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Key Points:

- Association of Esb and CEEJ during summer is solar flux dependent and it gets stronger with increasing solar flux
- Prenoon CEEJ assists the formation of Esb at an earlier time than the usual postnoon period
- Percentage occurrence of total blanketing Esb events (fbEs ≥ 8 MHz) is larger on magnetically disturbed days

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Quiet and Disturbed Time Characteristics of Blanketing Es (Esb) During Solar Cycle 23

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Abstract A sporadic *E* layer with dense ionization blocks the upper ionospheric layers in ionosonde observations and it is called, blanketing sporadic *E* (Esb). Although earlier studies have demonstrated that Esb occurrence is dependent on solar activity, seasons, local time, and equatorial electrojet/counter equatorial electrojet (EEJ/CEEJ) strength, the physics behind this dependence is not well established particularly at the dip equatorial stations. Moreover, fewer comprehensive studies are available on Esb. Present work is a detailed statistical study of Esb occurrence and its characteristics during solar cycle 23 (1996–2006) at Indian dip equatorial station Trivandrum (dip latitude 0.5°N). In present study, solar flux dependence of Esb occurrence is clearly evident not only for magnetically quiet but also for the disturbed periods with maximum during low solar activity. Known seasonal peak Esb occurrence during summer (May–August) is found to be dominated by larger percentage of total blanketing events (fbEs ≥ 8 MHz) on magnetically disturbed days as compared to quiet days. We noticed prevalent Esb occurrence in the postmidnight (00–06 India Standard Time) periods during low solar activity. Besides Esb characteristics, the present study aims to investigate effect of solar flux on association of Esb and CEEJ. Coexistence of Esb and CEEJ is emphasized in earlier observational studies. However, any dependence of their association on solar flux is not yet examined. We find that their association is weaker during low solar activity as compared to high solar activity in summer, indicating that Esb occurrence is highly likely on CEEJ days during high solar activity periods.

1. Introduction

Thin layers of increased ionization are observed at an altitude between 100 and 120 km in the *E* region of the ionosphere. These layers, called sporadic *E* (Es), exist in patches and are transparent to radio signals which are transmitted from ionosondes and reflected from upper ionospheric layers (Rishbeth & Garriott, 1969). When an Es layer has sufficiently dense ionization, it blocks these upper layers in ionosonde observations. Such a layer is termed as blanketing sporadic *E* (Esb). Occasionally, layers of enhanced ionization are also seen at relatively higher heights (120–160 km), which are called as intermediate layers (Niranjan et al., 2010; Wilkinson et al., 1992). Es layers occur more frequently at mid latitudes, and their occurrence decreases closer to the dip equator, but it is still significant (Oyinloye, 1971; Reddy & Matsushita, 1969). Arras (2010) estimated global Es occurrence using GPS radio occultation technique, which indicates that Es occurrence is maximum at mid latitudes in local summer. On rare occasions *E* region irregularities, in presence of Esb, can produce scintillations of radio signals in VHF band (Yadav et al., 2015). The main difference is that, unlike Esb layer, the ionization in nonblanketing Es layers is not high enough to blanket the upper ionospheric layers to the radio signal transmitted from ground-based ionosonde.

Although Esb is a subtype of Es layers and both are observed at mid, low, and equatorial latitudes, their formation involves different physical processes at the dip equator. For example, equatorial sporadic *E* (Esq) is nonblanketing type Es, which is linked with equatorial electrojet (EEJ) current and it is commonly observed at dip equatorial stations. Two stream instability and gradient drift instability are the widely accepted theories to explain the formation of Es at dip latitudes (Devasia et al., 2006; Whitehead, 1989, and references therein). At low and mid latitudes, Es layer formation can be explained with the wind shear mechanism (Axford, 1963; Whitehead, 1961). Recently, formation of Es layer through wind shear mechanism has been simulated using extended MIRE (*E* region ionosphere model) and it is found to be in good agreement with observed Es (Resende et al., 2017). Vertical shear in zonal winds or meridional winds can produce convergence of ionization at specific altitude through inclined magnetic field lines at mid latitudes. Such convergence of ionization in a narrow altitudinal belt is required for the formation of Esb. However, wind shear mechanism fails at the dip equator due to the horizontal nature of the Earth's magnetic field in that region, which makes this mechanism inefficient to produce vertical convergence of charged species (Axford & Cunnold, 1966). In other words, the formation of Esb over dip equator cannot be explained using wind shear mechanism and further theoretical efforts are needed for its better understanding. In this context, Resende et al. (2016) have examined the role of tidal wind and vertical electric field in the formation of Esb at quasi equatorial station São Luís (dip latitude 0.95°S). This modeling study demonstrates that stronger vertical electric field can inhibit the effect of wind shear in the formation of Esb in regions closer to the dip equator.

Occurrence of Esb close to dip equator has been studied in the past revealing many interesting features. During quiet period, it has been reported to exhibit dependence on solar activity level, seasons, local time, and EEJ/counter equatorial electrojet (CEEJ) strength (Bhargava & Subrahmanyan, 1964; Chandra & Rastogi, 1975; Devasia, 1976; Devasia et al., 2006; Oyinloye, 1971; Tsunoda, 2008; Yadav et al., 2014). However, the physics behind such dependence is still at large. Chandra and Rastogi (1975) have explored daytime occurrence of Esb during 1954–1966 and found inverse correlation between Esb occurrence and solar activity. Devasia et al. (2006) have investigated occurrence of Esb for more than a complete solar cycle and shown that in addition to the occurrence, morphological features like onset time, fbEs, and the height of Esb layers are also dependent on solar activity. They have concluded that Esb often coexists with CEEJ. Yadav et al. (2014) have reexamined this association using Esb occurrence on quiet days during extremely low solar activity period of 2007–2009. Their study suggests that the association between Esb occurrence and CEEJ varies seasonally and it is the weakest during summer solstice. It indicates that Esb is likely to be present even on non-CEEJ days during summer. However, the solar activity dependence of the association between Esb and CEEJ is yet to be investigated.

Role of EEJ/CEEJ in formation/inhibition of equatorial sporadic *E* (Esq), which are simply the backscattered echoes from Type I/II irregularities in *E* region, are well studied (Fambitakoye et al., 1973; Rastogi, 1997). Previous observational studies have reported occurrence of Esb on CEEJ days, but they do not explain how the presence of CEEJ facilitates the convergence of ionization, particularly over dip equator. Reddy and Devasia (1973) had proposed convergence of ionization along magnetic filed lines by horizontal shear in meridional winds. However, this mechanism does not explain the seasonal occurrence pattern of Esb. Later, it was suggested that local zonal winds varying with height could form CEEJ (Reddy & Devasia, 1981). As Esb is generally observed along with CEEJ events, it is speculated that such winds having vertical shear could be playing a role in formation of Esb. However, it does not explain the convergence mechanism of ionization at the dip equator. Recent study by Resende et al. (2016) sheds some light on the possible role of vertical polarization electric field in the disruption of Esb close to the dip equator.

