Chapter III

Seeding Perturbations for Equatorial Spread F

3.1. Introduction

One of the most complex phenomena of the nighttime equatorial ionosphere is Equatorial Spread F (ESF). ESF involves a hierarchy of instabilities, one providing base for the other, thereby resulting in the generation of plasma density irregularities over a wide range of scale sizes. ESF takes its name from the spread observed in the ionograms recorded at stations near the dip equator. This phenomenon was first reported by Booker and Wells [1938], who observed some ‘diffusive echoes’ from the F-region in the ionogram traces from the Huancayo (12°S; 75°W; dip latitude 0.6°S) Ionosonde. The ionogram traces, as the Ionosonde frequency was changed showed a range of virtual heights, as if the echoing region was spread over a range of altitudes (range spread). At times, the spread showed only at the high frequency end and looked more like a spread in the frequency for a given virtual height (frequency spread). Apart from the observations as spread in ionograms, it is known that ESF manifests itself in the form of plumes in HF and VHF backscatter radars [Woodman and LaHoz, 1976; Rastogi and Woodman, 1978; Patra et al., 1997; Hysell and Burcham, 1998; Tiwari et al., 2004], intensity bite outs in thermospheric airglow [Mendillo and Baumgardner, 1982], depletions in the plasma densities (or bubbles) in the in situ satellite and rocket measurements [Rino et al., 1981; Laakso et al., 1995], and also as scintillations in VHF and UHF satellite beacon receivers [Krishnamoorthy et al., 1979; Rastogi et al., 1981; Tsunoda, 1985; Basu et al., 1996; Rama Rao et al., 2006a].

There are three fundamental aspects to be addressed to, with regard to the ESF phenomena. The first one is its occurrence itself, the second one being its duration once it gets triggered and the third aspect would be its intensity. The aspect of ESF triggering, largely depend on the background electrodynamic and neutral dynamical conditions in the F-region, which is explained in detail in the next section. The importance of ambient Ionospheric/Thermospheric conditions in the initiation and non-linear development of ESF and its dynamics is well recognized [Hanson et al., 1986; Sekar and Kelley, 1998]. However, one of the unaddressed problems is the day-to-day variability of ESF occurrence. To address this problem, the approach all along had been to examine the physical processes
described by the various terms in the R-T growth rate equation. In most of the earlier studies, it has inherently been assumed that the seed perturbation was omnipresent.

In this context, the present study deals with the identification of the seed perturbations for ESF through the unique dayglow measurements made using the Multi Wavelength Dayglow PhotoMeter (MWDPM) from the magnetic equatorial location of Trivandrum (8.5°N; 77°E; dip latitude 0.5°N) in India.

3.2. Generation mechanism of ESF

As explained in Chapter 1, the primary generation mechanism for the ESF irregularities is the Collisional Rayleigh-Taylor instability (CRT) operating in the bottomside of the F-region [Haerendel, 1973; Hysell and Kudeki, 2004], followed by a hierarchy of other instabilities. A detailed description of the R-T instability is given in Chapter 1. The generalized growth rate of the R-T instability is given by [Sekar and Raghavarao, 1987; Kelley, 1989]:

\[
\gamma = \frac{1}{L} \left[ \frac{g}{\nu_{in}} + \frac{E}{B} + W_x \left( \frac{\nu_{in}}{\Omega_i} \right) - W_z \right]
\]  

(3.1)

where \( L \) is the plasma scale length, \( g \) is the acceleration due to gravity, \( \nu_{in} \) is the ion-neutral collision frequency, \( E \) is the zonal electric field in the F-region, \( B \) is the geomagnetic field, \( W_x \) and \( W_z \) are the zonal and vertical winds respectively and \( \Omega_i \) is the ion gyro-frequency.

The generalized R-T instability involves driving forces such as gravity [Haerendel, 1973], electric fields [Hanson et al., 1986], zonal winds in the presence of tilted ionosphere [Kelley et al., 1981] and vertical winds [Sekar and Raghavarao, 1987].

It is now fairly well established that in the presence of an initial perturbation, the vertical electron density gradient through its plasma scale length \( L \), and the base height of the F-region (essentially through the \( \nu_{in} \)) are extremely important for the instability to get triggered. Also, it is very clear from equation (3.1) that the occurrence/non-occurrence of ESF is controlled by a large number of factors, thereby making it a many body problem. The following section describes the various terms in the R-T growth rate equation.

3.2.1. Factors affecting the local growth rate of the R-T instability

The present understanding of the generation mechanism of ESF is summarized in figure 3.1.
Figure 3.1: A schematic representation of the electrodynamic/neutral dynamic processes playing roles in the instability mechanism leading to the generation of equatorial spread F. $U_x$ and $\Delta U_x$ are the thermospheric wind and its longitudinal/local time gradients respectively. $\nabla . E E J$ is the electrojet convergence at sunset; $\Sigma_p$ and $\Delta \Sigma_p$ are the integrated Pedersen conductivity and its longitudinal gradient at sunset. $\Delta n/n$ is the inverse of the bottomside density gradient scale length and $\Delta n_i/n_i$ is the inverse of the longitudinal scale length of the electron density.

