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THE THERMOSPHERE AT SOUTH POLE

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Abstract: The Earth's thermosphere provides the first layer of atmosphere to filter the sun's optical radiation on its way to the surface. In addition, it absorbs most of the energetic particles swept up from interplanetary space and guided downwards along magnetic field lines. The most variable components of these sources of incoming energy are the energetic particles associated with the aurora and the extreme ultraviolet radiation dependent on solar activity. Because of this defensive role, the thermosphere is the place where incoming radiations are converted to heat. At high latitudes, such as South Pole, the thermospheric temperature is strongly dependent on solar and geomagnetic activity. Energetic photons and charged particles ionize the thermosphere, creating the ionosphere. Currents of millions of amps flow in the high latitude ionosphere causing additional heating and associated dynamical forcing through ion drag on the neutral gas particles. Winds driven by this drag are a persistent feature of the high latitude thermosphere. The electric fields which drive them originate the solar-terrestrial dynamo and are subject to reversals dependent on the sign of the interplanetary magnetic field component in the plane of the solar ecliptic. Hence the winds and temperatures in the thermosphere depend strongly on interplanetary phenomena.

1. Introduction

The upper atmosphere of the Earth has several layers named for their particular and distinguishing properties. Above the stratosphere, in ascending altitude, the mesosphere, thermosphere and exosphere have been defined by reference to their physical characteristics. The mesosphere is a region of decreasing temperature where turbulent dissipation and exothermic chemical reactions supplement solar radiation in maintaining the heat budget. The thermosphere begins where the turbulence ends, at about 100 km altitude and continues upwards to the point where the mean free path of atoms and molecules exceeds the scale height (height over which the density changes by a factor of e) of the atmosphere. The exosphere is a region where the lack of collisions permits substantial orbital motion of atmospheric particles.

The thermosphere is the prime absorber of solar EUV and FUV emissions. Hence it is partially ionized and chemically modified and for that reason it behaves differently to regions closer to Earth. Also, since much of the EUV and FUV energy eventually becomes heat, the upper thermosphere is hot and transports the heat energy downwards to the lower atmosphere. The high altitude heating supports the positive temperature gradient with altitude which tends to support stable stratified conditions. Such is the stability that molecular diffusion is the main means of vertical transport. Lighter particles (atoms) are transported higher than the heavier molecules resulting causing a steady change in composition with altitude from mainly molecular in the lower thermosphere to mainly atomic in the upper thermosphere. Atomic species result from photodissociation and chemical reactions. Hence, atomic oxygen gains in proportion to molecular nitrogen as altitude increases, and ionized oxygen is normally the dominant component of the ionized region (the ionosphere) at 300 km.

In addition to solar EUV and FUV, the thermosphere is also the prime absorber of particles from the solar wind, some of which enter the geomagnetic environment and precipitate into the atmosphere at high latitudes causing the polar aurora. The thermal budget of the thermosphere is changed substantially in processes which result from the absorption of particles from the solar wind, making the behavior of polar thermospheres of particular interest since they are subjected to such a great variation of inputs. The seasonal and solar-cycle changes in solar electromagnetic inputs are also important factors, making the winter thermosphere less ionized than in the summer, also less ionized in the minimum in the eleven year solar cycle.

Given these factors, it is interesting to investigate the variability of winds and temperatures as a function of solar cycle, season, auroral disturbance (otherwise called geomagnetic disturbance). This paper describes what is known about the South Pole thermosphere and its variation with those factors just mentioned, and other interesting factors such as the direction of the interplanetary magnetic field.