Equatorial *E* region exhibits phenomena like EEJ/CEEJ, Es/Esb, Type I/II irregularities which occur in a narrow belt around 90–120 km. During the course of understanding the Esb characteristics from earlier reports, it is noted that there are few studies related to Esb after the 1980s. Also, there have been fewer comprehensive studies on Esb occurrence during magnetically disturbed times. Information on the type of Esb (for example, *f*, *l*, *c*, and *h* type (Wakai et al., 1985)) is equally important, as it may give some clue about the generation process of Esb. These Esb types are associated with wind shear (Abdu et al., 1996; Denardini et al., 2016). Some studies have demonstrated that Esb occurring close to evening hours at low latitudes can play important role in the generation and dynamics of postsunset equatorial spread *F* (ESF) irregularities (Joshi, 2016; Patra et al., 2004; Prakash, 1999). Abdu et al. (2003) have shown that the evening time prereversal enhancement (PRE) disrupts the Es layer, which indicates coupling of *E* and *F* regions. In light of the above points, we realize that extensive studies on Esb using large data sets are essential to bring out a clear understanding of the various *E* and *F* region phenomena. With this motivation, we have investigated the occurrence of Esb on quiet and disturbed days during solar cycle 23 at dip equatorial station Trivandrum. We have further examined the effects of solar activity on Esb and its association with CEEJ. The data used and analysis technique are described in section 2. Results are explained in section 3. The present work is discussed in section 4 and concluded in section 5.

2. Data and Analysis

We utilized ionograms recorded every 15 min by Digisonde at Trivandrum (8.5°N, 76.6°E, dip latitude 0.5°N), India, to ascertain the presence of Esb. These ionograms were visually scanned to note the occurrence of Esb and blanketing frequency (fbEs) for the period 1996–2006. The value of fbEs is the minimum frequency at which the *F* region trace appears on the ionograms. Each day was divided in 96 bins of 15 min intervals for representing the occurrence of Esb. If Esb occurred during a certain 15 minute interval, then that bin was marked as a bin with Esb. Whenever two or more fbEs values were found during a 15 min interval due to 5/10 min sampling interval of ionograms, the largest fbEs value during that 15 min interval was chosen for the corresponding bin. The events with fbEs $\geq$ 4 MHz were considered as Esb to avoid ambiguous events. Esb events with 4 MHz $\leq$ fbEs $<$ 8 MHz were considered as partial Esb and the events with fbEs $\geq$ 8 MHz were considered as total Esb. The total duration of Esb events during a day should be at least 30 min for that day to be considered as an Esb day. If fbEs $\geq$ 8 MHz for at least 15 min on an Esb day, then it is classified as a total blanketing case, else it is classified as partial Esb. In addition to this, we gathered information on the types of Esb as per Wakai et al. (1985) for all Esb days.

For a statistical study using large database, like the one presented here, we need to know the average magnetic activity on a given day. In such studies, planetary geomagnetic activity index Kp/Ap is preferred and have been used in many of the earlier ionospheric studies at low and equatorial latitudes (Fejer et al., 1991, 2005; Kakad et al., 2007). Here days with $\sum Kp > 24$ were classified as disturbed days and the rest as quiet days. Also, ground-based observations of geomagnetic field's horizontal component (H) with 1 h resolution at Tirunelveli (8.7°N, 77.8°E, dip latitude 0.6°N) and Alibaug (18.6°N, 72.9°E, dip latitude 14.1°N) were utilized to estimate EEJ during 1996–2006 (Chandra et al., 2000; Patil et al., 1990a, 1990b). EEJ is estimated by subtracting the variation of H component recorded at Alibaug ($\Delta H_{A,t} = H_{A,t} - H_{A,\mathrm{midnight}}$) from the H component recoded at Tirunelveli at same time t ($\Delta H_{T,t} = H_{T,t} - H_{T,\mathrm{midnight}}$). Here $H_{A,t}$ and $H_{T,t}$ represent the values of horizontal component at time t recorded at Alibaug and Tiruneliveli, respectively.

Lei et al. (2005) have shown that various ionospheric parameters show a better correlation with a new solar activity proxy, which is defined as

$$\Phi^i{}_{10.7P} = (\Phi^i{}_{10.7} + \Phi^i{}_{10.7A})/2 \tag{1}$$

where $\Phi^i{}_{10.7A}$ is the mean of previous 81 days' daily solar flux at 10.7 cm wavelength such that

$$\Phi^i{}_{10.7A} = \frac{1}{81}\sum_{n=i-81}^{n=i-1} \Phi^n{}_{10.7} \tag{2}$$

Here $\Phi^i_{10.7}$ represent 10.7 cm solar flux for the ith day. Thus, in the present study we have used $\Phi_{10.7P}$ as the solar activity index.

3. Results

The results obtained from the data analysis are discussed here as (i) general characteristics of Esb occurrence, (ii) its dependence on solar activity and seasons, (iii) variation of fbEs and duration of Esb, and (iv) dependence of Esb on CEEJ. The figures are displayed in Indian Standard Time (IST), instead of local time of Trivandrum (LT = IST − 0.39 h).

3.1. General Characteristics of Esb

Daily occurrence of Esb at 15 min resolution as a function of IST for each year during 1996–2006 is shown in Figure 1. Each red patch at a given 15 min bin indicates occurrence of Esb on a quiet day. Similarly, each blue patch indicates occurrence of Esb on a disturbed day. White and cyan patches in the figure respectively represent loss of ionosonde data and no occurrence of Esb on quiet or disturbed days. It can be clearly seen that there was frequent data loss in 1996, 1997, 1998, and 2003. Figure 1 indicates that the occurrence of Esb is prevalent during postnoon time. A set of ionograms for 18 June 2002 shown in Figure 2 illustrates the evolution of Esb layer. It first appears at 14:15 IST and takes a distinctive cusp shape in the subsequent ionograms. This Esb layer is known as "c" or cusp type which persists till 15:30 IST. At 15:45 IST the Esb layer lowers in altitude and takes a flat shape and remains like that till it disappears. This flat type layer is known as "l" or low type. It should be noted that the c type layers are observed at a higher height than the l type layers. Similar flat type Esb layers are sometimes observed during nighttime as well. However, these are called as "f" type and not l type, which are flat Esb layers seen during daytime hours.

We computed yearly percentage occurrence of Esb for quiet and disturbed periods, which is depicted in Figure 3. Figure 3a shows solar activity levels represented by $\Phi_{10.7}$ (grey color) and $\Phi_{10.7P}$ (blue color) for solar

