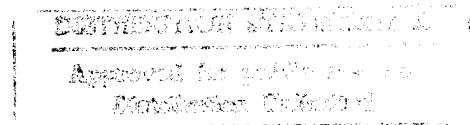Report F49620-93-1-0010DEF

VALIDATION OF FIRST-PRINCIPLES MODEL CALCULATIONS OF THE UPPER ATMOSPHERE

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Because of its effects on human activity, mostly through effects on every type of radio signal, it is important to understand the ionosphere and to understand its coupling with the thermosphere and other atmospheric regions. These effects are often considered under the umbrella of space weather. The purpose of this project was to extend several aspects of our understanding of the ionospheric F region. The techniques used were a combination of comprehensive observations with incoherent-scatter radars and detailed comparisons of such observations to simulations made with first-principles models of the ionosphere. Three inputs to these models were examined: electron heat flux, soft particle precipitation, and meridional winds. Procedures were developed to obtain, manipulate, and display the radar data. A first principles model was developed that places more emphasis on the topside F region than previously. This model was used to examine the cause of an anomalous F-region maximum sometimes reported at mid latitudes. The cause was found to be a particularly strong meridional winds. However, to properly account for the maximum, the rate of collisions between the dominant ions and neutrals had to be increased by 70%. The tools are now in place to perform a number more detailed comparisons.

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VALIDATION OF FIRST-PRINCIPLES MODEL CALCUALTIONS OF THE UPPER ATMOSPHERE—FINAL REPORT

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Abstract. The ionosphere is important for human activity for enabling and affecting communications and radar surveillance among points on the ground and between points on the ground and satellites in orbit. The ionosphere is also immersed in the much denser neutral atmosphere, the thermosphere. Because of the effects on this human activity, it is important to understand the ionosphere and to understand its coupling with the thermosphere and other atmospheric regions. The purpose of this project was to test several aspects of our understanding of the ionospheric F region by comparing the results of first-principles model calculations with good observations, mainly from incoherent-scatter radars. There are three aspects of such comparisons. While these models are themselves very complex to be able to solve the coupled, partial-differential equations describing continuity, momentum, and energy, the ability to solve these equations correctly is not sufficient to make a good simulation of the ionospheric F region. They also depend on a myriad of inputs such as the solar EUV flux, neutral-atmospheric densities and temperatures, neutral wind, chemical reaction rates, and heat and particle exchange fluxes between the ionosphere and plasmasphere. At high latitudes, they also depend on particle fluxes of energetic electrons and protons, convection electric fields, and Joule heating. Thus the first aspect of performing these comparisons is to carefully examine these inputs. If they are incorrect, what can be learned from the comparison is significantly reduced. The second aspect is to properly choose and prepare the data sets. The third aspect is to perform the comparisons, which entails performing enough and appropriate variations of the model calculations to learn something useful from the results. In this project we looked at three different inputs to the model calculations, we extended the Utah State University ionospheric modeling to place greater emphasis on the upper portion of the F region, and we applied the model to an anomalous mid-latitude situation.

A. INTRODUCTION

Our attention in this work is focused primarily on that part of the upper atmosphere consisting of the F region of the ionosphere and thermospheric part of the neutral atmosphere. The physical parameters that we usually associate with the ionosphere are the electron and ion densities, the electron and ion temperatures, and the velocities of the ions and electrons. The parameters that we usually associate with the thermosphere are neutral densities, temperatures, and winds. The ionosphere and thermosphere form part of a very complex, coupled system. The plasma and the neutrals coexist in the same region, constantly interacting—chemical reactions, momentum transfer, and energy exchange. They are affected very directly by the sun's electromagnetic radiation, particularly the FUV and EUV parts of the spectrum that dissociate and ionize. They

are affected by coupling to the lower atmosphere, in particular, by a spectrum of wave effects generated in the troposphere and stratosphere that grow as they propagate upward. From above, the plasma and neutrals are also affected by the outflow of particles from the sun and the magnetic field these particles carry with them. This occurs because the solar wind and interplanetary magnetic field (IMF) interact with the magnetosphere, which extends into the high-latitude upper atmosphere and creates the ring current that interacts with the upper atmosphere at mid and low latitudes. Horizontally, plasma and neutrals are coupled between low and high latitudes and between different longitudes by horizontal transport from electric fields and winds.

