Diurnal and seasonal variations in sporadic E-layer (Es layer) occurrences over equatorial, low and mid latitude stations - A comparative study

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The simultaneous hourly ionograms, from an equatorial station Trivandrum (8.47°N, 76.91°E), a low latitude station Waltair (17.70N, 83.3°E) in the Indian sector and a mid latitude station Kokubunji (35.7°N, 139.5°E) in the Japanese sector during the high sunspot year 2001, are scaled for the study of E-region parameters, namely the virtual height of sporadic E-layer (h′Es) and the critical frequency of sporadic E-layer (foEs). The diurnal, seasonal and day-to-day variations in h′Es and foEs are studied for all the three stations. It is observed that the sporadic E-layer is absent in the early morning and post sunset hours over Trivandrum during three different seasons. The values of h′Es are more at Kokubunji as compared to those at equatorial (Trivandrum) and low latitude (Waltair) stations during the three different seasons. The critical frequency of sporadic E-layer (foEs) over Trivandrum shows higher values, compared to those over Waltair and Kokubunji during daytime hours, in three different seasons indicating that foEs decrease as the latitude increases. The seasonal variation in foEs shows higher values during daytime hours of equinox and winter months over equator (Trivandrum) compared to those over low (Waltair) and mid (Kokubunji) latitude stations. The variations in h′Es and foEs for quiet and disturbed conditions indicate that the h′Es variation during quiet days of equinoctial months at Kokubunji shows a primary peak around morning hours while it is absent at Waltair and Trivandrum. Further, the behaviour of blanketing frequency of Es layer fbEs, and foEs−fbEs are also studied.

Keywords: Ionospheric disturbances, Sporadic E-layer, Critical frequency, Blanketing frequency

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1 Introduction

The radio wave communications are often subjected to marked changes in their performance owing to changes in the ionosphere. A few decades ago a worldwide network of vertical incidence sounders were established to measure the ionospheric parameters such as the virtual height and critical frequency of E- and F-layers. The result of this research established that ionized regions exist approximately from 70 to 1000 km above the earth’s surface. At lower altitudes, atoms are more numerous increasing the rate of ionization but at the same time allowing increased rate of recombination. A further mechanism is the absorption of the incident energy, which is a function of the gas density and composition, causing attenuation to increase at lower altitudes. The resultant effect is horizontal stratification of the ionosphere denoted as the D-, E-, and F-Layer. The D-region presence is sun-synchronous and thus disappears at night. The E-region exists predominantly in the daytime and begins to disappear at dusk due to recombination. The F-layer splits into F1 and F2 and the F1 layer is observed only during daytime.

The first detailed study on the lower region of the ionosphere, termed the E-layer by Appleton & Naismith', gave a measure of maximum density of the charged particles causing the reflection of radio waves. Chapman2 suggested that the observed penetration frequencies were markedly controlled by the solar ionizing radiations, reaching a maximum near noon and falling to minimum values during the night. Appleton3 and Henderson4 made it clear that the principal ionizing agency is electromagnetic radiation from the Sun. Often a sharply reflecting stratum appears a little below the height at which the E-layer is usually formed and it is seen on vertical and oblique ionograms near the height of maximum ionization of the regular E-layer5,6. Because of the variability of its occurrence and the rapid changes which occur in its upper frequency limit, this stratum is commonly referred to as sporadic E (Es) layer.
The physics behind the formation of sporadic E-layers relies on the so called wind shear theory, which is now widely accepted as the mechanism responsible for their occurrence. For generation of a dense sporadic E-layer, ionospheric plasma of a large volume is swept together to a thin layer. This is possible by the combined effect of neutral wind shears of tides and gravity waves in the upper atmosphere, ion-neutral collisions and the geomagnetic field B yielding a V x B plasma drift. Vertical shears in the horizontal wind can drive, by the combined action of ion-neutral collisional coupling and geomagnetic Lorentz forcing, the long-lived metal ions in the lower thermosphere to move vertically and converge into dense plasma layers. Atmospheric wave dynamics play the key role in this formation process by providing the vertical wind shears needed for ion convergence. Of particular importance are the wind shears in relation with the diurnal and semi-diurnal tides which are present regularly in the lower thermosphere.