The gravity term in equation (3.1) is inversely dependent on $v_{in}$ and thus increases with the height gaining importance over the height independent electric field term around 350 km at the F layer bottomside [Kelley, 1989]. Thus, an initial post sunset layer uplift by an eastward electric field is necessary for the gravity term to take over an instability process initiated by the very same eastward electric field. This electric field, that is, the evening prereversal enhancement (indicated as PRE in Fig. 3.1) is believed to be produced by the action of the eastward thermospheric wind, $U_x$ and its longitude gradient $\Delta U_x$, on the integrated Pedersen conductivity longitudinal gradient that exists across the sunset terminator. The exact mechanism for the post sunset F-layer uplift i.e. whether it is due to the F-region dynamo electric fields getting freed from the field line E-region loading effect [Farley et al., 1986] or due to the irrotational nature of the electric field at the sunset terminator manifesting itself as an enhanced zonal wind [Rishbeth, 1981] or due to the
evening Equatorial Electrojet [Haerendel et al., 1992] is still not fully understood. There are experimental evidences for the first two mechanisms to be operating with nearly comparable effects [Sridharan et al., 2002]. However, whatever be the mechanism, the fact is that the F-layer during the post sunset hours gets lifted up, the magnitude of which may vary from day-to-day, thereby providing conducive conditions for the triggering of the primary R-T instability, in the presence of an initial perturbation [Kelley and Maruyama, 1992].

While studying the effect of the neutral winds and background Pedersen conductivity on the non-linear development of the R-T instability leading to spread F, Zalesak et al. [1982] have shown that the plasma away from the equatorial plane makes a finite contribution to the magnetic field line integrated Pedersen conductivity, thus causing an incomplete coupling of the plasma motion to the neutral wind. Also, simulations without the neutral wind revealed that the E-region Pedersen conductivity effects can result in a slowing down of ESF and bubble formation. This highlighted the role of neutral winds in the generation and evolution of ESF. Thus, the growth rate is also controlled by the neutral winds (both zonal and vertical), with an opposing gradient enhancing the growth rate. The zonal wind is important in the presence of a zonal electron density gradient, which is the case during the sunset hours. Further, it is the same zonal wind that causes the activation of the F-region dynamo in conjunction with the north-south magnetic field, thereby leading to PRE and the subsequent post sunset uplift of the F layer [Kelley, 1989]. The in situ measurements and theoretical simulations have shown that in addition to the zonal winds, the vertical winds also play a major role in triggering ESF [Sekar et al., 1994]. Sekar and Raghavarao [1987] have shown that the vertical wind needed to destabilize the plasma density at F-region altitudes is only few meters per second. Sultan [1996] showed that for a realistic estimation of the R-T growth rate, the flux tube integrated Pedersen conductivity extending from the F-region to the E-region should also be taken into account. The non-linear evolution of plasma bubbles in the equatorial ionosphere was also studied using the magnetic-flux-tube integrated model [Keskinen et al., 1998].

Another important contributor to the winds over the dip equator would be the presence of the Equatorial Temperature and Wind Anomaly (ETWA), explained in detail in Chapter 1. Using the DE-2 satellite, Raghavarao et al. [1993] observed vertical neutral winds that are upward (downward) at the crests (trough) of Equatorial Ionization Anomaly (EIA), which can be explained as possibly due to the setting up of a meridional circulation.
cell in association with ETWA. They proposed a new wind system, with the wind velocity vector being upward at the crests, equatorward between the crests and downward at the trough with the return flow somewhere in the dynamo region. The ground based measurements of the winds [Biondi and Sipler, 1985] broadly seem to agree with the above proposed mechanism. The existence of such a wind system has important implications in the context of ESF occurrence, since equatorward converging winds over the dip equator would appear as vertical winds in the growth rate equation, thereby enhancing the growth rate.

The F layer bottom side density gradient, shown as $\Delta n/n$ in Fig. 3.1, is another important factor that controls the growth rate of the R-T instability. The latter is controlled by the north-south symmetry/asymmetry conditions in the ionization distribution of the EIA produced by a meridional transequatorial wind. Maruyama [1988] and Mendillo et al. [1992] studied the effects of the meridional winds (trans-equatorial) on the ESF occurrence. They showed that a poleward wind would inhibit ESF by pushing the ionization along the field lines to the E-region. The increased conductivity in the E-region loads the F-region dynamo, thereby opposing the upliftment of the base of the F-region to greater heights and thus inhibiting the ESF occurrence. However, it was later shown by Devasia et al. [2002] that over the equatorial location of Trivandrum, the polarity (equatorward/poleward) and magnitude of the meridional winds play a significant role only when the maximum height of the post sunset F-layer ($h'F$) is below a critical height. Above the critical height, the polarity of the winds doesn't seem to have any role.

From the above discussions, it is very clear that the occurrence/non-occurrence of ESF on a particular day is essentially controlled by a large number of background electrodynamical and neutral dynamical factors. The statistical occurrence pattern of ESF is well understood [Aarons, 1993; Abdu, 2001]. However, the enigmatic day-to-day variability presents challenge to the complete understanding of this phenomenon. For instance, under seemingly identical conditions in a given season within a solar epoch, ESF might occur on one night and might be absent on another.

