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Mapping the Wind in the Polar Thermosphere

A Case Study Within the CEDAR Program

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Introduction

The thermosphere is that region of neutral atmosphere in which atmospheric constituents are gravitationally bound to the Earth but are barometrically distributed according to their molecular or atomic weights. Unlike the lower atmosphere, mixing processes are weak, which allows each constituent gas to behave independently. The thermosphere begins at about 100-km-altitude and extends up to 500 km or beyond. The temperature increases with height throughout the layer, which is a stabilizing influence. Solar ultraviolet radiation partially ionizes the ambient gas to produce an ionosphere.

The lower thermosphere is host to the E region of the ionosphere in which the ions move with the neutral atmosphere since their collision frequency with neutral atoms far exceeds the gyrofrequency. The upper thermosphere where the F region of the ionosphere may be found contains ions which, in the presence of an applied electric field E, are free to drift in the $E \times B$ direction (where B is the geomagnetic field vector) since here the gyrofrequency far exceeds the collision frequency.

The fact that the ionosphere and thermosphere are interpenetrating fluids causes interesting coupling phenomena in which, at low altitudes, the thermospheric wind drives the ionosphere across magnetic field lines in the E region in a giant atmospheric dynamo. At high altitudes above 180 km and particularly at high latitudes, upper thermospheric motion is partly driven by the drag from collisions with ions moving at high speed with the ionospheric $E \times B$ drift (hereafter called convection). At high latitudes the pattern of convection often has a twin cell form in which the flow is antisolar across the magnetic pole and sunward at the dawn and dusk flanks.

The collisional coupling between the ionosphere and the thermosphere is of primary importance in the global dynamics and thermodynamics of the region [*Killeen et al.*, 1983, 1984, 1985; *Killeen and Roble*, 1984; *McCormac and Smith*, 1984; *McCormac et al.*, 1985, 1987; *Meriwether*, 1983; *Rees et al.*, 1986; *Rees and Fuller-Rowell*, 1987; *Roble*, 1983; *Roble et al.*, 1984; *Sica et al.*, 1986*a*, *b*; *Smith et al.*, 1982, 1985, 1988]. This coupling is of great importance to the high-latitude region in that it is a source of heat and momentum to the neutral medium. Ultimately, however, the power source is the solar wind with the energy inflow mediated by the magnetosphere and the ionosphere.

Mid- and low-latitude regions also receive energy and momentum from this source, but the input is indirect. Polar heating and momentum is communicated to lower latitudes by the strong equatorward winds (of several hundred meters per second) and horizontal traveling waves of long wavelength. Also, the equatorward motion of the auroral zone boundaries enlarges the effective polar region and brings the power source closer to lower latitudes.

The thermosphere couples back into the ionosphere by the diurnal cycle of heating and cooling of the atmosphere induced by solar heating and the rotation of the Earth. Also, the meridional component of the neutral wind induces field-aligned diffusion of ionospheric plasma, changing the F layer height and density on a global scale. Additionally, the same meridional wind affects the global F region energy budget through the movement of mass, energy, and reactive minor constituents via a giant pole-to-pole Hadley cell.

Thermospheric wind investigations at all latitudes are crucial in context of this coupling in order to study the dynamics of the global interactive system of which the thermosphere is a part. Simulations have been made by coupled ionospheric-thermospheric general circulation models which take these global effects into account [*Rees and Fuller-Rowell*, 1987; *Roble et al.*, 1982, 1987]. They show that the strength of the coupling between the two fluids is dependent on the ionization density or the conductivity of the ionosphere. This is a variable factor, dependent on short-term effects of auroral ionization, also the short- and long-term effects of solar ionization as it varies in the diurnal, seasonal, and solar cycles. In the present case under investigation of a period of dark winter conditions in the polar cap at solar minimum, the coupling was expected to be weak.

CEDAR Approach to Global Studies

We are now in the postsatellite era of global study of the thermosphere when the necessary wide-scale coverage must be gained by internationally organized ground-based campaigns of observation. Through the CEDAR (Coupling, Energetics and Dynamics of Atmospheric Regions) program of the Atmospheric Sciences Division at the National Science Foundation, such campaigns are organized and carried out with the help of our colleagues in the United States and overseas.