Thus the upper atmosphere is a laboratory for studying how the sun's energy is deposited in the atmosphere and how that energy is redistributed. As gathered from the foregoing, there are two aspects to the energy input. One is the light or electromagnetic radiation from the extreme ultraviolet (EUV), through the visible, to the infrared (IR) that is deposited on the part of the earth facing the sun. Because of the earth's rotation and its orbit around the sun, this energy input undergoes important diurnal and seasonal modulations. The differential heating sets up major circulation patterns that redistribute this energy input. Neutrals are ionized and dissociated, and then, in some cases, transported elsewhere. The other aspect of the solar energy input is the continuous emission of solar-wind particles, mostly electrons and protons, and the IMF, the direction of which strongly affects the interaction of the solar wind with the outermost region of the earth's atmosphere, the magnetosphere. This interaction affects the entry of particles, the electric fields that govern the high-latitude plasma motions, and the occurrence of geomagnetic activity, most noticeably substorms and magnetic storms.

This mix of energy inputs into the Earth's atmosphere leads to the complexity of the upper atmosphere described above. We are interested in the physics that describes this system, the eventual goal being to understand and predict the behavior of the system. However, in addition to this being a very interesting physics laboratory, this system affects the way modern people live and the way governments interact. For instance, limiting the discussion to just the ionosphere and thermosphere, a number of significant effects occur. There are several radio or propagation phenomena, for example, unusual propagation paths and the disruption of HF radio communications. These lead to difficulty for radio-direction finding and for over-the-horizon radar. At higher frequencies, these phenomena lead to the degradation of satellite communication by causing fading and scintillation of satellite signals. Another manifestation of the interactions among atmospheric regions is a large variation in electron density and, hence, in total electron content. These variations affect satellite ranging and the prediction of orbital elements. During periods of strong interaction between the magnetosphere and upper atmosphere, i.e., during magnetic storms, the neutral density at high altitudes is significantly increased, giving rise to increased atmospheric drag on satellites, which in turn causes more rapid orbital decay, earlier reentry into the atmosphere, and sometimes "loss" of satellites for extended periods. During these same periods, the meridional neutral winds are significantly enhanced, forcing the F region, even at mid-latitudes, to higher altitudes thereby affecting HF propagation. Electric fields also penetrate to mid-latitudes where they give rise to currents not only in the ionosphere, but also in long conductors. One consequence, for instance, has been extensive power blackouts in Canada and Sweden, and equipment failures on the U.S. power grid.

Hence there is a converging of interest between the desire to understand our environment and the need to prevent untoward happenings in our lives. At a conceptual level much is understood. However, at a more detailed level, much is still to be learned, especially if the goal is to predict the behavior of the system.

Much of our understanding of the upper atmosphere and the complex interactions that occur there is embodied in large and very complicated first-principles models which are also sometimes called physical models. They can be of the F region, as will be discussed, the thermosphere, or the two regions combined. They start from basic physical principles (conservation of mass, momentum, and energy), a set of energy and momentum inputs, a set of initial conditions, and boundary conditions at low and high altitudes. They provide a natural framework for relating observations of several atmospheric variables such as electron density, electron and ion temperatures, ion velocities, neutral wind, etc. They can also provide a framework for relating observations of these atmospheric parameters from many locations, or for extrapolating spatially from a few locations to the whole globe. Eventually they may be used to extrapolate forward in time from current observations.

