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MITHRAS STUDIES OF THE AURORAL OVAL AND POLAR CAP

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Geoscience and Engineering Center

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University of Michigan

SRI Project 3573

Prepared for:

Department of the Air Force
Air Force Office of Scientific Research
Bolling Air Force Base
Washington, DC 20332

Attn: Lt. Col. James Stobie
Directorate of Chemical and
Atmospheric Sciences

AFOSR Contract F49620-87-K-0007

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MITHRAS is a program of coordinated experiments dedicated to the study of the coupling between the magnetosphere, the ionosphere, and the thermosphere. The MITHRAS observations mostly involve the Sondrestrom radar in Greenland, but the other incoherent scatter radars around the world were also used.

The highlights of the scientific accomplishments during this contract can be summarized as follows:

1. The most extensive comparisons ever made between incoherent scatter radar data and numerical simulation models were performed. These comparisons were based on both individual case studies and averaged data, and included observations from all the incoherent scatter radars. The theoretical models used are widely recognized as the most sophisticated and accurate currently

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available. The comparisons showed general agreement between the observations and model calculations, but they also showed significant differences.

2. During solar-maximum conditions the contribution to the height integrated Pedersen conductivity from solar-produced F-region ionization can be as large as 60% of the total. This large contribution had been overlooked in the past.

3. Under certain geophysical conditions it appears possible to identify the low-altitude cusp and distinguish it from the cleft. The cusp proper appears to be characterized by enhanced F region plasma density collocated with elevated F region electron temperature. It does not appear to be associated with a particular signature of the plasma flow pattern.

4. A new mechanism was proposed to explain how auroral surges might be formed. It was suggested that the surge was associated with a distortion of the poleward boundary of the aurora, and that this distortion was caused by the field-aligned currents within the head of the surge.

5. Snapshots were obtained of the high-latitude convection pattern, as well as of the currents, and Joule heating rates, by combining data from radars, magnetometers and satellites.

6. The large scale convection pattern appears to depend on season, an unexpected finding.

7. The first measurements of the reconnection rate, a fundamental quantity in solar wind-magnetosphere coupling, were provided.

In conclusion, the MITHRAS work has led to a better understanding of magnetosphere-ionosphere-thermosphere coupling processes.

CONTENTS

ILLUSTRATIONS

I INTRODUCTION

MITHRAS is a program of coordinated experiments dedicated to the study of the coupling between the magnetosphere, the ionosphere, and the thermosphere. This AFOSR program was started in 1981 to take advantage of the unique opportunity to probe the high-latitude ionosphere and neutral atmosphere from three incoherent scatter radars (ISR) widely spaced in longitude. Initially, those radars were Chatanika (Alaska), Millstone Hill (Massachusetts), and EISCAT (Northern Scandinavia). The EISCAT and Chatanika radars were at similar geomagnetic latitudes, but almost 180° apart in longitude. Together, they were in operation for a very limited time period--between June of 1981, when EISCAT's operation started, and February of 1982, when the Chatanika radar was dismantled to be moved to Sondre Stromfjord, Greenland. Since March of 1983, MITHRAS-coordinated experiments have been conducted among the Sondrestrom, EISCAT, and Millstone radars.

In addition to the radars, a number of satellites, including the Dynamics Explorer [DE] 1 and 2, the NOAA and DMSP satellites, the Swedish Viking satellite, and the Japanese EXOS-D satellite contributed data to the MITHRAS program. Ground-based instruments, including coherent backscatter radars, magnetometers, Fabry-Perot interferometers, and auroral imagers were also utilized.

The MITHRAS effort consists of comprehensive observations, in-depth data analysis and interpretation, and comparisons with a number of theoretical models and simulations. MITHRAS has proven to be quite successful. The results from the program have been published in several scientific reports and in refereed scientific publications, and presented at national and international conferences. Overall, there are 52 MITHRAS publications and conference proceedings, along with the reports. In addition, the MITHRAS effort has been the basis of three Masters theses. The professional staff members associated with this research effort are O. de la Beaujardière, C. Leger, and J. Watermann, as well as R. Johnson (now at the University of Michigan), and V. Wickwar (now at Utah State University).

This program has supported the development of the tools and methodology needed to coordinate complicated, multi-instrument campaigns, and to deal with large amounts of data from disparate sources. We have developed new radar operating modes as well as computer codes to determine physical parameters from the radar observations and to display the data in various ways. We have also developed software tools to exchange data among experimenters. Some of these tools have been adopted by the upper-atmosphere community. For example, the National Center for Atmospheric Research (NCAR) data base format was based on the concepts developed under the MITHRAS project.

In this report, we briefly summarize some key accomplishments from the present contract, highlighting the new and important findings that have taken place as a result of the MITHRAS effort. A complete list of MITHRAS-related publications is given in

Appendix A, which also includes the list of theses. Preprints of papers that have not yet been published are included in this mailing.

II SCIENTIFIC ACCOMPLISHMENTS

The work accomplished on this MITHRIS project spanned the regions from the lower thermosphere up to the magnetosphere. In what follows, we describe the key points of the most recent MITHRAS papers. We categorize the work into two broad areas: the coupling between the neutral atmosphere and the ionosphere, and the coupling between the ionosphere and the magnetosphere.

A. IONOSPHERE-THERMOSPHERE COUPLING

1. Lower Thermosphere

Several studies of lower thermospheric neutral winds and densities have recently been completed. Observations obtained at Sondrestrom during the Lower Thermospheric Coupling Study (LTCS) (21-25 September 1987) have been analyzed and compared with other observations as well as with the tidal and thermospheric general circulation model calculations. The results will be published in five papers to appear in an upcoming special issue of JGR.

a. Winds and Tides

Observations of tidal motions were performed for the first time at Sondrestrom by Johnson (1991). These observations provided the opportunity to compare actual measurements with theoretical predictions by Forbes and coworkers. It was found that, although the diurnal tidal amplitudes and phases at Sondrestrom were in reasonable agreement with tidal modeling results (Forbes, 1982; Forbes and Hagan, 1988), semidiurnal tidal amplitudes and phases were not well represented in the recent calculations of Forbes and Vial (1991). Neutral winds observed under geomagnetically active conditions during the LTCS-1 experiment revealed that the effects of both Joule heating and ion drag must be considered to understand the disturbed wind field.

The first simultaneous lower-thermospheric wind observations by two high-latitude radars were presented by Johnson and Virdi (1991). The observed winds at the two radars were found to be in reasonably good agreement, although the tidal diurnal amplitudes tended to be larger at Sondrestrom than at EISCAT.

Extensive comparison with the NCAR Thermosphere Ionosphere General Circulation model (TIGCM) was also performed. An example of such comparison is illustrated in Figures 1 and 2. These figures correspond to a short time interval (22 to 23 September) when magnetic activity was high. The figures display the theoretical predictions at three different pressure surfaces, -4.5, -4.0, and -3.5 (corresponding approximately to 115, 125, and 135 km, respectively), and winds deduced from the EISCAT and Sondrestrom measurements at 120 km. An eastward surge in the neutral wind near magnetic midnight is seen at both