In the past, there had been several attempts to forecast the occurrence of ESF. The first indication of a significant role of EIA intensification in the ESF generation was shown by Raghavarao et al. [1988]. It was shown by them that the ratio of the electron densities at fixed heights of 270 and 300 km, between a location under the EIA crest-Ahmedabad
(23°N; 72.6°E; dip latitude 18.6°N) and a location between the crest and trough of EIA-Waltair (17.4°N; 83.3°E; dip latitude 10.6°N) showed an increase by a factor of 8 to 30 at ~1830 LT only on the ESF days. This suggested that the strength of the EIA in the day and evening hours could be an important parameter for the ESF generation. Sridharan et al. [1994] followed it up and demonstrated that there existed a precursor for ESF in the OI 630.0 nm dayglow intensities obtained from a dayglow photometer located at Waltair. The time variation of the dayglow intensity represented the evolution of EIA and the estimated strength of the EIA revealed significant differences in the EIA contribution to the dayglow intensities on the ESF and non-ESF days. This study enabled the prediction of ESF atleast 3 hours (1600 LT) prior to its actual occurrence, thus again pointing towards the significant control of the daytime EIA in triggering the post sunset ESF. Devasia et al. [2002] provided the missing link between EIA and ESF through meridional winds. It was suggested that the equatorward winds observed on the ESF days could be the outcome of the pressure bulges associated with ETWA [Raghavarao et al., 1993].

Mendillo et al. [2001] using 13 days of data from the Multi-Instrumented Studies of Equatorial Thermospheric Aeronomy (MISETA) campaign of September 1998, showed that the best available precursor for premidnight ESF is the strength of the EIA pattern at sunset and 85% successful forecasts had been achieved. It was shown by them that if the required seeding perturbation for ESF onset was essentially assumed to be omnipresent, then the magnitude of the eastward electric field that causes the upward drift was both the necessary and sufficient parameter to forecast the onset of ESF with reasonable success. Anderson et al. [2004] also demonstrated that the necessary and sufficient condition before bottomside spread F can percolate upward and form equatorial bubbles was the \( \mathbf{E} \times \mathbf{B} \) drift to be above a threshold value and that the seeding mechanism was always present. Using the latitudinal distribution of Total Electron Content (TEC) measurements at 2000 LT, Valladares et al. [2001] showed that a high crest to trough ratio was prevalent on the ESF days. Thampi et al. [2006], in their attempt to predict the occurrence of ESF based on the background ionospheric conditions were successful to a level of >95%, by defining a critical ionospheric parameter. They had indicated that 100% deterministic prediction would be possible if additional inputs on the seed perturbations were also available and this would be extremely crucial for operational forecasting purposes.
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Thus, it is clear that in addition to ambient Ionosphere/Thermosphere conditions, there is very likely an additional random factor in the occurrence of ESF which might hinder the attempts to develop the predictive capability. This stems from the ability of internal gravity waves to organize the equatorial plasma into high and low density regions with the same horizontal wavelength as the gravity wave. Once such a perturbation occurs, the generalized R-T instability can take over and cause the oscillation to grow. Thus, the wave can act as a seed for the instability and greatly decrease the time needed to develop a large amplitude disturbance. The nature and role of the seeding perturbations in triggering ESF is described in the following section.

3.3. Seeding Perturbations for ESF

The nature of the seed perturbations for ESF is widely believed to be gravity waves [Kelley et al., 1981], but their precise sources, variabilities therein and their deterministic role is still unknown and least explored. It was Whitehead [1971] who first proposed that gravity waves can produce large-amplitude ionospheric irregularities, when the phase speed of the waves becomes equal to the drift speed of ionization, known as spatial resonance mechanism. Rottger [1973, 1976, 1978] presented using the RTI maps, from the Jicamarca (12°S; 76.9°W; dip latitude 1°N) coherent scatter radar, the observations of large scale wavelike structures of the F-region irregularities and suggested that these wavelike structures were produced by gravity waves at spatial resonance. Klostermeyer [1978] made a nonlinear calculation of the spatial resonance effect and concluded that the gravity waves could organize the F layer plasma into large-scale horizontally modulated contours, thus indicating a possible connection among spatial resonance and ESF.

Kelley et al. [1981], using the Jicamarca radar backscatter maps for several consecutive nights in March 1979, showed the gravity wave modulation of large scale plumes and argued that gravity waves were capable of seeding ESF via the spatial resonance mechanism. Furthermore, the growth from ion density variations due to thermal fluctuations may not account for the observed rapid development of the bubbles after sunset, owing to the smaller growth rate (~10^{-4} \text{ s}^{-1}) of the R-T instability. Tsunoda and White [1981], using east-west scans of the ALTAIR backscatter radar, observed that electron density contours in the bottomside F-layer were altitude modulated over regions as large as 1200 km in the east-west direction with an average east-west wavelength of about 400 km, a wavelength similar to that found by Rottger [1973] for ESF patches. The
observations of seeding and layering of ESF by gravity waves was also reported by Hysell et al. [1990]. All these researchers suggest that the relation between the gravity waves and spread F is that the gravity waves initiate the R-T instability via spatial resonance, then the instability grows and amplifies the initial perturbations and finally the plasma bubbles and spread F result.

In the numerical simulations of the nonlinear evolution of the R-T instability [Scannapieco and Ossakow, 1976; Zalesak et al., 1982; Sekar et al., 1994; Keskinen et al., 2003], the initial perturbations were taken to be horizontal with roughly of 5% amplitudes.

