Indian Journal of Radio & Space Physics
Vol 41, April 2012, pp 285-293

Sporadic E over Allahabad during the extremely prolonged low solar activity period of 2007-2009

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Received October 2011; accepted 2 April 2012

In this paper, the characteristics of sporadic E (Es) layer echoes, observed using a Canadian Advanced Digital Ionosonde (CADI) from equatorial ionization anomaly crest region of Allahabad (25.3ºN, 81.5ºE, and dip latitude 16.3ºN) during extremely prolonged low solar activity period of 2007-2009, have been investigated. Quarter hourly ionograms have been used to study the Es characteristics, viz. the top frequency reflected by the Es layer (ftEs), the blanketing frequency (fbEs), virtual height of Es (h'Es) and their local time and seasonal variations. Also, the occurrence statistics of Es and total blanketing type Es are presented. The most notable feature of the sporadic Es layer at Allahabad is the high percentage occurrence during daytime in the summer months. Interestingly, observation shows that the occurrence of total blanketing type Es layer is more during the nighttime of summer months than in other times and other months. Height migration of h'Es shows descending pattern indicating the role of tidal winds. These results are finally compared with those reported earlier and discussed in the light of current understanding of the solar cycle and seasonal variability of the temperate latitude Es.

Keywords: Sporadic E (Es) layer characteristics, Es layer top frequency (ftEs), Es layer blanketing frequency (fbEs), Es layer virtual height, Es layer occurrence, Low solar activity period

PACS Nos: *94.20.dg; 96.60.qd*

1 Introduction

The E-layer of the ionosphere, which lies in the altitude region of 90-150 km, often shows irregular patches of high ionization confined to a small region commonly known as sporadic E (Es) layer. The term 'sporadic E' has been derived from the ionosonde observations to describe a variety of E region echoes[1]. These layers often are composed of metallic ions and have been a topic of active research over many decades. Excellent review on the progress made in the observations and understanding of the mid and low-latitude Es have been presented by Whitehead[2,3], Mathews[4] and references therein. The mid and low-latitude Es layers appear in different forms, viz. l, f, c and h types[5] and are known to be formed via wind/wind-shear mechanism[2,3,6-8]. According to this mechanism, vertical shear in the horizontal wind, by the combined action of ion-neutral collisional coupling and geomagnetic Lorentz forcing, can drive the long-lived metal ions in the lower thermosphere to move vertically and converge into dense plasma layers. In this, atmospheric wave dynamics plays the key role in the layer formation process by providing the vertical wind shears needed for the ion convergence. The wind shears linked with the diurnal and semidiurnal tides, which are present regularly in the lower thermosphere, play important role in the generation of these layers[4,9].

In contrast, the Es-layer formation process at the magnetic equator is known to be quite different from those at middle and high latitudes. The q-type Es echoes observed in the height region of 105-110 km in the daytime equatorial ionograms are found to be the manifestation of the type II irregularities of the equatorial electrojet (EEJ) produced by the well known gradient drift instability mechanism[10].

The Es variability showing large seasonal dependence with pronounced summer maximum, however, could not be explained by the wind-shear theory alone. In an attempt to explain the seasonal dependence of mid-latitudes sporadic E-layers, Haldoupis *et al.*[11] have shown that seasonal dependence of the sporadic E-layer occurrence correlates well with that of sporadic meteor deposition in the upper atmosphere. The seasonal variation of the Es characteristics continues to be elusive.

Extensive studies have been made in the past on the Es occurrence and its association with solar activity but no definite correlation has been established between them. Mitra & Dasgupta[12] presented the occurrence of midday Es for thirty-three stations in different regions of the globe and examined in relation to the solar activity for the period 1953-1959. They have shown that in general, middle latitude noon time Es occurrences with one or two exceptions indicate a definite positive correlation with solar activity. On the other hand, Kotadia[13] has studied the occurrence of sporadic E for the tropical latitude station of Ahmedabad and reported decreasing tendency of the Es occurrence with increasing solar activity.

In this study, an attempt has been made to investigate the characteristics of Es over Allahabad under extremely prolonged low solar activity during 2007-2009. Observations are discussed in the light of reports available in the literature.

2 Observations and Data analysis

A Canadian Advanced Digital Ionosonde (CADI) has been installed at the regional centre of Indian Institute of Geomagnetism, KSKGRL, Allahabad (25.3°N, 81.5°E, dip latitude 16.3°N) in June 2006. CADI is a solid-state technology based, swept frequency (1 - 20 MHz) pulsed, ionosonde designed for routine vertical incidence sounding of the ionosphere. It has been in continuous operation since January 2007 till date with data acquisition at every 15 minutes interval. Major data gaps occurred during August-October 2007 when CADI was not in operation due to technical problems. Three years of data from January 2007 to December 2009 have been analyzed to study different parameters of the Es layer over Allahabad. Figure 1(a-c) shows the month-wise distribution of CADI data for the year 2007, 2008 and 2009, respectively. Numbers of days of data available are 174, 339, and 354 during 2007, 2008 and 2009, respectively. The parameters studied are ftEs (top reflection frequency), fbEs (blanketing frequency) and h'Es (virtual height of the Es layer). All these Es parameters were scaled manually.

