

II. SCIENTIFIC/TECHNICAL/MANAGEMENT SECTION

INVESTIGATION OF THERMOSPHERIC AND IONOSPHERIC CHANGES DURING IONOSPHERIC STORMS WITH SATELLITE AND GROUND-BASED DATA AND MODELING

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1.0 INTRODUCTION

The purpose of this proposed research is to improve our basic understanding of the causes of ionospheric storm behavior in the midlatitude F region ionosphere. This objective will be achieved by detailed comparisons between ground based measurements of the peak electron density (N_mF_2), Atmosphere Explorer satellite measurements of ion and neutral composition, and output from the Field Line Interhemispheric Plasma (FLIP) model. The primary result will be a better understanding of changes in the neutral densities and ion chemistry during magnetic storms that will improve our capability to model the weather of the ionosphere which will be needed as a basis for ionospheric prediction. Specifically, this study seeks to answer the following questions

- 1) To what extent are negative ionospheric storm phases caused by changes in the atomic to molecular ratio?
- 2) Are the changes in neutral density ratio due to increased N_2 , decreased O, or both?
- 3) Are there other chemical processes (e.g. excited N_2) that increase O^+ loss rates during negative storms?
- 4) Do neutral density altitude distributions differ from hydrostatic equilibrium?
- 5) Why do near normal nighttime densities often follow daytime depletions of electron density?
- 6) Can changes in h_mF_2 fully account for positive storm phases?

Negative storm phases are decreases in electron density with respect to quiet values while positive storm phases are increases in electron density with respect to quiet values. Good reviews of ionospheric storms have recently been given by *Rishbeth* [1991] and *Prölss* [1995]. The review by *Prölss* [1995] lists 15 possible causes of the positive phase and 16 possible causes of the negative phase. Proposed causes of positive storms include changes in neutral composition and horizontal transport, but the most likely cause is the uplifting of the F -layer by equatorward winds or electric fields in the early hours of a storm. Similarly, many mechanisms have been proposed for negative phases with changes in the atomic to molecular neutral density ratio being favored. Positive phases are generally seen in the hemisphere which is in sunlight at the time the storm commences. Negative phases are generally not seen until the hemisphere which was in darkness when the storm commenced rotates into daylight. Using a comprehensive thermospheric general circulation model, *Fuller-Rowell et al.* [1996] have shown that upwelling, as a result of energy deposition in the auroral regions, generates a composition disturbance zone (bulge) with increased mean molecular mass. The global storm circulation pattern, in which winds blow from high to low latitudes, transports the bulge equatorward. A seasonal asymmetry is produced as the prevailing summer-to-winter

circulation transports the composition bulge from summer polar regions to mid to low latitudes. In winter, the composition bulge is constrained to remain at high latitudes by the flow from the summer hemisphere. The increases in mean molecular mass associated with the composition bulge cause depletions in ionospheric electron density at midlatitudes. Recently, *Szuszczewicz et al.* [1998] found evidence that both positive and negative phases tend to co-rotate with the Earth. Whatever the cause of the negative storm phase, it must allow the ionosphere to recover quickly to normal levels as frequently observed.

The recent results from thermospheric general circulation models show great advances in modeling ionospheric storms but the changes to the neutral atmosphere cannot be adequately verified because there are no suitable data sets of both neutral density profiles and auroral drivers. The Atmosphere Explorer data set from the 1970s has appropriate neutral density information for model verification but there is a lack of data on the auroral energy inputs (B. Emery, private communication). Analyses of auroral images can yield information on the relative column abundance of O and N₂ but do not provide information on their altitude distribution. From DE 1 images, *Strickland et al.* [1998] deduced large depletions in the O to N₂ density ratio during magnetic storms.

From numerous satellite observations *Prölss* [1980, 1991, 1992, 1995] has found a strong relationship between day-to-day changes in electron density and atomic to molecular neutral density ratios at midlatitudes. Prölss modeled ground based observations of daytime peak electron density using satellite neutral density measurements to normalize a thermospheric model. In our proposed study we will investigate the relationship between the neutral and electron density changes with the aid of a more sophisticated time-dependent ionosphere model which can be constrained to follow the peak height ($h_m F_2$) of the measured electron density. We will also compare the measured and modeled densities of minor ion and neutral species.

In his comprehensive 1995 review, Prölss lists twelve unsolved problems relating to ionospheric storms. This study particularly seeks to answer his question number 6, namely, **“Are neutral composition changes at higher and middle latitudes (i.e. increases in the O/N₂ density ratio) sufficient to explain the rather large negative storm effects observed during periods of high solar activity or are additional mechanisms (e.g., vibrationally excited species) required?”** Our study will be conducted with data from the Atmosphere Explorer-C satellite, which had a comprehensive suite of measurements of ion and neutral densities and temperatures, and made a major contribution to our current knowledge of the chemistry of the upper atmosphere.

In summary, the proposed study will use a sophisticated ionosphere model, capable of being constrained by key measurements, to relate ground-based and satellite data. The comparison of model and data for several different ion species should enable the determination of the relative importance of changes in chemistry versus neutral and ion density. For example, if the O⁺ + N₂ reaction rate is enhanced during storms due to vibrational excitation of N₂, we would expect an enhancement in the NO⁺ density relative to the O₂⁺ density.

2.0 IONOSPHERIC MODEL

The field line interhemispheric plasma (FLIP) model has been employed in numerous studies of the ionosphere since its development began more than 20 years ago. The model has recently been modified to handle the

effects of ExB drifts. Since September 1996 the PI has been an author on 14 published papers employing the FLIP model. This productive record has been achieved because the PI has freely provided modeling support to a large number of co-workers from across the nation and around the world.

The PI has devoted considerable effort to making the model accessible and has made the FLIP model freely available. A VMS version of the FLIP model has been widely used for many years and has been installed at the following locations: Boston University; Univ. of Mass. Lowell; La Trobe University and Univ. of Newcastle, Australia; Univ. of Michigan; Utah State University; Tokyo, Japan; Madrid, Spain; Naval Research Laboratory; Univ. of Arizona; Univ. Alabama Huntsville; Marshall Space Flight Center; Computational Physics Inc., and the Univ. of Alaska. A version of the FLIP model has been developed for the unix environment and is installed at Millstone Hill Observatory, Univ. Texas, Dallas, Clemson, in Japan, France, and Belgium.

