Auroral E-field Variability Effects in the Ionosphere

M. V. Codrescu

Cooperative Institute for Research in Environmental Sciences, University of Colorado, and National Oceanic and Atmospheric Administration Space Environment Center, Boulder, Colorado

Tomoko Matsuo

High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado

Abstract. The recently derived characteristics of small scale variability associated with the Weimer E-field convection model (Matsuo et al. 2002) are used as an additional input to the Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model (CTIPE) to study the influence of auroral E-field variability on the thermosphere and ionosphere during quiet times. It is assumed that the Weimer electric field model has an approximate Gaussian distribution of small-scale variability around the mean and that this variability is fully defined by the high-latitude standard deviation pattern associated with the mean. The variability as described by the standard deviation is larger than the mean in most of the polar cap and auroral zone. Since in the Gaussian distribution case the average field and the variability have equal weight contributions to Joule heating generation, the inclusion of small-scale variability in CTIPE more than doubles the hemispheric Joule heating generation. The inclusion of variability brings the modeled thermospheric temperature and neutral composition structure in better agreement with observations during geomagnetic quiet conditions, resulting in better ionospheric modeling.

1. Introduction

The underestimation of the high-latitude energy input by general circulation models (GCMs) of the thermosphere has been known for some time. The underestimation is due to small scale E-field variability that causes a large difference between the average of the square and the square of the average of the E field. In the absence of knowledge of the true E-field, only average fields were used in Joule heating calculations. To maintain the temperature structure of the thermosphere, an increase in Joule heating by an arbitrary factor up to 2 or 3 has been applied in the past.

It is known that the high-latitude electric fields are variable on a variety of spatial and temporal scales. Since the amount of Joule heating is proportional to the average of the square of the E field, and not the square of the average as used in GCMs, neglecting the variability leads to an underestimation of the high-latitude energy input. The characteristics of the small-scale variability are beginning to emerge and therefore it is important to try to understand their effects on the thermosphere and ionosphere.

In this paper we present the effects of small-scale E-field variability on the neutral temperature, neutral composition and peak electron density of the F2 layer (NmF2) for equinox conditions. We use the coupled thermosphere ionosphere plasmasphere electrodynamics (CTIPE) model to perform simulations with and without small-scale E-field variability, and compare the results with climatological, empirical models of the thermosphere and ionosphere. The variability pattern was derived from the DE-2 measurements by Matsuo et al, [2002] and are associated with the Weimer E-field model.

2. Model runs

The CTIPE model is a non-linear, coupled thermosphere ionosphere plasmasphere physically based numerical code that includes a self-consistent electrodynamic scheme for the computation of dynamo electric fields. The model consists of four distinct components which run concurrently and are fully coupled. Included are a global thermosphere, a high-latitude ionosphere, a mid and low-latitude ionosphere/plasmasphere and an electrodynamics calculation of the global dynamo electric field.

The thermospheric model was originally developed by Fuller-Rowell (*Fuller-Rowell and Rees*, [1980], *Rees et al.*, [1980]) and is fully described in the PhD thesis of *Fuller-Rowell* [1981]. The high-latitude ionospheric model was developed by S. Quegan (*Quegan*, [1982]; *Quegan et al.*, [1982]). The model of the Earth's mid- and low-latitude plasmasphere is based on the model of *Bailey* [1983]. These first three components are described in more detail under the name of coupled thermosphere ionosphere plasmasphere (CTIP) by *Millward et al.*, [1996]. The electrodynamic calculation was developed by *Richmond and Roble*, [1987] and was included in the CTIP model by *Millward*, [2001] resulting in the creation of CTIPE. The version of CTIPE used in this study incorporates several further changes from previous descriptions of the model. These changes are described next.

We use the *Weimer*, [1995] high-latitude potential model for high-latitude convection as opposed to the *Foster*, [1986] Millstone Hill model used in the past. The use of the Weimer model allows investigations of the interplanetary magnetic field (IMF) B_y effects on the thermosphere and ionosphere and in particular on the thermospheric neutral wind and its influence on the ionosphere. However, all the simulations presented in this paper are for the B_y = 0 case. The B_y dependence of the thermospheric and ionospheric parameters will be presented in a future paper. The input values (solar wind B_{tot} in the YZ plane, solar wind velocity, solar wind angle, and tilt) used for the Weimer model are described below. The variability patterns associated with the Weimer high-latitude potential model were derived by *Matsuo et al.* [2002].