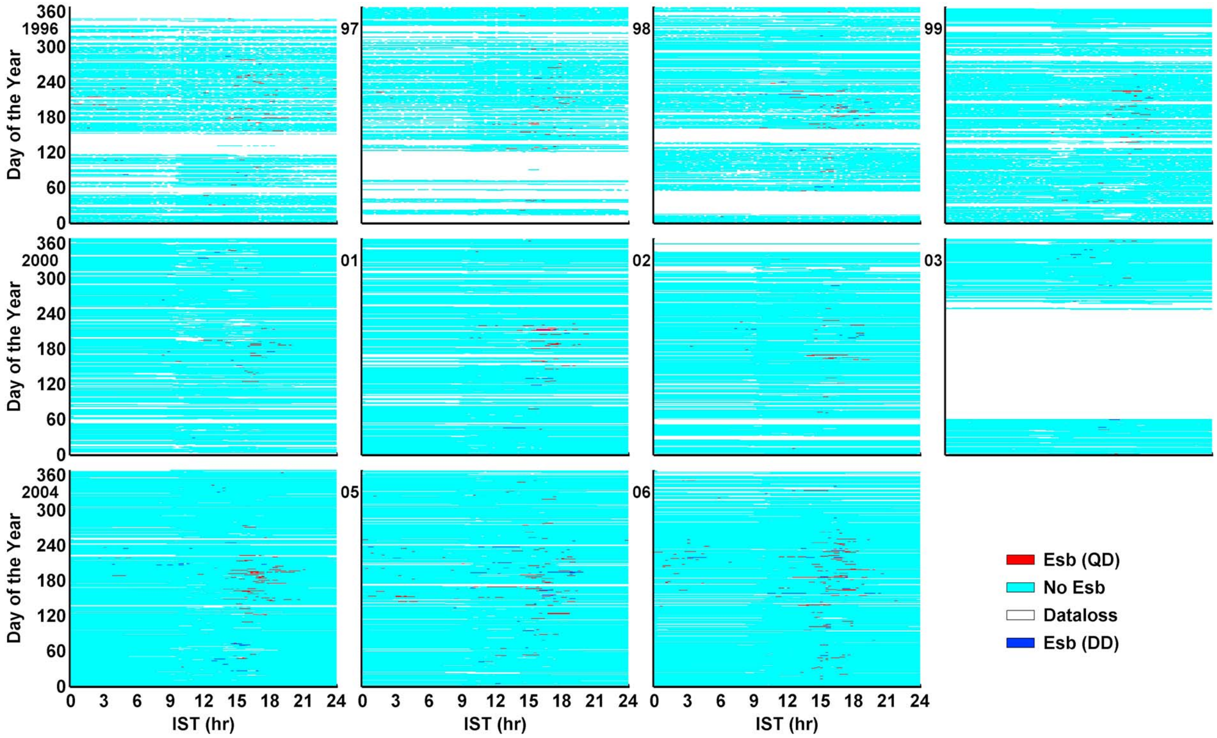

Figure 1. Occurrence of Esb as a function of IST during 1996–2006. Days with $\sum Kp \geq 24$ are considered as magnetically disturbed days.

cycle 23. Red circles indicate availability of ionosonde data on a given day. If the total duration of Esb event is 30 min or more on a day, then that day is considered as day with Esb. Data loss days are the days on which data loss for more than 30% of time is encountered. Adopting these criteria, we estimated the annual percentage occurrence of Esb for quiet and disturbed days during 1996–2006. Figure 3b (Figure 3c) shows annual percentage of days with Esb for all quiet (disturbed) days in the form of bars. Data loss is shown by asterisks in corresponding panels. If the annual percentage of data loss days exceeds 33% of all quiet or disturbed days, then the percentage of days with Esb is not shown for that year to avoid skewed statistics. The numbers above each bar in Figures 3b/3c represent Esb days (n) out of all quiet/disturbed days (N), mentioned as n/N. Green bars represent the annual percentage of days with Esb during the extremely low solar activity period

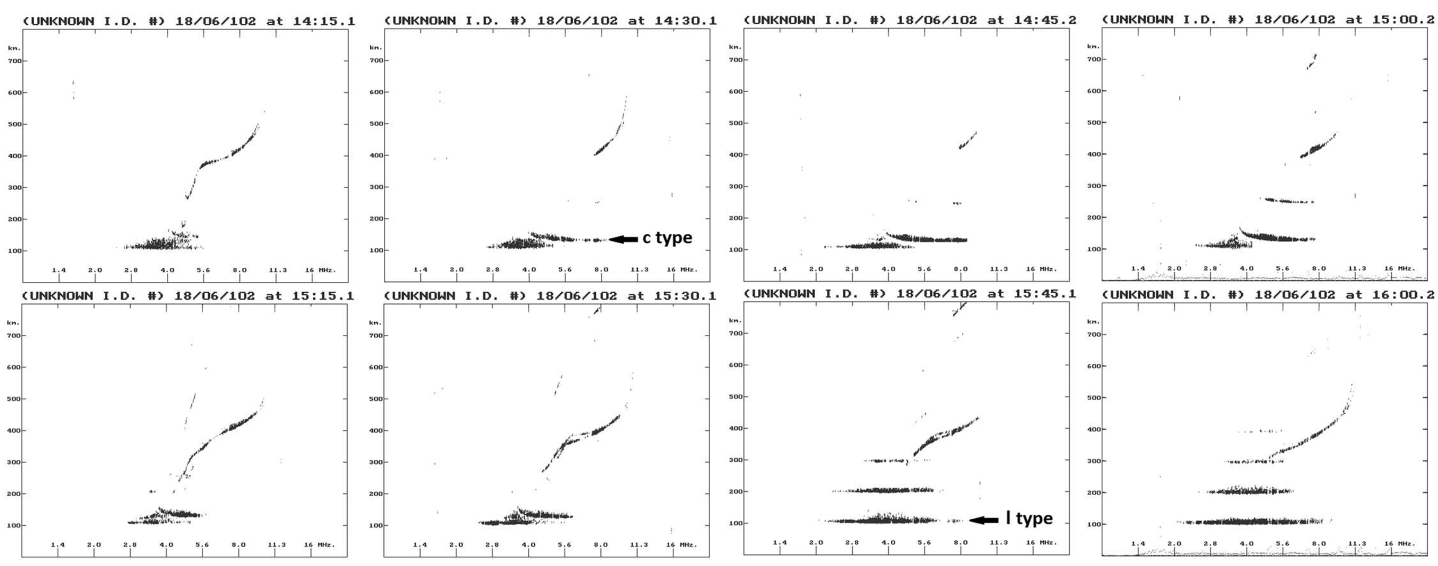

Figure 2. Ionograms for 18 June 2002 showing evolution of Esb layer. Note the presence of "c" type layer till 15:30 IST and the presence of "l" type layer after that.