This program continues a long history of investigation of the thermosphere and many previous programs which have been organized to gain a global perspective, such as the Global Thermospheric Mapping Study, and satellite programs such as the NASA Atmospheric Explorer series and Dynamics Explorer. The purpose of this paper is to present one part of the CEDAR program which illustrates the power of combination of full vector wind data from several data sites in the northern arctic.

In principle, the investigation of the coupling of the ionosphere and thermosphere can be achieved by the combination of measurements from optical interferometers, incoherent scatter radars, and radio sounders (ionosondes). The incoherent scatter radars are relatively few in number (six at the time of the experiment reported here) but are the most valuable component for the determination of ionospheric drift, temperatures, and densities as a function of altitude over a wide area surrounding the site. The meridional component of the thermospheric wind may be deduced indirectly from the data. The optical interferometers whose global distribution is shown on the world map presented on the cover are good for the measurement of thermospheric wind at all latitudes and for all components of motion, although being passive and optical, they are dependent on clear weather for good observations to be made.

These measurements also rely on an independent determination of the height of emission since one cannot utilize a ranging technique as for the radar and radio sounders. Ionosondes record the radio reflection height as a function of frequency and are useful for determining the electron density variation with height up to the F-region peak which is frequently near 250 km. Also, with some careful analysis of the data, mid-latitude ionosondes can be used to infer the meridional component of the thermospheric wind [*Miller et al.*, 1986].

A special, internationally coordinated campaign was organized for the 4-day period January 14–17, 1986. This campaign had a global distribution of 22 possible optical stations and six possible radars specially organized to participate covering both hemispheres. Ionosonde stations were also alerted to the existence of this special period. In the event, four optical stations were operating in good weather at high northern latitudes: Svalbard,

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Cover. This illustrated map of optical stations specializing in the measurement of thermospheric winds by high-resolution spectroscopy was compiled by J. W. Meriwether, Jr. See "Mapping the Wind in the Polar Thermosphere," this issue.

Kiruna, Thule, and Fairbanks, and these were able to contribute major amounts of vector wind data representative of heights close to 250 km. These stations, being in contiguous regions and close to the three northern hemisphere high-latitude radars, have been selected for a study of the wind field during one day of the period when the activity was particularly low (Figures 1 and 2). On this day there was data from all stations, but Kiruna was in daylight at the time of interest and thus unable to observe. The coordinates of the stations used in the study are given in Table 1.

TABLE 1. Coordinates of Stations

Station	Geographic Latitude	Geographic Longitude	Magnetic Latitude
Sondrestrom	67.0	−50.0	75.0
Fairbanks	65.1	−147.5	64.8
Svalbard	78.2	15.6	75.0
Thule	76.5	−68.7	85.7

This paper concentrates on the dynamics of the high-latitude region using the optical wind data and the radar ion drifts to study the situation. These observations will be considered against the backdrop of a representative general circulation model. This is the first study of its type to include such a good grouping of stations making it worthwhile to represent the data obtained on a scale of the entire high-latitude region.

Description of Data

The plot of the magnetic auroral index AU/AL for the day in Figure 1 shows continuous low activity. It is presumed for the discussion of the data that the rather quiet Q = 2 auroral oval [*Feldstein,* 1963] is appropriate for orientation. A sequence of four station maps is shown in Figure 2 with the auroral oval included for guidance on the topography with relation to magnetospheric coupling at 0900, 1200, 1400, and 1600 UT. Since these are estimates only, no great reliance should be placed on borderline positions of stations in relation to the auroral oval.

The polar cap, in the context of this work, is the region inside the inner circle of the auroral oval. Previous work [*McCormac and Smith,* 1984; *McCormac et al.,* 1985; *Rees et al.,* 1986] has indicated that the direction of the magnetic vector in the solar wind just upstream of the Earth is an important factor in determining the ionospheric drift pattern in the *F*-region and the thermospheric wind. The component of the solar wind field in the axial direction of the Earth's dipole (B_z) was initially southward but turned northward near 1000 UT and remained so until 1700 UT. The peak northward value was 6 nT. After 1700 UT, B_z was southward by a few nanotesla. For the whole period from 1000 UT to 2300 UT the transverse component (B_y) was toward dawn (negative).