2. Sources of Data

Measurements over Antarctica were first made from satellites with *in situ* probes (Spencer *et al.*, 1982) which permitted the determination of the cross-track wind and the temperature locally. The Dynamics Explorer satellite (Hoffman and Schmerling, 1981; Killeen *et al.*, 1982) was launched in 1981 carrying a flight Fabry-Perot Spectrometer permitting remote sensing of wind and temperature in the meridian. Results from these missions confirmed that the thermosphere in the southern hemisphere has many of the same dynamic and thermal properties as the northern hemisphere once observations have been ordered by geomagnetic rather than geographic coordinates. Whereas measurements from polar orbiting satellites obtain intermittent streaks of data crossing the polar cap along the track or path travelled, ground-based observations sample continuously in one locality. The first thermospheric wind and temperature observations made continuously over 24 hour periods in the polar cap were reported by Deehr *et al.* (1980) for Spitsbergen (75° magnetic latitude) in the Arctic. Since 1982, regular Fabry-Perot Spectrometer measurements have been made at Halley (HAL, 61° magnetic latitude) in the Antarctic. Other ground-based observing sites have since been set up at Mawson (MAW, 70° magnetic latitude), South Pole (SPO, 75° magnetic latitude) and Syowa (SYW, 66°). Also the Upper Atmosphere Research Satellite (UARS) has made some long-range measurements of winds and temperature in the lower thermosphere near the coasts of Antarctica. In the year 2000, it is expected that the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics satellite (TIMED) will provide further coverage thermospheric winds and temperatures.

3. General Considerations

Figure 1 shows a map of Antarctica with the auroral oval superimposed for 1200 UT. The ground stations mentioned above have also been marked, along the location of the magnetic south pole (MSP) which is 15° offset from the geographic pole. The auroral oval makes a diurnal rotation about MSP, reaching out to geographic latitudes 15° further equatorward near New Zealand than would happen if MSP and the geographic pole were coincident. By the same token, Halley station, which is −75° geographic, does not pass into the auroral zone under quiet conditions since its geomagnetic latitude is only −61°. Hence we find that thermospheric disturbance by aurora-related effects is weak near Halley but much stronger on the opposite side of the

