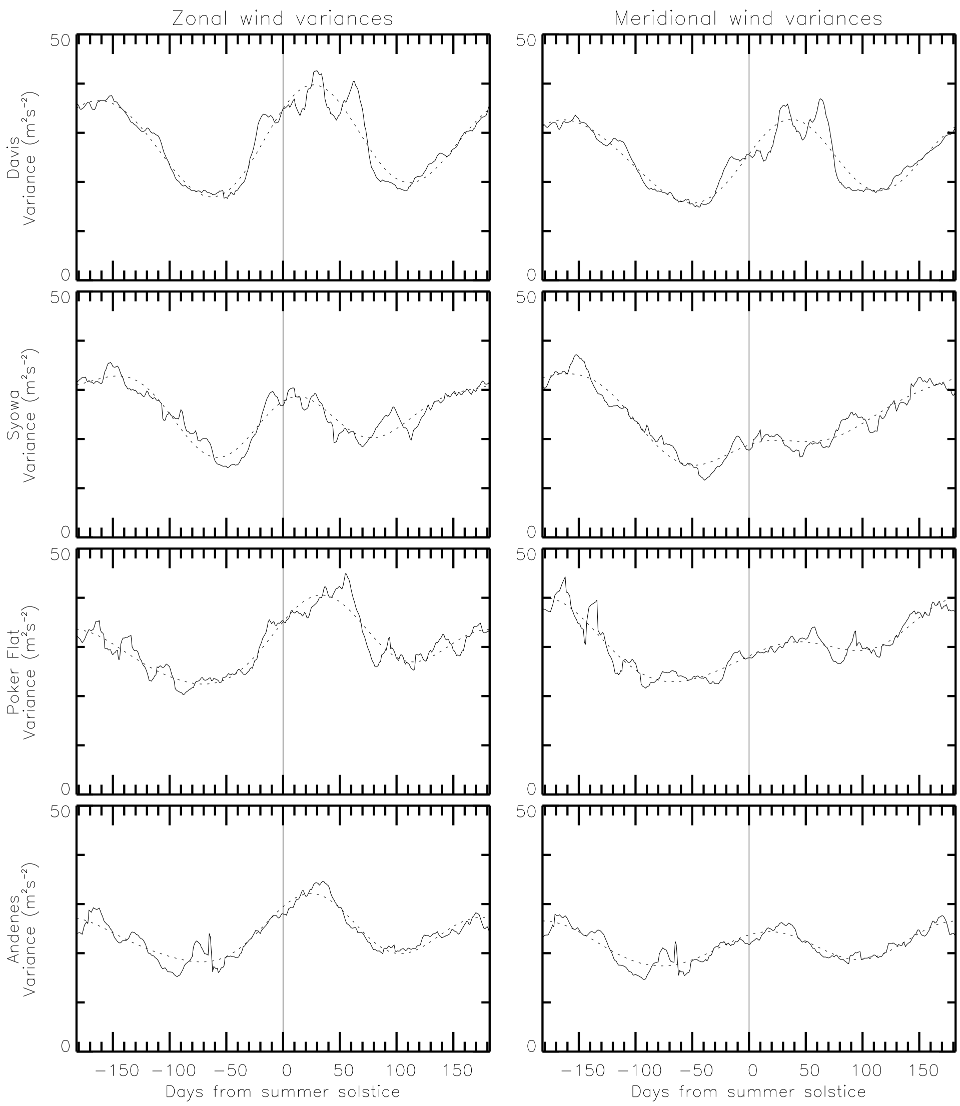

Figure 4.5: Time series of zonal and meridional wind variance averaged from 76-84 km for the period range 20-120 minutes plotted with respect to the summer solstice of each hemisphere. A 7-day running mean is applied, with the data averaged over all available years. The dotted lines represent least-squares harmonic fits to the data (consisting of the sum of the mean, annual, semi-annual and ter-annual components).

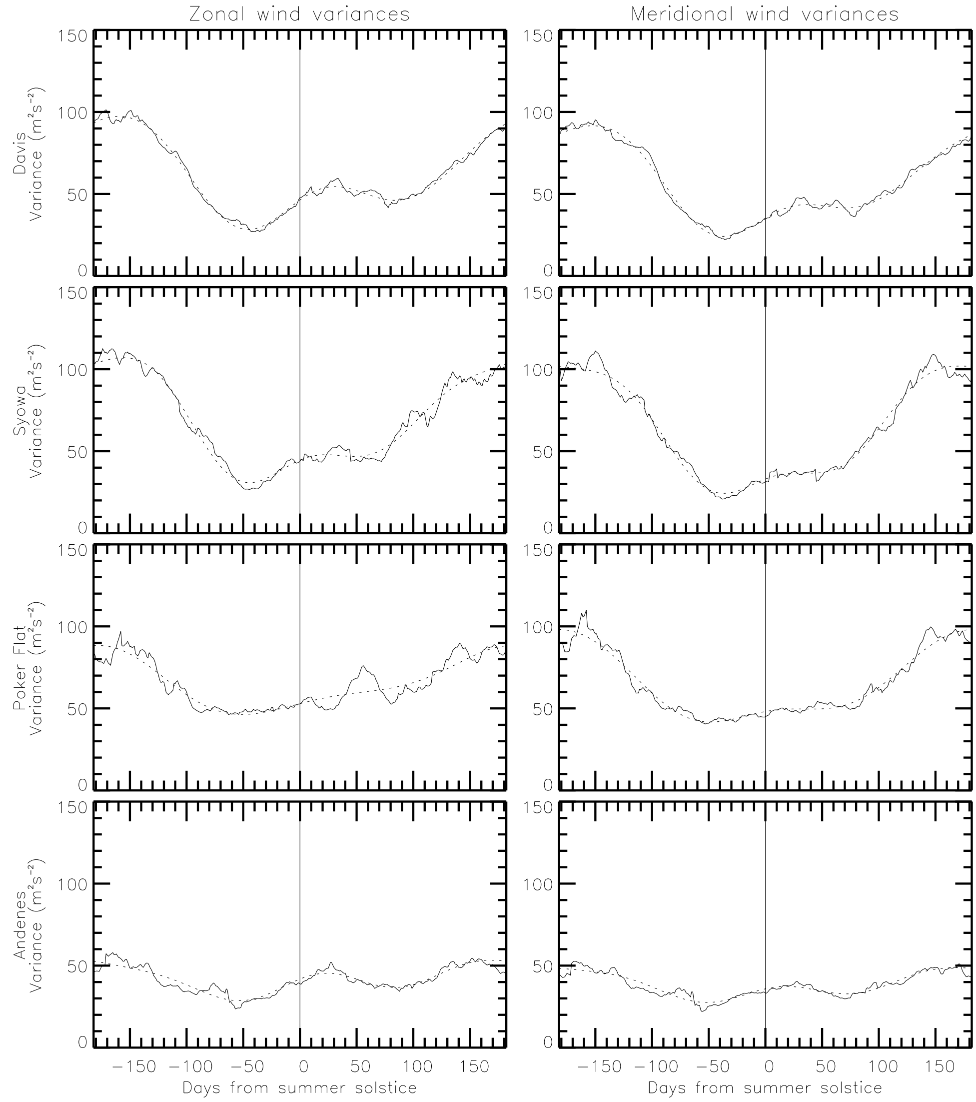

Figure 4.6: As for Figure 4.5, but for the variances in the period range 120-480 minutes averaged from 76-84 km.

