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Behaviour of the low-latitude ionosphere-plasmasphere system at long deep solar minimum

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The behaviour of the low-latitude ionosphere-plasmasphere system during the long deep solar minimum between solar cycles 23 and 24 is presented using the physics based model SUPIM and FORMOSAT-3/COSMIC satellite data. Using the vertical ion drift velocity measured by C/NOFS satellite, and neutral densities and wind velocities obtained from MSIS and HWM, SUPIM calculates the electron and ion (O^+, H^+, He^+, N_2^+, O_2^+, and NO^+) densities and temperatures and plasma fluxes within ±40° magnetic latitudes and 150-2000 km heights for Indian longitudes at equinox (F10.7 = 68, Ap = 4). FORMOSAT-3 measures the corresponding electron density up to 600 km height. The data and model show the ionosphere contracting to a thin layer during the long deep solar minimum. During daytime, the ionosphere has a half-width of only about 250 km over the equator and 150 km at EIA crests with a peak density of about 10^6 cm^{-3} and O^+/H^+ transition height at around 750 km. At night, the ionosphere reduces to a cold thin layer of half-width less than about 150 km at the crests with a peak density of about 10^5 cm^{-3}, and transition height about 500 km where the ion densities reduce to about 10^4 cm^{-3}. Plasma density in the plasmasphere (above transition height) remains nearly constant at about 10^4 cm^{-3} during both day and night, and decreases only very slowly with height. However, the temperatures increase rapidly at sunrise at all heights to reach about 2500 K (electron) and 2250 K (ion) at 0800 hrs LT at 2000 km height (at EIA crests), which decrease by a maximum of only 250 K until sunset. After sunset, both electrons and ions cool rapidly until about midnight and then decrease slowly to nearly constant temperatures at all heights to about 650 K prior to sunrise. SUPIM predictions and FORMOSAT-3 data agree also with C/NOFS and CHAMP satellite observations.

Keywords: Electron temperature, Equatorial ionization anomaly, Ionosphere-plasmasphere system, Ion temperature, Plasma flux, Vertical ion drift velocity, Wind velocity

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1 Introduction

The solar minimum between solar cycles 23 and 24 was an unusually long minimum lasting for more than three years during 2006-2009, which decayed to the deepest minimum in 2008 in nearly a century[1]. The extremely low solar activity is reflected as lowest values in the solar fluxes (UV, EUV and X-rays) that heat the upper atmosphere and produce the ionosphere, and in the solar activity indices F10.7 and sunspot number[2]. The long solar minimum provided unique opportunities to investigate the upper atmosphere, ionosphere and plasmasphere with minimum forcing from above. In the present paper, using the physics based model SUPIM (Sheffield University Plasmasphere Ionosphere Model)[3] and FORMOSAT-3/COSMIC satellite data[4], the behaviour of the low-latitude ionosphere-plasmasphere system at the deep solar minimum in Indian longitudes has been presented.

A number of interesting observations has been reported covering the unusual solar minimum. The thermosphere contracted to record low levels. This was revealed by the neutral density variations obtained from the analysis of orbital decay of satellites[5] and in site measurements of neutral scale height[6]. The contraction was also observed in minor constituents. For example, the Coupled Ion-Neutral Dynamics Investigator instruments onboard the Communication/Navigation Outage Forecast System (C/NOFS) satellite indicates a dominance of neutral helium near the satellite perigee (400 km) during June 2008-August 2009 (Ref. 6).

The ionosphere also contracted to extremely low levels. Using the C/NOFS data Heelis *et al.*[7] showed that the ionosphere contracted to a thin shell, with the O^+/H^+ transition height and ion temperature reaching record low values. The electron densities measured by CHAMP (400 km height) and GRACE (500 km height) satellites also showed the ionosphere contracting by 50% in 2008 and by more than 60% in 2009 as compared to IRI2007 (International Reference Ionosphere) predictions[8]. Global values of F-region critical frequency (foF_2) and GPS-TEC[9,10] reached their lowest values in the 23/24 solar minimum compared to the previous minimum. The yearly average difference in foF_2 between the 23/24 solar minimum and previous minimum was more negative during daytime than at night by up to -1.2 MHz during daytime[9].

Tides and waves found their way to the thermosphere and ionosphere more easily in the 23/24 solar minimum than in previous minima. The diurnal pattern of the vertical E×B drift velocity observed by the C/NOFS satellite shows downward drifts in the afternoon and upward drifts near midnight at some equatorial locations[11,12] instead of the usual upward drifts during daytime and downward drifts at night[13]. This is interpreted in terms of the effects of semi-diurnal tides propagating from lower atmosphere[12]. In addition, ionospheric irregularities are found to occur frequently during the 23/24 solar minimum compared to previous minima[14,15]. Observations also show clear evidence of planetary wave and gravity wave effects in the MLT region during the extended solar minimum[16,17].