An analytic theory for the gravity wave seeding of the R-T instability was proposed by Huang et al. [1993], wherein they showed that the instability initiated by large-amplitude long-wavelength gravity waves can grow to substantial amplitudes as is observed in nature. Further, they showed that the gravity waves can initiate the instability mainly in the nighttime and seem unlikely to do so during the daytime because of the existence of the highly conducting E-region. The nonlinear evolution of ESF under different conditions with the gravity waves as seed perturbations was studied by Huang and Kelley [1996a, b, c and d]. They studied the evolution of ESF for different parameters of the seeding gravity waves like amplitude, wavelength, timing and also its propagation direction. The values of the seed waves used in the simulations were: vertical velocity of few meters per second, horizontal wavelength of several hundred kilometers and vertical wavelength of few tens of kilometers. These values are reasonable for the F-region gravity waves. The observed ESF irregularities often manifest clear periodic structures with horizontal scale size of a few hundred kilometers. There is no other geophysical disturbance known with horizontal wavelength of a few hundred kilometers in the F-region except the gravity waves. The different ways in which the gravity waves at F layer heights can influence the ESF development can be stated as:

1) Modulation of the dusk time F layer heights through large undulations in electron density iso-lines whereby the elevated bottomside density gradient regions will become unstable to generalized R-T instability. An example for this is present in the events analyzed by Kelley et al. [1981].

2) Modulation of the PRE by having its peak intensity enhanced by in-phase superposition of zonal (eastward) winds from the background thermospheric tidal source and perturbation zonal winds due to gravity waves. Such an increase in the PRE amplitude can contribute to an enhanced gradient drift instability growth rate.
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factor besides lifting the F layer to greater heights where the gravitational R-T growth rate factor is enhanced as well. The zonal perturbation velocity of the gravity wave at sunset could also contribute a factor to the instability growth, as discussed by Kudeki et al. [2007].

3) Direct seeding of the instability by gravity waves providing the density perturbations/undulations and the development of the polarization electric fields that grow with the density perturbations, constituting the instability growth process. The gravity wave zonal and vertical winds contribute directly to the polarization electric field that feeds the instability growth. Example of this is presented by Abdu et al. [2009] and Kherani et al. [2009].

The first in situ evidence for the presence of wavelike ion density structures that could serve as a seed for the development of plasma bubbles, was shown by Singh et al. [1997], using the data from the Atmosphere Explorer E (AE-E) satellite. McClure et al. [1998] used a comprehensive analysis, based on the data from the AE-E satellite, to present the seasonal and longitudinal variations in the equatorial F-region irregularity occurrence probability. They also proposed that, given favorable background ionospheric conditions, the presence/absence of gravity waves would determine if ESF would occur or not on a given night.

Meriwether et al. [1986], Biondi et al. [1991] and Mendillo et al. [1992] had suggested that the thermospheric dynamics also play an important role in the onset of ESF. The first simultaneous ground-based multispectral optical observations of the F-region and the mesosphere, along with the thermospheric neutral winds, from a low-latitude station, Cachoeira Paulista (23°S; 45°W; dip latitude 16°S), in Brazil were analyzed by Fagundes et al. [1995] to study the role of seed perturbations in triggering ESF. The nocturnal intensity variations of the simultaneous F-region nightglow emissions and the mesospheric emissions showed the presence of gravity waves, which indicates the possibility of common sources, for both seed perturbations in the F-region and the wave disturbances in the mesospheric region. Kudeki et al. [1999] also presented the evidence for strong thermospheric gravity waves propagating in the equatorial ionosphere.

From all these, the role of gravity waves in the generation of ESF become very clear. However, there are three conditions required for the gravity waves to effectively act as seeds for ESF. These are (1) wave penetration to altitudes at which seeding occur, (2)
sufficient wave amplitudes at seeding altitudes to trigger R-T instability and ESF on time scales consistent with the observed events, and (3) phase speeds that can yield the resonance conditions suggested for successful coupling of wave and plasma processes [Hysell et al., 1990; Huang and Kelley, 1996a, b]. Vadas and Fritts [2004] have shown that the gravity waves arising from the mesoscale convective complexes (MCC) and having sufficiently large vertical wavelengths and group velocities above the shears at lower altitudes can penetrate to altitudes of ~200 km at the magnetic equator or lower altitudes for magnetic latitudes up to ±20°, thus satisfying the first of the three requirements. Their results also show that the wave amplitudes may be sufficiently large for seeding ESF and that, on occasions, wave phase speeds and plasma drifts are sufficiently aligned to satisfy the spatial resonance conditions believed to be required for seeding ESF. Thus, all the conditions required for the gravity waves to act as seeds for ESF are satisfied.

Therefore, it seems that gravity waves are the most possible candidate to act as seeds for ESF. The present study investigates the first condition required for the gravity waves to effectively act as seeds for ESF and provides the first observational evidence from the Indian longitude sector for the presence of gravity wavelike seed perturbations in ESF generation.