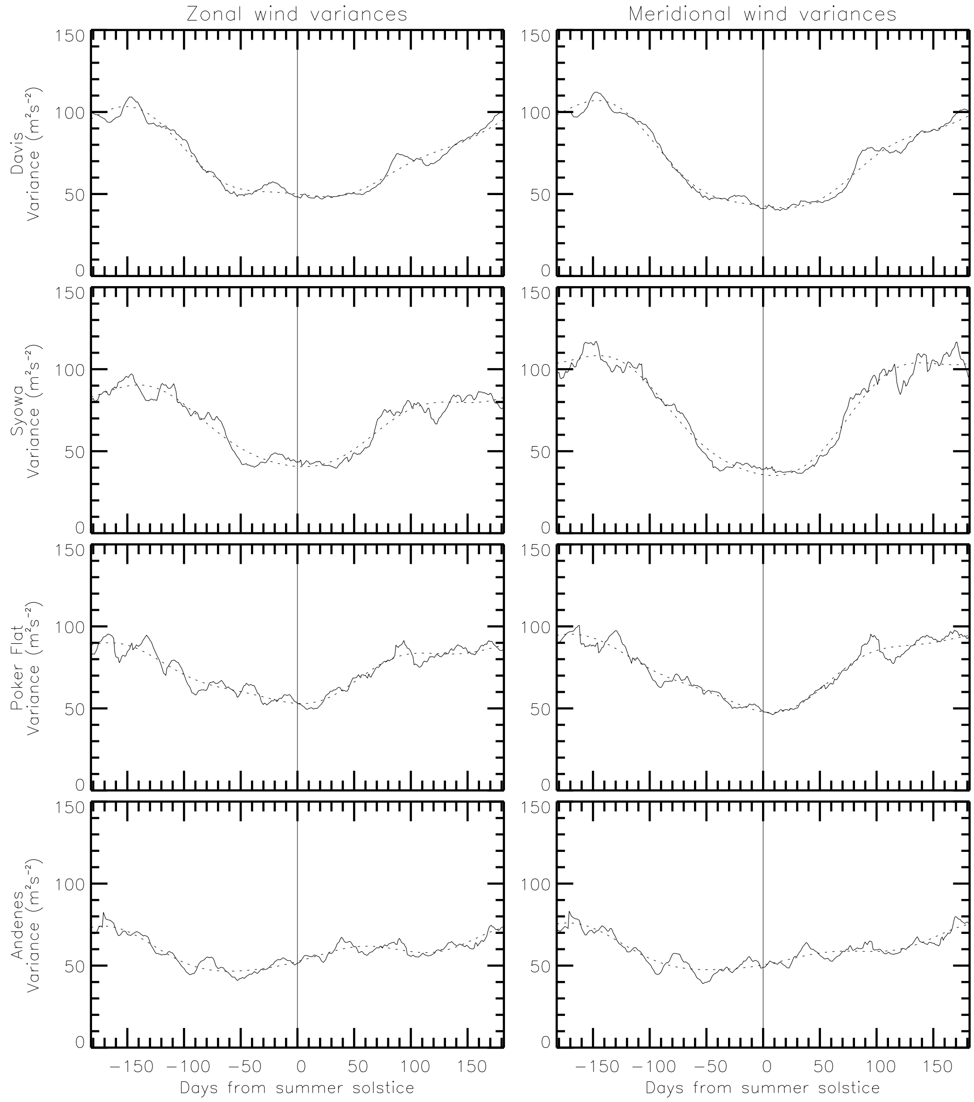

Figure 4.7: As for Figure 4.5, but for variances in the period range 20-120 minutes averaged from 86-94 km.

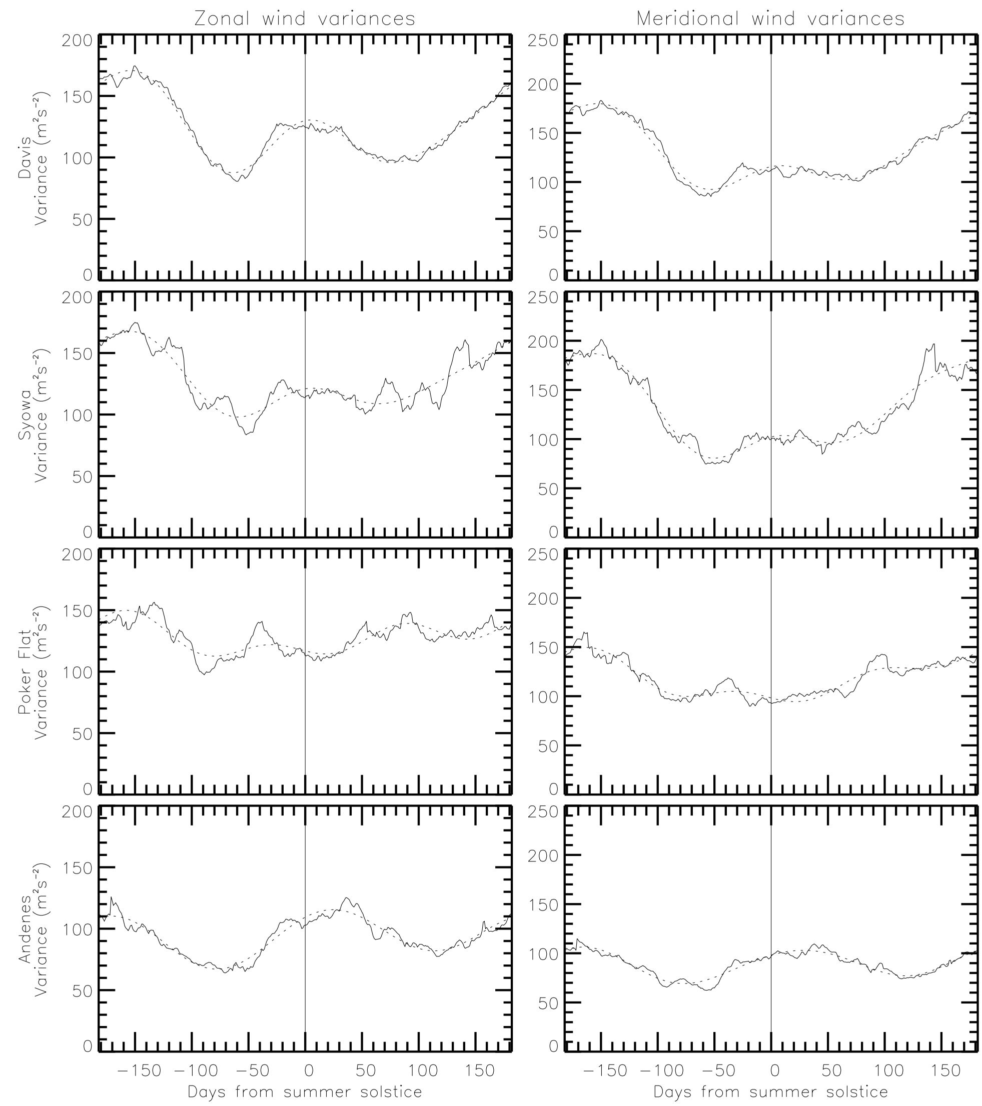

Figure 4.8: As for Figure 4.5, but for variances in the period range 120-480 minutes averaged from 86-94 km.

