Summary of sessions: Ionosphere – Thermosphere – Mesosphere Working Group

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Abstract. The topics covered by the sessions under the working group on Ionosphere–Thermosphere–Mesosphere dealt with various aspects of the response of the ionosphere-thermosphere coupled system and the middle atmosphere to solar variability. There were four plenary talks related to the theme of this working group, thirteen oral presentations in three sessions and six poster presentations. A number of issues related to effects of solar variability on the ionosphere-thermosphere, observed using satellite and ground-based data including ground magnetometer observations, radio beacon studies of equatorial spread F, and modeling of some of these effects, were discussed. Radar observations of the mesosphere-lower thermosphere region and a future mission to study the coupling of thunderstorm processes to this region, the ionosphere, and magnetosphere were also presented.

Index Terms. Disturbance dynamo, ionosphere-thermosphere, magnetic storms, prompt penetration electric fields.

1. Introduction

In the study of the Sun-Earth connected system, effects of solar variability on the ionosphere – thermosphere assume importance on account of the considerable influence these have on a variety of technological systems including satellite based communication and navigation systems. Majority of papers summarized here are based on observations of the ionosphere-thermosphere using different techniques. These range from remote sensing of the upper atmosphere and ionosphere with spectroscopic imagers operating in the far ultra-violet (FUV) spectral region to in-situ satellite data of electron density, electron temperature, and thermospheric density; and ground-based observations using magnetometers, radars, ionosondes, GPS, ionospheric scintillation and other radio beacon techniques. The roles played by promptly penetrating electric fields (PPEFs) as well as ionospheric disturbance dynamo (IDD) electric fields in the low latitude ionosphere have been discussed on the basis of these observations as well as modeling. Reviews of recent work on the response of the ionosphere and thermosphere to magnetic storms and substorms, presented in the plenary sessions, are summarized in section 2. This is followed by highlights of the papers dealing with specific themes.

2. Response of ionosphere-thermosphere to storms

In a review of geomagnetic storm effects on middle and low latitude thermosphere and ionosphere, *Fejer* (PL5, Plenary) described some of the processes involved in the interaction of the magnetosphere-ionosphere coupled system with the electric fields generated by the solar wind dynamo, and how they alter the dynamics of the ionosphere and thermosphere from auroral to equatorial latitudes during geomagnetic storms. In particular this talk focused on the large amplitude, relatively short-lived PPEFs which are seen in low- and mid-latitude ionosphere as well as the plasmasphere. Effect of PPEFs on the generation of post-sunset equatorial spread F (ESF) during magnetically disturbed periods was also discussed on the basis of VHF radar observations at Jicamarca.

An important aspect of the response of low- and mid-latitude ionosphere-thermosphere to geomagnetic storms is its longitude dependence. At low latitudes what is observed is that prompt penetration of magnetospheric electric fields from high to low latitudes, during periods with inadequate shielding or overshielding, often occurs in combination with IDD electric fields that are driven by storm-time changes in thermospheric winds and electrical conductivities. *Fuller-Rowell et al.* (PL15) reviewed the results obtained by modeling these processes for some storms in different longitude zones.

In a review of recent work on the response of the low-latitude/equatorial ionosphere to magnetic storms and substorms, *Sastri* (PL18) discussed some outstanding scientific issues that need further investigation. One of these is the characteristic of storm sudden commencement (SC) manifested in the dayside dip equatorial region. *Sastri* (PL18) has pointed out that although the SC arises as a result of sudden magnetospheric compression following the impact of shocks and discontinuities in solar wind on the dayside magnetopause and the consequent increase of magnetopause currents, explanation of the complex latitude and local time structure of the SC waveform may require consideration of the effects of near-earth currents flowing in the ionosphere.

The other major issue described by *Sastri* (PL18) is the appearance of PPEFs and the delayed IDD electric fields in the low-latitude/equatorial ionosphere and the implications that these magnetic activity related disturbances in the equatorial ionosphere have for the generation of equatorial plasma bubbles (EPBs).

3. Global view of the ionosphere-thermosphere system

It is now possible to obtain a global view of the response of ionosphere-thermosphere (IT) system to solar variability using UV images obtained from high Earth orbiting satellites. The Global Ultra Violet Imager (GUVI), which is a far ultraviolet spectrograph flown on the NASA TIMED satellite has provided detailed pictures of the equatorial ionization anomaly, including occasional large field-aligned depletions during nighttime. Images produced by GUVI have also shown large depletions in the O/N2 column density accompanied by low electron densities during intense geomagnetic storms [*Meier*, I5].