The first-principles models should be distinguished from empirical models that are usually based on statistical relationships between solar or geomagnetic indices and various geophysical parameters. The implicit assumption is that models based on physical laws can eventually do a more precise job of reproducing the complexities of the systems than empirical models based on statistical relationships. However the first-principles models (of the ionosphere) do rely to varying extents on empirical models or climatologies of such parameters as solar EUV flux, neutral-atmospheric densities and temperatures, neutral winds, and heat and particle exchange fluxes between the ionosphere and plasmasphere. At high latitudes, they also depend on particle fluxes of energetic electrons and protons, convection electric fields, and Joule heating. These are used to characterize energy and momentum inputs, initial conditions, and boundary conditions. This reliance on empirical models and climatologies arises because no first-principles model exists that starts from the electromagnetic and particle emissions from the sun and derives everything from there to the surface of the earth.

For this project we have carefully examined several aspects of the inputs to first-principles ionospheric models, we have developed a first-principles ionospheric model to use for comparisons with incoherent-scatter radar observations of the ionosphere and neutral atmosphere, and we have made extensive comparisons with mid-latitude observations from Millstone Hill. They are discussed next, in that order.

B. INPUTS TO MODEL CALCULATIONS

1. Electron Heat Fluxes

This is one of the parameters that couples the topside F-region to the plasmasphere, the magnetically conjugate ionosphere, or the magnetosphere. By heat conduction, energy flows

along the magnetic field line, down into the local, topside ionosphere. This affects the electron and ion temperatures and, through the scale height, it affects the electron density distribution. Therefore, it is important for the electron densities in the topside F region and for the total electron content. Usually it enters into models as a boundary condition at the highest altitude in the calculations. What is entered is usually a guess, because this parameter has essentially not been measured. (However, some reasonable limits have been established for the flux on the basis of theoretical calculations giving reasonable looking electron temperature profiles.)

In this part of the project, we derived the heat flux above two ISRs in very different latitude regions, hence under a variety of different conditions. To do the derivation, we combined radar observations of electron density, ion temperature, and electron temperature with the portion of the USU time-dependent ionospheric model (TDIM) that solves for the electron temperature given the electron density, ion temperature, and downward electron heat flux at the altitude of the highest observation. The heat flux was varied until the best fit was obtained between the calculated and observed electron temperatures above 350 km. This procedure worked very well and was shown to produce precise and accurate results.

This procedure was carried out for data from the Sondrestrom radar in Greenland (67.0 N, 51.0 W, 74 Λ) and the Millstone Hill radar outside of Boston (42.6 N, 71.5 W, 55Λ). The results are summarized in Table 1.

The Sondrestrom radar is at a very high geomagnetic latitude, such that it is in the polar cap at night and typically a little equatorward of the auroral oval near noon. Several hours before and after noon, the radar passes under the reversal in the ion convection pattern, which is usually considered to be the polar cap boundary. As we will discuss late, it is also the location for considerable soft particle precipitation, electrons in the afternoon sector and protons in the morning sector.

In contrast, the Millstone Hill radar is at mid latitudes. Except for very high geomagnetic activity, the field lines should be within the plasmasphere. However, there is still considerable variation because of the geometry of the geomagnetic field line. During the nighttime in summer (i.e., June), the magnetic field line from Millstone Hill will come back down into the F-region in the southern hemisphere in darkness. But in winter, it will come down into a sunlit ionosphere. Under these conditions there are still photoelectrons that can leave the conjugate point and heat ambient electrons along the field tube or travel all the way to the ionosphere above Millstone Hill. Hence we find a very different behavior at night in the two seasons. Table 1 gives a summary of the findings.

At Sondrestrom, the daytime measurements provided the most consistent results. The values are comparable to the daytime values from Millstone Hill, but they are much more scattered. While the Sondrestrom results appear to have a positive correlation with solar activity as measured by $F_{10.7}$, the Millstone Hill results appear to have a much cleaner positive correlation. As Sondrestrom moved under the convection reversal, the heat flux increased greatly, by roughly a factor of 10. However, on days with considerable geomagnetic activity, the factor could be as much as 30 or 40.