The main component of the FLIP model calculates the plasma densities and temperatures along entire magnetic flux tubes from 80 km in the northern hemisphere through the plasmasphere to 80 km in the southern hemisphere. The model uses a tilted dipole approximation to the Earth's magnetic field. The equations solved are the continuity and momentum equations for O^+ , H^+ , He^+ , and N^+ as formulated for the topside ionosphere by *St.-Maurice and Schunk* [1976]. The electron and ion temperatures are obtained by solving the energy equations [*Schunk and Nagy*, 1978]. Electron heating due to photoelectrons is provided by a solution of the two-stream photoelectron flux equations using the method of *Nagy and Banks* [1970]. The solutions have been extended to encompass the entire field line on the same spatial grid as the ion continuity and momentum equations.

Apart from the interhemispheric solutions listed above, the FLIP model uses local chemical equilibrium to determine the densities of the ions: $\text{O}^+(\text{D})$, $\text{O}^+(\text{P})$, NO^+ , O_2^+ , N_2^+ and solves diffusion equations for NO , $\text{N}(\text{D})$, and $\text{N}(\text{S})$ densities. The basic chemical scheme, which arose largely out of numerous studies using data from the Atmosphere Explorer program, is described by *Torr et al.*, [1990]. The FLIP model also solves for the vibrational populations of molecular nitrogen. This is important because the reaction rate of O^+ with vibrationally excited N_2 is much faster than with ground state N_2 .

In order to simulate the ionosphere, the FLIP model requires three key inputs: the neutral atmosphere, the solar EUV flux, and the meridional component of the neutral wind. The neutral densities and temperatures are provided by the mass spectrometer and incoherent scatter (MSIS-86) model [*Hedin*, 1987] while the basic solar EUV flux is provided by our recently developed solar EUV flux model called EUVAC [*Richards et al.*, 1994a]. The EUVAC model is particularly appropriate for this study because it is based on the F74113 standard reference spectrum measured on April 23, 1974, during the AE-C mission. With the F74113 spectrum as the standard reference and the solar cycle dependence measured by AE-E, the EUVAC model produces integrated solar fluxes that agree well with the most reliable rocket measurements. The EUVAC model also reproduces the measured photoelectron fluxes at solar minimum and solar maximum [*Richards et al.*, 1994a].

In the last several years we have developed a number of algorithms to incorporate actual measurements ($h_m F_2$, $N_m F_2$, and Te) into physical models [*Richards*, 1991, *Richards et al.* 1995]. Most recently, we have developed an algorithm for determining what changes in the thermospheric atomic to molecular density ratio are needed to bring

the model into agreement with measurements at the F2 peak height [Richards *et al.*, 1998; Richards and Wilkinson, 1998]. The purpose of all of these algorithms is to constrain as many parameters as possible in order to isolate inadequacies in specific model inputs. Traditionally, physical models like the FLIP model are run with a given set of inputs (neutral densities, solar EUV flux, winds, etc.) to see how well the output compares with measurements, or to elucidate the key physical processes. Some ad-hoc parameter adjustment may be done to try to bring the model into agreement with measurements but there are usually too many free parameters to get a unique solution. By adopting a subset of measurements as constraints, we have greatly enhanced the capability of the model to provide insight into the physical and chemical processes of the upper atmosphere.

2.1 Neutral winds in the thermosphere

Neutral winds play an important role in determining the electron density profile by raising and lowering the F-layer. Equatorward winds increase N_mF_2 by forcing the ions to high altitudes where they are lost more slowly, while poleward winds have the opposite effect. To a good approximation the change in altitude of the peak height is linearly proportional to the change in the wind speed [Rishbeth, 1972]. Winds may be input to the FLIP model from the HWM90 model [Hedin *et al.* 1991], or from a data file. However, at midlatitudes, the best results are obtained by using the algorithm of Richards [1991] which continually updates the model wind to ensure a close reproduction of the observed h_mF_2 as the model steps in time. This procedure yields an equivalent (or effective) neutral wind because it may contain an electric field component.

The discrepancy between the measured and modeled h_mF_2 is typically a few kilometers if the model time step is 15 minutes, but can be made even smaller by reducing the time step. In this study, the h_mF_2 is indirectly obtained from the measured values of f_oF_2 , $M3000(F_2)$, and f_oE with an accuracy of $\sim 5\%$ (~ 15 km) [Dudeney 1983].

The use of the measured h_mF_2 as a wind proxy greatly reduces the model uncertainty, but winds determined by this method also agree well with direct wind measurements. We recently compared equivalent neutral winds deduced from h_mF_2 with neutral winds from Fabry-Perot interferometer (FPI) measurements near Melbourne, Australia for 6 nights from March 1 to March 6, 1995 [Dyson *et al.*, 1997] and there was excellent agreement. These results have been confirmed by the analysis of several additional Melbourne data sets by Ujmaia *et al.* [1998].

2.2 Convective electric fields

Except for short periods of the order of an hour at the beginning of magnetic storms, midlatitude storm-associated electric fields are expected to be small due to shielding.

At midlatitudes, the ionospheric density can be affected by convective electric fields in two ways. The most important influence is through the lowering or raising of the ionosphere in a manner similar to neutral winds [Rishbeth, 1972]. This effect has long been implicitly included in the FLIP model through the equivalent wind calculated from the measured h_mF_2 . Electric fields can also directly influence the flow of ions between the plasmasphere and ionosphere. As a flux tube drifts inward, its volume is reduced and the plasma is heated and compressed producing an increased plasma flow to the ionosphere (although it is really the plasma that drifts, we use the concept of drifting flux tubes for convenience in this discussion). Conversely, if the flux tube drifts outward, the ion

flux to the ionosphere will be reduced. The FLIP model can now include ion drifts explicitly through the appropriate terms in the ion continuity equations and the energy equations [Richards *et al.*, 1999].