The Sondrestromfjord radar measured ion drift during this period as is shown in Figure 3. This figure represents in polar map form the available observations made during that day. Each vector is plotted with its tail fixed to the location of the observation; the direction and length represent the measured ion drift; bold vectors are westward, others are eastward. As time elapses, the Earth rotates on the dial and all measurements made with the radar at the same range and pointing direction are seen as a trail of vectors whose tails lie on a circle of latitude. This figure is not a snapshot representation of the drift but rather a presentation of the time-evolving drift which emphasizes its global context.

After 1700 UT when B_z was southward, the record is typical of B_y negative conditions in that the high-latitude vectors are predominantly eastward [*de la Beaujardiere et al.,* 1985]. Prior to that, the convection pattern appeared somewhat fragmented, probably because of a more complex situation which is common when B_z is northward. The pattern shows the wind directions which ion-neutral collisions were tending to set up in the vicinity of the Sondrestromfjord radar. Thermospheric wind behaves like a low-pass filter with a time constant of about one hour; hence only the longer-lived features on this plot would have had any effect.

Figure 4*a* shows the optical Doppler wind measurements made during a period of one hour centered on 0900 UT on the 17th of January 1986 in which wind vector data for Fairbanks, Thule, and Svalbard are shown against a backdrop of a representative instantaneous thermospheric general circulation simulation (arrows). In contrast to Figure 3, this is a snapshot, albeit with the equivalent of one-hour exposure. Each station has four vectors shown plotted with their tails on a one-hour-long latitudinal arc on its equatorward side and similarly, four poleward. These result from a combination of the single-component wind measurements made at a fixed elevation in the cardinal points of the compass.

The station map in Figure 2*a* shows Svalbard in the noon sector of the auroral zone while Thule lies in the central polar cap and Fairbanks is just equatorward of the evening auroral zone. The wind is antisolar at all stations and in reasonable agreement with the backdrop model and with many previous single-point observations and satellite crossings.

As time advances through 1100 UT, the pattern changes little. By 1200 UT, however, when the ionosphere on the dayside of the auroral zone has advanced into sunlight, Thule, which is a central polar cap station, began to see a region of sunward wind on the poleward side as shown in Figure 4*b*.

By 1300 UT, the unusual sunward wind was observed on the poleward side of Svalbard as well and is well developed by 1400 UT as shown in Figure 4*c*. At the same time, both Svalbard and Thule continued to see poleward winds to the south. The map at 1600 UT (Figure 4*d*) indicates that the sunward disturbance had crossed from the poleward to the equatorward side of Svalbard while remaining poleward of Thule. A noticeable wind divergence remained at Svalbard until the resumption of a normal pattern at 2000 UT. By this time, reference to Figure 2*d* shows that the station had moved across the Q = 2 oval and progressed into the polar cap. More normal winds returned to Thule by 1800 UT, approximately local noon for that station.

Discussion

There is no evidence that there was only one disturbance; there could have been one, two, or conceivably more than that. Likewise, it is not possible to fully and unambiguously distinguish temporal from spatial aspects of the observation. Since many aspects of the dynamics of the thermosphere in the polar cap are determined by factors which are almost stationary in an Earth-Sun coordinate system, we may suppose as a first approximation that the disturbance found in these observations is also a phenomenon fixed in that frame. Other possibilities such as a large-scale gravity wave are not entirely eliminated, but also not thought likely because of the low activity and expected lack of sources. This disturbance, first seen at around 1100 UT poleward of Thule in the morningside of the polar cap, was not observed 6 hours earlier when Svalbard passed at the same local time. It is reasonable to suppose that it appeared in the time period 0600–1200 UT. As mentioned above, the northward turning of B_z occurred at about 1000 UT. Any response to the accompanying changes in the convection pattern would be expected to take at least one hour under these circumstances of (assumed) weak coupling. Hence it is consistent with the observation that the first appearance of sunward winds due to the sunward polar cap convection expected for northward B_z conditions [*Heppner,* 1977; *Heppner and Maynard,* 1987; *Heelis,* 1984] appeared near 1200 UT.