The joule heating calculation at high latitudes includes the effects of small scale fluctuations in the E-field [*Codrescu et al.*, 2000]. Fluctuations are applied at high-latitude where the Weimer model E-field (here called average field) is larger than 2 mV/m. The fluctuations are generated using a gaussian distribution random number generator with 0 mean and standard deviation conforming to the small scale variability patterns (Matsuo et al., [2002]) associated with the Weimer E-field model. The fluctuations are added to the average field only for the Joule heating calculations. Only fluctuations less than $\pm$40 mV/m are allowed. In the steady state cases presented in this paper the average field at each grid point is constant throughout the simulation but the variability components are updated every 12 minutes at all grid points. A single random number sequence is used. This is the first time when a pattern of small scale variability is used as input. All previous model simulations have used an average single value (no spatial distribution) for small scale variability.

The tidal inputs at the lower boundary are based on results from the global-scale wave model (GSWM) [*Hagan et al.*, 1995; 1999]. The inclusion of the tidal forcing at the lower boundary as opposed to a higher pressure level as was done in previous versions of the model is described by *Mueller-Wodarg et al.*, [2001].

The model includes a chemical heat source due to the recombination of O^+. The O^+ recombination generates 4.0 eV when reacting with N_2 and 8.55 eV when reacting with O_2. This is important for the low latitude temperature structure as the large amount of ionization in the equatorial anomaly crests after sunset turns out to be a significant heat source [*Fuller-Rowell et al.*, 1997].

The CTIPE model was run in steady state for medium solar cycle (F10.7=125), equinox conditions, for average (Kp=3) geomagnetic activity. The choice of values for the radio flux and K_p is somewhat arbitrary. The steady state is necessary in order to compare results with climatological models (MSIS and IRI). The idea is to cover the most common conditions and to give an indication of the variability influence during a storm. Solstice results will be published in a future paper.

The input parameters for the Weimer high-latitude potentials model [*Weimer, 1995*] were derived from the OMNI data set (http://nssdc.gsfc.nasa. gov/omniweb/). The average solar wind total magnetic field strength in the GSM yz plane (B_t), the average angle of the magnetic field in the GSM yz plane (α), and the average solar wind velocity ($SWVEL$) were determined for K_p = 3 condition by binning the appropriate solar wind data. The obtained values are, B_t = 0.42nT, α = 180° and $swvel$ = 470kms^{-1}. The tilt angle is assumed to be 0 for the equinox runs although there is an 11° UT variation.

3. Results

Plate 1 shows the UT 1200 global temperature structure for MSIS (top left), CTIPE with E-field variability (bottom left), CTIPE without E-field variability (top right), and the difference between the model simulations with and without variability (bottom right) at 300 km. The scale is 800 to 1100 K for the the first three and 24 to 117 K for the difference plot. Red represents higher temperatures.

The CTIPE model shows more structure in the temperature field than the empirical model but the global features are very similar. The high latitudes are too cold in the absence of E-field variability. The inclusion of variability increases the temperature by more than 14 K everywhere at low latitudes and by up to 125 K at high latitudes. The difference in the amount of heating between the two hemispheres at this UT is due to differences in conductivities caused by different illuminations of the convection patterns.

The 1100 K contour is almost identical in the Southern hemisphere and only slightly shifted to later local times in the North between MSIS and CTIPE with variability. The simulation without variability does not reach 1100 K at 300 km. The diurnal variation at mid- and low-latitudes is about 250 K in MSIS, 150-180 K in CTIPE without variability, and 180-240 K for the variability run. The slightly larger increase in temperature at low latitudes in the midnight sector is probably dynamically driven by the increased global circulation due to the higher energy input.

Plate 2 shows the UT 1200 global mean molecular mass (mmm) for MSIS (top left), CTIPE with E-field variability (bottom left), CTIPE without E-field variability (top right), and the difference between the model simulations with and without variability (bottom right) at 300 km. The scale is 17 to 20 amu for the the first three and .12 to 1.6 amu for the difference plot. Please note that the change in mmm at a constant height is not linearly related to the temperature change.