To investigate quiet time behaviour of the Es parameters, observations made during five quietest days in each month have been scaled to get ftEs, fbEs and h'Es. These five quietest days have been chosen from the ten quietest days listed in the World Data Center for Geomagnetism, Kyoto University (http://wdc.kugi.kyoto-u.ac.jp/qddays/index.html) for the period 2007-2009. The seasonal variations of Es parameters have been studied for summer (May, June, July and August), winter (January, February, November and December) and equinox (March, April, September and October).

3 Observational results

At Allahabad, mostly l, f, c and h type Es layers are observed. On a few occasions, q type and total blanketing type Es are also observed. In general, f type Es is observed during the night while l, c and h type Es are observed during the day. Further, occurrence of c type Es is more common during 0800-1200 hrs IST and 1500-1630 hrs IST and h type Es during 1100-1500 hrs IST. Figure 2 depicts a few sample ionograms observed at Allahabad. Date and time of the observations and the type of Es are marked in each ionogram. In addition to the f, h, l, q and c type Es, which are commonplace in Allahabad observations, an example of total blanketing type Es observed at 1100 hrs IST on 22 May 2008 is also presented. The h and c types Es generally occur at higher altitude than the other types and are attributed to the intermediate layer[14-16].

Figure 3(a-c) shows maps of reflected/scattered HF frequency as a function of virtual height and time from the E-layer observed on (a) 22 January, (b) 23 May, and (c) 5 September 2009. These observations correspond to the northern hemisphere winter, summer, and equinox, respectively. It can be seen very clearly that weak Es patches were present during the noon hours on 22 January 2009. Appearance of an intermediate layer at an altitude of 160 km can also be seen very clearly prior to 1500 hrs IST, which subsequently descended to 120 km. This layer is very

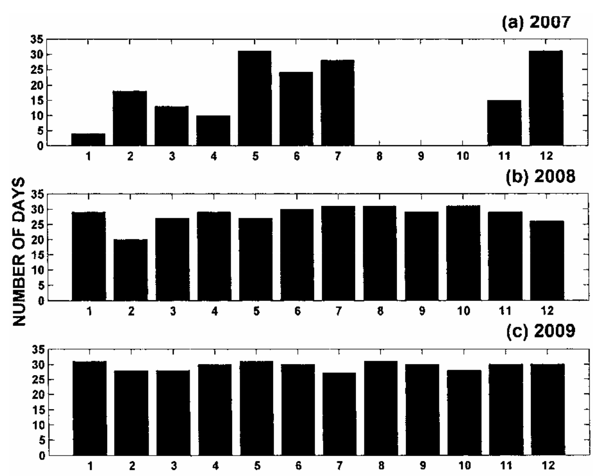

Fig. 1 — Monthly data availability of CADI observations in terms of number of days per month for the year (a) 2007, (b) 2008, and (c) 2009

similar to that reported and classified as intermediate layer by Niranjan *et al.*[16]. On 23 May 2009, Es layer was observed throughout the day and night and Es activity was very intense during the early morning hours (0100-0600 hrs IST) and in the afternoon-midnight hours. On this particular day, intermediate layer was found to clearly descend during 1100-1700 hrs IST. On 05 September 2009, however, Es was found to be intense only during the evening hours (1800-2100 hrs IST) and during the rest of the day and night, Es was rather weak. Again, descending type intermediate layer was observed after 1500 hrs IST in the same way as those observed on 22 January and 23 May and descended from 150 km to 100 km. The above results seem to suggest that intermediate layer occurs at ~1500 hrs IST over Allahabad. Further, these results clearly show that Es activity was most pronounced on 23 May, moderate on 05 September and least on 22 January.

Monthly mean Es occurrence was estimated every quarter hourly for all the available data to show the diurnal, seasonal and annual variability of Es occurrence. In this estimation, all types of Es have been considered. A detailed investigation on the occurrence of different types of Es layer will be taken up separately in future. Figure 4(a-c) shows temporal variations of Es occurrence (in percentage) as a function of month for the year 2007, 2008, and 2009, respectively. Gap in the percentage occurrence plots for the year 2007 is due to the unavailability of the ionosonde data in the months of August and September. As is evident, Es occurrence is the highest during the summer months and more specifically during 1000-1200 hrs IST in May 2007 (60-70%), during 0800-1600 hrs IST in June-July 2008 (90-100%), and during 0800-1200 hrs IST in August 2009 (90-100%). Also, note that Es occurrence is more during daytime than nighttime.