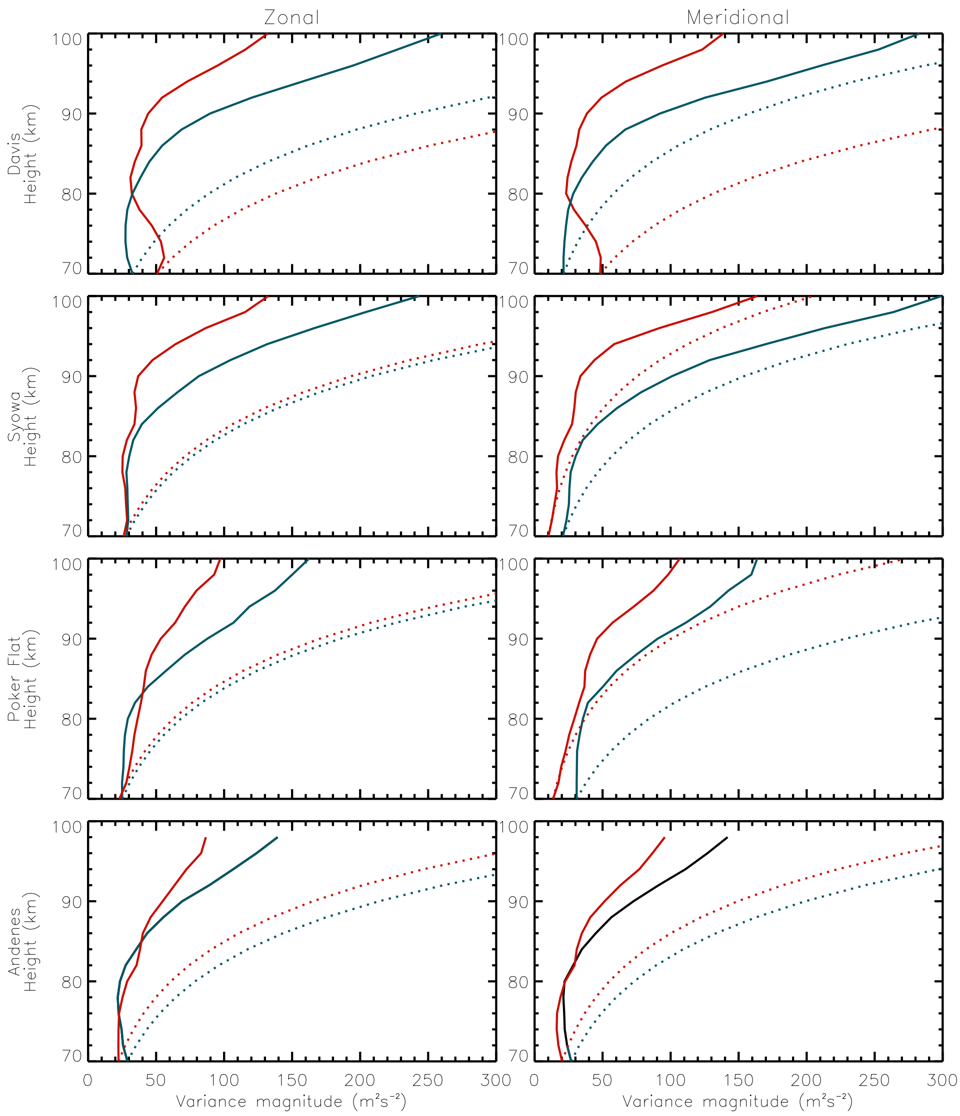

Figure 4.9: Height profiles of the variance climatologies averaged for summer (red lines), and winter (blue lines). Data are shown at Davis, Syowa, Poker Flat and Andenes for the zonal and meridional directions in the period range 20-120 minutes. The dotted lines provide an estimate of what would be expected if wave energy was being conserved. Summer (winter) values are defined here as the mean value during December and January (June and July) in the southern hemisphere and June and July (December and January) in the northern hemisphere.

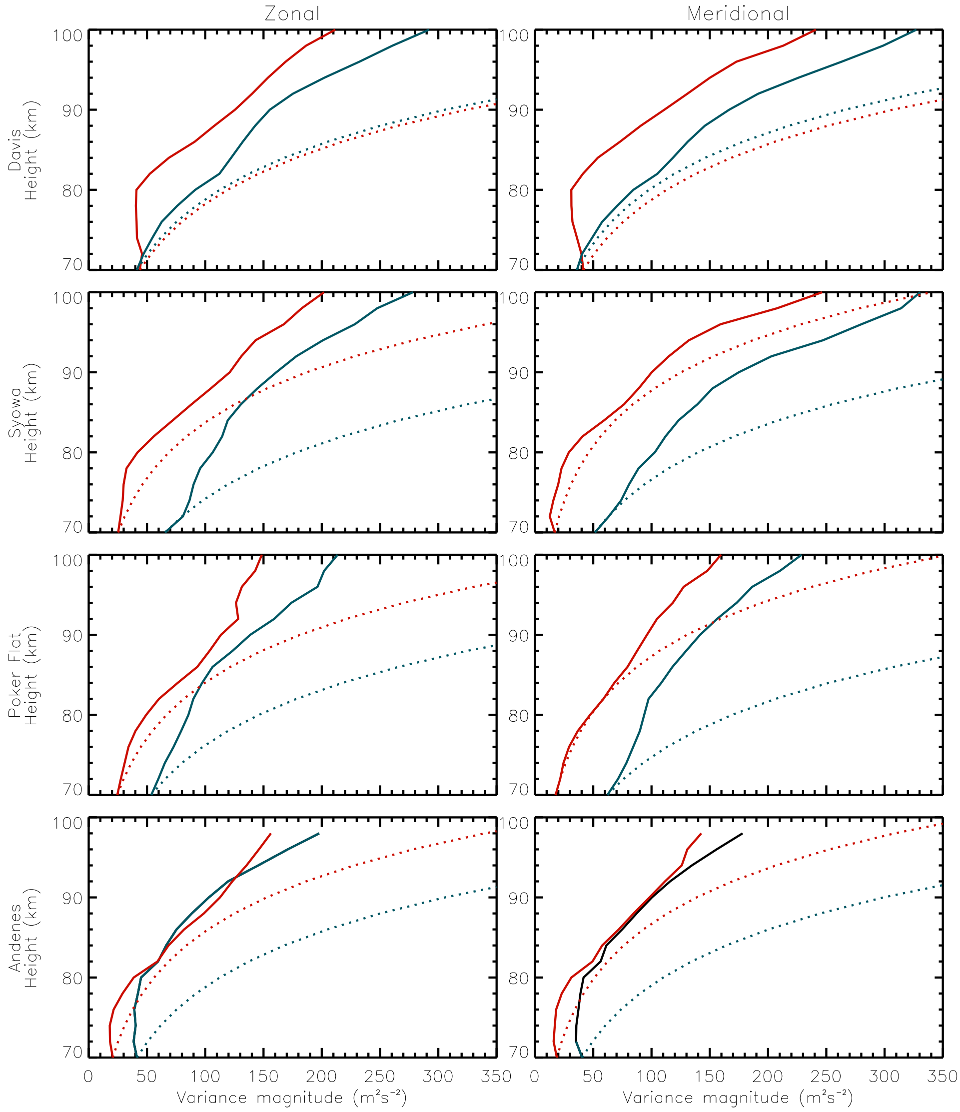

Figure 4.10: As for Figure 4.9, but for the period range 120-480 minutes.

