Chapter 5

Major stratospheric warming events

5.1 Introduction

MF radar data are available for five winters at the Arctic locations (from the winter of 1998/1999 until the winter 2002/2003). During these winters a total of six major stratospheric warming events occurred [*Manney et al.*, 2005]. This occurrence rate is about double the long-term average. However, the period of available Arctic MF radar data follows an unprecedented period of 9 consecutive northern winters during which no major stratospheric warmings were observed [*Manney et al.*, 1999].

A certain degree of vertical coupling exists between the various regions of the atmosphere [*Andrews et al.*, 1987; *Cevolani*, 1991; *Cho et al.*, 2004; *Osprey & Lawrence*, 2001]. It is therefore to be expected that major stratospheric warmings would have an influence on other regions of the atmosphere such as the mesosphere and thermosphere. This has been seen in the northern hemisphere, where mesospheric cooling and zonal wind reversals are generally found to occur during major stratospheric warmings [*Dunkerton & Buchart*, 1984; *Manson et al.*, 1984; *Jacobi et al.*, 2003; *Bhattacharya et al.*, 2004; *Pancheva et al.*, 2000; *Whiteway & Carswell*, 1994].

The influence that the southern hemisphere major warming had on the MLT remains largely unreported. *Liu & Roble* [2003] used a general circulation model to investigate the possible role of the mesosphere in the 2002 southern hemisphere major warming, finding significant changes in the wind and temperature fields occur first in the mesosphere before descending into the stratosphere. *Dowdy et al.* [2004] investigated MF radar observations of the large-scale dynamics of the MLT during the southern hemisphere major warming. This paper was published as part of this PhD research and is included as Appendix H.

The unprecedented southern hemisphere major stratospheric warming is particularly valuable for understanding these events. The climatological differences that exist between the two hemispheres (as seen in Chapters 3 and 4) mean that the southern hemisphere provides a unique perspective from which to observe major stratospheric warmings.

Stratospheric observations during the southern major warming have been compared with major warmings in the northern hemisphere [*Krüger et al.*, 2005], although hemispheric comparisons for the MLT region are virtually unreported. This chapter presents an overview of MF radar and UKMO mean winds during every major stratospheric warming coinciding with the available MF radar data. The major warmings are classified in terms of characteristics such as strength and duration, after which hemispheric comparisons are made.

5.2 The southern hemisphere major warming

5.2.1 Overview

The first major stratospheric warming ever observed in the southern hemisphere occurred towards the end of the 2002 southern winter. The circulation in the stratosphere was characterised by a series of planetary-wave events that weakened the vortex, preconditioning the atmosphere for the major warming event in late September [*Newman*

& Nash, 2005; *Baldwin et al.*, 2003].

Figure 5.1 shows the zonal-mean zonal winds during 2002 at 60°S obtained from the UKMO assimilated data set at a pressure level of 10 hPa. The major warming can be seen to occur towards the end of September where the winds suddenly reverse in direction to be westward. The reversal reaches a peak magnitude of 21 ms^{-1}, and lasts from September 26 until September 29 before reverting back to the eastward direction on September 30.

This event is not just an exceptionally early final warming as the polar vortex reforms and persists throughout October. The final warming can be seen in Figure 5.1 with the change to westward winds on November 1. The major warming occurred about one month earlier than any final warming ever observed in the southern hemisphere [*Baldwin et al.*, 2003].

5.2.2 MF radar data during the southern major warming

MF radar data are available from 11 Antarctic winters (from the winter of 1994 until the winter of 2004). MF radar data are available at Davis and Syowa around the time of the southern major warming.

About four months of data (from the start of July until early November) were made available from a MF radar located at Rothera (68°S, 68°W), Antarctica to study this unique event. The Rothera radar is similar in construction and operation to the other MF radars used in this study, using the spaced antenna method with FCA techniques to derive horizontal wind speeds.

Daily average winds at Davis, Syowa and Rothera around the time of the major warming event are shown in Figures 5.2 and 5.3 for the zonal and meridional direction, respectively. UKMO data are shown from the ground up to 0.3 hPa (∼56 km), and data from 60 km up to 100 km are from MF radar measurements.

Eastward zonal winds normally dominate the winter mesosphere at these locations (see Chapter 3). During the 2002 winter many brief periods of westward zonal winds occur in the mesosphere as can be seen from Figure 5.2. The largest of these zonal

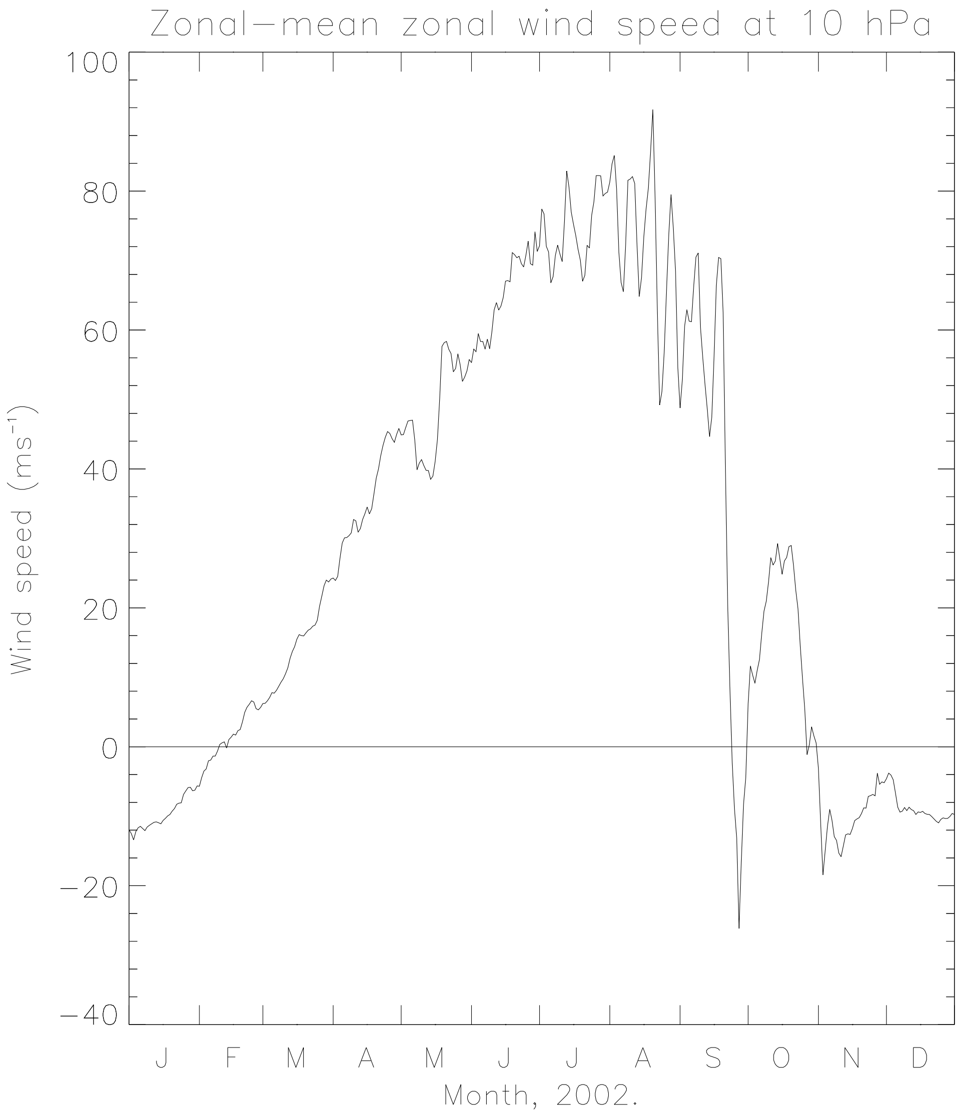

Figure 5.1: Zonal-mean zonal winds at 10 hPa for 60°S during 2002. The data were obtained from the UKMO assimilated data set. The major stratospheric warming can be seen in late November, with the final warming occurring in late October.

wind reversals occurs around the time of the major stratospheric warming at all three locations.

The zonal winds in the mesosphere revert back to being eastward in direction following the major warming. This period of eastward winds is shorter in duration in the mesosphere than in the stratosphere, with the final change to westward winds occurring near the start of October (about a month earlier than in the stratosphere).

The meridional winds (Figure 5.3) also show features relating to the major stratospheric warming event. Planetary wave signatures can be seen as alternating regions of northward or southward winds, extending at times from the ground continuously up to heights of 100 km (for the available data). Particularly strong wave activity can be seen during August and September leading up to the major warming event, with the meridional winds reaching large peak magnitudes.

Features such as the planetary wave signatures in the meridional winds and the zonal wind reversal associated with the major warming event show that the UKMO data and MF radar data are reasonably consistent with each other in terms of wind direction. It can be seen from the regions where the two data sets join that the UKMO winds are often larger in magnitude than the MF radar data. MF-FCA wind speeds are generally found to be smaller (e.g. *Holdsworth & Reid* [1995*b*]) than those from other systems such as meteor radars and satellite data. This bias is not expected to affect the validity of this thesis, and winds, gravity waves and planetary waves have been well studied with MF radars. It is interesting to note that the wind speeds are generally in better agreement in the Arctic (Figures 5.5-5.12) than in the Antarctic (Figures 5.2 and 5.3), suggesting limitations in the UKMO data set possibly due to a lack of observational data in the Antarctic.

It is evident that the horizontal wind fields at the three Antarctic locations show strong similarities in their response to the September 2002 major stratospheric warming. Given the large difference in longitude between Rothera and Davis and Syowa, the similarities suggest that many features are hemispheric in scale.

5.3 Northern hemisphere major warmings

5.3.1 Overview

Zonal-mean zonal winds at 60°N and 10 hPa are shown in Figure 5.4 for the five northern winters of available MF radar data. There were six major warming events

Start date	End date	Duration (days)	Peak magnitude (ms^{-1})
15 December 1998	20 December 1998	6	-26
25 February 1999	18 March 1999	22	-17
10 February 2001	24 February 2001	15	-14
29 December 2001	2 January 2002	5	-3
17 February 2002	18 February 2002	2	-3
18 January 2003	18 January 2003	1	-1

Table 5.1: The starting and ending dates of the zonal-mean zonal wind reversals at 60°N and 10 hPa associated with the major warmings for which Arctic MF radar data were available. Data were obtained from the UKMO assimilated data set. The durations and peak magnitudes of the reversals are also shown.

during these winters, occurring in December 1998, February 1999, February 2001, December 2001, February 2002 and January 2003 [*Manney et al.*, 2005]. The dates of the zonal-mean zonal wind reversals at 10 hPa and 60°N are listed in Table 5.1 for these events.

It can be seen from Table 5.1 that a large variation exists in the strength and duration of the northern hemisphere major warmings. The first three events have the strongest and longest duration zonal-mean zonal wind reversal associated with them, while the latter three events are shorter and weaker, only just qualifying as major warmings.

5.3.2 MF radar data during northern major warmings

5.3.2.1 The 1998/1999 northern winter

There were two major stratospheric warmings during the 1998/1999 northern winter. The first occurred in December and was an unusually early event, resulting in an abnormally warm and weak polar vortex throughout most of the winter. It was the first major warming that had occurred in about 8 years, and only the second major warming that had ever been observed as early as December [*Manney et al.*, 1999]. The second major warming of the 1998/1999 winter occurred during 1999 in February (a more common month for major warmings to occur).

The winds at Poker Flat and Andenes for the 1998/1999 winter are shown in Figures 5.5 and 5.6 for the zonal and meridional directions, respectively. Data from the ground up to a height of 0.3 hPa (~56 km) are from the UKMO assimilated data set, with MF radar data shown at heights from 60-100 km. Data are not available at Andenes for the December 1998 major warming since the available data set only begins in 1999 for the Andenes MF radar.

The zonal wind reversals associated with each of the two major warmings that occurred during the 1998/1999 northern winter can be seen in Figure 5.5. In each case the zonal wind reversal occurs earlier in the mesosphere than in the stratosphere. The zonal wind reversal associated with the December 1998 major warming stretches from the stratosphere all the way into the mesosphere at Poker Flat (for the available data), whereas it occurs at all heights for the February 1999 event at both Poker Flat and Andenes.

The polar vortex can be seen to reform following both major warmings. The zonal wind reversal of the final warming descends in height over a period of about a month at both locations, starting in the mesosphere around the end of March and reaching the stratosphere towards the start of May.

Planetary wave signatures are evident in the meridional winds (Figure 5.6). Alternating regions of northward or southward meridional winds can be seen around the times of the major warmings, with Poker Flat and Andenes generally being opposite in phase to each other at the time of the February major warming event. Planetary wave signatures in the mesospheric meridional winds around the time of major stratospheric warmings are investigated in more detail in Chapter 6.

5.3.2.2 The 2000/2001 northern winter

A major stratospheric warming did not occur during the 1999/2000 winter, with the next event occurring in February 2001. The UKMO and MF radar winds around the time of the February 2001 major warming are shown in Figures 5.7 and 5.8 for the zonal and meridional directions, respectively.

A zonal wind reversal occurs in the mesosphere at both Poker Flat and Andenes for this major warming (Figure 5.7). Again, the reversal begins earlier in the mesosphere than in the stratosphere at both locations. The zonal wind reversal at Poker Flat appears to be very short in duration, although this is partly ambiguous due to a period for which no data are available.

The zonal winds return to being eastward after the major warming. The final zonal wind reversal begins in April in the mesosphere and descends in height reaching the stratosphere about a month later in May.

This northern winter is also of interest because a strong Canadian warming occurs in November 2000. Canadian warmings rarely lead to major warmings. However, a zonal-mean zonal wind reversal occurs for about 9 days in the lower and middle stratosphere from about 65°N to the pole [*Manney et al.*, 2001]. The wind reversal reaches a peak on November 24 (day 328) although it can be seen from Figure 5.4 that the zonal-mean zonal winds at 60°N reduce but do not completely reverse at this time, so the warming does not constitute a major warming event.

A zonal wind reversal can be seen from Figure 5.7 in the stratosphere at Andenes at the time of the Canadian warming, with only a very short and weak reversal at Poker Flat over a narrow height range from about 24 km up to about 36 km. The zonal winds in the mesosphere do not reverse at Poker Flat and Andenes around the time of the Canadian warming.

5.3.2.3 The 2001/2002 northern winter

Two major warmings occurred during the 2001/2002 northern winter, one in December and one in February. The December 2001 event was only the third major warming ever to be observed this early in a winter, along with December 1987 and December 1998 [*Naujokat et al.*, 2002]. The UKMO and MF radar winds for the 2001/2002 winter are shown in Figures 5.9 and 5.10 for the zonal and meridional directions, respectively.

The zonal wind reversal associated with the December major warming has a vertical extent all the way from the ground up through the mesosphere at Andenes (for the available data), and from the upper stratosphere throughout the mesosphere at Poker Flat. The zonal wind reversal in the mesosphere for this event is stronger at Poker Flat than at Andenes. It begins and ends first in the mesosphere with a downward phase propagation reaching the upper stratosphere about a week later at both locations. For the February 2002 event no significant zonal wind reversal occurs at Andenes, and only a very weak reversal occurs at Poker Flat for a short duration only.

The zonal-mean zonal wind reversals for the December 2001 and February 2002 major warmings are smaller and shorter in duration than for the major warmings of the 1998/1999 and 2000/2001 winters at 60°N and 10 hPa (see Figure 5.4). This also appears to be the case in the stratosphere and the mesosphere at the latitude of the Arctic MF radars (from Figure 5.7).

The final warming occurs earlier in the mesosphere than in it does in the stratosphere. The zonal wind reversal defining the final warming shows a downward phase propagation over about a month from the mesosphere into the stratosphere.

The meridional winds (Figure 5.10) show some planetary wave activity during the 2001/2002 winter. Planetary wave signatures can be seen in the mesosphere, with Poker Flat and Andenes generally being opposite in phase to each other around the times of the December and February major warming events. This is consistent with the presence of zonal wave-1 planetary wave activity since Poker Flat and Andenes are almost opposite in longitude to each other.

5.3.2.4 The 2002/2003 northern winter

Stratospheric temperatures in the 2002/2003 northern winter were initially very low, although a major warming occurred in mid-January dominated by a wave-2 planetary wave event [*Kleinöhl et al.*, 2004], followed by minor warmings in February and March. A zonal-mean zonal wind reversal at 10 hPa associated with the major warming can be seen in Figure 5.4, along with reductions relating to the 2 minor warmings.

The zonal and meridional winds for this winter at Poker Flat and Andenes are shown in Figures 5.11 and 5.12, respectively. Data are not available from the Poker

Flat MF radar at the time of the major warming, although the data from Andenes and the zonal-mean zonal winds from Figure 5.4 indicate that this event is not very strong and is also very short in duration.

In the mesosphere at Andenes there is a zonal wind reversal that may or may not be related to the major stratospheric warming. It occurs slightly earlier than the zonal wind reversal in the stratosphere, but is weak in magnitude and short in duration.

5.4 Discussion and summary

The MF radar data from the Arctic and the Antarctic show that the mesosphere can be strongly effected by major stratospheric warmings. The 2002 southern hemisphere major stratospheric warming event was found to have a large influence on the mean mesospheric winds. Northern hemisphere major warmings were also found to influence mesospheric dynamics, although the degree to which this occurs varies largely between the six events investigated.

A large variation occurs in the strength and duration of the northern hemisphere major warmings. The peak zonal wind reversals at 60°N and 10 hPa for the northern hemisphere events, listed in order of occurrence, are -26 ms^{-1}, -17 ms^{-1}, -14 ms^{-1}, -3 ms^{-1}, -3 ms^{-1} and -1 ms^{-1} (as summarised in Table 5.1). It can be seen that the first three events are much stronger that the last three events, which could almost be classed as minor warmings.

The zonal-mean zonal wind reversal associated with the southern hemisphere event reaches a peak of -21 ms^{-1} at 60°S and 10 hPa. This is relatively similar in magnitude to the first three northern hemisphere major warmings, and much stronger than the latter three northern events.

A strong zonal wind reversal occurs throughout the mesosphere at Davis, Syowa and Rothera in the Antarctic. At each of these three locations the zonal wind reversal occurs first in the mesosphere, and then about a week later in the stratosphere. The complete vertical extent of the reversal is unknown above 100 km.

The zonal winds revert back to being eastward following the major warming for a much shorter time in the mesosphere then in the stratosphere. This is mostly due to the final warming occurring about a month earlier in the mesosphere than in the stratosphere.

The meridional winds in the 2002 southern winter show large amplitude planetary wave signatures at all three Antarctic locations. The planetary wave signatures stretch at times from the ground all the way up to 100 km (for the available data), and are particularly strong in August and September leading up to the southern hemisphere major warming. The meridional winds around this time are generally similar in direction at Davis and Syowa, and the opposite direction at Rothera. This suggests the presence of a wave-1 planetary wave since Rothera is similar in latitude but almost opposite in longitude to Syowa and Davis (investigated further in Section 6.2.1).

A large variation in the response of the mesospheric mean winds occurs between the six northern hemisphere major warming events studied in this chapter. The response ranges from no significant change, to strong reversals of long duration.

Strong zonal wind reversals occur in the mesosphere for the first three northern hemisphere events. The zonal wind reversals for these events occur earlier in the mesosphere than in the stratosphere, as was also seen for the southern hemisphere event.

During the northern hemisphere major stratospheric warmings, the mesospheric meridional winds at Poker Flat were often opposite in direction to the meridional winds at Andenes. The two Arctic locations are similar in latitude but almost opposite in longitude to each other, suggesting the presence of wave-1 planetary wave activity. This is a hemispheric similarity as wave-1 planetary wave signatures around the time of major stratospheric warmings seem to be a commonality of the two hemispheres.

It has been seen in this chapter that the stratospheric winds around the time of the southern hemisphere major stratospheric warming are similar in many ways to the three stronger events in the northern hemisphere (which occurred in December 1998, February 1999 and February 2001). The response of the mean winds at mesospheric heights to major stratospheric warmings also shows some hemispheric similarities. The dynamical response of the MLT to major stratospheric warmings is investigated more quantitatively in the following chapters.

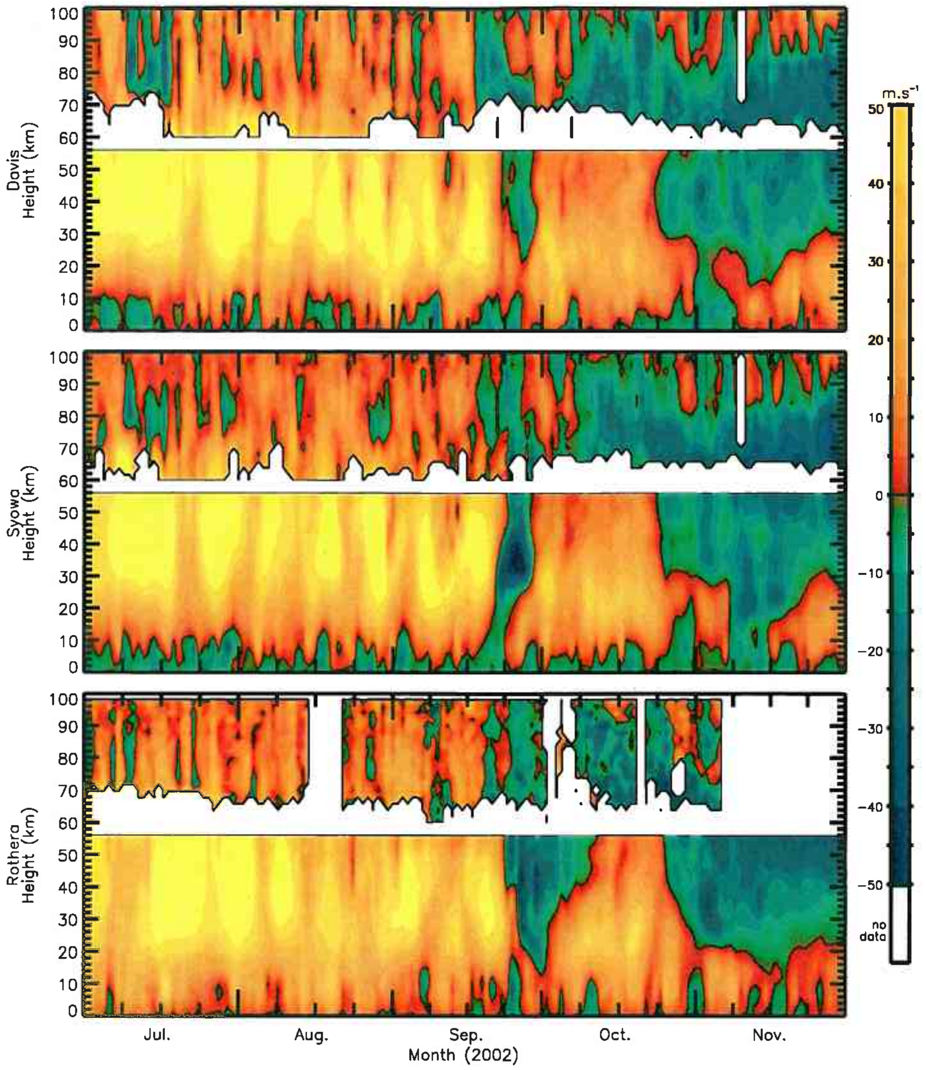

Figure 5.2: Daily average zonal winds around the time of the southern hemisphere major stratospheric warming in September 2002 at Davis, Syowa and Rothera. The winds from the ground up to a height of 0.3 hPa (~56 km) are from the UKMO assimilated data set, with MF radar data shown from heights of 60-100 km.