The daytime ionosphere is not affected by the flux tube compression because it is dominated by photoionization, but the plasmasphere is a significant source of ionization at night. Simulations by Richards *et al.* [1999] show that convection does not affect the nighttime ionosphere at a ground station unless the drifting flux tubes have a very different ion content than a corotating flux tube would have. This is easily understood because the flux between the ionosphere and plasmasphere is governed by the difference in plasma pressure between the two regions which depends primarily on the plasmasphere density. Satellite ion measurements typically yield equatorial H^+ densities in refilling flux tubes that are consistent with them having similar ion contents [Chappell, 1972].

2.3 Ionosphere Modeling With Modified Neutral Atmosphere

The MSIS model altitude profiles of thermospheric densities and temperatures are represented by the Bates-Walker model [see Hedin, 1987]. In the Bates-Walker model [Walker, 1965], the neutral temperature (T_n) altitude profile is completely specified analytically by only 3 parameters: the lower boundary temperature at 120 km, the exospheric temperature at high altitudes (T_∞), and a shape factor. Once the temperature has been specified, the neutral density at any altitude is obtained simply by specifying the density at the lower boundary and analytically solving the equation for hydrostatic equilibrium. Thus the MSIS model is really a global semi-empirical model in which the data are used to specify the lower boundary densities and temperatures, the exospheric temperature, and the shape factor as a function of latitude, longitude, solar activity, magnetic activity, etc.

The standard MSIS neutral atmosphere model [Hedin, 1987] is known to perform extremely well in an average sense, reproducing average satellite drag and mass spectrometer data to within about 15% [Hedin, 1988]. However, on particular days there may be large differences between measurement and model [see Hedin, 1988 Figure 4] and MSIS does not normally produce the large decreases in the atomic to molecular neutral density ratio that have been observed during ionospheric storms. Since we will have neutral density information available from the satellite measurements we could possibly insert these directly into the FLIP model then compare the results with the ionosonde measurements. However, additional information would still be needed because the measurements cover only a limited portion of the altitude grid of the model. This problem could be solved if the MSIS model densities were adjusted to match the satellite densities by the common procedure of adjusting the magnetic (A_p) and solar indices ($F_{10.7}$). However this method is rather difficult to implement and still only applies at the time of the orbit. Additional assumptions must also be made about the neutral atmosphere for several hours prior to the satellite measurements because the ion density distribution is time-dependent. An alternative, but equivalent, approach is to adjust the neutral atmosphere to produce the electron density observed by ionosondes, then compare the resulting model neutral densities with satellite measurements.

Richards *et al.* [1998] have developed a new, easy to implement, algorithm that enables the determination of the changes to the MSIS neutral atmosphere needed to explain differences between the measured and modeled $N_m F_2$. As the model steps in time, the neutral atmosphere is continually adjusted to bring the model into better agreement with the measured $N_m F_2$ similar to the way the winds are adjusted to reproduce the measured $h_m F_2$. This is primarily accomplished by modifying T_∞ to change the scale heights of the thermospheric species (T_∞ is the first param-

ter specified in the MSIS routine). However, just changing T_{∞} usually produces only a small change in the MSIS model atomic to molecular density ratio in the F -region so the algorithm includes a direct modification of the lower boundary atomic oxygen density at 120 km as well. The physical basis for this is that the atomic oxygen column density is small relative to N_2 (which constitutes 80% of the Earth's atmosphere) and may be altered on short time scales by large scale circulation patterns produced by solar heating or by magnetic storms as found by *Strickland et al.* [1998]. For example, the well known seasonal anomaly in the daytime peak electron density is due in part to the transport of atomic oxygen from the summer to winter hemispheres [*Rishbeth*, 1991]. The algorithm does not change the lower boundary N_2 density because it is unlikely to be affected on the time scale of storms [*Rishbeth*, 1991].

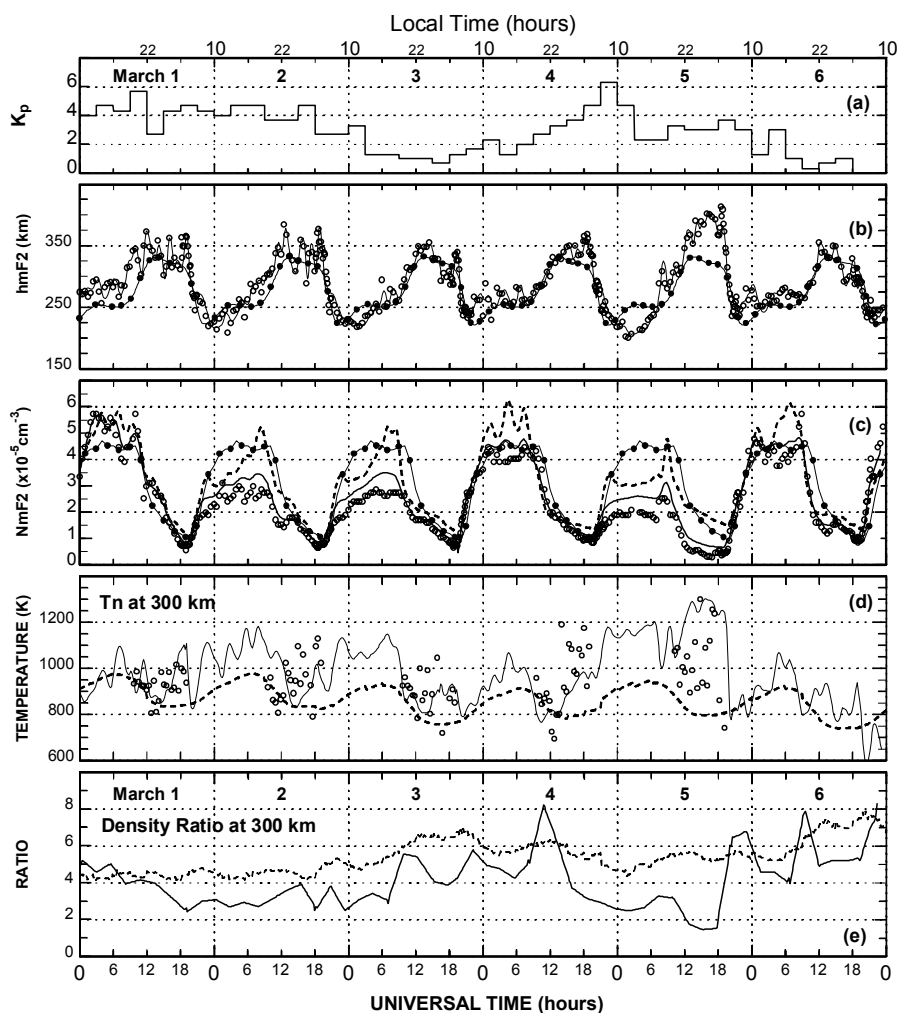


Figure 1. Calculated and observed parameters at Beveridge Australia (38S, 147E) during March 1-6 1995. Open circles indicate measured values while dashed lines are for the standard MSIS case. Solid lines are from the modified MSIS case. Solid lines with dots show monthly median values. Note that local time is given on the top axis.