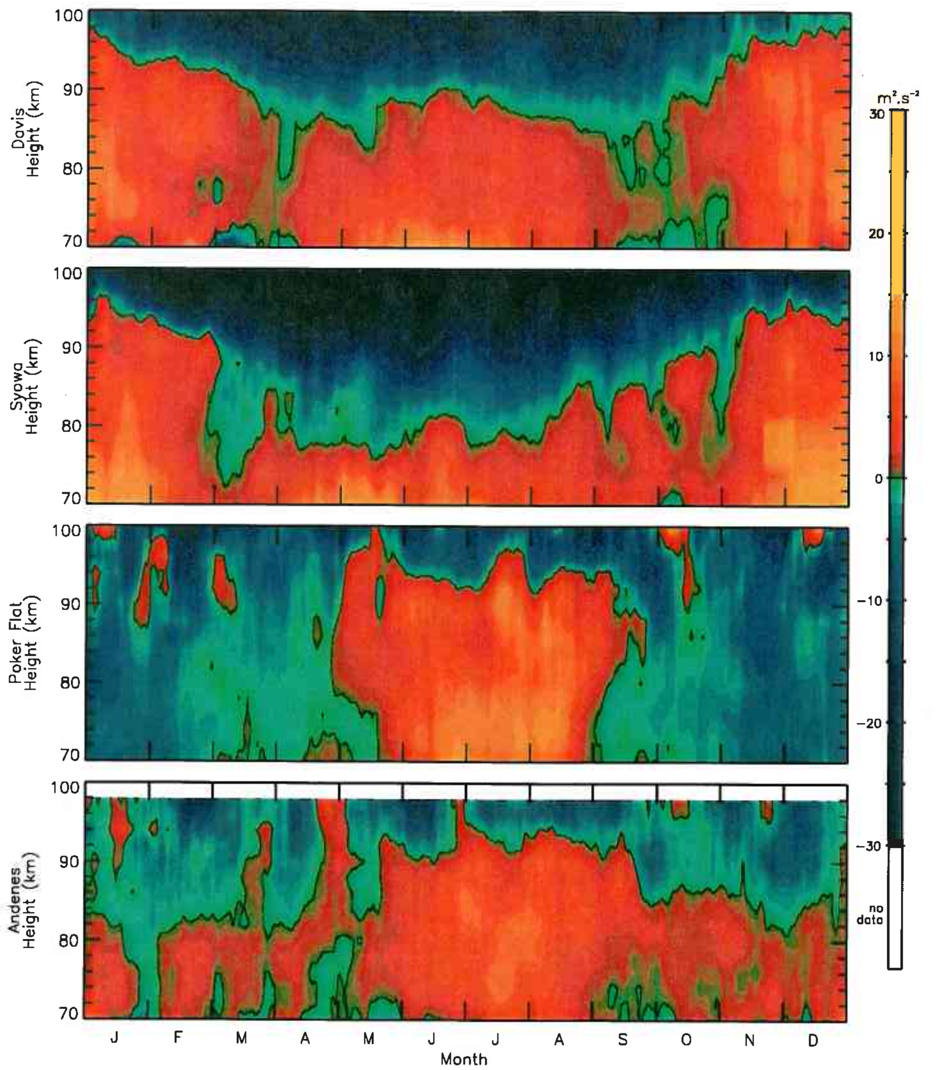

Figure 4.11: The variance difference, $\overline{u'^2} - \overline{v'^2}$, at Davis, Syowa, Poker Flat and Andenes in the period range 20-120 minutes. A 15-day and 4-km running mean is applied to the data which are averaged over all available years of data.

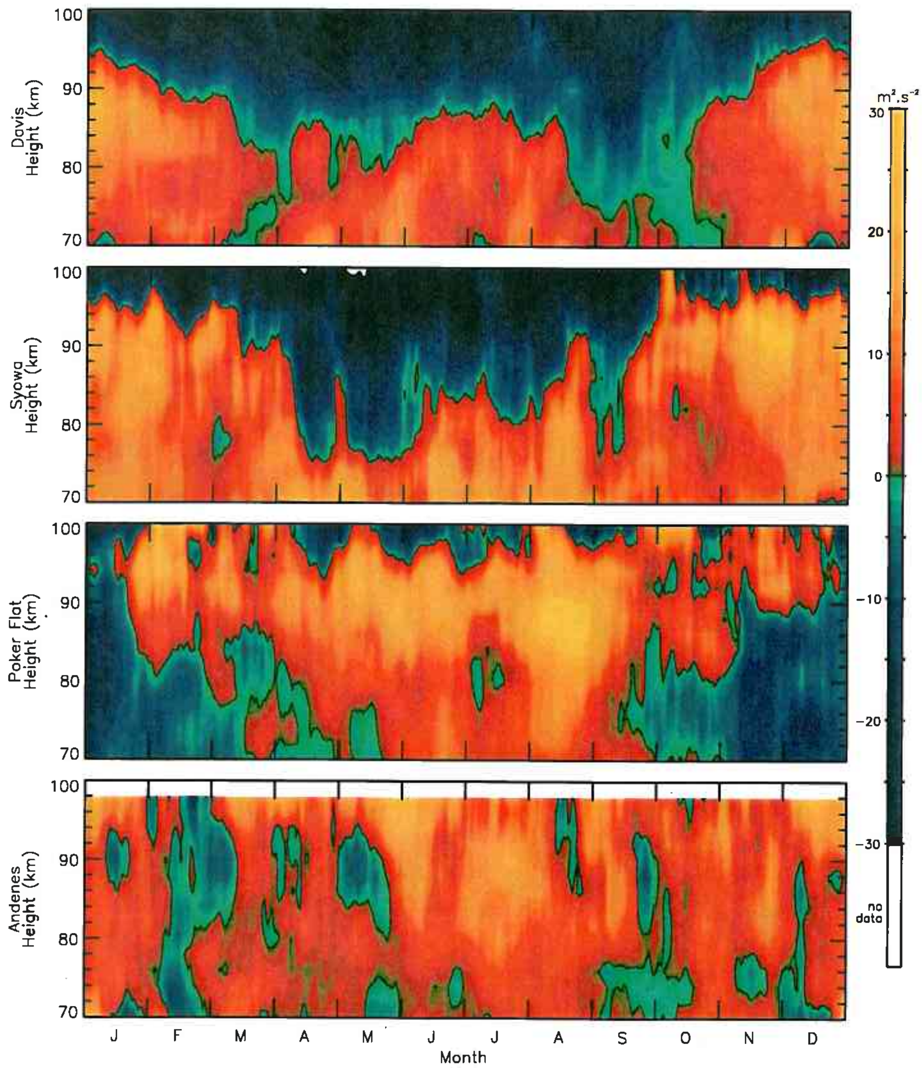

Figure 4.12: As for Figure 4.11, but for the period range 120-480 minutes.