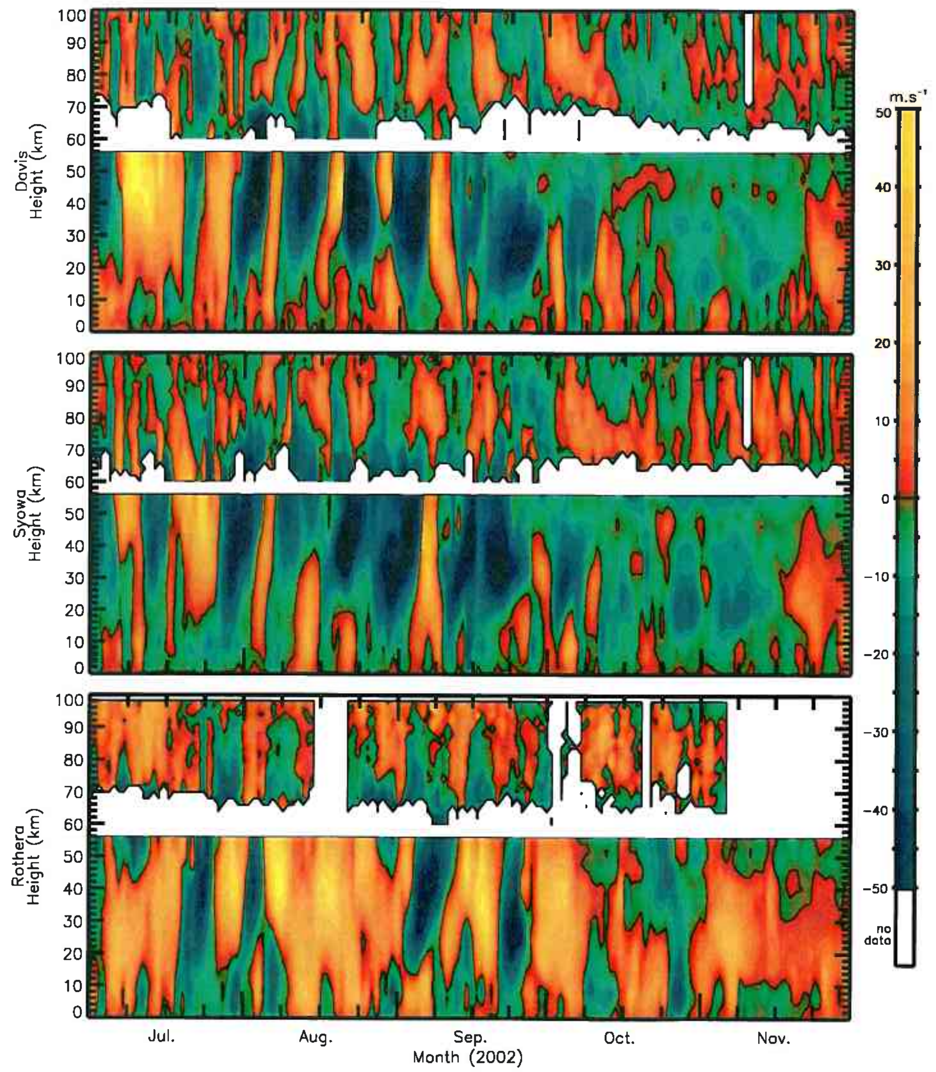

Figure 5.3: As for Figure 5.2, but for the meridional winds.

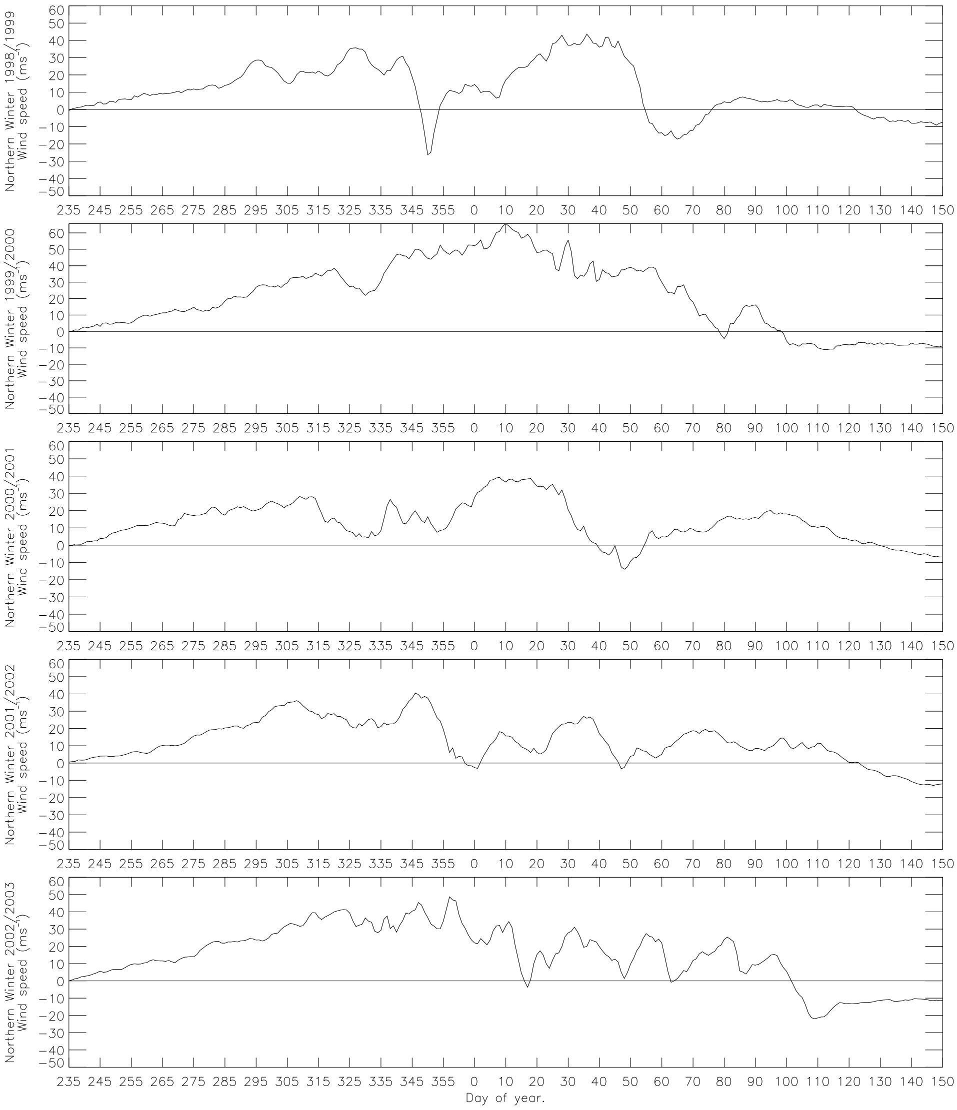

Figure 5.4: Zonal-mean zonal winds for 10 hPa at 60°N from the UKMO assimilated data set for the 5 winters for which Arctic MF radar data is available.

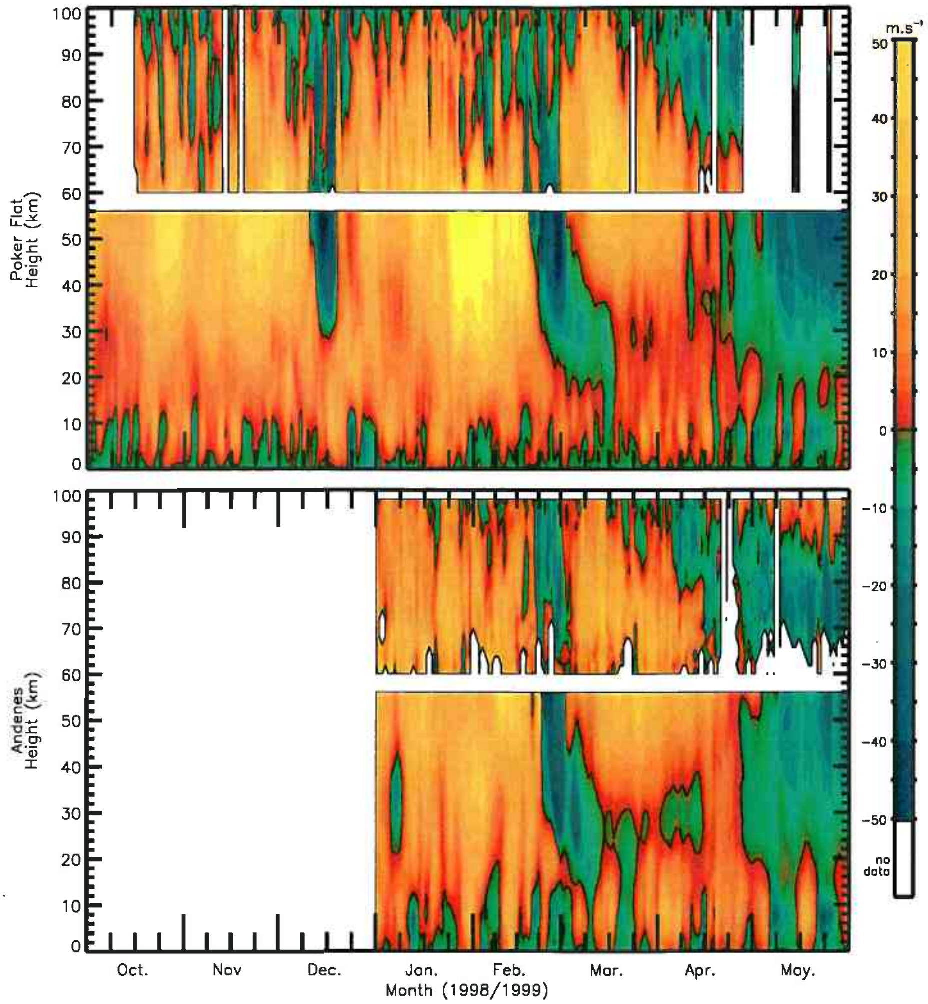

Figure 5.5: Daily average zonal winds at Poker Flat and Andenes for the 1998/1999 northern winter during which two major stratospheric warmings occurred (December 1998, and February 1999). The winds from the ground up to a height of 0.3 hPa (~56 km) are from the UKMO assimilated data set, and MF radar data are shown from 60-100 km.

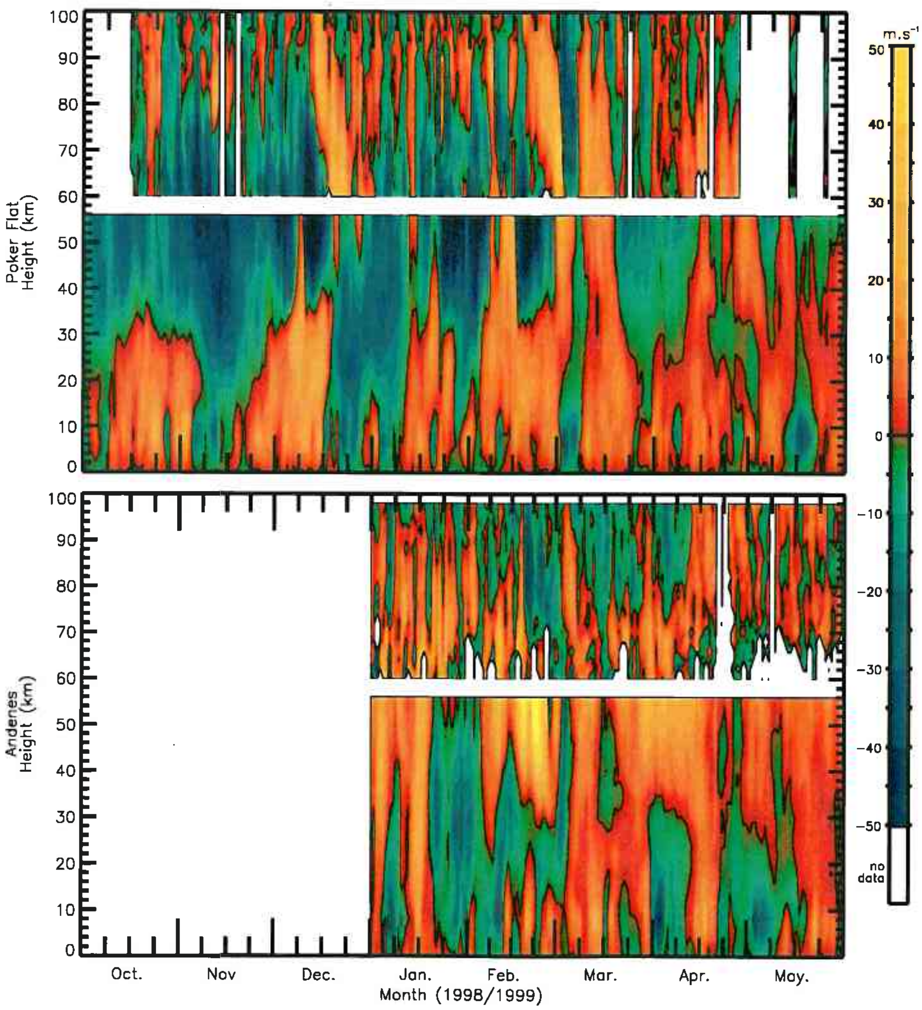

Figure 5.6: As for Figure 5.5, but for the meridional winds.

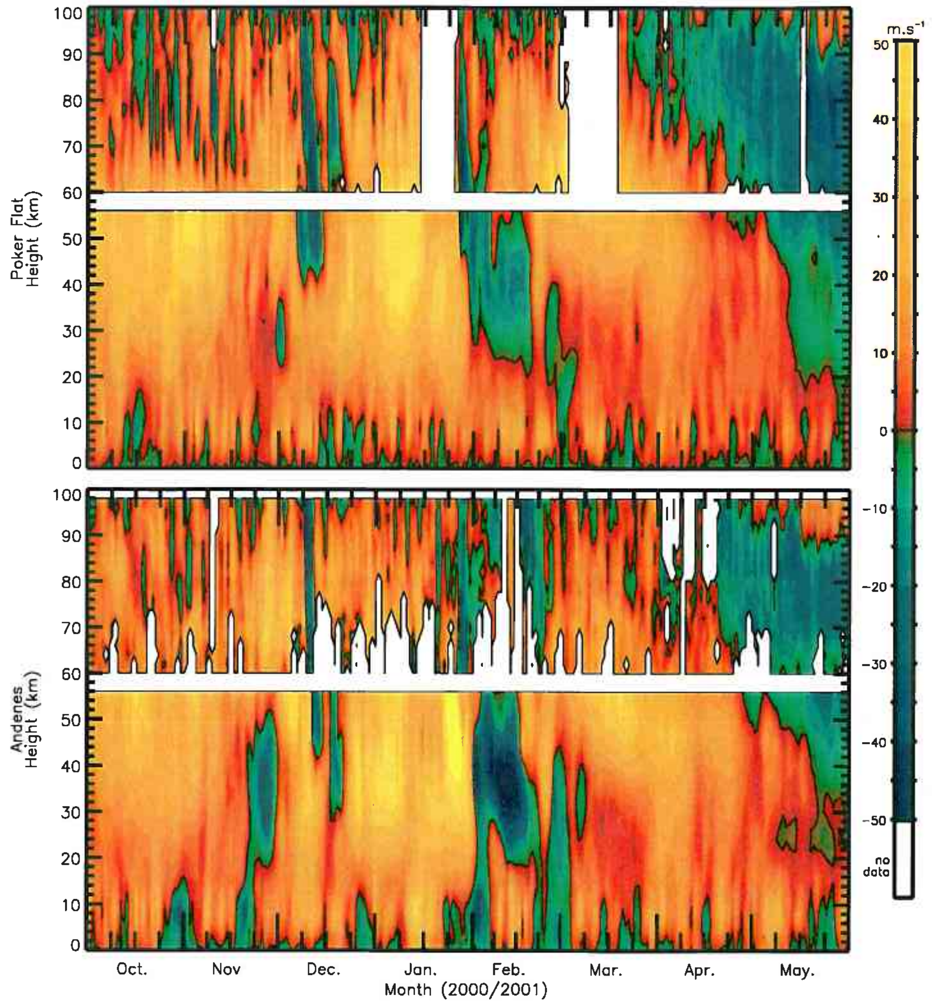

Figure 5.7: Daily average zonal winds at Poker Flat and Andenes during the 2000/2001 northern winter, with a Canadian warming in November and a major stratospheric warming in February. The winds from the ground up to a height of 0.3 hPa (~56 km) are from the UKMO assimilated data set, with MF radar data shown from 60-100 km.

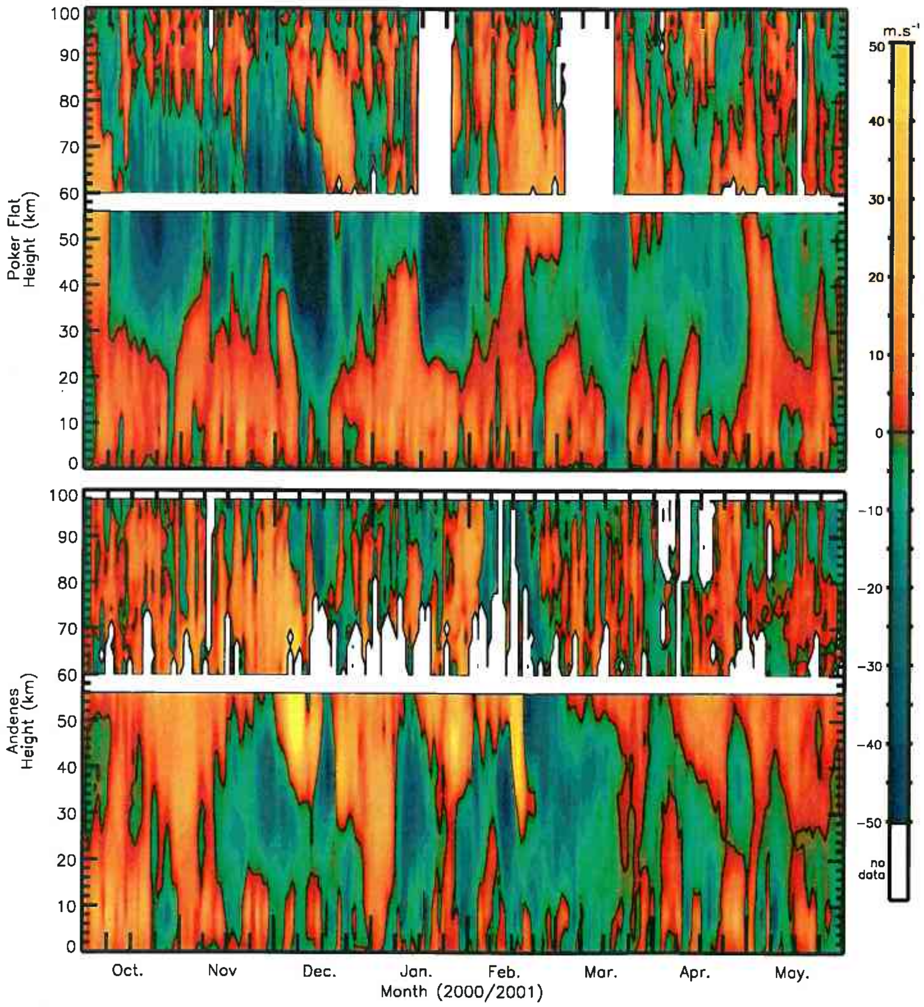

Figure 5.8: As for Figure 5.7, but for the meridional winds.

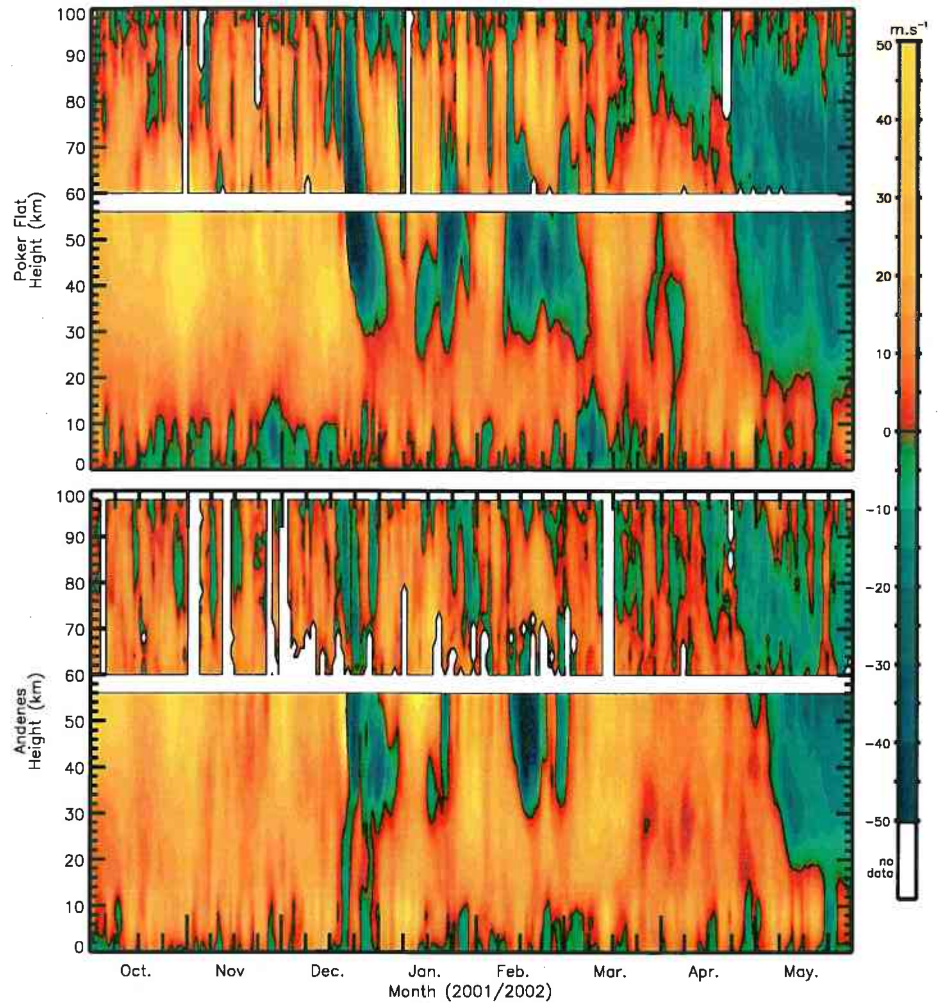

Figure 5.9: Daily average zonal winds at Poker Flat and Andenes during the 2001/2002 northern winter, with major stratospheric warmings occurring in December and February. The winds from the ground up to a height of 0.3 hPa (~56 km) are from the UKMO assimilated data set, and MF radar data are shown from 60-100 km.

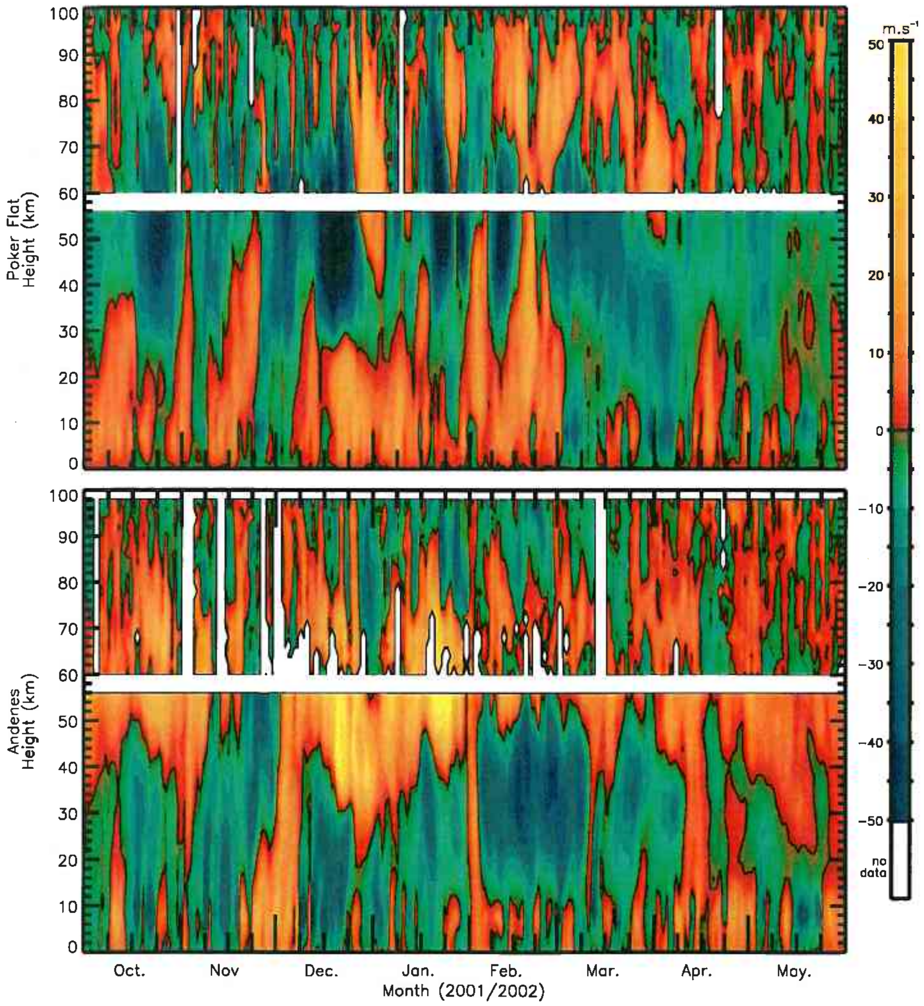

Figure 5.10: As for Figure 5.9, but for the meridional winds.

