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Horizontal meridional thermospheric winds over King George Island, Antarctica, during the June 1991 Geomagnetic storm

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Abstract

Diurnal variations of the magnetic meridional component of the thermospheric neutral wind have been derived from both a servo model based algorithm with ionosonde data input, and the HWM-90 empirical wind model for the 4–6 and 11–13 June 1991 geomagnetic storm at King George Island (62.2°S, 58.8°W). While the HWM-90 winds are predominantly equatorward, the servo model winds are predominantly poleward during the storm, with especially strong poleward winds in the pre-noon hours. Such strong poleward winds are not expected to occur during a major storm at such a low geomagnetic latitude (51.4°S), which is equatorward of direct ion drag forcing by magnetospheric convection electric fields. We speculate that this atypical thermospheric wind response may be associated with particle heating in the South Atlantic Anomaly. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

During the past few years, several studies have been published dealing with extreme geomagnetic storm effects in the thermosphere and ionosphere (e.g. Smith et al., 1994; Buonsanto, 1995; Salah et al., 1996). Particular intervals with very good data coverage have been identified for coordinated study by the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) Storm Study project (Buonsanto et al., 1997a). The present paper deals with one of these intervals, for a location in the southern hemisphere near a longitude sector where unusual effects may occur because of the presence of the South Atlantic Anomaly (SAA) in the geomagnetic field. Diurnal variations of the magnetic meridional component of the thermospheric neutral wind are derived from both a servo model (SM) based algorithm (Rishbeth, 1967; Rishbeth et al., 1978; Buonsanto, 1986; Buonsanto et al., 1989) with ionosonde data input, and the HWM-90 empirical wind model (Hedin et al., 1991) for the 4–6 and 11–13 June 1991 geomagnetic storm at King George Island (62.2°S, 58.8°W geographic, 51.4°S, 9.0°E geomagnetic). These winds are compared with servo model winds derived from ionosonde data for the five geomagnetically quietest days of the month. Although there are some neutral wind observations for the location using the Fabry-Perot technique (Kim et al., 1991), they relate to a few days and do not correspond to severe geomagnetic storms. Moreover, neutral wind model determinations for the same area using ionosonde data (Dudeney, 1973 , 1976; Dudeney and Piggott, 1978; Sojka et al., 1988), also are not representative of storm conditions. Thus, any determinations from a unique location such as King George Island are important for obtaining an understanding of the global morphology of upper atmospheric winds under these conditions. Fabry-Perot observations currently being carried out at the same location (Won, 1997, private communication) will be extremely valuable once a significant database of observations on clear nights has been built up.

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2. Data analysis and sources of error

F-region peak heights (hmF2) were first determined for each storm day, using a well known empirical equation (Bradley and Dudeney, 1973; Eyfrig, 1974), with foF2, M(3000)F2 and foE values scaled from ionograms recorded at 15 min intervals. When foE was not observed, it was calculated from a modified version of the CCIR formula (Buonsanto and Titheridge, 1987). Ionograms were carefully checked so as to identify possible Stable Auroral Red (SAR) arc signatures which could be present at this location (Rodger, 1984). Whilst there is evidence of this during the early hours of 5 and 6 June, no hmF2 values were derived for these intervals because spread-F did not permit accurate foF2 and M(3000)F2 determination. No evidence of SAR arcs is found on 11, 12 and 13 June. The derived hmF2 values and a discussion of their related uncertainties are found in Arriagada et al. (1993). The accuracy of hmF2 values derived from empirical formulae have been extensively discussed previously (e.g. Dudeney, 1974, 1976, 1983; Berkey and Stonehocker, 1989). Wind velocities were then determined for each day using the SM method. The magnetic activity level was specified by the daily geometric index Ap. The solar activity level was parameterised using the values of the 10.7 cm solar flux ($F_{10.7}$) for the current day and the previous day.

We have no measurements of electric fields, but we use the model of Richmond et al. (1980) to obtain a first-order electric field correction to the SM winds. The Richmond et al. model does not apply to storm conditions, so use of it can result in sizeable errors if the electric fields are strong. The electric field correction to the SM winds is given by $V_{\perp s}/\sin I$ in the southern hemisphere, where $V_{\perp s}$ is the component of the $\mathbf{E} \times \mathbf{B}$ drift perpendicular to the geomagnetic field, upward and southward, and I is the magnetic inclination angle. At Millstone Hill (55°N geomagnetic latitude) this correction was generally < 100 m/s during this storm, though there were some isolated intervals with larger values.