The Thule station spent about 4 hours in the sunward wind disturbance and saw it dis-

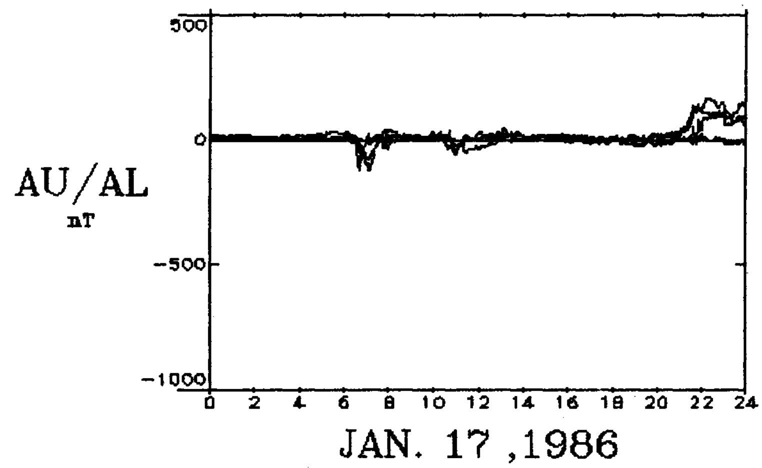

Fig. 1. Traces of AU and AL for January 17, 1986 (courtesy of S. -I. Akasofu).

appear at about local noon. The Svalbard station first saw the sunward wind disturbance at 1300 UT and observed it for several hours on the poleward side, then disappearing equatorward at about 1600 UT. The period of B_z northward ended near 1700 UT, which indicates that if the ionospheric convection pattern remained approximately constant during the 7-hour period, the Svalbard station merely passed under the nightside edge of part of the sunward wind disturbance.

Most modeled wind structures in the polar thermosphere show a broad swath of antisolar flow across the cap with minor changes of direction due to changing solar wind and the offset of the magnetic pole from the rotation axis. Recent coupled thermosphere-ionosphere modeling by the University College London group [*Fuller-Rowell et al.*, 1987] shows that it is reasonable to expect localized eddies of sunward wind in a generally antisunward flow for conditions such as occurred near noon UT on January 17, 1986. Figure 5 shows a plot of winds simulated by the UCL group over the northern polar cap at a height of about 300 km when B_y was negative and B_z was northward. This computation uses the convection model of *Heppner and Maynard* [1987], which has a region of sunward convection in the polar cap. The implication of the wind pattern shown is that near 1200 UT under winter solar minimum conditions ion-neutral collisions transfer sufficient