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Table 1. Summary of Electron Heat Flux Findings	
SONDRESTROM	
Situation	*Downward Flux [eV/cm²-s]*
10 am – 2 pm (local time)	$1\text{–}2 \times 10^{10}$
Convection Reversal	1×10^{11}
Sunlit Summer Nighttime	1×10^{10}
Dark Nighttime (Sparse)	$1 \times 10^{8} - 1 \times 10^{9}$
MILLSTONE HILL	
Situation	*Downward Flux [eV/cm²-s]*
Daytime $(F_{10.7} \sim 100)$	1×10^{10}
Daytime $(F_{10.7} \sim 200)$	2×10^{10}
Winter Nighttime	9×10^{8}
Summer Nighttime	2×10^{8}

Presumably, the daytime values reflect the effect of hot electrons that fill the flux tube. Normally these electrons would be heated by photoelectrons with enough energy and moving in the right direction to escape the local ionosphere. They will give up much of their energy to the ambient electrons in the flux tube (i.e., they will heat these electrons) by a series of Coulomb collisions. The scatter in the points from Sondrestrom indicates the presence of another heat source of comparable magnitude. A possible candidate might be compressional heating as a result of increased solar wind pressure. The high values of the heat flux at the convection reversal reflect other heating processes and the topology of the magnetic field. One contribution comes from soft particles, either electrons or ions, that deposit their energy above 250 km or so. The heating produced by these particles will give rise to an increase in the downward heat flux. However, for the events with the largest heat fluxes, the heating occurs at higher altitudes. Because it is difficult to heat electrons at these altitudes by particle precipitation, the energy has to conduct there from a more distant region of the magnetosphere that shares the same magnetic field line.

The nighttime proved difficult to study systematically at Sondrestrom because of the often low signal-to-noise ratio. When sunlit in summer, under geomagnetically quiet conditions, a flux near the low end of the daytime values was found. A combination of factors probably contribute to this. Because the F region is still sunlit, some hot photoelectrons are still apt to be heating the ambient electrons in the flux tube. In addition, the volume of the flux tube filled with hot electrons is so large at this high-latitude location that it will take hours for all the energy to be conducted away. However, in winter the nighttime signal usually was not good enough to deduce a value for the heat flux. Once in a while it was. Under these conditions values smaller than the daytime values by a factor of 10 to 100 were typical. The smallest value was approximately the same as the smallest nighttime value from Millstone Hill.

Turning to Millstone Hill, the daytime values and their dependence on $F_{10.7}$ have already been mentioned in passing, in the Sondrestrom discussion. The nighttime values are particularly interesting. Table 1 shows winter and summer values. To understand what is happening, one has to be aware of the topology of the magnetic field lines leaving the region above Millstone Hill. They can be traced to the southern hemisphere, where they come down into the ionosphere at a much higher geographic latitude than at Millstone Hill as well as considerably to the east. This is the magnetic conjugate point. In the northern hemisphere winter, when there are long

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dark nights, the magnetic conjugate point is in constant sunlight. Photoelectrons from that hemisphere continue to heat the electron gas in the flux tube, and a large (for nighttime) heat flux exists above Millstone Hill. In the northern hemisphere summer, the magnetic conjugate point is in darkness. Because of a finite heat capacity in the flux tube, the heat flux falls off after sunset to a minimum, the value given in Table 1. It falls off at a repeatable rate after local and conjugate sunsets, and starts to increase again after conjugate and local sunrises. The minimum nighttime value is much lower than the winter value and approximately the same value as at Sondrestrom, but it is still well above the minimum value that can be detected by this technique. It is not clear what is heating the electrons in the flux tube to maintain this heat flux. It might be stellar and geocoronal EUV ionizing a few neutrals high in the atmosphere at both ends of the magnetic field. It might be Coulomb collisions between the electrons in the flux tube and very energetic ions or electrons in the radiation belt. That remains to be understood.