For comparison with the HWM-90 winds, we use the O^+-O collision cross section recommended as an interim standard by the CEDAR community (Salah, 1993). More recent work favors a cross section approximately 25% smaller, and the CEDAR group has now recommended the cross section formula of Pesnell et al. (1993). Use of the smaller cross section would result in little change to our derived daytime winds, but significantly stronger winds (by approximately 30%) at night when the O^+ diffusion velocity is large (Buonsanto et al., 1989).

Another source of uncertainty in our calculations is the neutral composition, which we obtain from the MSIS-86 model (Hedin, 1987). Decreases of the atomic oxygen to molecular composition ratio by a factor of 2 or more are possible during major storms. It seems likely, however, that this composition disturbance zone was confined to latitudes higher than King George Island in the southern (winter) hemisphere (e.g. Prölss, 1995).

Theoretical results of Titheridge (1995) suggest that neutral winds derived from the servo model are inaccurate during the sunrise and morning period due to a shift in the zero-wind *F* peak downward from the zero-wind 'balance height'. However, we have neglected this 'sunrise effect' as more recent work (Buonsanto et al., 1997b) has shown it to be small relative to other sources of error in the analysis, especially in winter. Buonsanto et al. found excellent agreement between SM winds and winds derived from incoherent scatter ion drift data at Millstone Hill during a winter period (January, 1993). Derived winds using the SM method are quoted to be accurate to within 40 m/s by Titheridge (1995).

Magnetic meridional winds for each storm day were also obtained from the HWM-90 model (Hedin et al., 1991) using $F_{10.7}$ and daily Ap. HWM-90 winds were obtained for a fixed height of 300 km; results vary by only 10% within the 270–350 km range.

For the quiet-time reference curve, we obtained SM winds at 15 min intervals from the mean hmF2 values for the five geomagnetically quietest days of the month. A 9-point running mean was applied to these hmF2 values so as to reduce oscillations with periods of less than about 2 h. The 5-day means of the $F_{10.7}$ and Ap indices were used, and the electric field correction was again obtained from the Richmond et al. (1980) model. An estimation of quiet-time reference variability was computed for each hour, as twice the difference between wind velocities calculated for *mean heights plus a standard deviation* and those for *mean heights*. Heights reduced by a standard deviation were not used because corresponding derived daytime-poleward winds are considered unreasonably high, particularly during winter. The mean wind velocity variability representative of night-time and daytime conditions was then computed.

The validity of these quiet-time reference values can be assessed by comparison with diurnal variations of winds derived in the same manner for the same location during June 1989, which correspond to an interval of similar geophysical conditions (Arriagada et al., 1997). Differences between them, both with and without taking into account Titheridge corrections for the June 1989 values, are small by comparison with the observed variability, except around sunrise and sunset. However, corresponding diurnal variations determined for Argentine Islands (65.2°S; 64.2°W), located about 400 km South of King George Island, using an empirical hmF2 model in conjunction with a simple analytical model for the *F*-region reduced height (Dudeney, 1973), significantly differ in shape, mean wind and times of extreme wind values. By contrast, summer results for the two locations are almost identical.