3.4. Database used in the Present Study

The daytime airglow intensity measurements were made using the MWDPM at O\(^{(1D)}\) 630.0 nm and on two rotational lines at 731.6 and 740.2 nm in the OH Meinel (8-3) band from Trivandrum during the solar maximum year of 2001 and the solar minimum year of 2006. The main objectives had been to detect the presence of wavelike perturbations well before the occurrence of ESF and to identify the possible source regions through multiple airglow emissions originating at different altitude regions. The measurements for the zenithal sky were made between 0800 hours and local sunset (1800 hours). The thermospheric O\(^{(1D)}\) 630.0 nm emissions are typically centered at ~220 km [Hays et al., 1988]. The daytime OH emission intensity measurements were used to estimate the mesopause temperature, the method of which is described in detail in Chapter 2. These mesopause temperatures have already been compared and validated with the insitu WINDII satellite measured temperature and also with a collocated meteor wind radar measured temperature in the Indian region [Vineeth et al., 2005].
As the dayglow measurements are restricted to only clear sky conditions, the data length and continuity are rather restricted, with extensive cloud cover over Trivandrum, which is a tropical station. With the onset of the Indian monsoon, the airglow data collection becomes rather difficult. In this context, uninterrupted data are available only in the northern hemispheric winter/equinoctial months (December-March). Information on the occurrence of ESF and the post sunset ionospheric F-layer bottom height (h'F) at every 15 minutes interval is obtained using a collocated Ionosonde. The working principle of the Ionosonde is described in detail in Chapter 2.

3.5. Observations of the Seed Perturbations

The typical temporal variations of the thermospheric O(^1D) 630.0 nm dayglow emissions on few days during 2001 is shown in the different panels of figure 3.2.

![Figure 3.2: Typical temporal variation of daytime O(^1D) 630.0 nm thermospheric dayglow emissions over Trivandrum on different days during the year 2001.](image)

It is quite evident from Fig. 3.2 that within a solar epoch, the dayglow emissions exhibit large day-to-day variability in the overall maximum intensity level. For instance, the maximum intensity level reached on Feb 07, 2001 is about $1 \times 10^5$ arbitrary units and that on March 13, 2001 is $3 \times 10^5$ arbitrary units, almost 3 times larger. There also seems to be the presence of some small-scale periodicities (<2 hours) during the evening hours. The presence of the periodicities are observed more clearly in the ratio $I'/I$, where $I'$ are the
perturbations and I is the background 630.0 nm emission intensity. The time variation in the ratio I'/I during three days of 2001 is shown in figure 3.3.

The presence of short scale periodicities during the late evening hours (around 17:00 IST) is clearly observed on the days shown in Fig.3.3 and the amplitude of the periodicities show considerable day-to-day variation. It is also observed that on March 13, 2001, perturbations are present even during the daytime (11:00-12:00 IST). However, as explained earlier, these perturbations cannot trigger the R-T instability during the daytime because of the highly conducting E-region.

![Figure 3.3: Temporal variation of the ratio I'/I over Trivandrum on different days during the year 2001.](image)

In order to find the dominant periodicities present, the ‘Morlet’ wavelet analysis [Torrence and Compo, 1998] is performed on each time series of the ratio I'/I on all available days of 2001. Emphasis is given to periodicities less than 2 hours. From the wavelet analysis performed, it is found invariably that on all the days, a dominant periodicity of around 20-30 minutes (with >95% significance level) is present with varying amplitude. Table 3.1 illustrate the maximum amplitude of the 20-30 minutes periodicity observed on the different days of 2001, along with the maximum post sunset bottom height of the F-layer (h’F).
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It is clear from table 3.1 that each day of the year 2001 is characterized by a different $h'$F and also the amplitude of the 20-30 minutes periodicity exhibits large day-to-day variability. A similar analysis performed for the solar minimum year of 2006 yielded identical results. The waves with period of 20-30 minutes correspond to the gravity waves and it is well known that the gravity waves act as seeds for ESF. Therefore, to find if these waves thus obtained, with 20-30 minutes periodicity indeed act as seeds for ESF, days with identical background ionospheric conditions within a solar epoch are compared.

**Table 3.1:** Variation in the maximum amplitude of the 20-30 minutes periodicity along with the maximum post sunset bottom height of the F-layer ($h'$F) during the year 2001.

<table>
<thead>
<tr>
<th>Date</th>
<th>Maximum amplitude of the 20-30 minutes periodicity</th>
<th>Maximum h'$F'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 07/2001</td>
<td>0.01244</td>
<td>348.2</td>
</tr>
<tr>
<td>Feb 10/2001</td>
<td>0.13783</td>
<td>400</td>
</tr>
<tr>
<td>Feb 12/2001</td>
<td>0.00392</td>
<td>350</td>
</tr>
<tr>
<td>Feb 14/2001</td>
<td>2.69795</td>
<td>348.2</td>
</tr>
<tr>
<td>Feb 15/2001</td>
<td>0.00208</td>
<td>316.1</td>
</tr>
<tr>
<td>Feb 17/2001</td>
<td>0.01165</td>
<td>373.2</td>
</tr>
<tr>
<td>Feb 28/2001</td>
<td>0.00726</td>
<td>421.4</td>
</tr>
<tr>
<td>March 01/2001</td>
<td>0.00217</td>
<td>378.6</td>
</tr>
<tr>
<td>March 02/2001</td>
<td>0.02581</td>
<td>392.9</td>
</tr>
<tr>
<td>March 04/2001</td>
<td>0.00301</td>
<td>371.4</td>
</tr>
<tr>
<td>March 05/2001</td>
<td>0.41406</td>
<td>373.2</td>
</tr>
<tr>
<td>March 06/2001</td>
<td>1.62628</td>
<td>382.1</td>
</tr>
<tr>
<td>March 08/2001</td>
<td>0.01566</td>
<td>425</td>
</tr>
<tr>
<td>March 09/2001</td>
<td>0.38295</td>
<td>378.6</td>
</tr>
<tr>
<td>March 13/2001</td>
<td>1.51036</td>
<td>371.4</td>
</tr>
<tr>
<td>March 14/2001</td>
<td>2.07075</td>
<td>371.4</td>
</tr>
<tr>
<td>March 15/2001</td>
<td>0.03701</td>
<td>319.6</td>
</tr>
</tbody>
</table>