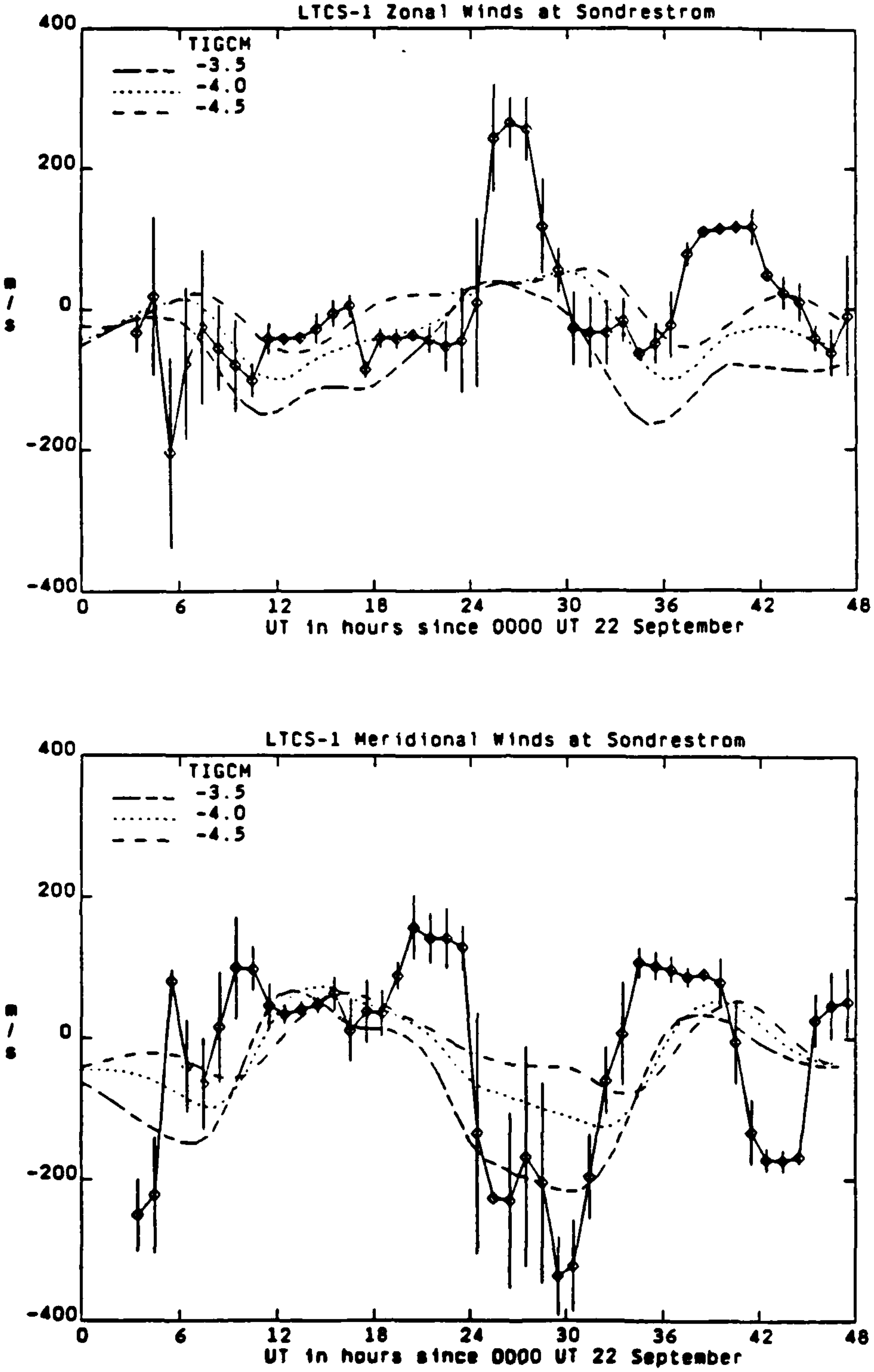
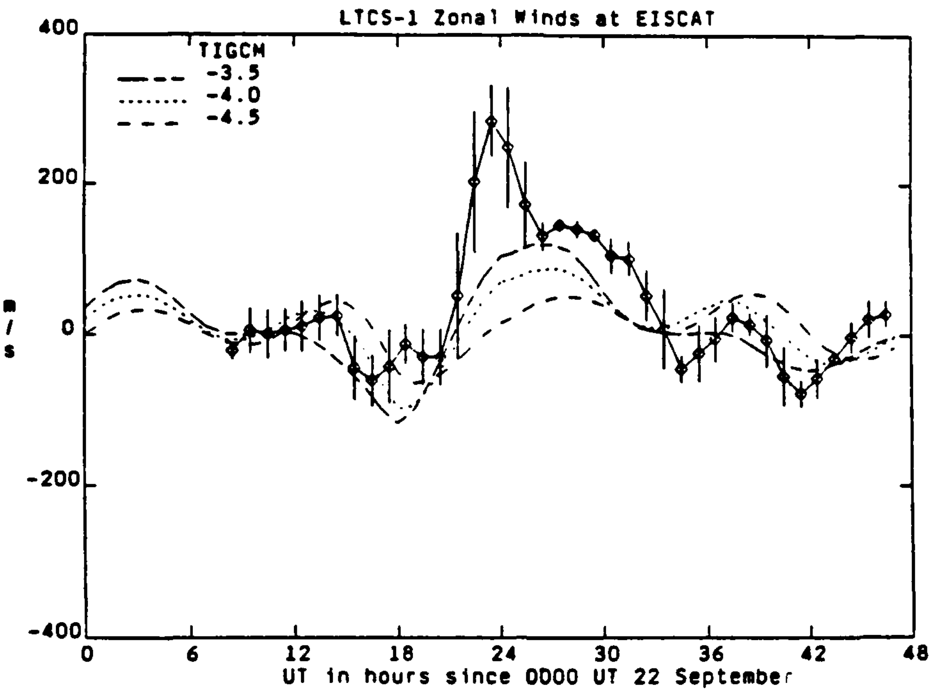


FIGURE 1 **A COMPARISON OF MEASURED EISCAT and TIGCM SIMULATED WINDS. Panels (a) and (b) are for the zonal and meridional winds (positive east and north). The model results are at the -4.5, -4.0, and -3.5 pressure surfaces (115, 125, and 135 km, respectively). 22 to 23 September, 1987.**



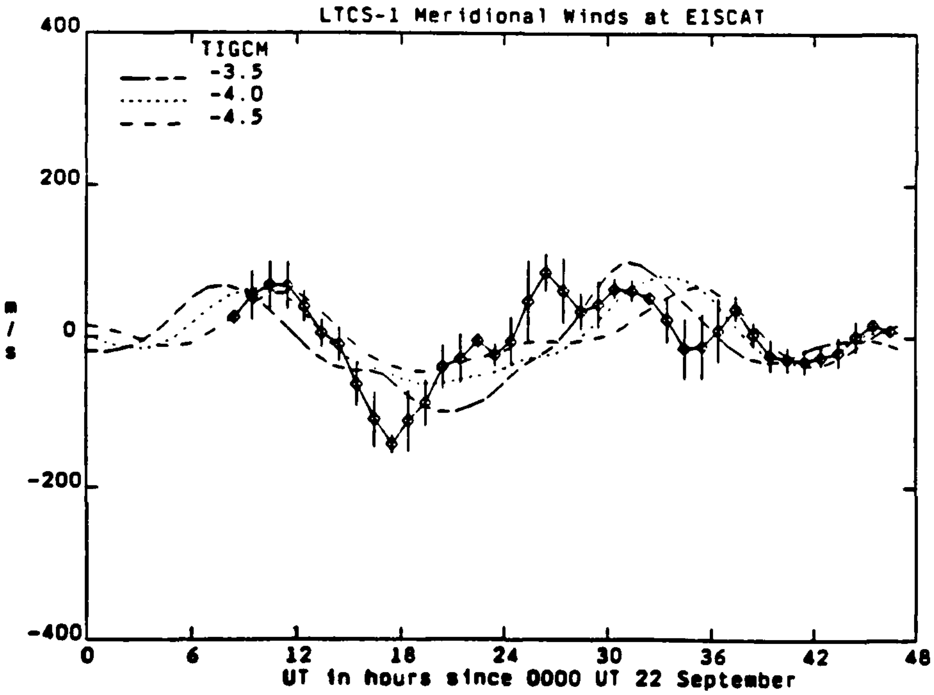


FIGURE 2 A COMPARISON OF MEASURED SONDRESTROM AND TIGCM SIMULATED WINDS. Panels (a) and (b) are for the zonal and meridional winds (positive east and north). The model results are at the -4.5, -4.0, and -3.5 pressure surfaces (115, 125, and 135 km, respectively). 22 and 23 September, 1987.

