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Intercomparison of Physical Models and Observations of the Ionosphere

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Abstract. Five physical models of the ionosphere were compared with each other and with data obtained at the Millstone Hill Observatory. Two of the models were self-consistent ionosphere-thermosphere models, while for the other ionospheric models the thermospheric parameters were provided by empirical inputs. The comparisons were restricted to midlatitudes and low geomagnetic activity, but four geophysical cases were considered that covered both the summer and winter solstices at solar maximum and minimum. The original motivation of the study was to determine why several physical models consistently underestimated the F region peak electron density, by up to a factor of 2, in the midlatitude, daytime ionosphere at solar maximum. This problem was resolved, but the resolution did not identify a lack of physics in any of the models. Instead, various chemical reaction rates, photoionization processes, and diffusion coefficients had to be adjusted, with the main one being the adoption of the Burnside factor of 1.7 for the diffusion coefficients. The subsequent comparisons of the models and data were for "standard" simulations in which uncertain inputs or processes were not adjusted to get better agreement with the data. For these comparisons, the five models displayed diurnal variations that, in general, agreed with the measurements. However, each one of the five models exhibited a clear deficiency in at least one of the four geophysical cases that was not common to the other models. Therefore, contrary to expectations, the coupled ionosphere-thermosphere models were not found to be superior to the uncoupled ionospheric models for the cases considered. The spread in $N_mF_2$ calculated by the five models was typically less than a factor of 2 during the day but was as large as a factor of 10 at certain local times during the night. The latter problem was traced to insufficient nocturnal maintenance processes in two of the uncoupled ionospheric models. The general findings of this study have important implications for the National Space Weather Program.

1. Introduction

The physics of the terrestrial ionosphere is reasonably well understood and is described by a set of first principles equations [Schunk, 1988]. Efforts to simulate the ionosphere by solving the first principles equations have met with a high degree of success, as shown by comparisons of the model predictions with observations. The shortcomings in the model/data comparisons are frequently attributed to inadequate constraints on the model inputs; hence it is difficult to establish the capabilities of an individual model by such comparisons. This study is based upon an intercomparison of five physical models that include the ionosphere. We use an alternative method to test the predictive capabilities of the models by carrying out an in-depth intercomparison of the models and an observational database. The test is based on standard model runs, with no allowance for adjusting uncertain input parameters. With this method, differences in how the physical formulations affect the model output can be evaluated, which may lead to identification of the strengths and weaknesses associated with each model.

The verification of the physical models, or at least the identification of relative merits of the models, is timely from another viewpoint. During the past solar maximum period, considerable interest focused on the detrimental effects of strong geomagnetic activity on communication systems, power grid operations, pipe line corrosion, and semiconductor manufacture [Allen et al., 1989]. Although the ionospheric models in themselves do not predict the geomagnetic impact on these terrestrial systems, they do provide a measure of our understanding of storm effects. Accordingly, efforts to validate ionospheric models have been initiated both nationally and internationally. The international component
of this effort is the URSI commission working group on validation of ionospheric models (VIM) and the national component is the National Science Foundation coupling energetic and dynamics of atmospheric regions (NSF CEDAR) working group on problems related to ionospheric models and observations (PRIMO). The objectives of these two groups are complementary: PRIMO emphasizes the investigation of first-principal physical models, while VIM is interested in the validation of all ionospheric models, including empirical, semiempirical, hybrid, and physical models.

An initial objective of this study was to try to understand why there seemed to be a factor of 2 discrepancy between calculated and observed $F$ region peak densities during the day at midlatitudes for solar maximum conditions. Electron density profiles derived from Digisonde ionograms [Reinisch and Huang, 1983] in the American and European sectors showed systematic differences from profiles calculated by data-driven or physical models [Reinisch et al., 1994]. It appeared that the model results consistently underestimated $N_{\text{max}}$ values for high levels of solar activity ($F_{10.7}$ cm flux index values greater than 200), producing noontime values of $\sim 1 \times 10^{12} \text{el m}^{-3}$ instead of the observed $2 \times 10^{12} \text{el m}^{-3}$. Since the models were incorporating climatological neutral parameters (densities, temperatures and winds), and established solar EUV production rates, charge exchange loss rates and ambipolar diffusion rates, it was unclear where the factor of two discrepancy originated from.

A study was initiated in 1991 to address this issue. Five ionospheric models were involved in the effort. Three of the models calculated ion and electron densities without self-consistent coupling to the neutral atmosphere, while two were fully coupled ionosphere-thermosphere models. The database of observations used in the study was to be from the extensive network of digital sounders [Reinisch, 1995] established by the U.S. Air Force and the University of Massachusetts-Lowell. These data were later augmented with Millstone Hill incoherent scatter radar measurements to cover low solar cycle conditions, for which no digital sounder data were yet available.

This paper presents the first intercomparison of the five physical ionospheric models. The models are the coupled thermosphere-ionosphere model (CTIM), the National Center for Atmospheric Research (NCAR) thermosphere-ionosphere general circulation model (TIGCM), the Utah State University time-dependent ionospheric model (TDIM), the University of Alabama at Huntsville field line interhemispheric plasma model (FLIP), and the Phillips Laboratory global theoretical ionospheric model (GTIM). It is important to bear in mind that the five models have different heritages, reflecting their development for different purposes. Since the models are not equivalent, it is not useful, or possible, to rank them by their capabilities in reproducing a selected subset of observations.

Section 2 presents details of the models and the observations used for verification. The extended descriptions of each model include identification of key caveats; these should be borne in mind in the later comparisons of the models with each other and with the observations. For simplicity we have carefully chosen the geophysical conditions and geographic location of the observations to minimize ambiguity and complications. Accordingly, the observational data set selected corresponds to quiet geomagnetic conditions at middle latitudes. Observations are taken from the extensive Digisonde and incoherent scatter radar (ISR) databases at the Millstone Hill location (42.6° N, 288.5° E). The data selected for model validation cover the winter and summer solstices for solar cycle minimum and solar cycle maximum. The limitations of the observations are also discussed.

The intercomparisons of the models with each other and with the observations are presented in section 3. Section 4 discusses the degree of agreement and attempts to identify the limits of the physical models in the context of this study. The final section outlines possible extensions of the work for other locations and conditions.

2. Models and Observations

The five models used in this study were developed for different purposes over more than a decade. Each model has an extensive history of model development and validation that has appeared in the literature. In the following five sections each model is briefly described from the perspective of this study. To help the reader in contrasting the different attributes of these models, Table 1 summarizes the key features of each model. This summary of features emphasizes the differences in the models that are potentially relevant to this study.

2.1. NCAR TIGCM

The NCAR TIGCM represents an intermediate step in the development of a global thermospheric/ionospheric general circulation model by Roble and Dickinson and colleagues. The model was initially formulated in order to investigate the neutral composition and dynamics of the upper thermosphere [Dickinson et al., 1981, 1984; Roble et al., 1982]. The incorporation of ionized species in the model was a more recent development [Roble et al., 1988].

