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SEASONAL AND SOLAR CYCLE VARIATIONS IN HIGH- LATITUDE THERMOSPHERIC WINDS

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Abstract. Thermospheric wind measurements have been collected systematically every winter for over nine years from a high-latitude site at Kiruna, Sweden (67.8°N, 20.4°E). The database contains 1242 nights of data collected with a Fabry-Perot Interferometer (FPI), perhaps the largest single- site database of thermospheric winds. This analysis shows a marked seasonal and solar cycle variation. Particularly at high solar activity, sunward winds of the evening period (16 - 20 UT) are more than 50% stronger at Spring than at Autumn equinox. This large asymmetry in the behaviour of high-latitude thermospheric winds at spring and autumn equinox has not yet been predicted by model simulations.

Introduction

There have been a number of investigations into the seasonal and solar cycle variations of the thermosphere. Empirical studies include Jacchia and Slowey, [1973], Wickwar et al., [1984], Hedin [1987], Biondi et al., [1990], Burnside and Tepley, [1989] and de la Beaujardiere et al., [1991]. Theoretical and numerical studies of thermospheric wind behaviour have also been conducted [Roble et al., 1977, Dickinson et al., 1981, Fuller-Rowell et al., 1988, Rees and Fuller-Rowell, 1989 and Fesen et al., 1991]. Consequently, the main trends in the behaviour of the thermosphere are thought to be well known and quite well understood. However, databases used in previous empirical surveys of the thermosphere using data from Fabry-Perot Interferometers and radars have generally contained observations from fewer than 50 days, limiting the number of categories into which a specific database can be divided. Thus seasonal analyses of the thermosphere have generally concentrated on the contrast between summer and winter behaviour. This has been thought to be adequate since the two solstitial seasons are expected to represent the two extremes of the seasonal variation, in tune with the annual variation of the solar heating of each hemisphere. Consequently, less emphasis has been placed into investigating the comparative behaviour of the thermosphere during spring and autumn equinox, on the assumption that they are equivalent. For example, the model results of Roble et al., [1977] and empirical results of Alcayde et al., [1974] presented the behaviour of autumn alone, or a conglomeration of the two, as sufficient representation of both equinoxes. However, a comparison of the average thermospheric winds observed at Kiruna in autumn and spring shows that the two equinox periods should be dealt with independently, since they are as different from each other as they are different from the winter solstice period.

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Description of the Database

The FPI at Kiruna has been described previously in detail [Rees et al., 1989]. Thermospheric wind speeds are calculated from the Doppler shifts of the 6300A emission of $O(^3P-^1D)$, which has a peak volume emission rate close to 240km altitude [Rees and Roble, 1986]. The FPI makes sequential observations in 6 azimuthal directions at a zenith angle of 60°, plus the zenith direction and a neon calibration source. The field of view consequently covers a diameter of around 800km at the average emission altitude.

Observations by a FPI are normally limited to nighttime hours, when the sun is more than 8° below the horizon, to provide adequate contrast of the $O(^3P-^1D)$ emission. There is a large seasonal variation in the length of the night at the latitude of Kiruna, and the FPI is only run between early September and mid-April. During the summer months the solar depression angle is always too small for useful observations.

The thermospheric wind database used in this analysis extends from November 1981 to April 1990. Data from periods of overcast skies or precipitation, as identified by the Kiruna all-sky camera, have been removed to avoid contamination from light scattering by cloud, which mixes signals with distinct Doppler shifts from various parts of the sky. However, with wind measurements from 1242 nights of observations, the database retains statistical significance when divided into six groups: the three seasons: autumn, winter and spring; each at two levels of solar activity.

For the seasonal analysis, data within 45 days of September 21 and March 21 were classified as 'autumn' and 'spring' winds, respectively, while data within 45 days of December 21 were classified as 'winter' winds. The average dates of the nights contributing to each season were found to occur on October 9, December 21 and March 4. Both equinox averages are similarly biased towards the winter solstice.

A core period, between 18UT and 03UT is well-observed during all three seasons. The maximum observing period, of seventeen hours, occurs in winter, between 14UT and 07UT. The winter period has the largest database, with three full months of observation, and with each night spanning 15 hours. The wind values calculated for the first and last two hours of the observing period are an average of data from the longest nights for that season. These nights are closest to the winter solstice, so that these wind values are slightly biased towards 'winter' behaviour. The effect is most extreme in the equinox data, when the average dates of the samples of the first and last hours of data can be about 8 days closer to winter solstice than those of the remaining samples.