In addition, particle precipitation, low recombination rate of metallic ions of meteors, ice clouds and other ionization sources have been considered for explanation of the great variety and the high ionization densities of the observed layers. Near the magnetic equator, a distinctive type of equatorial Es is observed which is patchy and transparent to waves reflected from higher layers. It is strongly associated with the electrojet current. The Es layer is a sensitive indicator for the impact of solar variability, decrease of geomagnetic field and anthropogenic effects on the upper atmosphere, e.g. cooling of upper atmosphere because of greenhouse effect. On the other hand, global monitoring of Es layer enables a better selection of perturbation free radio links for communication and navigation.

Based on the characteristic features of the Es layer, as observed in different geographic zones, Tremellen & Cox and Mastushita made a zonal classification of the Es layer types as auroral, mid latitude and equatorial which are physically and phenomenologically distinguishable. In the high latitude zone, Es layer is mainly believed to be caused by the precipitation of charged particles. In the mid latitude, Es layer is formed mainly by a vertical shear in the east-west component of horizontal winds in the E-region. When combined with the horizontal component of earth’s magnetic field, a horizontal wind in the neutral gas of the E-region of the ionosphere can move the ionization in upward and downward direction below and above, respectively, thereby, causing a concentration of ionization to occur. However, in the equatorial zone Es is believed to be due to the presence of a strong eastward electric field during day called equatorial electrojet. Thunderstorms, meteors and ionospheric current systems, etc. also play an important role in the formation of Es layer. In the Auroral zone, the Es layer is predominantly a nighttime phenomenon, with little seasonal variability and in mid latitude zone, Es layer is predominantly a summer time phenomenon, its occurrence being high both by day and night, but more intensively by day. In equatorial zone, Es layer is purely a day time phenomenon with little seasonal variations.

Blanketing frequency of the Es layer represents the frequency to which the Es-layer is not transparent for sounding radio waves it screens the overlying ionosphere. An intensive effort to obtain more detailed information associated with sporadic E-layer and QP structures was the sporadic-E experiment over Kyushu (SEEK) carried out in southern Japan in 1996. Studies, using the VHF radar and ionospheric sounders, suggested that the irregularities are closely related to the localized plasma density gradient within Es-layers. Maruyama et al. reported that the field aligned irregularities are closely related to Es activity and found good correlation between QP radar echoes and enhanced value of foEs – fbEs. It was suggested that for a non-uniform Es layer, the difference between foEs and fbEs was shown to be related to irregularities present in these layers. Krishna Murthy et al. hypothesized that blanketing type Es, providing sharp electron density gradient, would be required for the excitation of gradient drift instability during daytime conditions, since the background electric fields are generally low at low latitudes. Phanikumar et al. suggested that the large values of foEs-fbEs enhance the occurrence of field aligned irregularities during day time. In the present paper, the diurnal, day-to-day, seasonal and geomagnetic variations of h’Es and foEs are presented. Further, the variations of fbEs and foEs-fbEs are also presented for the three stations.

2 Data

Simultaneous data of hourly ionograms from the three different stations, i.e. equatorial station, Trivandrum; a low latitude station, Waltair in the Indian sector; and a mid latitude station, Kokubunji in the Japanese sector (co-ordinates listed in Table 1) during the high sunspot year 2001 (annual mean
Rz=119) for the representative months of each of the seasons, namely March for equinox, November for winter and May for summer are considered in the present study. The ionosondes at Trivandrum and Waltair are of KEL, IPS-42 model and are operated in the frequency range 1 – 22 MHz with 5 KW transmitting power and 41.67 µs pulse width. These sound the ionosphere at regular intervals by the pulse-echo technique at vertical incidence and plot the relationship between the virtual height to the frequency of reflection and the ionogram is stored by recording on a magnetic tape. The ionosonde data over Kokubunji is downloaded from the website http://wdc.nict.go.jp/IONO/HP2009/ISDJ/index-E.html.