The model self-consistently solves the coupled nonlinear equations for momentum, energy, continuity, hydrostatics, and the equation of state for the neutrals and the ions. Densities of $N_2$, $O_2$, $O$, $N_2(S)$, $N_2(D)$, NO, $N_2^+$, $O_2^+$, $O^+$, $NO^+$ and $N^+$ are calculated, as are the ion, electron, and neutral temperatures and the neutral winds. The latitude-longitude grid is $5^\circ \times 5^\circ$, with 24 levels in the vertical direction from 97 to about 500 km. Upward propagating tidal components are incorporated as perturbations to the lower boundary, as described by Fesen et al. [1991], and contributions from the semidiurnal modes (2,2) through (2,6) and the diurnal (1,1) mode are included [e.g., Forbes et al., 1993]. The semidiurnal tidal amplitudes and phases are provided by the lower atmosphere model of Forbes and Vial [1989]. In the simulations reported here, the diurnal (1,1) mode is specified by an amplitude of $4.0 \times 10^4$ geopotential centimeters and a phase of 4.0 hours at the model lower boundary near 97 km.

The lower boundary conditions of the model for the neutral chemical constituents depend on the species, and can be either photochemical equilibrium or a specified mass mixing ratio or mass flux. The ionized species are assumed to be in photochemical equilibrium at the lower boundary. The neutral mean temperatures and winds at the lower boundary are prescribed by an annual tide consistent with the Cospar International Reference Atmosphere climatology; semidiurnal and diurnal tidal variations are imposed as described above. The ion temperature is assumed to be equal to the neutral temperature. The upper boundary conditions are diffusive...
equilibrium for the neutral and ionized constituents and zero vertical gradients for the temperatures. The O⁺-O collision frequency is multiplied by the Burnside factor of 1.7 [Salah, 1993].

The ion drifts in the model are obtained from the empirical model of Richmond et al. [1980] for low and middle latitudes and from the empirical model of Heelis et al. [1982] for high latitudes. The Richmond et al. [1980] model represents solar cycle minimum conditions; the drifts during solar cycle maximum are known to be substantially different, at least at low latitudes [e.g., Fejer, 1991].

The high-latitude processes included in the model are magnetospheric convection and particle precipitation, which result in momentum forcing and Joule heating. The auroral parameterizations used in the TIGCM are described by Roble and Ridley [1987]. The empirical convection model of Heelis et al. [1982] is used for calculations of ion drag and Joule heating, which are updated at each time step. The model representation of particle precipitation is based on satellite data for various levels of auroral activity. Geomagnetic disturbances produce increases in the auroral zone half width, mean particle energy, and particle flux, which are adjustable model parameters that vary with magnetic local time. The geographic and geomagnetic poles are offset in the model. The displacement of the auroral oval toward the nightside in geomagnetic coordinates results in its location at higher geographic latitudes on the dayside.

In terms of this study, the following facts are of particular interest. First, the model uses an Eulerian (fixed grid) approach. The upper boundary is determined by the radiation condition and may vary from approximately 300 to 600 km, depending on solar activity. Near solar maximum, the peak of the F layer may lie very near the top boundary of the model. In extreme cases, it may even fall outside the model grid. Also, interhemispheric plasma fluxes and, consequently, conjugate effects are not included. As noted earlier, the ion drifts are imposed in the present model version, and currently they represent solar minimum conditions. As a consequence, the postsunset reversal of the E x B drift in the model is very small. Finally, it is emphasized that this model couples the neutral and ionized atmospheres, including the winds and the ion and neutral densities. There is no opportunity, for example, to adjust the neutral winds to reproduce the observed F layer heights, as can be done with some of the purely ionospheric codes.

The TIGCM simulations presented here are for June 21 and December 21. The solar activity is represented by the F₁₀.⁷ cm index, which is taken to be 75 (195) for solar cycle minimum (maximum). All simulations are for quiet geomagnetic conditions: the cross-polar-cap potential is 30 kV and the total hemispheric power is 3 GW. This corresponds roughly to a Kp level of 1. For each simulation the model is run to diurnally reproducible solutions; that is, the value of a modeled field at a given grid point and at a given universal time falls within a few percent of the value calculated on the previous day. Thus the results discussed here represent "steady state" conditions.

2.2. Utah State University TDIM

The TDIM model was developed over a two-decade period by Robert Schunk and coworkers. This model simulates a wide range of physical processes in the E and F regions of the...
ionosphere and uses state-of-the-art input models to represent
the neutral atmosphere, magnetosphere, and solar EUV. The
physical model is based on the transport formulation, and in
its present form solves the set of continuity, momentum, and
equations. Coupled continuity and momentum equations are solved for \( O^+ \), \( NO^+ \), and \( O_2^+ \) as major ions, and then solutions are obtained for \( N_2^+ \), \( N^+ \), and \( He^+ \), assuming they are minor ions; charge neutrality is assumed. Ion and
electron energy equations are solved at each time step to
obtain the \( O^+ \) and electron temperatures. The coupled
equations are solved as a function of altitude on a fixed grid,
and a Lagrangian procedure is used to follow convecting
plasma flux tubes. This facilitates the running of both global-
scale and high-resolution, local-scale, simulations with the
same formulation. An extensive effort has gone into
midlatitude and high-altitude research, including auroral and
polar cap magnetospheric dependencies. This work has also
involved studying ionospheric weather features, such as polar
cap patches, dayside troughs, Sun-aligned arcs, polar holes,
etc.

The ionospheric model was initially developed as a
midlatitude, multi-ion (\( NO^+ \), \( O_2^+ \), \( N_2^+ \), and \( O^+ \)) model by
Schunk and Walker [1973]. The time-dependent ion continuity
and momentum equations were solved as a function of altitude
for a corotating plasma flux tube including diurnal variations
and important \( E \) and \( F \) region processes. This model was
extended to include high-latitude effects due to convection
electric fields and particle precipitation by Schunk et al.
[1975, 1976]. At that time, a simplified ion energy equation
was also added, which was based on the assumption that local
heating and cooling processes dominate (valid below 500 km).
Flux tubes of plasma were followed as they moved in response
to convection electric fields. A further extension of the model
to include the minor ions \( N^+ \) and \( He^+ \), an updated
photochemical scheme, and the mass spectrometer/incoherent
scatter (MSIS) atmospheric model was undertaken by Schunk
and Raitt [1980].

The addition of plasma convection and particle
precipitation models was undertaken by Sojka et al. [1981a, b], so that three-dimensional plasma distributions could be
obtained. Schunk and Sojka [1982] expanded the model to
include ion thermal conduction and diffusion thermal heat
flow, with the result that the ion temperature is now rigorously
calculated at all altitudes between 120 and 1000 km. The
adopted ion energy equation and conductivities are those given
by Conrad and Schunk [1979]. The electron energy equation
was included by Schunk et al. [1986], and consequently, the
electron temperature is now rigorously calculated at all
altitudes. The electron energy equation and the heating and
cooling rates were taken from Schunk and Nagy [1978], and
the conductivities were taken from Schunk and Walker [1970].
The incorporation of the Sterling et al. [1969] equatorial
ionospheric model and the various improvements to this
model were undertaken by Sojka and Schunk [1985].

