Preface

The solar minimum between solar cycles 23 and 24 was an unusually long minimum lasting more than three years during 2006-2009, which decayed to the deepest minimum in 2008 in nearly a century (*see* figure). The record low solar minimum gave a good opportunity to investigate the inherent properties of the upper atmosphere-ionosphere-plasmasphere system and its interactions with regions below with minimum forcing from above. Systematic studies of this interesting topic have been carried out around the world. This special issue consolidates various studies of the upper atmosphere-ionosphere-plasmasphere system made at low latitudes in Asian sector and a review paper on equatorial F-region irregularities. Twenty four papers from various institutions in India, Japan, China, Taiwan, Indonesia, UK and Brazil are organized in the order of those dealing mainly with thermosphere-ionosphere-plasmasphere system and its interactions with the mesosphere-lower thermosphere (MLT) region below and magnetosphere above.

The long term trend of solar minimum is presented first. Using data from different sources, Girish & Gopakumar present the evolution of solar and geomagnetic conditions, galactic cosmic ray flux, and solar energetic particle occurrences for over 300 years. The study shows that long deep solar minimum like the recent one is repeated with the Gleissberg periodicity of 90-100 years. The authors also show that the solar EUV flux during the Maunder minimum would have been only 9% less than that during the recent deep minimum, implying that the earth's ionosphere existed even during the deepest (Maunder) solar minimum known till date.

Climatology of thermosphere-ionosphere and plasmasphere

A theoretical model of the ionosphere-plasmasphere system SUPIM predicts (Balan *et al.*) thin daytime ionosphere at the deep solar minimum that rapidly decays to a cold thin layer at night. Around noon, at equinox the ionosphere has a half-width of about 250 km over the equator and 150 km at the equatorial ionization anomaly (EIA) crests in Indian longitudes, with a peak density of about 10^6 cm^{-3} and O^+/H^+ transition occurring at around 750 km. At night, the ionosphere reduces to a thin layer of half-width less than about 150 km and peak density about 10^5 cm^{-3}, and the O^+/H^+ transition height falls to around 500 km where the ion densities reduce to about 10^4 cm^{-3} and ions cool to about 600 K prior to sunrise.

Sripathi presents the climatology of the ionosphere using the electron density data measured by COSMIC Radio Occultation technique. The climatology at the unusual solar minimum is similar to that at higher levels of solar activity. The author also suggests some equatorial electrojet control on the well known equinoctial asymmetry in plasma density. Using the daily peak total electron content (TEC) data recorded at Rajkot (22.29°N, 70.74°E, 31.6°N dip angle). Chakrabarty *et al.* investigate the role of solar activity and neutral dynamics on the TEC variation over the EIA crest region. The results show the daily mean peak TEC in 2009 increasing at higher rates than the corresponding mean EUV and F10.7 cm solar fluxes, indicating the roles of the residual (difference between annual averages) effects of the trans-equatorial winds and thermospheric composition changes. It is also shown that the inherent solar periodicity of around six months has no consistent causal connection with the semi-annual variation in TEC.