Thus this technique worked extremely well for finding the downward heat flux into the atmosphere. It could be used in comparisons with data to find the time-varying value needed for the upper boundary condition in model calculations. It could be applied to a much larger data set from these two radars and from other radars to develop an empirical model that could be invoked like the MSIS neutral model or the Hedin wind model (HWM) in first principles models.

This work on heat fluxes was part of a student's thesis research. A paper describing this research and the results will be prepared.

2. Soft Particle Precipitation at the Convection Reversal

In the Sondrestrom ISR data, a feature that stands out is a colocated increase in F-region electron density and temperature that occurs at the reversal in the ion-velocity convection pattern. Having both of these enhancements at the same place is a strong indication that they originate from particle precipitation. Because of the F-region altitudes, the energy of the particles has to be less than 500 eV. (This is very different from the E-region enhancements produced by the 1–10 keV electrons that give rise to auroral emissions.) These low-energy particles are often called "soft" particles. From the directions in which the ionospheric ions are moving (convecting) and arguments about current continuity, we deduce that at the afternoon convection reversal, the precipitating particles are electrons, and at the morning reversal, the precipitating particles are ions, presumably protons. Using the densities and temperatures, we can deduce the energy-loss rate from the electrons to the ions and neutrals. Assuming a steady-state situation, which is reasonable, this energy-loss rate is equal to the energy-input rate. Hence we can deduce the energy input from these soft particles. While not large compared to the particle or Joule heat input in an aurora, it is a large input to the F region compared to what the input would be from the overhead sun. Hence it will be responsible for considerable local heating and for the generation of neutral winds.

This particle input was found to be a regular feature of the high-latitude ionosphere. It is large enough that it should have a significant impact on the behavior of the high-latitude F region.

This will need to be parameterized for incorporation into first principles models of the high-latitude regions.

A reasonable question is why this has not been identified previously. Early in the satellite era, low-energy particles could not be easily detected: now they can be. Hence during the early days of exploration, they were not considered. More recently, they have not had much attention because the total energy input to the atmosphere is low. This is an important distinction. Although their total energy input to the atmosphere is low, their input to the F region can be large compared to any other source. However, in the radar data the soft-particle precipitation stands out as does its association with the F region. But, it is not an easy task to deduce the energy input from the observations.

Another totally different aspect of the work on soft-particle precipitation is its implication for the structure of the magnetosphere and the interaction between the magnetosphere and the solar wind. This has to do with whether the precipitation is just equatorward of the convection reversal, or on both sides of it. The magnetic field lines on the equatorward side of the reversal, where the convection is sunward, are generally believed to map to closed field lines on the flank of the magnetosphere. The magnetic field lines on the poleward side of the reversal, where the convection is antisunward, are another matter. Some believe they map to open field lines that are connected to the solar wind. Others believe they map to closed field lines in the low-latitude boundary layer (LLBL) formed by a viscous interaction between the magnetosphere and the solar wind. The particle precipitation almost always varies continuously across the reversal boundary, providing a strong indication that viscous interaction almost always occurs between the solar wind and the magnetosphere and that the convection pattern nearest the reversal is part of a viscous cell.

This work on soft particle precipitation is part of a student's thesis research. He is almost finished. Afterwards, one or two papers describing this research and the results will be prepared.

3. Meridional Wind

The meridional neutral wind in the thermosphere is an important parameter when it comes to F-region behavior. But first, by "meridional wind," we are referring to a horizontal wind in the thermosphere blowing in the magnetic north-south direction. When blowing equatorward, it raises the layer thereby slowing down the rate of recombination. When blowing poleward, it lowers the layer thereby speeding up the rate of recombination. Thus it affects the altitude of the layer and its lifetime. Its effect will be discussed more below, in the section on modeling the F-region densities at Millstone Hill during 24 hours.