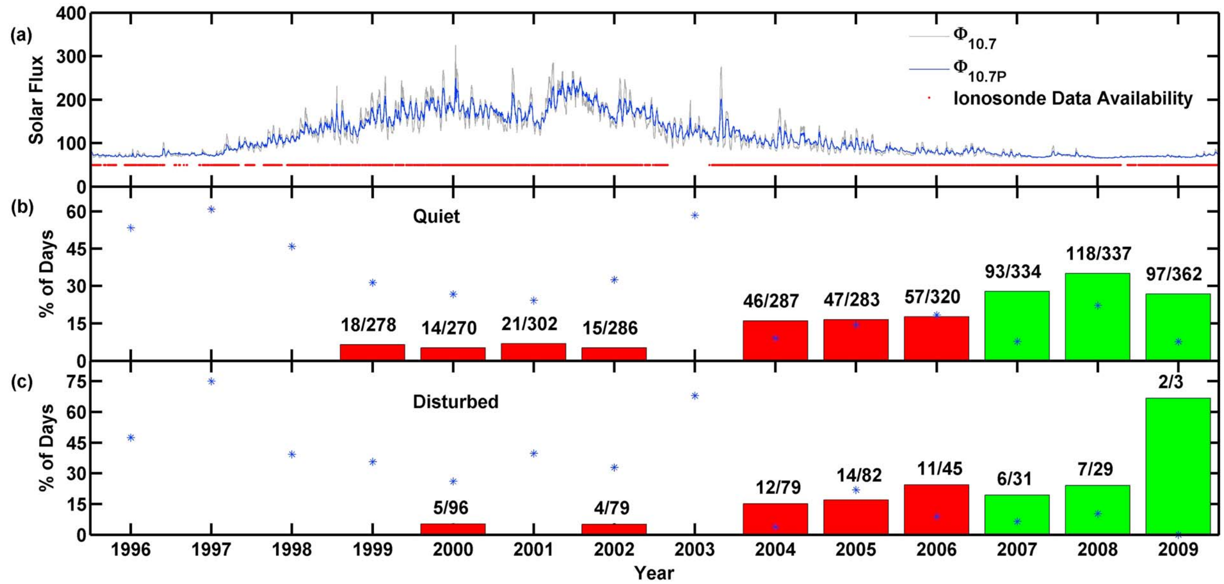

Figure 3. Annual percentage of Esb days for (b) quiet and (c) disturbed days during 1996–2006 using Digisonde data (red bars). The same has been shown for 2007–2009 using CADI data for comparison (green bars). Asterisks represent percentage of data loss days. Numbers above each bar represent the number of Esb days out of all days for which ionosonde data are available (n/N) in a given year. (a) The solar activity levels by daily $F_{10.7}$ solar flux and solar flux proxy along with the availability of ionosonde data.

of 2007–2009, observed at nearby dip equatorial station Tirunelveli. This statistic was obtained using CADI ionosonde observations (Yadav et al., 2014) and it is shown here only for comparison. These data have not been used for further analysis as they cover the extremely low solar activity period when the *E* region dynamics can be significantly different. It may be noted that the large percentage for disturbed days in 2009 is not reliable due to a very small number of disturbed days in that year.

Overall, Esb occurred on 12.5% days for solar cycle 23, which corresponds to 322 out of 2,577 days. In spite of data loss during certain years, the tendency of higher Esb occurrence during low to moderate solar activity in the decreasing phase of the solar cycle as compared to high solar activity years on quiet days is clearly evident. Disturbed days also exhibit similar trend. Since 1996–1998 have a large number of data loss days, we cannot comment on the occurrence of Esb during the low to moderate solar flux period of the ascending phase of the solar cycle.

Next, we examined the local time occurrence of Esb during the combined period of 1996–2006. The percentage occurrence of Esb is estimated for each 15 min bin using complete data of 1996–2006. Figure 4 illustrates the percentage occurrence of Esb as a function of IST for (a) quiet and (b) disturbed days. Each bar corresponds to 15 min interval. The data loss is shown by black dots. Percentage of data loss is higher mainly due to large data loss periods in 1996–1998 and 2003. It is noted that the quiet time Esb occurrence is observed mainly during 14–19 IST with the maximum around 16.5 IST. It is in general agreement with the earlier studies (Bhargava & Subrahmanyan, 1964; Chandra & Rastogi, 1975; Devasia, 1976; Devasia et al., 2006; Yadav et al., 2014). Another important observational feature is that occurrence of Esb is also observed during postmidnight period (00–06 IST), but it is relatively smaller as compared to the afternoon Esb peak occurrence. Such early morning occurrence has been reported earlier by Devasia (1976) for a period of high solar activity. It is clearly seen that Esb occurrence has a wider spread in local time on disturbed days as compared to that on quiet days. On disturbed days, the occurrence is observed mainly during 10–19 IST with the maximum around 15 IST. Also, the peak occurrence during the afternoon period is found to be marginally suppressed.

3.2. Solar Flux and Seasonal Dependence of Esb

Since there are relatively larger (few months) data losses during certain years, we could not draw a meaningful information on the trend of Esb occurrence throughout solar cycle 23. It should be noted that except the data loss during few months, the ionosonde observations are available for the remaining months of a given year. Thus, we excluded all data loss days for further analysis. We treated each day's observations as an information and compiled the database, which was later separated into multiple bins based on the solar flux proxy, viz.,

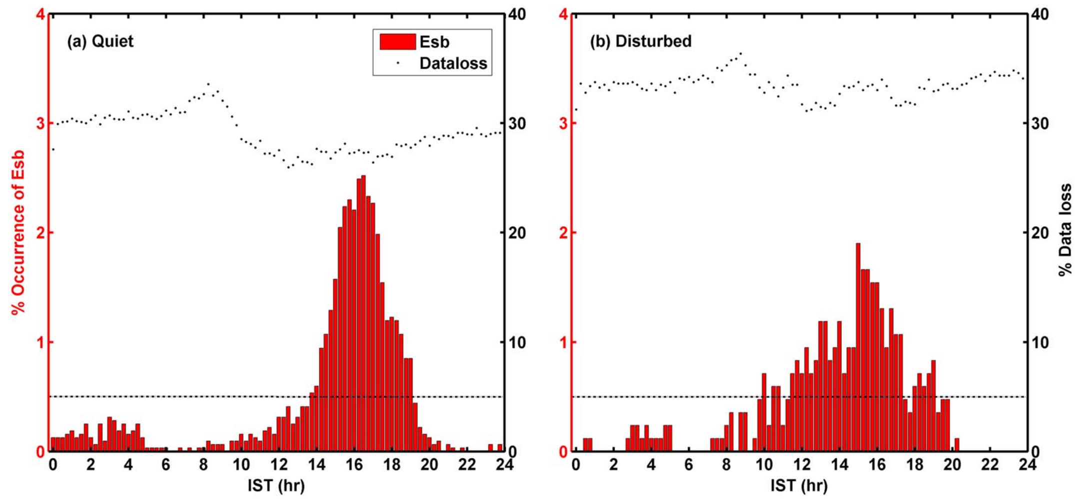

Figure 4. Percentage occurrence of Esb as a function of IST for (a) quiet and (b) disturbed days during 1996–2006. The horizontal lines indicate occurrence on 0.5% days.

$\Phi_{10.7P} \leq 90$, $90 < \Phi_{10.7P} \leq 110$, $110 < \Phi_{10.7P} \leq 130$, $130 < \Phi_{10.7P} \leq 150$, $150 < \Phi_{10.7P} \leq 180$ and $180 < \Phi_{10.7P}$ such that each category contains statistically significant number of days. We then plotted the percentage of days with Esb as a function of the average solar flux proxy to show the effect of solar activity on Esb occurrence. It is evident from Figures 5a and 5b that Esb occurrence decreases with increase in solar activity, as reported earlier (Chandra & Rastogi, 1975; Devasia et al., 2006). Second, it is found that solar flux dependence of Esb occurrence during magnetically disturbed time is similar to that during quiet time. It suggests that the solar flux dependence of Esb occurrence is less significantly affected by magnetic activity. The numbers in parenthesis represent total number of days and average of daily $\sum Kp$ for each solar flux category, respectively. It is evident from average of daily $\sum Kp$ values that the magnetic activity level did not change much between the categories for quiet days. The same holds true for disturbed days as well. Here we are discussing only Esb events and not the nonblanketing Es. Contrary to this, if we examine the occurrence of Es close to the dip equator, we will find opposite dependence on solar flux, as its formation is directly linked to the electrojet currents. As reported by earlier studies, the peak occurrence of Es is generally seen during equinoctial months of high solar activity, when polarization electric field associated with EEJ is stronger (Abdu et al., 1996; Oyinloye, 1969).