4. In-situ satellite observations

In the past, very few observations of the thermosphere have been available for comparison with model calculations during both quiet and magnetically disturbed periods. Continuous measurements of thermospheric density since August 2000, using a sensitive accelerometer on board the low-altitude polar orbiting CHAMP satellite, have revealed some major differences with models such as MSIS even for quiet conditions [*Lühr and Liu*, I4]. One such important observation is the significant influence of the main geomagnetic field on the thermospheric density distribution resulting in maximum densities at mid-latitudes around $\pm 30^\circ$ magnetic latitude instead of at the subsolar point. The most pronounced storm-time disturbances in thermospheric density were found to be in the dayside auroral region, where most of the storm-related heating took place. While such observations have been made in the past, no simple relation between current flow and heating could be determined leading *Lühr and Liu* (I4) to conclude that several additional factors also play a role in the heating, which would lead to better parameterization of thermospheric models. Prominent peaks in thermospheric density observed between 70° and 80° magnetic latitude around the noon sector have been related to Joule heating in the cusp region.

One of the consistent features seen in in-situ satellite observations of the response of low latitude topside ionosphere to magnetic storms is the simultaneous enhancement in electron density, N_e, and temperature, T_e, particularly during nighttime [*Lakshmi*, I3]. A possible explanation of this feature was given in terms of the precipitation of neutral particles as a result of charge exchange with ring current ions that have a particular pitch angle distribution. On the other hand, the significant enhancement in daytime T_e in the low latitude ionosphere at an altitude of about 600 km, in the absence of any change in N_e, has been partially explained by a decrease in electron thermal conductivity due to enhanced neutral densities at equatorial latitudes during a magnetic storm [*Lakshmi*, I3].

Prompt penetration of interplanetary/polar cap electric fields to the equatorial and near equatorial ionosphere during the absence of adequate shielding when the interplanetary magnetic field (IMF) turns southward may result in an enhanced eastward electric field at the equator on the dayside and consequent redistribution of ionospheric plasma. *Tsurutani et al* (I6) discussed the occurrence of the dayside ionospheric "Superfountain" (DIS) due to the peneration of long-duration unshielded eastward electric fields into the dayside equatorial ionosphere during a superstorm, using O^+ ion density as well as $O^+/(O^+ + H^+)$ density ratio obtained from DMSP satellite observations. These observations were compared with preliminary results derived from a modified version of the SAMI-2 model. The inclusion of a prompt-penetration eastward electric field of 4mV/m in the model showed many of the features expected to be associated with the DIS.

5. Studies using ground-based magnetometer observations

Anderson et al. (I7) used ground-based magnetometer observations to infer daytime vertical **E X B** drift velocities in the Peruvian, Phillippine, and Indian sectors to address two basic questions: the first regarding how well do these inferred vertical drifts for geomagnetically quiet periods compare with the Fejer-Scherliess quiet time climatological model (Scherliess and Fejer, 1999) in three different longitude sectors; and the second concerning the relationship between the interplanetary electric fields (IEFs) and low latitude electric fields during disturbed periods. The authors also used the incoherent scatter radar data available in the Peruvian sector to obtain the nighttime vertical drifts in that sector, along with daytime magnetometer-inferred **E X B** drifts in the other two sectors, to observe that during disturbed periods PPEFs occur simultaneously in all three longitude sectors.

The effect of storm time changes in the PPEFs that appear in the equatorial ionosphere has been studied by *Veenadhari and Alex* (P16) using a disturbance parameter, EEJ (Dis), based on the strength of the equatorial electrojet derived from equatorial and low latitude geomagnetic observations in the Indian sector. For a magnetic storm, which occurred during April 11-13, 2001, northward turning of the interplanetary magnetic field (IMF) caused the appearance of a counterelectrojet during recovery phase of the storm. The authors found a good correlation between the dawn-to-dusk electric field E_y ($= -V_{sw} \times B_z$) and EEJ (Dis) for this event.

The real-time MAGnetic Data Acquisition System of Circum-pan Pacific Magnetometer Network (MAGDAS/CPMN) proposed by *Yumoto et al.* (OS4) is expected to contribute extensively to real-time monitoring and modeling of (1) the global 3-dimentional current systems, (2) response of ionospheric plasma to transient solar events such as solar flares and coronal mass ejections, and (3) penetration of interplanetary/polar cap electric fields into the equatorial and low latitude ionosphere. The Space Environment Research Center of Kyushu University has already deployed such systems at 20 stations along the 210° magnetic meridian. Comparison of variations in the H component observed near the magnetic equator along this magnetic meridian, with Doppler shifts of HF radio waves obtained from FM-CW radar observations along the same meridian, indicated the presence of PPEFs in the equatorial ionosphere.