The low-latitude thermosphere and ionosphere also registered very clear effects of the sudden stratospheric warming (taking place in the polar stratosphere) during the unusual solar minimum[18,19]. The clear effects at the unusual minimum are interpreted in terms of the strengthening of the 8-hour tide during the warming events[20]. The effect of the 9-day periodicity in the solar wind was also clearly detected in the ionosphere at the unusual solar minimum[21]. Geomagnetic storms are rare during solar minimum. However, a few moderate geomagnetic storms occurred during the 23/24 solar minimum. During one of these storms, using GPS and Coherent Radio Beacon Experiment data, Mridula *et al.*[22] showed unusual modulations of the plasmaspheric content at low latitudes.

Though a number of interesting observations covering the record low solar minimum has been presented, no modeling study has been reported to our knowledge for any solar minimum condition. In the present paper, using SUPIM and FORMOSAT-3/COSMIC satellite data, the behaviour of the ionosphere-plasmasphere system has been reported within ±40° magnetic latitudes at 150-2000 km heights at the unusual solar minimum in Indian longitudes (60°E-120°E) at magnetically quiet (Ap = 15) equinoctial conditions. The equatorial ionization anomaly (EIA), electron and ion (O^+, H^+ and He^+) densities and temperatures and plasma fluxes are presented. The model results are also discussed with the observations reported in the literature.

2 Model and inputs

The physics based model SUPIM[3] solves the coupled time-dependent equations of continuity, momentum and energy for the electrons and ions (O^+, H^+, He^+, N_2^+, NO^+, and O_2^+) along closed eccentric-dipole geomagnetic field lines. The modeling procedure is same as that described recently[23]. The model inputs are the vertical E×B drift velocity at the equator, neutral wind velocities and neutral densities. The model calculations are for the Indian longitude 82.5°E at a deep solar minimum (F10.7 = 68) under magnetically quite (Ap = 4) equinoctial (day number 80) conditions.

The E×B drift pattern used [Fig. 1(a)] is the average spring equinox pattern in 2009 for 60°-120°E longitudes measured by C/NOFS satellite[12]; the nighttime velocities are slightly adjusted for near balance between the net upward and downward drifts (for model stability). As mentioned above the pre-reversal strengthening of the upward drift is absent at the deep minimum. The drift is applied to all field lines (apex height 150-11000 km) and hence, to all altitudes and latitudes. The neutral wind velocities are from HWM91 (Ref. 24) and neutral densities are from MSIS86 (Ref. 25). Horizontal wind model (HWM) and MSIS provide the neutral wind velocities and densities as function of altitude, latitude and local time. Figure 1(b) shows sample latitude variations of the effective magnetic meridional wind velocity (at 1000, 1200 and 1400 hrs LT) at 300 km height.

3 Results and Discussion

3.1 Equatorial ionization anomaly

A major feature of the low latitude ionosphere is the equatorial ionization anomaly (EIA) characterized by a trough around the geomagnetic equator and crests on either side. The EIA, which can cover about half the global area in 24 hours, has been studied for over 75 years[26,27]. The EIA has been modeled by several groups under medium and high solar activity conditions[28-32]. The generation of EIA involves

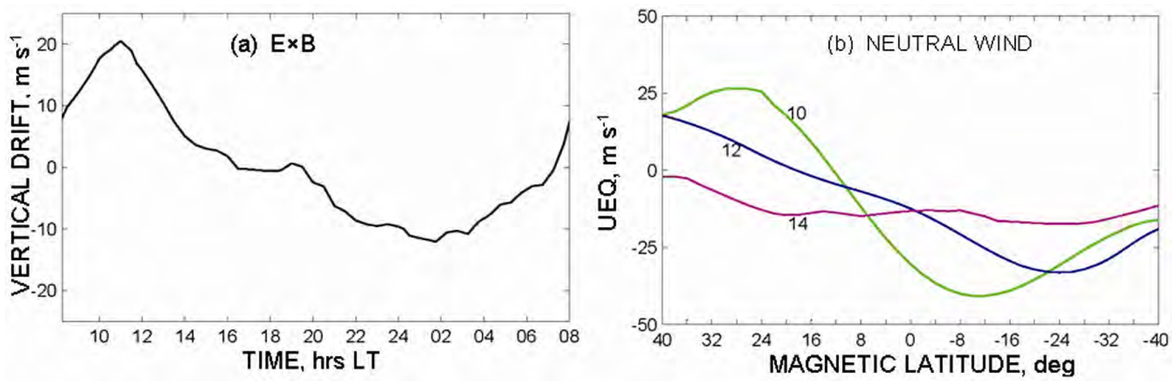

Fig. 1 — (a) Diurnal variation of the vertical E×B drift velocity at the equator from C/NOFS measurements; and (b) typical latitude variations of neutral wind velocities (at 1000, 1200 and 1400 hrs LT) from HWM91 used in the model calculations (positive latitude is north)

mainly the creation of the trough and crests by the upward E×B drift[33] and partly the addition of plasma at around the crests by downward diffusion[34]. However, the downward diffusion and E×B drift, in the absence of equatorward neutral winds, does not seem to strengthen the crests when they shift to latitudes beyond about ±20° where the geomagnetic field lines are more inclined[23].