Unfortunately, the meridional wind is not well known. Much of what we do know about it is incorporated into the HWM. However, this empirical model is far less advanced than the MSIS model of neutral atmosphere densities. For instance, basic characteristics like the solar-cycle dependence is not known. Also, as indicated in the previous section, the wind should be greatly affected by soft-particle input at the convection reversal. This can be highly variable, and it can

be very large during periods of geomagnetic activity. In addition, this variability extends far from the auroral zone. For instance, on a different project, we have been observing the thermospheric neutral wind here at mid latitudes with a Fabry-Perot interferometer (FPI). We observe very substantial enhancements in the meridional wind for Kp values greater than 4^-, which occur fairly frequently. Whether this mid-latitude variability is related to the variable energy input we deduced at high latitudes remains to be seen. That would require using several FPIs located between the auroral zone and mid latitudes.

The meridional wind can be derived from ISR data, but that component of the wind has not been extensively studied with that technique. One problem has been an uncertainty in the knowledge of the size of the Burnside factor, discussed below, which could introduce a systematic error into the wind derivation. Another problem has concerned several aspects of the formulation of the analysis procedure for deducing the wind. In working with French colleagues from Grenoble, we reexamined that formulation, verifying most of it, but finding an error in one of the published terms.

This work will be submitted for publication in the near future.

C. FIRST-PRINCIPLES MODEL WITH EMPHASIS ON THE UPPER F REGION

1. Model Development

A choice that arose almost immediately after receiving the award was whether to use the USU time-dependent ionospheric model (TDIM) or to develop a new model. Because some of the major unknowns in modeling the ionosphere involved the region above the F-layer peak, e.g., the electron-heat flux and the exchange flux (net flux of ambient ions) in the topside ionosphere, it was important to have a model that emphasized the physical processes in the topside ionosphere. In this way the importance of these fluxes could be properly assessed through comparisons with observations. To do that, it turned out we would need another model. The other important factor, in deciding to create a new model, was that in doing so my graduate student would know exactly what was in it. The model would not be a black box, which was important educationally. Another factor that emerged later as the development was under way, was that the new model would be the best available for studying rapidly time-varying phenomena, which might be important at sunrise and sunset, and at a later date for studying the effects of ionospheric HF heating experiments. For example, electrons or ions, depending on the geophysical conditions, can be greatly heated. This program could be used to simulate what happens as they cool off. This gives another way of probing the ionosphere.

The model uses the Navier-Stokes system of equations derived from Schunk's 13-moment expansion to describe the ionosphere. Two numerical techniques are combined to solve the mixed set of nonlinear, hyperbolic and parabolic, partial-differential equations: the flux-corrected transport (FCT) and the alternating-direction explicit (ADE) techniques. They are coupled using the time-step splitting technique. Both are explicit techniques. The first is well

suited to handling nonlinear, hyperbolic equations, whereas the second is needed to handle the dissipation terms arising from viscosity and heat conduction that have to be introduced.

The ionospheric description, going from 150 to 3000 km, includes upward and downward H^+ fluxes and an upward O^+ flux. The geometry is governed by the geomagnetic field, as given by the IGRF model. (To our knowledge, this is the first time that the "real" field has been used.)

To complete the description of the ionosphere, various inputs are needed. As is common practice, the latest version of the MSIS model is used for the neutral atmosphere. Also needed are the ion-production rates and the electron-heating rates. For added flexibility and for other applications of this program, we are working closely with Jean Lilensten from CEPHAG in Grenoble, France. He has a kinetic model, or suprathermal flux model, that starts with the solar EUV flux and, among other things, derives these two parameters. It does so as a function of altitude and time (or solar zenith angle). A benefit of working with the French group is that the model affords considerable control over the calculations. For instance, the solar spectrum and how it varies with solar cycle can be controlled. The effect of secondary ionization by energetic photoelectrons can be examined. Return to our model, the interactions among particles are included as chemical reaction rates and collision cross sections. The other input needed is the meridional neutral wind and our starting point has been the latest version of the HWM. We have also used the meridional wind derived from the radar data.