6. Prediction of post-sunset ESF

The significant solar control of the generation of ESF irregularities through factors such as the pre-reversal enhancement of the post-sunset ambient eastward electric field, neutral winds, and possible linkages with other equatorial phenomena such as the equatorial ionization anomaly (EIA), and equatorial temperature and wind anomaly (ETWA), was discussed by *Sridharan et al.* [PL12]. Use of an empirical parameter derived from observations of equatorial F layer height, and strength and asymmetry of the EIA as seen in the vertical total electron content (TEC), as a tool for a deterministic prediction of ESF occurrence was also described in this talk.

Thampi et al. (I14) used the strength as well as asymmetry of the EIA derived from ground-based TEC measurements for prediction of the occurrence of post-sunset ESF. These characteristics of the EIA were estimated using latitudinal profiles of TEC obtained from a single ground-based radio beacon receiver located at an equatorial station, as part of the Coherent Radio Beacon Experiment (CRABEX) being conducted in India. The recorded radio signals were transmitted from the Navy Ionospheric Monitoring System (NIMS) satellites. *Thampi et al.* (I14) attempted to construct a forecast parameter by combining the above EIA characteristics. Although higher values of this combined parameter tend to favour ESF occurrence, clearly there are other factors also involved. Hence it is necessary to have an in-depth science-based study of this problem of predicting ESF occurrence.

Height of the post-sunset equatorial F layer is known to play a key role in the generation of ESF irregularities. A statistical assessment of the effect of the pre-reversal enhancement (PRE) of the post-sunset vertical **E X B** drift at the equator, on the occurrence of VHF scintillations produced by ESF irregularities, was made by *Rama Rao et al.* (I12). They found that the percentage occurrence of VHF scintillations at an off-equatorial station, and the monthly mean PRE of the **E X B** vertical drift velocities at the equator obtained using data from two digital ionospheric sounders operated at equatorial and off-equatorial stations respectively, both show the same pattern of seasonal variation. Further, *Rama Rao et al.* (I12) also found that ionization anomaly gradient between an equatorial and an off-equatorial station shows a significant enhancement during post-sunset hours for days on which intense scintillation activity occurs.

The role of gravity waves in seeding the Rayleigh-Taylor (R-T) instability continues to be debated. An experiment was proposed by *Chakrabarti et al.* (I13), in which two imaging spectrographs would be flown on board a high-altitude balloon, from a low-latitude region of India, to detect the wave characteristics just before the occurrence of equatorial F region irregularities in order to shed light on the "seeding" issue. The spectrographs shall obtain high-resolution measurements of airglow emissions at three key wavelengths, which originate at altitudes of 85, 100, and 230 km, respectively. These observations shall be supplemented with ground-based observations using HF and VHF radars, ionosondes, and a multi-wavelength daytime photometer; and monitoring of satellite radio beacons. This should help in establishing whether the ESF trigger has its origin in the ionospheric E or F region.

Sekar and Chakrabarty (I16) investigated the effect of geomagnetic storms on the development of ESF using several case studies. The Indian MST radar observed two of these events, while one event observed by the Jicamarca radar was modeled using non-linear simulation of the development of the collisional R-T instability. These case studies indicate that pre-seeded structures may play a decisive role for the development of pre-midnight plasma bubbles when the nighttime electric field reverses direction from westward to eastward due to a PPEF caused by a sudden turning of the IMF B_Z from southward to northward.

7. Ionospheric scintillations

As stated in the introduction, a major concern regarding the effects of solar variability on technological system, are the effects on the performance of communication and navigation systems. Apart from the time delay introduced by the ionosphere in the propagation of a transionospheric radio wave signal, VHF and higher frequency radio signals undergo forward scattering by intermediate scale length (~ 100m to few km) irregularities. Movement of the irregularities relative to the signal path gives rise to temporal fluctuations or scintillations of the signal recorded by a ground receiver. The equatorial/low latitude and auroral/polar cap regions are particularly vulnerable to signal degradation due to occurrence of scintillations. Some of the factors that influence the generation of ESF irregularities, which are particularly implicated in causing outage of communication and navigation systems, are affected by long-term solar activity. Variation of L-band scintillation occurrence with local time, season, solar, and magnetic activity presented by *Dasgupta* (I11) on the basis of measurements carried out near the northern crest of the EIA in the Indian region, over a period of nearly five years, show a predominant solar cycle modulation of the development of ESF irregularities.