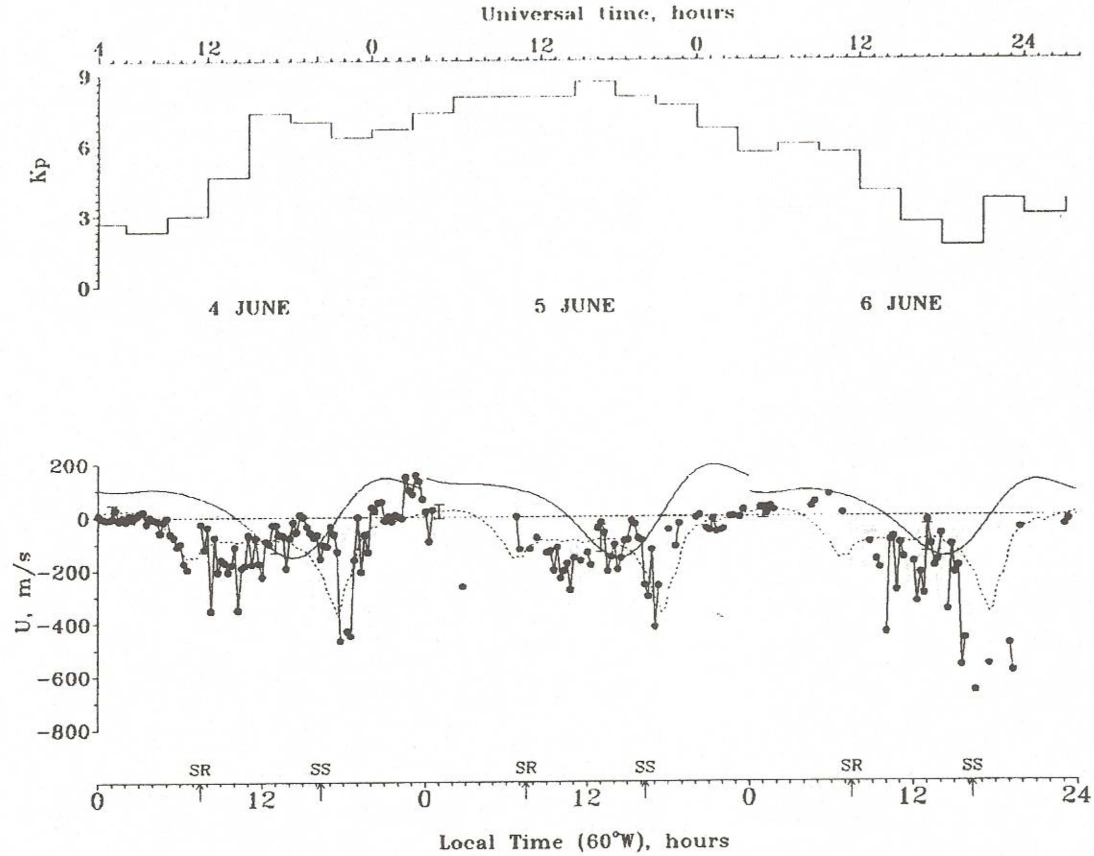

Fig. 1. Local time (60°W) variations of the geomagnetic index Kp (top) and of the magnetic meridional component of thermospheric neutral winds (bottom) at King George Island (62.2°S; 58.8°W geographic, 51.4°S; 9.0°E geomagnetic), for the interval 4–6 June 1991. Equatorward winds are positive. (Dots) Servo model. (Continuous line) HWM90 model. (Dashed line) Reference corresponding to the five geomagnetic quietest days of the month. Bars are for mean night-time and mean daytime wind variability for quietest days. Arrows indicate sunrise and sunset (at 120 km).

3. Results

The derived winds for 4–6 June are shown in the lower panel of Fig. 1 (equatorward positive). The top panel gives the 3 h geomagnetic index Kp. Corresponding results for 11–13 June are given in Fig. 2. A significant response of the winds to the geomagnetic disturbances are seen on all six days, although there are missing data for several hours early on 5 June due to the presence of spread-*F*.

Solar-geophysical conditions during this period were discussed by Buonsanto (1995). This was one of the most severely disturbed periods of solar cycle 22, associated with six X-class solar flares. The Kp index reached 9- on 5 June and 8- on 10 June and again on 13 June.

Figures 1 and 2 show that the HWM-90 winds are predominantly equatorward during the storm, and poleward only during the afternoon. At higher levels of geomagnetic activity (e.g. 5 June), the HWM-90 equatorward winds in the 0–10 and 18–24 h intervals are stronger, but there is little change in the HWM-90 afternoon poleward winds.

The SM winds on the quiet days are almost always poleward, with strongest poleward winds in the evening. Weak equatorward winds are seen on the quiet days for a few hours near midnight. In sharp contrast to the HWM-90 winds, the SM winds on the storm days are strongly poleward, except for a few hours near midnight. These winds appear similar to the SM winds on the quiet days, except that the storm-time winds are more strongly poleward in the morning, abate in the afternoon and turn strongly poleward again in the evening. This trend reversal around noon is the main signature of the storm seen in the SM winds.