Figure 2 illustrates the effects of diffusion, E×B drift and neutral wind on the generation of EIA at the deep solar minimum (F10.7 = 68). Figure 2(a) shows the latitude variation of N_{max} during morning-noon hours obtained from the model calculations with no E×B drift and no neutral wind (model run 1). In this case, diffusion alone produces a small EIA with crests at around ±8° magnetic latitudes and maximum crest-to-trough ratio about 1.15 (at 0800 hrs LT). The diffusion (alone) produced EIA is weak compared to observations (daytime crests at around ±15° and crest-to-trough ratio about 1.5); it also disappears by noon when the plasma pressure gradient along the field lines becomes weak.

When E×B drift is used in the model calculations (model run 2), the EIA [Fig. 2(b)] starts developing in the morning (0800 hrs LT) and becomes strong at around noon (1300 hrs LT) with crests at around ±16° magnetic latitudes and crest-to-trough ratio about 1.5. The introduction of neutral winds in the model calculations (model run 3) makes small changes in EIA [Fig. 2(c)]) with slightly strong crest in the hemisphere of equatorward (or less poleward) wind and strong plasma flux in the hemisphere of poleward wind. Figure 3 shows the plasma fountain at 1300 hrs LT obtained with drift and wind. These features of the daytime plasma fountain and EIA at the deep solar minimum are similar to those at higher levels of

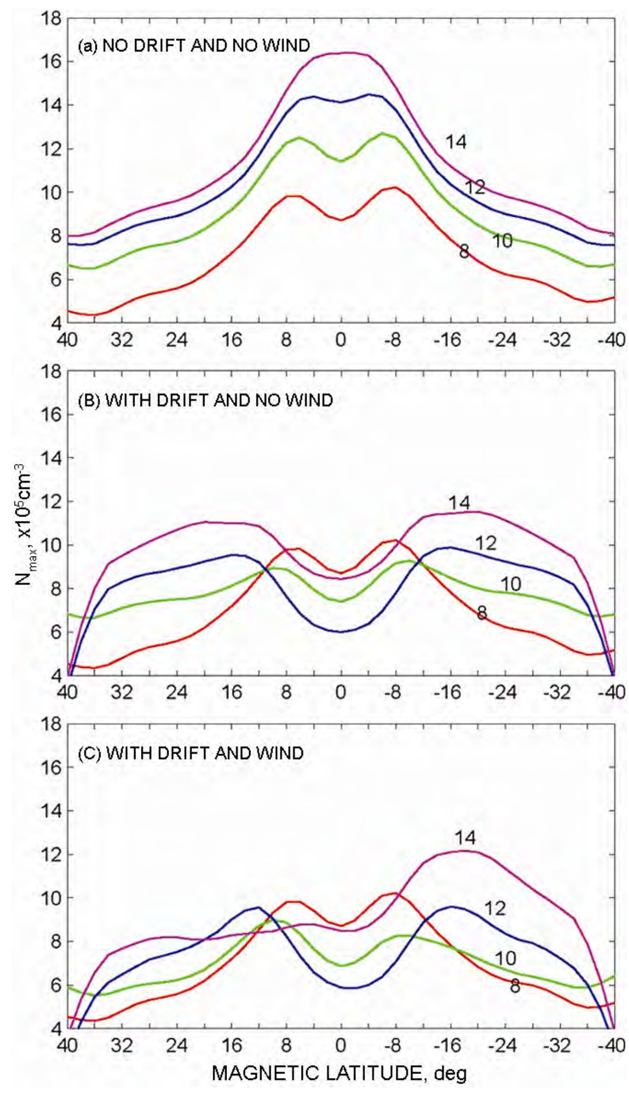

Fig. 2 — Latitude variations of N_{max} at 0800, 1000, 1200 and 1400 hrs LT obtained from the model calculations: (a) with no E×B drift and no neutral wind; (b) with E×B drift and no neutral wind; and (c) with both E×B drift and neutral wind (positive latitude is north)