The equinoctial months of 2001 are characterized by the occurrence of ESF on almost all the days in the Indian longitudes, whereas during the equinoctial months of 2006, its occurrence is significantly less. Since ESF is a multi-dimensional problem, the effect of seed perturbations can be studied only if we have days of ESF and non-ESF under nearly identical background ionospheric conditions with nearly the same base height. It's very difficult to get a large number of days satisfying this condition, which limits the database used in this study. Nevertheless, the results obtained from this case study, even with this limited database, make them relevant, important and unique.
Figures 3.4 & 3.5 represent the wavelet periodogram of the ratio $I'/I$ during 2001 and 2006 respectively. The top and the middle panels in Fig. 3.4 are for the two ESF days (March 13 & 14) and the bottom panel (March 04) is for a non-ESF day. In Fig. 3.5, the top panel represents an ESF day (March 03) and the bottom panel (March 09) a non-ESF day. The colorbar indicates the amplitude of the various periodicities in arbitrary units. The maximum $h'F$ before the onset of ESF and the onset time of ESF are shown in the parenthesis.

It is clear from Figs. 3.4 & 3.5 that the background ionospheric conditions on the three days during 2001 and for the two days during 2006 are identical, as shown by the $h'F$ values. Having ascertained that the background conditions are the same, the other two parameters, which could play a role in the day-to-day variability of ESF occurrence, are the polarity of the meridional winds and the presence/absence of the seed perturbations. Manju et al. [2007] have shown that, during the equinoctial months, the threshold height below which the polarity of the meridional winds is important for the generation of ESF irregularities is ~314 km for the solar maximum year and ~225 km for the solar minimum year. For the days presented in Figs. 3.4 & 3.5, $h'F$ is much above this threshold height, which means that the polarity of the meridional winds would not have any role. So the occurrence/non-occurrence of ESF can now be construed to be determined, to a significant extent, by the presence/absence of the seed perturbation.

From Fig. 3.4, representing three days of 2001, it is clear that a dominant periodicity of 20-30 minutes gets enhanced during the late evening hours (17:30-18:00 IST). The amplitude of this periodicity is ~2 on the ESF days, but on the non-ESF day, the amplitude is ~0.1 (20 times smaller as compared to that on the ESF days). In Fig. 3.5, the periodicity of 20-30 minutes during 2006 is observed on the ESF day, with amplitude of ~0.1. On the non-ESF day, the amplitude is only ~0.05 (a factor of 2 smaller compared to the ESF day). A comparison between the amplitude of the 20-30 minutes periodicity on the two ESF days during 2001 and one day of 2006 shows that it is higher by a factor of ~20 during 2001. It is to be noted that during the solar maximum year presented, an amplitude of ~0.1 is not sufficient to trigger ESF. Whereas, during the solar minimum year presented, this amplitude is found to be sufficient to trigger ESF, implying that the amplitude of the waves required for the irregularity generation shows considerable variation with the solar activity.
Figure 3.4: Wavelet periodogram of the ratio $I'/I$ for $<2$ hr periodicity on ESF days (top and middle panels) and a non-ESF day (bottom panel) during the solar maximum year of 2001. The numbers in the parenthesis indicates the maximum post sunset $h'F$ and the onset time of ESF. The colorbar indicate the amplitude of the periodicities in arbitrary units.

Figure 3.5: Same as for figure 3.4, but for the solar minimum year of 2006.
The significant differences in the amplitude of the seed perturbations, especially during different solar activity levels, are as per the expectations based on the background Ionosphere-Thermosphere conditions which in turn have large solar cycle dependence. The O(\(^{1}\)D) 630.0 nm dayglow emission is confined to the altitude region of 220±30 km [Hays et al., 1988]. As a consequence of the significant increase in both the neutral and plasma densities in a given altitude region with solar activity, the stabilizing factors mainly the ion-neutral collision frequency dominate the instability process thus requiring larger amplitude perturbations so as to trigger the instability. The results from the present study clearly bring out the fact that the perturbation amplitudes that could trigger the instability during low sunspot years are grossly inadequate during high sunspot years and even amplitudes larger by a factor of two would not suffice. Typically, the amplitudes required to trigger the instability during solar maximum conditions are larger by a factor of 20 compared to the solar minimum conditions. Such large amplitude requirements in the initial perturbation are suggested to be mainly due to the large increase in the background Ionospheric/Thermospheric densities.