A detailed review of the TDIM theoretical development is
given by Schunk [1988], while a review of observation model
comparisons is given by Sojka [1989]. Sojka [1989]
discusses the comparison of the TDIM with selected
observations, and in most cases, favorable results were
obtained. Often, however, this could be attributed to sparse
observational data sets, which were inadequate to constrain the
TDIM simulations. The PRIMO studies are attempting to
constrain the TDIM and the other models through a uniform
procedure. The TDIM depends on empirical representations for
the neutral atmosphere, MSIS-86 [Hedin, 1987], and the
neutral wind, HWM90 [Hedin et al., 1991]. In addition, the
Schunk and Nagy [1978] \( O- \) collision frequency is scaled by the
Burnside factor of 1.7 [Salah, 1993]. The magnetospheric
inputs (convection electric field and auroral precipitation) are
both assumed to be zero at the Millstone Hill latitude, where
corotation dominates under quiet geomagnetic conditions.

2.3. University of Alabama at Huntsville FLIP

2.3.1. FLIP model. The FLIP model, which has been
developed over a period of more than 10 years, has been
described previously by Richards and Torr [1988] and, more
recently, by Torr et al. [1990] and by Richards et al. [1994a, b]. The main component of this one-dimensional 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 \( O^+ \), \( H^+ \), and \( He^+ \), as
formulated for the topside ionosphere by St.-Maurice and
Schunk [1977]. The \( He^+ \) chemical and physical processes have
been discussed by Newberry et al. [1989]. Collisions between
ions and neutrals have been included in order to extend the
equations into the \( E \) and \( F \) regions.

The FLIP model also solves the continuity and momentum
equations for the first six vibrational levels of \( N_2 \) in order to
take into account the strong dependence of the \( O^+ + N_2 \rightarrow NO^+ 
+ N \) reaction rate on vibrational excitation of \( N_2 \) [Richards et
al., 1986; Richards and Torr, 1986]. However, for this study
involving the intercomparison of models, vibrationally
excited \( N_2 \) was not included.

The electron and ion temperatures are obtained by solving
the energy equations [Schunk and Nagy, 1978]. Electron
deoing 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.

2.3.2. Model parameters. In order to simulate the
ionosphere, the FLIP model requires three key inputs: the
neutral atmosphere, either \( h_F2 \) or the meridional component
of the neutral wind, and the solar EUV flux. The neutral
densities and temperatures are taken from the mass
spectrometer and incoherent scatter (MSIS-86) model [Hedin,
1987]. For winds, the FLIP model can input either modeled
or measured winds. However, for purposes of this paper, FLIP
employs winds from the HWM90 model [Hedin et al., 1991].
A better fit to the measured \( h_F2 \) could have been obtained by
using the algorithm of Richards [1991]. When using neutral
winds from the HWM90 model, the \( O^+ - O \) collision frequency
of Schunk and Nagy [1978] is scaled by the Burnside factor of
1.7, which has been adopted by the CEDAR community [Salah,
1993].

The EUV flux model has been described by Richards et al.
[1994c]. It is based on the standard F74113 fluxes in the 37
wavelength intervals proposed by Torr et al. [1979], except
that we have doubled the fluxes in the wavelength range below
250 \( \text{Å} \). This modification is necessary so that the shape of the
calculated photoelectron flux spectrum agrees with the shape of
the measured photoelectron flux spectrum. Richards and
Torr [1988] have shown that the model photoelectron fluxes are in good agreement with the measured fluxes of Lee et al. [1980]. The F74113 flux spectrum has been chosen as our solar minimum standard because it was employed very successfully in the aeronomical calculations from the Atmosphere Explorer (AE) program. The solar activity scaling of the F74113 reference fluxes is achieved using both $F_{10.7}$ and the 81 day average $F_{10.7}$ as proxies. The solar cycle variation of the integrated solar EUV flux in the 50-575 Å wavelength range is in very good agreement with rocket measurements and the fluxes from the model of Tobiska [1991]. The photoionization rates from our EUV flux model are about 10% higher than those calculated from the Hinteregger et al. [1981] model.

An important consideration is the coupling flux of ions from the plasmasphere, which helps maintain the nighttime ionosphere. The particle and energy coupling between the ionosphere, plasmasphere, and conjugate ionosphere are handled self-consistently in the FLIP model. However, there is still some uncertainty for altitudes with $L \geq 2$ due to the possibility that flux tubes may be in the process of refilling after being emptied by magnetic storms. For the calculations in this study, the flux tubes are assumed to be almost full, as they would be after several days free of storm activity. Thus the nighttime downward flux of ionization is close to the maximum possible.

2.4. Phillips Laboratory GTIM

A global, time-dependent, first-principles F region ionospheric model, GTIM, has been developed at the Geophysics Directorate of Phillips Laboratory. GTIM is an F region model that calculates O$^+$ ion densities as a function of altitude, latitude and local time. GTIM began as a low-latitude model [Anderson, 1971, 1973], evolved into a midlatitude model by assuming that the F region plasma corotates with the Earth, and finally became global by adding the high-altitude processes of $E \times B$ convection drifts and energetic electron and ion particle precipitation [Decker et al., 1994].

The model determines the O$^+$ ion density by numerically solving the time-dependent ion continuity and momentum equations. The production rate includes production by photoionization, photoelectron impact ionization, particle precipitation and nocturnal photoionization. The loss occurs by charge exchange with N$_2$ and O$_2$. It is within the momentum equations that the effects of gravity, pressure, the ambipolar electric field, and neutral wind are included in the model. To solve the final parabolic, partial differential equation, the finite differencing scheme of Crank and Nicholson [1947] is used to produce a set of linear algebraic equations, which are then solved using standard techniques for inverting a tridiagonal matrix. By applying this technique along a given magnetic field line, the O$^+$ density is determined along that field line as a function of time. Solving such an equation naturally requires that both initial and boundary conditions be specified. For the initial condition we can specify any O$^+$ profile along the field line that is desired. Normally, a generic profile appropriate for the initial time of the particular simulation is used. For the lower boundary condition at the foot of the field line (100 km), a local approximation is used to provide the O$^+$ density. At the upper boundary, usually above 1000 km, either an O$^+$ density or flux is specified. For low-latitude calculations, where the density is solved along the entire field line from one hemisphere to the other, the "upper" boundary really becomes the other end of the field line at 100 km. Finally, by going through this procedure for many field lines, global O$^+$ densities can be produced. A detailed description of the derivation and numerical solution of the appropriate equations can be found in the works by Anderson [1973] and Moffett [1979].

2.5. CTIM

The CTIM has evolved from an integration of a neutral thermospheric code and a high-latitude and midlatitude ionospheric model. The neutral thermospheric model was originally developed by Fuller-Rowell and Rees [1980] at University College London (UCL); the ionospheric model originated from Sheffield University [Quegan et al., 1982].