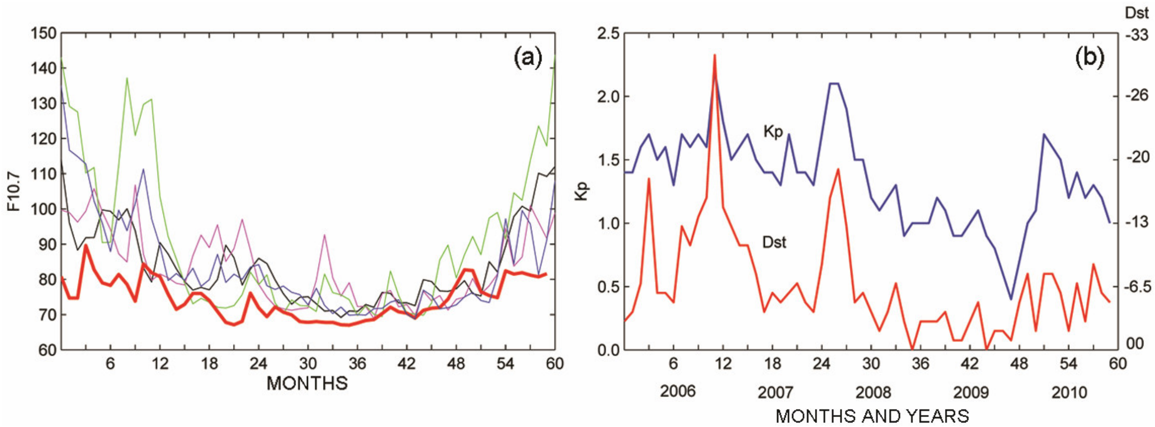

Fig. — (a) Monthly mean F10.7 for five years around the last five solar minima between solar cycles 19/20 (black), 20/21 (magma), 21/22 (green), 22/23 (blue) and 23/24 (red); and (b) Monthly mean Kp and Dst for five years during the recent long deep solar minimum (2006-2010)

Pavan *et al.* report the F_3 layer observations at 6.5°N magnetic latitude in India at the long deep solar minimum (2008-2009) and also during a high solar activity period 2002-2003. Whilst the characteristics of the F_3 layer at the deep solar minimum agree with those at nomal solar minimum, the critical frequency of the layer (f_oF_3) at the deep minimum is 2-3 MHz lower than that at normal minimum, which agrees with the contraction of the ionosphere due mainly to the low levels of solar ionizing radiation. Sumod *et al.* present the corrections to be applied to the apparent vertical plasma drift velocity measured using a HF Doppler radar at the equatorial station Trivandrum (8.50°N, 770°E, 0.50°N dip latitude) during morning and evening hours. The velocity is apparent due to the contributions from photochemical processes. It is shown that the correction depends strongly on altitude and season and can be as high as 10-15 m s^{-1}. Kumar & Singh study the effect of solar flares on the ionosphere at the solar minimum using the GPS-TEC data collected at Varanasi, an Indian station near the northern EIA crest. This study shows significant enhancement in TEC near the EIA crest location in association with the flare related EUV flux enhancement that increases ionization production. The effect of the possible changes in the flare related low latitude electrodynamics is also discussed.

Rajesh *et al.* report airglow observations carried out using Imager of Sprites and Upper Atmospheric Lightning (ISUAL) onboard FORMOSAT-2 satellite during the recent extreme solar minimum period over low and equatorial latitudes. Their study indicates that in the quiet conditions during the solar minimum epoch, the seasonal variations in the thermospheric airglow, i.e. $O(^1D)$ are less pronounced. The latitudinal distribution of the $O(^1D)$ intensity reveals frequent occurrence of airglow enhancements over the equatorial region at equinox months and in the summer hemisphere in both solstice periods. The airglow intensity on the whole seems to vary with the intensity of solar activity. Parihar *et al.* present the first nightglow observations of the thermospheric red line emission of atomic oxygen at 630 nm from Allahabad (25.4°N, 81.9°E), a low-latitude station in India, during October-November 2009 and 2010.

Pant *et al.* present the first Ionospheric Tomograms for the Indian longitude of 77°E obtained using India's indigenously developed satellite-based radio beacon payload called Radio Beacon for Ionospheric Tomography (RaBIT). This beacon is onboard India's small satellite YOUTHSAT, in a low earth orbit (~817 km) dedicated for upper atmospheric studies. The potential of the tomograms, thus generated, is discussed in context of the variability in the large scale ionospheric processes like the equatorial ionisation anomaly (EIA) at the deep solar minimum.

F-region irregularities

Abdu provides a brief review of our current understanding of the equatorial spread F irregularity (ESF) development related to the diverse processes that control or influence the spatio-temporal distribution and day-to-day variability in the occurrence of the irregularities during solar minimum conditions. This paper provides the relative roles of the pre-reversal enhancement of zonal electric field (PRE) and gravity waves with varied level of solar activity, and shows that the ESF occurrence pattern tends to have larger dependence on gravity wave distribution during solar minimum conditions (than during solar maximum). It also suggests that while the solar minimum spread F irregularities originating from the equatorial processes might be connected to the gravity waves from the tropical convective sources, the post-midnight spread F of the low-latitude region appears to be ruled mainly by the medium-scale traveling ionospheric disturbance (MSTID) of mid-latitude origin.