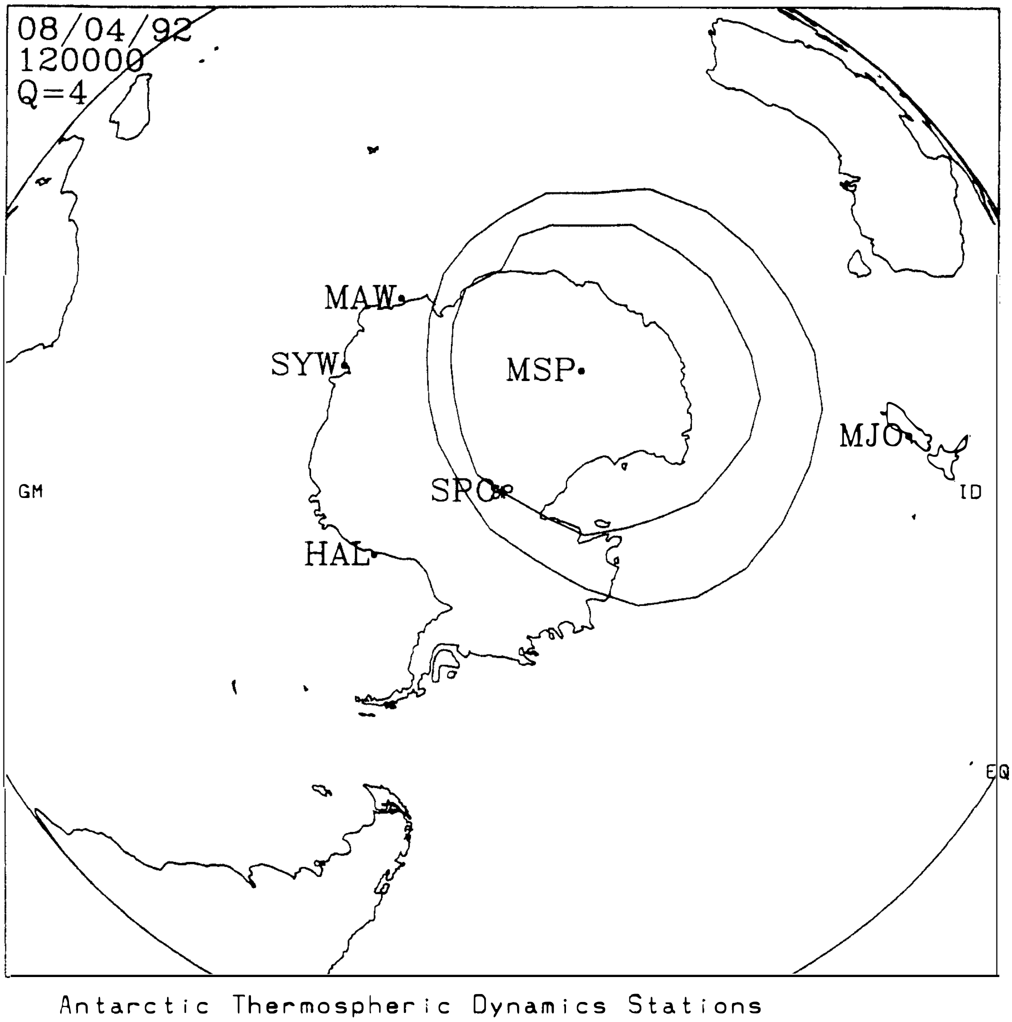

Fig. 1. Map of Antarctica showing the stations used in this paper. South Pole (SPO, −75.5 Inv), Mawson (MAW, −70.5 Inv), Syowa (SYW, −66 Inv) and Halley (HAL, −61.6 Inv). Also marked are the magnetic south pole (MSP) and the auroral oval for Q=4 (HOLZWORTH and MENG, 1975) conditions at 12 UT.

continent. South Pole station normally lies near the auroral zone near noon geomagnetic time (Note: noon geomagnetic time occurs when a station lies on the line joining the magnetic pole to the sun) and passes inside the oval near midnight.

Figure 2 shows the winds measured in the upper thermosphere at South Pole, averaged for quiet auroral conditions as a function of time, plotted in the form of a dial. Time is marked in magnetic local time (MLT) and the center of the plot is the south magnetic pole. Although this plot is strictly only showing evolution of the wind at one point in space as time passes over the day, since the data is averaged over many days, the pattern presented has meaning as a plot of average wind distribution. The major feature is the predominance of winds blowing away from the sun. This is shown clearly in the noon period and near midnight and early morning. In mid-morning and the evening sectors there are disturbances to this pattern which cause a weakening and rotation of the wind vector. Such a pattern is very common for South Pole with some small modifications which occur with changes in geomagnetic activity and the interplanetary magnetic field (IMF). Ignoring these latter for the present, we shall consider our present understanding of the normal averaged pattern.

EUV and FUV heating of the thermosphere causes a high pressure region centered at the subsolar latitude a few hours postnoon in local solar time. Together with the low pressure region on the nightside, this causes a global circulation which transports air parcels from the sunlit to the dark hemisphere. At thermospheric altitudes, viscosity