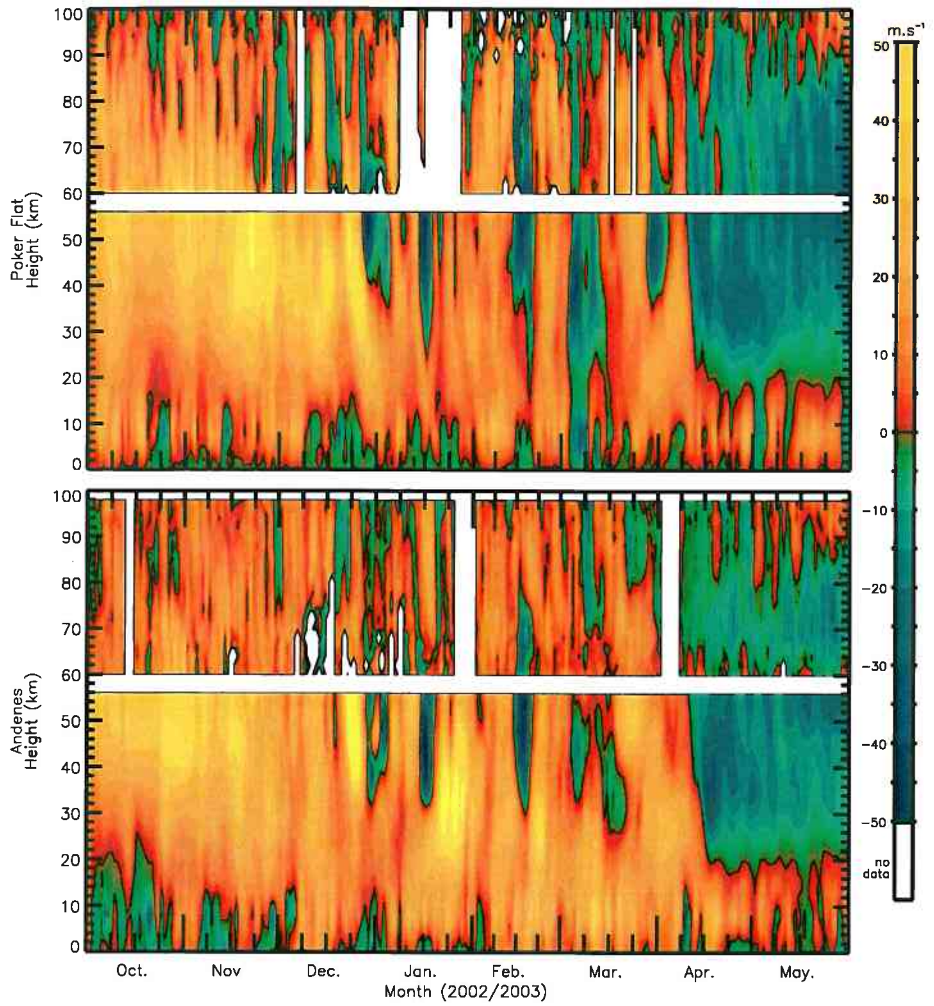

Figure 5.11: Daily average zonal winds at Poker Flat and Andenes during the 2002/2003 northern winter, with a major stratospheric warming in January. The winds from the ground up to a height of 0.3 hPa (~56 km) are from the UKMO assimilated data set, with MF radar data shown from 60-100 km.

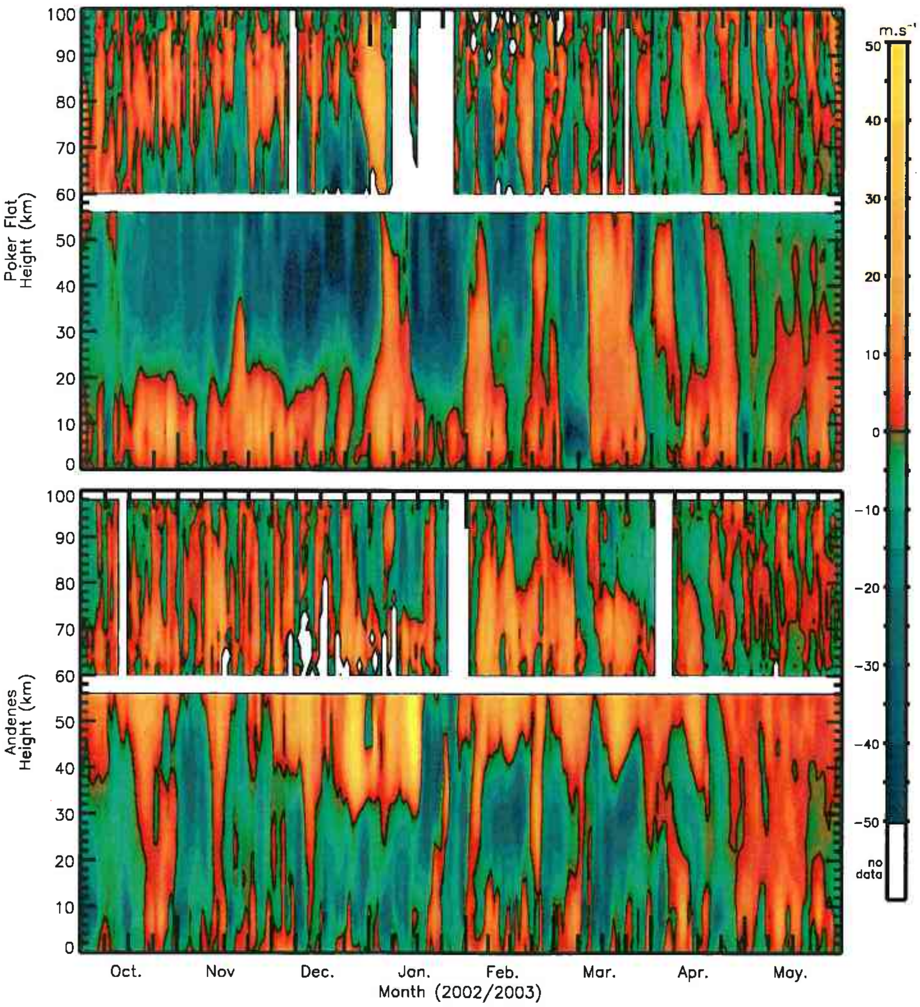

Figure 5.12: As for Figure 5.11, but for the meridional winds.

Chapter 6

Mean winds during major warmings

6.1 Introduction

In the previous chapter it was shown that major stratospheric warmings can have a strong effect on the dynamics of the MLT region. This chapter details the response of the mean winds in the MLT to major stratospheric warmings in a more quantitative manner than the overview presented in the previous chapter.

Results are discussed in relation to coupling mechanisms between the stratosphere and the MLT. One such process is planetary wave propagation from the stratosphere into the MLT. Planetary wave signatures are investigated in the MF radar winds using methods such as time series analysis, and harmonic fits.

6.2 Planetary waves in the MLT

6.2.1 Planetary waves in the MLT during the southern major warming

The 2002 southern hemisphere major stratospheric warming event was caused by a series of unusually large amplitude planetary waves propagating from the troposphere up into the stratosphere. There is strong evidence for linkage between planetary waves in the stratosphere and the MLT. The planetary wave induced oscillations of the meridional winds can be seen in Figure 5.3 to extend sometimes from the ground all the way up to 100 km (e.g., early September at Davis and Syowa).

As shown in the previous chapter, oscillations with periods of about 14 days occur in the meridional winds from about August to October at the three locations. Qualitatively, the oscillations at Davis and Syowa appear to be similar in phase, while an out-of-phase behavior occurs at Rothera. To investigate the planetary wave activity more quantitatively, a least-squares sliding harmonic fit to the daily average meridional winds at the three locations was made.

Harmonic fits of different periods were fitted to daily average meridional winds from 76-84 km from late August to early October at Davis, Syowa and Rothera. The optimum fit occurs for a period of 14 $\pm$ 1 days at each location.

Figure 6.1 shows daily values of meridional wind velocity averaged over the 76-84 km height range during a 45-day period from late August (August 22) to early October (October 8), with a fitted 14-day oscillation over-plotted at each location. Wave amplitudes are about 10 ms^{-1} at Davis and Syowa, but only about 5-7 ms^{-1} at Rothera.

Also shown in Figure 6.2 are the phases of the three fitted waves plotted with respect to longitude. The phase slope is consistent with the 14-day wave being a westward propagating planetary wave-1. No other wave structure, either eastward or westward propagating, is consistent with the data.

There is very little indication of quasi-stationary planetary wave activity in the meridional winds around the time of the 2002 southern hemisphere major warming. This can be seen from Figure 6.1 where the average meridional wind speed is relatively close to zero at all three locations (4 ms^{-1} at Davis, 0 ms^{-1} at Syowa and -1 ms^{-1} at Rothera).

Figure 6.2 shows the phase of the fitted 14-day wave to the meridional winds at Davis, Syowa and Rothera as a function of height. The dotted lines represent the standard deviation of the phase estimates. There is only a very small suggestion of a phase tilt with height in a sense that indicates upward propagation of energy, but the implied vertical wavelength is very large (ranging from about -220 km at Davis to about -450 km at Syowa).

Figure 6.3 shows the amplitude of the fitted 14-day wave to the meridional winds at Davis, Syowa and Rothera as a function of height. The dotted lines represent the standard deviation of the amplitude estimates. It can be seen that the amplitudes are generally larger at Davis and Syowa than at Rothera (with the exception of heights below about 80 km at Syowa).

6.2.2 Planetary waves in the MLT during northern major warmings

The large major stratospheric warmings for which MF radar data are available at both Poker Flat and Andenes occur in February 1999 and February 2001. Daily values of the meridional winds averaged from 76-84 km are shown in Figures 6.4 and 6.5 around the times of the February 1999 and February 2001 major warmings, respectively.

The meridional winds range from about 30 ms^{-1} to about -40 ms^{-1} at Poker Flat, and from about 30 ms^{-1} to about -30 ms^{-1} at Andenes around the time of the February 1999 major warming. This is a significantly larger range than was observed at Davis and Syowa around the time of the southern hemisphere major warming event (see Figure 6.1). The meridional winds at the two locations are generally opposite in direction to each other, suggesting the presence of zonal wave-1 planetary wave activity.

A harmonic oscillation does not fit as well as was the case for the southern hemisphere event. There is little indication of quasi-stationary planetary wave activity, with the meridional winds being slightly negative on average at Poker Flat (-1 ms^{-1}) and Andenes (-3 ms^{-1}) around the time of the February 1999 major warming,

The meridional wind variations for the February 2001 northern major warming event (Figure 6.5) range from about 30 ms^{-1} to about -10 ms^{-1} at Poker Flat and from about 20 ms^{-1} to about -20 ms^{-1} at Andenes. This variation of about 40 ms^{-1} at both Poker Flat and Andenes is similar in magnitude to the range of the meridional wind speeds observed at Davis and Syowa around the time of the southern hemisphere major stratospheric warming event. The meridional winds at the two locations are generally opposite in direction to each other, indicating the presence of zonal wave-1 planetary wave activity.

A harmonic oscillation does not fit very well to the winds, although there is some indication of quasi-stationary zonal wave-1 planetary wave activity. The winds are positive on average at Poker Flat (7 ms^{-1}) and slightly negative on average at Andenes (-1 ms^{-1}) around the time of the February 2001 major warming (Figure 6.5).

6.3 Winter mean wind climatologies

Figure 6.6 shows the zonal winds averaged during each winter of available data at Davis, Syowa, Poker Flat and Andenes. Winter is defined here as from November 1 to February 28 in the northern hemisphere, and from June 1 to September 30 in the southern hemisphere.

A significant feature of Figure 6.6 is that the average zonal winds during winter at the northern hemisphere locations are generally weaker at all heights then at the southern hemisphere locations. This is true for all years with the exception of 2002 where the zonal winds at the southern hemisphere locations are significantly weaker than usual (by about 10 ms^{-1}) and are more similar to mean values in the northern hemisphere.

Figure 6.7 is similar to Figure 6.6, but for the meridional winds. At the northern hemisphere locations, a systematic difference in the mean winter meridional wind speed does not occur between winters where large major warmings occur and other winters.

Below about 80 km the meridional winds are southward at Poker Flat and northward at Andenes, presumably due to the presence of quasi-stationary zonal wave-1 planetary wave activity. It is interesting to note that this feature is weakest for the 1999/2000 northern winter, which is the only one not to have a major stratospheric warming occur.

The meridional winds below about 80 km at the Antarctic locations during 2002 appear to be slightly weaker (closer to zero) than other years. At higher altitudes this difference is not observed. The meridional winds are generally opposite in sign at Davis and Syowa which may suggest the influence of some quasi-stationary planetary wave activity.

6.4 Analysis of zonal wind reversals

6.4.1 Zonal wind reversal during the southern major warming

In Chapter 5, the zonal wind reversal associated with the 2002 southern hemisphere major stratospheric warming was found to occur earlier in the mesosphere than in the stratosphere. This timing difference is detailed in Figure 6.8 which shows the MF radar zonal winds at 80 km averaged for Davis, Syowa and Rothera, and the zonal-mean zonal winds from the UKMO data at 10 hPa (∼32 km) and 68°S (the mean latitude of the three Antarctic MF radars).

The zonal winds begin reducing around day 259 (16 September) in the mesosphere, which is about 4 days earlier than in the stratosphere. The winds in the mesosphere become westward on day 262 (18 September), about 5 days earlier than the 10 hPa winds turned westward on day 267 (24 September). The mesospheric winds revert back to being eastward on day 273, which is 1 day earlier than this occurs in the stratosphere.

The zonal wind reversal associated with the major warming lasts for 11 days at 80 km, and for 7 days at 10 hPa at this latitude. The peak magnitude of the reversal is -12 ms^{-1} in the mesosphere and -26 ms^{-1} in the stratosphere. It is interesting to note that the peak magnitude of the mesospheric zonal wind reversal is less than half that of the stratosphere, although the reversal lasts for longer in the mesosphere.

6.4.2 Zonal wind reversals during northern major warmings

Zonal winds during the five northern winters for which MF radar data are available are shown in Figure 6.9. MF radar zonal winds are shown at 80 km with a 5-day running mean applied averaged for Poker Flat and Andenes, together with zonal-mean zonal winds from UKMO data at 10 hPa and 67°N (the average latitude of the two Arctic MF radars).

Zonal wind reversals can be seen in the stratosphere for the 6 northen major warming events in December 1998, February 1999, February 2001, December 2001, February 2002 and January 2003. The first three northern events are comparable in magnitude to the southern hemisphere event, and much larger than the last three northern events which could almost be classed as minor warmings. This is the same as what was observed at 60°N in Chapter 5.

Mesospheric zonal wind reversals are apparent in Figure 6.9 for the three strong northern hemisphere major warmings. The dates that these reversals begin and end in the stratosphere and mesosphere are shown in Table 6.1, along with their peak magnitude and duration.

The wind reversals occur earlier in the mesosphere than in the stratosphere in each case. The average timing difference is 6 days averaged for the three large northern major warmings. The duration of the wind reversal is not consistently longer for either height range.

Region	Start date	End date	Duration (days)	Peak magnitude (ms^{-1})
Mesosphere	11 Dec 1998	20 Dec 1998	10	17
Stratosphere	15 Dec 1998	20 Dec 1998	6	29
Mesosphere	19 Feb 1999	28 Feb 1999	10	10
Stratosphere	25 Feb 1999	20 March 1999	4	23
Mesosphere	26 Jan 2001	31 Jan 2001	6	5
Stratosphere	2 Feb 2003	21 Feb 2001	20	21

Table 6.1: The starting and ending dates of the zonal wind reversals associated with the strong major warmings for which Arctic MF radar data are available. The durations and peak magnitudes of the wind reversals are also shown. Stratospheric data are obtained from the UKMO assimilated data set zonal-mean zonal winds at 67°N and 10 hPa. Mesospheric data are obtained from MF radar data with a 5-day running mean applied at 80 km, averaged for Poker Flat and Andenes.

The average magnitudes of the zonal wind reversals are weaker in the mesosphere (11 ms^{-1}) than in the stratosphere (24 ms^{-1}), as was also the case for the southern hemisphere 2002 major warming. This appears to be a common response to all large major warmings in both hemispheres.

6.5 Wind time series during major warmings

A time series analysis is presented in this chapter to investigate the time evolution of the mean winds in the mesosphere during major stratospheric warmings.

6.5.1 Zonal wind time series during major warmings

Time series of zonal winds observed at 80 km at Davis and Syowa are shown in Figure 6.10. The winds during 2002 are shown in red, with all other years shown in black. The data are smoothed with 5-day running means. The dashed lines indicate the average values for all years excluding 2002.

Prior to about mid-April the winds for 2002 follow the summer to winter trend evident for other years. From about May onwards, the eastward winds at 80 km are on average 10 ms^{-1} weaker than the long term value at both Davis and Syowa. Weaker mean zonal winds during the 2002 southern winter also occur at other heights (as was seen in Figure 6.6).

The winter to summer zonal wind transition normally proceeds with remarkably little inter-annual variability at both Davis and Syowa. However, during 2002 the zonal winds are remarkably different to all other years, being weaker (more eastward) by 10-20 ms^{-1} during November. It is not until the start of December that the zonal winds become comparable in strength to other years.

Figure 6.11 shows time series of the zonal winds at 80 km at Poker Flat and Andenes. A 5-day running mean is applied. The northern winters in which a large major warming occur are shown in red (for the 1998/1999 winter) and in blue (for the 2000/2001 winter), with all other winters shown in black.

The zonal winds during the transition to the strongly negative values of summer are not weaker than other years following the large northern major warming events of February 1999 and February 2001. This is in contrast to what was observed at the Antarctic locations following the September 2002 southern hemisphere event. The zonal winds during these two northern winters are not weaker than other years earlier in the winter, which is also in contrast to the southern hemisphere event.

About a month before the summer solstice, the average zonal wind strength at the Arctic locations is about $\sim$20 ms^{-1}. This is similar to the average zonal wind strength at the Antarctic locations about a month before the 2002 summer solstice, which is about 20 ms^{-1} weaker than all other years of data at both Antarctic locations.

In this respect, the 2002 southern hemisphere spring transition is more similar to northern hemisphere climatological means than to southern hemisphere climatological means. The 2002 southern hemisphere final warming (see Figure 5.2) appears to be a typical southern hemisphere final warming in that it does not show a downward phase progression over a period of about month as is characteristic of the northern hemisphere final warming (as seen in Chapter 3).

6.5.2 Meridional wind time series during major warmings

Figure 6.12 is similar to Figure 6.10, but for the meridional winds at Davis and Syowa. The seasonal behavior of the meridional winds observed at 80 km in 2002 for the southern hemisphere locations is not markedly different to that of other years. Large wave-like variations start at the end of March and diminish in amplitude going from spring to summer.

Figure 6.13 is similar to Figure 6.11, but for the meridional winds at Poker Flat and Andenes. It can be seen once again that the magnitude of the meridional wind variations in the northern hemisphere are generally larger than the variations in the Antarctic. This is particularly true during winter, suggesting possible hemispheric differences in the influence of planetary waves signatures in the MLT region.

It can be seen from Figure 6.13 that strong variations in the meridional winds occur around the times of the large major warmings (February 1999 and February 2001). The meridional winds are generally opposite in direction to each other at Poker Flat and Andenes consistent with zonal wave-1 planetary wave activity.

The meridional wind time series during the northern winter of 2000/2001 show some features of interest. The meridional winds at Andenes increase throughout November 2000 to velocities significantly larger than other years. It was at this time that the Canadian warming event was taking place in the stratosphere [*Manney et al.*, 2001], with the vortex being shifted towards Europe.

Following the Canadian warming the winds at Andenes decrease suddenly from about 25 ms^{-1} to about -15 ms^{-1} while increasing at Poker Flat. This is coincident with the occurrence of a minor stratospheric warming. Figure 6.11 shows that a reversal of the zonal winds does occur in the mesosphere at both Poker Flat and Andenes at this time in early December 2000.

For the major warming event of February 2001 the meridional winds are poleward at Poker Flat and equatorward at Andenes. This is once again consistent with a flow over the pole associated with zonal wave-1 planetary wave activity.

6.6 Discussion and summary

The results of this chapter focus on the larger major stratospheric warming events (December 1998, February 1999 and February 2001 in the northern hemisphere, and the September 2002 southern hemisphere event). These events significantly affect the mean winds in the MLT.

The zonal wind reversals associated with the large major warmings occur earlier in the mesosphere than in the stratosphere in all cases. The average timing difference is about 6 days for the northern hemisphere events at Poker Flat and Andenes, and about 5 days for the southern hemisphere event at Davis, Syowa and Rothera.

Another common response between all of the large major warmings is that the peak magnitude of the zonal wind reversals is weaker in the mesosphere than in the stratosphere. The average difference is about 14 ms^{-1} for the northern hemisphere events, and also 14 ms^{-1} for the southern hemisphere event.

The meridional winds during August and September 2002 in the Antarctic mesosphere are dominated by a large amplitude westward propagating planetary wave with a period of about 14-days and a zonal wave number 1 structure. The wave amplitudes are larger at Davis and Syowa than at Rothera. Davis and Syowa are relatively close in longitude to each other compared to Rothera, so the smaller amplitude at this latter location may relate to the mean zonal circulation being displaced off the pole.

Zonal wave-1 planetary wave signatures in the mesospheric meridional winds are also observed around the times of the northern hemisphere events. This suggests that a common response between the hemispheres is a flow over the pole at mesospheric heights, associated with wave-1 planetary wave activity.

The variations of the mesospheric meridional winds during winter are generally about 50% larger in magnitude at the Arctic locations than at the Antarctic locations. One possible interpretation of this is that planetary waves have a stronger influence at these heights in the Arctic then they do in the Antarctic.

The winds around the times of major stratospheric warmings are compared with climatological means. The zonal wind speeds at both Davis and Syowa were about 10 ms^{-1} weaker on average during the 2002 winter than all other years, being more similar in magnitude to typical northern hemisphere values (see Figure 3.4).

The zonal winds are also weaker (by about 10-20 ms^{-1}) during the transition to the summer circulation following the 2002 southern major warming, being more similar to typical northern hemisphere magnitudes than typical southern hemisphere magnitudes at this time (with respect to the summer solstices).

During the northern winters for which large major warming events occurred (1998/1999 and 2000/2001), a reduction in the average zonal wind speed is not seen (in contrast to the case for the 2002 southern winter). Weaker zonal winds during the transition to the summer circulation are also not observed following these two northern winters.

It therefore appears that there are some hemispheric similarities between the response of the MLT winds to major stratospheric warmings, as well as some differences. The timing of the September southern hemisphere major stratospheric warming event is equivalent to a March northern hemisphere event (which is sometimes called an early spring warming as opposed to a mid-winter warming). The northern hemisphere events studies here occur only as late as February, a difference which could possibly have some influence on hemispheric comparisons.

The mesospheric response to stratospheric warmings depends on a number of factors that are not yet fully understood. Changes in momentum and energy budgets will be caused by changes in both planetary wave and gravity wave interactions with the mean flow. Changes in the stratospheric circulation produce changes in gravity wave filtering and hence in the gravity wave fluxes reaching the mesosphere.

Any reduction in the strength of the eastward stratospheric winds would allow an increased flux of eastward propagating gravity waves, producing an increased eastward forcing in the MLT. Since gravity wave momentum deposition drives the pole-to-pole meridional circulation that in turn drives mesospheric temperatures away from radiative equilibrium at the solstices (keeping the winter MLT warmer than would otherwise be the case [*Holton*, 1983]), mesospheric cooling might be expected during major warmings.

The mesospheric temperatures at the South Pole during the 2002 Antarctic winter (April-August) were reported by *Hernandez* [2003] to be cooler than usual, similar to the mesospheric cooling often observed during northern hemisphere stratospheric warmings [*Walterscheid et al.*, 2000]. However, long-term OH temperature measurements near the mesopause at Davis show that the winter of 2002 was warmer than long-term average winter values (*G. Burns*, personal communication, 2004).

Overall, there are complex changes in the residual circulation in the high latitude MLT that will influence the composition of important minor constituents such as atomic oxygen [*Liu & Roble*, 2002], and the effects are likely to be longitudinally dependent due to planetary wave modulation of gravity wave fluxes [*Dunkerton & Buchart*, 1984; *Manson et al.*, 2003]. The effect that major stratospheric warmings have on gravity wave activity in the MLT is investigated in the following chapter.