Sondrestrom and EISCAT. It is apparent that the model reproduces the observed winds at EISCAT better than at Sondrestrom. Nonetheless, the peak zonal winds observed at EISCAT during the surge near midnight on the 22nd are underestimated by approximately a factor of two, even at the z = 3.5 pressure surface, near 135 km. The TIGCM results do not extend this zonal surge to Sondrestrom, where it was clearly detected. However, the equatorward surge in the meridional wind is reasonably well represented by the TIGCM results at 135 km.

This work is important because Sondrestrom and EISCAT are at similar geographic latitudes, but at very different geomagnetic latitudes, and thus these observations provided the opportunity to assess the relative importance of forcing terms of geomagnetic origin with those due to the pressure gradients from solar heating.

In another paper, the University College London (UCL)-Sheffield thermosphere-ionosphere model was used to simulate the response of the lower thermosphere to various tidal-forcing distributions at its lower boundary (Fuller-Rowell et al., 1991). With acceptable ranges of tidal forcing, the model is able to simulate wind and temperature responses within the range of the observations at EISCAT, Sondrestrom, Millstone Hill, and Arecibo. The semidiurnal ion-temperature response is shown to be driven by geomagnetic processes, rather than tides, and differences between the ion and neutral temperatures are shown to penetrate down to 110 km during active conditions.

Salah et al. (1991) studied the consistency between the incoherent scatter wind and temperature observations at Arecibo, Millstone Hill, and Sondrestrom. Good agreement was found in the average temperature profiles, and semidiurnal phase profiles show reasonable consistency among the three stations.

b. Ion Neutral Collision Frequency

Ion-neutral collision frequencies obtained during LTCS-1 have been analyzed to obtain neutral densities (Rees et al., 1991a). Tidal analysis shows that the amplitudes of the diurnal and semidiurnal components are approximately equivalent. Comparison with TIGCM simulation shows that, although the semidiurnal phase profiles are in good agreement, the amplitudes are considerably larger than those from the TIGCM.

The analysis of ion-neutral collision frequencies described above has been expanded to include measurements obtained in Chatanika from 1976 through 1982 (Rees et al., 1991b). Collision frequency profiles throughout this period reveal a strong correlation with the solar cycle, indicating a dependence of the lower thermospheric mean temperature on the solar cycle. The percentage amplitudes of the semidiurnal tides observed at Chatanika are in agreement with the observations of Kirkwood (1986) at EISCAT.

2. F-region Electron Density and Neutral Atmosphere

Efforts related to the F-region ionosphere and thermosphere, which were part of a subcontract to Utah State University (USU), are summarized in a report (Wickwar, 1990) included as Appendix B. This work has appeared in journal articles and in three Masters' theses. The most salient aspects of this work are described below.

a. F-region Neutral Wind

Wickwar (1989) carefully reexamined how the meridional neutral wind is derived from incoherent scatter radar data. He found that in calculating the contribution of ion-neutral diffusion to the observed ion velocity, the neutral atmosphere density (particularly O and N_2) and the ion-neutral collision cross sections (particularly O^+-O) are extremely important. An error in these parameters can lead to systematic errors that are most significant during the night. Ion composition and thermal diffusion are not found to have significant effects.

Winds from incoherent scatter radars at high and mid-latitudes were examined (Wickwar et al., 1990) and compared to both the UCL-Sheffield coupled model and the NCAR TIGCM. The comparisons showed general agreement between the observations and model calculations, but they also showed significant differences. The modeled daytime winds at high latitudes are too strong to the north. The modeled seasonal variation at high latitudes is too small. Significant phase differences exist between the modeled and observed winds, with the NCAR model ahead of the observations and the UCL model behind. The NCAR-modeled southward wind during the nighttime at mid-latitudes is too strong.

b. Oxygen Collision Frequency

The O^+-O collision cross section and the number density of atomic oxygen [O] were examined (Christie, 1990). This was done by comparing nighttime thermospheric winds obtained by two techniques at Sondrestrom from 11 nights between 1983 and 1988. The horizontal winds in the magnetic meridian were derived indirectly from ISR measurements of the component of ion drift velocity parallel to the magnetic field, and directly from Fabry-Perot interferometer (FPI) measurements of Doppler shifts of the 6300-Å emission from atomic oxygen. In deriving the radar winds, the O^+-O collision frequency, which involves the product of the O^+-O collision cross section and [O], was scaled by a factor f that was varied from 0.5 to 5.1. The best agreement between the ISR and FPI winds was obtained when f was increased substantially, to between 1.7 and 3.4. If it were assumed, in agreement with Burnside et al. [1987], that the O^+-O collision cross section should be increased by a factor of 1.7, then any departure of f from that value would indicate a variation of the atomic oxygen density [O] from the value determined by the MSIS-86 model of the neutral atmosphere. The full range of [O] was then varied from 1/3 to 3 times the MSIS value, the best agreement with optical measurements was obtained when this factor was 1 during periods of moderate solar activity ($F_{10.7} > 100$) and 2 during periods of low solar activity ($F_{10.7} \sim 70$), characteristic of solar-cycle minimum.

c. Global Distribution of Electron Densities

F-region densities derived from the USU Time Dependent Ionospheric Model (TDIM) were compared to Sondrestrom, Millstone Hill, and Arecibo data using more than 50 days of observations (Rasmussen et al., 1986, 1988a; Johnson, 1990). The overall first-order result of the comparisons is that the model reproduces the electron densities at the three radars for a variety of diurnal, seasonal, geomagnetic, and solar-cycle conditions However, some significant discrepancies were also found. These include a fall-spring asymmetry in the Sondrestrom densities, a secondary electron density peak in the evening at Millstone Hill, and a strong time variation in the Arecibo densities. These differences are believed to stem from inadequacies in the inputs to the theoretical model, and require further investigation.

B. MAGNETOSPHERE-IONOSPHERE COUPLING

1. Conductivities

A number of studies were devoted to the Hall and Pedersen conductivities. Ionospheric conductivity is a fundamental parameter in magnetosphere-ionosphere coupling: it regulates how much energy is dissipated by Joule heating, modifies the direction of the electrojet currents in the ionosphere, and determines the ionospheric closure of field-aligned currents.

The height-dependent conductivities were derived from theory by Rasmussen et al. (1988b). In a separate study, de la Beaujardière et al. (1991a) examined the Pedersen conductivities at F-region altitudes above 180 km, using Chatanika and Sondrestrom radar data. It was shown that during solar-minimum conditions, the F region contributes less than 20% to the height-integrated Pedersen conductivity, Σ_p. In contrast, during solar-maximum conditions the contribution to Σ_p from solar-produced F-region ionization can be 60%.

This large contribution from the F region to the height-integrated Pedersen conductivity had been overlooked in the past. It has the following consequences in terms of high-latitude electrodynamics:

(1) Over a significant fraction of the F layer, the ions do not move in precisely the $\mathbf{E} \times \mathbf{B}$ direction; instead, collisions have the effect of deflecting them toward the direction of **E**.

(2) Some of the rotation of the current vector, $\mathbf{J}_\perp$, occurs within the F region, rather than wholly within the E region.

(3) A large fraction of the field-aligned current closure by Pedersen current occurs in the F region.

In a separate study (Watermann et al., 1991), we have collaborated with F. Rich from the Geophysics Laboratory on a comparison between Σ_P inferred from coincident DMSP-F7 electron spectrometer and Sondrestrom radar measurements. The contribution of energetic electron precipitation to Σ_P was calculated after Robinson et al. (1987). In the dark ionosphere, the agreement between their model and Σ_P estimated from radar observations proved to be good.

In the sunlit ionosphere, however, the radar-derived Pedersen conductivity term that is due to photoionization from solar UV and EUV radiation remained consistently smaller than values obtained from various models, including those of Robinson and Vondrak (1984), Rasmussen et al. (1988a), and Kroehl et al. (private communication). The discrepancy between model and radar measurements appears to increase with decreasing solar cycle and solar zenith angle.