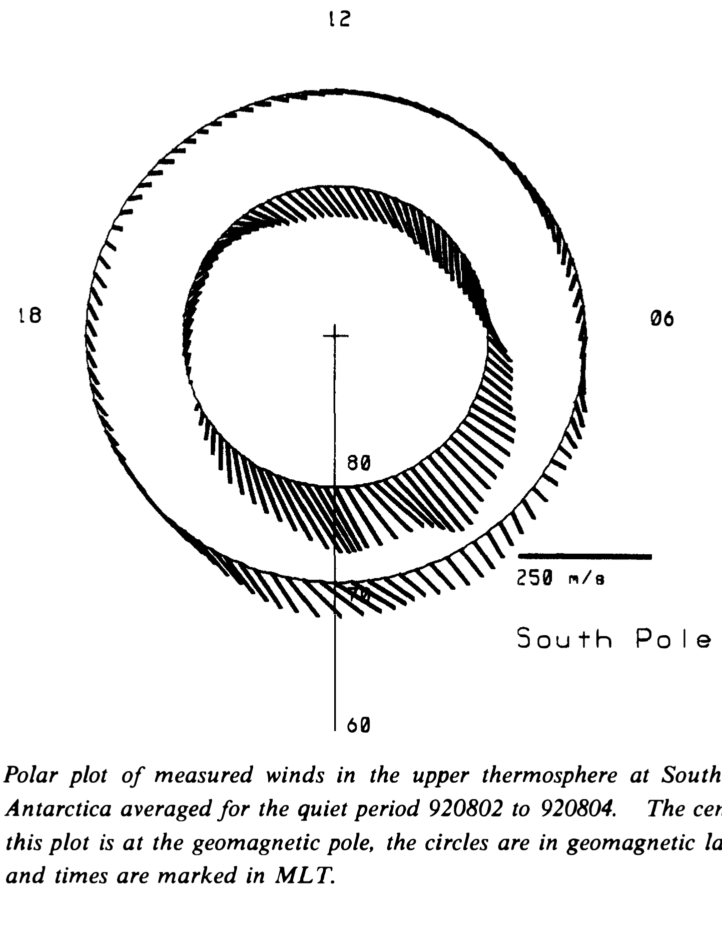

Fig. 2. Polar plot of measured winds in the upper thermosphere at South Pole, Antarctica averaged for the quiet period 920802 to 920804. The center of this plot is at the geomagnetic pole, the circles are in geomagnetic latitude and times are marked in MLT.

damps out the tendency for the winds to adopt a geostrophic pattern. Part of this circulation appears across the polar caps, hence there is a tendency for the overall wind pattern to appear antisunward at high latitudes such as South Pole. As KOHL and KING (1967) showed, the upper thermospheric antisunward wind strength was expected to be about 100 m/s. The observation of about 50 m/s on the dayside and 200 m/s on the nightside in Fig. 2 shows that it has been found to be somewhat lower and also that air parcels appear to accelerate as they cross the polar cap. In addition to the global antisunward wind, at high latitudes there is ionospheric convection due to the action of an electric field generated by the solar wind and the geomagnetic field. Frequently, this convection pattern has been found to be bi-cellular with antisunward flow in the polar caps and sunward flow in the auroral zones at evening and morning (see, for example, HEELIS *et al.*, 1982; HEPPNER and MAYNARD, 1987). Collisions between convecting ions and neutral atmospheric constituents cause a transfer of momentum to the neutral thermosphere. In the absence of other driving forces, the winds would eventually adopt a circulation pattern very similar to the ionospheric convection. The actual circulation is the result of a blend of pressure gradient, ion drag, viscosity, and Coriolis forces. Since ionospheric convection in the vicinity of South Pole is frequently antisunward, the winds accelerate as air parcels enter the antisunward convection region. Figure 2 shows that about 150 m/s has been added to air parcels in passage across the polar cap. This work has been done by the electric field generated by the solar wind.

4. The Effects of Geomagnetic Activity

As geomagnetic activity rises, convection speeds and ionospheric densities increase, in general. The ionosphere supports currents in the 100–150 km altitude region which generate heat causing the thermospheric temperature to rise. The upper panel in Fig. 3 shows the effects of geomagnetic activity, as measured by the planetary A index, on the wind magnitude and temperature in the upper thermosphere. Magnetic noon is at 1530 UT and midnight at 0330 UT. There was a consistent trend for winds to be stronger near midnight MLT compared to noon. However, the dip in wind strength centered on 08 MLT (12 UT) gradually disappeared as activity increased until at the highest activity shown it was not detectable. The other region of low wind occurred at 20 MLT (2400 UT) was little affected by change in geomagnetic activity until the highest level was reached.

Current understanding of this behavior is that that the winds increased in strength because of stronger momentum transfer by ion-neutral collisions in the thermosphere. The twin cell pattern in ionospheric convection became more evident, causing both evening and morning vortices in the wind. At the same time as the activity increased, the convection pattern also expanded to cover a wider region, making the central cross-polar antisunward jet broader. As the highest levels of activity were reached, the jet was wide enough so that the morning vortex no longer appeared over South Pole and the evening vortex also began to move away. What remained was a broad region of flow which was nearly all antisunward, accelerating from the dayside towards the nightside.