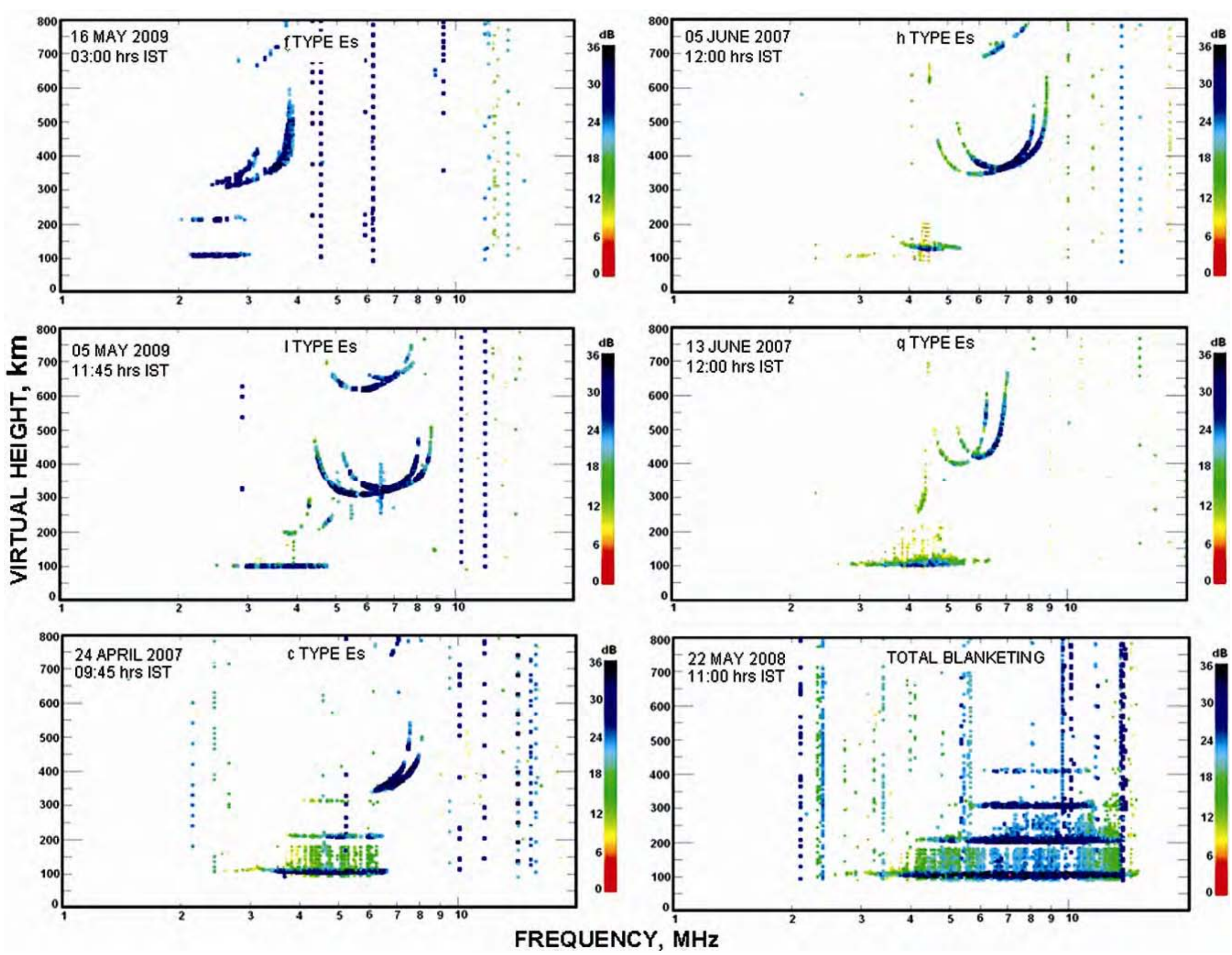

Fig. 2 — Different types of Es layers recorded in the ionograms at Allahabad (date and time marked in the inset)

On several occasions during the summer, Es appearance was noticed right from 0000 hrs IST to 1600 hrs IST. Although there are significant short period changes present in the seasonal pattern, the most noticeable feature is the dominant summer maximum. This can be considered as a typical behaviour in the sporadic E occurrence over Allahabad. Also, two distinct periods of maximum occurrence in the summer months of 2007 and 2009 can be noticed. In all the three years, occurrence of Es layer has been found to be very low in the winter months.