Mmm reflects the neutral chemical composition which controls both production and loss of plasma and is therefore important for the proper modeling of the ionosphere. The mmm field shows more structure in CTIPE than in the climatological MSIS model but the global features are quite similar. The diurnal variation at low latitudes is about 1 amu and is not affected by the introduction of variability.

The 20 amu contour covers the high-latitudes in MSIS but not in CTIPE without variability. The CTIPE with variability increases the mmm too much at high latitudes in the South (the 20 amu contour reaches -50 deg. latitude). The mid- and low-latitude mean molecular mass is not affected by variability (the difference plot shows no change).

Plate 3 shows the UT 1200 global $\log_{10}$(NmF2) for IRI (top left), CTIPE with E-field variability (bottom left), CTIPE without E-field variability (top right), and the ratio between the model simulations with and without variability (bottom right). The scale is 11.1 ($1.3\text{x}10^{11}$) to 12.2 ($1.7\text{x}10^{12}$ m^{-3}) for the CTIPE model, 11.2 ($1.5\text{x}10^{11}$ m^{-3}) to 12.6 ($2.7\text{x}10^{12}$) m^{-3} for the IRI model and .62 to 1.32 for the ratio plot. There is considerably more structure in the CTIPE modeled NmF2 than in IRI. This is expected as IRI is a long term average over conditions resulting from fast varying processes.

The mid- and low-latitude structure in the NmF2 ratio plot is produced by the dynamics and electrodynamics acting on the plasma. The amount of structure produced by the inclusion of variability is