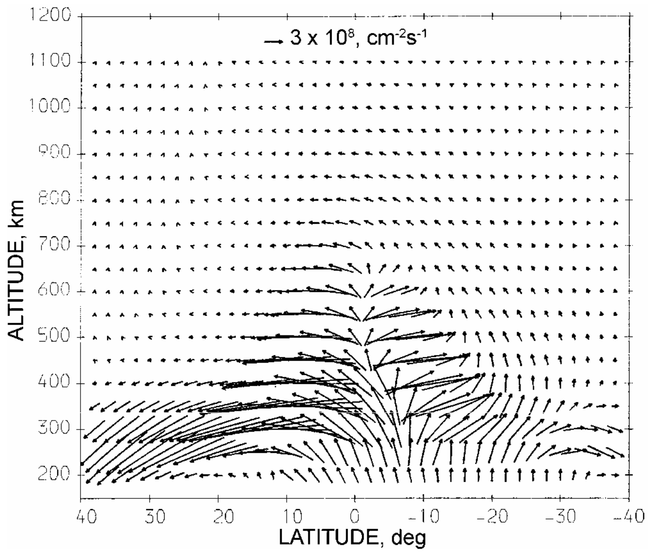

Fig. 3 — Plasma fountain at 1300 hrs LT obtained from model calculations using E×B drift and neutral wind (plasma fluxes are plotted on a linear scale; minimum (zero) vector length corresponds to plasma fluxes less than $2x10^5$ cm^{-2} s^{-1}; positive latitude is north)

solar activity[30]. However, unlike at higher solar activity, the EIA at the deep solar minimum is found to become weak after about 1400 hrs LT due to the early downward turning of the drift velocity.

Figure 4 shows the altitude extent of EIA at 1300 hrs LT [Fig. 4(a)] and 2000 hrs LT [Fig. 4(b)] at the deep solar minimum, latitude variations of the electron density at fixed heights obtained from the model calculations using drift and wind (model run 3) are shown. At 1300 hrs LT [Fig. 4(a)], the anomaly is strong in latitude extent and crest-to-trough ratio as at higher levels of solar activity; however, in altitude the anomaly extends only to about 550 km, which is less than the altitude extent at medium solar activity by about 200 km (Ref. 30). The low altitude extent of EIA at 1300 hrs LT, consistent with the plasma fountain (Fig. 3), is mainly due to the small plasma density at solar minimum.

At 2000 hrs LT, the anomaly [Fig. 4(b)] at the solar minimum is weak in all aspects, the crests are only up to about ±10° latitudes, maximum crest-to-trough ratio is only 1.2, and altitude extent is only up to 450 km. These features are weak compared to higher solar activity when the anomaly is strong in all aspects at 2000 hrs LT (Ref. 30). The weak anomaly at 2000 hrs LT at the solar minimum is mainly due to the absence of pre-reversal strengthening of the upward E×B drift [Fig. 1(a)] and small background plasma density, and partly due to the absence of production of ionization (as at higher levels of solar activity).

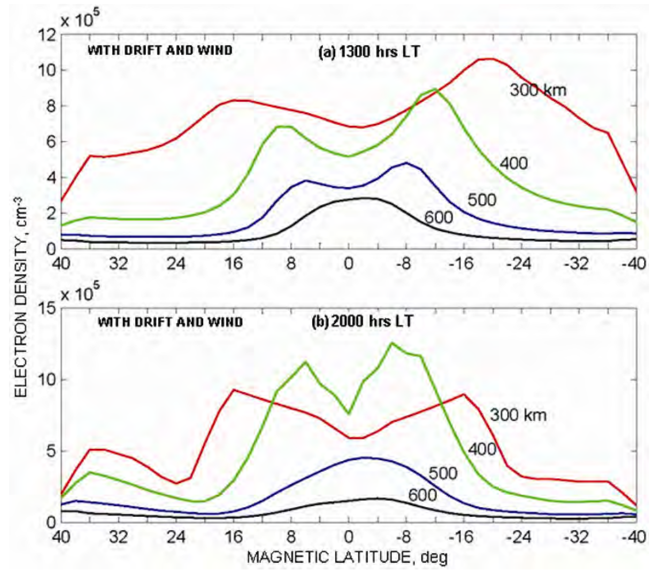

Fig. 4 — Latitude variations of electron density Ne at: (a) 1300 hrs LT; and (b) 2000 hrs LT, at different heights (noted in the figure) obtained from the model calculations using E×B drift and neutral wind (positive latitude is north)