Degradation of transionospheric VHF and higher frequency radio wave signals due to ionospheric scintillations is determined by the evolution of small-scale structure in the irregularities as well as their movement relative to the signal. Although there are many studies of the occurrence pattern of ESF, little attention has been paid to the solar cycle effects on the structuring of equatorial plasma bubbles (EPBs) after they develop on the bottomside of the equatorial F-region. *Bhattacharyya et al.* (I15) address this issue and find that the more rapid decay of small scale irregularities with increasing solar activity actually causes the fading rate of a scintillating signal to stabilize, whereas the increase in the pre-midnight drift speed of the irregularities across the signal path with increasing solar activity would otherwise cause the fading rate to monotonously increase with solar activity. As far as the effect of geomagnetic activity on the generation of ESF irregularities is concerned, techniques such as ionospheric scintillation observations are unable to distinguish between freshly generated irregularities and those that were generated a few hours earlier and then drifted across the signal path. *Bhattacharyya et al.* (I15) have suggested a method to resolve this issue and obtained the statistics of fresh generation of EPBs as a result of magnetic activity.

For the practical problem of nowcasting equatorial scintillations, *Groves et al.* (I10) discussed the evolution of spatial structure in EPBs, especially since different scale size irregularities are involved in producing scintillations on VHF and L-band signals. They presented a data-driven scheme for projecting scintillation activity 2-3 hours into the future based on estimates of decorrelation time and coherence bandwidth obtained from current data. They also presented results from modeling the effects of scintillations on GPS positioning performance.

Nighttime equatorial F region plasma drifts may be obtained from spaced receiver scintillation observations once the perturbation electric field associated with the equatorial plasma bubbles are eroded. In the initial stage of EPB development, the **E X B** drift arising from the perturbation electric field associated with the R–T instability contribute to the zonal drift of the ground scintillation pattern caused by scattering of radio waves by the irregularities. A disturbance dynamo electric field changes the pattern of local time variation of the equatorial ionospheric F region plasma drift and this is clearly seen in nighttime drifts calculated from spaced receiver scintillation observations [*Engavale et al.*, P14]. These authors have related the maximum deviation of the disturbed drifts from the quiet time pattern, with an empirical measure of the Joule energy input at high latitudes for different magnetic storms, to estimate the time delay required to produce the maximum disturbance dynamo effect in the nighttime equatorial ionosphere.

8. Mesospheric Lower Thermospheric (MLT) region

Observations of migrating atmospheric tides over the low-latitude station Trivandrum (8.5°N) using a meteor radar have been reported by *Deepa et al.* (PI3) and *Kumar et al.* (PI5). Absorption of solar IR and UV radiations by tropospheric water vapour and stratospheric ozone respectively is the primary driver of such tides. The tidal characteristics such as amplitudes of diurnal, semi-diurnal, and terdiurnal tides show significant seasonal variation as also signatures of coupling with semi-annual oscillations [*Deepa et al.*, PI3]. Wavelet analysis of the amplitudes also shows tidal variability on a time scale of 20-30 days, which has been attributed to solar activity by *Kumar et al.* (PI5).

9. Future missions

It is proposed to mount the Atmosphere-Space Interactions Monitor (ASIM), which is a suite of instruments including several optical cameras and photometers for viewing towards the limb as well as the nadir, and an X-ray sensor, on an external platform on the International Space Station [*Neubert et al.*, FM5]. This mission is expected to enhance the limited knowledge we have of the MLT region, which is too low for in-situ spacecraft observations and beyond the reach of balloon observations. Major scientific objectives for ASIM are: (1) studies of the coupling of thunderstorm-driven processes such as sprites, jets, elves, and relativistic electron beams, to the upper atmosphere, ionosphere, and magnetosphere; (2) investigation of the effects of lightning-induced precipitation of radiation belt electrons on the mesosphere and thermosphere.

Another future mission that would considerably enhance our knowledge of the ionosphere-thermosphere system is the *Swarm* mission, identified by ESA as a European contribution to ILWS [*Lühr and Liu*, I4]. This mission, with a constellation of three satellites carrying a complementary suite of instruments, would help in resolving the spatio-temporal ambiguity which plagues single satellite measurements.

10. Conclusion

In recent years, there has been a great deal of interest in 'space weather' related issues within the geospace community. Effects of solar variability on the ionosphere-thermosphere-mesosphere form an important component of 'space weather'. The global nature of these effects calls for international collaborations as envisaged in international programs such as ILWS, IHY, and CAWSES (Climate and Weather of the Sun-Earth System). This workshop provided a platform to bring together scientists from the three broad areas represented by the three working groups for exchanging new ideas across disciplines. The working group on ionosphere- thermosphere-mesosphere contributed to this effort through a number of topical presentations.