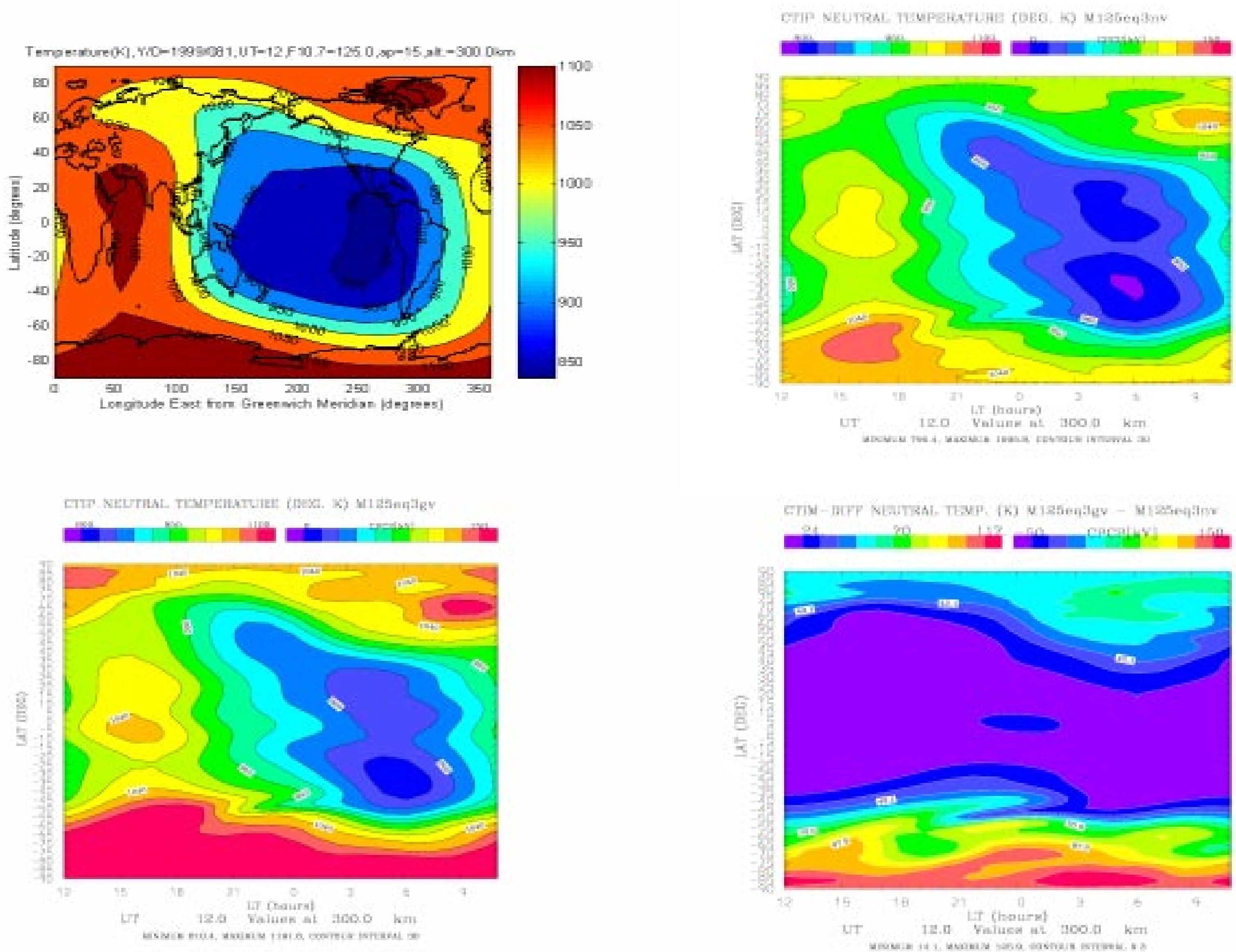

Temperature(K),Y/D=1999/081,UT=12,F10.7=125.0,ap=15,alt.=300.0km
Latitude (degrees)
Longitude East from Greenwich Meridian (degrees)
CTIP NEUTRAL TEMPERATURE (DEG. K) M125eq3ov
CTIP NEUTRAL TEMPERATURE (DEG. K) M125eq3gv
CTIM - DIFF NEUTRAL TEMP. (K) M125eq3gv - M125eq3ov
LAT (DEG)
LT (hours)
UT 12.0 Values at 300.0 km