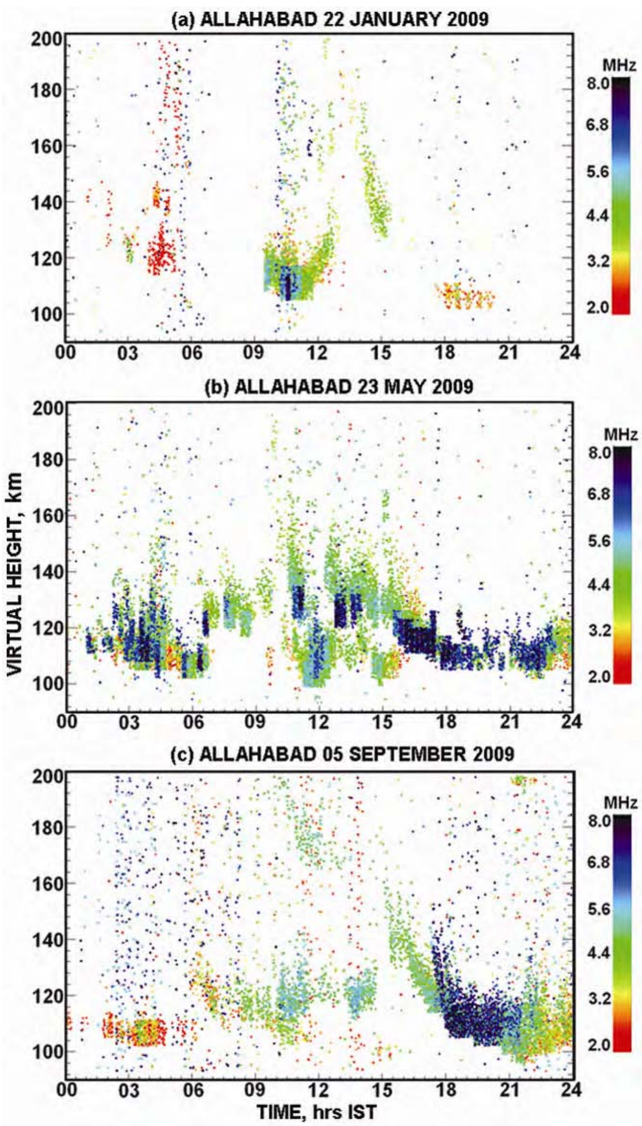

Fig. 3 — Sample virtual height-time-frequency map observed by CADI at Allahabad on: (a) 22 January, (b) 23 May, and (c) 5 September 2009

Similar to the occurrence of Es shown in Fig. 4, monthly mean occurrence of total blanketing Es (total blanketing type Es which blankets both F1 and F2 layers completely) has been estimated every quarter hourly. Figure 5(a-c) shows temporal variations of occurrence of total blanketing Es (Esb) layers as a function of month for the year 2007, 2008, and 2009, respectively. It can be seen clearly that total blanketing Es also shows maximum occurrence during the summer months in the early morning hours (0300-0500 hrs IST). Esb occurrence is found to be maximum (60%) in June 2008 occurring around 0400 hrs IST. Occurrence of total blanketing type Es layer also shows significant short period changes in the seasonal pattern similar to that of Es layer. During the winter months, Esb occurrence is minimum. On many occasions (10-15% occurrence) during the equinoxial months of 2008 and 2009, blanketing Es layers were observed.

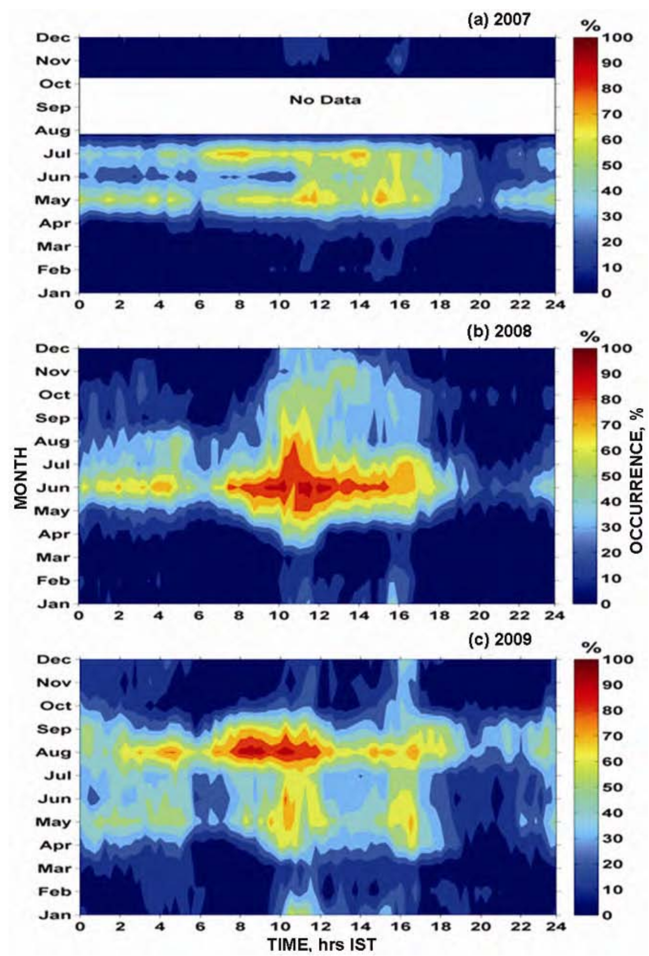

Fig. 4 — Es-layer occurrence as a function of months and local time during: (a) 2007, (b) 2008, and (c) 2009