The original UCL version simulated the time-dependent structure of the vector wind, temperature and density of the neutral thermosphere by numerically solving the nonlinear primitive equations of momentum, energy and continuity. The global atmosphere was divided into a series of elements in geographic latitude, longitude and pressure. Each grid point rotates with the Earth to define a noninertial frame of reference in a spherical polar coordinate system. The latitude resolution is 2°, longitude resolution 18°, and each longitude slice swept through all local times with a 1-min time step. In the vertical the atmosphere is divided into 15 levels in logarithm of pressure from a lower boundary of 1 Pa at 80 km altitude.

The solution of a time-dependent mean mass equation was incorporated into the model by Fuller-Rowell and Rees [1983]. This formalism assumed the upper atmosphere could be approximated by two species, atomic oxygen and the sum of molecular nitrogen and oxygen. More recently, the major species composition was improved to include solution of the three major species (O, O$_2$, and N$_2$), including chemistry, transport and the mutual diffusion between the species.

The time dependent variables of southward and eastward wind, total energy density, and concentrations of O, O$_2$ and N$_2$ are evaluated at each grid point by an explicit time-stepping numerical technique. After each iteration, the vertical wind is derived, together with temperature, density, and heights of pressure surfaces. The parameters can be interpolated to fixed heights for comparison with experimental data.

Fuller-Rowell et al. [1987] coupled the neutral thermosphere with the Sheffield University high-latitude and midlatitude ionospheric convection model [Quegan et al., 1982]. Traditionally, ionospheric models are evaluated in a Lagrangian system, where the evolution of ion density and temperature of plasma parcels are computed along their convection paths. In the coupled model the ionospheric Lagrangian frame has been modified to be more compatible with the Eulerian frame by implementing a semi-Lagrangian technique [Fuller-Rowell et al., 1988]. Adoption of a rotating frame of reference for the ionosphere eliminates the need for a "corotation potential."

Transport under the influence of the magnetospheric electric field is explicitly treated, assuming $E \times B$ drifts and collisions with the neutral particles. The atomic ions H$^+$ and O$^+$ and ion temperature are evaluated over the height range from 100 to 10,000 km, including horizontal transport, vertical diffusion, and the ion-ion and ion-neutral chemical processes. Below 400 km, additional contributions from the molecular ion species N$_2^+$, O$_2^+$ and NO$^+$, and the atomic ion N$^+$ are included.

The magnetospheric input to the model is based on the statistical models of auroral precipitation and electric field
described by Fuller-Rowell and Evans [1987] and Foster et al. [1986], respectively. Both inputs are keyed to a hemispheric power index (PI), based on the TIROS/NOAA auroral particle measurements, and are mutually consistent in this respect. The PI index runs from 1 to 10 to cover very quiet to storm levels of geomagnetic activity; the relationship between PI and $K_p$ is given by Foster et al. [1986]. Equatorward of the auroral oval, a soft midlatitude background electron precipitation has been added to the TIROS/NOAA auroral model at all latitudes and local times. The spectrum of this additional particle source is assumed to be Maxwellian with an energy flux of 0.05 mW m$^{-2}$ and a mean energy of 50 eV. The magnitude of the electric fields are increased by 30% above the original model values due to statistical smoothing.

The (2,2) and (2,4) tidal modes are imposed at 97 km altitude [Fuller-Rowell et al., 1991] with 300 m amplitude and a phase of 12 hours. The tides are imposed by adjusting the height of pressure level 4, near 97 km. Winds and temperatures respond through the physical processes included in the model and their influence propagates to higher altitudes. The EUV flux is calculated from the Hinteregger et al. [1981] reference spectra for high and low solar activity based on the Atmospheric Explorer (AE) measurements. The Schunk and Nagy [1978] O-O$^+$ collision frequency has been scaled by the Burnside factor of 1.7 [Salah, 1993].

To simulate the periods of interest for the present study, the day of year defines the solar declination angle, and the $F_{10.7}$ cm index the solar EUV flux; both of these parameters are set in common with the other models; see section 3. The level of geomagnetic activity is the TIROS/NOAA power level 5, which defines a quiet to average level of magnetospheric input. The auroral power input to each hemisphere is 12 GW and the cross-polar-cap potential is 47 kV, conditions roughly equivalent to a $K_p$ of 2. The model was run for several days at the prescribed levels of solar and geomagnetic activity until the results were diurnally reproducible.

As with the NCAR model, the neutral atmosphere is computed self-consistently with the ion density, so there is no opportunity to adjust the neutral wind or composition to "tune" the model. It is only possible to adjust the primary drivers of the thermosphere-ionosphere system.

### Table 2. Solar Cycle and Seasonal Study Periods

<table>
<thead>
<tr>
<th>Day</th>
<th>Year</th>
<th>$F_{10.7}$</th>
<th>$K_p$ Sum</th>
<th>Prior $K_p$ Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 19</td>
<td>1990</td>
<td>176</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>December 19</td>
<td>1990</td>
<td>198.5</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>June 25</td>
<td>1986</td>
<td>69.7</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>December 11</td>
<td>1986</td>
<td>70.4</td>
<td>15</td>
<td>13</td>
</tr>
</tbody>
</table>

$^a$ Monthly mean value. $^b$ Daily average for the prior 3 days.

The $N_mF_2$ and $h_mF_2$ derived from the Millstone Hill ISR data are shown in Figures 3 and 4 and are reasonably consistent with diurnal variations given by the IRI-90 model [Bilitza, 1990; Bilitza et al., 1993], which represents monthly averaged conditions. Mendillo et al. [1975] calculated standard deviations for each of 62 months of $N_mF_2$ data at Wallops Island. The average value of these standard deviations varied from about 22% during the day to 28% at night. Hagan et al. [1992] compared $N_mF_2$ at Wallops Island for quiet days in January 1985, 1986, and 1987, and found daytime values of $N_mF_2$ that varied from approximately 0.4 x 10$^{12}$ m$^{-3}$ on one day in 1987 to approximately 0.65 x 10$^{12}$ m$^{-3}$ on one day in 1985. Less interannual variability was found for $h_mF_2$. The MHO $N_mF_2$ and $h_mF_2$ data presented here are within the range of these Wallops Island solar minimum results.

### 2.6. Observations

The observations used for comparisons are all from Millstone Hill, Massachusetts; its location is 42.6°N latitude and 288.5°E longitude. This station was selected for the following reason. Observations of the middle latitude ionosphere are available from a latitude chain of Digisondes lying along the longitude of the east coast of North America. The Digisondes observations during solar maximum conditions were examined, and it was found that the observations from Millstone Hill were representative of the whole midlatitude ionosphere for the periods used in this study. Hence the data and model comparisons presented here are specifically for Millstone Hill, but the comparison is applicable to the entire midlatitude domain at this longitude.