3.2 Thickness and transition height

Figure 5 shows altitude profiles of the electron and ion (O^+, H^+ and He^+) densities obtained from the model calculations using E×B drift and neutral wind (model run 3). Figures 5(a and b) are for the equator and EIA crest (16°N) at around noon (1300 hrs LT) when the ionosphere is strong; Fig. 5(c) is for early morning hours (0500 hrs LT) when the ionosphere is weakest and correspond to 16°. As Fig. 5 shows, the ionosphere at the deep solar minimum contracts to a thin layer at lowest heights. The daytime ionosphere has maximum half-width of only about 250 km centered at around 300 km height at the equator [Fig. 5(a)] and about 150 km centered at around 250 km height at the crest [Fig. 5(b)], with a maximum density of about 10^6 cm^{-3} at the crest. An additional layer (F_3 layer) developed over the equator before noon has drifted to the topside ionosphere by 1300 hrs LT as topside ledge [Fig. 5(a)]. At night [Fig. 5(c)], the ionosphere decays to an extremely thin layer of peak density about 10^5 cm^{-3} and half-width only 125 km centered at around 225 km height.

The O^+/H^+ transition height is about 750 km during daytime over the equator [Fig. 5(a)] and at the crest [Fig. 5(b)]. At night, the transition height falls rapidly to about 500 km [Fig. 5(c)] prior to sunrise when the

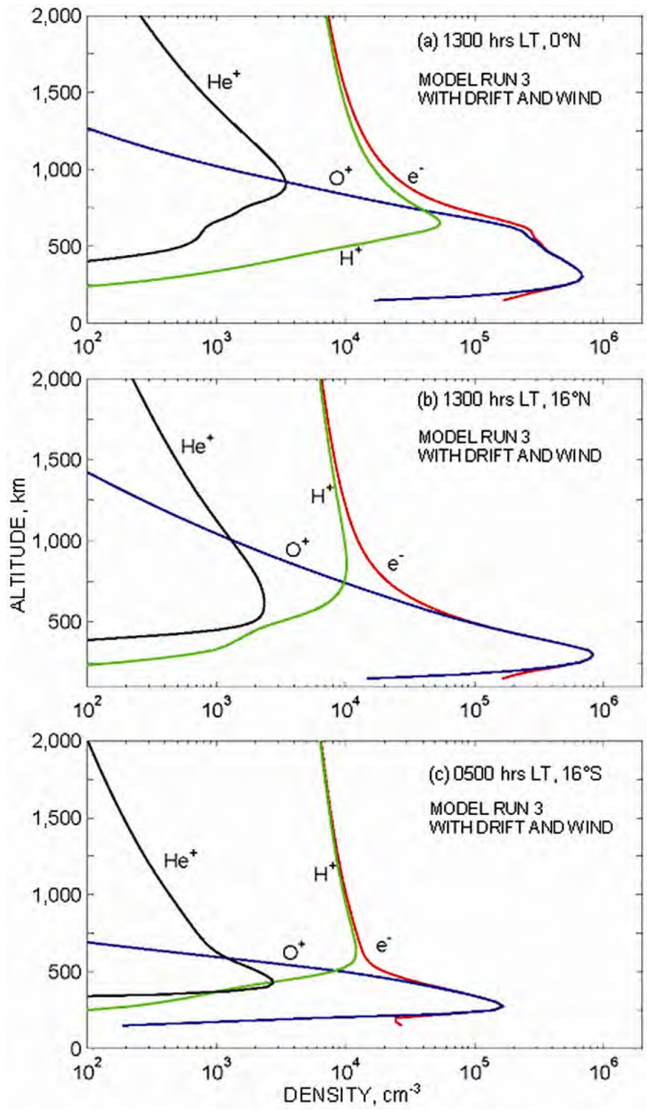

Fig. 5 — Altitude profiles of electron density and O^+, H^+ and He^+ ion densities: (a) at the magnetic equator at 1300 hrs LT; (b) at 16°N magnetic latitude at 1300 hrs LT; and (c) at 16°S magnetic latitude at 0500 hrs LT, obtained from the model calculations using E×B drift and neutral wind

ion densities at the transition height reduce to about 10^4 cm^{-3}. Also, except at around the equator, the electron density above the transition height (or in the plasmasphere) remains nearly constant (about 10^4 cm^{-3}) during day and night and decreases only slightly with height [Figs 5(b and c)]. These model results are in good agreement with observations. Using the C/NOFS satellite data during the unusually low solar minimum Heelis *et al.*[7] showed that the ionosphere contracted to a thin shell, with the O^+/H^+ transition height reaching record low values (about 500 km), and ion number densities at the transition height