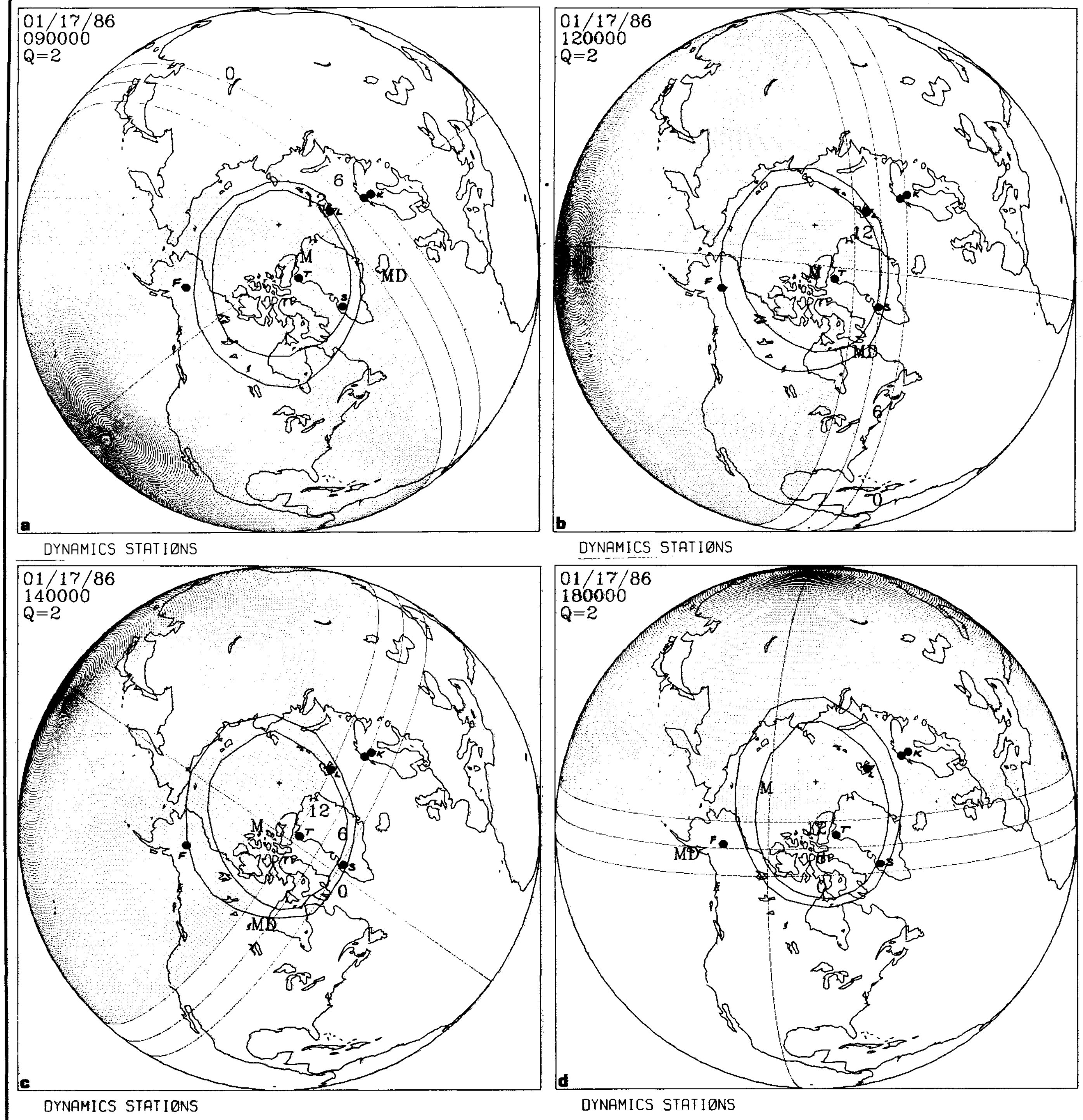

Fig. 2. Maps showing the relative positions of stations (Thule (T), Svalbard (L), Sondrestromfjord (S), Kiruna (K), and Fairbanks (F)) involved in this study and the $Q = 2$ Auroral Zone. The shaded part indicates regions of darkness beyond 12° solar depression. The terminator and loci of 6° and 12° solar depression are also shown. The curve marked M is the boundary of moonlit atmosphere, the dark side being indicated by MD. Panels (a)–(d) show the changing relationship of the stations to the oval as a function of Universal Time.