Plate 1

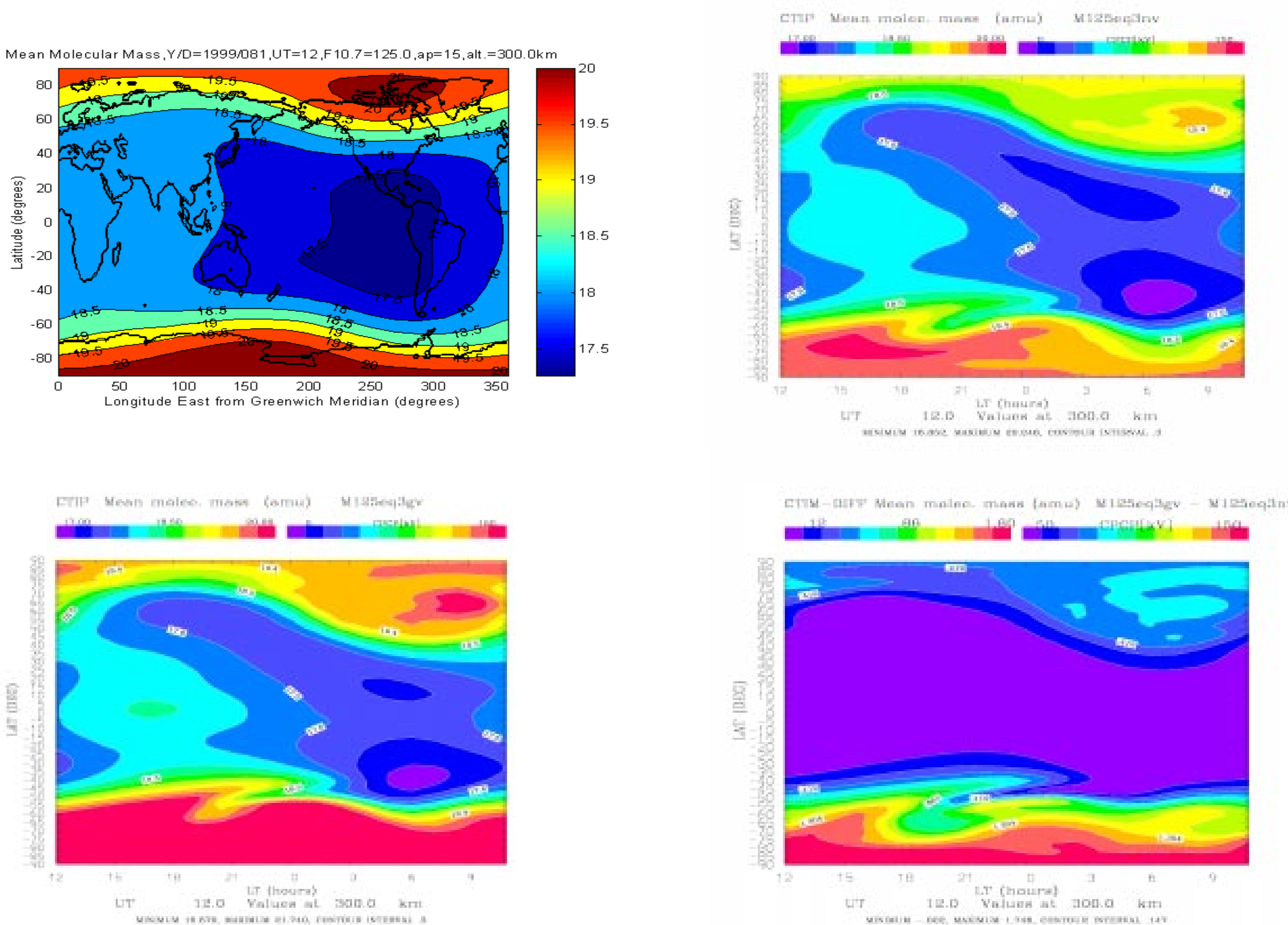
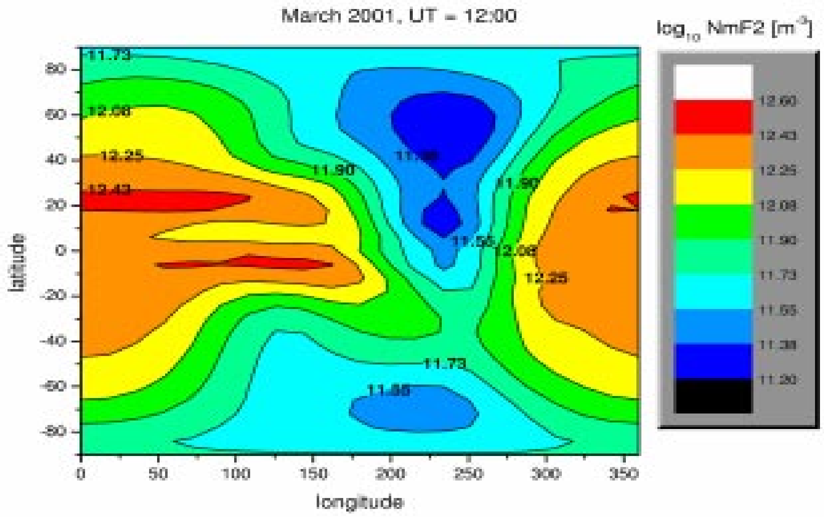
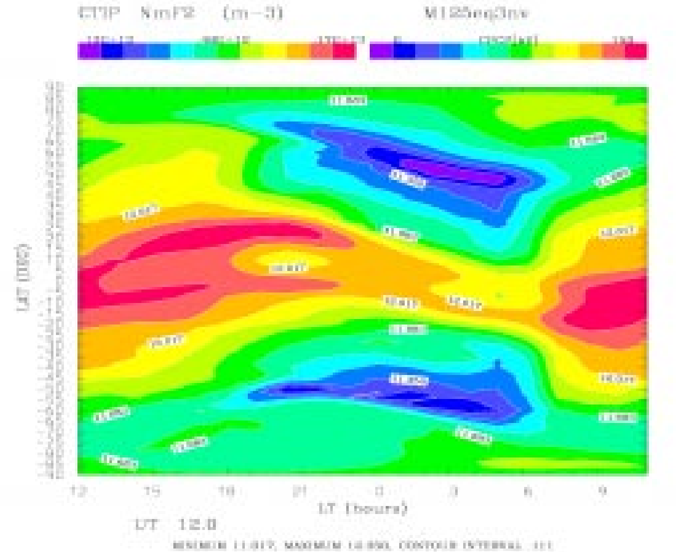
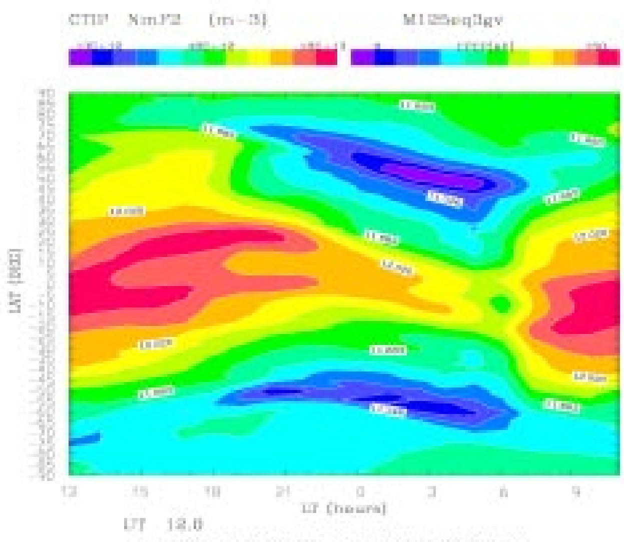