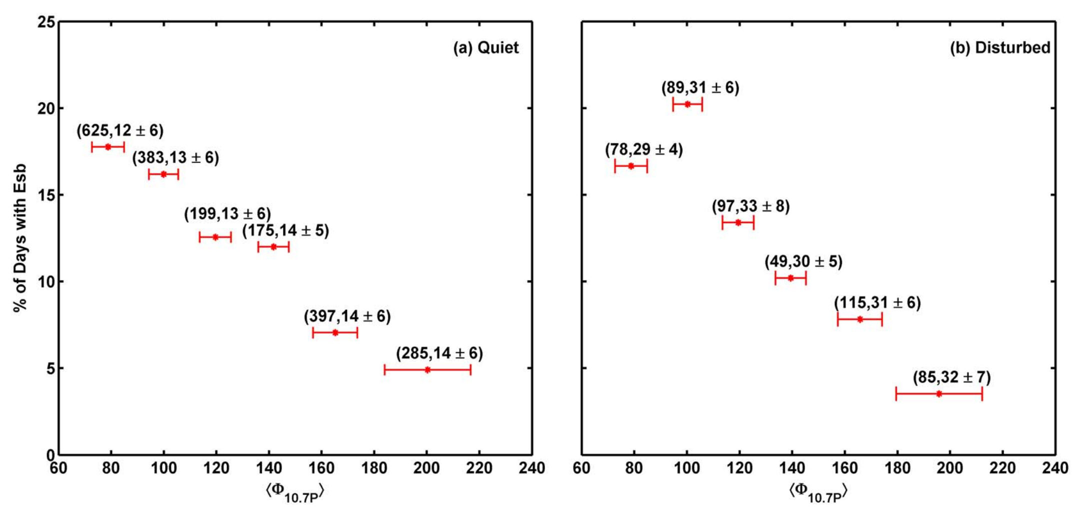

Figure 5. Percentage of days with Esb as a function of the average solar flux proxy during 1996–2006 for (a) quiet and (b) disturbed days. The numbers in parenthesis represent number of days for which ionosonde data are available and the average of daily $\sum Kp$, respectively, for each solar flux category. As solar activity increases, the occurrence of Esb decreases for quiet as well as disturbed days, which clearly indicates the inverse relation between the two parameters.

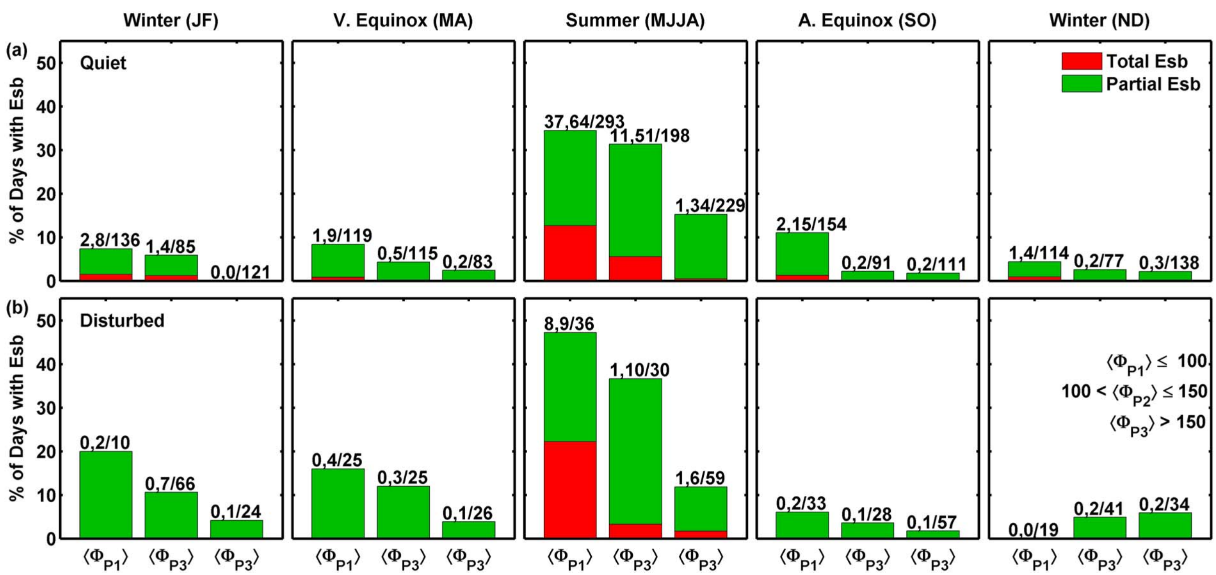

Figure 6. Percentage of Esb days for low, moderate, and high solar activity on (a) quiet and (b) disturbed days during various seasons in 1996–2006. Red bars represent days where blanketing frequency fbES ≥8 MHz is observed for an interval of 15 min or more. The three numbers mentioned on each bar represent the number of total blanketing and partial blanketing days out of all days for which ionosonde data are available, respectively.

Further, to investigate the seasonal variation of Esb occurrence for different solar flux conditions, we have separated the observations into three levels of solar activity, viz., low ($\Phi_{10.7P} \leq 100$), moderate ($100 < \Phi_{10.7P} \leq 150$), and high ($\Phi_{10.7P} > 150$). For these three categories, the characteristics of Esb are investigated and they are presented here. The average solar flux proxy for each of these categories is represented by $\langle\Phi_{P1}\rangle$, $\langle\Phi_{P2}\rangle$, and $\langle\Phi_{P3}\rangle$ respectively. Figure 6 shows seasonal percentage of Esb days in each solar activity based category for (a) quiet and (b) disturbed days. The seasons are winter (January–February), vernal equinox (March–April), summer (May–August), autumnal equinox (September–October), and winter (November–December). The bars represent the percentage of Esb days, where the green portion of a bar represents partial blanketing days and the red portion represents total blanketing days. It is seen that the occurrence of Esb is highest during the summer as compared to other seasons for all three levels of solar activity. It is in accordance with earlier studies (Bhargava & Subrahmanyan, 1964; Chandra & Rastogi, 1975; Devasia, 1976; Devasia et al., 2006; Yadav et al., 2014). If we compare Esb occurrence during a given season for different solar activity levels, then it is found to exhibit peak during the low solar activity period, $\langle\Phi_{P1}\rangle$. Summer days of high solar activity ($\langle\Phi_{P3}\rangle$) exhibit much lower occurrence as compared to low ($\langle\Phi_{P1}\rangle$) and moderate ($\langle\Phi_{P2}\rangle$) solar activity days. In other seasons, the occurrence is much smaller and mainly confined to low solar activity days only. The tendency of Esb occurrence on disturbed days is similar to that on quiet days. But the percentage occurrence of Esb is higher on magnetically disturbed days as compared to that on magnetically quiet periods in summer (May–August).