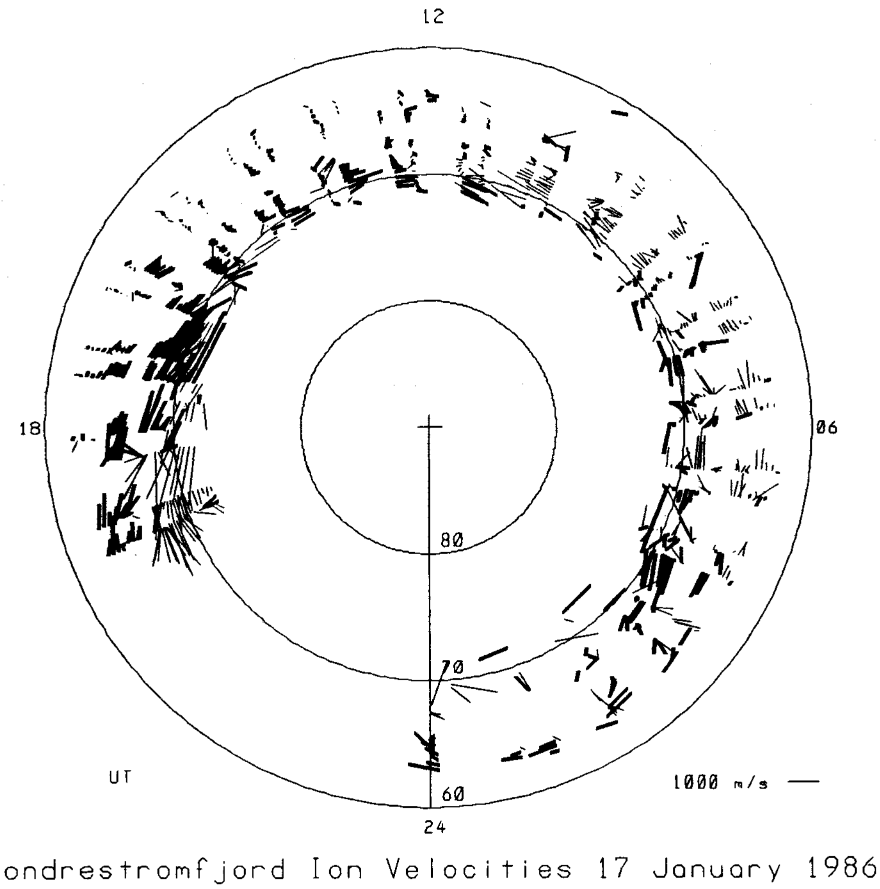

Fig. 3. Polar plot of ion drift measured by the Sondrestromfjord radar for January 17, 1986, as a function of latitude and Universal Time. The vectors are plotted with their tails on the point of measurement; those which are westward are in bold face.

momentum to reverse the normal antisunward flow in restricted regions, one in the morning and one in the afternoon. The collisions also generate heat and raise the temperature of the gas as is seen from the dark-shaded tongue extending into the morningside of the polar cap from noon. This is where the strong sunward ion drift is located which causes the thermosphere also to flow sunward. It will also be noticed that there is another region of sunward flow at relatively high latitudes up to 80° geographic on the evening side. At 1200 UT the local time at Thule is about 0700, which places it near the morning eddy. The 1200 plot shows that the poleward vector has turned sunward. According to observation, the eddy lies poleward of the station as it does in the simulation. Svalbard local time is 1300, which places it near the start of the evening eddy. At 1200 UT the antisolar wind vector on the poleward side from Svalbard is reducing as if to turn sunward. At 1300 UT both stations show sunward wind on their poleward sides which is very much as simulated by the UCL model. The model also indicates that Thule should rotate out of the poleward flow by about 1100 LT (1500 UT) and that the region of sunward flow will pass equatorward of the Svalbard meridian after 1800 LT (1700 UT). These latter comments assume that the 1200 UT pattern from UCL model remains fixed over some 5 hours. The 1800 UT plot from the model shown indicates that this is not so but that even with constant B_z northward conditions, the sunward parts of the eddies disappear with changing UT. Thus the simulation suggests that the observed disappearance of sunward wind features was due to their dying out.

Conclusion

The multistation data documenting this sunward wind disturbance is consistent with the hypothesis that it occurred due to ion-neutral coupling associated with sunward ion drift accompanying the northward turning of B_z. This is a much more detailed and convincing application of thermospheric wind modeling to multistation data than has been possible in the past. It has been difficult to obtain good simultaneous optical coverage in contiguous regions during an event as interesting as this one discussed here to provide a testing situation.

It would have been argued in the past that the coupling efficiency between ions and neutrals in the dark winter solar minimum polar cap would be too small to allow such a departure from the strong antisolar flow which is so commonly seen. The situation of strong ion-neutral coupling is now accepted to prevail at solar minimum despite weakened coupling which is known to exist. This case is a triumph for the CEDAR approach and shows that not only can we observe such things in unprecedented detail if we organize enough good multistation campaigns such as this, but the data can also agree with the simulation even in a relatively complex case such as this.