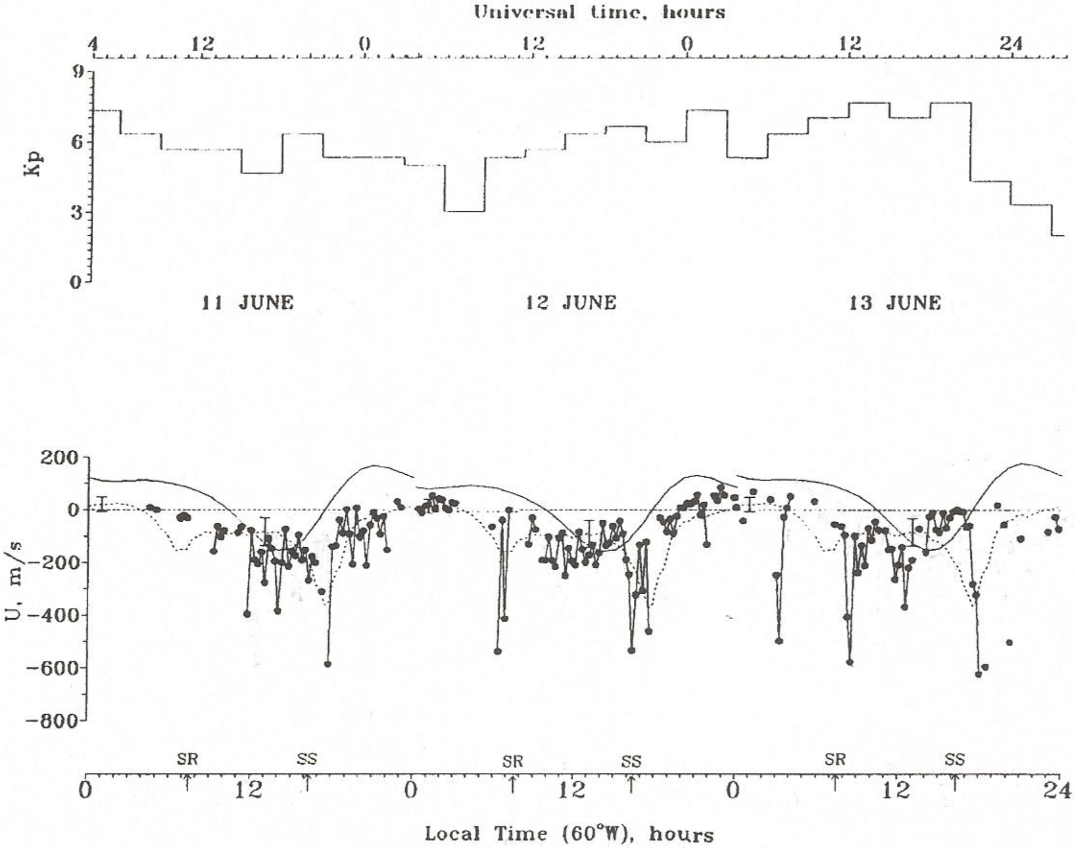

Fig. 2. Local time (60°W) variations of the geomagnetic index Kp (top) and of the magnetic meridional component of thermospheric neutral winds (bottom) at King George Island (62.2°S; 58.8°W geographic, 51.4°S; 9.0°E geomagnetic) for the interval 11–13 June 1991. Equatorward winds are positive. (Dots) Servo model. (Continuous line) HWM90 model. (Dashed line) Reference corresponding to the five geomagnetic quietest days of the month. Bars are for mean night-time and mean daytime wind variability for quietest days. Arrows indicate sunrise and sunset (at 120 km).

4. Discussion

The normal thermospheric circulation at middle latitudes consists of a poleward wind during the day, and an equatorward wind at night. In addition, the diurnal mean tends to be more strongly poleward in winter than in summer because of the well-known summer to winter thermospheric circulation pattern seen in both theoretical models (e.g. Dickinson et al., 1981) and observations (e.g. Buonsanto, 1986). During geomagnetic storms, high latitude winds may be very strong as they are driven by ion drag due to magnetospheric convection electric fields. Joule and particle heating result in thermal expansion of the high latitude upper atmosphere, which causes pressure gradients resulting in enhanced equatorward winds which may extend to middle latitudes, and equatorward surges in the wind which may reach the opposite hemisphere. However, during winter, these are opposed by the prevailing summer to winter flow (e.g. Fuller-Rowell et al., 1996). We may speculate that particle precipitation in the SAA might also give rise to pressure gradients which may drive a poleward wind in the vicinity of King George Island. Then the combined effects of the prevailing summer to winter flow and the SAA might explain the predominantly poleward wind at the southern hemisphere mid-latitude (winter) location of King George Island during the June 1991 storm.