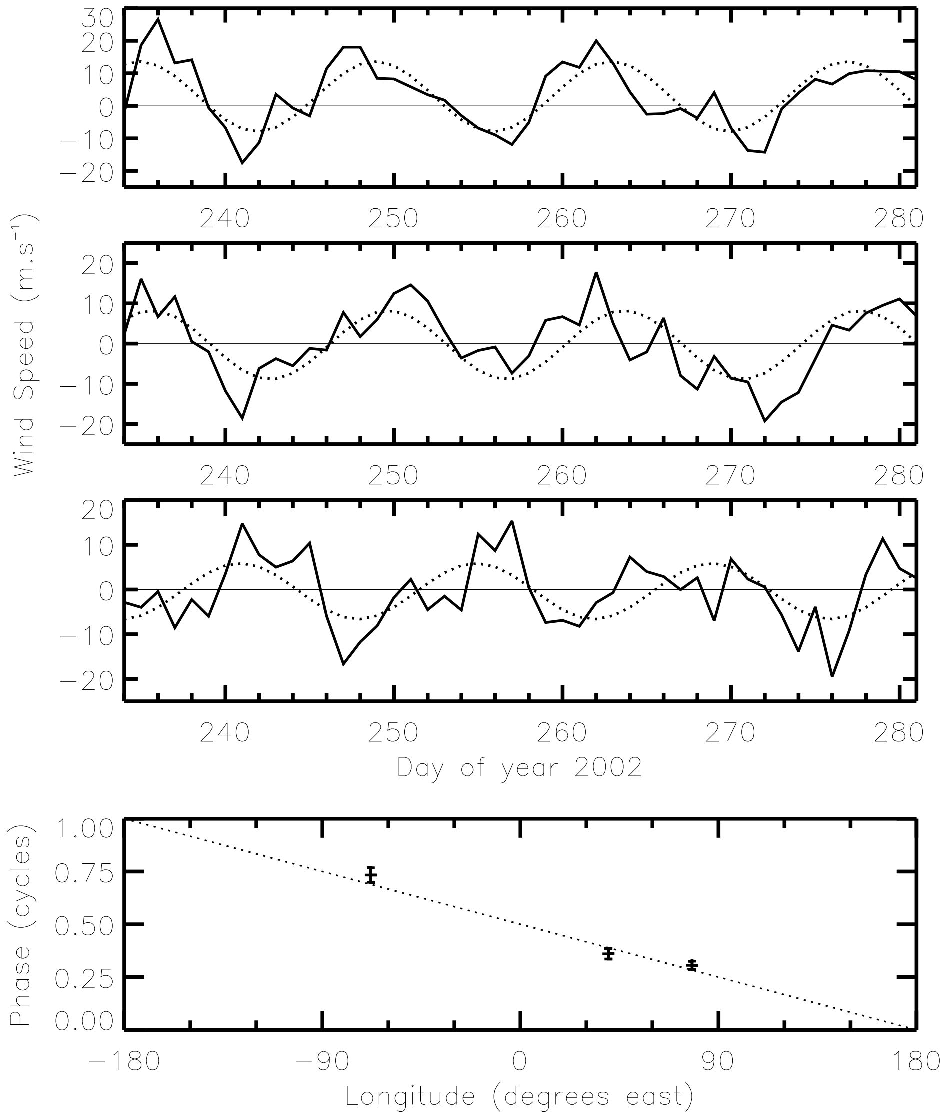

Figure 6.1: Daily average meridional winds (solid) averaged over the 76-84 km height range plotted as a function of day of year (January 1 = day 0) at Davis (top panel), Syowa (second panel) and Rothera (third panel). The dotted lines represent least-squares fitted 14-day oscillations. The bottom panel shows the phases as a function of longitude, with the error bars representing the standard deviation of the phase estimates. The dotted line has the slope of a zonal wave number 1.

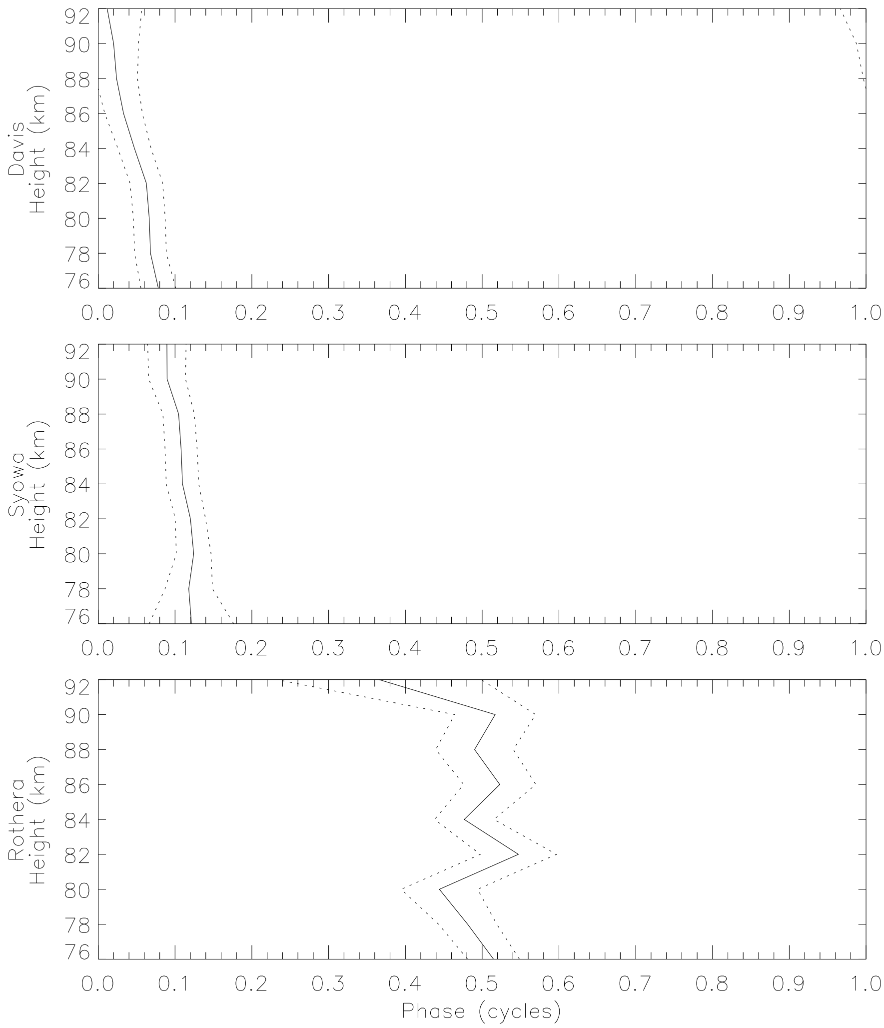

Figure 6.2: The phase of the fitted 14-day oscillations to daily average meridional winds from late August until early October at Davis, Syowa and Rothera. The dotted lines indicate the standard deviation of the phase estimates.

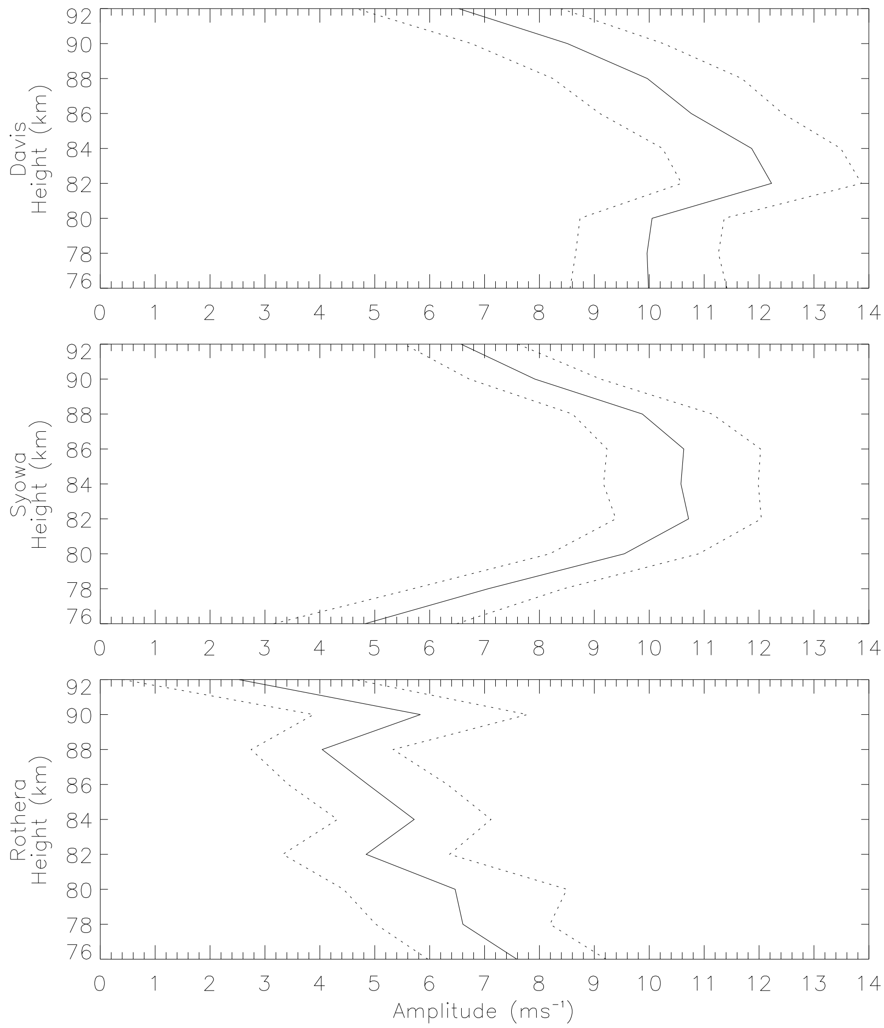

Figure 6.3: The amplitude of the fitted 14-day oscillations to daily average meridional winds from late August until early October at Davis, Syowa and Rothera. The dotted lines indicate the standard deviation of the amplitude estimates.

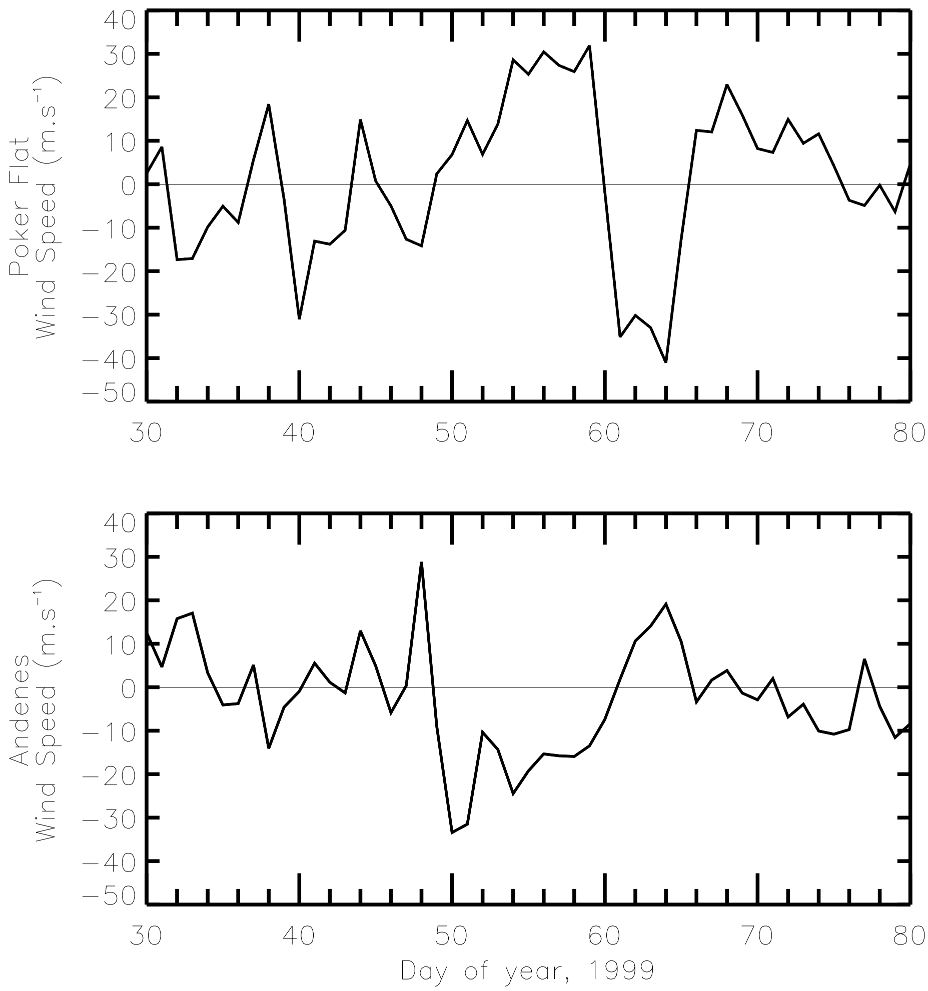

Figure 6.4: Daily average meridional winds (solid) averaged over the 76-84 km height range as a function of day of year (January 1 = day 0) around the time of the February 1999 major stratospheric warming at Poker Flat (upper panel) and Andenes (lower panel).

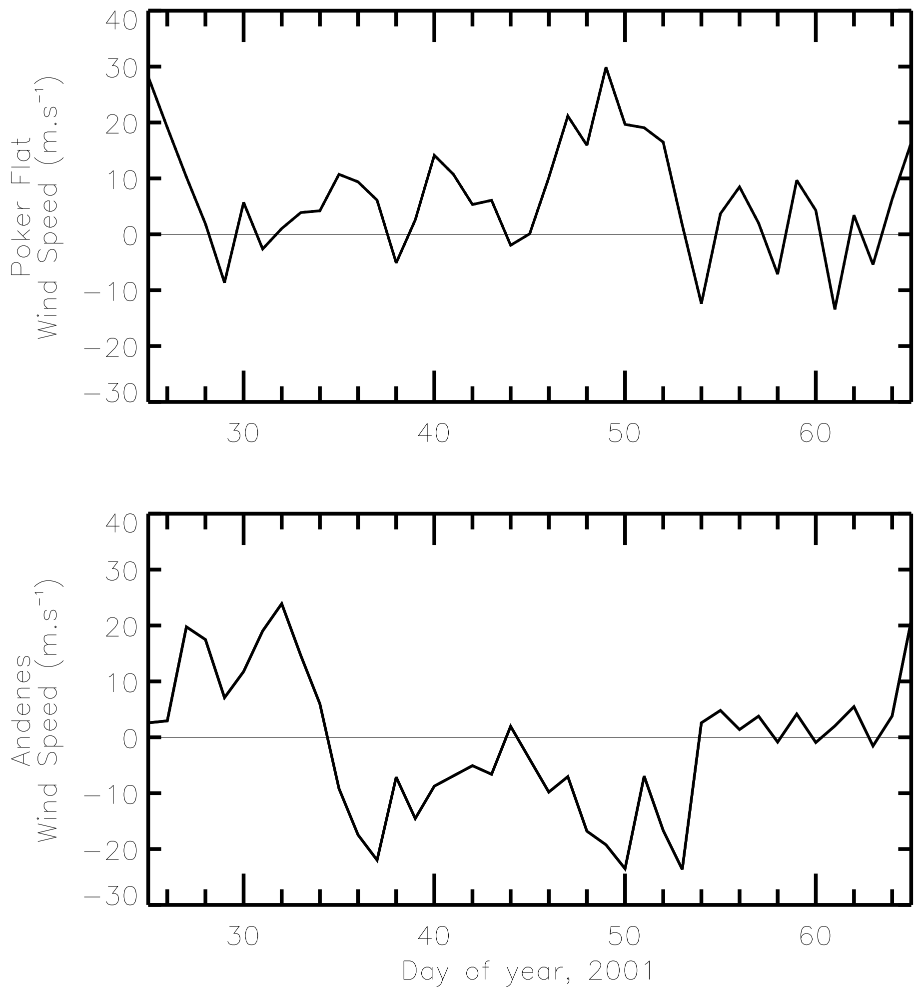

Figure 6.5: As for Figure 6.4, but for the February 2001 northern hemisphere major stratospheric warming.

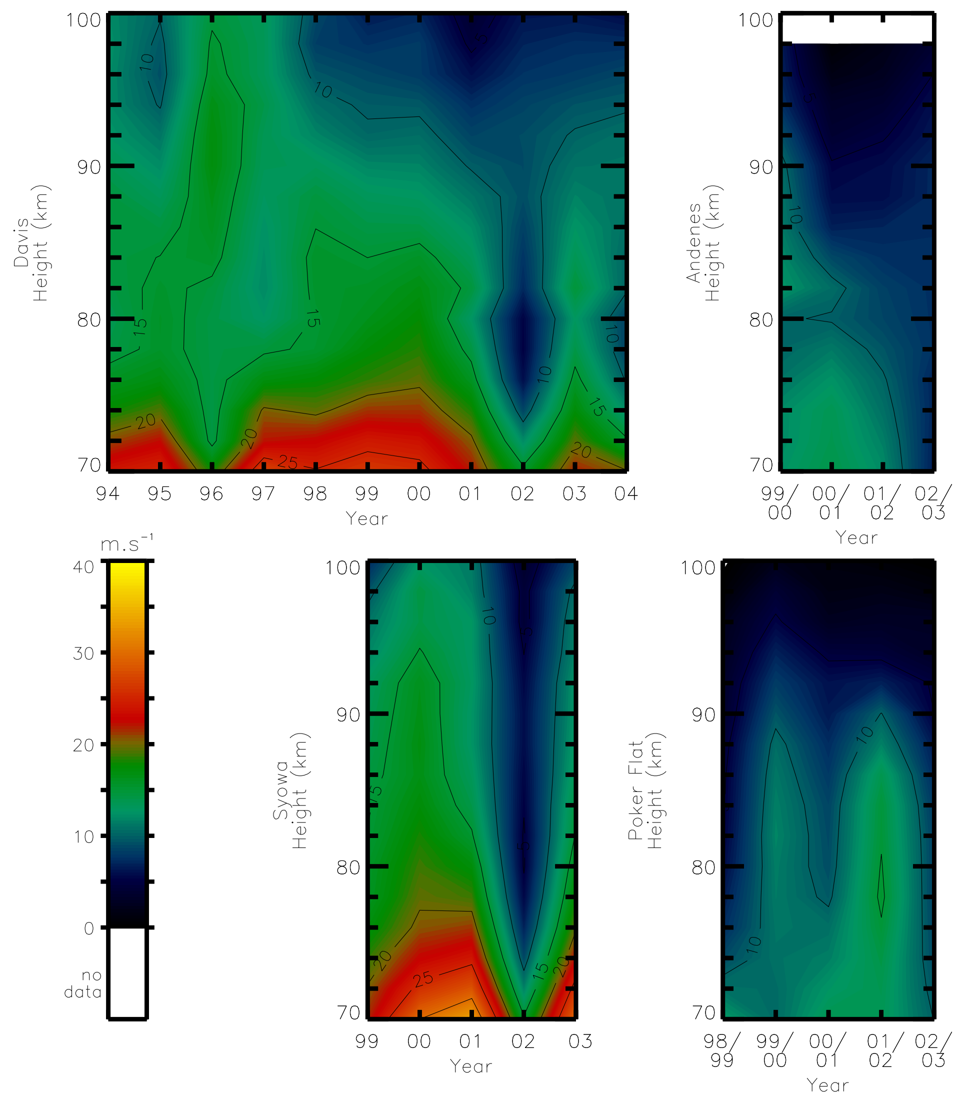

Figure 6.6: Zonal winds averaged during winter (May, June, July and August for Davis and Syowa, and November, December, January and February for Poker Flat and Andenes).

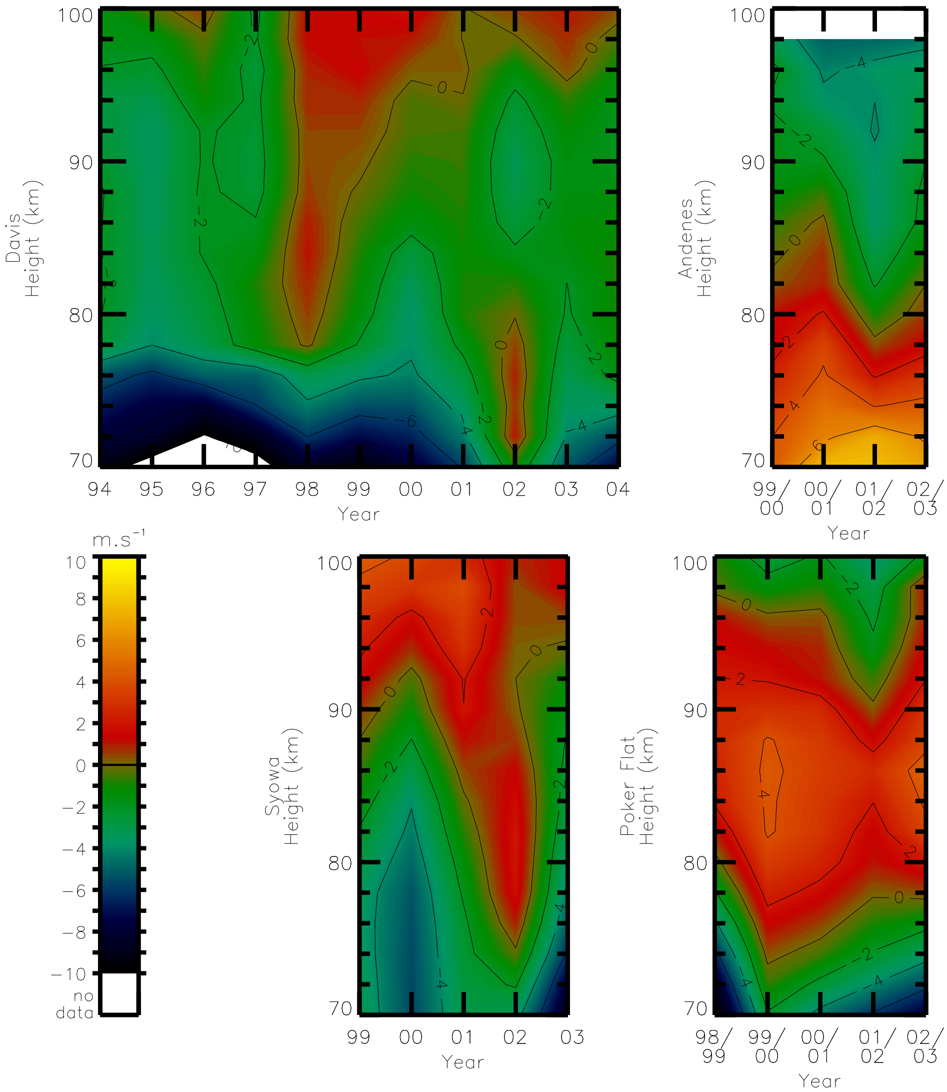

Figure 6.7: As for Figure 6.6, but for the meridional winds.

Figure 6.8: Daily average zonal winds around the time of the 2002 southern hemisphere major warming. Zonal-mean zonal winds are shown in black for UKMO data at 10 hPa and 68°S, and in red for MF radar zonal winds at 80 km averaged for Davis, Syowa and Rothera. Data are shown in days from January 1.

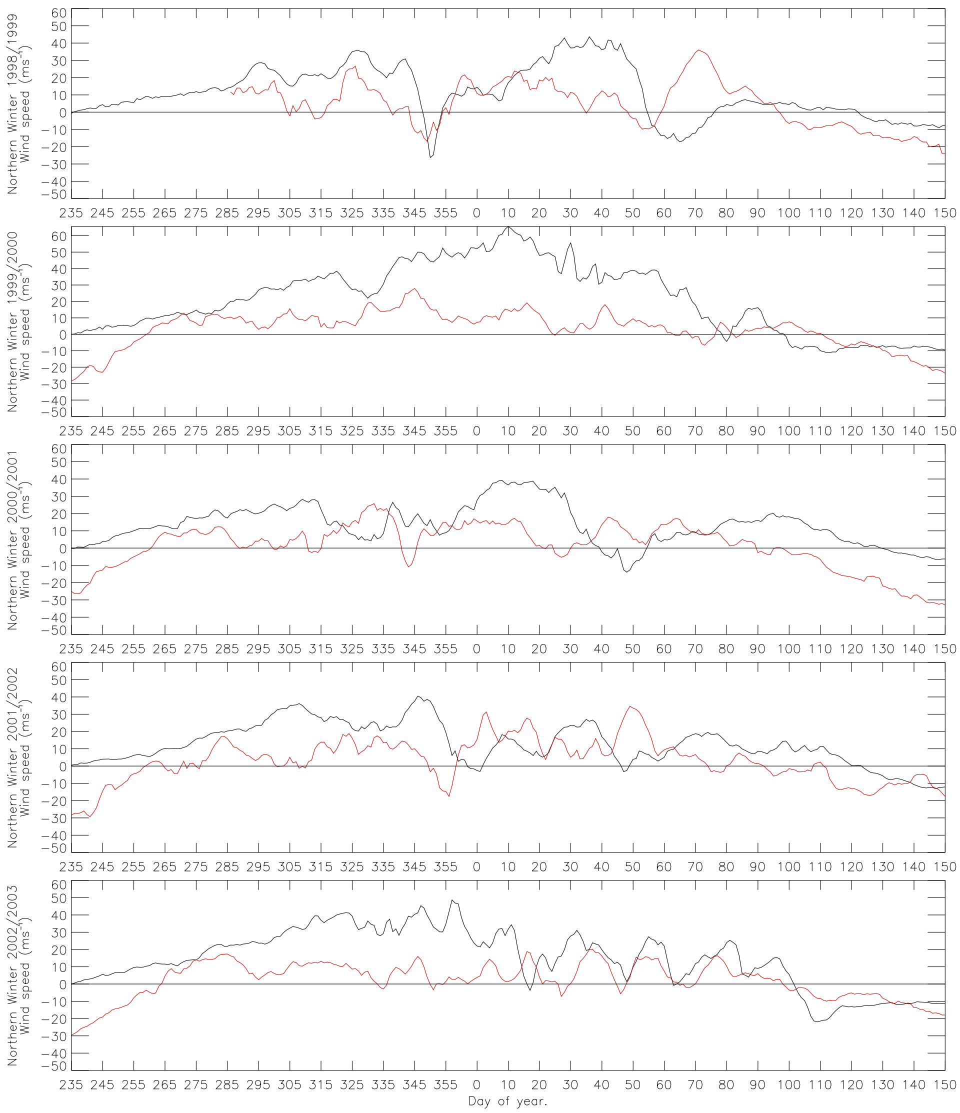

Figure 6.9: Zonal winds during the five northern winters for which Arctic MF radar data are available. Zonal-mean zonal winds are shown in black for UKMO data at 10 hPa and 67°N, and in red for MF radar zonal winds at 80 km with a 5-day running mean applied averaged for Poker Flat and Andenes. Data are shown in days from January 1.