The density modification algorithm was first applied using data from Beveridge (38S,147E), Australia March 1-6, 1995 [*Richards et al.*, 1998]. Figure 1 shows the calculated (lines) and observed (circles) densities and tempera-

tures. The curves with broken lines were obtained using the standard MSIS model while the solid curves were obtained when MSIS was modified. The lines with dots represent the monthly median values. Figure 1d shows that the modified T_n produced by the algorithm agrees well with the measurements by a Fabry-Perot interferometer (FPI). On most nights, the modified T_n agreed best with the FPI observations. In particular, both the measured and modified T_n usually increase after midnight and both increase very sharply after midnight on March 4, apparently in response to increased magnetic activity (Kp) towards midnight [Figure 1a]. The daytime N_mF_2 was close to the monthly median values (solid lines with dots) on March 4 and 6, but was severely depleted during the daytime on March 2 and 3. The ionosphere recovered on March 4 but was again depleted on March 5. Unlike March 2 and 3, which are close to the monthly median, the nighttime N_mF_2 was also severely depleted on March 5 and h_mF_2 was greatly elevated. The changes to the MSIS neutral density ratio are shown in Figure 1e. Note how well the model (solid line, no dots) reproduces the measured h_mF_2 while the neutral atmosphere is simultaneously being modified. The algorithms are also very stable. Our density modification algorithm could have been implemented by developing our own hydrostatic equilibrium model and using the MSIS model just to provide the lower boundary parameters, but this would have been a lot of unnecessary effort.

Our March 1995 study described above and in more detail by *Richards et al.* [1998] illustrates the power of this neutral density modification algorithm to pinpoint discrepancies between the modeled and measured electron density that cannot be accounted for by nominal adjustments to the neutral atmosphere. In a separate study of the ionosphere over the Australian-Japanese sector during November 1993 [*Richards and Wilkinson, 1998*] we found very little modification of the MSIS model was needed most of the time to reproduce the measured electron densities.

In summary, the ability of the FLIP model to use key measurements as constraints makes it unique among time-dependent ionospheric physical models. Because the model uses data as constraints, and because the coupling to the plasmasphere and conjugate ionosphere eliminates the need for ad-hoc upper boundary particle and heat fluxes, there are few adjustable parameters. Thus, it is ideally suited to comparisons between model and data. Numerous previous studies indicate the EUVAC solar flux model and the MSIS neutral atmosphere model generally produce good agreement between modeled and measured ionospheric densities during magnetically quiet periods.

3.0 DATA

The major thrust of this study will be the use of a comprehensive ionospheric model to provide a link between ground based ionosonde and Atmosphere Explorer (AE) satellite data.

Over 50 years of ionosonde measurements are available from NGDC via the World Wide Web and on CD-ROM. The ionosonde data presented in this proposal were obtained from the CD-ROM but we also made use of the Web access for quick graphical looks at the data. The database for the 1974-80 time period of the Atmosphere Explorer mission consists of hourly measurements from about fifty midlatitude ionosondes around the world. Ionosondes measure the f_oF_2 (N_mF_2) to better than 1% accuracy 80% of the time [*Wilkinson, 1978*]. The error in the determination of h_mF_2 is discussed in section 2.1.

The purpose of the AE mission was to investigate the thermosphere, with emphasis on the energy transfer and processes that govern its state. The study of photochemical processes accompanying the absorption of solar EUV

radiation in the earth's atmosphere was accomplished by making closely coordinated measurements of most reacting constituents and the solar input. This data set is ideally suited to our study, not only because it contains the required measurements, but also because of its extensive verification and accessibility. Each instrument team summarized their data every 15-seconds for inclusion in a unified abstract (UA) database. Numerous studies of the ion and neutral chemistry of the upper atmosphere have benefited from the use of AE data base. The AE program was a major source of data for the MSIS model. In addition, the thermosphere and ionosphere chemical scheme in general use today owes much to the use of AE data to verify the applicability of laboratory measured reaction rates to the space environment.

The AE missions consisted of 3 spacecraft each carrying similar instrumentation. The AE-C satellite was launched December 16, 1973 into an elliptical orbit which was altered many times in the first year of life by means of an onboard propulsion system employing a 3.5-lb thruster. The purpose of these changes was to alter the perigee height to 129 km. After this period, the orbit was circularized and was raised periodically to about 390 km when it would decay to 250 km altitude. During the first year, the latitude of perigee moved from about 10 degrees up to 68 degrees north and then down to about 60 degrees south. AE-D mission (launched October 6, 1975) was planned to sample the high latitude regions at the same time that the AE-E mission (launched November 20, 1975) was sampling the equatorial and low latitude regions with similar instrumentation to AE-C. The AE-D polar orbit provided the sampling of all latitudes and the perigee moved through all latitudes in 3 months and all local times in 4 months. Unfortunately, a failure in the power supply system resulted in the termination of operations on January 29, 1976, after slightly less than 4 months of useful life. However, all the regions at the perigee altitudes were sampled during this time. The payload on all 3 satellites included instrumentation for the measurement of solar EUV; the composition of ions and neutral particles; the density and temperature of neutral particles, positive ions, and electrons; airglow emissions; photoelectron energy spectra; and proton and electron fluxes up to 25 keV.