When it comes to the source region of the perturbation, especially while ascertaining whether they are insitu generated or propagated from below, simultaneous monitoring of parameters at different altitudes becomes handy. The time variation in the mesopause temperature data for the three days during 2001 and for the two days during 2006 is shown in figures 3.6 (a) & (b).

*Figure 3.6(a): Temporal variation of daytime mesopause temperature over Trivandrum on different days during the year 2001.*
It is clear from Figs. 3.6 (a) & (b) that the mesopause temperature exhibits large day-to-day variability within a solar epoch. During 2001 (Fig. 3.6(a)), the temperature varies between 160 K and 190 K, whereas during 2006 (Fig. 3.6(b)), the temperature variation is between 180 K and 210 K. There also seems to be the presence of short scale periodicities (<2 hours) during the evening hours on March 13 and March 14 of the year 2001, but such a periodicity seems to be absent on March 04, 2001. Similarly, on March 03, 2006, there seems to be the presence of short scale (<2 hours) periodicity during the evening hours.

To find the dominant periodicities present, the mesopause temperature variations are also subjected to a similar wavelet analysis in order to check whether waves/perturbations similar to the O(1D) 630.0 nm dayglow intensity are present in it or not. The periodogram of the mesopause temperature data for the same days of 2001 and 2006 are shown in figures 3.7 & 3.8 respectively. The colorbar indicates the amplitude of the periodicities in degree K.

From Fig. 3.7, it is clear that a dominant periodicity of 20-30 minutes (with >95% significance level) gets enhanced during the evening hours on the two ESF days of 2001 with an amplitude of ~1.5 K, whereas such a periodicity is conspicuously absent on the non-ESF day. Fig. 3.8 illustrates the wavelet periodogram for the two days during 2006, with the top panel representing ESF day and the bottom panel a non-ESF day. The mesopause temperature in 2006 showed the presence of higher periodicities as well. The 20-30 minutes periodicity although present on the ESF day, with a power of ~0.6 K, does not come out clearly as in the case of the solar maximum year.
Figure 3.7: Wavelet periodogram of the mesopause temperature for <2 hr periodicity for the same days as shown in Figure 3.4. The numbers in the parenthesis indicates the maximum post sunset h'F and the onset time of ESF. The colorbar indicate the amplitude of the periodicities in degree Kelvin (K).

Figure 3.8: Same as for figure 3.7 and for the days given in Figure 3.5.
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It can be noted from Figs. 3.7 & 3.8 that there is an increased gravity wave activity at the mesospheric altitudes around 12:00-13:00 IST, but simultaneously, there is no gravity wave activity at the thermospheric region (Figs. 3.4 & 3.5). Mesopause is the region which exhibits significant variability not just temporally but spatially also. Theoretically, a range of periodicities can be present in the mesosphere and below. However only certain wave modes can reach the mesospheric and thermospheric heights as a result of wave mean-flow, wave-wave and wave-tidal interactions during the upward propagation of the waves. In this context, the appearance of increased wave-activity in the mesopause around 12:00-13:00 IST can be construed to be the result of wave-tidal interactions, as some of the tidal modes maximize in the Mesosphere Lower Thermosphere Ionosphere (MLTI) region around this time. Studies using rocket based chemical and vapour release experiments, have clearly shown the presence of very large wind shears existing in the lower thermosphere, which also showed significant temporal variability [Raghavarao et al., 1987; Larsen et al. 2005]. As is known, these strong wind shears can lead to the dissipation of the upward propagating waves. Therefore, there can be times when waves observed in the mesopause region may not be observed in the thermosphere.

The presence of gravity wavelike perturbations with 20-30 minutes periodicity simultaneously in the mesopause temperature and in the intensity of the thermospheric O(1D) 630.0 nm dayglow emissions suggest that they could have originated lower below and propagated to the thermosphere. It is also observed that the amplitude of the seeding perturbations have a control on the ESF irregularity generation, while bringing out distinctly different requirements for the solar maximum and minimum conditions. The most important outcome of the present study is that it provides the first observational evidence for the presence of gravity wavelike perturbations, serving as seeds for ESF. Even with the limited database, the study clearly brings out that given identical ionospheric conditions within a solar epoch, the amplitude of the gravity wavelike perturbations controls the triggering of ESF.

3.6. Discussion

Although gravity waves are known to act as seeds for the ESF, the unresolved questions related to the seed perturbation could be stated as: (1) possibility of insitu generation of the gravity waves through (a) motion of the solar terminator across the lower thermosphere, (b) evening F layer rise permitting zonal wind acceleration and associated
strong vertical shear [Anderson et al., 1982], and (c) deposition of momentum at \( z \approx 180 \) km from the dissipation of gravity waves from the lower atmosphere [Vadas and Fritts, 2006].

2. Remote sources such as tropospheric convection activity that could produce upward propagating gravity waves [Rottger, 1981, Larsen and Swartz, 1982; Lane et al., 2003].

Gravity waves produce turbulence by depositing their energy and momentum through breaking, thereby influencing the general circulation, thermal regime and composition of the middle atmosphere [Fritts and Alexander, 2003]. The condition of vertical propagation and dissipation of the waves depends on the wave characteristics (wavelength and phase velocity) and the filtering by the background wind system. However, short period gravity waves generated by convective storms have the potential to influence regions extending even up to mesospheric altitudes, as had been demonstrated through numerical simulations [Alexander et al., 1995]. Recently, Ogawa et al. [2006] compared ionospheric scintillations and Earth's black body temperatures over the Indian Ocean and found a correlation between them, indicating a possibility of dynamical coupling from the troposphere to the ionosphere.