3 Results and Discussion

3.1 Day-to-day variability of h’Es

The day-to-day variability of h’Es at the three stations are presented in Fig. 1. It is seen from this figure that the day-to-day variability in h’Es is significant at the three stations during the three different seasons. The h’Es reaches a peak value in early morning hours of 0500 – 0600 hrs LT at all the three stations. At Waltair and Kokubunji, h’Es reaches a peak value in late afternoon hours around 1800 - 1900 hrs LT, whereas at Trivandrum the magnitude of h’Es peak is small. During morning time, the h’Es is more prominent than that of the evening time at the three different stations. The magnitude of the Es layer peak altitude at the

<table>
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<th>Geomagnetic</th>
<th>Dip angle, °N</th>
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<td>Waltair</td>
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<td>Kokubunji</td>
<td>35.7</td>
<td>139.5</td>
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Table 1 — Coordinates of the stations considered for the present study

Fig. 1 — Day-to-day variability of h’Es at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during the high sunspot year 2001
equatorial station (Trivandrum) is small compared to the one at mid latitude station (Kokubunji), which in turn shows that the peak height of Es layer depends on the latitude, i.e. as the latitude increases, the height of the Es layer increases. It is interesting to note from Fig. 1 that the Es layer is absent in the early morning and late night hours at Trivandrum. However, both at Waltair and Kokubunji, the Es layer showed its presence during night time hours, except during equinox. From this result, it is inferred that the frequency of occurrence of the Es layer increases from equator to higher latitudes.

3.2 Day-to-day variability of foEs

The critical frequency of Es layer (foEs) is yet another important parameter, which is of vital importance in the radio wave communication. This parameter is measured continuously from several locations spread over the globe and global ionospheric maps of foEs are made available for the purpose of application in the ground based radio wave communication. The day-to-day variations of foEs at the three different stations are presented in Fig. 2. From this figure, it is observed that the Es layer is absent during early morning hours and late night hours at the equatorial station (Trivandrum), while this is not the case with low (Waltair) and mid (Kokubunji) latitude stations. The fluctuations in critical frequency of Es layer is found to be more in summer months compared to those during equinox and winter months at the three different stations. A significant morning dip in foEs around 0600 hrs LT is observed at Kokubunji during summer month.

3.3 Diurnal variation of h’Es at equatorial, low and mid latitudes

In the present study, an attempt is made to study the temporal (hour-to-hour) as well as spatial (as a function of latitude) variations of h’Es. The simultaneous monthly mean variation of h’Es for each hour at Trivandrum, Waltair and Kokubunji for the whole year from January to December 2001 as a function of local time is presented in Fig. 3. The variation of h’Es is represented by green line for

![Fig. 2 — Day-to-day variability of foEs at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during the high sunspot year 2001](image-url)
(Trivandrum), black line for (Waltair) and red line for (Kokubunji). From a comparison of these variations at the three different stations, it is seen that h’Es, in general, varies from a minimum of about 100 km to a maximum of about 140 km. The h’Es values are higher over Kokubunji, showing a primary peak around 0600 hrs LT and a secondary peak around 1600 hrs LT. While the h’Es variation over Waltair and Trivandrum is nearly similar during all the twelve months except for some random fluctuations in the early morning and evening hours.

### 3.4 Diurnal variation of foEs at equatorial, low and mid latitudes

The monthly mean diurnal variation of foEs over equatorial, low and mid latitudes is presented in Fig. 4. It is seen from this figure that during equinoxes and winter, the foEs values are higher over Trivandrum, lower over Kokubunji and lies in between over Waltair. The monthly mean variation of foEs shows higher values in the daytime compared to those in the night time hours at all the three stations during equinox and winter months. The day maximum values of foEs are higher over Trivandrum and lower over Kokubunji during equinocial and winter months. Over Waltair, the diurnal variation of foEs does not show much variation between day time and night time values, whereas at the other two stations, the difference between day time and night time values of foEs is significant. Low latitude Es activity reported earlier from the Indian sector showed strong seasonal dependence with strong Es activity in summer as compared to other seasons.