After developing the model, we did many calculations and comparisons to verify that it was working properly. These involved checking important quantities such as conservation of charge, momentum, and energy, and performing extensive comparisons with the TDIM. It is much easier to start with another model than with observations. If the inputs are all the same, then the results should be the same in the regions where their validity overlaps. We found agreement in the regions of overlap for the two models. But in doing so we found that we had to be very careful about several inputs. These included the meridional winds, the ionization rates by energetic photoelectrons, electron-heat losses to the fine structure of the ground state of atomic oxygen, and the Burnside factor. The latter is a scale factor by which to change the product of the atomic oxygen density and the collision frequency between oxygen ions and atomic oxygen. In the last decade many aeronomical results have suggested that the value should be increased from 1.0 to something larger, such as 1.7. However, several authors argue strongly that it should not be changed. It is not clear whether this factor applies to the collision frequency or to the atomic oxygen density in the MSIS model. The cross section for these collisions comes from a very difficult theoretical calculation. It is very hard to measure in the laboratory at the energy of thermal particles, i.e., it has not yet been done. The model density model depends on old and difficult observations of atomic oxygen. None of these have been made for years, except occasionally from an isolated rocket.

2. Application of the Model

The first application of this model was to a dramatic phenomenon that we had previously identified at mid latitudes. We used data from the mid-latitude ISR at Millstone Hill, to which

we were attracted for two reasons. The first was the unusual nature of the phenomenon, namely that in late evening, the F-region electron density was as great or greater than the usual maximum that occurs in the early afternoon. This elevated density occurred on enough of the days we examined, that it has to be considered a regular ionospheric feature, at least at Millstone Hill. The second reason was that a series of simulations with the TDIM several years ago did not give any hint of the presence of this elevated electron density. Although simulating the densities very well earlier in the day, it was low by approximately a factor of two in the late evening. This anomalous F-region occurs in the years near solar-cycle minimum and is most prominent in summer.

To examine this problem, we performed a dozen, 24-hour, time-dependent simulations for 26 June 1984. The simulations involved two first-principles models, our extended F-region model and a photoelectron model developed and run for us by colleagues in Grenoble, France. Their model provided us with ion production rates and electron heating rates. We performed that large a number of simulations to examine numerous possible causes for the large densities. While no uniqueness theorem can be invoked to say we found the correct answer, we made enough comparisons under very demanding conditions—full altitude profiles, multiple ionospheric variables, 24-hour time duration—that we are very confident in our findings.

We found the cause of the late afternoon-early evening density maximum to be the southward meridional wind. In essence, in late afternoon and continuing until late at night, this component of the wind was very large, considerably larger than in the HWM. However, it was consistent with the wind derived from the ISR data. In making these comparisons, we also found that the most reasonable set of values for the meridional wind were obtained when a Burnside factor of 1.7, as opposed to 1.0, was used. This means we found that the product of the atomic oxygen density and the collision frequency between oxygen ions and atomic oxygen needs to be increased by 70% above the accepted value. Unfortunately, we only learn about the product of these quantities. Either the neutral atmosphere model or the collision frequency could be in error by up to 70%.

Another result of these comparisons is that we needed to include a downward, electron, heat flux at night from the plasmasphere to account for the observed nighttime temperatures. This confirms our earlier results found in a slightly different way. The importance of this is that it confirms one of the inputs to the ionospheric system that people have only been able to guess at until now.