A notable feature is that total blanketing is more frequent during low solar activity, particularly for disturbed days. If we consider individual seasons, then the relative percentage of total blanketing is found to be much higher during summer. So (i) dominant occurrence of total blanketing Es on quiet days of summer during low solar activity, and (ii) significant increase in its occurrence during magnetically disturbed periods are two important observational aspects that emerge from Figure 6. We need to understand the possible cause for such dependence. In a review article by Haldoupis (2011), it is mentioned that tidal wind, the Earth's horizontal magnetic field component, and the meteoric deposition of metallic material play an important role in the dynamics of Es/Esb. Studies have demonstrated that the meteoric input peaks around local summer (Janches et al., 2004; Singer et al., 2004). In a recent study, Vineeth et al. (2016) have shown that meteoric input in Earths atmosphere peaked around local summer during low solar activity period of 2006–2007 by using observations from Trivandrum. However, there are some exceptions as well. Janches et al. (2006) have shown that the occurrence of micrometeors peaks around June and it remains high till January with maximum duration of 6 h in autumn (September–October). As meteor contribution from different distant sources varies with location and time, variations in seasonal peak are expected. Apart from meteor counts, the mass influx

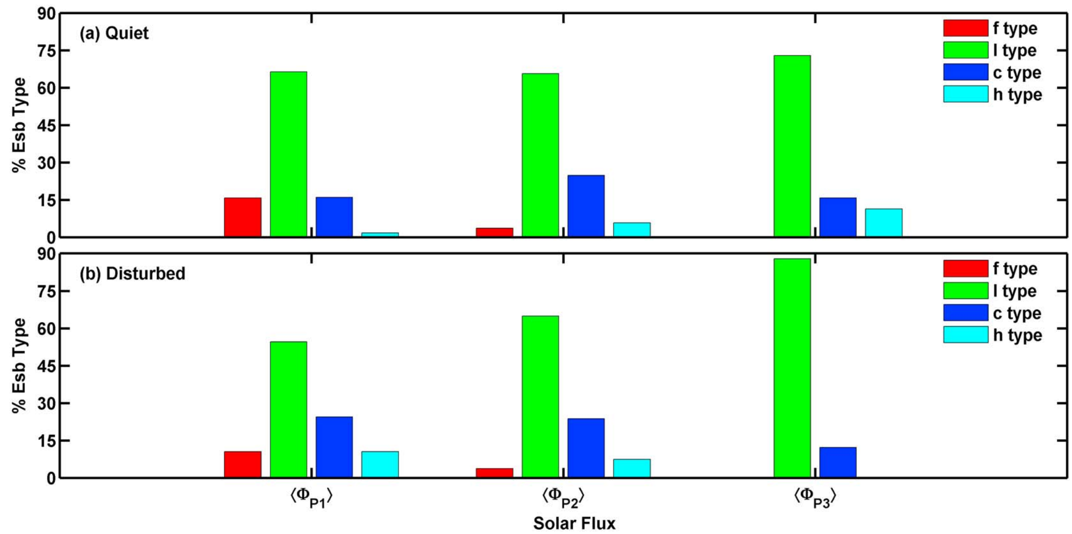

Figure 7. Percentage of different types of Esb (*f*, *l*, *c*, and *h* type as per Wakai et al. (1985)) out of all Esb events for low, moderate and high solar activity categories on (a) quiet and (b) disturbed days.

of meteors is equally important as meteor showers have lower mass influx as compared to sporadic meteors (Mathews et al., 2001). Meteors deposit their energy at *E* region and enhance the metallic ion density at that altitude. Due to their lower recombination rates, these metallic ions can assist in sustaining the ionization for longer duration once the generation process of Esb is initiated. Thus, we propose that the enhanced meteoric input during local summer can help in sustaining higher electron densities, resulting in higher blanketing frequencies. On disturbed days, presence of higher fbEs during a geomagnetic storm has been reported for a station close to dip equator in the Brazilian sector (Denardini et al., 2016). *E* region tidal winds and electric fields play key roles in the formation of Esb (Resende et al., 2016, 2017), even at latitudes closer to the dip equator. Modulation in electric field and ambient winds resulting from geomagnetic activity are known to us. These modified ambient conditions might be assisting the formation of Esb with enhanced blanketing frequencies close to the dip equator.

In addition to the presence/absence of Esb, we noted the types of each 15 min Esb event. Figure 7 shows the percentage occurrence of *f*-, *l*-, *c*-, and *h*-type Esb out of all Esb events in each category of low, moderate, and high solar activity on (a) quiet and (b) disturbed days. The sum of all types' occurrence is 100% for each flux category. Hence, the percentage occurrences indicate relative contribution of the four types out of all Esb events in each flux category. We find that both on quiet and disturbed days, *l*-type Esb is dominantly observed at Trivandrum, followed by *c*-type Esb. The occurrence of *c*- and *h*-type Esb is clearly higher on magnetically disturbed days as compared to quiet days for low solar activity. The occurrence of each type is more or less the same for quiet as well as disturbed days for moderate solar activity levels. For high solar activity, only *l* type's occurrence is higher on disturbed days, whereas *c* and *h* type have higher occurrence on quiet days. For all solar activity levels combined, percentage occurrence of *f*-, *l*-, *c*-, and *h*-type Esb are 9.9 (6.8), 67.1 (62.9), 18.6 (22.3), and 4.4 (8.0), respectively, for quiet (disturbed) days. To the best of our knowledge, this is probably the first comprehensive information on types of Esb based on a large data set close to dip equatorial station.

3.3. Variation of Blanketing Frequency and Duration of Esb

Here we have explored two important characteristics of Esb, viz., blanketing frequency and duration, during quiet and disturbed periods for the three different solar activity levels. Further, we classified fbEs of all Esb events into $4 \le$ fbEs < 6 MHz, $6 \le$ fbEs < 8 MHz, and fbEs ≥ 8 MHz categories. These categories are made to examine the impact of solar activity on fbEs. Figure 8 shows the percentage occurrence of Esb in these three fbEs ranges as a function of IST for low, moderate, and high solar flux on (a) quiet and (b) disturbed days. Average solar flux proxy ($\langle \Phi_{10.7P} \rangle$) and average of daily $\sum Kp$ are mentioned for each solar flux category having *n* number of days. Overall Esb occurrence is mainly seen during low to moderate solar activity days during both quiet and disturbed periods. Nighttime occurrence is mainly seen during low solar activity with lower fbEs values, whereas larger fbEs (≥8 MHz) occurs mostly in afternoon period during low solar activity for