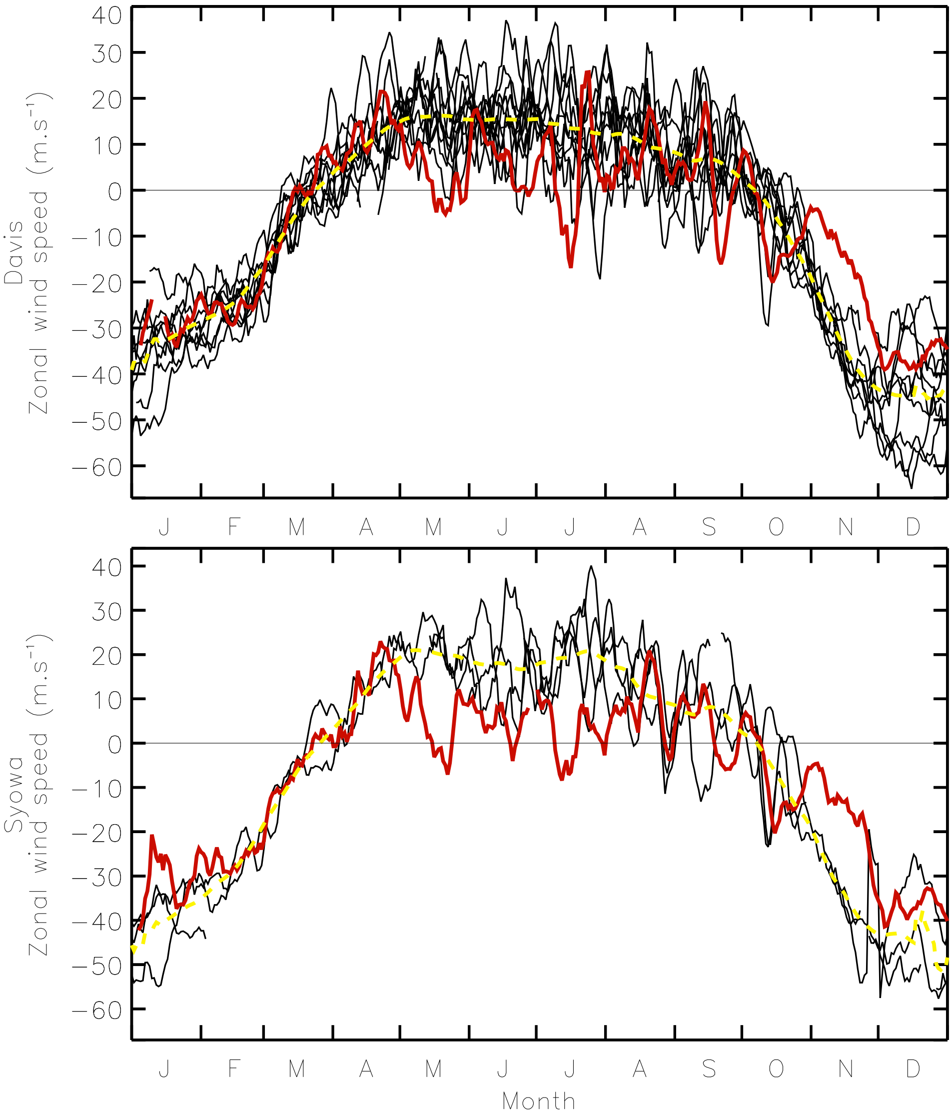

Figure 6.10: Zonal winds at 80 km for Davis and Syowa with a 5-day running mean applied. The red lines represent data for 2002, and the black lines represent data for other years. The long-term average values (excluding 2002) are indicated by the dashed lines.

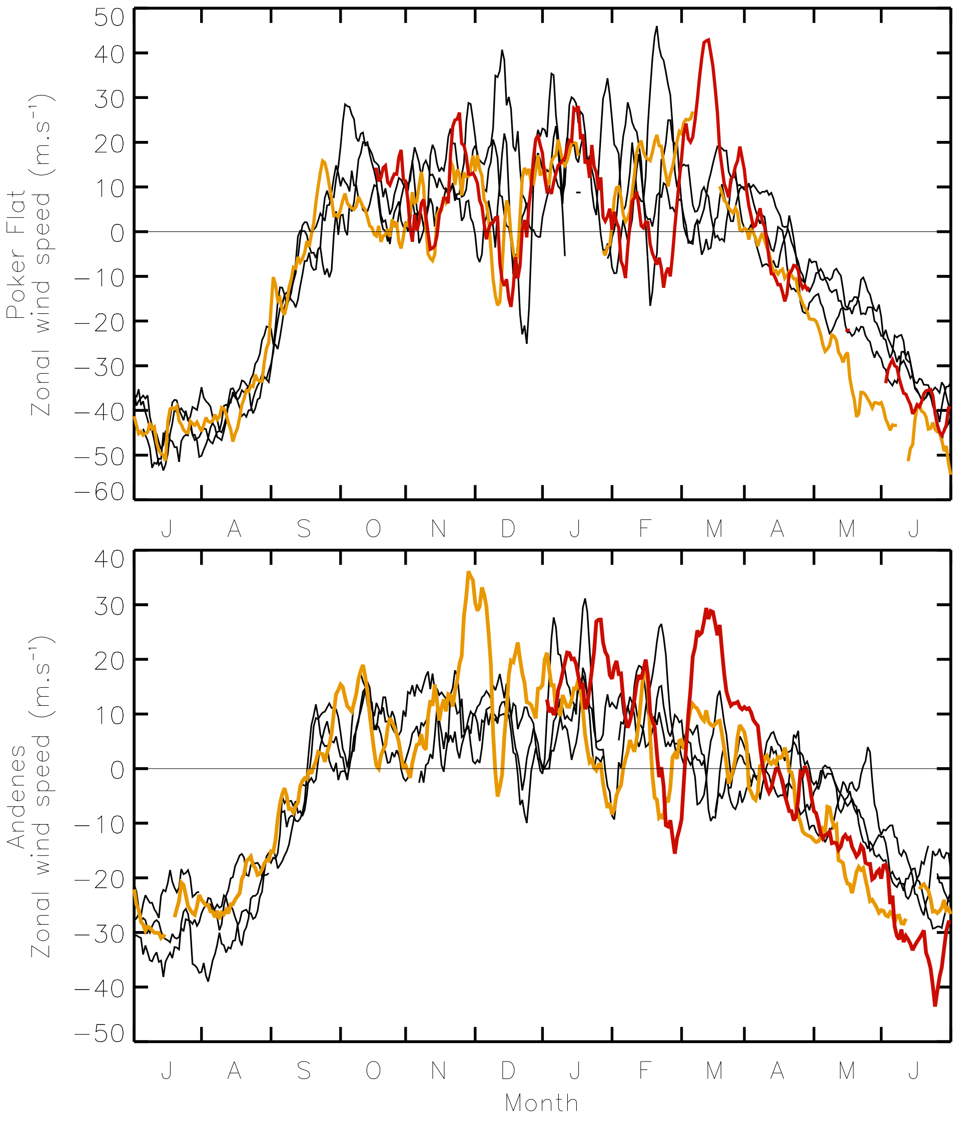

Figure 6.11: Zonal winds at 80 km for Poker Flat and Andenes, with the winters that had a large major stratospheric warming shown as a coloured line (red: 1998/1999, orange: 2000/2001). The black lines represent data for other winters. A 5-day running mean is applied.

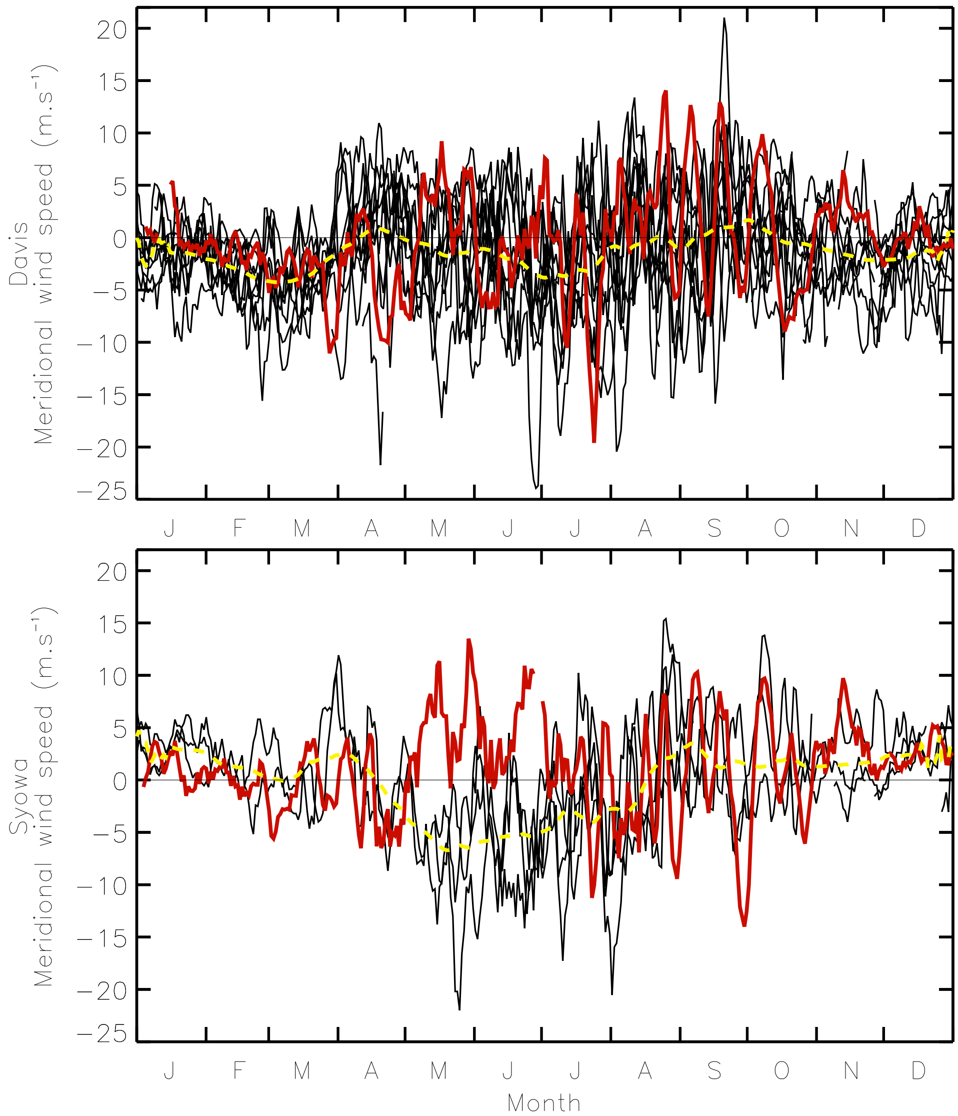

Figure 6.12: As for Figure 6.10, but for daily average meridional winds.

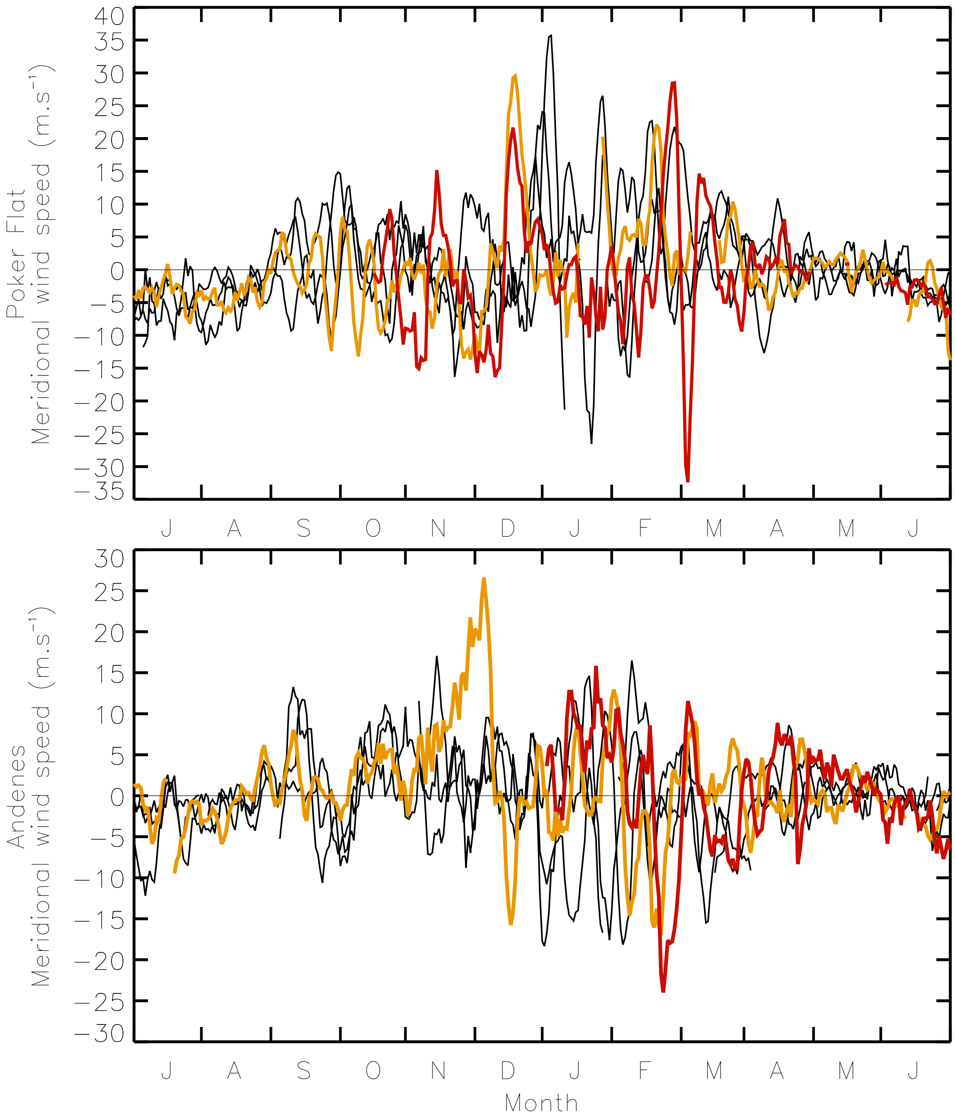

Figure 6.13: As for Figure 6.11, but for daily average meridional winds.

Chapter 7

Gravity waves during major warmings

In Chapters 5 and 6, it was found that major stratospheric warmings can have a strong influence on the mean winds in both the Arctic and Antarctic MLT regions. This chapter investigates the effects that major stratospheric warmings have on gravity wave activity in the MLT region. Changes in magnitude, spectral content and polarisation are investigated around the times of major stratospheric warmings in both hemispheres.

The gravity wave fields around the time of major stratospheric warmings are compared with the climatological means investigated in Chapter 4. The response of the mean winds to stratospheric warmings (from Chapters 5 and 6) is used to aid in interpreting the gravity wave observations. Mechanisms that could affect the gravity wave field in the MLT are discussed, such as changes in wave dissipation caused by changes in the stratospheric winds.

7.1 Gravity waves during the southern major warming

The large increase in gravity wave amplitude with height makes it difficult to detail small temporal changes in wind variance. To overcome this, the percentage difference from the mean at a particular height is used. This quantity, $\delta(d, h)$, is defined here as:

$$\delta(d,h) = \frac{x(d,h) - \overline{x(h)}}{\overline{x(h)}}$$

where: $x(d, h)$ is the variance on day, d, at height, h,
and $\overline{x(h)}$ is the mean variance at height, h, for the given time period.

Although plotting this quantity enhances rapid changes in variance strength, it also emphasises seasonal changes due to the long time period used to create the average $\overline{x(h)}$. Seasonal variations are therefore important to keep in mind when looking for the effects of sudden stratospheric warmings when using this quantity.

7.1.1 Gravity waves in the period range 20-120 minutes

The quantity $\delta(d, h)$ is shown at the time of the southern hemisphere major warming in Figure 7.1 for the period ranges 20-120 minutes. A 5-day and 4-km running mean is applied. The starting and ending dates of the major stratospheric warming are shown as dotted lines (from the zonal-mean zonal wind reversal at 10 hPa and 68°S).

A significant reduction in variance strength is apparent from Figure 7.1 at Davis coincident with the time of the major stratospheric warming. The reduction is stronger at lower altitudes. Quantitatively, the percentage reduction (on average from 80-90 km) during the major warming is 24% and 23% for the zonal and meridional variances, respectively, as compared to the mean of other values during September and October.

The wave field at Syowa is significantly different to that at Davis. A reduction in variance strength is not observed at Syowa during the major warming indicating that mesospheric gravity wave activity during major stratospheric warmings can vary significantly even over relatively short distances.

Oscillations in variance strength occur leading up to the warming event in late September at both Davis and Syowa. These oscillations are often in phase vertically over large height ranges. The oscillations often appear to have a periodicity of about 2 weeks, which is similar to the periodicity observed in the mesospheric wind speeds at this time (see Chapter 6). There are also indications at times of shorter period oscillations of about 1 week.

7.1.2 Gravity waves in the period range 120-480 minutes

Figure 7.2 is similar to Figure 7.1, but for the longer period variances (in the range 120-480 minutes).

The reduction in wave activity coincident with the major warming is very strong at Davis for this period range (about twice as strong as for the shorter period range). The reduction is generally larger at lower heights (as was seen for the shorter period waves), and larger for the zonal variances than for the meridional variances.

The percentage reduction (on average from 80-90 km) during the major warming is 49% and 51% for the zonal and meridional variances, respectively, as compared to other values during September and October. This is not seen at Syowa, as was the case for the shorter period range.

Oscillations in the variances strength occur, with periods of about 2 weeks. Oscillations with periods of about 1 week can also be seen, for example at Davis around the start of September at heights from 80-90 km.

7.2 Gravity waves during northern major warmings

7.2.1 Gravity waves during the 1998/1999 winter

7.2.1.1 Gravity waves in the period range 20-120 minutes

The quantity $\delta(d, h)$ is shown during the 1998/1999 northern winter in Figure 7.3 for the period range 20-120 minutes. A 5-day and 4-km running mean is applied. The starting and ending dates of the December 1998 and February 1999 major stratospheric warmings (from Table 6.1) are shown as dotted lines.

As was seen around the time of the southern major warming event, the changes in variance strength often show periodic behaviour that is coherent over large height ranges.

A reduction in the zonal and meridional variance strength occurs at Poker Flat about a week after the beginning of the December 1998 major stratospheric warming. It is not clear whether of not this reduction is related to the stratospheric warming event. The reduction is strongest at the lower heights as was also seen at Davis during the southern hemisphere event.

A reduction occurs for both the zonal and meridional variances at Poker Flat that is coincident with the start of the February 1999 major warming (once again being stronger at the lower heights). This reduction does not persist throughout the entire length (24 days) of the major stratospheric warming, lasting only for about 2 weeks. A reduction in gravity wave activity at Andenes may possibly be occurring during the February 1999 major stratospheric warming at heights below about 90 km, although this is unclear and may relate to seasonal variations.

7.2.1.2 Gravity waves in the period range 120-480 minutes

Figure 7.4 is similar to Figure 7.3, but for the longer period variances (in the range 120-480 minutes).

The reduction in variance strength at Poker Flat in December 1998 is similar to that observed for the shorter period variances, although it is not significantly stronger at lower heights and is more coincident in timing to the December major stratospheric warming. The timing of the reduction is almost exactly coincident with the stratwarm at heights above about 80 km for both the zonal and meridional variances, and shows some downward phase progression, occurring later at lower heights.

Another contrast to the shorter period variances is that the reduction at Poker Flat around the start of the February 1999 major stratospheric warming appears to persist throughout the entire duration of this event.

The change in wave activity at Andenes appears to be similar to that observed for the shorter period variances, with the exception that the reduction generally occurs at all heights rather than being confined to the lower altitudes. It is once again not entirely clear how much of the reductions at Poker Flat and Andenes relate to seasonal variations and how much relate to the influence of stratospheric warmings.

7.2.2 Gravity waves during the 2000/2001 winter

7.2.2.1 Gravity waves in the period range 20-120 minutes

The quantity $\delta(d,h)$ is shown during the 2000/2001 northern winter in Figure 7.5 for the period ranges 20-120 minutes. A 5-day and 4-km running mean is applied. The starting and ending dates of the February 2001 major stratospheric warming (from Table 6.1) are shown as dotted lines.

The data gaps present at Poker Flat in January and March make it difficult to observe changes in wind variance around the time of the February 2001 major stratospheric warming. The variances at Andenes appear to be relatively normal around the time of this event. Some vertically coherent structures can be seen with periods of about 2 weeks such as above about 80 km in January and February for the zonal variances, and for both the zonal and meridional variances in March.

7.2.2.2 Gravity waves in the period range 120-480 minutes

The variances at Andenes show strong reductions at heights beneath about 84 km that begin and end at about the same time as the February 2002 major warming. The reductions are much stronger than observed for the shorter period variances during this time period at Andenes. It appears to be a relatively common feature that the observed reductions are larger at lower heights.

7.3 Comparisons between major warmings and climatologies

7.3.1 Southern hemisphere comparisons with climatologies

Variances at Davis and Syowa are shown in Figures 7.7 and 7.8 at heights of 80 km and 90 km, respectively. Variances are shown for the entire available period range (from 20-480 minutes), and consist of the sum of the zonal and meridional components with a 3-day and 4-km running mean applied. Data for 2002 are shown in red. All other years of available data are shown in black. The starting and ending dates of the major stratospheric warming event are shown as vertical dotted red lines.

The variances at Davis are generally weaker than average throughout the 2002 southern winter. This is true at both 80 km and 90 km, particularly in the months leading up to the major warming event, and is similar to what was observed at this time for the mesospheric mean zonal winds (see Chapter 6).

Large oscillations in the variance strength can be seen at Davis leading up to major warming, particularly at 90 km with a period of about 2 weeks (as was seen for the MLT meridional winds at this time in Chapter 6). The variances decrease suddenly at Davis during the major warming (at both heights). The variances at Syowa do not appear to be significantly weaker than average during the early winter, however they decrease in late July and remain relatively weak leading up to the major warming event.

7.3.2 Northern hemisphere comparisons with climatologies

Gravity wave variances obtained from the Arctic MF radars are shown at heights of 80 km and 90 km in Figures 7.9 and 7.10, respectively. Variances are shown for the entire available period range (from 20-480 minutes), and consist of the sum of the zonal and meridional components with a 3-day and 4-km running mean applied. Data for the 1998/1999 northern winter are shown in red, with the vertical red dotted lines indicating the beginning and end of the February 1999 major warming (from Table 6.1). Data for the 2000/2001 northern winter are shown in blue, with the vertical dotted blue lines indicating the beginning and end of the February 2001 major warming (from Table 6.1). All other northern winters of available data (1999/2000, 2001/2002 and 2002/2003) are shown in black.

The gravity wave activity during the northern winters for which large major warmings occur are not significantly weaker on average than other winters. This is in contrast to what is seen at Davis and Syowa leading up to the southern hemisphere major warming event.

7.4 Wave polarisation during major warmings

This section investigates the polarisation of the gravity wave field in the MLT around the times of major warmings. Wave polarisation is determined using the Stokes parameter method (as detailed in Section 4.6).