In sporadic E studies, ftEs is used widely to quantify the layer intensity and variability. The analysis presented here refers to the highest reflection frequency irrespective of different types of Es. Figure 6(a-c) shows temporal variations of ftEs for summer, winter and equinox. Results for 2007, 2008 and 2009 are presented in the top, middle and bottom panels, respectively, for comparison. The black line with error bars represents the hourly mean values of ftEs. As is evident, ftEs varied between 2-18 MHz and show large variability during summer months with maximum values occurring during noon hours. During the winter and equinox, ftEs values are rather small and less variable except for the equinox of 2007. This large variability could be due to the non-availability of data during September-October 2007. In all the years, noontime mean values of ftEs during the summer are centered around 6 MHz and during the winter and equinox centered on 4 MHz.

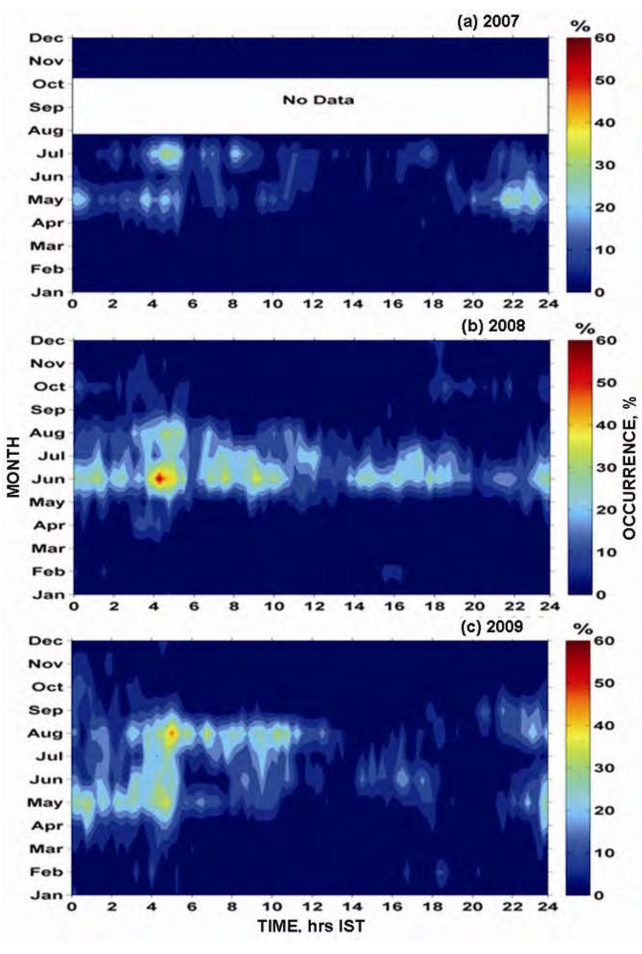

Fig. 5 — Total blanketing type Es-layer occurrence as a function of months and local time during: (a) 2007, (b) 2008, and (c) 2009

Figure 7(a-c) shows temporal variations of fbEs for the summer, winter and equinox months. The results for 2007, 2008 and 2009 are presented in the top, middle and bottom panels, respectively, for comparison. The black line with error bars represents the hourly mean values of fbEs. The fbEs varies between 2 and 14 MHz and shows large variability during summer months with maximum values during daytime. During winter and equinox, fbEs values are small and less variable except during the equinox of 2007.

Figure 8(a-c) shows temporal variations of h'Es for the summer, winter and equinox. The results for 2007, 2008 and 2009 are presented in the top, middle and bottom panels, respectively, for comparison. The black line with error bars represents the hourly mean values of h'Es. The h'Es varies in the range 90-160 km and shows large variability during the summer. On many occasions, during the summer of 2007; winter of 2007, 2008 and 2009; and equinox of 2008 and 2009, h'Es appeared at around 160 km at ~1200 hrs IST and descended down to 120 km. This is due to the daytime descending intermediate layers that appear at the bottom of the F-region in summer, winter and equinox[16]. The monthly median height characteristics reveal that the layers descend and different tidal modes control the layers in different months. Since here only 5 quiet days of ionograms have been examined for each month, it cannot be commented on its day-to-day, seasonal and annual occurrence characteristics.

4 Discussions

Observations presented above clearly show that at Allahabad Es layer occurs in different forms depending upon the local time and season. The q type Es, which occurs frequently at the magnetic equator, has also been observed over Allahabad at times. Such Es is known to be associated with the gradient drift instability. This implies that the E-layer over Allahabad also becomes unstable possibly in the same manner as that in the magnetic equatorial E-region. Then the Es other than the q type may be broadly attributed to the wind shear mechanism. It has also been noted that ftEs show large day-to-day variability and has a strong seasonal dependence. It is found to be the strongest in the summer and weakest in the winter. It has also been found that Es activity peaks during the noon time.