Secondly, the database was then analysed by both season and solar activity. Figure 1 shows the variation of F10.7 solar flux from 1981 to 1992. The FPI database covers a large part of an eleven year solar cycle. A solar flux value of F10.7 = 110 was chosen to divide the database into two similar sized portions. Data collected in the two periods between November 1981 and April 1983, and between September 1988 and April 1990 represent solar maximum, while that collected between September 1983 and April 1988 represent solar minimum. The data were then subdivided into autumn, winter and spring, as described above.

Seasonal Variation

The seasonally-averaged wind components for autumn, winter and spring are displayed in Figures 2, 3 and 4, respectively. These plots show the meridional and zonal wind components observed to the geographic north and west of Kiruna, using southward and eastward as the positive directions. The seasonal averages for the whole database (solid lines) are plotted, as are the averages obtained when the database is divided into solar maximum and solar minimum periods. The individual wind speed errors are around $15ms^{-1}$, yet the standard deviation of the averaged winds can be over $100ms^{-1}$. The average standard deviation is around $75ms^{-1}$. The large standard deviations show that even sorting the winds by season and solar activity fails to account fully for the variability of the high-latitude thermosphere.

Between 18UT and 04UT, the average nighttime meridional winds are southward for all 3 seasons, however, there is a small seasonal variation of the times when the meridional component reverses from northward to southward and then returns northward. During winter and spring, the nighttime meridional winds flow southward for 12.5 hours compared with a period of southward flow in the autumn of only 11.25 hours. In spring, the meridional winds turn southward at

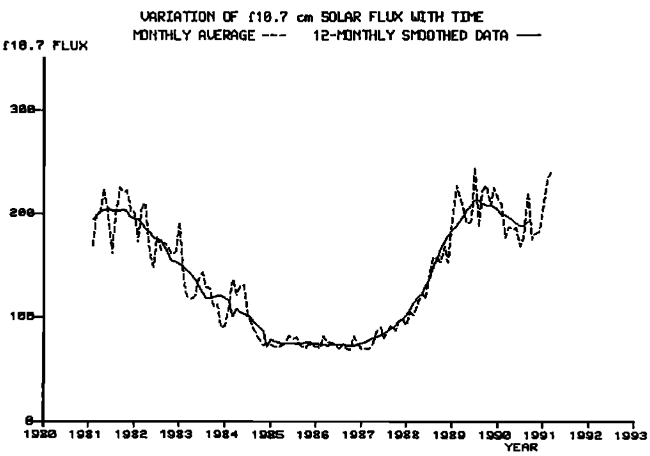

Fig. 1. Variation of f10.7cm solar flux from 1981 to 1991.

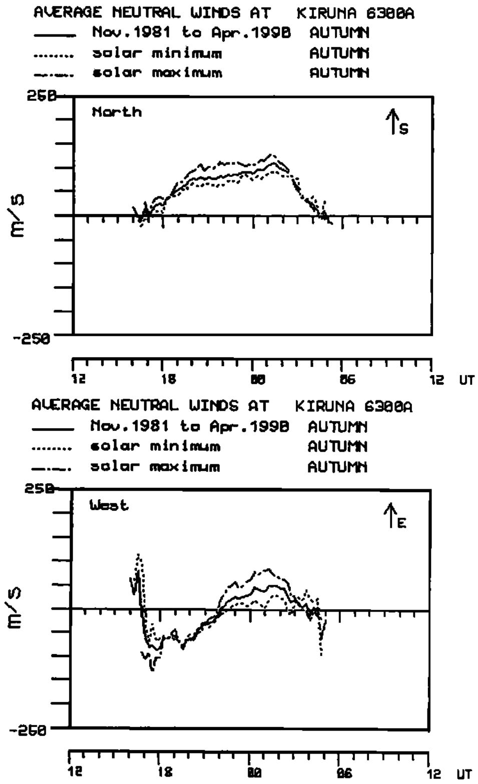

Fig. 2. Average nighttime thermospheric winds observed during the autumn for various levels of solar activity.

17UT, 15 minutes later than in winter. This behaviour largely agrees with the results of simulations using numerical models of the thermosphere [Fuller-Rowell et al., 1988, Rees and Fuller-Rowell, 1989] where the effects of global pressure gradients induced by solar heating are modified by ion-drag resulting from the high-latitude ionospheric convection pattern, and by the energy input from auroral precipitation and Joule heating.