Four periods were selected for model data comparisons: winter and summer during solar cycle minimum and maximum. These represent extremes in both seasonal and solar cycle conditions. Table 2 lists the solar and geophysical conditions during the four periods. For each period the average daily $K_p$ sum is given for the preceding 3 days. These average values indicate that for all four periods the preceding days were also quiet and hence that the ionosphere was in a relatively quiet state. This was a key factor in selecting these particular periods.

#### 2.6.1. Millstone Hill incoherent scatter radar (MHO) data.

$N_mF_2$ and $h_mF_2$ for June 23-25, 1986, and December 10-12, 1986, were obtained from incoherent scatter electron density profiles measured with the 68 m zenith-pointing antenna. Profiles of backscattered power versus height were obtained using a 0.32 ms pulse to give 48 km altitude resolution. These profiles were calibrated using $f_sF_2$ measurements from the local ionosonde, and temperature corrected using the $T_o / T_i$ ratio obtained from longer pulse (0.64 ms) data. The shorter pulses provide better altitude resolution, while the longer pulses are required for better spectral information needed to determine the temperatures. More details are provided by Buonsanto [1989].

The $N_mF_2$ and $h_mF_2$ derived from the Millstone Hill ISR data are shown in Figures 3 and 4 and are reasonably consistent with diurnal variations given by the IRI-90 model [Bilitza, 1990; Bilitza et al., 1993], which represents monthly averaged conditions. Mendillo et al. [1975] calculated standard deviations for each of 62 months of $N_mF_2$ data at Wallops Island. The average value of these standard deviations varied from about 22% during the day to 28% at night. Hagan et al. [1992] compared $N_mF_2$ at Wallops Island for quiet days in January 1985, 1986, and 1987, and found daytime values of $N_mF_2$ that varied from approximately 0.4 x 10$^{12}$ m$^{-3}$ on one day in 1987 to approximately 0.65 x 10$^{12}$ m$^{-3}$ on one day in 1985. Less interannual variability was found for $h_mF_2$. The MHO $N_mF_2$ and $h_mF_2$ data presented here are within the range of these Wallops Island solar minimum results.

#### 2.6.2. Millstone Hill Digisonde data.

During the solar maximum summer and winter periods listed in Table 2 (June and December 1990), a chain of Digisondes was operating. These Digisondes [Reinisch, 1996] developed by the University of Massachusetts-Lowell, were automated such that its operation, data collection, and electron density profile analysis [Huang and Reinisch, 1996] would be carried out unattended. Doppler interferometry was applied to determine echo arrival directions [Reinisch et al., 1997]. This capability is particularly necessary in the selection of the vertical ionogram traces. For the applications of this study, this latter feature was crucial because both the critical frequency of the F layer and its true height were required.

Observations from five Digisondes (Bermuda 32.2°N, Wallops Island 37.9°N, Millstone Hill 42.6°N, Argenta 47.3°, and Goose Bay 53.2°) were obtained from the VIM database (Reinisch et al., 1994). These data had all been manually inspected to ensure that the automated Digisonde analysis had been successful and to add data quality
information. This additional analysis had been carried out by Bodo Reinisch's group in the Center for Atmospheric Research at Lowell. As stated earlier, these observations from five stations were used to verify that the MHO observations were indeed representative of the midlatitude region at this longitude. Figures 1 and 2 show the Millstone Hill Digisonde observations.

3. Comparisons of Models and Observations

Comparison of the observed \( N_m F_2 \) and \( h_m F_2 \) with the five physical models are shown in the following figures. Some of the differences that will be seen are intrinsic to the specific model or associated with input functions that are based upon climatology trends from limited observations. Where appropriate, comments to this effect are provided. In each figure the thick gray lines represent the Millstone Hill observations. The other lines indicate the various model results. The model results were obtained for the particular day of the observations using the solar and geomagnetic conditions listed in Table 2, or as specified earlier for equivalent conditions.

3.1. Solar Maximum: Winter

The thick gray line in Figure 1a shows the Millstone Hill Digisonde observations of \( N_m F_2 \) for December 19, 1990, in a logarithm to the base 10 format. The observed values of \( h_m F_2 \) are shown in Figure 1b, also as a thick gray line. Both \( h_m F_2 \) and \( N_m F_2 \) observations are 1 hour values. The uncertainty in \( N_m F_2 \) derived from a measure of the F layer critical frequency is negligibly small in the context of the spread in model values shown in Figure 1a. Of more relevance is the question of how well this \( N_m F_2 \) diurnal variation is representative of ionospheric solar maximum, winter, low geomagnetic activity conditions at Millstone Hill? In part, this has been answered in section 2.6, where "similar days" show about a 20% standard deviation. This is not the same for the ISR and Digisonde \( h_m F_2 \) values. The Digisonde \( h_m F_2 \) are computed from path delays through the ionosphere to the peak [Chen et al., 1994]. The variability from hour to hour in the observed \( h_m F_2 \) is in fact a reasonable indication of the uncertainty in the analysis. A probable uncertainty of ± 10 km is consistent with the scatter for the Digisonde \( h_m F_2 \).

3.1.1. TIGCM. The dashed curves in Figure 1 represent the TIGCM calculated \( N_m F_2 \) and \( h_m F_2 \). The model densities are larger than those observed at all times, except between 0000 and 0500 LT. Maximum differences are of the order of 50%. Bigger discrepancies are found in the comparison of \( h_m F_2 \). The model predicts a nearly flat diurnal variation, with the height varying from about 290 to 315 km. The observations, on the other hand, indicate the height changes by over 100 km, from 250 to over 350 km. The calculated layer is too high during the daytime and too low at night. An increase in the daytime neutral wind could improve the agreement. However, this is not a free parameter in the TIGCM, which self-consistently calculates both winds and composition.

3.1.2. TDIM. The lines with circles in Figure 1 represent the TDIM calculated \( N_m F_2 \) and \( h_m F_2 \). \( N_m F_2 \) is in very good agreement with the observations during the day, with values about 20% below those measured. At night the model \( N_m F_2 \) values are about 40% too low. During the day the \( h_m F_2 \) agreement with observations (Figure 1b) is good, but during the night the modeled \( h_m F_2 \) occasionally exceeds the observations by up to 50 km. Note that the three uncoupled ionospheric models (TDIM, FLIP, and GTIM) use the same

![Figure 1a](image1a.png)  
**Figure 1a.** A comparison of the observed \( N_m F_2 \) diurnal variation at Millstone Hill (thick shaded line) with five physical ionospheric models for solar maximum, winter conditions. The model results are for the TIGCM (dashed line), TDIM (line with circles), FLIP (dotted line), GTIM (solid line), and CTIM (line with squares).

![Figure 1b](image1b.png)  
**Figure 1b.** A comparison of the observed \( h_m F_2 \) diurnal variation at Millstone Hill (thick shaded line) with five physical ionospheric models for solar maximum, winter conditions. The model results are for the TIGCM (dashed line), TDIM (line with circles), FLIP (dotted line), GTIM (solid line), and CTIM (line with squares).
neutral wind model (HWM90) in their calculations, and the three uncoupled models predict NmF₂ values that agree to within ±5 km. This indicates that the discrepancies between the hₘF₂ values calculated by these models and those measured are due to the adopted HWM90 model.