The lower panel in Fig. 3 shows what happened to the upper thermospheric

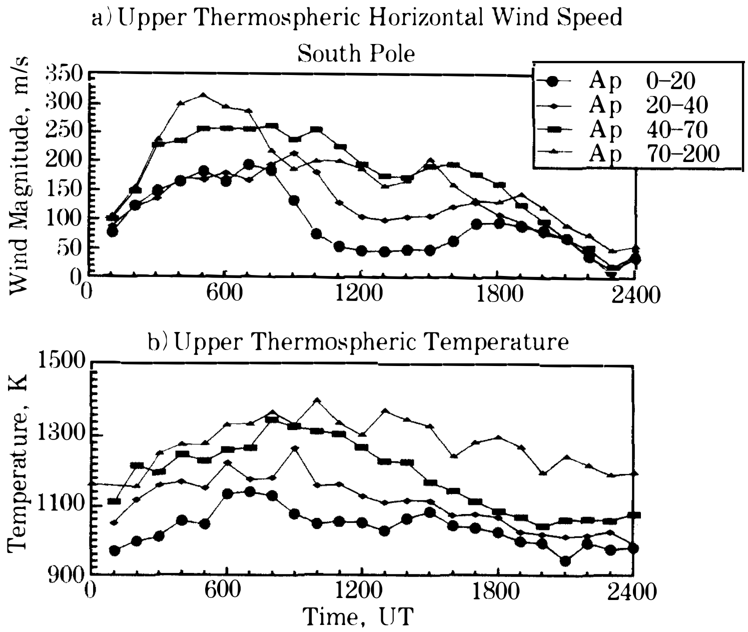

Fig. 3. (a) Upper thermospheric winds measured at South Pole averaged for the Ap index in discrete ranges from 0–200. (b) Thermospheric temperatures averaged for the same ranges of Ap as for (a).

temperatures for the same subdivisions of geomagnetic activity. At low activity levels, the diurnal temperature pattern has a high just after midnight MLT and a low just after noon. The temperature difference was about 100 K. At medium levels, the same pattern was found but with higher mean temperature and the amplitude of the diurnal variation had increased to nearer 200 K. At the highest levels of activity the diurnal pattern became lost in irregular fluctuations due to insufficient data, but temperatures were now about 800 K higher than for low activity and a maximum appeared more in the mid-morning hours MLT than the early morning of lower activity levels.

The interpretation of the near midnight MLT high seen at lower activity is that there was frictional heating of the thermosphere during the acceleration by ion drag. Smith *et al.* (1998) showed that 100 K rise due to frictional heating was reasonable. The changes in phase of the diurnal temperature variation as activity increased are not currently understood.

5. Modifications Due to the Interplanetary Magnetic Field (IMF)

The effects of the IMF are frequently considered by reference to the components in the direction of the sun (x), in the direction of the Earth's magnetic dipole (z) and the azimuthal direction (y). Effects on thermospheric dynamics due to the x-component alone have not been identified. Effects due to changes in sign of the y and z components have been found to be profound. The fundamental effect in both cases lies in the modifications which occur to the ionospheric convection pattern. In addition, changes in the sign of IMF B_z negative (southwards) and positive switch on and off the strong mode of coupling between the solar wind and the Earth's magnetic cavity (the