### 3.5 Seasonal variation of h’Es

By making the morphological studies of any parameter, the gross features are derived by taking advantage of long term data of a season or of a solar cycle. In the present case, pertaining to the high sunspot year 2001, the h’Es data for the three different seasons namely equinox, winter and summer for all the three stations, Trivandrum, Waltair, and...
Kokubunji are grouped for making a comparative study. The seasonal average plots of the diurnal variation of h’Es as a function of local time are made and presented in Fig. 5. The green line with open stars, black line with rectangular open box and red line with open circles represent the variations of h’Es over Trivandrum, Waltair and Kokubunji, respectively. It is seen from this figure that the h’Es variation over Trivandrum and Waltair is nearly constant around 105 km with an early morning peak around 0600 hrs LT in the three different seasons. Another distinct difference in the h’Es variation observed over these three stations is that the morning peak is higher at Kokubunji compared to those over Trivandrum and Waltair during the three different seasons. The peak value of h’Es over Kokubunji is observed to be around 145, 135 and 125 km during equinox, winter and summer, respectively showing that the mid latitude Es layer forms at higher altitudes compared to that at the equatorial and low latitudes. After sunrise, a fall in the h’Es is observed over Trivandrum and Kokubunji during the three seasons. Phanikumar et al.\textsuperscript{25} have also reported a sharp fall in the h’Es after sunset at a low latitude station, Sriharikota.

3.6 Seasonal variation of foEs

As mentioned earlier, the gross features in the nature of variation of foEs are better reflected when studies are made with large data base covering different seasons or solar cycles. With this objective in view, the average variation of foEs during the three different seasons, namely equinox, winter and summer at the three stations, namely Trivandrum, Waltair and Kokubunji, are separately computed and presented in Fig. 6. The green line with open stars, black line with rectangular open box and red line with open circles represent the variations of h’Es over Trivandrum, Waltair and Kokubunji, respectively. The mean seasonal foEs variations show higher values during day time hours in equinox and winter.
Fig. 5 — Average seasonal behaviour in the diurnal variation of $h'_{Es}$ at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during the high sunspot year 2001.

Fig. 6 — Average seasonal behaviour in the diurnal variation of $f_0{Es}$ at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during the high sunspot year 2001.
over Trivandrum compared to those at the other two stations (Waltair and Kokubunji). A marked variation in foEs over Trivandrum is observed throughout the day in the three different seasons. However, around 0600 hrs LT at the three different stations, an increase in foEs is observed while there is a decrease in foEs around 1800 hrs LT during the three different seasons. Arons & Whitney\textsuperscript{27} showed that the mid-day summer scintillation has a high probability of occurrence when foEs > 5 MHz. Ogawa \textit{et al.}\textsuperscript{20} compared the occurrence of radar echoes with the variation of Es parameters over a mid latitude station Shigaraki and shown that the occurrence of radar echoes depend on the strength of the Es parameters and FAI generation is closely related to localized density gradients within Es.

3.7 Effect of geomagnetic activity on h’Es

The studies on the effect of space weather phenomena such as those resulting from the geomagnetic field variations followed by the changes such as coronal mass ejections (CME) from the sun have gained significant importance in the recent times owing to the impediments they create in the ground based as well as satellite based navigating and communication system. With a view to study the effect of such a phenomenon on the variation of the height of Es layer (h’Es), an attempt is made to study the variation of this parameter during geomagnetically quiet and disturbed periods.