In these models, the solar-produced conductivities are calculated as a function of the solar 10.7 cm radio flux, F 10.7. A possible explanation for the discrepancy between model and data might be that, as shown by Barth et al. (1990), the intensity of the ionization by solar radiation is not always proportional to the F 10.7 flux, as is assumed in the conductivity models. Therefore, our preliminary conclusion is that the F 10.7 flux might not be a good parameter for estimating the solar contribution to the E-region ionization and conductivities.

2. Ionospheric Signatures of the Polar Cusp

We have begun to examine data from a series of Sondrestrom incoherent scatter radar experiments with the objective of identifying ionospheric cusp signatures. The cusp is the region where magnetosheath particles have direct access to the earth's ionosphere; it is characterized by large fluxes of low-energy particles. To determine where the cusp was locat' d at a given time, we interrogated the remotely accessible DMSP data base (Newell et al., 1990), which provides compact information about low-altitude footprints of magnetospheric regions. The DMSP categorization is based on spectral properties of energetic ion and electron precipitation.

Our preliminary results (Watermann et al., 1990) suggest that it is possible under certain geophysical conditions to identify the low-altitude cusp and distinguish it from the cleft (dayside portion of the auroral oval). The cusp proper appears to be characterized by enhanced F region plasma density collocated with elevated F region electron temperature. It is not associated with a particular signature of the plasma flow pattern. In contrast to the more energetic cleft particles, the basically soft cusp precipitation with an average energy of the order of 100 eV produces no significant effects in the ionospheric E region. Electron energy balance calculations are invoked to permit distinction between local plasma density enhancement through ionospheric convection and through ionization from precipitating electrons.

This work is still in progress and will be pursued using additional observations of the Sondrestrom radar coincident with DMSP as well as with a variety of spacecraft. These include the Akebono (formerly EXOS-D), DE-1, and DMSP-F6, -F8 and -F9 satellites. We regularly obtain updated orbital elements of the spacecraft and monitor their trajectories across the western part of Greenland. We have developed software to plot the tracks of the spacecraft and of the footprints of the associated field lines in the ionosphere. The software allows us to routinely predict upcoming spacecraft passes, select suitable observation periods, and schedule appropriate radar coverage. Agreement on collaboration with the Principal Investigators has been established. We have exchanged data with the Akebono Science Team and collaborate with the Aerospace Corporation on analyzing an interesting event of coincident Sondrestrom/DMSP-F6/DMSP-F8 observations. We also have identified a number of passes of the Swedish Viking satellite covered by radar operation, and started data exchange and collaboration with the Viking team. Joint efforts on data analysis have begun and will continue in the future.

3. Relationship Between Birkeland Currents and Particle Precipitation Regions

Coincident DMSP/Sondrestrom observations were analyzed to determine how the particle precipitation regions such as cusp, mantle, or cleft are related to electric field and Birkeland currents. This work, still preliminary, was described in de la Beaujardière et al. (1990). The conclusions reached can be summarized as follows:

The convection reversal is at the boundary between open and closed field lines in only 50% of the cases. No systematic relationship seems to exist between the region 1 current and the convection reversal location. The Birkeland current boundaries do not generally correspond to the particle population boundaries. The local time extent of the traditional "cusp" currents is not limited to the longitude of the cusp proper. The "cusp" currents flow entirely on open field lines. The region 1 current straddles the polar cap boundary. This is consistent with Stern [1973] and Siscoe et al. [1990] who showed that the region 1 currents are generated by the solar wind dynamo and flow within the separatrix.

4. Substorms

Several MITHRAS studies involved magnetic substorms. The two most recent ones were concerned with auroral surges. In the first one, coincident SSF and Viking imager data were analyzed, along with ground-based magnetometer data (Lyons et al., 1990). Several substorm expansion-phase onsets were examined. At the onsets, auroral brightenings developed within the region of the electric field gradient of the Harang discontinuity and, if not already present, a westward electrojet developed poleward of the eastward electrojet. Immediately following onsets, the poleward boundary of the westward electrojet moved further poleward, along with the poleward boundary of the aurora where the auroral surge formed.

This work is significant in that it resulted in a new mechanism to explain auroral surge formation. We suggest that the surge was associated with a distortion of the poleward boundary of the aurora, and that this distortion was caused by the field-aligned currents within the head of the surge.

In a second study, we looked at the electric field signature of auroral surges (Robinson et al., 1990). The significant results of this study are that we showed that surges are well-defined events at latitudes above 70°, consisting of intense precipitation and westward ionospheric currents. Several cases were presented, all showing evidence for poleward motion of both the precipitation and the electrojet. Each event was characterized by the sudden onset of a negative bay in the ground magnetic H component. However, apart from these features, the electrodynamics of different events can be quite distinct. In one of the cases studied, it is fairly clear that the electric field changed in a manner that could not be attributed to motion of a boundary. In the other two cases, the convection reversal boundary that moved poleward during the event may have been present at lower latitudes before the event. We showed that these differences are related to the location of the measurements relative to the center of the expanding bulge.

5. Determination of Instantaneous Convection Patterns

In a collaborative effort with A. Richmond and coworkers we obtained snapshots of the high-latitude convection pattern, as well as of the currents, and Joule heating rates, by combining data from radars, magnetometers and satellites. The Assimilative Mapping of Ionospheric Electrodynamics (AMIE) technique (Richmond and Kamide, 1988) was applied to several long-duration experiments (Richmond et al., 1988, 1990; Knipp et al., 1989, 1990; Emery et al., 1990). This work is extremely important because the AMIE technique provides a means to estimate the two-dimensional global pattern of plasma convection. These patterns are obtained with a very good temporal resolution (10 min) and for long periods of time (1 to 5 days).

6. Seasonal Dependence of High-Latitude Convection Patterns

We studied how the convection pattern depends on season by analyzing five years of Sondrestrom electric field observations (de la Beaujardière et al., 1991b). We found that the large-scale convection pattern changes significantly with season, as illustrated in Figure 3. This figure shows the electrostatic potential calculated from the averaged electric fields using the method described by Alcaydé et al. (1986). (In the ionospheric F region, the plasma flows along these lines of constant potential.) The seasonal change involves the overall shape of the convection pattern, as well as the electric field intensity--and thus the total dawn-dusk potential across the polar cap. The cross-polar-cap potential drop is largest