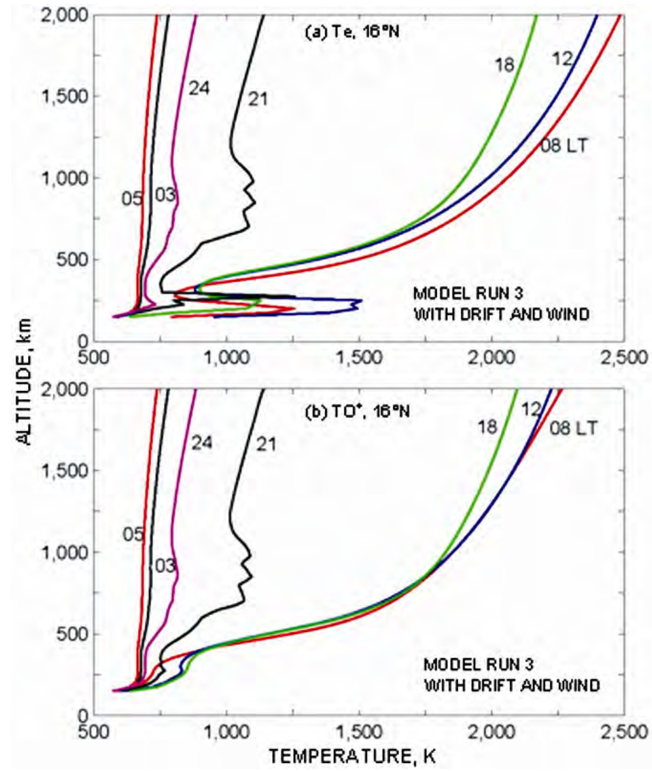

Fig. 6 — Altitude profiles of: (a) electron temperature; and (b) ion (O^+) temperature, at different local times (noted in the figure) at 16°N magnetic latitude

falling below 10^4 cm^{-3} prior to sunrise. The model reverse plasma fountain at night (2000-0500 hrs LT, not shown) is found to be confined below about 500 km altitude and within ±20° magnetic latitudes, consistent with the small plasma density and low transition height.

3.3 Electron and ion temperatures

Another interesting feature is the temperature of the ionosphere-plasmasphere system at the unusual solar minimum. Figure 6 shows the altitude profiles of the electron [Fig. 6(a)] and ion [Fig. 6(b)] temperatures at different local times at the EIA crest latitude of 16°N obtained from the model calculations using E×B drift and neutral wind (model run 3). Both temperatures start rising rapidly at sunrise at the deep solar minimum (compare the profiles at 0500 and 0800 hrs LT). The rapid rise at sunrise, known as morning overshoot, is due to photoelectrons heating the morning low density background plasma[35].

During daytime (0800-1800 hrs LT), there is a steep rise in both electron and ion temperatures in the ionosphere up to the base of plasmasphere (about 750 km height), above which there is slow rise in the temperatures; the temperatures reach about 2500 K (electrons) and 2250 K (ions) at 2000 km height. The temperatures decrease only slightly by a maximum of about 250 K until sunset (1800 hrs LT); electron temperature also exhibits a nose-type temperature peak in the bottom side ionosphere during daytime, which agrees with observations[36]. With sunset, both electrons and ions cool rapidly and attain equal temperatures (compare profiles during 1800-2400 hrs LT). By midnight, both temperatures reach nearly constant values at all heights and fall to record low values of only 650 K prior to sunrise. The model temperatures are in good agreement with observations; C/NOFS satellite data showed the unusually contracted ionospheric shell around the equator cooling to a temperature of about 600 K prior to sunrise[7].

4 FORMOSAT/COSMIC data

The FORMOSAT-3/COSMIC satellite measures the electron density up to about 600 km height on a global scale using radio occultation technique[4]. However, the electron density in the bottom-side ionosphere (below about 200 km) may not be very reliable due to the limitations of the technique. The FORMOSAT-3 electron density data have revealed several new aspects of the ionosphere, especially at low solar activity, including plasma caves in the bottom-side low latitude ionosphere[4], four peaked longitudinal structure of EIA[38], mid-latitude trough during solar minimum[39], and electron density derivations using tinny photometer[40]. For the present study, the data at the equinoxes (March, April, September and October) in 2008 and 2009 has been used. Altitude-latitude plots of the mean electron density under magnetically quiet (Ap less than 15) conditions in the 60-120°E longitudes are made as a function of local time.

Figures 7(a and b) show the plots during daytime (0900 and 1300 hrs LT) in 2008 [Fig. 7(a)] and 2009 [Fig. 7(b)]. Nighttime (2000 and 0500 hrs LT) plots are shown, in Fig. 7(c) only for 2009 for simplicity. The white histograms at the bottom of the figures give the number of electron density profiles (altitude) available in each 2.5° latitude bin. The mean F10.7 of the days of data used are noted at the top of the figures. As shown, the ionosphere contracts to a thin layer agreeing with the model predictions, and C/NOFS and CHAMP satellite data[7,8]. In addition, the COSMIC data give detailed picture