The h’Es variation as a function of local time for the representative months of April (equinox), November (winter) and May (summer) at the three different stations, namely Trivandrum, Waltair and Kokubunji during the quiet and disturbed days are presented in Fig. 7. The plot with closed triangles represents monthly mean variations of h’Es during the quiet days and the plot with open circles represents the variations of h’Es during disturbed days. The h’Es variation during quiet days of equinoctial months at

Fig. 7 — Variation of mean h’Es during quiet and disturbed days at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during the high sunspot year 2001
Kokubunji shows a primary peak around morning hours (0600 hrs LT) with a $h'Es$ value of 155 km while it is absent at Waltair and Trivandrum. However, the night time values of $h'Es$ are randomly varying over Waltair and Kokubunji. The $h'Es$ values over Trivandrum, Waltair and Kokubunji during most of the day time hours vary around 110 km during the disturbed days. However, during summer months, the nature of variation of $h'Es$ at the three different stations during quiet and disturbed periods is similar except with some higher values of $h'Es$ over Kokubunji.

3.8 Effect of geomagnetic activity on $foEs$

Similar to the studies made with $h'Es$ data, the $foEs$ data has also been analyzed and similar plots for the three different seasons at the three different stations during both quiet and disturbed days are made and presented in Fig. 8. From this figure, it is seen that the $foEs$ values over Trivandrum are higher compared to those over Waltair and Kokubunji during the three different seasons of disturbed days. The $foEs$ variation over Trivandrum ranges from a minimum of 3 MHz to a maximum of 8 MHz, whereas at Waltair it varies from a minimum of 2 MHz to a maximum of 6 MHz during winter and summer months of both quiet and disturbed periods. It is interesting to note that there is no marked variation in $foEs$ values during quiet and disturbed days of winter month over Waltair.

3.9 Variation of blanketing Es

The diurnal variation of the blanketing frequency of the Es-layer ($fbEs$) over the three stations during three typical months of October, December and July 2001 representing equinox, winter and summer seasons, respectively are presented in Fig. 9. It is seen from this figure that the blanketing Es is observed more over Kokubunji during all the hours of the day for three months. Over a low latitude station Waltair, the blanketing Es is not observed between 1200 and

Fig. 8 — Variation of mean $foEs$ during quiet and disturbed days at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during the high sunspot year 2001
1600 hrs LT during October and between 0800 and 1200 hrs LT during December, whereas the blanketing Es is observed more during the summer month of July 2001. At the equatorial station Trivandrum, the blanketing Es is not observed during October and December while it is observed during a few nights of July 2001. The values of fbEs over Kokubunji are more during July varying from a minimum of 1 MHz to a maximum of 15 MHz and between 1 and 5 MHz during October and December 2001. The fbEs values over Waltair vary between 2 and 8 MHz during July and October, between 2 and 6 MHz during December. The fbEs values are more during July 2001 over Waltair and Kokubunji compared to those during October and December 2001. It was reported earlier that the blanketing Es layers occur most frequently during local summer months with a characteristic diurnal variation with a prominent peak around 1700 hrs LT\textsuperscript{28,29}.

The diurnal variation of foEs over three stations during July, October and December 2001 are presented in Fig. 10. The foEs values over Trivandrum are more during October and December 2001 (vary between 4 and 9 MHz) compared to those of July 2001 (vary between 2 and 8 MHz). At Waltair and Kokubunji, foEs values are more during the summer month of July 2001 (vary between 2 and 14 MHz) and less during October and December 2001 (vary between 1 and 6 MHz). The difference between foEs and fbEs (foEs-fbEs) are presented for the three stations in Fig. 11 during October, December and July 2001. It is seen from this figure that the difference is more during summer months particularly during night time hours having a maximum value of 7 MHz over Waltair and Kokubunji. During October and December 2001, foEs-fbEs values vary up to 2 MHz except during the night time hours of October 2011 at Waltair, where it varies up to 6 MHz. The variation of foEs-fbEs over Waltair does not show a considerable association with the occurrence of night time scintillations. Patra et al.\textsuperscript{30} reported a poor correlation between field aligned irregularities (FAI) strength and (ftEs-fbEs) values over low latitudes. Phanikumar et al.\textsuperscript{25} also reported that the seasonal variation of Es parameters and FAIs do not show any clear relationship at low latitudes. It is regretted that the irregularity data over Kokubunji is not available to carry out the similar

Fig. 9 — Variation of fbEs at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during October, December and July months of high sunspot year 2001
Fig. 10 — Variation of foEs at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during October, December and July months of high sunspot year 2001.