Also, the interaction of gravity waves and the tides could influence the F-region through electrodynamical processes. Upward propagating tides over the dip equator are known to significantly influence the background wind in the lower ionosphere, which in turn through the E-region dynamo leads to the generation of the global electric field. The interaction of the tides with the gravity waves are known to modify the amplitude and phase of the tides [Hagan, 2000], which would cause global electric field modulations and vice versa. Also, any perturbation in the dynamo region away from the equator would get promptly imprinted in the F-region above along the magnetic field lines, thus providing one more means of imprinting the perturbations as seen in the \( \text{O}(^1\text{D}) \) 630.0 nm dayglow [Prakash, 1999; Abdu, 2001].

In the equatorial mesopause region (80 to 100 km), gravity waves with a period of 5 to 30 min, horizontal wavelength of 10 to 100 km, phase velocity of 20-80 m/s, are frequently observed by airglow imaging method [Wrasse et al., 2006]. Some of these waves have a condition to propagate above 100 km, even up to 200 km in the ionosphere [Vadas and Fritts, 2004], where they could lead to the seeding of the R-T instability [Hysell et al., 1990; Fritts et al., 2008; Abdu et al., 2009]. Gravity waves with periods of 30 to 90 minutes have been detected in the mid-latitude thermosphere using the MU radar [Oliver et al., 1994]. Vadas [2007] showed that dissipative filtering is the reason that only gravity waves
with periods of 20-60 minutes can propagate well into the thermosphere, consistent with the MU radar observations. The gravity wave penetration to the thermosphere under varying solar activity and mean winds was studied by Fritts and Vadas [2008]. Their results emphasize that independent of the gravity wave source, solar activity (i.e. variations in the thermospheric temperature) and filtering conditions (i.e. mean winds), those gravity waves that penetrate to the highest altitudes have increasing vertical wavelengths and decreasing intrinsic frequencies with increasing altitude. The observed and intrinsic periods were typically ~10 to 60 min and ~10 to 30 min respectively, with the intrinsic periods being shorter at the highest altitudes.

Recently, during the Spread F Experiment Campaign of 2005, carried out in the South American magnetic equatorial region, simultaneous observations of the OH and OI 630.0 nm airglow were made to investigate for any possible relation between the bubble seeding in the ionosphere and the gravity wave activity in the mesosphere. These results, as discussed by Takahashi et al. [2009], show a good correlation between the mesospheric gravity wave horizontal wavelength and the distance of the 630.0 nm depletions, suggesting that the observed ionospheric plasma depletions are strongly related to the mesospheric gravity wave activities, mainly with their horizontal wavelength.

The role of the lower atmosphere dynamical activities (gravity waves, tides and winds) in the ESF triggering is today well discussed. However, very few direct evidences on the ESF seeding by specific dynamical event in the lower atmosphere are available [Fritts et al., 2008; Abdu et al., 2009]. This study provides the first observational evidence for the ESF triggering by the gravity waves, presumably of lower atmospheric origin.

The most critical piece of the observations presented here is that the gravity wavelike perturbations in the OH layer occurs at almost the same time as in the O1(1D) 630.0 nm dayglow intensity, indicating that the waves could be the ones propagating from the lower atmosphere. The simultaneous observation of the gravity waves in the OH layer and in the O1(1D) 630.0 nm dayglow is as expected from the theoretical studies of Vadas and Fritts [2004], since the gravity waves that are observed in the OH layer have vertical group velocities of only 15 ms\(^{-1}\), while those which are able to propagate to the bottomside of the F layer have vertical group velocities of 2 to 3 times that amount, 30-45 ms\(^{-1}\). Therefore, these slower gravity waves propagate from 10 to 90 km in about the same time as the faster waves propagate from 10 to 200 km [Vadas and Fritts, 2004].
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The unique observations through dayglow measurements, well before the occurrence of ESF, reported herein substantiate that the amplitude of the seed perturbations has a significant role in deciding the day-to-day variability of ESF and the subsequent nonlinear evolution of the equatorial plasma bubbles.

3.7. Conclusions

The present chapter reports the study on one of the major phenomena of the Equatorial Ionosphere Thermosphere System, namely ESF. The first observational evidence for the presence of gravity wavelike perturbations acting as seed for ESF irregularities is presented through unique dayglow measurements. These waves are observed simultaneously in the intensity of the thermospheric O(1D) 630.0 nm dayglow emissions and also in the daytime mesopause temperature in the evening hours. The amplitude of the waves shows considerable day-to-day variability and also significant solar activity effect. This is shown to have a control on the generation of ESF, which is a multidimensional problem, determined by the combined effects of the prevailing neutral dynamical (winds and neutral temperature) and electrodynamical conditions. Under nearly identical Ionospheric and Thermospheric conditions within a solar epoch, the generation/inhibition of ESF is conclusively shown to be due to the variability in the seed perturbations presumably originating lower below in the pre dusk hours. The continuous monitoring of the dayglow emissions would therefore take us one step ahead towards understanding the enigmatic problem of the day-to-day variability of ESF occurrence.