3.1.3. FLIP. The dotted line shows the FLIP model results. The FLIP model NₘF₂ values are about 20% less than the observed densities during the day and about 50% less during the night. The agreement between the model and data would be improved during the day if the model were constrained to follow hₘF₂ with the algorithm of Richards [1991] instead of using the HWM90 winds. On the other hand, the model NₘF₂ would then be much too low at night because the HWM90 winds yield hₘF₂ values that are more than 50 km higher than the observed hₘF₂ at times during the night. The higher layer helps to preserve the ionospheric density. The hₘF₂ from uncoupled ionospheric models, which use the standard HWM90 winds, indicate that the nighttime equatorward HWM90 winds may be too large on this occasion.

3.1.4. GTIM. The solid lines in Figure 1 represent GTIM calculated NₘF₂ and hₘF₂. Throughout the daytime and to about midnight, the comparison with the observed NₘF₂ is very good. From midnight to dawn, the modeled NₘF₂ decays to lower values than observed in much the same way as the TDIM. The comparison between GTIM and observed hₘF₂ values is also in excellent agreement throughout most of the daytime hours. However, between 1800 and 0800 LT, the calculated hₘF₂ values exceed the measurements by about 25 to 50 km. This again indicates that the HWM90 winds at night need to be improved, which requires a more extensive neutral wind database.

3.1.5. CTIM. The CTIM NₘF₂ and hₘF₂ are plotted as lines with squares. Both parameters follow the observations very well. CTIM is the only model that achieves a slight night-early morning NₘF₂ increase, which occurs at 0500 LT, in comparison to the observations that show a slight maximum at 0300 LT. None of the models achieve a nighttime NₘF₂ morphology that looks like that observed. In fact, the five models have relatively diverse nighttime morphologies.

3.2. Solar Maximum: Summer

Digisonde observations for June 19, 1990, are shown in Figure 2 by the thick gray lines. The five models runs for this day are for the conditions listed in Table 2. The calculated values of NₘF₂ and hₘF₂ are also shown in Figure 2 and are described below. In addition, a comparison of Figures 1a and 2a, in terms of the seasonal anomaly, is given.

3.2.1. TIGCM. The model predictions are shown in Figure 2 by the dashed curves. The observed NₘF₂ shows little diurnal variation, while the model predicts a much larger variation. The TIGCM peak electron densities are too large during the day and too small at night. The largest discrepancy occurs from midnight to dawn, during which time the model predictions are nearly an order of magnitude too small. During the day, the model densities are, at most, about double those observed. The comparison of hₘF₂ shows that the model layer height is typically higher than that observed. The differences are a maximum of 75 km during the day and 50 km at night. An increase in the daytime poleward winds would improve both NₘF₂ and hₘF₂ in the model.

The comparison of the summer/winter densities for both the observations and the model illustrate the seasonal anomaly: daytime NₘF₂ are observed to be larger in winter than in summer. Here we compare the model and measurement at 1200 LT. The observations indicate a winter/summer NₘF₂ ratio of 2.91 and the model predicts a ratio of about 3.0.

3.2.2. TDIM. The model predictions are shown in Figure 2 by the lines with circles. During the day, the NₘF₂ values are about 25% larger than observed, while in the night/predawn sector, the modeled densities are only slightly higher. The modeled hₘF₂ are at higher altitudes during the day.
and slightly lower altitudes at night relative to the observations. The fact that both the modeled \( N_mF_2 \) and \( h_mF_2 \) are larger than observed during the day indicates that the differences are likely to be due to the adopted neutral wind. The observed seasonal anomaly is 2.91 at 1200 LT and the ratio in the TDIM is 1.61. This difference is due to the model predicting larger summer densities than observed.

3.2.3. FLIP. The FLIP model (dotted line) \( N_mF_2 \) values are in good agreement with the data both during the day and at night. The HWM90 winds also yield good agreement between the FLIP model and the measured \( h_mF_2 \) for this day, with the model \( h_mF_2 \) being about 25 km higher. Bringing the model \( h_mF_2 \) into better agreement with the measurement by adjusting the wind would produce even closer agreement for the densities. Richards et al. [1994a] also found good agreement between the FLIP model and Digisonde data for summer 1990 at Millstone Hill. Summer solar maximum is the time when vibrationally excited \( N_2 \) is expected to be most important [Richards and Torr, 1986; Ennis et al., 1995]. Therefore such good agreement between the model and measurement without vibrationally excited \( N_2 \) suggests that the aeronomy of vibrationally excited \( N_2 \) may not yet be fully understood. On the other hand, if vibrationally excited \( N_2 \) were included, it would act to further improve the agreement between the model and measurements during the day.

3.2.4. GTIM. The model results are depicted by the solid line in Figure 2. Throughout the entire 24-hour period, calculated \( N_mF_2 \) values exceed observed values by about 20%. During the daytime, calculated \( h_mF_2 \) values exceed observations by 20 km. The GTIM and TDIM results for both \( N_mF_2 \) and \( h_mF_2 \) are very similar, as expected since these two models have the most similar \( F \) region representation of all five models. Apparently, neutral winds can account for the discrepancy between GTIM and observed values, because, as in the TDIM comparison, GTIM calculated \( h_mF_2 \) values are greater than observed. A stronger poleward wind would lower the calculated \( h_mF_2 \) values and would tend to decrease \( N_mF_2 \) because of the larger loss rates at the lower altitudes.

3.2.5. CTIM. The daytime comparisons of \( N_mF_2 \) and \( h_mF_2 \) are very good, with the CTIM densities (lines with squares) being only 20% lower than observed. During the night (2000 to 0400 LT), the CTIM \( F \) layer is about 30 km too low and this is reflected in the lower \( N_mF_2 \) values. However, overall the CTIM solar maximum results are in reasonable agreement with the observations.

3.3. Solar Minimum: Winter

MHO ISR observations for December 10-12, 1986, are shown in Figure 3 by the thick gray curves. The observed \( N_mF_2 \) for 2 days is shown in Figure 3a. Both days show a minimum at midnight and then an increasing density toward dawn. This feature, a nighttime increase in density by a factor of 3 or more on a corotating plasma flux tube, usually implies a significant plasma source. The predictions from the five models are also shown in identical format to that in Figures 1 and 2.

3.3.1. TIGCM. The TIGCM predictions are shown in Figure 3 by the dashed curves. The agreement between the modeled and observed \( N_mF_2 \) and \( h_mF_2 \) is good to very good. The major discrepancies occur at night; the modeled peak densities are too large from about 0000 to 0400 LT, and the layer height is too low by about 25 km. Adjustments to the neutral wind cannot simultaneously resolve these two discrepancies.