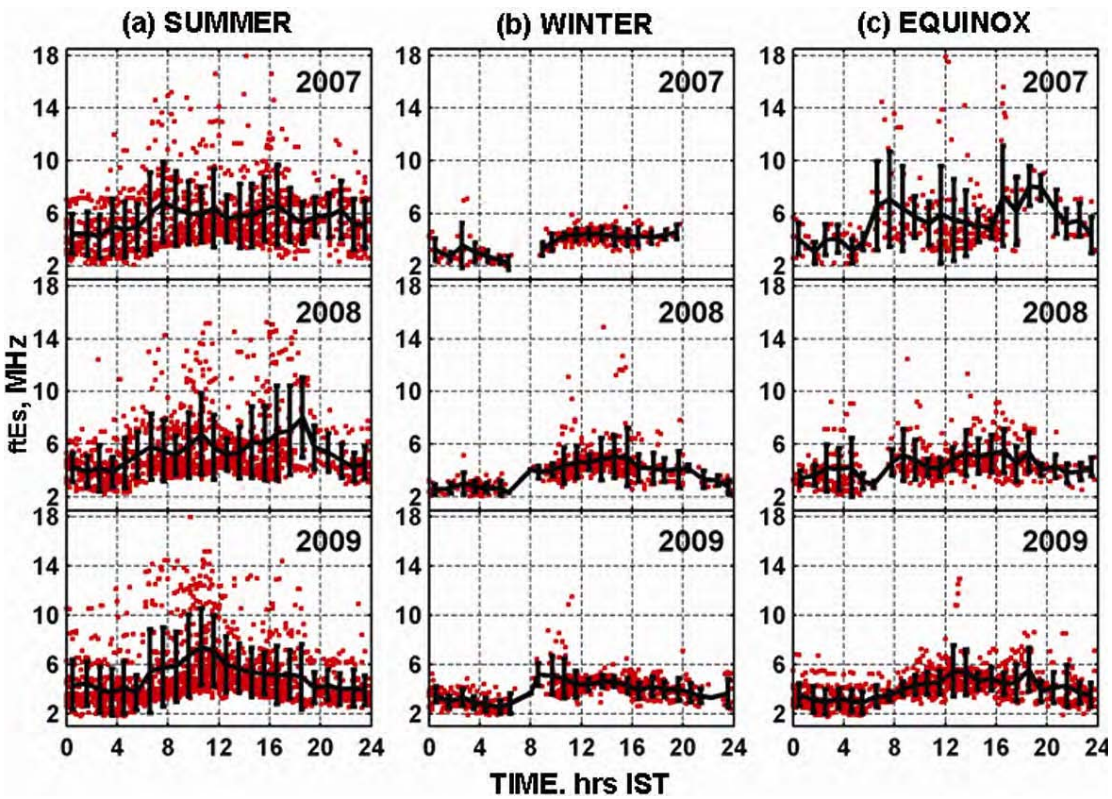

Fig. 6 — Temporal variations of ftEs observed during: (a) summer, (b) winter, and (c) equinox (results for 2007, 2008 and 2009 are shown in the top, middle and bottom panels, respectively, for comparison; black line with error bars represents the hourly mean values of ftEs)