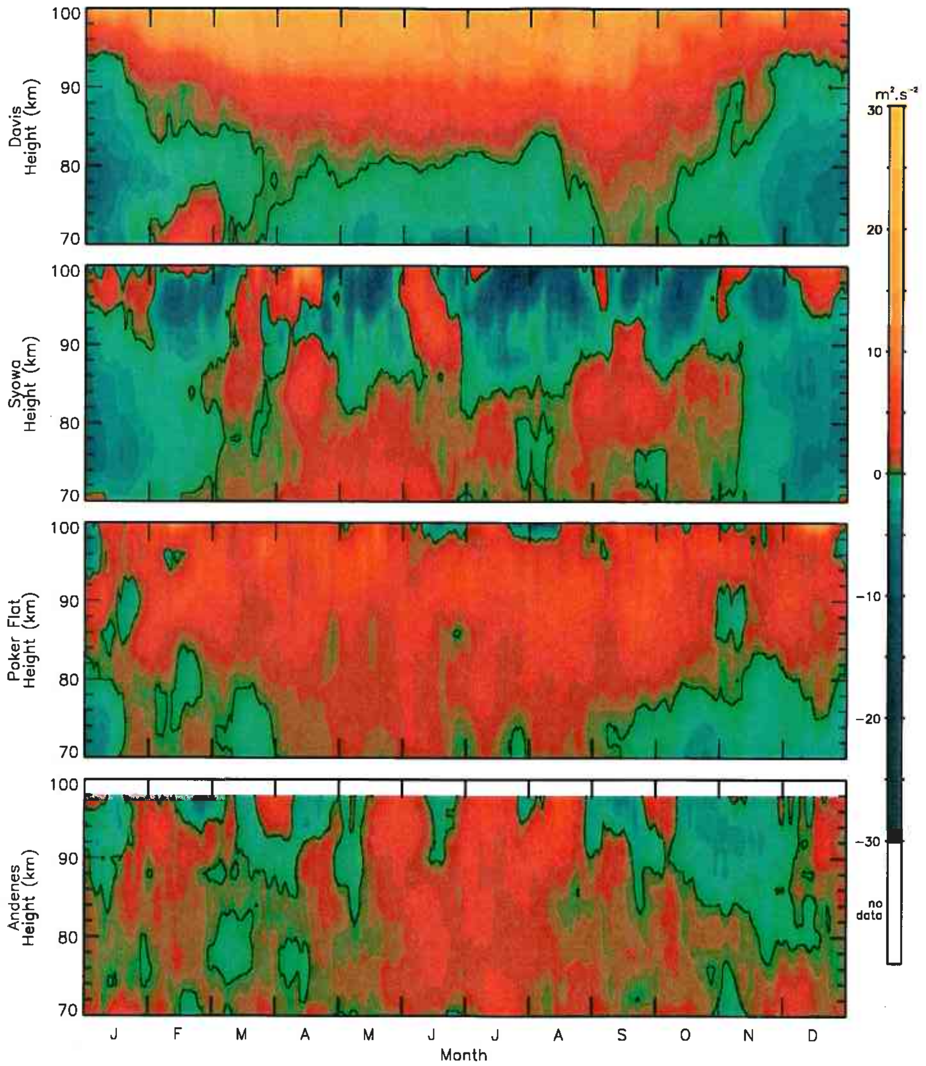

Figure 4.13: Covariance of the zonal and meridional winds, $\overline{u'v'}$, at Davis, Syowa, Poker Flat and Andenes in the period range from 20-120 minutes. A 15-day and 4-km running mean is applied to the covariances which are averaged over all available years.

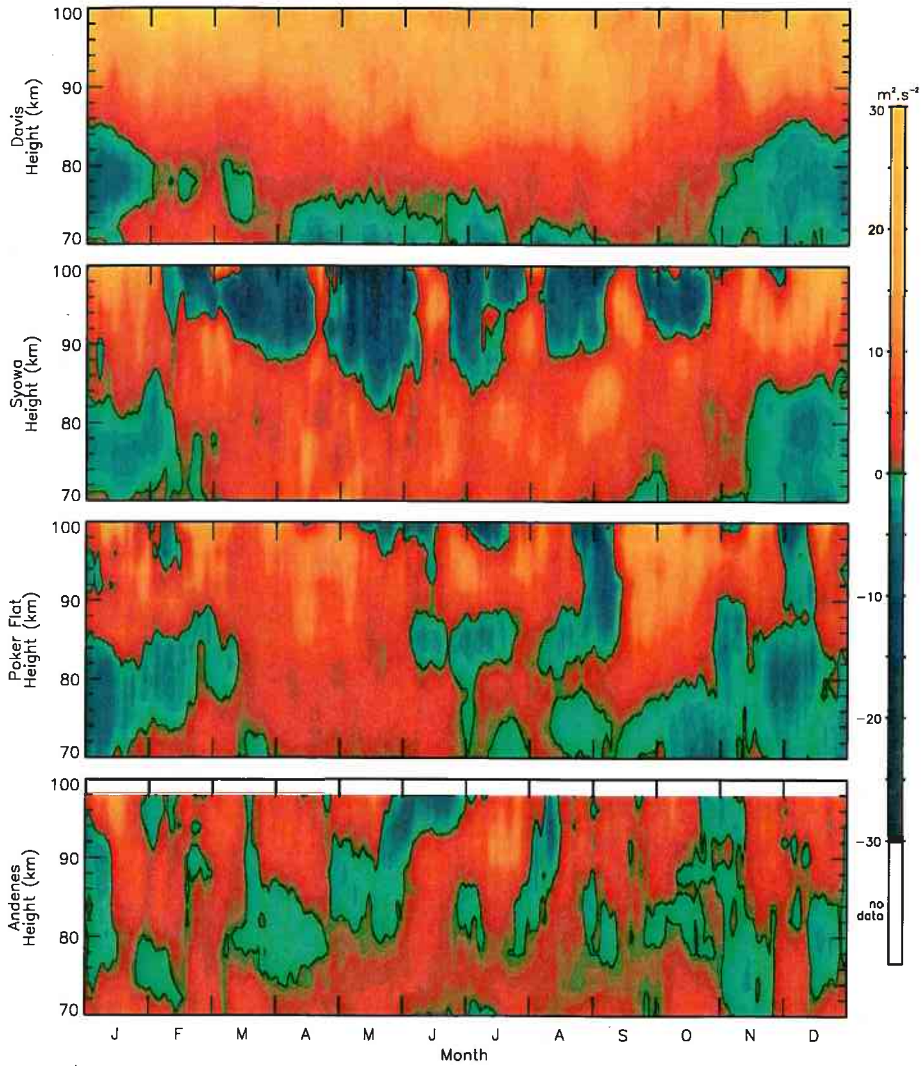

Figure 4.14: As for Figure 4.13, but for the period range 120-480 minutes.