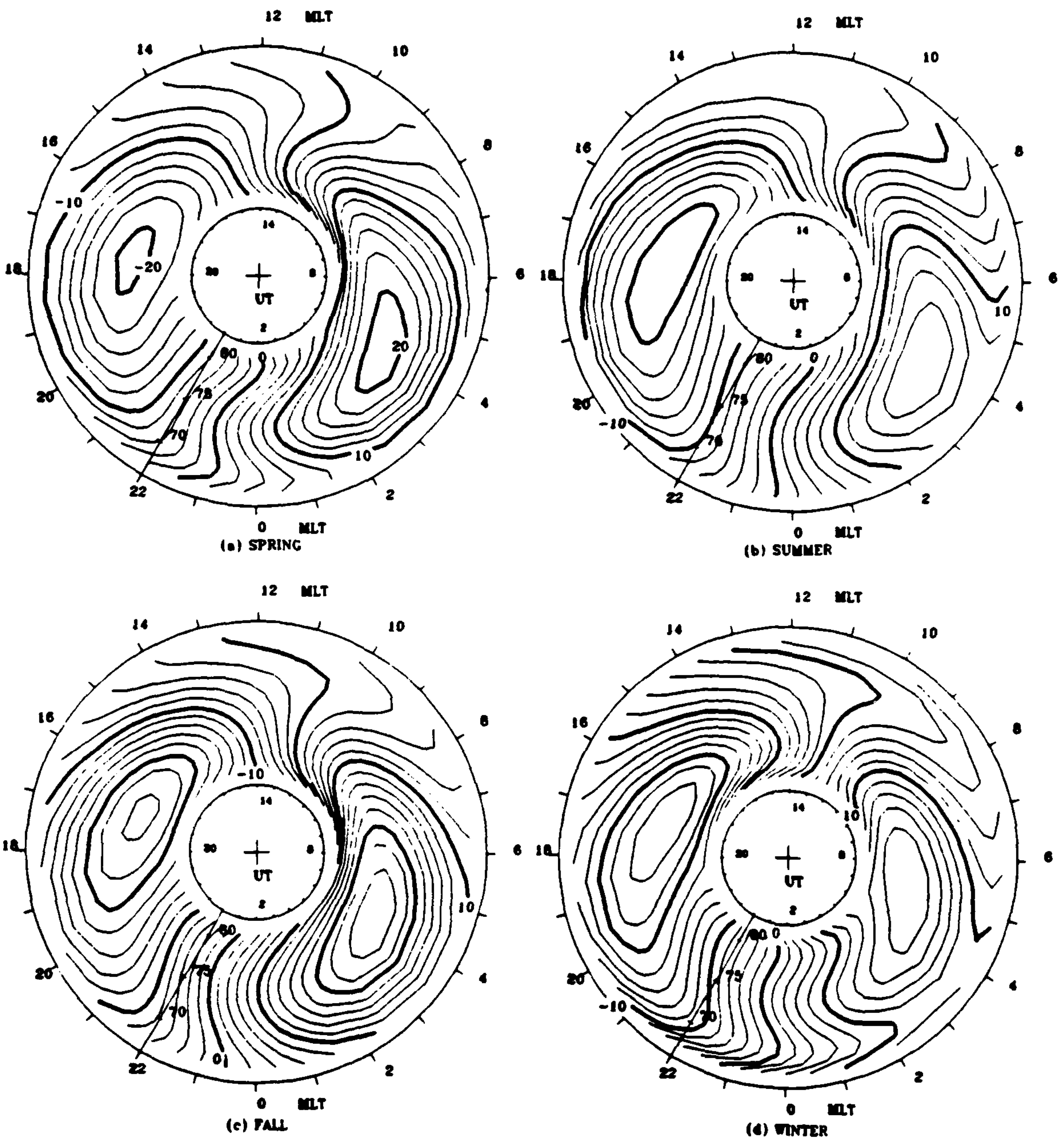


FIGURE 3 ELECTROSTATIC POTENTIAL OBTAINED BY FITTING CURL-FREE POTENTIALS FROM THE FOUR SEASONAL AVERAGES OF SONDRESTROM ELECTRIC FIELDS. The contour intervals are 2 kV.

in fall, followed by winter, spring, and summer (Figure 4). The small difference found between the summer and winter cross-polar-cap potential can be attributed to differing field-aligned potential drops. In view of the relationship between field-aligned currents and parallel potential drop (Lyons et al., 1979), a difference in field-aligned potential drop is consistent with the observations that Birkeland currents are more intense in summer than in winter.

Changes in the overall shape of the convection pattern are consistent with the simple notion that the whole pattern is shifted toward the nightside (as well as, to a lesser extent, toward the dawnside) in summer as compared to winter. This assumption is based on the following observed effects: (1) The rotation of the overall convection pattern toward earlier local times with respect to the noon-midnight direction is maximum for summer on the dayside. (2) On the nightside, the Harang discontinuity is typically located within the radar field of view (Λ = 67 to 82) in the winter averaged patterns, but it is equatorward of the field of view in summer. (3) The line that joins the dawn and dusk potential maxima is shifted toward the midnight sector in summer as compared to winter by about 5°. (4) In the dawn cell, the latitude of the convection reversal is the lowest during summer; in the dusk cell the latitude of the reversal is the lowest during winter. The shift in the antisunward direction is attributed to the dipole tilt angle variation, whereas the shift in the dawn-dusk direction is attributed to the differing day-night conductivity gradients. This work is the first systematic study of how electric fields in the polar regions vary with season. The new results are important in several respects: First, they shed a new light on our knowledge

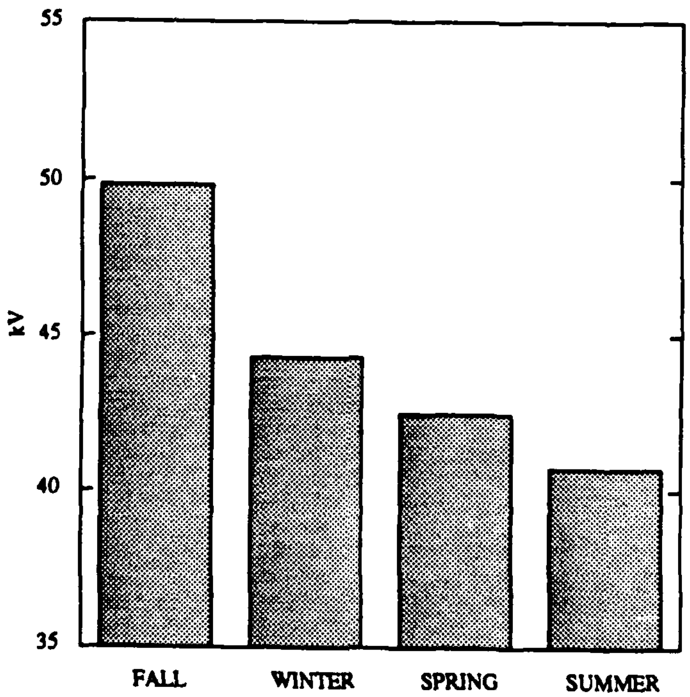


FIGURE 4 TOTAL CROSS POTENTIAL OBTAINED FROM THE POTENTIAL DISTRIBUTIONS OF FIGURE 3.

of solar wind magnetosphere-ionosphere coupling. Whereas it had been assumed almost universally that the ionospheric convection would not vary with season, we showed that both the strength of the electric field and the overall shape of the convection pattern are seasonally dependent.

Second, our results have implications for global modeling of the ionosphere and thermosphere. Indeed, the electric fields affect the ionospheric density and temperatures, as well as the thermospheric winds and temperature. In particular, predictive models of the ionosphere and thermosphere, which are an important aspect of the work funded by AFOSR, require a global convection pattern for their calculations. This convection should be known as accurately as possible, and our effort to characterize how the convection changes with season is important in this respect.

7. Determination of the Reconnection Electric Field from Ionospheric Measurements

We used the Sondrestrom incoherent scatter radar to estimate the reconnection electric field (de la Beaujardière et al., 1991c). The reconnection electric field is a fundamental quantity in magnetosphere-ionosphere coupling because it describes the rate of transfer of solar wind energy to and from the closed field line region of the magnetosphere. It is not possible to measure directly the reconnection electric field in the magnetosphere, but in the ionosphere, the reconnection rate can be calculated from the electric field and the motion of the polar cap boundary. We devised a technique to perform this measurement, and evaluated the advantages and limitations of the technique. To our knowledge, this work represents the first measurement of the reconnection electric field.

We applied this technique to obtain estimates of the reconnection electric field during substorms. Figures 5 and 6 illustrate the results. Figure 5 displays the latitude of the separatrix as a function of time and invariant latitude. The separatrix is the polar cap boundary, which is identified in this nighttime data set as the poleward edge of the E-region precipitation. Periods of polar cap contraction, which correspond to substorm expansion phases, alternate with periods of polar cap expansion, which correspond to substorm recovery.

Measured velocities in the direction perpendicular to the L shells are displayed in Figure 6. Figure 6(a) shows the boundary velocity (V_B). Figure 6(b) shows the plasma velocity (V_P) measured in the F region at the invariant latitude of the boundary, and Figure 6(c) shows the velocity of the plasma in the separatrix reference frame (V_R). It can be seen that individual separatrix velocities often exceeded 300 m/s, and the largest velocity measured was 530 m/s equatorward. The plasma velocity changes relatively little throughout the period of substorm activity. It is fairly large, around 600 m/s, which corresponds to a 30 mV/m electric field, and it appears to be independent of the direction of motion of the separatrix.