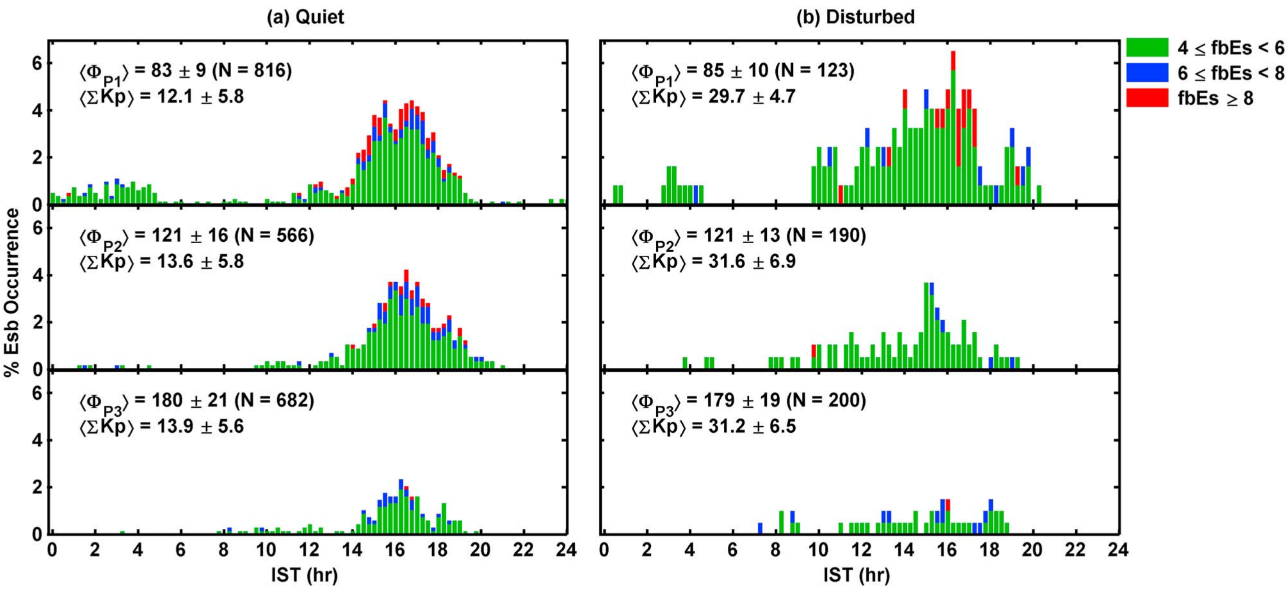

Figure 8. Percentage occurrence of Esb, categorized into three ranges of fbEs, as a function of IST for low (Φ_{P1}), moderate (Φ_{P2}), and high (Φ_{P3}) solar activity on (a) quiet and (b) disturbed days during 1996–2006. Average solar flux proxy ($\langle\Phi_{10.7P}\rangle$) and average of daily $\sum Kp$ are mentioned for each category having N number of days for which ionosonde data are available.

quiet as well as disturbed days. Moderate solar activity days show lower occurrence of Esb with large fbEs. For high solar activity, this occurrence is still lower. This indicates that blanketing frequency, fbEs decreases with increase in solar activity. An important feature observed here is the postmidnight (00–06 IST) occurrence of Esb during low solar activity period. Such a tendency has been reported earlier by Devasia (1976) at Trivandrum during high solar activity period of 1969–1972 (average solar flux 136 ± 19), but it is worth noticing that during that period Trivandrum was located south of dip equator (dip latitude ∼ 0.6°S). Also, the peak occurrence of Esb during that period was seen around 18.5 LT at 75° longitude (or 19 IST), which is 3 h later than the peak occurrence time of 16 IST reported in the present study. The inclination varies between 0.6°–1.85° during 1996–2006 for Trivandrum. Although efficiency of wind shear mechanism is low close to dip latitude, it can be still operational to produce Esb when the vertical polarization electric field in the *E* region is weaker (Resende et al., 2016). Christakis et al. (2009) suggested that diurnal and semidiurnal modes of tidal winds are effective at different times of the day. The semidiurnal component of tidal wind is mainly responsible for sporadic *E* observed in late evening hours (Arras et al., 2009). Thus, the variation in the time of peak Esb occurrence noticed during 1969–1972 and 1996–2006 may be attributed to different tidal wind modes, which could be effective at different times on a given day. The influence of dip latitude on the time of peak Esb occurrence is manifested through the local dynamics of ambient tidal winds. In addition to this, it may be noted that Devasia (1976) has not employed any threshold limit on the blanketing frequency while attributing a given time interval to the Esb occurrence. Whereas in our study, we have particularly chosen stronger Esb events (fbEs ≥ 4 MHz). This limiting criterion may have some influence on the local time distribution of Esb occurrence.

The variation in fbEs is reported for the first time for quiet and disturbed periods in the present study. It is seen that Esb observed during postmidnight in low solar activity period are associated with lower fbEs values. However, their formation during this period is not yet clearly understood.

We have also studied the impact of solar activity on the duration of Esb. For this, we classified the duration of Esb on a day (D) in three ranges, $0.5 \le D < 1$, $1 \le D < 2$, and $2 \le D$, where D is in hours. The percentage of days having Esb duration in each of these categories for three different levels of solar flux is illustrated for (a) quiet and (b) disturbed periods in Figure 9. It indicates that the percentage of short ($0.5 \le D < 2$) duration Esb is in general higher in comparison with long duration Esb ($2 \le D$) for both quiet and disturbed periods. Second, it is noted that the percentages of long ($2 \le D$) duration Esb events are lower during high solar activity period as compared that during low solar activity period mainly for disturbed periods. This means that during high solar activity, Esb events are likely to be of short duration. Thus, not only the occurrence of Esb is higher

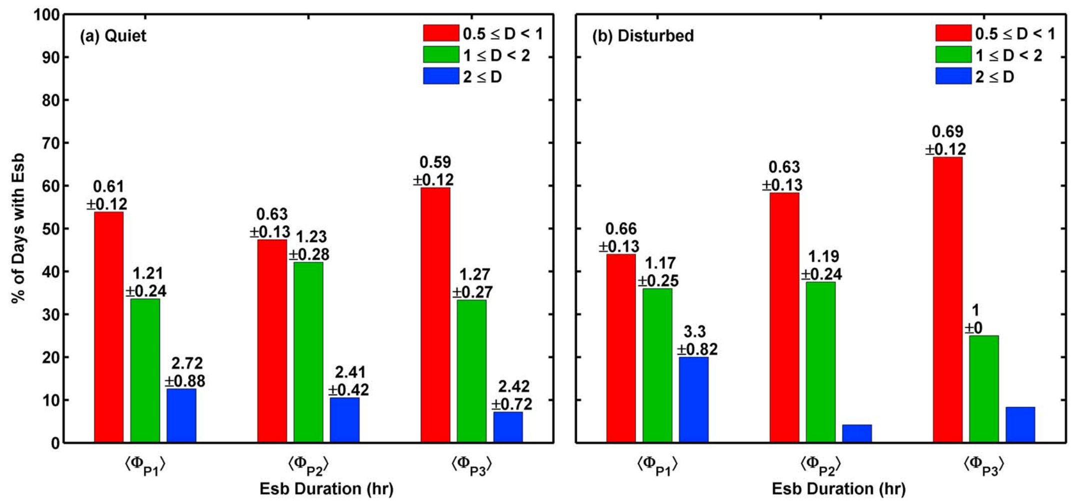

Figure 9. Percentage of Esb days, categorized as per Esb duration (*D*), for low (Φ_{P1}), moderate (Φ_{P2}), and high (Φ_{P3}) solar flux on (a) quiet and (b) disturbed days during 1996–2006. Average duration of Esb for each category is mentioned over each bar. The average duration is not mentioned on corresponding bar if the number of Esb days under that category is less than 3.

during the low solar activity, but their persistence and the blanketing frequency is larger as well for disturbed periods. This tendency is only marginal for quiet periods. The other evident feature is the twofold increase in the percentage occurrence of long-duration Esb on magnetically disturbed days as compared to quiet days for low solar activity period. It indicates that magnetic disturbance assists Esb to sustain for longer duration, which is attributed to changes in tidal wind and electric field due to magnetic activity.