Mean Molecular Mass,Y/D=1999/081,UT=12,F10.7=125.0,ap=15,alt.=300.0km
Latitude (degrees)
Longitude East from Greenwich Meridian (degrees)
CTIP Mean molec. mass (amu) M125eq3nv
LAT (DEG)
LT (hours)
UT 12.0 Values at 300.0 km
CTIP Mean molec. mass (amu) M125eq3gv
CTIM-DIFF Mean molec. mass (amu) M125eq3gv - M125eq3nv

Plate 2


March 2001, UT = 12:00
latitude
longitude
log10 NmF2 [m-3]
12.60
12.43
12.25
12.08
11.90
11.73
11.55
11.38
11.20


CTIP NmF2 (m-3)
M125eq3nv
LAT (DEG)
LT (hours)
UT 12.0


CTIP NmF2 (m-3)
M125eq3gv
LAT (DEG)
LT (hours)
UT 12.0

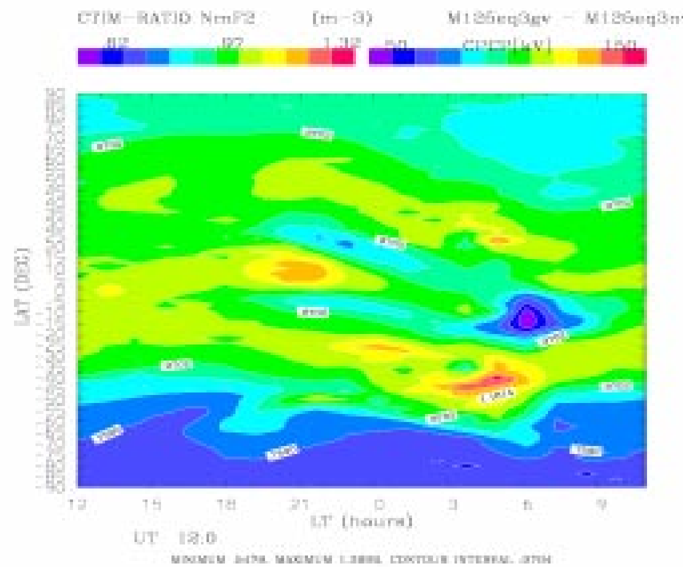

CTIM-RATIO NmF2 (m-3)
M125eq3gv - M125eq3nv
LAT (DEG)
LT (hours)
UT 12.0

Plate 3

an indication of the influence that high-latitude processes have on low latitude plasma parameters. The largest decrease in NmF2 is in the southern hemisphere and is due to chemical composition changes as there is a larger increase in mean molecular mass at southern high-latitudes at this UT.

4. Conclusions

We have implemented for the first time a pattern of small scale variability in a general circulation model. The model includes the coupled thermosphere, ionosphere, and plasmasphere, and self-consistent electrodynamics.

The inclusion of variability improves the agreement between CTIPE temperature and chemical composition and the MSIS climatology for steady state common conditions: medium solar cycle (F10.7=125), average (Kp=3) geomagnetic activity, equinox conditions).

The inclusion of variability produces considerable structure in the ionospheric parameters at low and medium latitudes. The structure is the result of dynamics and electrodynamics. Large but more uniform changes in the peak electron density of the F2 layer are produced at high-latitudes by the inclusion of variability. The high latitude effects are caused primarily by changes in neutral chemical composition.

References

Bailey, G. J., *Planet. Space Sci., 31*, 389, 1983.

Bilitza, D., (ed.), International Reference Ionosphere 1990, NSSDC 90-22, Greenbelt, Maryland, 1990.