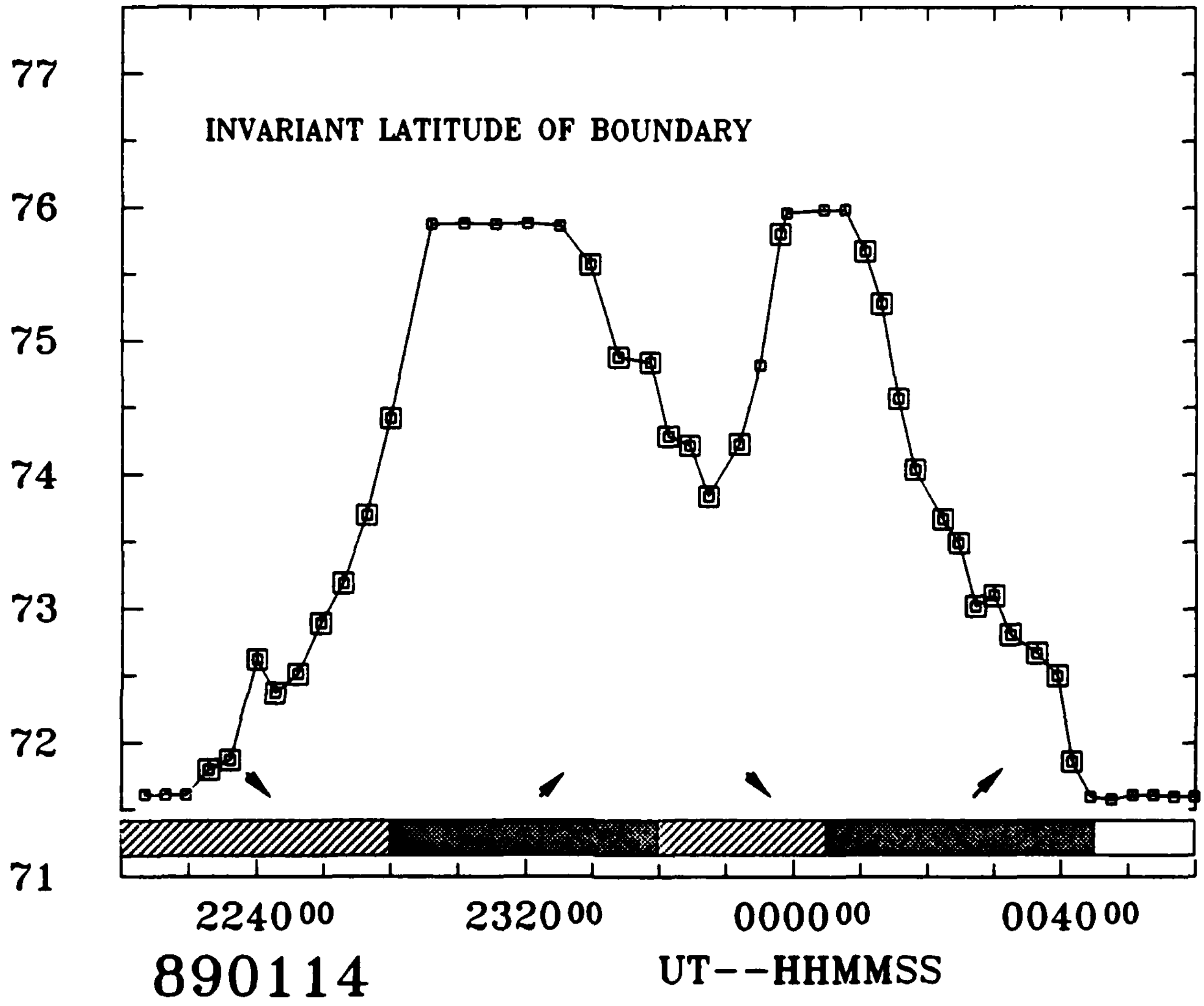


FIGURE 5 LATITUDE OF THE POLAR CAP BOUNDARY FOR THE FIRST SUBSTORM PERIOD ON 14-15 JANUARY 1989. The small squares denote times when the boundary was beyond the radar field of view, either equatorward or poleward. At the bottom, the light and heavy shadings represent times when the magnetogram H component was decreasing and increasing, respectively.

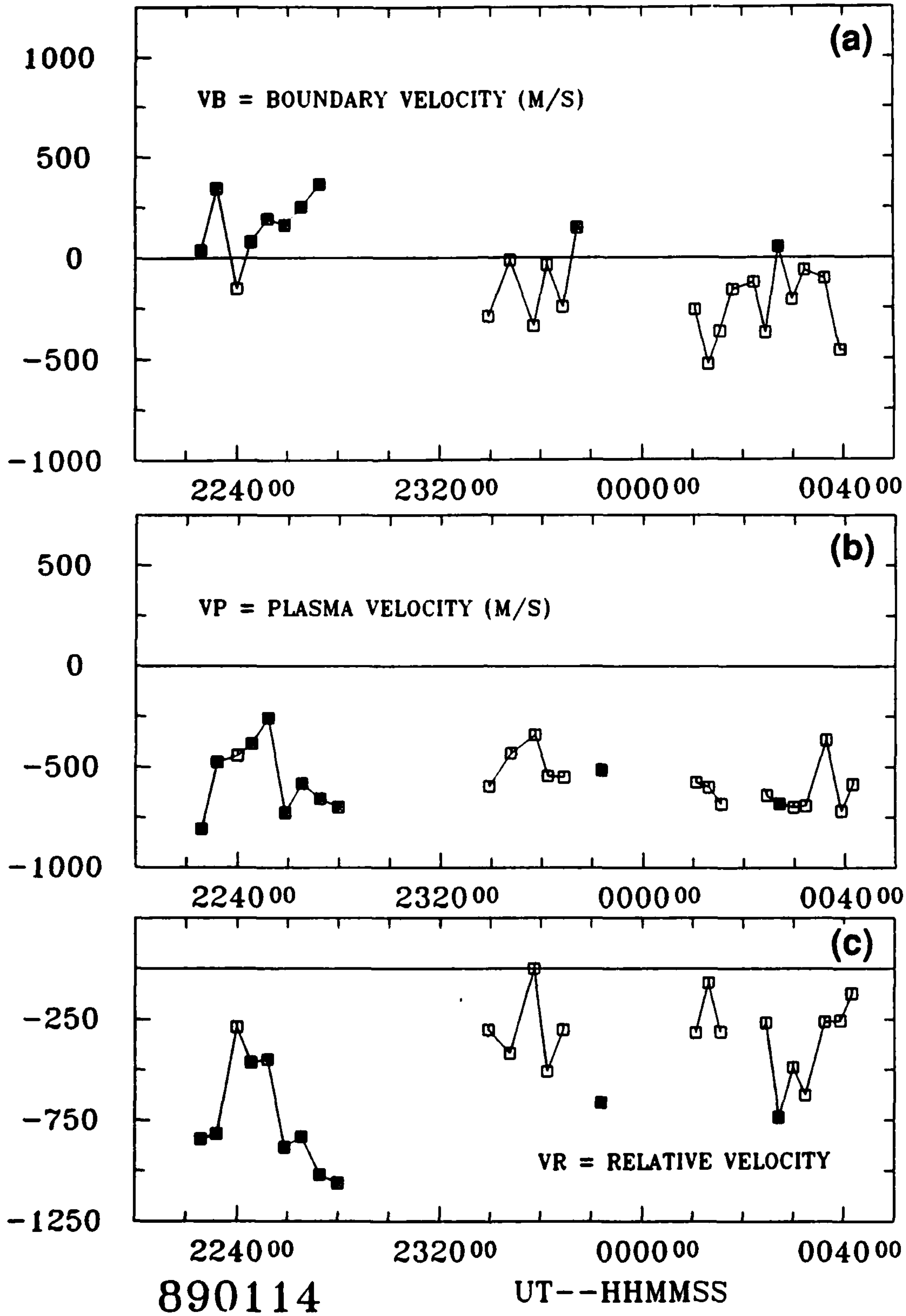


FIGURE 6 POLAR CAP BOUNDARY VELOCITY (6a); PLASMA VELOCITY IN THE RADAR REFERENCE FRAME (6b); AND PLASMA VELOCITY RELATIVE TO THE BOUNDARY VELOCITY (6c). Dark and clear squares represent times when the boundary moves poleward or equatorward, respectively.