3.3.2. TDIM. The agreement between the modeled (lines with circles) and observed \( N_mF_2 \) and \( h_mF_2 \) values is very good. The only discrepancy is in the predawn densities, which are too small in the TDIM. Such a decay of the nighttime \( F \) layer was not experienced to the same extent in earlier TDIM studies when simple meridional winds were used in place of the

Figure 3a. A comparison of the observed \( N_mF_2 \) diurnal variation at Millstone Hill with five physical ionospheric models for solar minimum, winter conditions.

Figure 3b. A comparison of the observed \( h_mF_2 \) diurnal variation at Millstone Hill with five physical ionospheric models for solar minimum, winter conditions.
HWM90 winds but was also present at solar maximum, winter with the HWM90 winds (Figure 1a). However, this again points to the need for a resolution of the nighttime maintenance of the F layer, that is, what is the role of nighttime winds, topside plasma fluxes and in situ plasma sources? The discrepancy shown in the density can be reduced by a suitable choice of the topside flux or an adjustment to the wind [Sica et al., 1990]. However, the observed factor of 3 enhancement in $N_mF_2$ from 0000 LT to 0600 LT would be difficult to mimic with just a topside flux adjustment.

3.3.3. FLIP. For the solar minimum, winter comparison, there is generally good agreement between the FLIP model $N_mF_2$ (dotted line) and the data, except between midnight and sunrise when the measured $N_mF_2$ increases by a factor of 3. At these times the FLIP $N_mF_2$ values merely stabilizes as a result of a downward plasmaspheric flux. The large increase in measured $N_mF_2$ at night indicates that a substantial nocturnal ionization source is present and the plasmaspheric flux in the FLIP model is not adequate even though it is being supplied by a nearly full flux tube. There is generally good agreement between the modeled and measured $N_mF_2$ for this day, indicating that the HWM90 winds are appropriate for most of the daytime and early evening, but the predawn enhancement issue needs to be studied further.

3.3.4. GTIM. The solid line depicts the calculated GTIM $N_mF_2$ and $h_mF_2$ values in Figure 3. The agreement in both $N_mF_2$ and $h_mF_2$ throughout the daytime and predawn hours is very good and is again very similar to that for the TDIM. The greatest discrepancy between calculated and observed $N_mF_2$ occurs between 0100 and 0600 LT, as was the case for the other two uncoupled models.

3.3.5. CTIM. The line with squares represents the CTIM $N_mF_2$ and $h_mF_2$ in Figure 3. During both day and night, the model follows the observations and very good agreement is found. As with the TIGCM, this model is able to generate an increase in the predawn $N_mF_2$ values that follows the observations. However, between 0800 and 1600 LT, the daytime $N_mF_2$ morphology is somewhat different from both the other models and the observations. CTIM has an $N_mF_2$ maximum that occurs at 0830 LT and then continually decreases throughout the day, while the observed $N_mF_2$ values peak between 1100 and 1400 LT. The other models also show differing daytime morphologies of $N_mF_2$, with GTIM, TDIM, and FLIP exhibiting $N_mF_2$ peaks at about 1400 LT.

3.4. Solar Minimum: Summer

ISR observations from Millstone Hill for June 23-25, 1986, are shown in Figure 4 by the thick gray curves. The $h_mF_2$ observations shown in Figure 4b have a very large variability during the daytime; for example, from 0800 to 0900 LT it increases by about 100 km and then returns to its lower value by 1100 LT. During solar minimum, summer conditions, a well-known G condition exists in the dayside midlatitude ionosphere in which the $h_mF_1$ layer electron density can be equal to or slightly greater than that of the $h_mF_2$ layer [Buonsanto, 1990]. Hence the daytime $h_mF_2$ data shown in Figure 4b is probably a mixture of $h_mF_1$ and $h_mF_2$. In general, altitudes lower than 200 km are $h_mF_1$ and are associated with a molecular ion peak, while those above 200 km are associated with the $O^+$ peak ($h_mF_2$). From this specific ISR data set it is not always possible to distinguish between these two layers. For this study, all the models display $O^+$ layer results, which pertain to $N_mF_1$ and $h_mF_2$. Hence the ISR observed altitudes greater than 200 km should be considered as $h_mF_2$, while those below 200 km are probably $h_mF_1$. Since the ISR only measures the electron density, and not the composition, it is not possible to unambiguously separate these two layers under G conditions. The predictions from the five models are also shown in Figure 4 in identical format to that in the three earlier figures.
3.4.1. TIGCM. The model predictions are shown in Figure 4 by the dashed curves. As with the winter comparison, the agreement between model and observations generally ranges from good to very good. The major discrepancies occur for the model densities from 1800-0200 LT, when the model values are too low. However, the predicted nighttime heights are fairly good, with a maximum difference of about 25 km from 0000 to 0300 LT. The observed seasonal anomaly during solar cycle minimum is 1.90 and the TIGCM predicts 1.6.

3.4.2. TDIM. The model daytime densities (line with circles) are about 50% higher than those observed, and the model F layer heights are also higher by about 50 km. The solar minimum seasonal anomaly is 1.90 in the observations and 1.30 in the simulations. As with solar maximum, the difference can be attributed to the modeled summer densities being too high as a result of $h_mF_2$ being too high. An increased poleward wind would rectify this problem.

3.4.3. FLIP. In summer at solar minimum, the FLIP model $N_mF_2$ (dotted line) is in excellent agreement with the data during the day, but it is too large between midnight and sunrise. In our experience, it is unusual for the FLIP model density to be too high at night. This could be partially explained by the model $h_mF_2$ being about 25 km higher than the measured $h_mF_2$ at night. The model $h_mF_2$ also appears to be too high during the day, but there is a lot of scatter in the radar data.

3.4.4. GTIM. During solar minimum, summer conditions, good agreement between GTIM (solid curve) and observed $N_mF_2$ values occurs from 0800 to 2100 LT, but the nighttime GTIM values exceed the measurements by a factor of 2 to 4. The apparent reason for the discrepancy can be traced to the neutral wind, which exhibits an increase in the equatorward component before sunset. This raises $h_mF_2$ values significantly, from 250 to 300 km by 2100 LT, thereby causing a much slower decay of $N_mF_2$ at night because of the slower loss rate at the higher altitudes.

3.4.5. CTIM. The CTIM (curve with squares) daytime $F$ layer is low in density (about a factor of 2) and high in altitude (about 25 km). This particular combination of differences is not consistent with a problem in the neutral wind, not that the wind is an adjustable parameter in this model. In comparison with the other models, this low dayside $N_mF_2$ is anomalous. All five models have very similar daytime $h_mF_2$ values, and the other four have $N_mF_2$ in agreement with observations or slightly higher. Hence a stronger dayside wind would lower $h_mF_2$, but it would also decrease the $N_mF_2$ values further. Therefore, viewing the wind as the source of the error may not be the proper interpretation of the difference shown in the observed and modeled $h_mF_2$ and $N_mF_2$. This issue is referred to again in the discussion section.