Because this study will make extensive use of the Open Source Neutral Mass spectrometer (OSS) number density measurements of the neutral thermosphere from AE-C, it is important to realize some of the potential limitations of the data. A detailed description of the instrument and its operation was given by *Nier et al.* [1973] and the techniques used to obtain the atomic oxygen number density are fully explained by *Nier et al.* [1976]. The reactive nature of O means it recombines in the instrument to form O₂. The OSS operated in "normal" mode above approximately 200 km but operated in "fly through" mode at lower altitudes. In "normal" mode, the atomic oxygen concentration was calculated by assuming the ambient thermosphere O₂ density is very low compared to O above 200 km so the O₂ measured by OSS gives very nearly the concentration of ambient atomic oxygen. The OSS instrument and data have provided the most reliable measurements of thermospheric atomic oxygen density ever obtained with an estimated upper limit of error of $\pm 30\%$ [*Mauersberger et al.*, 1976].

We have a copy of the UA data base for all 3 AE satellites on CD-ROM. Our investigation will primarily deal with AE-C data because its orbital characteristics in the initial year provide altitude profiles at midlatitudes. AE-D and AE-E data will also be used where possible but the short lifetime of AE-D limits its usefulness and the low inclination of AE-E is less suitable for midlatitude studies.

4.0 PROPOSED STUDIES

The primary purpose of this proposal is to determine whether changes in neutral densities can fully account for the observed midlatitude electron density variations during ionospheric storms by combining ground based and satellite borne measurements with the aid of the FLIP model. We also plan to investigate the role of vibrationally excited nitrogen in negative storms and search for experimental evidence that the major neutral species deviate from hydrostatic equilibrium.

These studies are only now feasible because the FLIP model can be constrained by key measurements and because models generally produce electron densities in good agreement with measurements during magnetically quiet periods [Richards *et al.*, 1994b; Wilkinson *et al.*, 1996; Richards and Khazanov, 1997]. Therefore, the basic quiet ionospheric chemistry and dynamics seems to be well understood. However, ionosphere models rarely reproduce the negative phases observed during ionospheric storms. Some of the inability of models to reproduce negative storm phases is certainly related to the inability of the MSIS model to predict the required changes in the neutral atmosphere model. We plan to rectify this lack of neutral density information by utilizing the AE data.

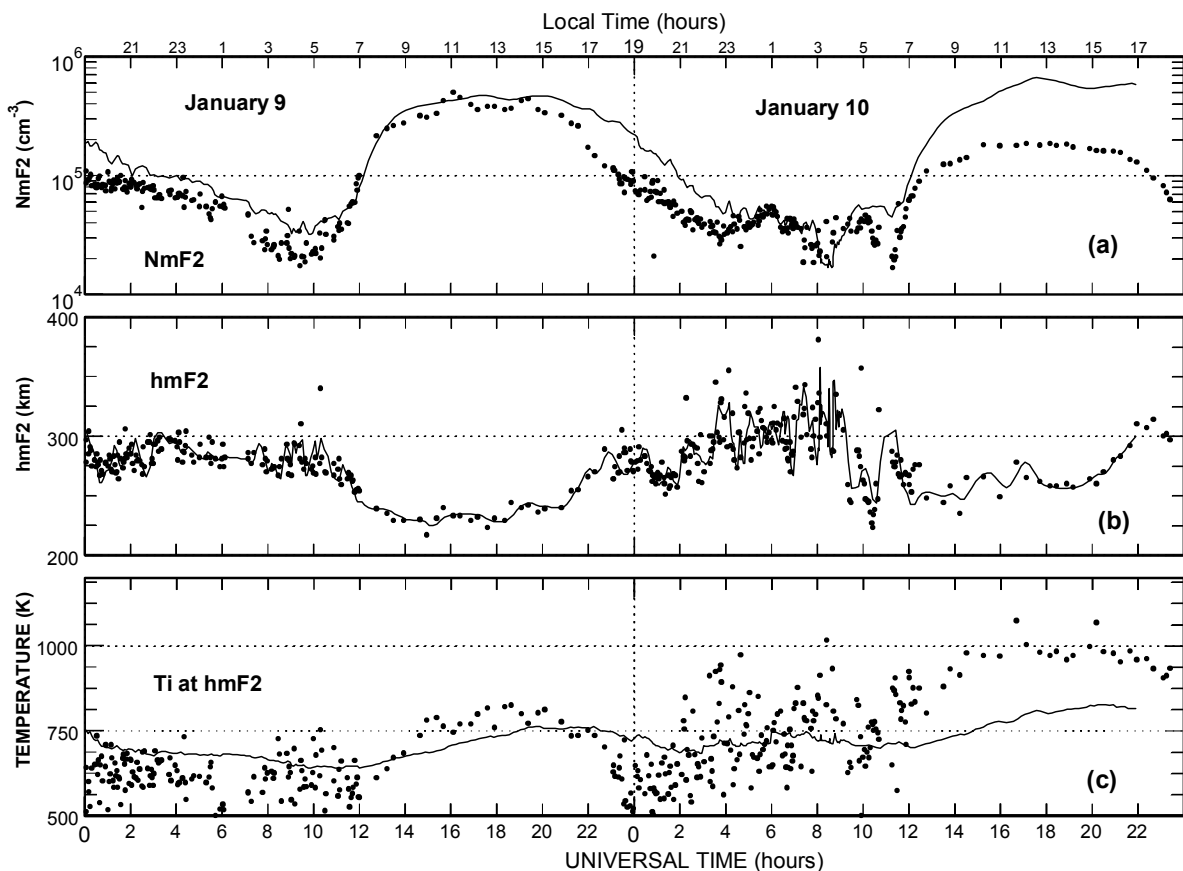


Figure 2. Comparison of observed (dots) and modeled (lines) densities and temperatures at Millstone Hill January 9-10, 1997.

Figure 2 shows an example where the MSIS model was unable to produce the observed temperature during a major storm at Millstone Hill (43N,288E) on January 10, 1997. Between January 6 and 9, the model T_i was in good agreement with the measured T_i at $h_m F_2$ but, while the measured T_i increased by over 200^0K on January 10,

the model T_i increased by only 50^0K as shown in Figure 2c (at midlatitudes, T_i is an effective proxy for T_n below 300 km because of the close thermal coupling between the ions and neutrals). Figure 2a shows the FLIP model, using the standard MSIS model, was in good agreement with the daytime $N_m F_2$ on January 9 but actually predicted an increase on January 10, instead of the observed decrease of more than a factor of 2. This increase in the model $N_m F_2$ is caused by an increase in daytime measured $h_m F_2$ from January 9 to January 10 [Figure 2b].