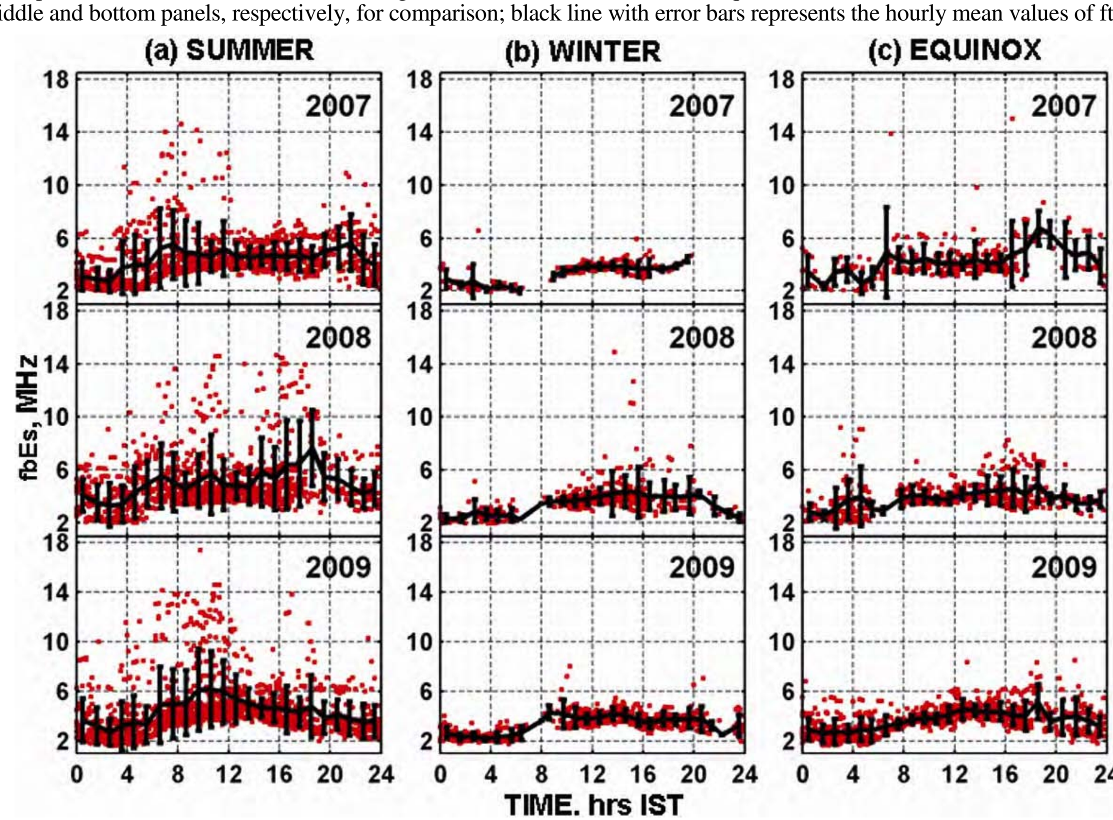

Fig. 7 — Temporal variations of fbEs observed during: (a) summer, (b) winter, and (c) equinox (results for 2007, 2008 and 2009 are shown in the top, middle and bottom panels, respectively, for comparison; black line with error bars represents the hourly mean values of fbEs)

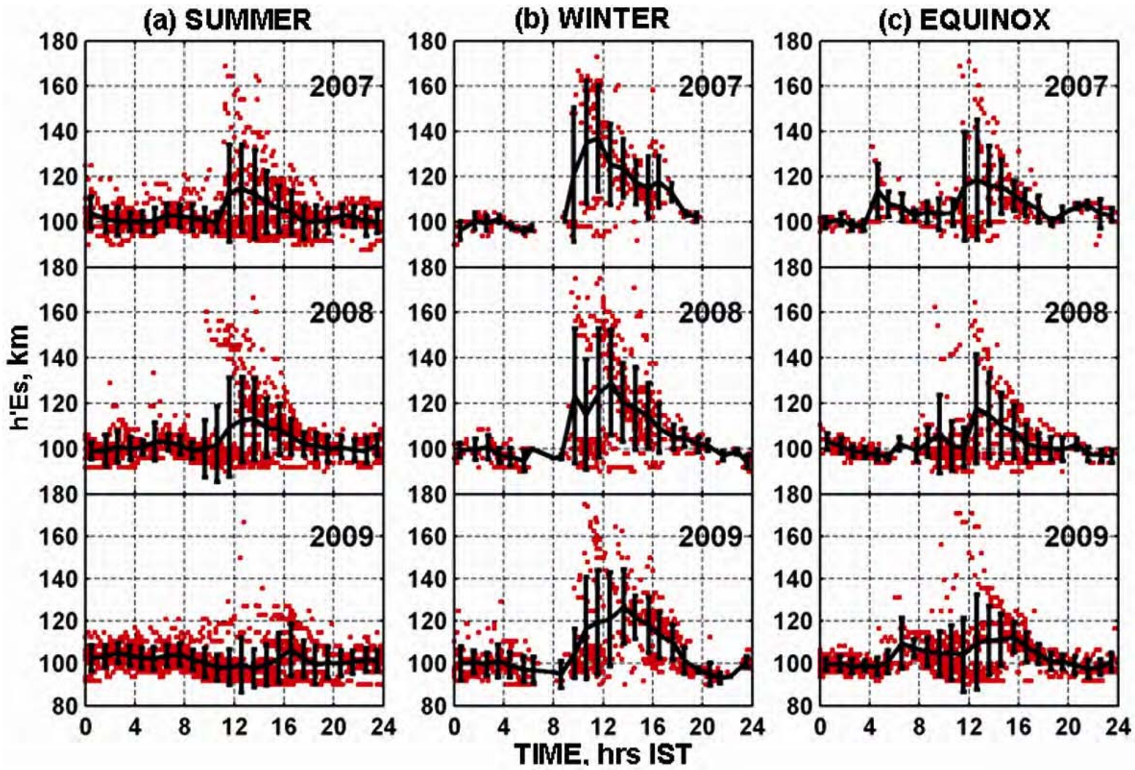

Fig. 8 — Temporal variations of h'Es observed during: (a) summer, (b) winter, and (c) equinox (results for 2007, 2008 and 2009 are shown in the top, middle and bottom panels, respectively, for comparison; black line with error bars represents the hourly mean values of h'Es)