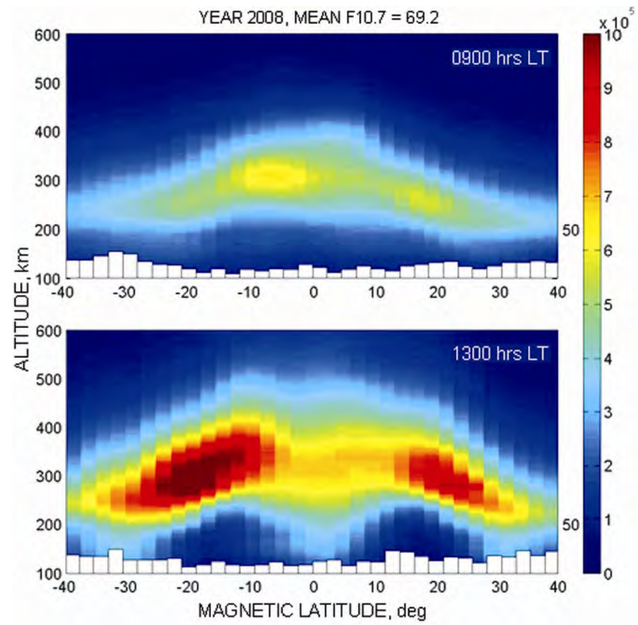

Fig. 7(a) — Altitude-latitude plots of mean electron density at: (top) 0900 hrs LT; and (bottom) 1300 hrs LT, obtained from FORMOST-3/COSMIC data in 60°E-120°E longitudes at the equinoxes (March, April, September and October) in 2008 under magnetically quiet (A_p < 15) conditions [white histograms at the bottom give the number of electron density profiles (altitude) available at each 2.5° latitude bin; positive latitude is north)

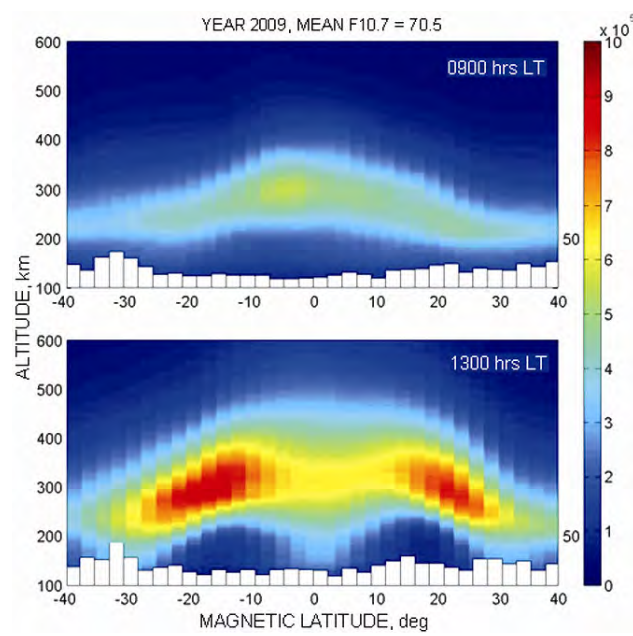

Fig. 7(b) — Altitude-latitude plots of mean electron density at: (top) 0900 hrs LT; and (bottom) 1300 hrs LT, obtained from FORMOST-3/COSMIC data in 60°E-120°E longitudes at the equinoxes (March, April, September and October) in 2009 under magnetically quiet (A_p < 15) conditions [white histograms at the bottom give the number of electron density profiles (altitude) available at each 2.5° latitude bin; positive latitude is north)

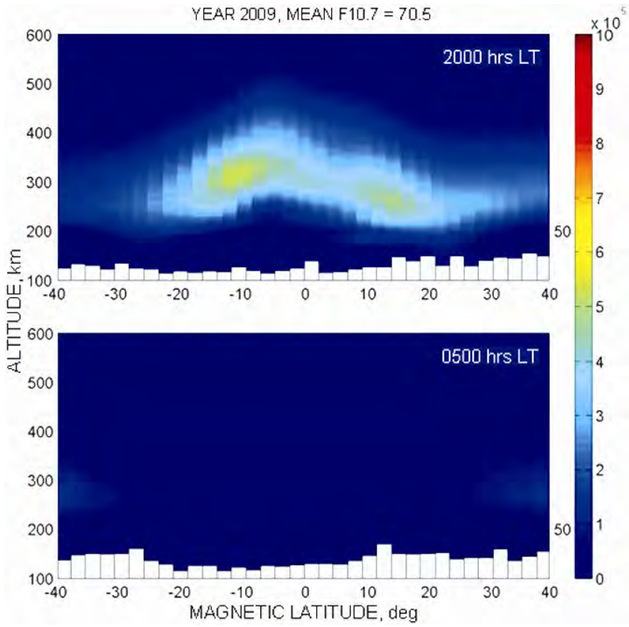

Fig. 7(c) — Altitude-latitude plots of mean electron density at: (top) 2000 hrs LT; and (bottom) 0500 hrs LT, obtained from FORMOST-3/COSMIC data in 60°E -120°E longitudes at the equinoxes (March, April, September and October) in 2009 under magnetically quiet (A_p < 15) conditions [white histograms at the bottom give the number of electron density profiles (altitude) available at each 2.5° latitude bin; positive latitude is north)