4. Discussion

In reviewing the preceding $F$ region model-model and model-observation comparisons, the concern that one may be mixing oranges and apples is not substantiated. All the models exhibit diurnal morphologies consistent with observed seasonal and solar cycle trends. Each model, at some period of time and/or geophysical condition, has a deficiency, but it is not shared by the other models. Hence the identification of a common shortcoming in the physics, the inputs, or the boundary conditions is not possible. One is left with rather unspecified areas of concern. For example, in Figure 3, the TDIM and GTIM densities in the presunrise hours are particularly low and the temporal variation is different from the observations. From earlier TDIM studies [Sica et al., 1990], this problem was resolved by adjusting either the neutral wind and/or the topside flux within "reasonable" ranges. However, the specific values are ill determined by observation. In prior studies, the TDIM nighttime maintenance was achieved by stronger nighttime neutral winds than the HMW90 model provides. Hence, in this study, where the HMW90 is used without modification, adjustments in the topside plasma flux are needed. The effect of such a topside plasma flux can be seen by comparing the FLIP model results in Figure 3 with the TDIM and GTIM results. The FLIP results are also based on HWM90 winds but include a downward plasmaspheric flux for the case of a full flux tube. The effect of such a downward plasma flux is to maintain $N_mF_2$ at a nearly constant level during the early morning hours. On the other hand, the measurements and coupled ionosphere-thermosphere models (CTIM and TIGCM) indicate that $N_mF_2$ actually increases in the early morning (Figure 3). Hence for these geophysical conditions (solar minimum, winter) and local times (0000-0600 LT) the coupled ionosphere-thermosphere models are superior to the uncoupled models (TDIM, GTIM and FLIP). Unfortunately, this is not generally true, and at other times and/or geophysical conditions the coupled models are inferior to the uncoupled models.

A significant cause of the difference between the self-consistent thermosphere and ionosphere models (CTIM and TIGCM) and the stand-alone ionospheric models (GTIM, TDIM, and FLIP) is the dependence on neutral composition. Wells et al. [1997], in particular, showed that the CTIM tends to underestimate the O/N$_2$ ratio in the summer hemisphere compared with MSIS. The cause of the low summer CTIM $N_mF_2$ values in Figures 2a and 4a is probably related to this problem. In the winter hemisphere, the CTIM composition is closer to MSIS, and the resulting $N_mF_2$ values are in closer agreement with the data. Similarly, the disagreement in $N_mF_2$ between TIGCM (TIEGCM) and the data may be due to discrepancies in the neutral densities, particularly the molecular densities [Buonsanto et al., 1997; Fesen et al., 1997]. Fesen et al. [1997] presented comparisons of the O/(N$_2$ + O$_2$) ratio predicted by TIEGCM and MSIS for January near solar cycle minimum; the ratio ranged from 15 to 40 in the TIEGCM but was typically less than 10 in MSIS. The difference was due to the larger molecular densities in MSIS, which exceeded those in TIEGCM by factors of 2 to 4. The differences were especially pronounced at night. Changing the molecular densities would also affect the TIGCM (TIEGCM) representation of $h_mF_2$, since the altitude where chemical loss balances diffuse transport would be altered, as discussed by Fesen et al. [1997].

It is a puzzle why three of the models (TDIM, FLIP, and GTIM) use the HMW90, but they do not experience the same problems. In fact, in the FLIP model the topside flux is not a free parameter; it is computed self-consistently and, in general, the nightside $F$ layer is maintained in a manner similar to that observed.

At midlatitudes during quiet conditions, the $F$ layer dynamics and field-aligned transport is most dependent upon the neutral wind. Overall, the neutral wind is the primary source of the problem for the ionospheric models, but it is a self-consistent part of the coupled ionosphere-thermosphere models. A need exists to extend the observational databases of
the neutral wind models and to undertake careful investigation of the self-consistent winds generated in the coupled models, especially at other longitudes.

The fact that the results do not show the models having common deficiencies makes it particularly difficult to produce a profound conclusion. One is left arguing that each model uses dissimilar numerical techniques, spatial resolutions, even boundary conditions, which could account for the dissimilar behavior. Indeed, the models do not even share a common set of adjustable parameters. As already pointed out, for common processes (i.e., O-O$^+$ diffusion or O photochemistry), these have been made the same in each model.

Each of the models produced significantly more information than displayed in Figures 1 through 4. Several iterations and double checks on inputs and boundary conditions were made. In fact, a long list of other parameters that could be checked have been discussed in the PRIMO workshops. As a group, the decision to bring closure to the first PRIMO objective, that of resolving the factor of 2 deficiency in modeled noon $N_mF_2$ at solar maximum, has been achieved. This was done by a set of adjustments to the diffusion coefficient, the photoionization chemistry, secondary electron production, and other model specific adjustments. Furthermore, the presentation of model results in Figures 1 through 4 represents a rather unique icntercomparison of physical ionospheric models; one might even argue it is an exoscope of how well (or poorly) the models perform.

5. Conclusion

The comparison of the five physical models has important implications for the National Space Weather Program. Specifically, plans are underway to use ionospheric models for specification and forecasting and for providing time delay corrections of Global Position System signals. It is therefore important to determine how reliable the model predictions are for different geophysical conditions.

In this study, five physical models containing ionospheres were compared with each other and with data obtained from the Millstone Hill Observatory. Two of the models were self-consistent ionosphere-thermosphere models, while for the other three models the thermospheric parameters were provided by empirical models. The comparisons were conducted for the easiest case (midlatitudes and quiet magnetic activity), and for four geophysical conditions covering both summer and winter at solar maximum and minimum. All of the simulations were based on standard model runs, with no allowance for adjusting uncertain model inputs or processes.

Perhaps the most important result obtained is that the self-consistent ionosphere-thermosphere models are not quantitatively or qualitatively superior to the uncoupled ionospheric models for the conditions studied. All of the models predicted diurnal variations that were consistent with the observed trends, and this was true for all four geophysical cases. However, each one of the models displayed a clear deficiency in at least one of the four geophysical cases that was not common to the other models. Quantitatively, the spread in $N_mF_2$ calculated by the five models was the smallest during the day, typically less than a factor of 2, but at night the spread in the model results was as large as a factor of 10 at certain local times. The latter problem was traced to a lack of nighttime maintenance processes in some of the uncoupled ionospheric models. These results imply that reliable quantitative predictions cannot be obtained from a "standard" model run, regardless of the model used. Data ingestion techniques will be required to obtain more reliable ionospheric predictions.

In the future, it would be useful to extend the comparison of the five models to the equatorial and high-latitude domains and to geomagnetically active conditions. It would also be useful to compare the five models when selected data sets are ingested into the models in order to determine what the improvement is and which of the models performs the best under these circumstances. Specifically, incoherent scatter radar and other data sets are available that can help constrain the models. For example, instead of using the HWM-93 empirical wind model to drive the uncoupled ionospheric models, one can use the observed winds. The observed winds can also be used to validate the winds calculated by the coupled ionosphere-thermosphere models. In addition, one can compare the observed and modeled ion and electron temperatures, vertical O$^+$ fluxes, and electric fields.

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