Acknowledgments

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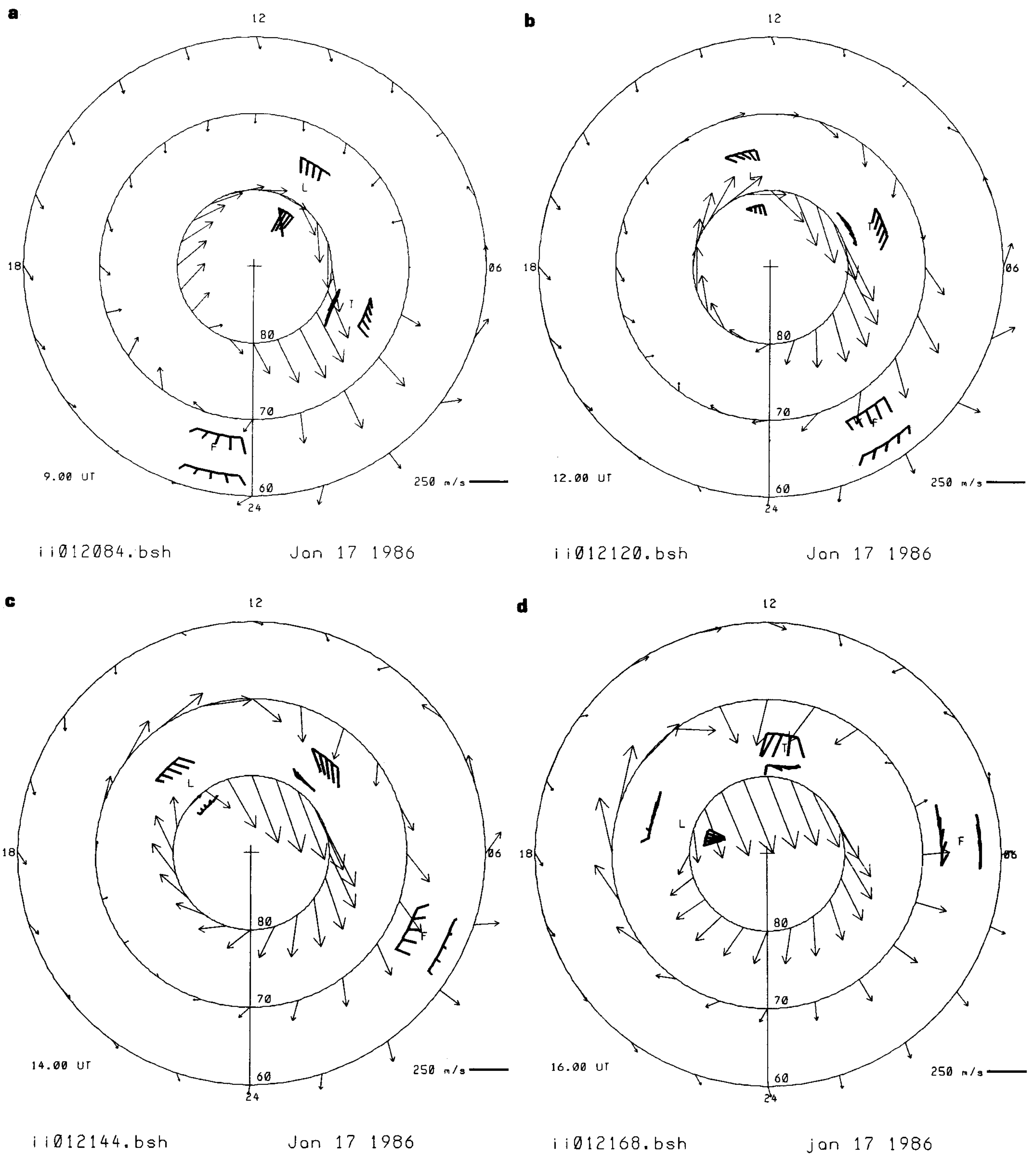

Fig. 4. Polar plots of the neutral wind measured from the four stations, Thule (T), Svalbard (L), and Fairbanks (F). Panels (a)–(d) cover Universal Times 0900, 1200, 1400, and 1600. Vectors are drawn with tails fixed to short arcs which represent the locus of the station as a function of time. For comparison, a simulation is shown as a backdrop with arrows.