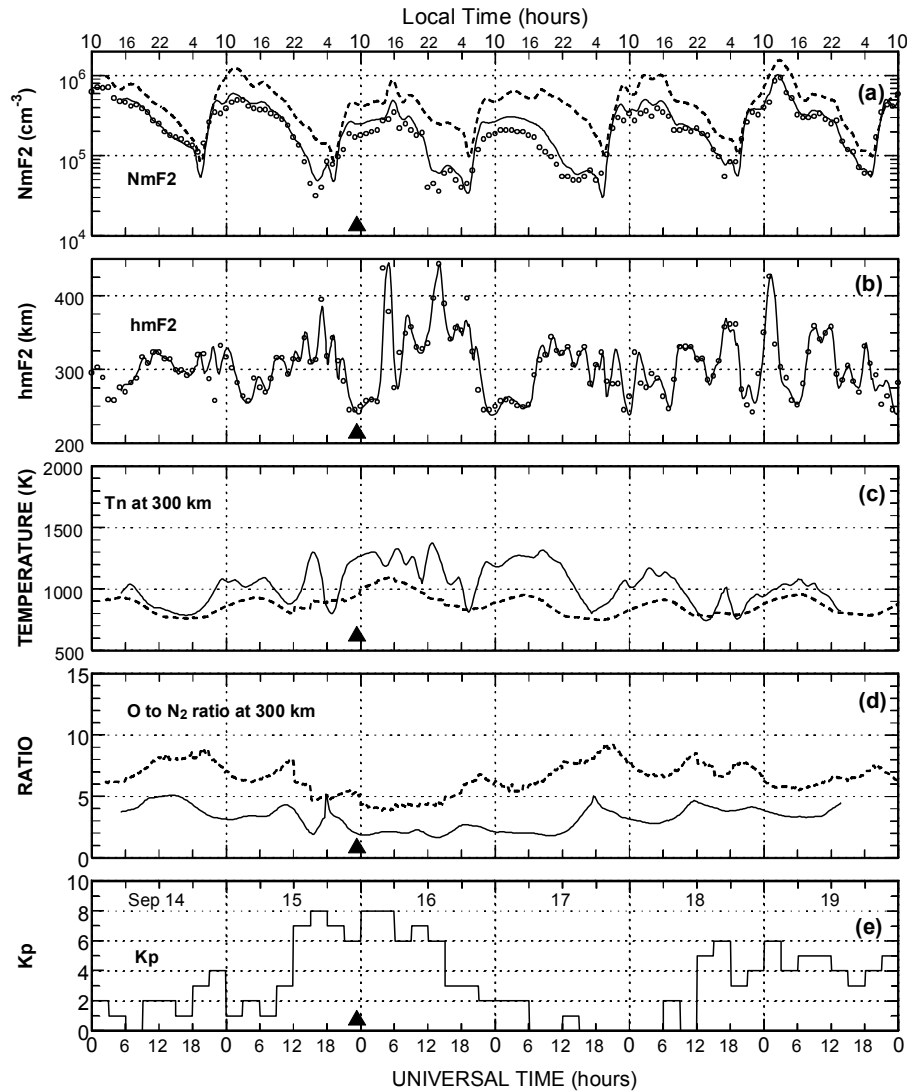


Figure 3. Observed (circles) and modeled (lines) densities, $h_m F_2$, neutral temperature, and O to N_2 ratio at Canberra September 14-19, 1974. Dashed lines are for the standard MSIS model. Solid lines are for the modified MSIS model. The solid triangle indicates the time of satellite over-flight of Canberra on September 15.

The inability of the MSIS model to reproduce the measured temperature during storms means the changes in neutral densities will also be incorrect. However, as was the case during the March 1995 and November 1993 storms, just increasing T_n in the MSIS model does not produce the observed changes in $N_m F_2$. It is also necessary to make substantial changes to the O to N_2 ratio at the lower boundary in the MSIS model. In fact, to reproduce the observed electron density on January 10 would require a factor of 3 change in the lower boundary neutral density

ratio [Mikhailov and Forster, 1999, Richards et al., 1999]. Such changes are much larger than the changes in the MSIS neutral density ratio at 120 km over an entire solar cycle.

The model-data comparisons shown in Figures 3 and 4 illustrate the type of study to be conducted with this funding. The FLIP model was run to simulate the ionosonde measured electron density over Canberra, Australia (35S,149E) from September 14 to 19, 1974. The results of this calculation were then compared with data from an over-flight by AE-C near 2400 UT on September 15, 1974 [Figure 4]. Following a sharp increase in Kp on September 15 [Figure 3e] there was a negative ionospheric storm beginning on September 15 and lasting until September 17. The FLIP model was first run using the standard MSIS model and also the measured $h_m F_2$ as a constraint. The standard model (dashed line) did produce a mild negative phase on the disturbed days as a result of an increase in T_n and a reduction in the O to N_2 ratio (see Figures 3c,d). However, unlike our previous studies, the model also significantly overestimated $N_m F_2$ on the magnetically undisturbed days during this period. Next the model was run with the modified MSIS by adjusting T_∞ and [O] to match the measured $N_m F_2$ and the results are plotted as solid lines in Figure 3. Note how well the model (solid line) reproduces the measured $h_m F_2$ while at the same time modifying the neutral atmosphere. The modified T_n was 100-200⁰K higher than the standard T_n on the quiet days and 300-400⁰K higher on the most disturbed days [Figure 3c]. There was also a factor of 2-3 reduction in the O to N_2 density ratio as shown in Figure 3d.