As far as the Es observations from low-latitude in the Indian sector is concerned, Kotadia[13], based on observations from Ahmedabad, showed that noon time foEs (6.3 MHz) had a sharp peak in the summer months of 1955 (Zurich sunspot number Rz = 38, medium solar activity) and midnight foEs was also maximum in summer, although the peak foEs was lower than their noontime counterpart. Noon-time yearly mean foEs varied from 3.6 MHz to 4.2 MHz for the low solar minima year of 1954 (Rz=43) to high solar maxima (Rz=190). Kotadia[13] also found strong seasonal variation in the Es occurrence with first maxima occurring in the summer and second maxima in the winter and minima in the equinoxes. Further, the occurrence of Es was high in the year of low sunspot number with maximum occurrence in 1955 and decreased with the increase in sunspot activity. Kotadia[13] also showed that blanketing Es is practically absent in the winter and equinoxes and is an afternoon phenomenon during the summer. This is in contrast to the present observations, where it has been shown that blanketing Es occur equally well or better in the morning period than during the afternoon period. In addition, the present study shows that the occurrence of blanketing type Es (Esb) is lower in the daytime than during the midnight-morning hours. Chandra[17] has reported the nighttime seasonal variations on Es occurrence during high (1958), medium (1961, 1967) and low (1964-65) solar activity from Ahmedabad. In their study, clear seasonal variation is noted with maximum occurrence around June-July and minimum in March. The nightime Es occurrence at Ahmedabad was found to be increasing with decreasing solar activity.

Rao & Rao[18] in an investigation of the sporadic-E layer over Waltair, a low-latitude location, showed that mean fEs during daytime (0600-1800 hrs IST) were slightly higher during 1956-57 (R=143) than those during 1961-62 (R=65). They found that the occurrence of Es also increased with the increase in the sunspot activity.

On the other hand, Devasia *et al.*[19] have shown that at equatorial station of Trivandrum, the onset time of the Esb layers is mostly confined to the afternoon hours during the solar minimum periods, whereas it is confined more and more towards evening hours as the solar activity increases. Also, at the equatorial station, the appearance of blanketing Es layers is found to be closely associated with the occurrence of afternoon counter equatorial electrojet

(CEEJ). These observations suggest that the generation mechanisms of the low-latitude Es are different from those of the magnetic equator.

Thus, as far as seasonal occurrence of Es is concerned, it has been found that the present observations are broadly in agreement with those reported from low latitudes in the Indian sector. Especially, the high occurrence rate in the summer months is common in all the observational studies. It appears that the large occurrence rate must be linked with the common causes, such as the wind system that provides the convergent wind node and the metallic ions. It would be interesting to examine these aspects, which will be taken up in the future.

A finding that is consistent in all the three years of observations from Allahabad is the occurrence of descending intermediate layer in the afternoon hours. The present study also shows that the semi-diurnal tide, which dominates over the diurnal tide in the upper E-region, plays an important role not only in the formation and transport of the descending intermediate layers but also on the lower E-region sporadic E-layers, especially during evening and night time hours.

Niranjan *et al.*[16] presented a study on the daytime descending intermediate layer over Indian station of Waltair using ionosonde data for the low solar activity year of 2004. They found that these layers occurred in the altitude range of 140-160 km with maximum occurrence during the winter solstice, moderate during the equinox and low during the summer solstice. Lee *et al.*[20] have also investigated the intermediate layers using a digisonde from Chung-Li (Taiwan), a location near the equatorial anomaly crest region, for the year 1996. Statistical results in their study also show that the occurrence of the intermediate layer is more during the daytime of the spring/winter months.

Haldoupis *et al.*[9] also investigated sporadic E-layer (Es) using CADI observations from the island of Milos (36.7ºN, 24.5ºE) and found the role of tides in the Es layer variability. Their analysis revealed a pronounced semidiurnal periodicity in the layer descent and occurrence. Mathews[4] also showed that diurnal and semidiurnal tides are responsible for the formation and descent of sporadic E-layers which are referred as tidal ion layers (TILs). In a statistical study on Es using ISR measurements from Arecibo, Christakis *et al.*[21] have shown the mean seasonal behaviour of sporadic E in terms of tidal variability along with altitudinal structure and dynamics of narrow sporadic E-layers. They have investigated in details on diurnal trace, upper daytime trace and upper nighttime trace of the Es and their association with the diurnal and semidiurnal tides. They found that semi-diurnal-like upper traces are less frequent than the prevailing diurnal trace at lower altitudes. They also found that daytime layers are more frequent than those of the nighttime. Further investigations based on Allahabad observations are required to understand its occurrence statistics, diurnal, day-to-day, seasonal, annual and long term variability of the intermediate layers and the role of the important tidal modes in the layer behaviour.

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