of the evolution of EIA at the long deep solar minimum. The EIA starts to develop in the morning (0900 hrs LT) in both years [2008 and 2009, Figs 7(a and b)] as at higher levels of solar activity. The EIA becomes strong at around noon (1300 hrs LT) with crests at ± 14°-18° latitudes, maximum crest-to-trough ratio about 1.5, altitude extent up to about 500 km, and a small north-south asymmetry. These features of the COSMIC data are in good agreement with the model predictions (Figs 2 and 4). In 2008 [Fig. 7(a)], the peak electron density at the EIA crests is about 10^6 cm^{-3}, which also agrees with the model. In 2009 [Fig. 7(b)] the peak electron density (at the crests) decreases by about 25% compared to 2008 [Fig. 7(a)]. This may be due to the continued contraction of the thermosphere-ionosphere system (in 2008-2009) as also reported using CHAMP data[8].

Unlike at higher levels of solar activity when the EIA continues to become strong until about 2000 hrs LT, the EIA at the long deep solar minimum is found to contract after about 1400 hrs LT. This could mainly be due to the weak drift velocity during this period [Fig. 1(a)] and small background density. By 2000 hrs LT [Fig. 7(c)], the EIA has contracted to have crests only at around ±10° latitudes, peak density about $5x10^5$ cm^{-3}, maximum crest-to-trough ratio about 1.2, and altitude extent about 400 km. These features also agree reasonably well with the model predictions though the model peak density is higher than observed (Fig. 4). The difference seems to suggest that the HWM91 nighttime meridional wind velocity at the unusually low solar minimum could be more equatorward than the actual wind velocity; the actual wind velocity is not available for comparison. Prior to sunrise [0500 hrs LT, Fig. 7(c)], the low latitude ionosphere becomes flat in latitude and altitude with peak density only about $4x10^4$ cm^{-3}. These features agree also with C/NOFS observations[7].

The model predictions and FORMOSAT-3 data agree also with those measured by CHAMP (400 km height) and GRACE (500 km height) satellites[8]. Luhr & Xiong[8] compared the electron densities measured by CHAMP and GRACE during the unusual solar minimum with those predicted by IRI2007. They found the ionosphere contracting by 50% in 2008 and by more than 60% in 2009 compared to the IRI predictions. From an inspection of the latitudinal and local time distributions of the electron densities, Luhr & Xiong[8] interpret that the too high predictions of IRI primarily occur at low altitudes during daytime hours. From these comparisons, they argue that IRI2007 is strongly overestimating the equatorial plasma fountain effect during the deep solar minimum; the anticipated plasma fountain seems to be similar to the model plasma fountain (Fig. 3). However, as mentioned above, the weakening of the plasma fountain is mainly due to the reduction in the background plasma density. There is not much difference in the drift velocities before noon at the solar minimum [Fig. 1(a] (Ref. 12) compared to higher levels of solar activity.

5 Conclusions

SUPIM model and FORMOSAT-3/COSMIC satellite data show that the ionosphere-plasmasphere system (within ±40° magnetic latitudes and 150-2000 km height) at the unusually long deep solar minimum between solar cycles 23 and 24 obeys its usual laws of behaviour but the ionosphere contracts to a thin layer. During daytime, the ionosphere has a half-width of only about 250 km over the equator and 150 km at the EIA crests with a peak density about 10^6 cm^{-3} and O^+/H^+ transition height at around 750 km. However, ion and electron temperatures rise rapidly at sunrise at all heights and reach up to about

2500 K (electron) and 2250 K (ion) at 0800 hrs LT in the plasmasphere (2000 km height), which decreases by a maximum of only 250 K until sunset. At night, the ionosphere reduces to a cold thin layer of half-width less than about 150 km at the crests with a peak density of 10^5 cm^{-3}, and transition height about 500 km where ion densities reduce to 10^4 cm^{-3}. The electron and ion temperatures at all heights fall rapidly after sunset until mid-night and decrease slowly to about 650 K prior to sun rise. The electron density in the plasmasphere (above transition height) remains nearly constant at about 10^4 cm^{-3} during both day and night, and decreases only slowly with height. SUPIM predictions and FORMOST-3 data agree also with C/NOFS and CHAMP satellite observations.

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