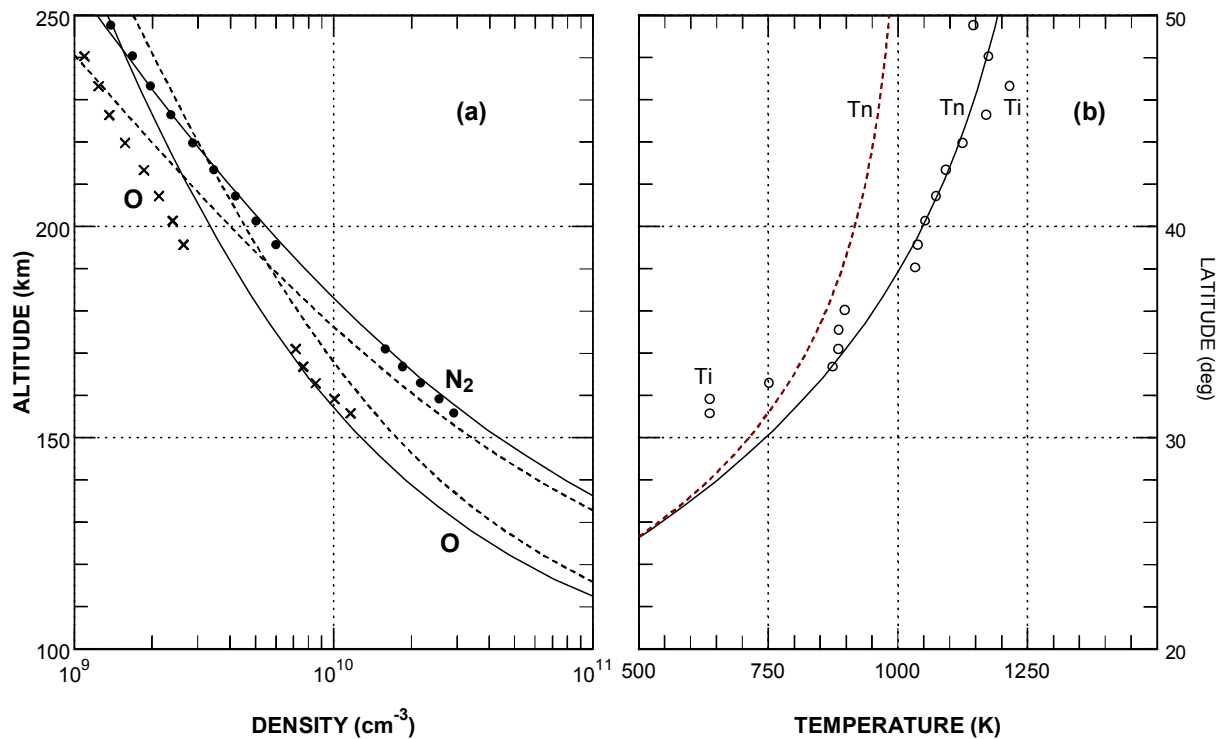


Figure 4. Comparison of measured values with model values at Canberra (35S,149E) just before 2400 UT on September 15. Dashed lines are from the standard MSIS model. Solid lines are from the modified MSIS model. The measurements are crosses (O), dots (N₂), open circles (Ti). Approximate latitude (south) is given on the rightmost Y axis.

Figure 4 shows a comparison of altitude profiles of the model neutral densities and temperatures with AE-C measurements (crosses and dots) near 2400 UT on September 15, 1994 (the time of these measurements is also shown by the solid triangles in Figure 3). The dashed lines in Figure 4 show the output from the standard MSIS model while solid lines are from the modified MSIS model run. The measured N_2 densities in Figure 4a are a factor of 1.3 higher than the standard MSIS N_2 densities at all altitudes on this orbit. Therefore, in order to compare the calculated and measured $N_m F_2$, we need to increase the lower boundary density in MSIS for this day. Moreover, if the MSIS model generally underestimates the N_2 density by 30% in mid-September 1974, this would explain why the FLIP model is also too high on the quiet days. Based on the observation that the FLIP model $N_m F_2$ was too high even on the quiet days, the lower boundary molecular densities were increased by a factor of 1.3 for the entire 6 days of the modified MSIS run shown in Figures 3 and 4 (solid lines). After the fixed adjustment to the molecular densities, the FLIP model was then free to adjust only T_∞ and $[O]$ to bring the model $N_m F_2$ into closer agreement with the ionosonde measurement as described in section 2.2. **As part of this proposed study we plan to examine satellite data during quiet periods of September 1974 to see if there are indeed elevated N_2 densities.**

T_n was not measured on this orbit but the ion temperature can be used as a proxy below about 300 km. Figure 4b shows the modified T_n is in excellent agreement with the measured T_i between 170 and 250 km and the scale height from the modified MSIS model does clearly fit the measured N_2 profile best. Thus the N_2 density profile can be well fit by a hydrostatic equilibrium model based on the measured temperature profile. This is an important result because upwelling is expected to increase the amount of molecular species at high altitudes [Fuller-Rowell *et al.*, 1996; Prölss, 1995] and invalidate the assumption of hydrostatic equilibrium. These AE-C measurements do not indicate any significant departure from hydrostatic equilibrium for the N_2 density on this orbit. This is perhaps not surprising in this particular case because N_2 is the dominant constituent to high altitudes, and it is generally assumed that the gas as a whole is in hydrostatic equilibrium. **In this study, we will compare the satellite N_2 density data on quiet and storm days for evidence of departures from hydrostatic equilibrium.**

The model-data comparison for atomic oxygen gives mixed results on this particular orbit. Between 155 and 170 km altitude, the modified $[O]$ agrees well with the measured $[O]$ while the standard MSIS $[O]$ is about 30% too high. However, above 200 km, even the modified O density is too high and the standard MSIS O density is almost a factor of 2 higher than the measurement. The measured O scale height is also smaller than both model scale heights. This may indicate departure from hydrostatic equilibrium but may also result from latitudinal gradients as the satellite moves from 48 to 35 degrees south latitude while the altitude changed from 250 to 170 (the geographic latitude is given on the right Y-axis of Figure 4). The mismatch between the densities above and below 200 km may be caused by the difficulty of making atomic oxygen measurements at low altitudes where there is a significant presence of O_2 . We also ran the model with the MSIS modification algorithm as well as a 40% reduction in O density and this does allow the model to better reproduce the observed $N_m F_2$. However, further modeling work and additional data sets are clearly needed.