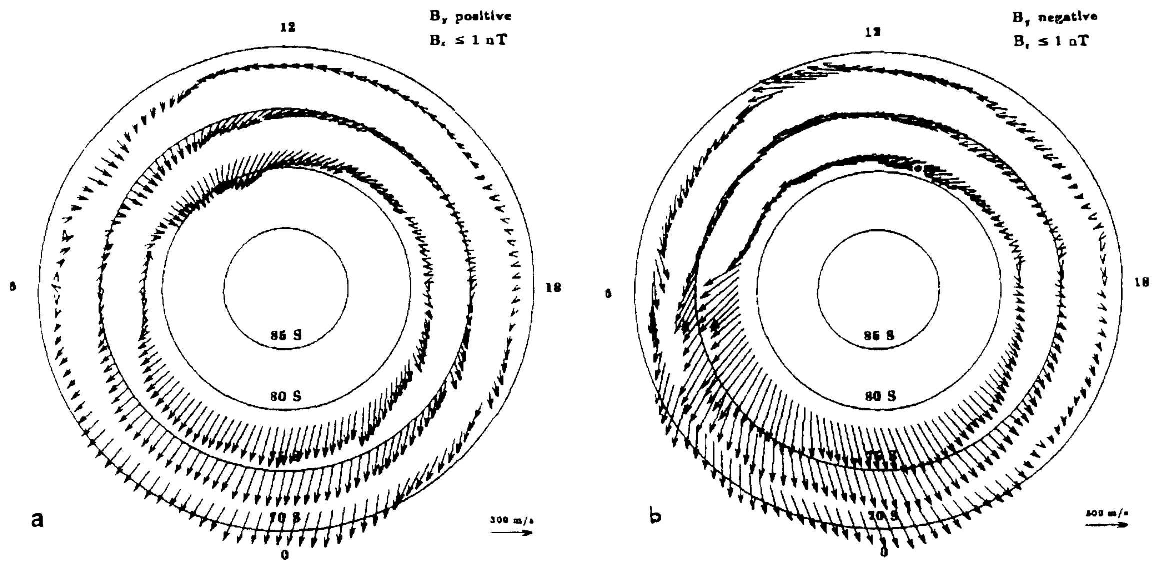

Fig. 4. *(a) Polar plots of measured winds in the upper thermosphere at South Pole, Antarctica, averaged for B_y positive and B_z negative conditions. (b) The same as (a) but averaged for B_y negative conditions. Note that time is plotted in the opposite sense from Fig. 2.*

magnetosphere). For IMF B_z positive under nighttime conditions, auroral activity is reduced and ionospheric densities may be too low for ion drag to be dominant. Hence the ionospheric convection pattern takes longer to appear in the winds, and may not appear strongly at all.

McCormac and Smith (1984) were the first to show that there is a strong reproducible IMF B_y effect on thermospheric winds at northern high latitudes at Spitsbergen (75° geomagnetic latitude). Later work by Rees *et al.* (1984c) and Hernandez *et al.* (1991) demonstrated the effect at South Pole. Figure 4, from Hernandez *et al.* shows polar wind plots for IMF B_z negative averaged for IMF B_y negative (a) and positive (b). The two major contrasts are the direction of the winds near noon MLT which are much more strongly westward in case (a) and direction of outflow on the nightside which tended to westward for (a) and eastward for (b). The strength of the response depends the phase of the solar cycle, and is particularly strong in this case because it was near the peak. The underlying cause of the IMF B_y effect in the winds at South Pole is believed to be the change in the ionospheric convections pattern which occur for change in B_y.

6. Vertical Winds

Early studies of winds in the upper thermosphere at high latitudes were conducted on the assumption that vertical winds were very small. Many papers have appeared in the last 15 years indicating that strong vertical winds are found under disturbed conditions (Rees *et al.*, 1984a, b; Price *et al.*, 1995; Smith and Hernandez, 1995). Observations at South Pole show that ratio of vertical to horizontal wind is normally less than 10% for low geomagnetic activity (Smith and Hernandez, 1995). Air parcels may rise or fall relatively slowly in the sense that the trajectory is angled upwards or

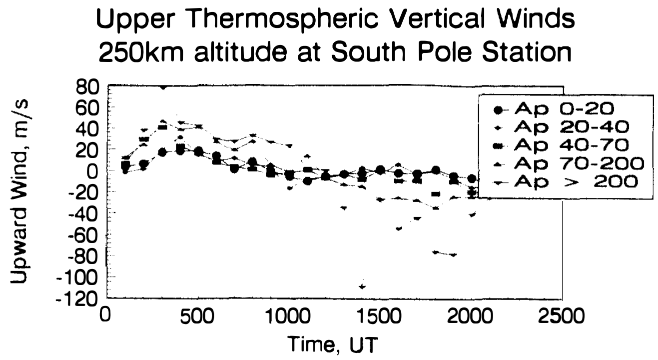

Fig. 5. Mean upper thermospheric vertical winds above South Pole for 1991 plotted as a function of universal time and averaged for ranges of Ap between 0 and 200.

downwards at a small angle. Local disturbance is limited because parcels do not rise very far in the local air column. An equivalent statement is that air parcels follow the surface of constant pressure and local hydrostatic equilibrium is preserved.