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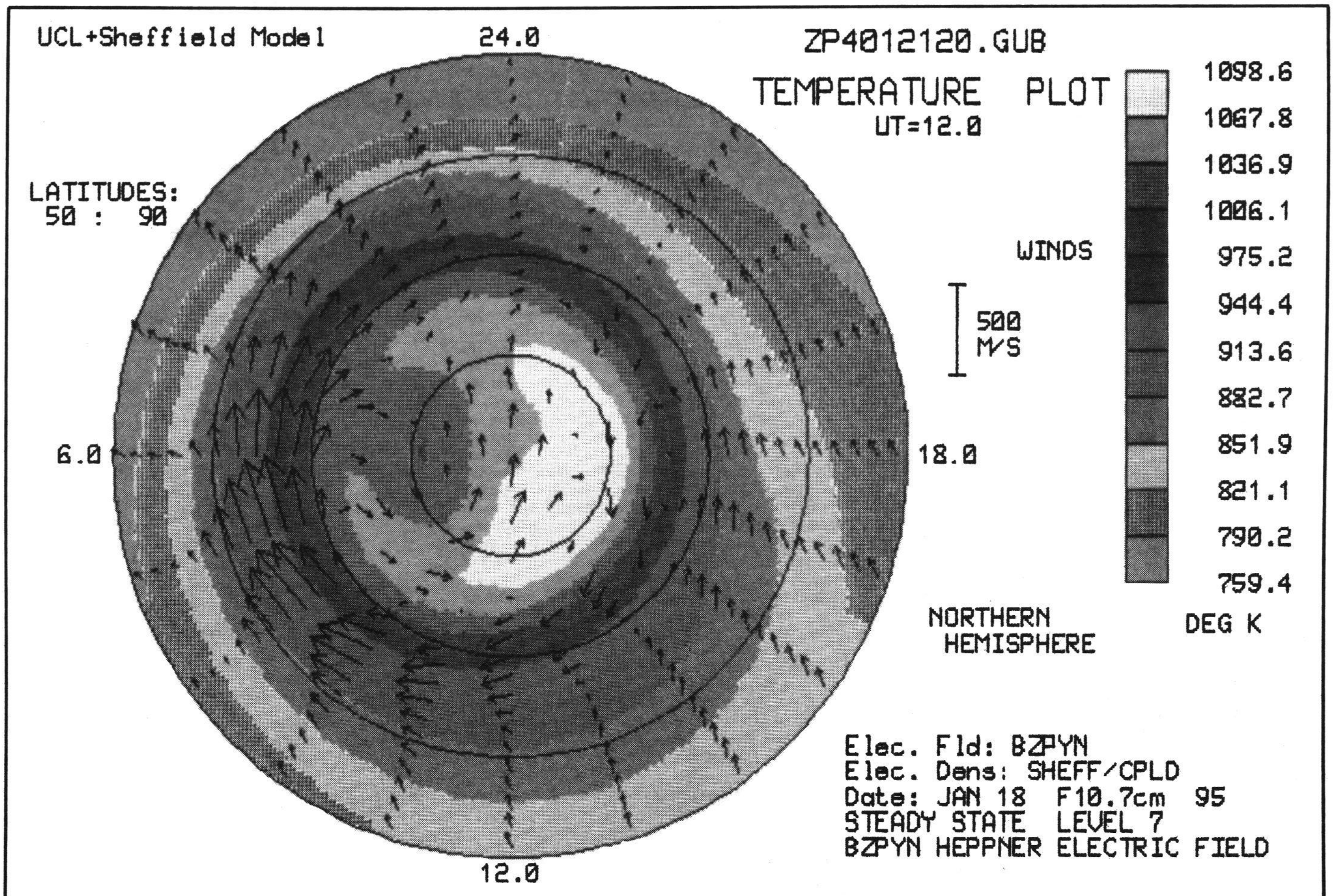

Fig. 5. Simulation by the coupled thermosphere-ionosphere model developed at University College London and Sheffield University for conditions of solar minimum winter solstice when IMF B_z is northward and B_y is negative. Winds are shown by the vectors at a constant pressure level near 300 km altitude along with underlying shading indicating the temperature at the same height. This figure originally appeared in full color. See the back of the second volume of 1989 (Volume 70, Numbers 27-52) for the color plate.

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