Li *et al.* study the F-region irregularity using the Sanya VHF radar, GPS scintillation/TEC receiver and ionosonde, together with the C/NOFS satellite *in situ* density measurements during the period 2009-2010, and show that the field aligned irregularities (FAI) appear frequently at post-sunset hours during equinox and mostly at midnight/post-midnight in June solstice. They show that while some post-midnight FAI structures over Sanya may originate from equatorial F-region and then extend to Sanya latitude along magnetic field lines, others could resemble the irregularities of localized origin not associated with the equatorial process. Otsuka *et al.* using the observations made by a 30.8 MHz radar at Kototabang (0.20°S, 100.32°E, dip latitude 10.4°S), Indonesia show that FAIs appear frequently at the post-midnight sector between May and August every year from 2006 to 2010. For the first time, they show statistics of the zonal propagation velocity of the post-midnight FAIs, which show that between May and August, 46% of the post-midnight FAIs propagated westward, 14% propagate eastward, and zonal propagation was not discernible for 40% of the post-midnight FAIs. Average velocity is approximately 50 m s^{-1} westward. They also find that post-midnight FAIs are likely associated with either plasma bubbles or MSTIDs. Joshi *et al.* study the F-region FAI observed from Gadanki during the low solar activity period of 2008-2009 and made a detailed comparison with those observed during the high solar activity period 2002-2003. Observations show that the occurrence probability of the F-region field-aligned irregularities (FAI) on night-to-night basis was 65% in the high solar activity and 30-40% in the low solar activity. While they were confined to pre-midnight hours and extend to 600 km in altitude in the high solar activity, they extended well beyond post-midnight until dawn and limited to 400-500 km in altitude in the low solar activity. Concurrent observations of Es layer displayed descending behaviour, reminiscent of tidal/gravity wave associated winds, which eventually led to disruption of Es during the evening hours when the high altitude plumes appeared. Examination of the growth perspective of the Rayleigh-Taylor instability suggests that even though the height of the F-layer in the post-sunset hours was lower during the low solar activity period than that during the high solar activity period, the chance of bubble formation is nearly equal owing to the advantage of lower ion-neutral collision frequency in low solar activity than in high solar activity. Dashora *et al.* investigate the F-region irregularities in the Indian low-latitude zone and their evolution characteristics during the recent solar minimum using simultaneous GPS TEC/Scintillation receiver, radar, ionosonde and airglow photometer measurements. Their study addresses the space-time evolution of pre- and post-midnight plasma bubbles and zonal drift of the depleted regions, along with the observed absence of sub-kilometer scale irregularities in the presence of its higher and lower scale irregularities. Interestingly, no correlation is found between DROTI and S4 indices. This study has significant implications in GPS based communication navigation applications.

Thampi *et al.* study the evolution of plasma bubbles using the ground based reception of Coherent Electromagnetic Radio Tomography (CERTO) beacon signals from the Communications/Navigation Outage Forecasting System (C/NOFS) satellite from Bac Lieu, Vietnam (9.2°N, 105.6°E geographic, 1.7°N magnetic dip latitude) and ionosonde observations from Bac Lieu and Chumphon (10.7°N, 99.4°E, 3.3° magnetic dip latitude). They also analyse the spectral characteristics obtained from successive passes demonstrating the signatures of the cascading process. Their results show the patchy nature of the ESF irregularities and the longitudinal variability of ESF during the deep solar minimum period. Manju *et al.* attempt to study the role of neutral dynamics on the asymmetric occurrence pattern of equatorial spread F (ESF) in the vernal equinox and autumnal equinox using ionosonde observations made from the magnetic equatorial station Trivandrum and low latitude station SHAR. They find that large poleward winds to be prevalent during autumnal equinox compared to that in vernal equinox. They argue that large neutral winds, in autumnal equinox, result in an increase in off equatorial E-region conductivity, thereby, inhibiting or weakening the F-region dynamo. Das *et al.* study the effects of equatorial ionization density irregularities on trans-ionospheric communication and navigation links during the abnormally prolonged minima of the 24th solar cycle from Calcutta, a station situated virtually underneath the northern crest of the equatorial ionization anomaly in the Indian longitude sector. Scintillations at L-band have been sparse during the period 2008-2010. They find that the ambient ionization and strength of the equatorial electrojet was high on those days when scintillation was observed.