For an hour either side of midnight, the average meridional wind speeds in autumn and winter are similar, about $95ms^{-1}$, however, the meridional wind in spring is $160ms^{-1}$, 70% larger. During spring and autumn the increase and decrease of the southward meridional wind is asymmetric about midnight (UT), peaking just after 01UT. In contrast, the nighttime variation of the southward meridional wind during winter is more symmetric.

There is also a significant seasonal difference in the average nighttime zonal winds. Between 17UT and 21UT, the zonal winds during equinox are more westward than during winter. However, between 21:45UT and 03:30UT, the eastward zonal winds in winter are up to 65% stronger than those at either equinox. After 03:30UT, the winter zonal winds become strongly westward, reaching a maximum value of $84ms^{-1}$ at 06UT. The zonal winds during spring also turn westward at 03:30UT, but reach a maximum value of only $42ms^{-1}$ at 05UT before turning eastward at 05:45UT. In the autumn, the zonal winds turn westward at 03:45UT, stay at low values until 05UT and then become increasingly westward.

In general, the behaviour of the thermospheric winds above Kiruna during autumn

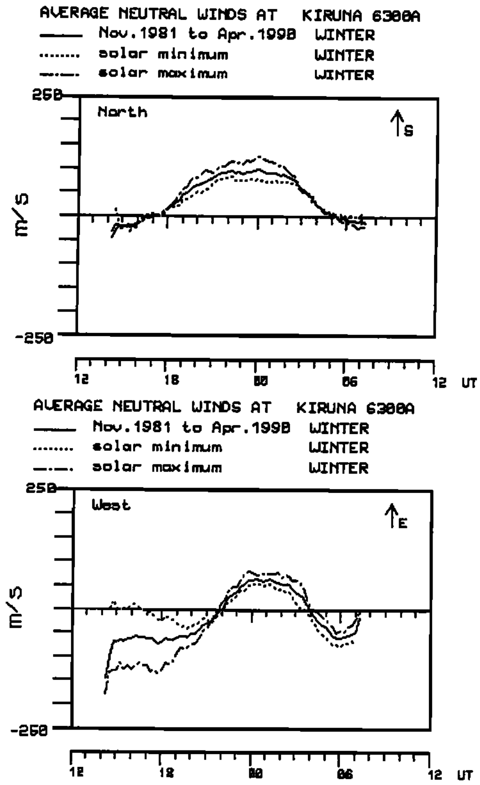

Fig. 4. Same as Fig. 2 but for spring observations.

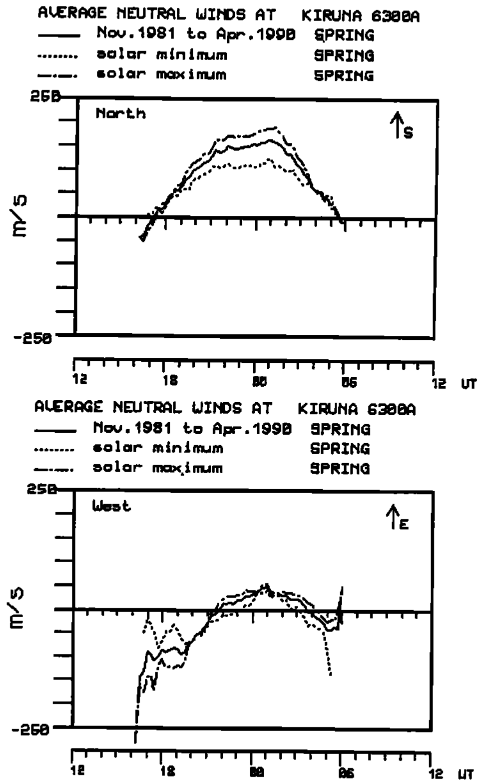

Fig. 3. Same as Fig. 2 but for winter observations.

and winter is relatively similar, while being distinct from that observed in spring. During spring the winds exhibit the largest magnitudes, especially in the midnight period. A seasonal variation in thermal forcing might explain the increased spring-time winds compared with those during winter, since the period of solar heating at high latitudes is much shorter in winter than during equinox. However, the observed asymmetry between the autumn and spring equinox winds does not support this argument.