At times of stronger disturbance, upward and downward speeds have been measured exceeding 100 m/s and also exceeding 30% of the horizontal component. As described and explained in Rees *et al.* (1984b), motions of this kind are likely to have caused a partial breakdown of hydrostatic equilibrium and to have induced strong vertical mixing. In such locations, upward motions introduce molecular species at much greater heights than normal, changing the chemistry and thermodynamics of the locality. In the storm of June 1991, Fig. 5 shows how the very strong downward motion which was found to occur on the dayside of the auroral oval and upward motion poleward of the oval at night increased with the logarithmic geomagnetic index Kpsum. Open symbols represent measurements near solar maximum while filled symbols represent data nearer solar minimum. While the upwelling was explained in terms of locally strong Joule heating due to currents in the lower ionosphere (Smith and Hernandez, 1995), major downwelling cannot be understood that way.

A mechanism for strong downwelling was first proposed by Rees *et al.* (1984b). Primary downward motion, not associated with a nearby upwelling, requires a pump which removes air parcels from a column of atmosphere. Upper air parcels then descend to re-establish hydrostatic equilibrium. Divergent flow induced by divergence in the ion convection pattern acts as a pump, reducing the pressure locally, principally at the height where drag is strongest. Some published ionospheric convection patterns (*e.g.*, see Heppner and Maynard, 1987) show convergent flow regions in the dayside near the throat where ionospheric plasma enters the polar cap.

7. Strong Storm Conditions at South Pole

Figure 6 shows the variation of upper thermospheric temperatures measured at South Pole during the June 1991 storm. Disturbance reached extremely high levels during June 5, 11 and 13. Correspondingly there were peaks of temperature more than 500 K above normal on each of those days. Horizontal and vertical winds were also

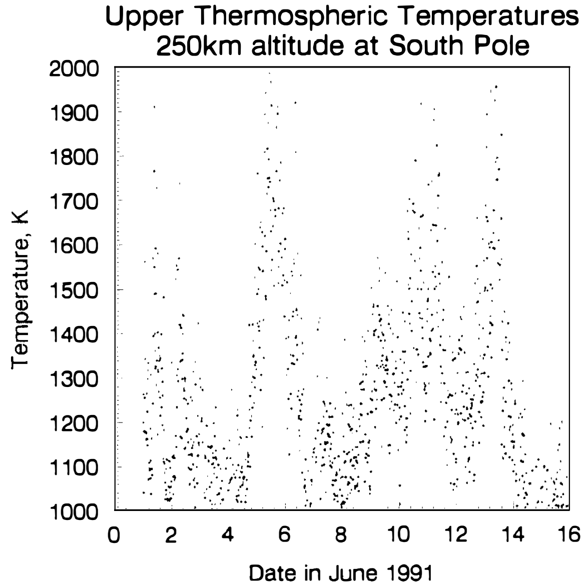

Fig. 6. Upper thermospheric temperatures measured at South Pole during the geomagnetic storm period June 1-15, 1991.