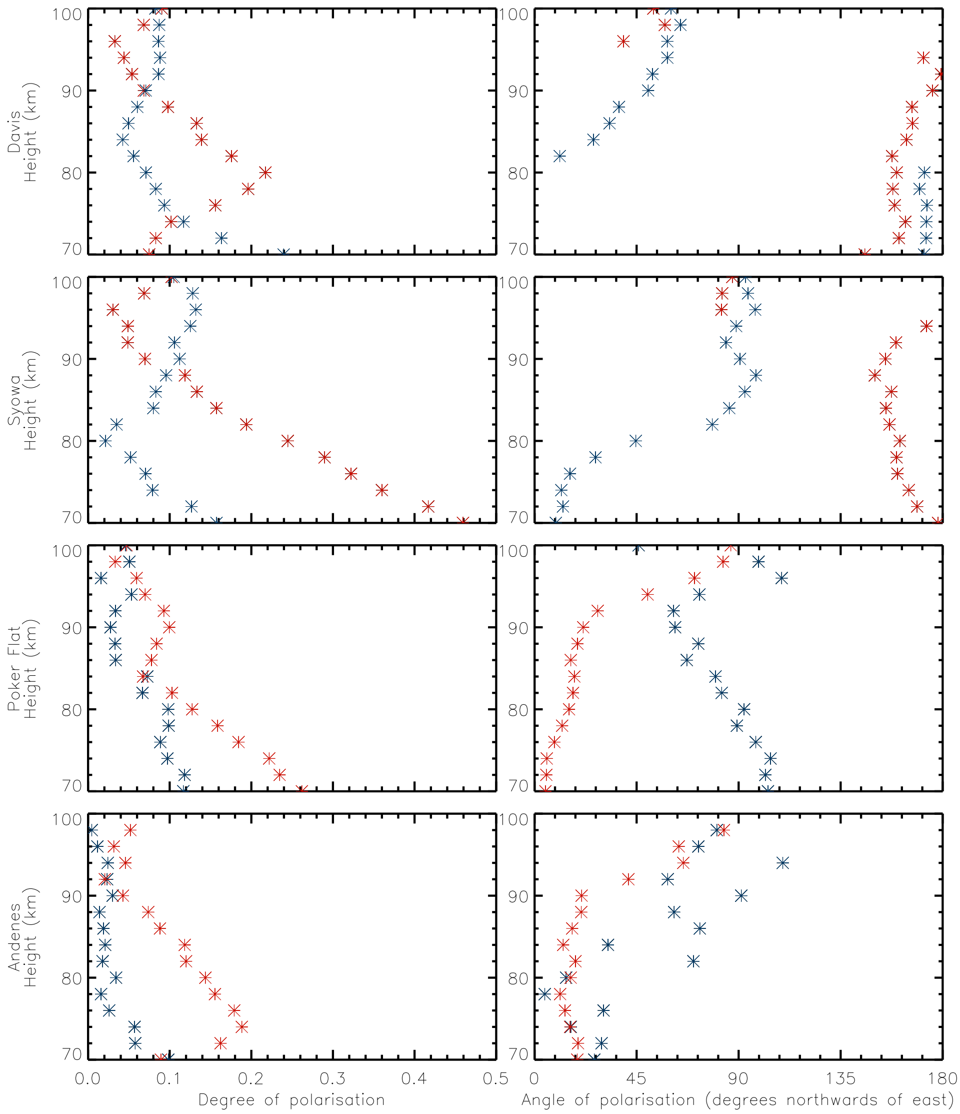

Figure 4.15: The degree and angle of wave polarisation in the period range 20-120 minutes at Davis, Syowa, Poker Flat and Andenes during summer (red) and winter (blue). Summer values are defined here as the mean value during December and January in the southern hemisphere and June and July in the northern hemisphere, with the opposite being the case for winter.

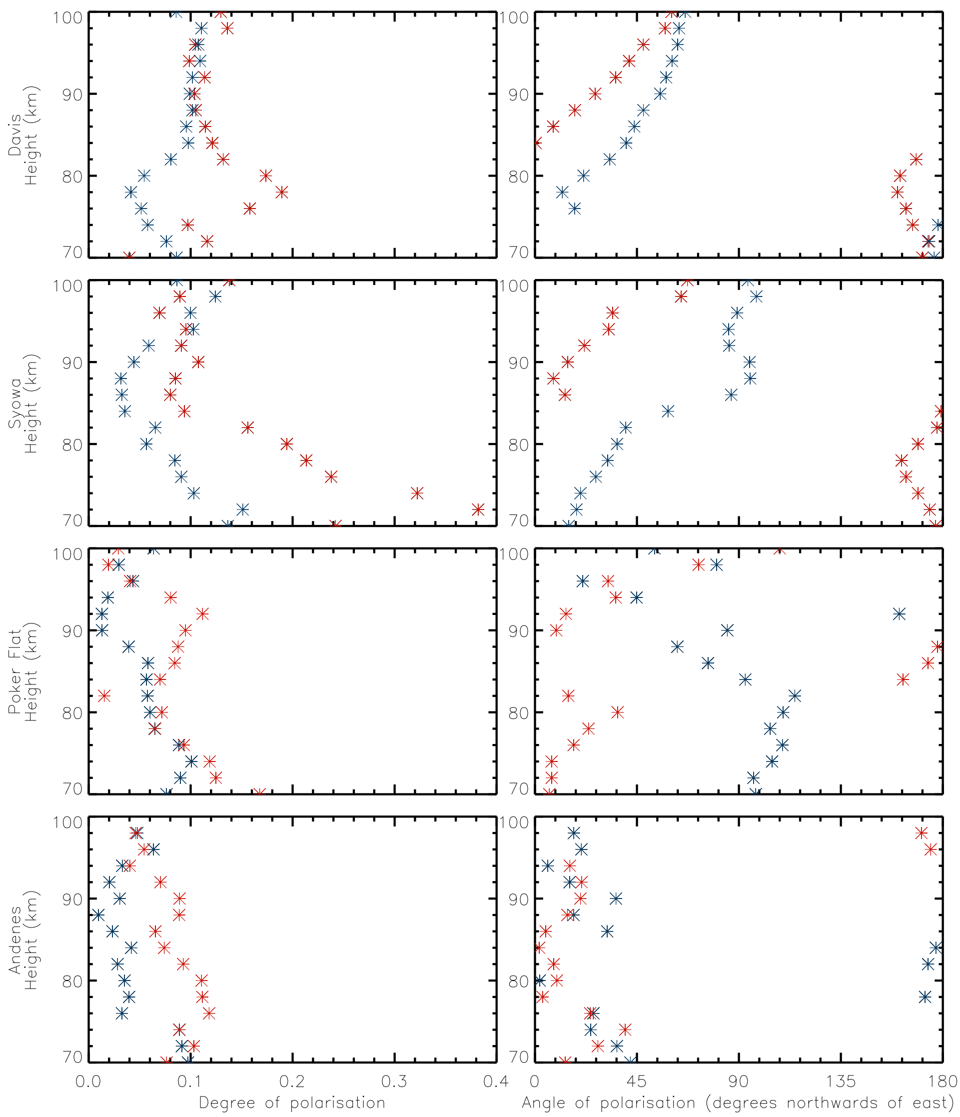

Figure 4.16: As for Figure 4.15, but for the period range 120-480 minutes.