Seasonal and Solar Cycle Variation

The seasonal averages of the nighttime thermospheric winds show an obvious solar cycle variation. During the four hour period around midnight, the average magnitude of the wind vector is up to 70% larger at solar maximum than at solar minimum. There is also a solar cycle variation in the times at which the nighttime meridional wind flow reverses from northward to southward, and vice versa. At solar minimum, the winter meridional wind turns southward at 16:15UT and then turns northward at 05:15UT, while at solar maximum it turns southward at 17UT and returns northward at 04:45UT. During both equinoxes, peak values of the meridional wind occur just after 01UT at both solar maximum and solar minimum. The asymmetry between the spring and autumn meridional winds is enhanced at solar cycle maximum. At solar minimum, the peak spring meridional wind speed is 33% larger than that of the autumn ($125ms^{-1}$ compared with $94ms^{-1}$), while at solar maximum it is 45% larger ($189\ ms^{-1}$ compared with $130ms^{-1}$).

Meridional wind speeds have been derived recently from EISCAT field-aligned plasma flow measurements (70° N, 240 km altitudes) during the period 1985-1987 [Titheridge 1991], corresponding to solar minimum. His results show that the maximum meridional wind speed derived from the EISCAT data for the two equinox periods combined is about $145ms^{-1}$ and for winter is about $170ms^{-1}$. This compares with the direct measurements of the solar minimum meridional winds by the FPI to the north of Kiruna (overlapping the region measured by Titheridge), which gives maximum meridional wind speeds of $94ms^{-1}$ in autumn, $125ms^{-1}$ in spring and $82ms^{-1}$ in winter. The meridional winds derived from the radar measurements are thus in poor agreement with the average meridional winds presented here. However, since the radar observations are not limited to clear sky conditions, the FPI and radar techniques have somewhat different sampling criteria. The HWM87 Model [Hedin et al, 1988], largely based on data from Dynamics Explorer, predicts larger peak nighttime meridional winds, about $180\ ms^{-1}$ for the combined equinoxes and $250\ ms^{-1}$ for winter solstice. The radar-derived meridional winds in winter exceed those at the combined equinoxes, whereas the FPI shows the reverse trend, due to the much larger winds of spring equinox.

The largest solar cycle variation occurs in the winter and spring zonal winds in the dusk part of the auroral oval before magnetic midnight (21UT). At 18UT, the spring-time zonal wind at solar minimum is westwards, at $48ms^{-1}$, while at solar maximum, it is westwards, at $121ms^{-1}$. The change in the winter zonal winds before 21UT is even more dramatic. Before 16:30UT, the zonal wind at solar minimum during winter has a small eastward value (less than $10ms^{-1}$), while at solar maximum it is strongly westward, reaching a maximum value of $133ms^{-1}$ at 17UT. In contrast, during autumn the zonal winds between 18UT and 21UT have very little solar cycle dependence.

Conclusions

There is a large seasonal and solar cycle variation in the thermospheric winds observed with a FPI at Kiruna, Sweden. These results are of significance for two reasons. Firstly, present theoretical models do not predict such a large difference between the winds during spring and autumn. Rather, such models predict a symmetrical seasonal behaviour about winter solstice, while observations show that the autumn winds are more winter-like than the spring-time winds. A plausible explanation of this equinoctial asymmetry has been proposed which involves a diurnal and seasonal asymmetry in the coupling of the Interplanetary Magnetic Field with the magnetosphere, generating consequent variations in the high-latitude convection field [Aruliah et al., 1991]. Without an equinoctial asymmetry in the high-latitude plasma flow the spring-autumn thermospheric wind asymmetries cannot easily develop purely due to solar heating and photoionisation at high solar activity. The corroborating evidence of an equinoctial asymmetry in the plasma velocities is presented in an accompanying paper by Farmer and Jarvis, [1991].

Secondly, there is no appreciable solar cycle variation in the thermospheric winds observed at low-latitudes [Burnside and Tepley, 1989]. Therefore, the solar cycle dependence shown by the average nighttime winds over Kiruna appears to be associated with phenomena occurring in the vicinity of the auroral oval. Aruliah et al., [1991] suggest that, at low-latitudes, increased pressure gradients at solar maximum are offset by the effects of increased ion drag. Within the auroral oval, ion drag acceleration of the neutral gas, due to ion convection driven by the magnetospheric electric field, is enhanced by increased plasma densities, creating thermospheric winds which are often much greater than those driven by global pressure gradients generated by solar heating.

We note also that a recent derivation of thermospheric meridional wind from the EISCAT radar at solar minimum does not agree with the magnitudes or seasonal variation demonstrated here from the FPI observations.

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