The covariances $\overline{u'v'}$ and the difference between the zonal and meridional variances $D = \overline{u'^2} - \overline{v'^2}$ in the MLT region were calculated for both period ranges 20-120 minutes and 120-480 minutes around the times of major warmings in both hemispheres and are shown in Appendix A.

7.4.1 Wave polarisation during the southern major warming

7.4.1.1 Wave polarisation in the period range 20-120 minutes.

The degree and angle of gravity wave polarisation at Davis and Syowa were calculated from the Stokes parameters around the times of the September 2002 southern hemisphere major stratospheric warming. These quantities are shown for waves in the period range 20-120 minutes in Figures 7.11 and 7.12 averaged over the height ranges 76-84 km and 86-94 km, respectively.

There are well defined features evident in the time evolution of the degree and angle of wave polarisation. The angle of polarisation changes from being more northward (or southward) to being more eastward (or westward) during the major stratospheric warming, with the only exception occurring at Syowa at the higher altitudes.

A maximum in wave polarisation is observed for the lower height range at Davis immediately prior to the stratospheric zonal wind reversal, reducing dramatically immediately after the event. This does not occur for the higher height range or at Syowa for either height range. There appears to be some periodicity (∼4 weeks) in both degree and angle of polarisation at Davis and Syowa in the higher altitudes (Figure 7.12).

7.4.1.2 Wave polarisation in the period range 120-480 minutes.

Figures 7.13 and 7.14 are similar to Figures 7.11 and 7.12, but for wave motions in the longer period range 120-480 minutes. The time evolution of the degree of polarisation of the longer period waves shows some similarities as well as some differences to what was observed for the shorter period range waves.

The longer period variances change from being oriented in a northward (or southward) direction to being more eastward (or westward) during the major stratosphric warming. This is true for both height ranges at both davs and Syowa.

The degree of polarisation peaks in mid-November (just prior to the stratospheric zonal wind reversal) with ∼25% at Davis and ∼20% at Syowa for the 76-84 km height range, oriented in a direction slightly east of north. This peak is more coincident with the timing of the zonal wind reversal in the MLT which was found (in Chapter 6) to occur about 5 days earlier than in the stratosphere. The degree of polarisation reduces by a factor of ∼10 to be ∼2% at the end of September immediately after the warming.

7.4.1.3 Critical level filtering

Figure 7.15 shows regions of forbidden phase speeds due to critical level filtering resulting from the background wind profiles (also shown). MF radar winds are shown at heights above 60 km, with UKMO winds at lower altitudes. The winds are averaged during the time of the zonal-mean zonal wind reversal at 68°S at 10 hPa associated with the September 2002 major stratospheric warming (see Figure 6.8).

The regions of excluded phase speeds are quite different between Davis and Syowa due to the stronger westward stratospheric wind reversal during this time at Syowa. The winds exclude phase speeds which are oriented in a more south-west direction at Syowa as compared with a more southward direction at Davis. This may account for some of the differences observed between the gravity wave fields at Davis and Syowa around the time of the major warming.

7.4.2 Wave polarisation during northern major warmings

Appendix B shows plots of the degree of polarisation and angle of polarisation for the northern hemisphere locations around the times of the strong northern major stratospheric warmings (during the 1998/1999 and 2000/2001 northern winters). As was seen for the southern hemisphere locations, well defined variations in wave polarisation are evident at the northern hemisphere locations of Poker Flat and Andenes.

The variations in wave polarisation around the time of the major warmings show some similarities to what was observed for the southern hemisphere major warming. Oscillations in the angle of polarisation can be seen at various times, as well as rapid and large fluctuations of the degree of polarisation.

The features present at the northern hemisphere locations for the wave polarisations are not very consistent between either the individual major warming events, locations, wave period ranges or height ranges. It appears that the effect of major stratospheric warmings on gravity wave polarisation in the mesosphere is variable and difficult to classify.

7.5 Stratospheric winds and MLT gravity waves

7.5.1 Antarctic stratospheric winds and MLT gravity waves

The connection between stratospheric winds and gravity waves in the MLT during the 2002 southern winter is investigated in this section. MF radar wind variances are plotted against stratospheric wind speeds from the UKMO assimilated data set at 10 hPa (see Appendix C). This is done at Davis and Syowa for both the zonal and meridional variances averaged in 2 different height ranges (76-84 km and 86-94 km), and also for both period ranges (20-120 minutes and 120-480 minutes) and both the zonal and meridional stratospheric winds individually. Data are shown in red during the major stratospheric warming and in black for the rest of winter.

Table 7.1 summarises the correlations between the stratospheric winds and the gravity wave activity in the MLT. The 99% significance level from Student's t-test is 0.195. This is assuming that the daily values are independent of each other which may not always be the case (for example planetary wave induced stratospheric wind oscillations could reduce the number of degrees of freedom at times).

The correlation coefficients are greater than the 99% significance level at Davis and Syowa in almost all cases. The only exceptions occur for the short period zonal variances at Syowa which are not always significantly correlated with the stratospheric winds.

Location	Variance direction	Period range (minutes)	Height range (km)	Correlation with zonal stratospheric winds	Correlation with meridional stratospheric winds
Davis	zonal	20-120	76-84	0.39	0.20
Davis	zonal	20-120	86-94	0.46	0.24
Davis	zonal	120-480	76-84	0.29	0.29
Davis	zonal	120-480	86-94	0.41	0.27
Davis	meridional	20-120	76-84	0.41	0.33
Davis	meridional	20-120	86-94	0.45	0.21
Davis	meridional	120-480	76-84	0.39	0.43
Davis	meridional	120-480	86-94	0.47	0.38
Syowa	zonal	20-120	76-84	0.04	0.21
Syowa	zonal	20-120	86-94	0.22	0.26
Syowa	zonal	120-480	76-84	0.12	0.37
Syowa	zonal	120-480	86-94	0.23	0.189
Syowa	meridional	20-120	76-84	0.04	0.18
Syowa	meridional	20-120	86-94	0.08	0.30
Syowa	meridional	120-480	76-84	0.20	0.34
Syowa	meridional	120-480	86-94	0.27	0.22

Table 7.1: Correlation coefficients between the stratospheric winds at 10 hPa (from UKMO data) and MF radar wind variances at Davis and Syowa during the 2002 winter (May, June, July, August and September).

7.5.2 Arctic stratospheric winds and MLT gravity waves

Similar plots to Appendix C are shown in Appendices D and E for the northern winter months (November, December, January, February and March) during 1999 and 2001, respectively. The correlation coefficients between the variances in the MLT and the stratospheric winds are shown for the Arctic locations in Tables 7.2 and 7.3 for 1999 and 2001, respectively.

The variances are generally significantly correlated with the zonal stratospheric winds but not with the meridional stratospheric winds during 1999 (from Table 7.2). This is not seen for 2001 (Table 7.3), where significant and insignificant correlation exist for both stratospheric wind directions.

Location	Variance direction	Period range (minutes)	Height range (km)	Correlation with zonal stratospheric winds	Correlation with meridional stratospheric winds
Poker Flat	zonal	20-120	76-84	0.18	0.136
Poker Flat	zonal	20-120	86-94	0.21	-0.08
Poker Flat	zonal	120-480	76-84	0.39	0.09
Poker Flat	zonal	120-480	86-94	0.18	0.11
Poker Flat	meridional	20-120	76-84	0.38	0.03
Poker Flat	meridional	20-120	86-94	0.20	0.00
Poker Flat	meridional	120-480	76-84	0.41	0.03
Poker Flat	meridional	120-480	86-94	0.32	0.07
Andenes	zonal	20-120	76-84	0.24	-0.12
Andenes	zonal	20-120	86-94	0.33	0.16
Andenes	zonal	120-480	76-84	0.44	-0.06
Andenes	zonal	120-480	86-94	0.29	0.15
Andenes	meridional	20-120	76-84	0.30	-0.14
Andenes	meridional	20-120	86-94	0.31	-0.04
Andenes	meridional	120-480	76-84	0.30	-0.25
Andenes	meridional	120-480	86-94	0.21	-0.07

Table 7.2: Correlation coefficients between the stratospheric winds at 10 hPa (from UKMO data) and MF radar wind variances at Poker Flat and Andenes during the 1999 winter months (January, February, March, November and December).

7.6 Discussion and summary

The effect of large major stratospheric warmings on gravity wave acivity in the MLT was investigated in this chapter. It can be concluded that major stratospheric warmings can have a large effect on gravity wave motions in the MLT, but that these effects are not always consistent between warming events or geographic locations.

Significant periods of reduced ($\sim 25-50\%$) mesospheric gravity wave activity at Davis coincide with the September 2002 major stratospheric warming. The reduction is stronger for the longer period range than for the shorter period range, and is also stronger at lower heights.

Reductions are not observed at Syowa during the warming, showing that the effect of major stratospheric warmings on gravity wave activity can vary over relatively short distances. Significant differences between Davis and Syowa in stratospheric critical

Location	Variance direction	Period range (minutes)	Height range (km)	Correlation with zonal stratospheric winds	Correlation with meridional stratospheric winds
Poker Flat	zonal	20-120	76-84	0.39	0.40
Poker Flat	zonal	20-120	86-94	0.06	0.13
Poker Flat	zonal	120-480	76-84	0.54	0.22
Poker Flat	zonal	120-480	86-94	0.13	0.29
Poker Flat	meridional	20-120	76-84	0.42	0.30
Poker Flat	meridional	20-120	86-94	0.00	0.09
Poker Flat	meridional	120-480	76-84	0.51	0.21
Poker Flat	meridional	120-480	86-94	0.10	0.38
Andenes	zonal	20-120	76-84	0.22	-0.04
Andenes	zonal	20-120	86-94	0.04	0.07
Andenes	zonal	120-480	76-84	0.42	-0.01
Andenes	zonal	120-480	86-94	0.23	0.13
Andenes	meridional	20-120	76-84	0.26	0.03
Andenes	meridional	20-120	86-94	-0.12	-0.19
Andenes	meridional	120-480	76-84	0.31	0.04
Andenes	meridional	120-480	86-94	0.18	0.00

Table 7.3: Correlation coefficients between the stratospheric winds at 10 hPa (from UKMO data) and MF radar wind variances at Poker Flat and Andenes during the 2001 winter months (January, February, March, November and December).

level filtering were calculated during the major warming, which may account for the observed differences in gravity wave activity.

Some reductions in gravity wave activity occur at Poker Flat and Andenes around the times of the large northern major stratwarms, although it is not entirely clear how much relates to seasonal variations and how much relates to the influence of the stratospheric warmings. The reductions are generally stronger at lower heights (lower than about 84 km), similar to what occurs at Davis during the southern event.

The September 2002 southern major warming and the February 1999 and February 2001 northern major warmings are all at a time leading up to the spring minima in the climatological mean variance strength (see Chapter 4). The observed reductions will therefore be partly due to normal seasonal variations. However, this does not explain the abruptness of the changes in wave activity seen at Davis, or the reductions observed around the time of the December 1998 major warming.

The gravity wave activity around the times of the major warmings show periodic variations which are often in phase over large height ranges. These oscillations often have periods of about 2 weeks, and also about 1 week at times. The one week periodicity could arise through a period doubling effect. Due to the 180 degree ambiguity in gravity wave polarisation, planetary waves with periods of about 2 weeks (as were observed in Chapter 6) could cause periodic variations of about 1 week due to critical level filtering of gravity waves.

Variations in wave polarisation occur around the time of the southern hemisphere major warming. The direction of polarisation is variable, but generally changes from a more northward (or southward) orientation prior to the major stratospheric warming event, to a more eastward (or westward) polarisation during the event (with the exception of Syowa at higher altitudes in the short period range). The critical level filtering expected from the stratospheric winds during this time suggest that low phase speed waves would be excluded more in a southward direction at Davis and a southwest direction at Syowa.

The effect of northern hemisphere major stratospheric warmings on gravity wave polarisation is difficult to classify as considerable variation exist between the individual warming events.

A positive correlation was often found to exist between the stratospheric zonal wind speed and gravity wave activity in the winter MLT. This occurs in both the Arctic and the Antarctic, but is generally difficult to classify due to its variability.

The stratospheric vortex during the polar winter has been found to influence gravity wave activity at stratospheric heights in other studies. *Whiteway et al.* [1997] found that gravity wave activity was a maximum within the vortex jet and at the edge of the vortex, a minimum inside the vortex and intermediate outside the vortex. Rayleigh lidar studies during a stratospheric warming at Eureka, Canada (80°N, 86°W) found substantially greater dissipation of gravity wave energy during the warming than during the preceding and following periods [*Whiteway & Carswell*, 1994].

Duck et al. [1998] report increased gravity wave activity in the vortex jet during a stratospheric warming, and suggest that the decreased wave activity found by *Whiteway & Carswell* [1994] was in fact due to the movement of the polar vortex over Eureka so that Eureka was beneath the vortex core.

Ratnam et al. [2004] analysed gravity wave activity in the stratosphere on a global scale using the Challenging Minisatellite Payload (CHAMP) satellite, finding an enhancement of wave activity during the 2002 southern hemisphere major stratospheric warming. During the major warming the gravity wave potential energy was 3 times higher than usual near the edge and outside the polar vortex, but not inside the vortex.

These studies all suggest that the position of the vortex relative to a location plays a large role in determining the characteristics of the gravity wave fields during stratospheric warmings. A ray tracing analysis using the position of the vortex may provide further insight into the observations presented in this chapter although this is beyond the scope of this thesis.

The findings of *Ratnam et al.* [2004] appear to be the only published results so far on gravity wave activity during the southern hemisphere major warming, are only at heights up to 30 km. The results presented in this chapter are unique in that they investigate the effect of major warmings on gravity waves in both hemispheres, and also because this is done for gravity wave activity in the MLT.

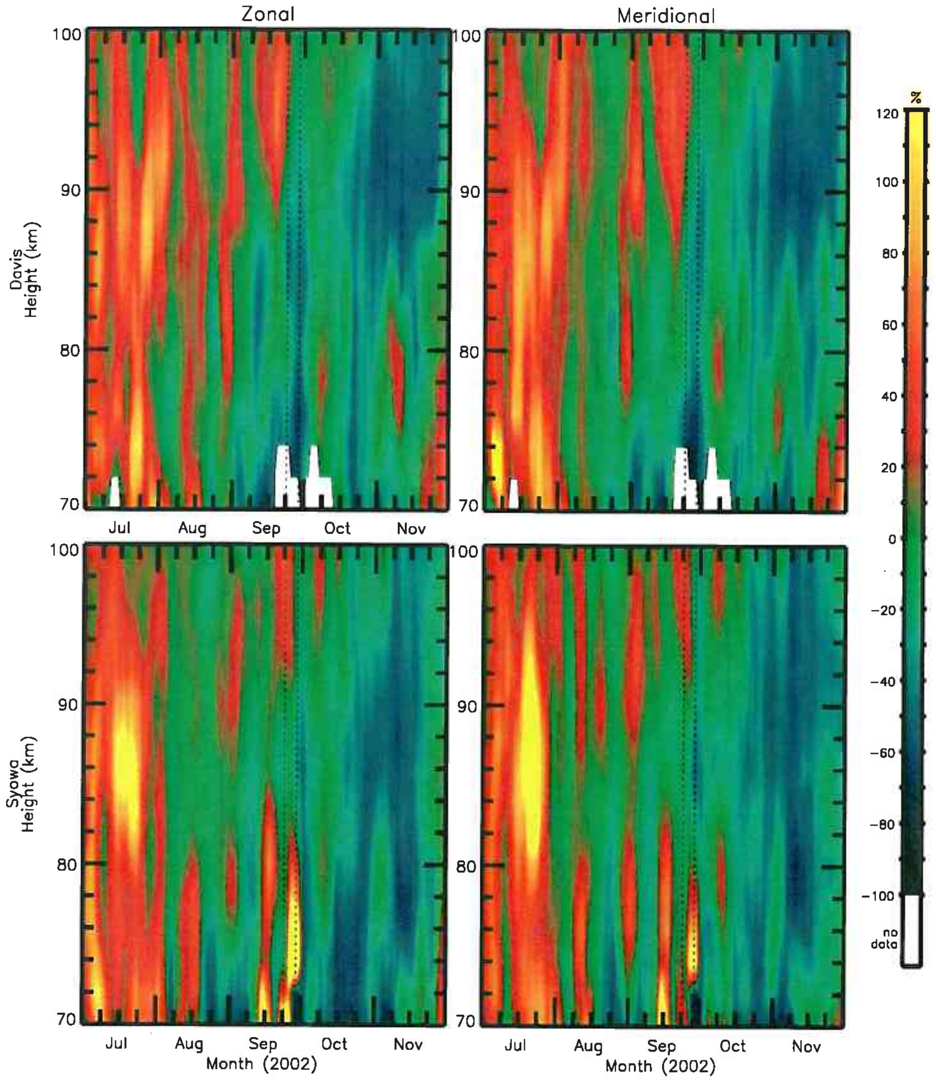

Figure 7.1: Percentage difference from the mean variance at a particular height shown for Davis and Syowa around the time of the southern hemisphere major stratospheric warming. Variances are in the period range 20-120 minutes, with a 5-day and 4-km running mean applied. The starting and ending dates of the zonal-mean zonal wind reversal at 68°S and 10 hPa from UKMO data are shown as dotted lines.

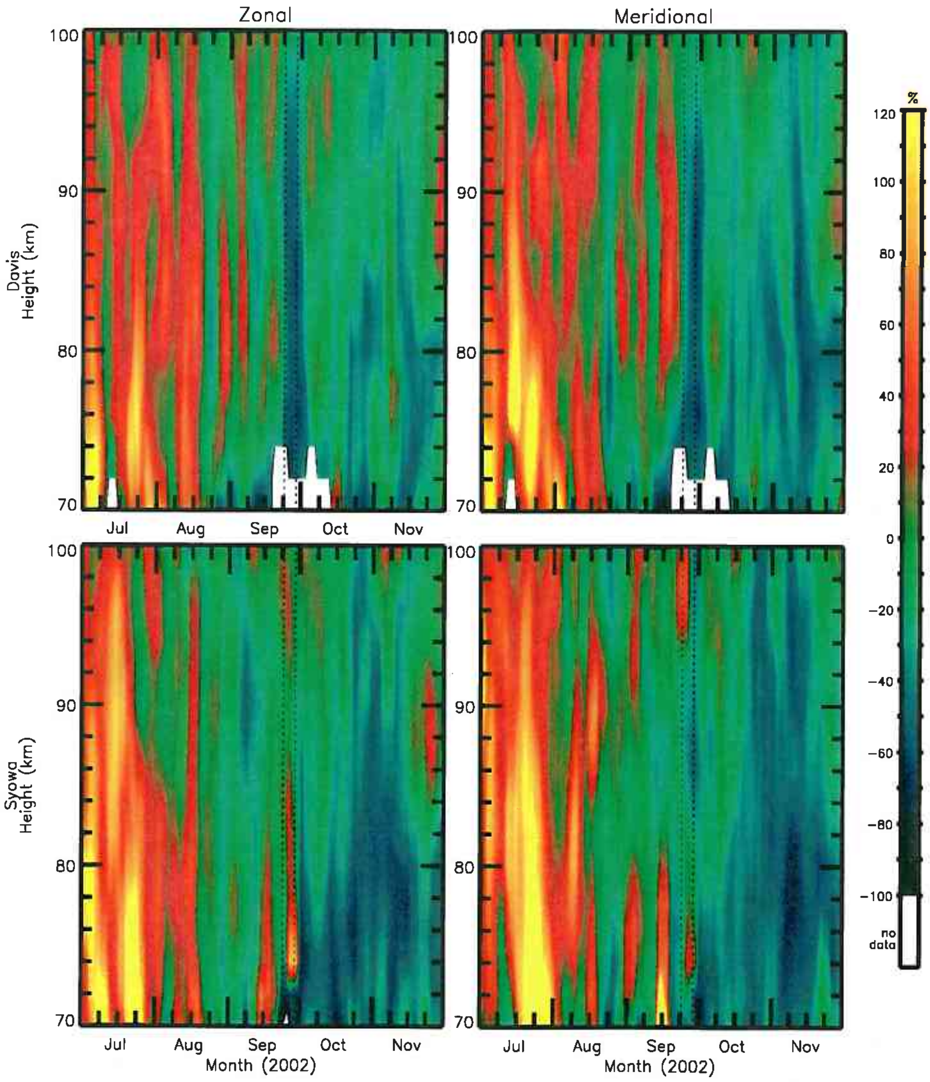

Figure 7.2: As for Figure 7.1, but for the period range 120-480 minutes.

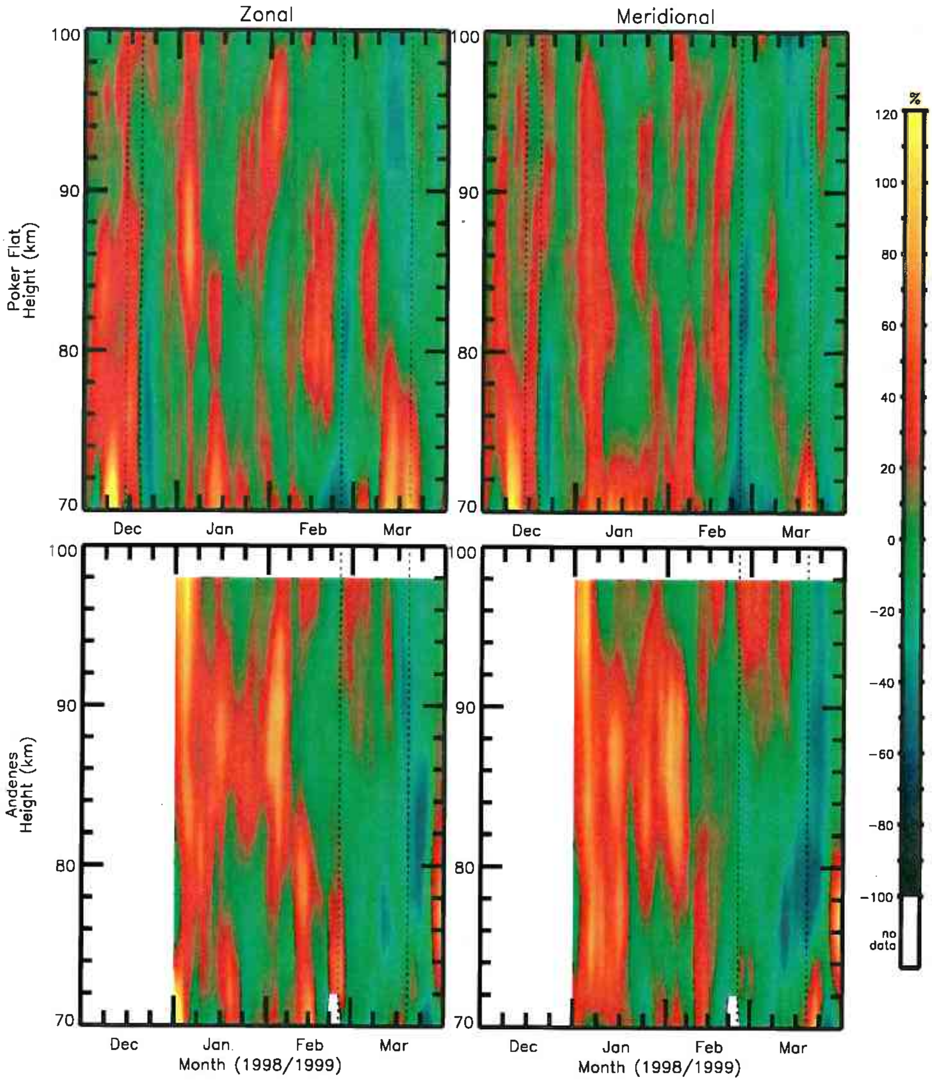

Figure 7.3: Percentage difference from the mean variance at a particular height shown for Poker Flat and Andenes during the 1998/1999 northern winter. Variances are shown in the period range 20-120 minutes with a 5-day and 4-km running mean applied. The starting and ending dates of the major stratospheric warmings (from Table 6.1) are shown as dotted lines for the December 1998 and February 1999 major stratospheric warmings.