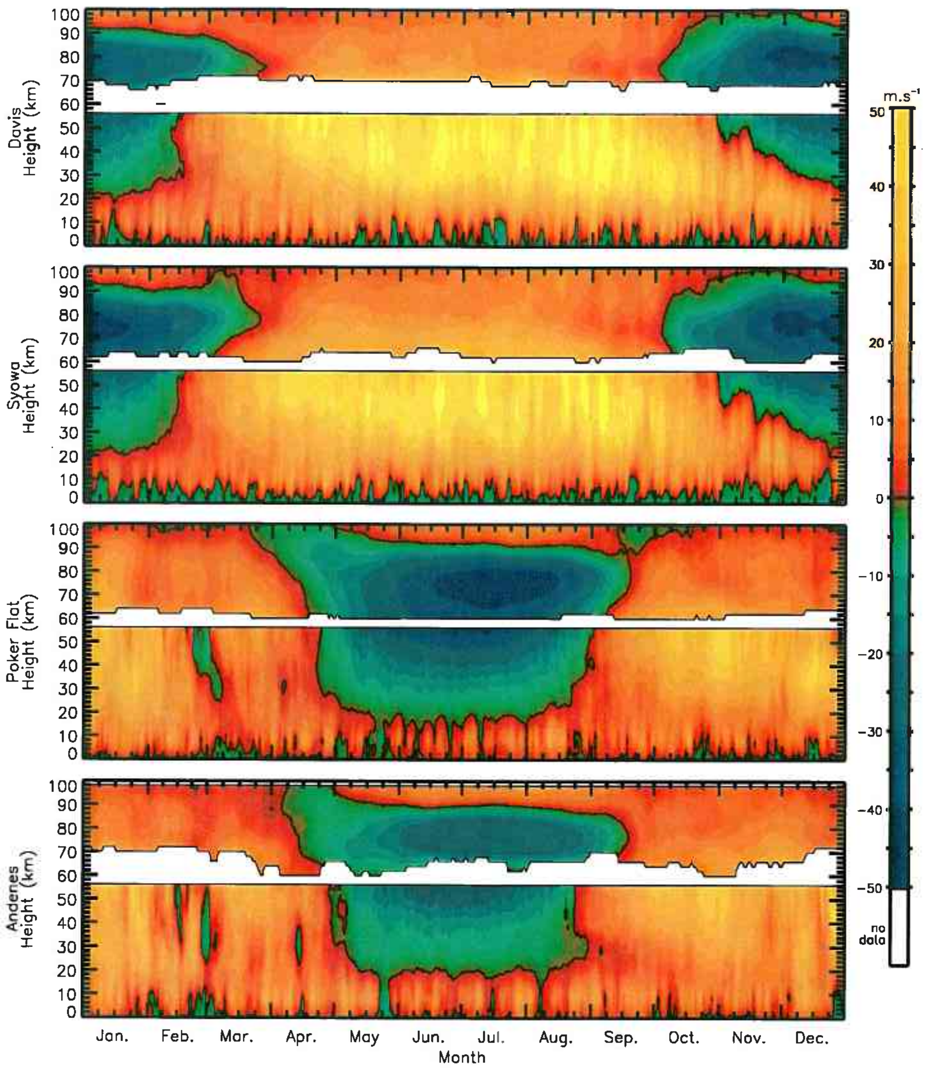

Figure 4.17: Zonal wind climatologies for Davis, Syowa, Poker Flat and Andenes. UKMO data is shown from the ground up to 0.3 hPa (~56 km) averaged from 1999-2002, and MF radar data is shown from 60-100 km (as shown in Figure 3.1).

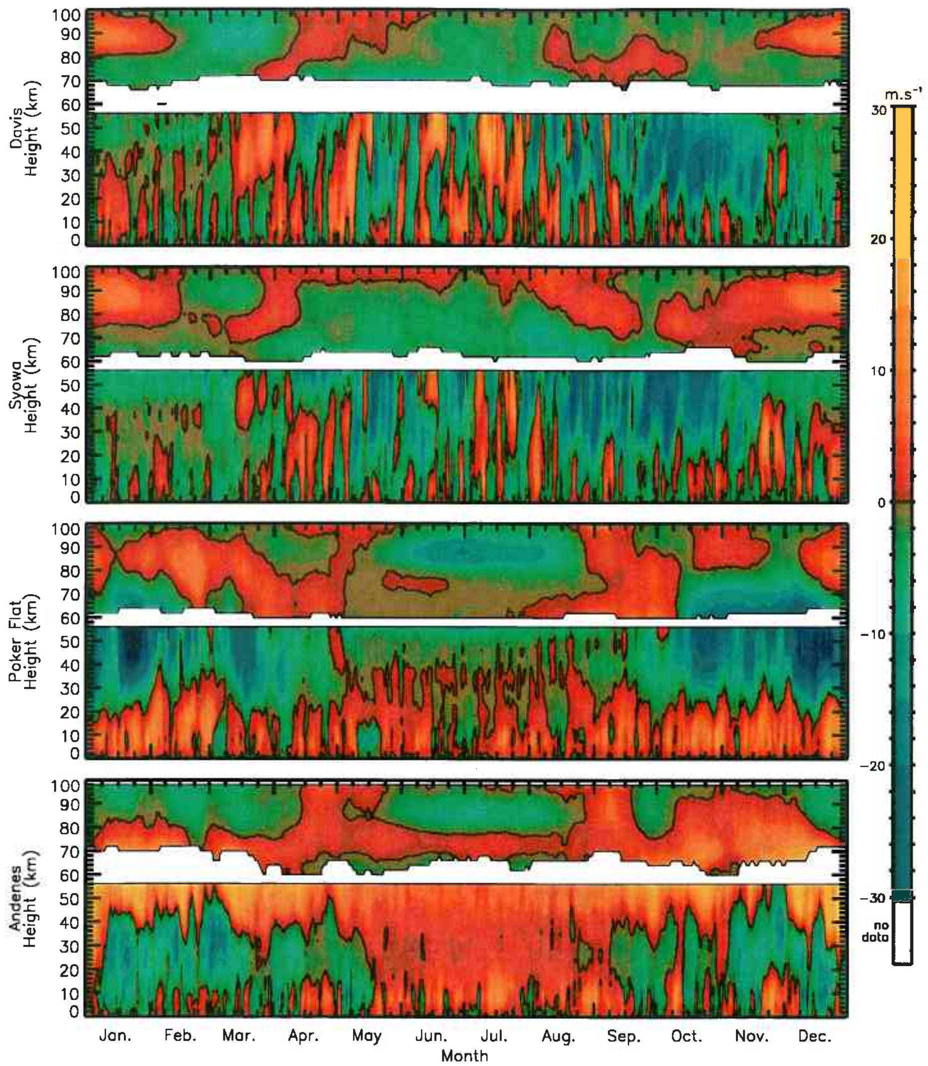

Figure 4.18: Meridional wind climatologies for Davis, Syowa, Poker Flat and Andenes. UKMO data is shown from the ground up to 0.3 hPa (~56 km) averaged from 1999-2002, and MF radar data is shown from 60-100 km (as shown in Figure 3.5).