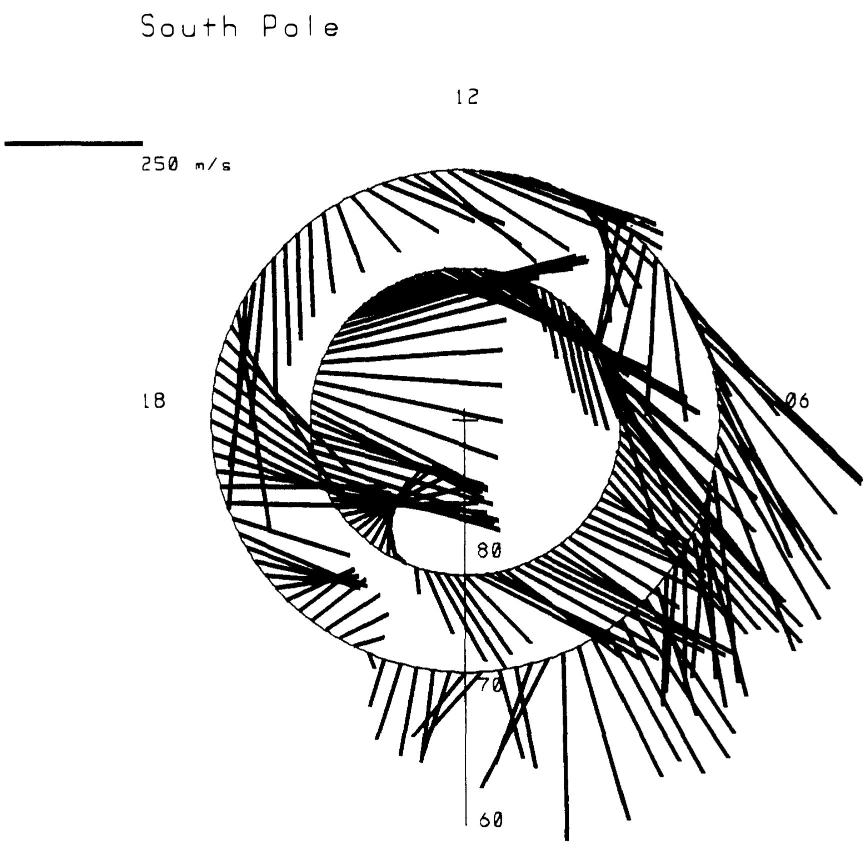

Fig. 7. Polar plot of measured winds in the upper thermosphere at South Pole, Antarctica for the storm day June 5, 1991. The center of this plot is at the geomagnetic pole, the circles are in geomagnetic latitude and times are marked in MLT.

stronger. In the study of Space Weather, the thermosphere is the last element of the chain of exchange of energy dumped in the Earth's environment. The immediate effects were strong heating and the generation of unusually strong winds, as are shown in Fig. 7 for June 5. A comparison of Fig. 7 with Fig. 2 illustrates the great change in wind magnitudes from magnetically quiet times.

The dissipation of dumped heat and momentum occurs by the enlargement of the area of strong winds hence spreading flow momentum over a wider area. As the storm subsides, the region of hot windy thermosphere retreats to more normal proportions. Study of these strong storm effects enables the estimation of the total heat and momentum coupled into the atmosphere during a storm event. Evaluation of the rise and fall times of the disturbance in the upper thermosphere reveals insights into the maximum power developed by the solar wind-magnetosphere system and the recovery processes of the thermosphere, respectively. Both are important factors in the study of Space Weather.

8. Conclusions

The thermosphere at South Pole is subjected to a wide range of stimuli causing changes of temperature, wind and composition. Once fully understood, observation of these changes can be used to diagnose the state of the coupled solar wind-magnetosphere-ionosphere-thermosphere system. Reports of research available at the time of writing show that many of the gross features of thermospheric behavior at high latitudes can be simulated by fully-featured thermosphere-ionosphere general circulation models such as the TIEGCM (RICHMOND *et al.*, 1992; SMITH *et al.*, 1998). Several important issues remain, such as a full evaluation of the consequences of the powerful vertical winds and the search for the remaining factors which will enable a precise prediction of thermospheric behavior during magnetic disturbance. Progress in this area requires measurements which will enable the computation of all important terms in the momentum equation. Satellite measurements of the density and composition of the thermosphere must be combined with a full description of the wind field and ionospheric convection. The TIMED satellite planned for launch at the turn of the millennium will remotely sense the density and wind fields at 90 minute overpasses. Further observations of winds are required in order to coordinate with the Southern Hemisphere SUPERDARN radar observations of ionospheric convections.

Acknowledgments

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