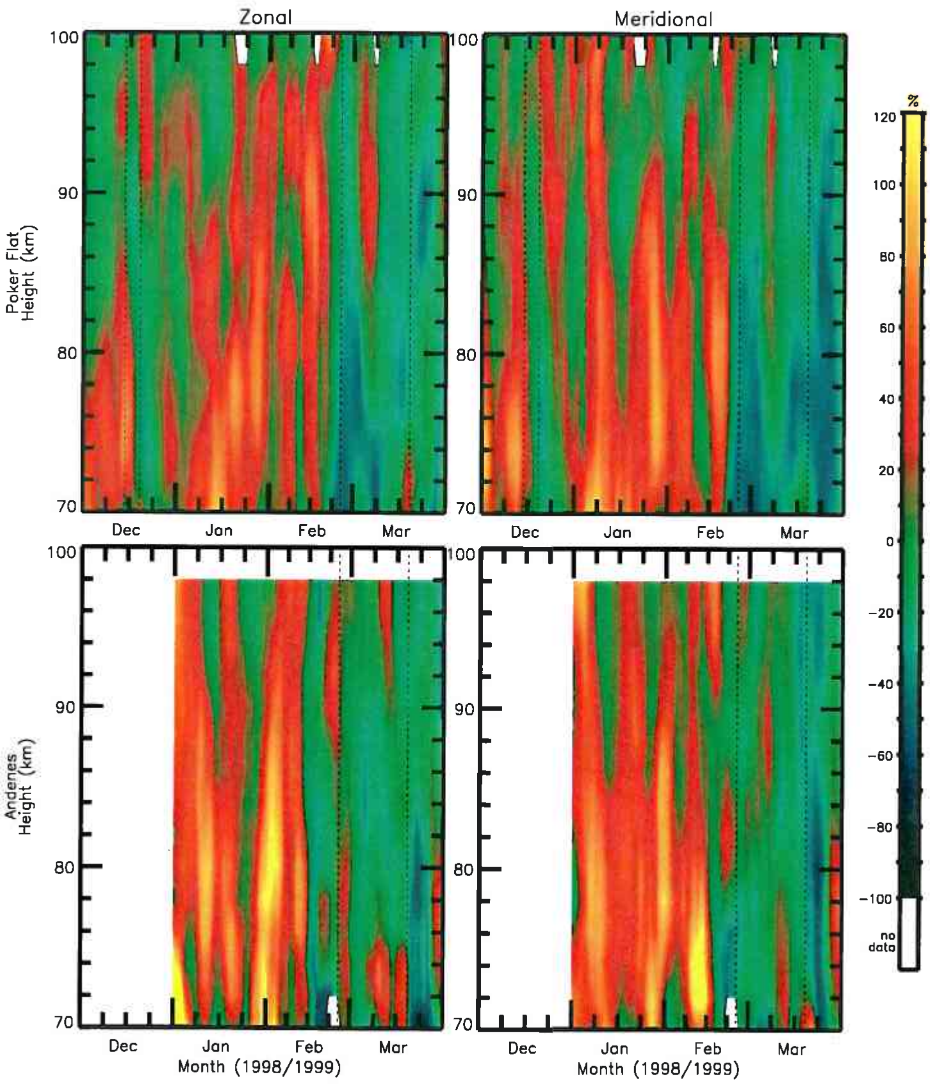

Figure 7.4: As for Figure 7.3, but for the period range 120-480 minutes.

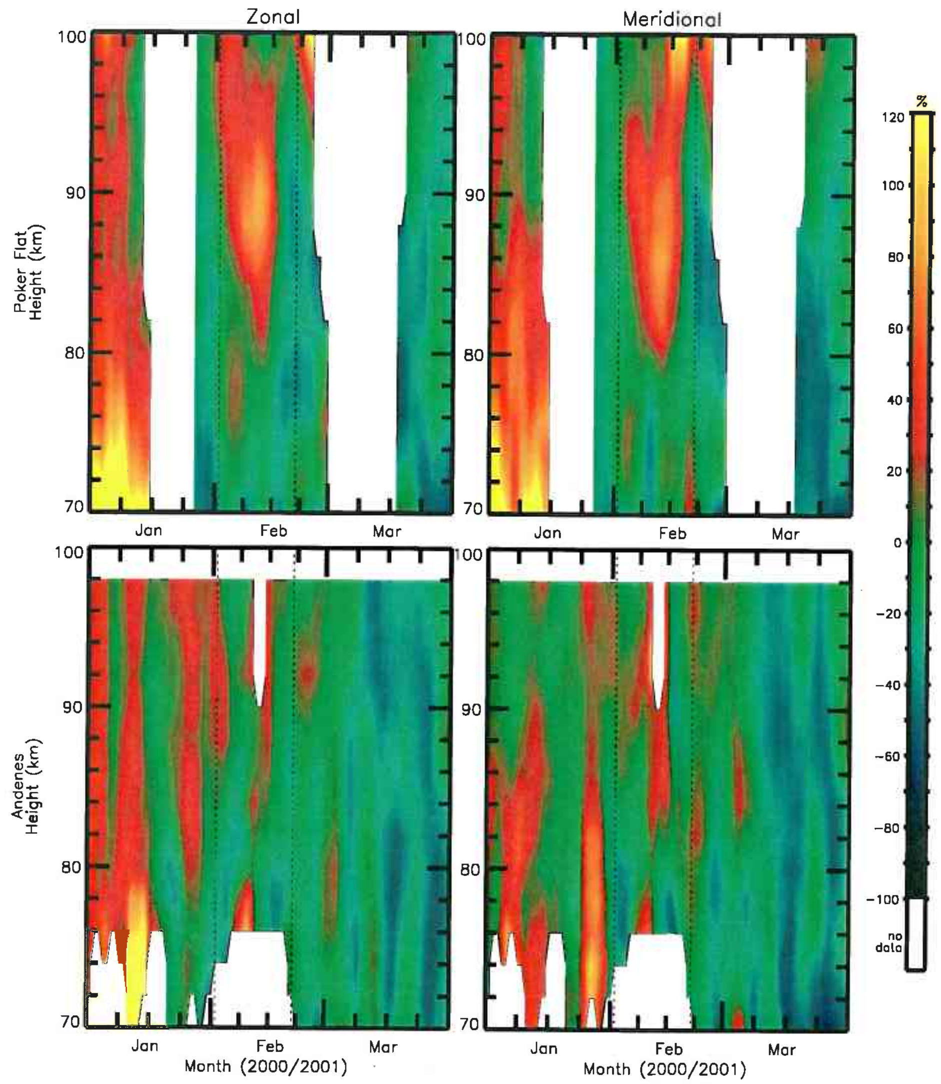

Figure 7.5: Percentage difference from the mean variance at a particular height shown for Poker Flat and Andenes during the 2000/2001 northern winter. Variances are shown in the period range 20-120 minutes, with a 5-day and 4-km running mean applied. The starting and ending dates of the February 2001 major stratospheric warming (from Table 6.1) are shown as dotted lines.

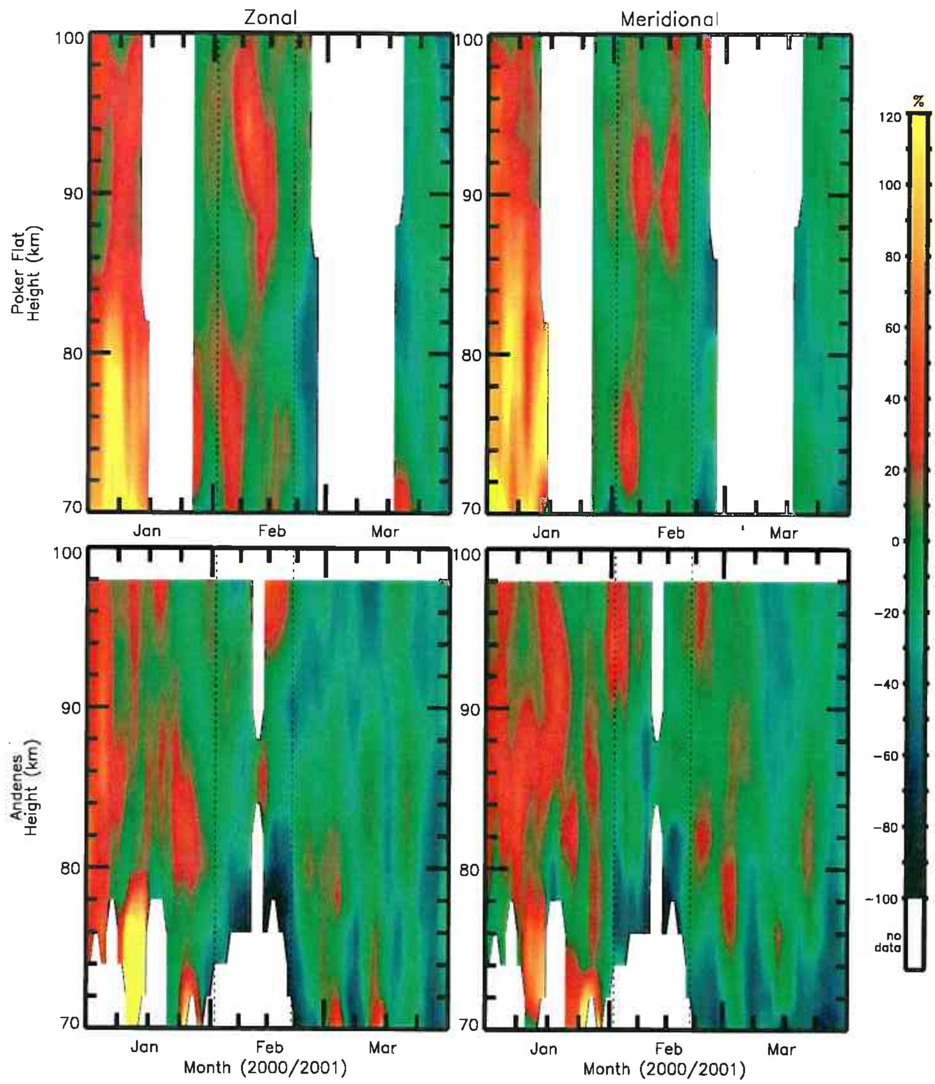

Figure 7.6: As for Figure 7.5, but for the period range 120-480 minutes.

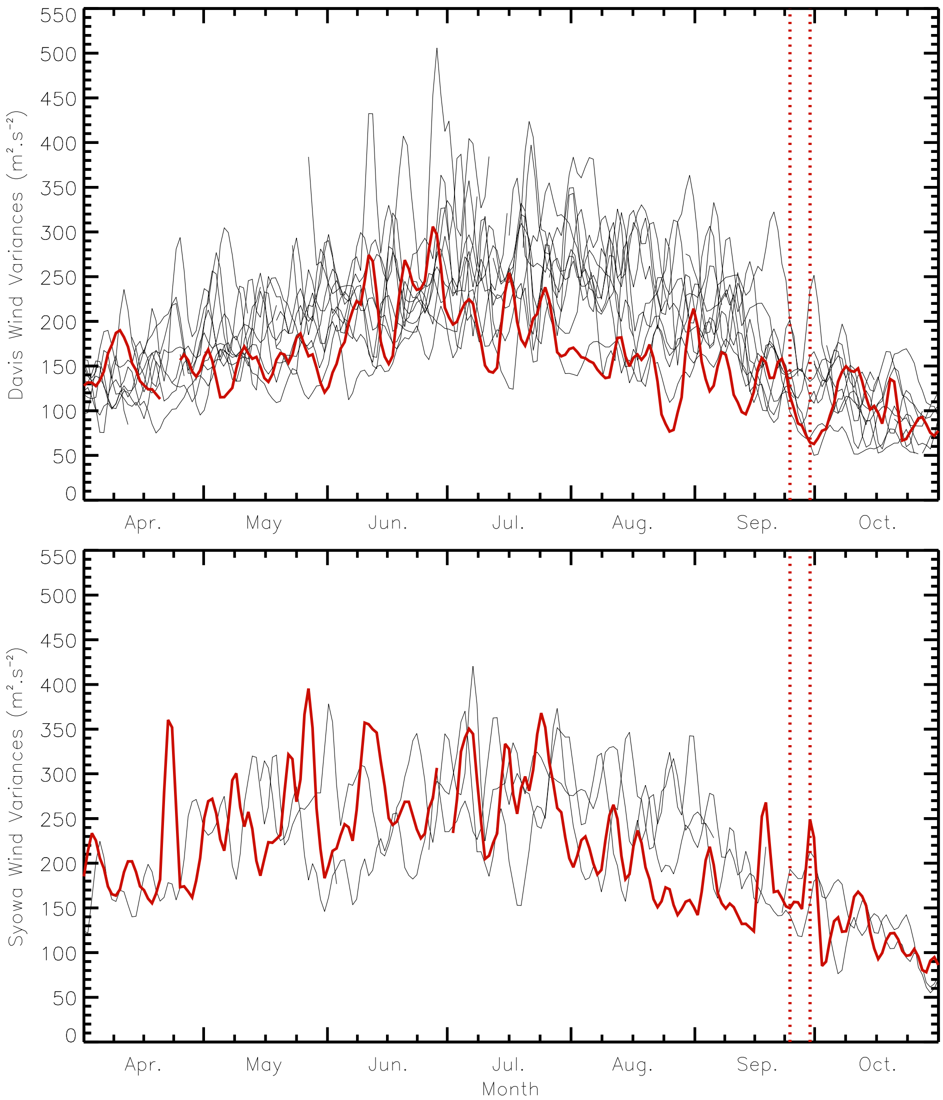

Figure 7.7: Variances at Davis and Syowa at a height of 80 km in the period range 20-480 minutes, consisting of the sum of the zonal and meridional components with a 3-day and 4-km running mean applied. Variances are shown in red for 2002. All other years of available data are shown in black. The starting and ending dates of the major stratospheric warming are shown as vertical dotted red lines.

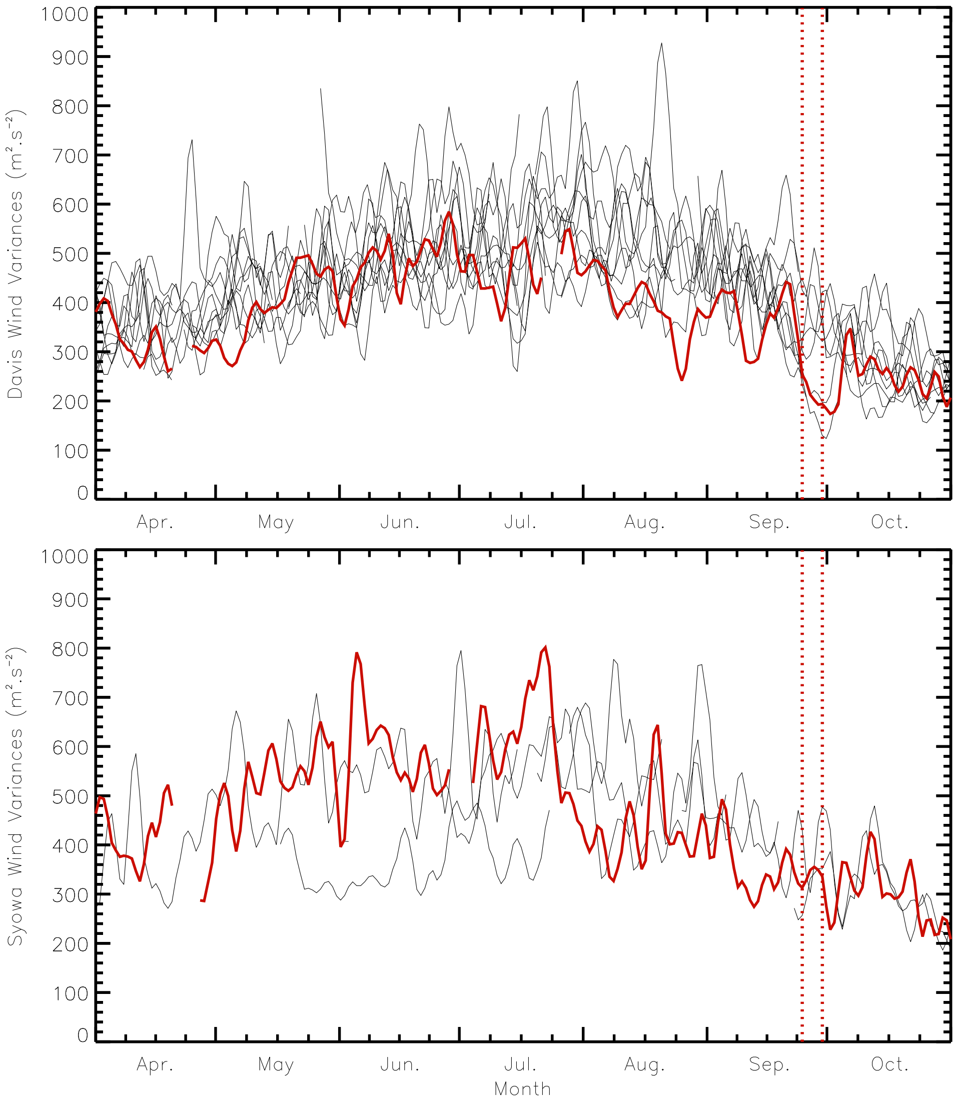

Figure 7.8: As for Figure 7.7, but for a height of 90 km.

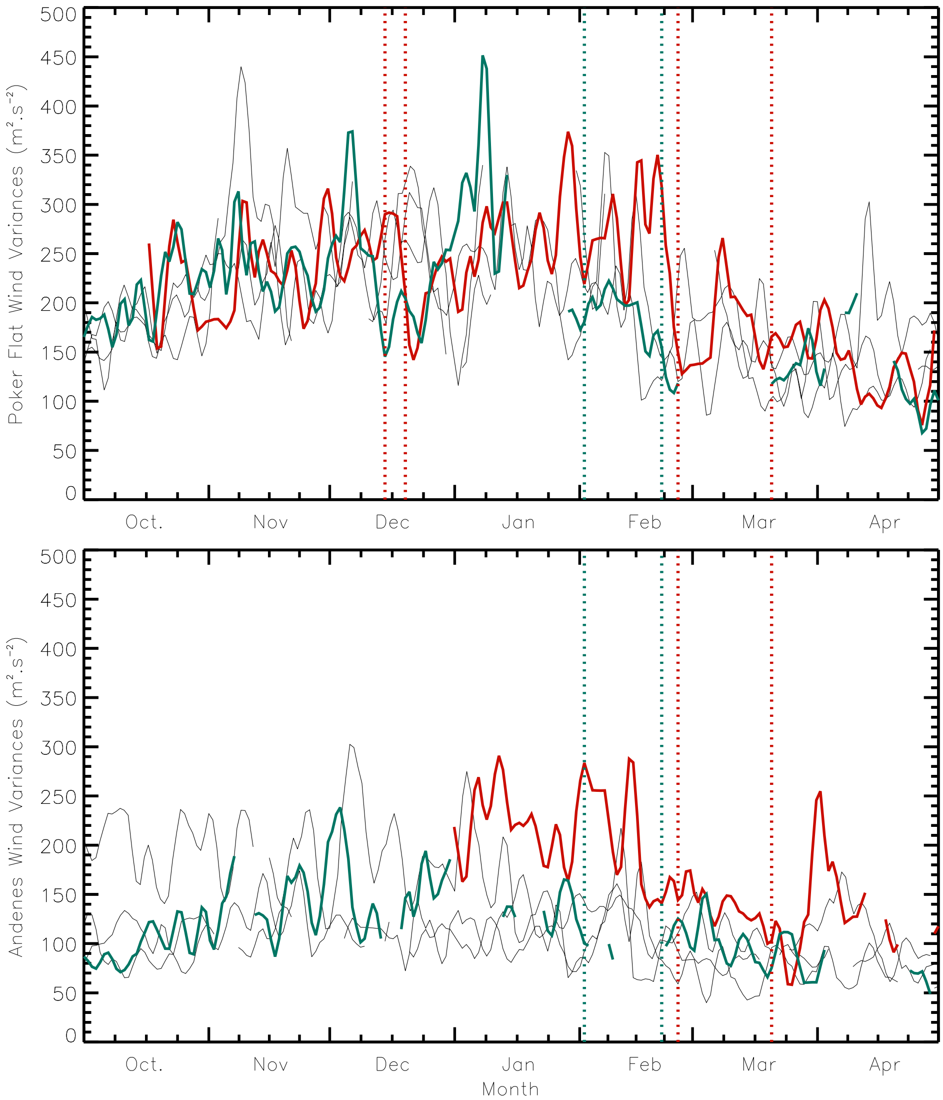

Figure 7.9: Variances at Poker Flat and Andenes at a height of 80 km in the period range 20-480 minutes, consisting of the sum of the zonal and meridional components with a 3-day and 4-km running mean applied. Variances are shown in red for the 1998/1999 northern winter, with vertical red dotted lines indicating the starting and ending dates of the December 1998 and February 1999 major stratospheric warmings (from Table 6.1). Variances are shown in blue for the 2000/2001 winter, with vertical blue dotted lines representing the starting and ending dates of the February 2001 major stratospheric warming (from Table 6.1). All other winters of available data are shown in black.

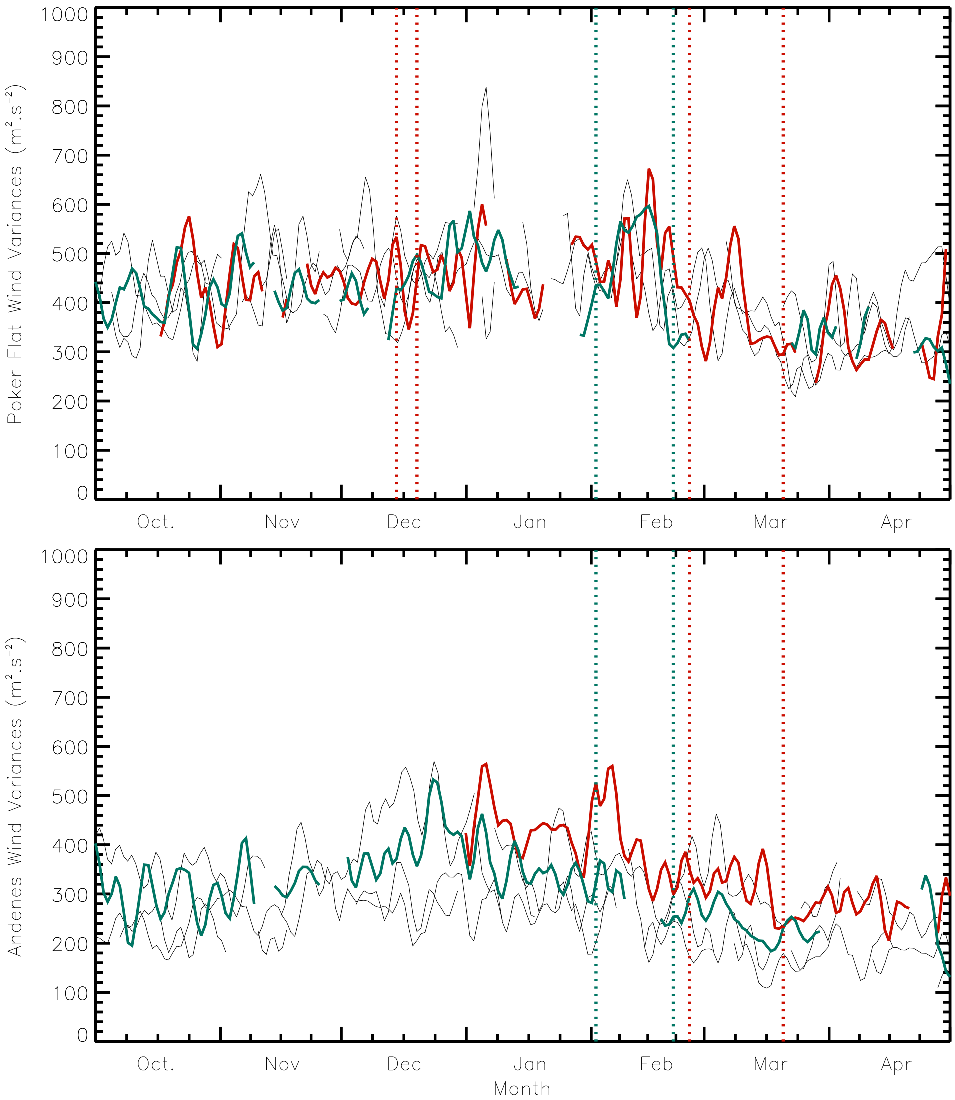

Figure 7.10: As for Figure 7.7, but for a height of 90 km.