Mesosphere-lower Thermosphere (MLT) dynamics and coupling

Using a unique Dayglow photometer and Proton Precession Magnetometer over the equatorial station Trivandrum (8.5°N, 77°E; dip latitude 0.5°N), Vineeth *et al.* report evidences of enhanced gravity wave activity of 1-2 hour periodicity at mesopause altitudes during counter electrojet (CEJ) events. The wave activity at the mesopause also fades out when the mesospheric zonal wind reverses from west to east, indicating a possible upward penetration of the gravity waves into the lower thermosphere region during CEJ events. Taori *et al.* examined the linkage between the low latitude mesospheric gravity waves and the equatorial plasma bubble (EPB) using simultaneous Rayleigh lidar and VHF radar observations from Gadanki (13.5°N, 79.2°E) and ionosonde observations from Tirunelveli (8.7°N, 77.8°E) made during 2007 and 2009 when solar activity was undergoing a deep minima. Observations show that the occurrences of plume structures in the radar observations have a close link with the amplitudes of the short period gravity waves in the mesospheric temperature. They argue that such waves have an important role in seeding the Rayleigh-Taylor (RT) instability manifesting EPB.

The role of planetary-scale waves in the mesosphere-lower thermosphere-ionosphere (MLTI) coupling during the deep solar minimum period of solar cycles 23-24 is investigated in detail by Dhanya *et al.* They show that in the absence of severe magnetic disturbances, much of the observed variations in low latitude ionospheric current system, the equatorial electrojet (EEJ), in particular, are driven by global scale waves propagating from below. They also show concurrent occurrence of 3.5-day oscillations in zonal winds and EEJ around summer solstice when the background wind changes direction. Interestingly, they find that these signatures are not consistent during winter solstice and report, for the first time, a semi-annual oscillation (SAO) type signature akin to mesospheric winds for the 6.5-day wave variability in EEJ supporting the assumption that planetary waves propagating from below do contribute substantially to the short term variations in EEJ. Tiwari *et al.* study the sporadic

E activity during 2007-2009 using a newly installed digital ionosonde at Allahabad (25.3ºN, 81.5ºE, and dip latitude 16.3ºN). Their observations show largest occurrence rate of sporadic E during summer. They also show that total blanketing type Es layer is more during nighttime of summer than in other times and other months. Height migration of h'Es shows descending pattern indicating the role of tidal winds.

Forcing from magnetosphere

As indicated by geomagnetic activity (Fig.), the ionosphere-plasmasphere system at the long-deep solar minimum behaved with minimum forcing from the magnetosphere. However, the interaction of the magnetosphere with the co-rotating interaction regions (CIRs) of solar origin produced weak recurrent geomagnetic storms at solar rotational (27-day) and its sub-harmonic (13.5 and 9-day) periodicities. By analyzing the neutral and plasma densities measured by CHAMP and FORMOSAT-3/COSMIC satellites, Tulasiram *et al.* show that both the neutral and ionized upper atmospheric properties at the long deep solar minimum ring with these periodicities; and the 9-day periodicity becomes dominant. Penetration of electric field from high to low latitudes, which usually occur during intense geomagnetic storms, is rare at solar minimum. However, Veenadhari *et al.* by analyzing the equatorial electrojet (EEJ) strength show the penetration of electric fields of considerable strength and 2-3 hours duration occurring in the morning-noon longitude sector during the main phase of some moderate recurrent geomagnetic storms at the unusual solar minimum. The penetration is confirmed from a linearly dependence of the EEJ strength and changes in interplanetary electric field (IEF_Y).

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***N Balan*[1]*, A K Patra*[2] *& T K Pant*[3]**

[1]Institute of Space Sciences, National Central University, Chung-Li 32054, Taiwan

[2]National Atmospheric Research Laboratory, Gadanki 517 112, India

[3]Space Physics Laboratory, VSSC, Trivandrum 695 022, India