Codrescu, M. V., T.J. Fuller-Rowell, J. C. Foster, J. M. Holt and S. J. Cariglia, Electric Field Variability Associated With the Millstone Hill Electric Field Model, *J. Geophys. Res., 105, 5265-5273,* 2000.

Fejer, B. G. and L. Scherliess, Empirical models of storm-time equatorial zonal electric fields, *J. Geophys. Res., 102*, 24047, 1997.

Fuller-Rowell, T. J., Codrescu, M. V., B. G. Fejer, W. Borer, F. Marcos, and D. N. Anderson, Dynamics of the low-latitude thermosphere: quiet and disturbed conditions, *J. Atmos. Solar-Terr. Phys., 59*, 1533-1540, 1997.

Fuller-Rowell, T.J., *J. Geophys. Res. 89*, 2971-2990, 1984.

Fuller-Rowell, T. J., A three dimensional time dependent global model of the thermosphere, PhD thesis, University College London, 1981.

Fuller-Rowell, T. J. and D. Rees, *J. Atmos. Terr. Phys., 43*, 701, 1981.

Fuller-Rowell, T. J. and D. Rees, A three dimensional time dependent model of the thermosphere, *J. Atmos. Sci., 37*, 2545, 1980.

Hagan, M. E., J. M. Forbes, and F. Vial, On modeling migrating solar tides, *Geophys. Res. Lett., 22*, 893-896, 1995.

Hagan, M. E., M. D. Burrage, J. M. Forbes, J. Hackney, W. J. Randel, and X. Zhang, GSWM-98: Results for migrating solar tides, *J. Geophys. Res., 104*, 6813-6828, 1999.

Hedin, A. E., MSIS-86 Thermospheric Model, *J. Geophys. Res. 92*, 4649, 1987.

Hedin, A. E., M. J. Buonsanto, M. Codrescu, M.-L. Duboin, C. G. Fesen, M. E. Hagan, K. L. Miller, and D. P. Sipler, Solar activity variations in midlatitude thermospheric meridional winds, *J. Geophys. Res., 99*, 17,601-17,608, 1994.

Hinteregger, H. E., K. Fukui, and B. R. Gilson, Observational, reference and model data on solar EUV, from AE-E, *Geophys. Res. Lett., 8*, 1147-1150, 1981

Matsuo, T., A. D. Richmond, and K. Hensel, High-latitude electric field variability and electric potential derived from DE-2 measurements: solar IMF condition and dipole tilt dependence, submitted to J. Geophys. Res. , 2002.

Millward, G. H., R. J. Moffett, S. Quegan, and T. J. Fuller-Rowell, A coupled thermosphere ionosphere plasmasphere Model (CTIP), in STEP handbook on Ionospheric Models, edited by R. W. Schunk, Utah State University, 239-279, 1996.

Millward, G. H., I. C. F. Mü ller-Wodrag, A. D. Aylward, and T. J. Fuller-Rowell, A CTIP model investigation of the influence of tidal forcing on F-region equatorial vertical ion drift, J. Geophys. Res., , in press, 2001.

Mueller-Wodarg, I.C.F., A.D. Aylward and T.J. Fuller-Rowell, Tidal Oscillations in the Thermosphere: A Theoretical Investigation of their Sources, *J. Atmos. Terr. Phys.*, in press, 2001.

Quegan, S., PhD Thesis, University of Sheffield, 1982.

Quegan, S., G. J. Bailey, R. J. Moffett, R. A. Heelis, T. J. Fuller-Rowell, D. Rees, and R. W. Spiro, A theoretical study of the distribution of ionisation in the high-latitude ionosphere and the plasmasphere: first results on the mid-latitude trough and the light ion trough, *J. Atmos. Terr. Phys., 44*, 619, 1982.

Rees, D., T. J. Fuller-Rowell, and R. W. Smith, *Planet. Space Sci., 28*, 919, 1980.

Richmond, A. D., E. C. Ridley, and R. G. Roble, A thermosphere/ionosphere general circulation model with coupled electrodynamics, *Geophys. Res. Lett., 19*, 601, 1992.

Roble, R.G., E.C. Ridley, and R.E. Dickinson, J. Geophys. Res., 92, 8745-8758, 1987.

Weimer, D. R., Models of high-latitude electric potentials derived with a least error fit of spherical harmonic coefficients, *J. Geophys. Res., 100*, 19,595, 1995.