Thus, the tools have been painstakingly developed over the last four years for obtaining, displaying, and working with the ISR data, and for modeling, or simulating, the F-region ionosphere to compare with the data. The first extended comparison has been successfully carried out, showing that this approach can be used very successfully to further our understanding of ionospheric behavior. Because of its extended coverage of several ionospheric variables in altitude and time, the ISR data base is an extremely valuable resource to use for additional comparisons with detailed, first principles, model calculations. And, many problems still exist for these comparisons.

This work is part of the dissertation research of a graduate student who should be finishing in the next 3–9 months. A paper on the model and a paper on this simulation are being prepared.

D. CONCLUSIONS

Considerable progress has been made under this grant toward improving our understanding of several inputs to the first principles models. One area was the first extensive study of the electron heat flux into the topside ionosphere under several conditions. At mid latitudes, at Millstone Hill, it was found for daytime and nighttime conditions. During the nighttime different values were found depending on whether the magnetically conjugate atmosphere was or was not sunlit. At high latitudes, at Sondrestrom, primarily daytime values were found. The daytime values at both locations were very similar, except that at high latitudes they were more variable, probably indicating another heating term in addition to photoelectrons. In both places the flux appeared to be positively correlated with solar activity. At high latitudes the electron heat flux could increase by more than an order of magnitude in the vicinity of the convection reversal. This probably occurred because the magnetic field lines mapped into a region of the magnetosphere with a very hot particle reservoir. The lowest values of the nighttime electron heat flux seen at both locations were very similar, about two orders of magnitude less than the daytime value.

A prominent feature in the radar data from Sondrestrom, Greenland, at 74 Λ is an incident flux of soft or low-energy electrons or protons. They show up at F-region altitudes as simultaneous and colocated enhancements of electron density and temperature. Penetrating no further than to 150–200 km, indicates that they have energies less than 500 eV. They also show up in a derived parameter, the total electron energy loss rate, Le, which is approximately equal to the rate at which these particles deposit energy in the F region. According to this parameter, the rate at which these soft particles deposit energy in the F region, often exceeds the rate at which the solar EUV deposits energy in these regions during the daytime. Consequently, significant thermospheric responses should result. One would be a heating of the neutral atmosphere, which would cause it to expand upward and would lead to an enhancement of the equatorward meridional wind. This might be part of the missing high-latitude heat source. This might also be similar to what happens at mid latitudes during magnetic disturbances of $Kp = 4^-$ or more, when we see very large meridional winds near USU, at 50 Λ, with a very sensitive, Fabry-Perot interferometer. In these events there is also enhanced red-line emission such as would be produced by precipitating soft electrons and, prior to that, evidence for a strong northward electric field.

A new ionospheric model has been developed that is particularly suited for performing comparisons with observations throughout the F region. (The calculations are performed from 150 to 3000 km.) The model uses the real geomagnetic field, emphasizes O^+ and H^+ ions in the topside ionosphere, and has extremely good time resolution. It has been set up to readily use solar inputs, ionization rates, and electron heating rates, all from several sources. It is well adapted for examining the effects of electron heat fluxes and exchange fluxes. It has been

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extensively compared to the USU TDIM to show that the very different numerical techniques have been implemented properly.

The model has been applied to ISR data from the Millstone Hill radar, from summer, near solar-cycle minimum. These data include altitude profiles of electron density, electron and ion temperatures, and the derived horizontal neutral wind in the magnetic meridian. The day selected was one of many from near solar-cycle minimum when, according to an earlier study, we would see anomalous F-region behavior, i.e., a very large F-layer peak density in the evening that exceeded the usual diurnal maximum in the early afternoon. The modeling showed two important effects: the importance of the southward neutral wind in the magnetic meridian in the afternoon and evening, and the need for a Burnside factor of approximately 1.7. This is yet another aeronomical result supporting the need for a large Burnside factor. What remains to be determined is whether the Burnside factor applies to the density of atomic oxygen or whether it applies to the O^+-O collision frequency.