The above model-data comparison supports the general idea that changes in the neutral density and temperature play a definite role in producing the negative storm effect, but it is still not clear that they are entirely responsible. Another possible explanation for the daytime depletion of $N_m F_2$ could be a change in the ionospheric chemis-

try. For example, vibrationally excited N_2 (N_2^*) increases the loss rate of O^+ but its role of in determining the F-region electron density has yet to be resolved. The calculations of *Richards and Torr* [1986], *Pavlov* [1994], and *Ennis et al.* [1995] all indicated N_2^* should reduce the peak electron density by a factor of 2 in summer at solar maximum. It may also contribute to the negative phase of ionospheric storms [*Richards et al.*, 1989, 1994b; *Pavlov*, 1994; *Pavlov et al.*, 1999]. However, the previous studies have been inconclusive. While the inclusion of N_2^* generally helps to produce the low densities on storm days, it often worsens the agreement on quiet days. For N_2^* to be responsible for the negative phase, there must be a process that enhances vibrational excitation on a storm day but not on quiet days. This process must also switch off quickly because the ionosphere often fully recovers in one day. One possibility is that the neutral density changes also cause changes in the chemistry. For example, large depletions in [O] will enhance the vibrational excitation of N_2 because it is the prime sink for vibrational quanta in the F region. If N_2^* is responsible for a large part of negative storms, we expect to see greatly enhanced NO^+ densities in the measurements. The satellite measurements of [O] will provide more accurate calculations of N_2^* during storms. By comparing the model ion densities with the measured ion densities on both quiet and disturbed periods, we will assess the importance of N_2^* in the ion chemistry.

In order to determine the relative role of neutral density changes and chemical changes, we plan to expand our study to include many more ground stations and many more AE-C orbits. There will be adequate storm periods to model as an examination of ground based measurements reveals negative storms occurring with a frequency of greater than one per month during the first year of the AE-C satellite lifetime. The rapid movement of the satellite in both altitude and latitude can cause problems when comparing satellite and ground based measurements. However, the use of the FLIP model and the inclusion of more stations will help overcome this problem. For example, the latitude of the Hobart ionosonde (43S,147E) corresponds to 230 km altitude in Figure 4. We have examined the Hobart ionosonde data for September 14-19, 1974 and it closely resembles the Canberra data. Several other Australian and New Zealand stations (Brisbane, Townsville, Mundaring, Auckland, Norfolk Island) have data along this orbit and there are similar midlatitude clusters of ionosondes in Europe and Russia. We also need to compare satellite and ground based data for quiet periods prior to storms to determine how well the MSIS model fits the data. Examining different ground based stations will provide comparisons over different altitude regions. It will be particularly useful to examine the higher altitude data where the effect of temperature on the density scale heights will be easier to detect. **We will also include comparisons of measured and modeled ion densities and the electron temperature in order to define the relative importance of chemical and neutral density changes during storms.**

A positive storm (increase in N_mF_2), clearly associated with a sharp increase in h_mF_2 , is also evident in Figure 3 just after 0000 UT on September 19. The relative time variation of this feature is well reproduced by the FLIP model. Although it appears the increase in h_mF_2 is responsible for this positive phase, we will examine the AE data for suitable coincidences to see if other factors may be operating. Because positive phases are short lived compared to negative phases, it will be more difficult to find suitable coincident data sets.

Although elliptical orbits will provide the important altitude coverage for this investigation, circular orbits will also be useful as the model provides a bridge between the ground-based data and the satellite orbit altitude. Com-

parisons between the model, AE data, and measurements of incoherent scatter radars are also possible. However, the scarcity of radars and their limited operating time make suitable storm time coincidences unlikely. Nevertheless, some data do exist as *Roble et al.* [1978] have compared model calculations with coincident AE and Millstone Hill radar for the magnetically quiet days of February 14 and 15, 1974.

5.0 CONCLUSION

The overall purpose of the proposed study is to determine to what degree the observed ionospheric storm effects are due to changes in neutral densities and temperatures. Specifically, this study seeks to answer the following questions

- 1) To what extent are negative storm phases caused by changes in the atomic to molecular ratio?
- 2) Are the changes in neutral density ratio due to increased N_2 , decreased O, or both?
- 3) Are there other chemical processes (e.g. excited N_2) that increase O^+ loss rates during negative storms?
- 4) Do neutral density altitude distributions differ from hydrostatic equilibrium?
- 5) Why do near normal nighttime densities often follow daytime depletions of electron density?
- 6) Can changes in $h_m F_2$ account for positive storm phases?

To answer these questions, we plan to combine ground-based and spaced-based measurements with the aid of our ionospheric model which is ideally suited to this purpose. The ionosonde data provide a means of determining the extent of the day-to-day changes in the electron density while the satellite provides the details of the neutral and ion densities and temperatures. The model provides a means of linking the measurements together in space and time. The viability of this approach has been demonstrated by a preliminary analysis of a sample data set.

While in principle this study would benefit from additional simulations using a thermospheric general circulation model (TGCM), this is not feasible because key inputs are not available to accurately drive the TGCMs for the elliptical orbit period of the AE-C mission (B. Emery, private communication). Unfortunately, since the AE mission, there has not been a satellite mission that provides a suitable set of neutral and ion parameters as a function of altitude for comparison with TGCMs.

These proposed studies will lead to a better capability to predict long term ionospheric variability, leading to better predictions of ionospheric weather. Also, if differences between the measured and modeled $N_m F_2$ are shown to be related to problems with the neutral density model, our studies could also lead to improved thermospheric models.

6.0 PROGRAMMATICS

This study will be carried out under the supervision of the PI with the aid of a research Associate (Tsao Chang) and a graduate research assistant. Tsao Chang has several years of experience in running the FLIP model and will be responsible for updating the model where necessary and the overall interpretation of the results while the GRA will be directly responsible for preparation of the data and running the model.

In the first year, we will conduct detailed comparisons for magnetic storms occurring during the elliptical phase of AE-C. We will first model the ion and neutral densities for the orbit of September 15 bringing in addi-

tional ionosonde data. As with any research project, we anticipate some initial discrepancies between the model and the data that will need to be resolved. We will also examine and model data from magnetically undisturbed periods as a benchmark. A considerable amount of time is necessary to model each set of ground-based data and compare it with each satellite overflight. In the second year, we will continue our studies for additional magnetic storms during the AE-C elliptical phase and also look for instances of satellite measurements during positive phases. In the third year, we will compare the modeled results with data from the AE-C circular orbits as well as with the data from the AE-D and E satellites.

Finally, in addition to enabling us to carry out this important study, this funding will also allow the PI to continue to provide modeling support to the ITM community. The PI has a faculty position 50% funded for the academic year.