Strong precipitation of > 1 MeV electrons in the SAA near 15°S geomagnetic latitude near the coast of Brazil was reported and discussed by Sheldon (1991). Energetic electrons from the inner radiation belt are almost exclusively absorbed by the atmosphere in this region due to the low geomagnetic field intensity. Electrons undergoing gradient and curvature drift precipitate from the drift loss cone in the SAA as they cannot complete a drift period without encountering the atmosphere.

Gledhill (1976) reviewed work dealing with the aeronomic effects of the SAA. Very significant, though highly variable, effects were seen in the F2 region electron number density and ion composition. These effects appeared to be larger during geomagnetic storms. As the early June 1991 period was characterised by very extreme and long-lived geomagnetic storm effects, precipitation from energetic particles in the inner radiation belt may have increased enough to cause significant effects on the F region ionosphere and thermosphere. While we have no measurements of the energetic particle fluxes for this period, this mechanism might be a factor in producing the strong poleward winds observed above King George Island during the June 1991 storm.

Arriagada et al., (1997) compared winds from King George Island with winds from Invercargill (43°S; 176°E geographic, 47°S; 257°E geomagnetic) published by Titheridge (1993). At winter solar maximum, the diurnal mean winds are poleward, being only 15 m/s at Invercargill compared with about 60 m/s at King George Island. Smith et al. (1994) reported on winds from 11–13 June 1991 obtained from 630 nm nightglow observations taken with a Fabry-Perot spectrometer from Mt. John, a station near Invercargill. The data cover 14 h periods centred on midnight, and correspond to a mean height of about 250 km, below the F2 peak. Observations to the South of the station indicated the presence of red aurora. The winds in this direction showed a strong equatorward component, as might be expected from ion drag due to magnetospheric convection electric fields. Observations to the North of the station correspond to a geographic latitude of about 39°S, or geomagnetic latitude of about 45°S. The mean meridional winds were poleward, averaging about 25 m/s. These are only a little smaller than the mean poleward winds for comparable 14 h nighttime periods at King George Island. We must be cautious in interpreting the differences found between the winds reported by Smith et al. and those at King George Island because of the much higher geographic latitude of King George Island, the strong latitude gradients in the winds seen by Smith et al., and the different techniques used. However, the similarity in the winds at the two locations underlines the point that further studies will need to be carried out using observations of winds at different locations in the southern hemisphere before we can reach definitive conclusions about the possible influence of the SAA on upper thermosphere meridional winds.

The servo model or other techniques which derive winds from ionosonde data can be usefully employed in such future studies. However, during disturbed conditions, uncertainties due to poor knowledge of the electric field correction or possible inadequacies of the MSIS-86 model need to be taken into account. The meridional neutral wind depends on a competing mix of forcings which depend on longitude, as well as latitude, time of day, season, magnetic and solar activity. Our results and those of Arriagada et al. (1997) indicate that the HWM-90 model needs improvement to account better for the hemispheric, longitudinal and magnetic activity dependencies.

5. Conclusions

We have determined diurnal variations of the magnetic meridional component of the thermospheric neutral wind using the servo model method above King George Island during a severe geomagnetic storm which occurred in June 1991. We compare our results with those from a quiet period and from the HWM-90 model. Results differ significantly from HWM-90, both in the shape of the diurnal variation and in the mean value. The SM winds during both the storm and the quiet periods are predominantly poleward, while the HWM-90 winds are mainly equatorward. On most storm days, the poleward winds abate in the early afternoon, suggesting an increased polar forcing, a feature which may be considered the storm signature. The strong poleward winds observed at King George Island during this storm lead us to speculate that significant low-latitude forcing due to charged particle heating in the South Atlantic Anomaly may have occurred. However, more data at this and other southern hemisphere locations will be needed before definitive conclusions can be drawn about the possible influence of the SAA on the neutral winds.

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