The reconnection electric field is proportional to the relative velocity [Figure 6(c)], calculated as the difference between the plasma and the boundary velocities. Because the north-south velocity of the plasma itself does not appear to depend on the motion of the boundary, the relative velocities are modulated mostly by the motion of the separatrix. On average, the relative velocities are about 300 m/s when the separatrix moves equatorward, and 800 m/s when it moves poleward. These numbers correspond to reconnection electric fields of 15 and 40 mV/m, respectively. In a few instances, V_R is close to zero. These are instances of adiaroic motion when the ionospheric plasma moves with the separatrix. Our results show that such motion was not common during the time period considered, and that the reconnection rate was significant when the polar cap locally expanded, as well as when it contracted.

III CONCLUSION

Overall, the MITHRAS program has been very successful and has contributed to a better understanding of the neutral atmosphere, the ionosphere, the magnetosphere, and the interactions between these regions.

The most extensive ever comparisons between ISR data and numerical simulation models were performed. These comparisons were based on individual Sondrestrom observations and on statistical radar data averages, as well as on data from the other ISR around the world. They were performed on the following four theoretical models, which are widely recognized as the most sophisticated and accurate:

1. NCAR TIGCM of winds in the E and F regions
2. Coupled UCL-Sheffield model of both winds and electron densities
3. USU models of electron densities
4. Forbes models of lower thermosphere tides.

These comparisons are an essential part of model development and evaluation. They contribute to model improvements, in that they help refine the model input functions, and boundary conditions. Work is still in progress to carefully examine the reasons for the discrepancies as well as the successes in the models' ability to duplicate the observations.

In terms of magnetosphere-ionosphere coupling, the recent MITHRAS work has led to significant findings. For example, we have shown that the large-scale convection pattern depends on season, a result that was unexpected. We have provided the first inferences of the reconnection rate, a fundamental quantity in solar wind-magnetosphere coupling.

This project has clearly demonstrated that ground-based observations of ionospheric parameters can help resolve some fundamental questions related to magnetosphere-ionosphere-thermosphere interactions. These efforts have opened the door to new possibilities for future studies, and we look forward to continued work. In particular, we would like to concentrate our future efforts on the ionospheric region close to the boundary between open and closed field lines. This region maps to the magnetopause and plasma sheet boundary layers where most of the exchange of mass, energy and momentum takes place between the solar wind and the magnetosphere.

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APPENDIX A

MITHRAS PUBLICATIONS, REPORTS, AND THESES

I. PAPERS IN REFEREED PUBLICATIONS

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APPENDIX B

Global Studies
of the Thermosphere and F Region of the Ionosphere
with Emphasis on the Meridional Neutral Wind

Research Summary
Subcontract No. C-12118 from SRI to USU
AFOSR Contract F49620-87-K-0007
"MITHRAS STUDIES OF THE AURORAL OVAL AND POLAR CAP"

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Global Studies of the Thermosphere and F Region of the Ionosphere with Emphasis on the Meridional Neutral Wind

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Our abilities to observe the upper atmosphere and to model it have reached the stage that it is possible to consider careful comparisons of several geophysical parameters to test our understanding of the physics and chemistry of this region. It is no longer sufficient to perform comparisons at just one point in space and time, as has been done in the past. From such past comparisons the impression has developed that the global circulation models of the neutral atmosphere and the global ionospheric models represent the upper atmosphere very well. The ability to observe the upper atmosphere on a global scale has now developed to the point that observations and model calculations can be better compared. The research performed under this subcontract has examined how best to determine two geophysical parameters crucial for such comparisons--meridional neutral wind and exospheric temperature--and has performed comparisons of two observed and modelled geophysical parameters--meridional wind and electron density. The comparisons show that there is still much to be learned about the climatology of the winds and the electron densities. This report summarizes the research findings. Figures and references can be found in the resultant papers and theses.

Among the parameters that can be deduced from incoherent-scatter radar (ISR) measurements in the thermosphere is the meridional wind--the horizontal neutral wind in the magnetic north-south direction. Since this was first realized in 1967, radar observations have contributed greatly to the study of thermospheric dynamics. At mid and low latitudes, they have shown the important impact that tides propagating upward, from the lower atmosphere have on the dynamics at F-region altitudes. At high latitudes, radar measurements have demonstrated the effects momentum and energy transfer from the magnetosphere have on the dynamics at F-region altitudes, including local ion drag, the equatorward surge near midnight, the IMF By component, local Joule heating, high-latitude heating, and the midnight abatement and reversal. More generally the radar data have been used to confirm basic ideas about the global meridional circulation. Initially this was accomplished with individual radars; now coordinated observations by a network of radars acquire data for periods of from one to five days. These global observations provide measurements of the full diurnal pattern at multiple locations as a function of season, magnetic activity, solar cycle, and of many other geophysical parameters. These multiday campaigns contribute significantly to major ongoing programs such as the Coupling, Energetics, and Dynamics of Atmospheric Regions program (CEDAR) and Worldwide Ionospheric-Thermospheric Study (WITS), and will support future ones, such as the Solar-Terrestrial Energy Program (STEP). The inclusiveness and breadth of these programs is especially significant today. The radar observations, when combined with those from other instruments, can be used in conjunction with global theoretical models to test our quantitative understanding of the myriad physical processes and interactions that give rise to the winds and other geophysical parameters in the upper atmosphere.

The technique for deriving the meridional wind has been evolving for two decades. For global studies, the winds from the individual radars are being combined with winds determined from other techniques and compared with increasingly sophisticated theoretical models. It is therefore appropriate to reexamine their derivation and their dependence on such parameters as ion composition, neutral densities, ion-neutral collision cross sections, and thermal diffusion. This was done. From an experimental point of view, it is reemphasized that a current magnetic field model is required to determine the component of ion velocity parallel to the magnetic field. Otherwise, strong electric fields can lead to incorrect neutral winds. Precise corrections to the ion velocity have to be made for transmitter chirp. As short a pulse as possible should be used to derive the electron density profile and its altitude derivative. In calculating the contribution of ambipolar diffusion to the observed ion velocity, the neutral atmosphere, particularly O and N_2, and the ion-neutral collision cross sections, particularly O^+-O, are extremely important--a conclusion that is not unique to the wind derivation. An error in these parameters can lead to systematic errors in the wind that are most significant during the night. Ion composition and thermal diffusion are not found, in practice, to have significant effects. Because of the great importance of neutral atmospheric densities and collision cross sections for many aeronomy problems, it is concluded that considerable effort should be placed on determining both of them.