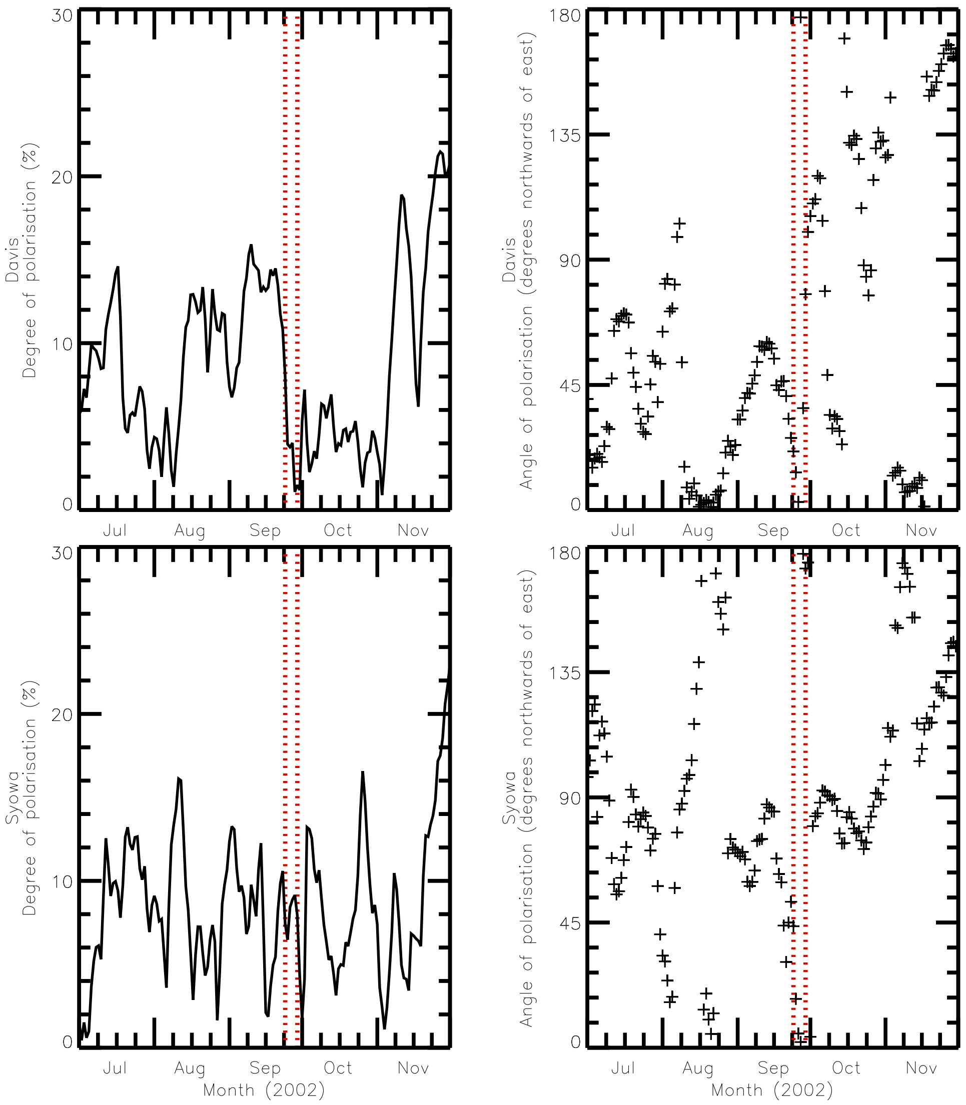

Figure 7.11: The degree and angle of wave polarisation at Davis and Syowa around the time of the 2002 major stratospheric warming. Variances and covariances used are in the period range 20-120 minutes, with a 7-day running mean applied and are averaged from 76-84 km. The dotted red lines indicate the starting and ending of the stratospheric zonal-mean zonal wind reversals at 68°S and 10 hPa (from UKMO data).

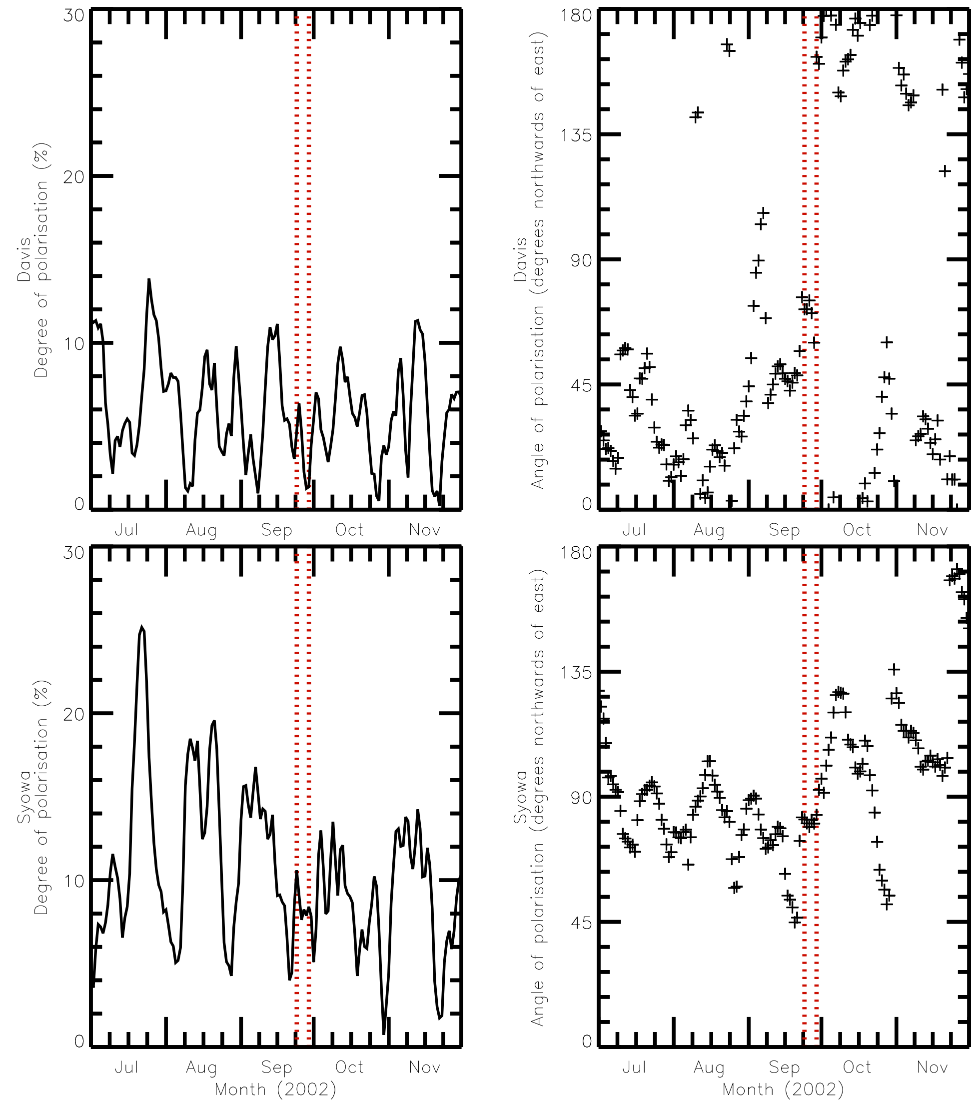

Figure 7.12: As for Figure 7.11, but for the height range 86-94 km.

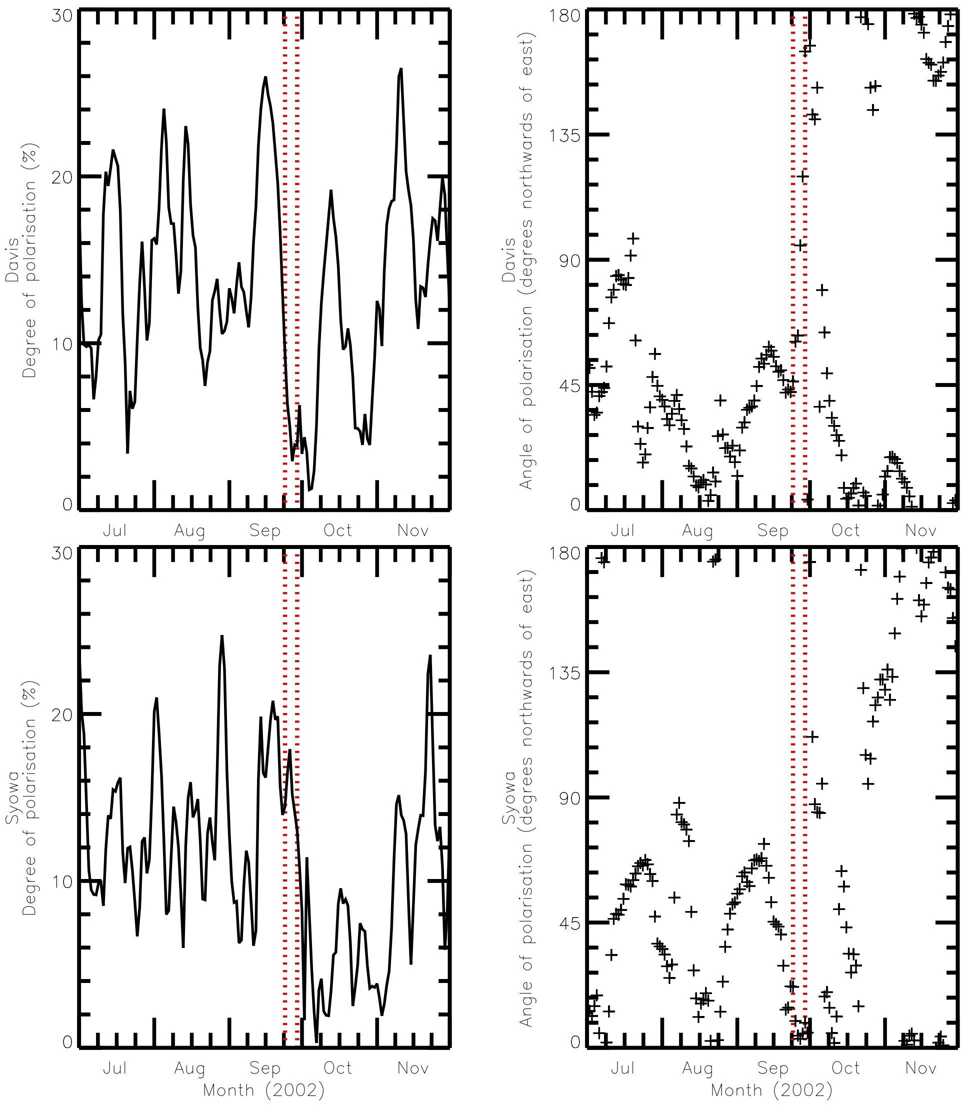

Figure 7.13: As for Figure 7.11, but for the period range 20-120 minutes in the height range 76-84 km.

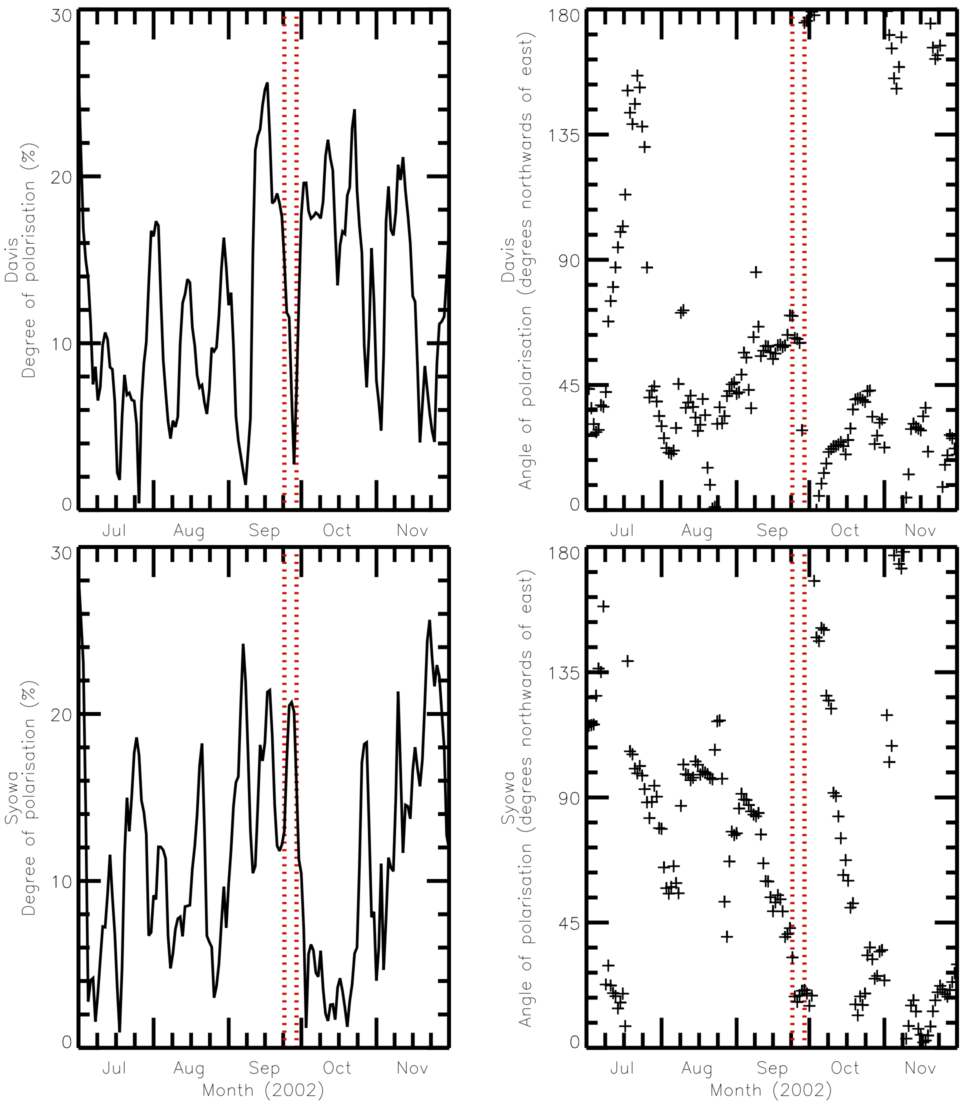

Figure 7.14: As for Figure 7.11, but for the period range 20-120 minutes in the height range 86-94 km.

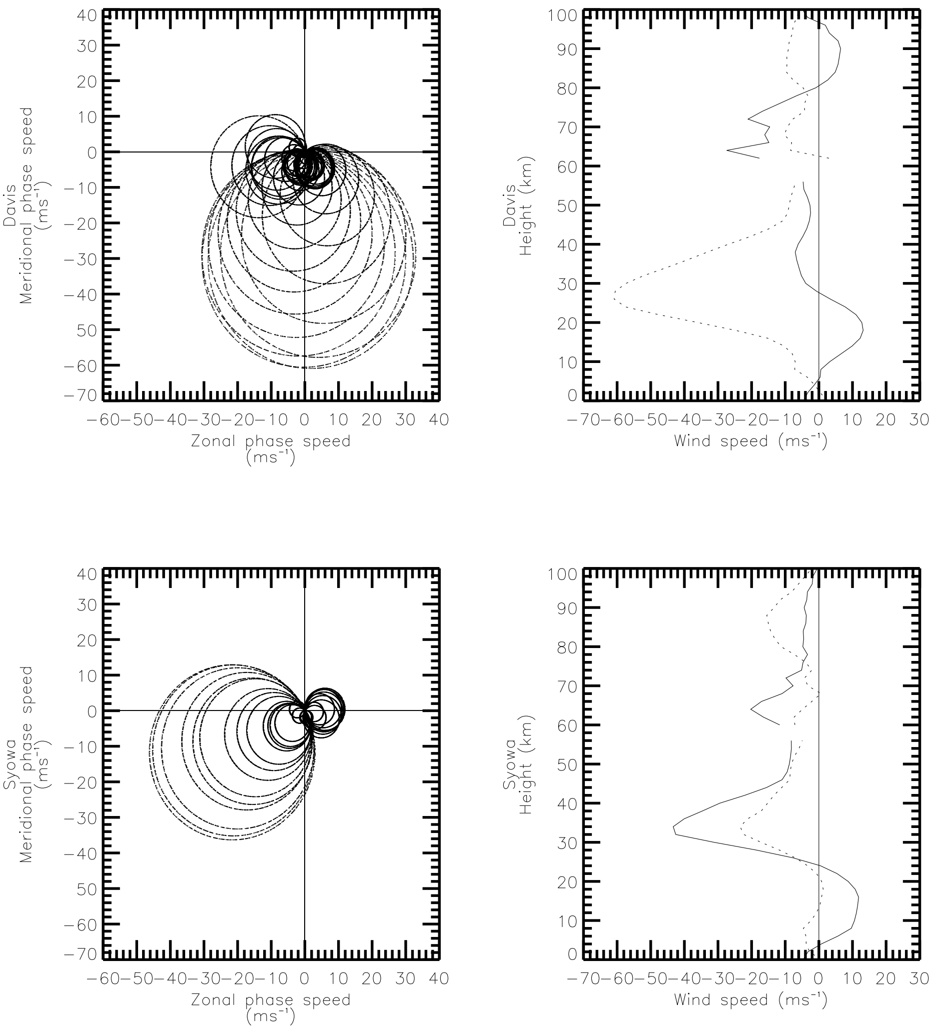

Figure 7.15: Regions of forbidden phase speeds due to critical level filtering resulting from the shown background wind profiles (zonal winds: sold lines, meridional winds: dotted lines). The winds are averaged during the time of the zonal-mean zonal wind reversal at 68°S and 10 hPa associated with the September 2002 major stratospheric warming (see Figure 6.8). MF radar winds are shown at heights above 60 km, with UKMO winds at lower altitudes.

Chapter 8

Summary and conclusions

This thesis has investigated the dynamics of the MLT region using MF radars located in the Antarctic and Arctic. Mean wind and gravity wave climatologies were studied at Davis, Syowa and Rothera in the Antarctic and Poker Flat and Andenes in the Arctic. Significant departures from these climatologies are observed around the times of major stratospheric warmings.

Background information of relevance to this thesis was presented in Chapter 1. Descriptions of phenomena such as gravity waves and stratospheric warmings were presented, together with a general overview of the structure of the Earth's atmosphere.

The individual MF radars along with the data analysis techniques that were used were discussed in Chapter 2. Mean wind and gravity wave observations were also presented in this chapter for the entire period of available data ($\sim$10 years of data from Davis, $\sim$4 years from Syowa, $\sim$4 months from Rothera and $\sim$5 years from both Poker Flat and Andenes).

Mean wind climatologies at Davis, Syowa, Poker Flat and Andenes were investigated in Chapter 3. Significant differences occur between the four locations, with these differences often being hemispheric in nature.

Quasi-stationary zonal wave-1 planetary wave activity appears to be a climatological feature of the meridional winds in the Arctic winter MLT. This does not appear to be the case in the Antarctic, where the meridional winds are generally weaker than in the Arctic.

A westward zonal wind peak and an equatorward meridional wind peak occur in the MLT during summer. The peaks both occur earlier (closer to the summer solstice) in the Antarctic than in the Arctic. The equatorward jet was found to persist for about 2 weeks later in summer in the Arctic than in the Antarctic, as was also found to be the case for PMC observations from the SME satellite

The similarity of the periods of PMC observations and equatorward winds gives support to the theory that the mean meridional winds can be used as a proxy for the adiabatic cooling associated with gravity wave drag in this region. The period of PMSE observations from a VHF radar at Davis was also reasonably similar to the period when the equatorward jet was occurring.

The greater symmetry around the solstice of phenomena such as the zonal and meridional winds during summer indicates that radiative effects may play a larger role in controlling the state of the southern polar MLT than in the northern hemisphere, where dynamical effects may be more important.

Gravity wave climatologies were investigated in Chapter 4 using MF radar wind variance from Davis, Syowa, Poker Flat and Andenes. Given the role that gravity wave drag plays in closing the zonal jet and driving the meridional circulation, the hemispheric differences in the mean wind climatologies suggest that the wave driving may be different between the two hemispheres.

The gravity wave climatologies are consistent with the wind climatologies in that they suggest more wave drag may be occurring in the Arctic MLT than in the Antarctic MLT. Wave activity is generally similar in magnitude at lower heights, but larger at higher altitudes in the Antarctic than in the Arctic. The wave fields are also generally more strongly polarised in the Antarctic than in the Arctic.

UKMO winds were used to calculate the forbidden phase speeds due to critical level filtering in the stratosphere and troposphere. This was combined with the results of a Stokes parameter method which determines the degree and angle (with a 180° ambiguity) of the wave polarisation. The combined results show that during summer the majority of wave activity reaching the MLT region would either be oriented towards the east, or have 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 strongly southward) phase speeds at Poker Flat.

Seasonal variations in 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 near the solstices and minima near the equinoxes). Both the winter maxima and spring or summer minima occur later at the southern hemisphere locations than at the northern hemisphere locations (with respect to the time of the summer solstice in each hemisphere). The change in magnitude from the winter maxima to the spring or summer minima is about 90% larger (and occurs at a faster rate) at the Antarctic locations than at the Arctic locations.

The short period range (20-120 minutes) zonal variances have strong summer maxima at heights around 80 km, (but not for the longer period range (120-480 minutes), or the meridional variances in general). This was not observed at higher altitudes (around 90 km) where a summer minima occurs, suggesting that the short period zonally oriented waves are causing large amounts of wave drag near the summer mesopause.

The summer maxima occur on average about 4 days later in the Arctic than in the Antarctic, with the minima following the summer maxima occurring about 14 days later in the Arctic. The magnitude of this delay is similar to the delay for the equatorward jet which reaches peak values about 4 days later in the Arctic, and persist for about 13 days longer than in the Antarctic (with respect to the summer solstices).

MF radar data were available during major sudden stratospheric warmings in both hemispheres (6 in the northern hemisphere, together with the unprecedented southern hemisphere event in September 2002). The southern hemisphere major stratospheric warming has a large influence on the dynamics of the MLT region. Northern hemisphere major warmings also influence the MLT region, although the degree to which this occurs varies largely between the six events.

The northern major stratospheric warmings were classified in terms of strength and duration in Chapter 5. Three of the events are very weak and short in duration, and could almost be classed as minor stratospheric warmings. The other three northern major stratospheric warmings are more similar in strength and duration to the southern hemisphere major stratospheric warming event.

In Chapter 6, the response of the mean winds to major stratospheric warmings was investigated.Similarities exist between the three larger northern major stratospheric warmings and the southern hemisphere event. Zonal wind reversals in the mesosphere associated with the warmings occur earlier, and are weaker in the mesosphere than in the stratosphere. The magnitudes of the differences between the height regions are similar in both hemispheres.

Another hemispheric similarity is that the meridional winds suggest the presence of zonal wave-1 planetary wave activity, and an associated flow over the pole. Around the time of the southern hemisphere major stratospheric warming, the mesospheric meridional winds at Davis, Syowa and Rothera show regular oscillations consistent with the presence of a 14-day westward propagating zonal wave-1 planetary wave. Strong periodic oscillations are not obvious at the Arctic locations around the time of the large northern major stratwarms as was seen at the Antarctic locations around the time of the southern major stratwarm.

The zonal winds are weaker on average during the 2002 southern winter, and are also weaker during the transition to the summer circulation. These differences are not observed following the large northern hemisphere major stratospheric warmings. It appears that there are both hemispheric similarities and differences in the response of the mean winds in the MLT to major stratospheric warmings.

Major stratospheric warmings (and the associated enhanced planetary wave activity) were seen in Chapter 7 to have an influence on the gravity wave activity in the MLT. Reduced gravity wave activity at Davis coincides with the timing of the stratospheric zonal wind reversal associated with the September 2002 southern hemisphere event.

Large reductions are not observed at Syowa, possibly due to the differences in critical level filtering at stratospheric heights. Some reductions in gravity wave activity occur at Poker Flat and Andenes around the time of the large northern major stratwarms, although it is unclear as to how much of the reductions relate to stratospheric warmings and how much to regular seasonal variations.

Variations in wave polarisation are observed, although this is difficult to quantify due to the considerable variation between the individual major stratospheric warming events. The variations in polarisation are also often significantly different between locations such as Davis and Syowa, indicating that the gravity wave field during major stratospheric warmings can vary significantly even over relatively short distances.

A positive correlation was often found to exist between the stratospheric winds and gravity wave activity in the winter mesosphere. The position of the stratospheric vortex with respect to a particular location has been reported in other studies to influence the effect that stratospheric warmings have on gravity wave activity [*Ratnam et al.*, 2004; *Whiteway et al.*, 1997; *Duck et al.*, 1998]. Possible scope for furthering the investigations presented in this thesis would be to use ray tracing techniques combined with a more synoptic scale view of the stratospheric polar vortex.

The results of this thesis should benefit (through existing and yet to be published papers) a variety of different communities such as GCM modellers (e.g., for gravity wave parameterisation), the ozone community (for the unique stratospheric warming research), polar research communities (particularly those interested in mesospheric layered phenomena) or government stakeholders (such as those involved with topics such as global climate change). Reprints of 3 papers which have already been published as a result of this PhD research are included as Appendices F, G, and H:

Appendix G:

Dowdy, A. J., R. A. Vincent, K. Igarashi, Y. Murayama and D. J. Murphy, A comparison of mean winds and gravity wave activity in the northern and southern polar MLT, *Geophysical Research Letters,* **28(8)**, 1475-1478, (2001).

Appendix H:

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Appendix I:

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