Fig. 11 — Variation of foEs-foEs at equatorial (Trivandrum, India), low (Waltair, India) and mid (Kokubunji, Japan) latitude stations during October, December and July months of high sunspot year 2001.
comparison. The results observed over Trivandrum are consistent with the earlier results reported by Chandra & Rastogi wherein it is inferred that the blanketing Es at equatorial latitudes is a local summer phenomena. The blanketing type of Es commonly observed at temperate latitudes is explained in terms of the convergence of metallic ions due to the vertical wind shears but this mechanism fails to operate at the dip equator. Movement of ionization layers from higher to lower latitudes or even to magnetic equator due to a horizontal wind with significant north-south component could explain the occurrence of blanketing Es near magnetic equator. Thus, the blanketing Es at equator should occur at times when the meridional wind is strong. The observed features of the occurrence of blanketing Es could be explained on the basis of the occurrence of counter-electrojet events, which occur mostly in the afternoon hours with small occurrence in the morning and are almost absent around noon hours.

4 Summary

Using ionosonde data of hourly ionograms from an equatorial station, Trivandrum (847°N, 76.91°E), a low latitude station, Waltair (17.7°N, 83.3°E) in the Indian sector and a mid latitude station, Kokubunji (35.7°N, 139.5°E) in the Japanese sector during the high sunspot year 2001 (annual mean Rz=119), diurnal and seasonal variations in the h’Es and foEs are studied. It is observed that the Es layer is absent in the early morning and post sunset hours over Trivandrum during the three different seasons. The values of h’Es are more at Kokubunji compared to those at equatorial and low latitude stations during the three different seasons. During early morning hours particularly at Kokubunji the peak values in h’Es are higher (155 km) compared to those in the evening hours (135 km). The peak value of h’Es over Kokubunji is observed to be around 145, 135 and 125 km during equinox, winter and summer, respectively showing that the mid latitude Es layer forms at higher altitudes compared to that at the equatorial and low latitudes.

The critical frequency of Es layer (foEs) over Trivandrum shows higher values compared to those over Waltair and Kokubunji during daylight hours, in the three different seasons, indicating that foEs values decrease as the altitude increases. The h’Es shows maximum values during equinox (150 km) and minimum during summer (125 km) over Kokubunji, whereas over Waltair and Trivandrum lower values of h’Es (115 km) are observed for the three different seasons. The seasonal variation in foEs shows higher values during day time hours of equinox and winter months over equator (Trivandrum) compared to those over low (Waltair) and mid (Kokubunji) latitude stations. The h’Es variations during quiet days over Kokubunji show a primary peak around morning hours (0600 hrs LT) with a value of about 155 km, while it is absent over Waltair and Trivandrum during equinox. The night time values of h’Es over Waltair and Kokubunji are randomly varying. The foEs vary between 3 and 8 MHz over Trivandrum, between 2 and 6 MHz over Waltair, and between 2 and 5 MHz over Kokubunji during winter and summer months of both quiet and disturbed periods.

The occurrence of blanketing Es layer is more at Kokubunji during the three seasons with higher values of fbEs during summer months. At Waltair, the occurrence of blanketing Es is less during day time hours of equinoctial and winter months while it is observed more during summer months with higher values of fbEs. At an equatorial station Trivandrum, blanketing is absent during equinoctial and winter months and is observed only during few summer nights. The values of foEs-fbEs are higher during night time hours than day time hours with summer maximum at Kokubunji and Trivandrum.

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