We examined the O^+-O collision cross section and the number density of atomic oxygen [O]. This was done by comparing nighttime thermospheric winds obtained by two techniques at Sondrestrom, Greenland (66.99 N, 50.95 W, 75 invariant), from 11 nights between 1983 and 1988. The horizontal winds in the magnetic meridian were derived indirectly from ISR measurements of ion velocities antiparallel to the magnetic field and directly from Fabry-Perot interferometer (FPI) measurements of Doppler shifts of the 6300-A emission from atomic oxygen. In deriving the radar winds, the O^+-O collision frequency, which involves the product of the O^+-O collision cross section and [O], was scaled by a factor *f* that was varied from 0.5 to 5.1. On the basis of several arguments the average altitude of the emission was taken to be 230 km. The best agreement between the ISR and FPI winds was obtained when *f* was increased substantially, to between 1.7 and 3.4. If the average peak emission altitude were higher, these factors would be larger; if it were lower, they would be somewhat smaller. However, if the average altitude were substantially lower it would have been more difficult, if not impossible, to have obtained agreement between the two techniques. If it were assumed, in agreement with *Burnside et al.* [1987], that the O^+-O collision cross section should be increased by a factor of 1.7, then any departure of *f* from that value would indicate a variation of the atomic oxygen density [O] from the value determined by the MSIS-86 model of the neutral atmosphere. The full range of [O] variation was then from 1/3 to 3 times the MSIS value, with the most frequently found factor being 1 during periods of moderate solar activity ($F_{10.7}$>100) and 2 during periods of low solar activity ($F_{10.7}$~70), i.e., solar-cycle minimum. In addition, *f* and therefore [O] were often found to vary significantly during the night. an increase was associated with the appearance of gradients in the FPI meridional wind, suggesting auroral activity as a common cause. Finally, superimposed on the radar wind, close to the time during a particular day when Kp increased from 2 to 4-, were two periods of a large-scale gravity wave. If the observations had not been made frequently enough to determine the gravity-wave oscillations, the comparisons could have been seriously in error.

The density of atomic oxygen in the thermosphere, as well as that of the other neutral constituents, is in part determined by the neutral temperature profile, which is characterized by its asymptotic value T_{INF}. While this parameter is relatively easy to determine at mid and low latitudes from ISR data, it is difficult to determine in the same way at high latitudes because of Joule heating of the ions. To circumvent these problems, statistical methods were investigated for deriving T_{INF} from Sondrestrom radar data. The results were evaluated by comparisons to neutral temperatures obtained from coordinated FPI observations. The study was based on two main premises: that Joule heating is spatially and temporally localized in the radar's field of view; and that a contaminated neutral temperature population representing Joule heating can be separated from the non-enhanced temperature population by statistical means. Exospheric temperatures were derived from the Sondrestrom ISR data using the ion-energy equation in the usual mid-latitude manner. The effect of the O^+-O collision cross section was tested by increasing it in the ion energy equation by a factor of 1.7 for the reduction of data from two days. The resultant increase in the deduced exospheric temperatures averaged 10 K. The fitting procedure uses the Bates expression for the neutral temperature profile to relate the neutral temperature at one altitude to that at another altitude. Tests to examine the sensitivity of the T_{INF} results to the s parameter and to the 120-km temperature in that expression found little sensitivity provided the s value was 0.023 or greater, as is inferred from the MSIS-86 empirical model. Three tests were developed to delimit the non-Joule heated population of derived T_{INF} values from the Joule heated population: the Student t test, the normal distribution test, and the chi-squared test. Each test depends on slightly different assumptions. They were applied to either the 15 positions in an elevation scan or the set of 11 positions used in the radar "World Day" mode. A mean exospheric temperature was then calculated from the non-Joule heated values. The T_{INF} values from the three statistical methods were often identical, although the number of points selected sometimes differed and hence the resultant average value. The procedures were evaluated by comparing these radar-derived T_{INF} values with neutral temperatures derived from FPI observations for 10 nights of coordinated observations between 1983 and 1988. (Many of the dates were the same as for the meridional wind comparisons.) These exospheric temperatures were also used to calculate the neural temperature at 225 km for a more direct comparison to the FPI-deduced temperatures. Bivariate scatter-plot analysis shows high correlations between the two data sets for the three statistical tests and for both the exospheric and extrapolated temperatures. This approach to extracting the exospheric temperature from high-latitude ISR data appears to produce realistic and reasonably unbiased exospheric temperatures. An examination of the temperatures determined by both radar and optical techniques show several two-hour periods when T_{INF} increases 100 to 200 K above a smooth background temperature curve. In addition, the derived T_{INF} values were compared to values calculated from the MSIS-86 empirical model. The derived values were usually within 100 K of the model values.

Having gained an increased confidence in the radar-derived meridional winds, an extensive comparison was performed between observation and model calculations. The meridional wind was derived from observations from Sondrestrom, Millstone Hill, and Arecibo during the period from 1983 through 1986. The O^+-O cross section was increased by a factor of 1.7 above the usually assumed value. The neutral atmosphere was represented by the MSIS-83 model. (In the ISR-FPI wind comparison discussed above, it was also shown that the winds derived with the MSIS-83 and MSIS-86 models are almost identical.) The winds from between 250 and 300-km altitude were averaged together. The data were divided into summer, winter, and equinox, with each season assumed to be 3 months long and the two equinoxes combined. The seasons were phased such that winter solstice was centered on 21 December. Both the National Center for Atmospheric Research (NCAR) and University

College London (UCL) Thermosphere-Ionosphere General Circulation Models (TIGCM) were used for the model comparisons. They were run for solar-cycle minimum conditions, for the three seasons, for several levels of magnetic activity, and for variations in the bottom boundary conditions to include tides propagating upward from the lower atmosphere. The formalisms used to represent the global convection and particle precipitation patterns were different in the two models. The comparisons showed general agreement between the observations and model calculations, but they also showed significant differences. The modelled daytime winds at high latitudes are too strong to the north. The modelled seasonal variation at high latitudes is too small. Significant phase differences exist between the modelled and observed winds, with the NCAR model ahead of the observations and the UCL model behind. The NCAR modelled southward wind during the nighttime at mid latitudes is too strong. The modelled tidal variations at low latitudes, where tides are most important, do not match the observations. Thus significant differences do exist between the observed wind climatology and the appropriate model calculations of the wind. These differences were found, in part, because this is the most extensive comparison ever made. Three locations at different latitudes were involved; enough data existed that seasonal averages could be formed; daytime winds were included, and summer winds at high latitudes were included.

Comparisons of observed and modelled meridional winds is one approach to testing our understanding of the upper atmosphere. Another is to compare observed and modelled electron densities in the F-region. In the past the most extensive comparison involved two ISRs and a 24-hour period. This time the observations involved three ISRs--Sondrestrom, Millstone Hill, Arecibo--and over 50 days during 3 1/2 years, distributed almost symmetrically about the 1986 solar-cycle minimum. These coordinated observations occurred on the Coordinated Incoherent-Scatter World Days. Some of these periods were 24 hours long, while others such as those for the GITCAD, GISMOS, and LTCS campaigns were up to 5 days long. The model used is the Utah State University first-principles, time-dependent ionospheric model (TDIM). The overall first order result of the comparisons is that the model reproduces the electron densities at the three radars for a variety of diurnal, seasonal, geomagnetic, and solar-cycle conditions. However, some significant discrepancies were also found. These include a fall-spring asymmetry in the Sondrestrom densities, a secondary electron density peak in the evening at Millstone Hill, and a strong time variation in the Arecibo densities. These differences are all believed to stem from inadequacies in the inputs to the theoretical model, and they all require further investigation.

Thus research under this subcontract has provided more confidence in the derivation of meridional neutral winds from ISR data and has found a way to derive T_{INF} from high-latitude ISR data. It has also included major comparisons between observed and modelled meridional winds and electron densities. The discrepancies in both these comparisons show there is much still to be understood in the behavior of the upper atmosphere.

LIST OF PUBLICATIONS, REPORTS, THESES, AND PRESENTATIONS

Utah State University

Subcontract No. C-12118 from SRI to USU
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"MITHRAS STUDIES OF THE AURORAL OVAL AND POLAR CAP"

PUBLICATIONS, REPORTS, and THESES

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Multi-Radar Study of Ionospheric Trough Dynamics During the SUNDIAL-86 Campaign, M. Lester, J.C. Foster, V.B. Wickwar, and G. Gustafson.

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Incoherent-Scatter Observations at Four Stations during the Geomagnetic Storm of September 1986, R.G. Burnside and V.B. Wickwar.

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