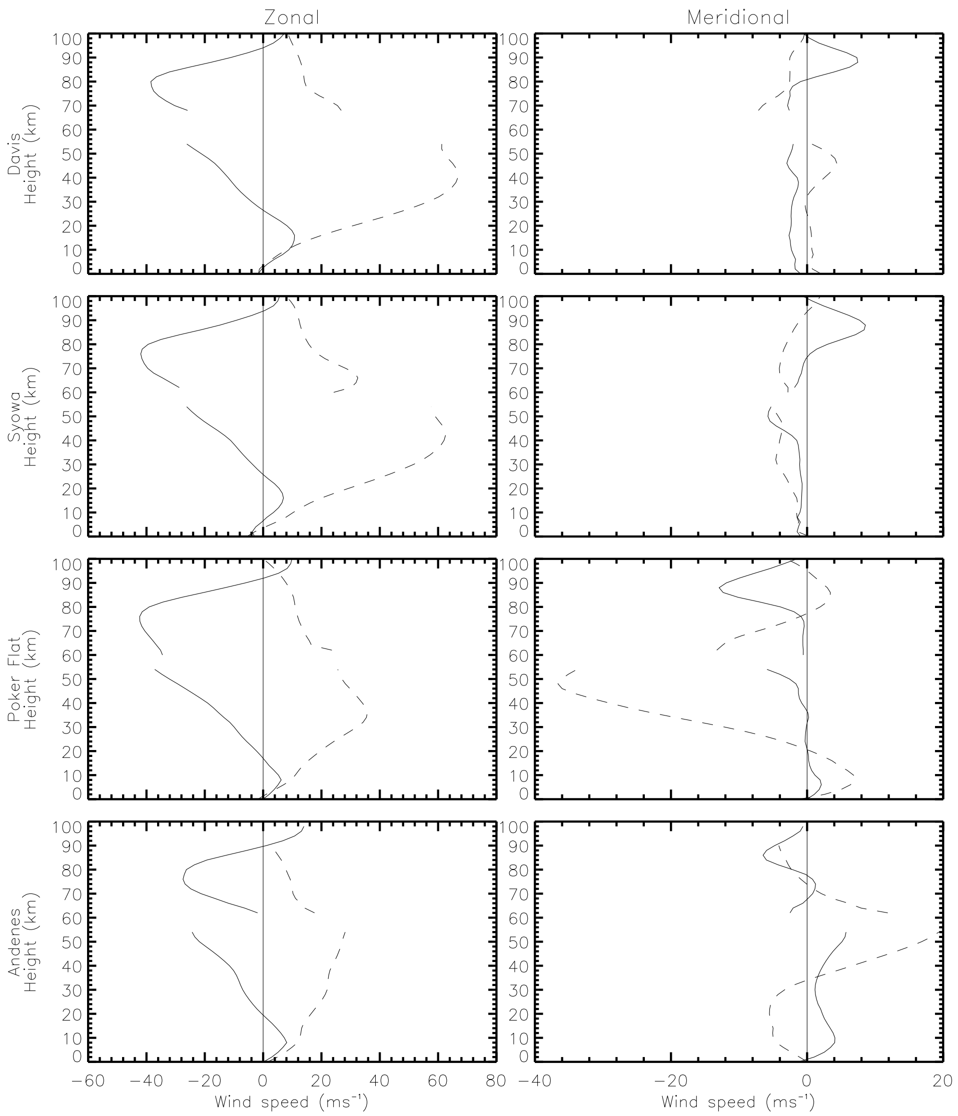

Figure 4.19: Zonal and meridional wind height profiles at Davis, Syowa, Poker Flat and Andenes during summer (solid) and winter (dotted). UKMO data is shown from the ground up to 0.3 hPa (∼56 km) averaged from 1999-2002, and MF radar data is shown from 58 km up to 100 km where available (as shown in Figures 3.1 and 3.5). Summer (winter) values are defined here as being the mean during December and January (June and July) in the southern hemisphere, and June and July (December and January) in the northern hemisphere.

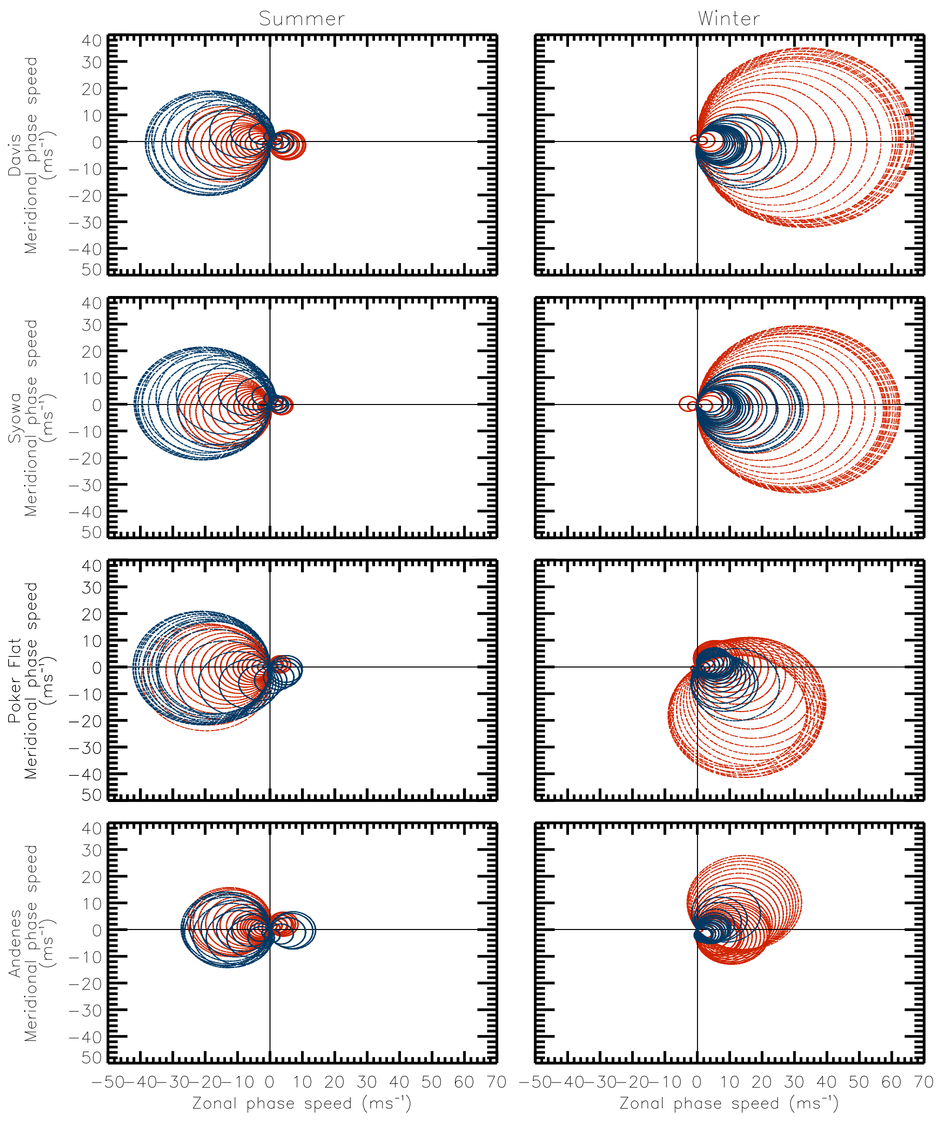

Figure 4.20: Exclusion circles defining regions of forbidden gravity wave phase speeds due to critical level filtering by the UKMO winds (red) and the MF radar winds (blue) shown in Figure 4.19.