3.4. Association of Esb and CEEJ

Many previous studies have reported coexistence of Esb and CEEJ, which means that Esb is often found to be present during the time of CEEJ. The two phenomena also primarily occur in afternoon hours in summer at dip equatorial regions. Based on this, the earlier researchers have attributed the occurrence of Esb to CEEJ (Bhargava & Subrahmanyan, 1964; Chandra & Rastogi, 1975; Devasia et al., 2006; Sen Gupta & Krishna Murthy, 1975). However, these studies did not examine the occurrence of Esb on non-CEEJ days. Mere simultaneous occurrence of the two phenomena does not necessarily mean that CEEJ and Esb are driven by the same mechanism. In fact, it is known that ambient zonal electric field and wind-driven component of electric field together contribute to the vertical electric field and, hence, to the presence/absence of CEEJ (Richmond, 1973; Stening, 1985), whereas Esb is formed through wind shear mechanism at mid, low, and quasi equatorial locations. However, their coexistence at many occasions motivated us to investigate this relationship more rigorously. If CEEJ and Esb are independent phenomena exhibiting higher occurrence during the same periods, then their simultaneous occurrence is quite likely. Let us assume that there are some common ambient source drivers, presence of which is (i) assisting the formation of Esb, and (ii) contributing to the vertical polarized electric field responsible for the CEEJ. Hence, it is important to examine the occurrence of Esb on non-CEEJ days as well. In this context, Yadav et al. (2014) have attempted to understand this association. These authors examined the occurrence of Esb on CEEJ and non-CEEJ days and showed that the association of Esb and CEEJ is season dependent. However, this work encompasses only the extremely low solar activity period of 2007–2009. As a result, it is not yet known if this association has any solar activity dependence. To answer this question, we need to examine the association of Esb and CEEJ during different seasons for varying solar activity levels. This exercise has been performed only for quiet days as the conventional estimation of CEEJ/EEJ on disturbed days can be uncertain due to the presence of ring current (Rastogi, 1992; Uozumi et al., 2008). We have fixed a threshold of −10 nT for CEEJ to identify unambiguous CEEJ events. A day with the minimum of EEJ ≤ -10 nT is considered as a CEEJ day. As Esb occurrence is dominantly seen during postnoon periods, we have considered only afternoon CEEJ events and morning CEEJ days are excluded. To do so, we applied a condition that $EEJ_{min} > -10$ nT before 11.5 IST and $EEJ_{min} \leq -10$ nT after 11.5 IST. Here a day with total Esb duration $\geq$30 min during 06–22 IST is considered as Esb day. This has been done to exclude the days having only nighttime Esb occurrence. After this, the analysis used by Yadav et al. (2014) has been performed, that is,

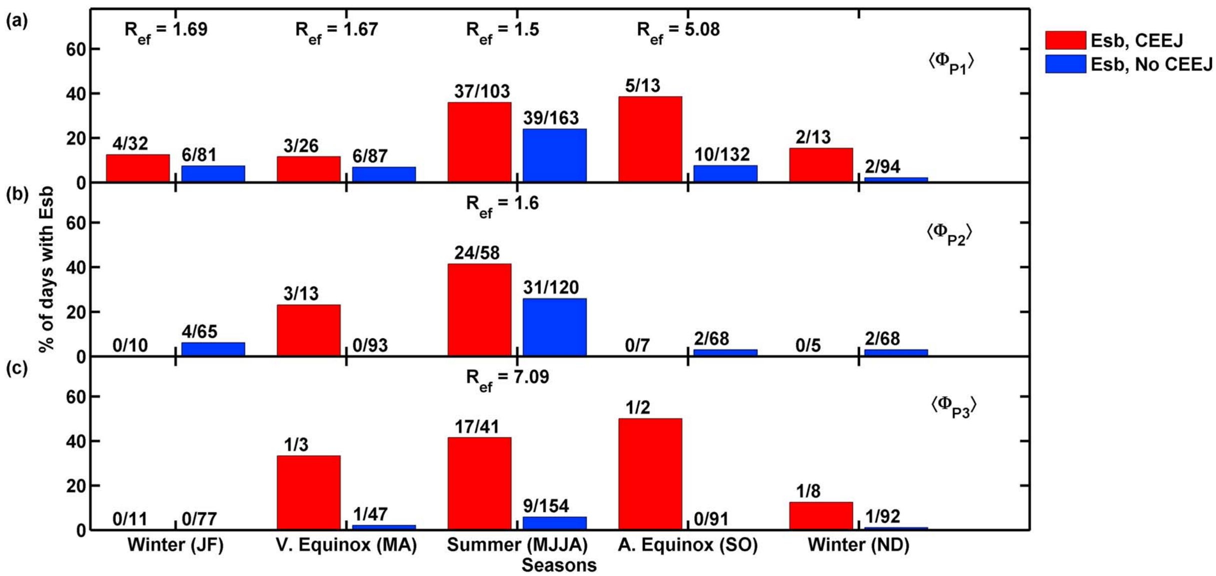

Figure 10. Percentage of number of Esb days for category I (with CEEJ) and category II (without CEEJ) for (a) low, (b) moderate, and (c) high solar activities on quiet days during various seasons in 1996–2006. The number of days displayed above each bar represent the number of Esb days and total days in the corresponding category. R_{ef} is the ratio of percentage of Esb days for category I to that for category II. R_{ef} is not calculated wherever either of the percentages is less than 5.

we determined the percentage of days with Esb on CEEJ (category I) and non-CEEJ days (category II) as shown in Figure 10. We then calculated the ratio of these two percentages, R_{ef}, which indicates the efficiency of Esb and CEEJ association. It should be noted that R_{ef} has been calculated only for those cases where the percentage of Esb days is ≥5% in both the categories to get a reliable value of R_{ef}. Due to this, R_{ef} is available only for summer season for all the solar activity levels when Esb occurrence is more likely as compared to other seasons. It is found that R_{ef} is greater than 1 for all the solar activity levels, and it increases with increase in the solar activity. This implies that Esb occurrence is certainly more likely on CEEJ days as compared to non-CEEJ days. However, this association strengthens as solar flux increases. It means Esb is most likely to occur on CEEJ days during high solar activity, whereas occurrence of Esb is quiet likely even on non-CEEJ days during low solar activity. It should be noted that the number of CEEJ days during high solar activity is lesser as compared to low solar activity. However, for summer during high and low solar activity periods the number of CEEJ days is 41 and 103, respectively, which are statistically adequate to investigate such dependence. The observed solar flux dependence of coexistence of Esb and CEEJ can be understood in light of the recent study by Resende et al. (2016), which suggests that formation of Esb through wind shear mechanism closer to the dip equator is more favorable if vertical polarization electric field is weaker than 3.85 mV/m. During high solar activity, EEJ is stronger as compared to low solar activity period, indicating presence of substantially stronger electric fields (both zonal and vertical). Weaker vertical polarization electric field can be easily present during CEEJ events. Therefore, the association of CEEJ and Esb is stronger during high solar activity periods.

Further, we looked at the percentage occurrence of Esb as a function of IST and corresponding EEJ profiles for the 17 days in category I of high solar activity when Esb and CEEJ both occurred on the same day as shown in Figure 11a. The average EEJ profile is shown by the black curve. It can be seen that Esb occurs mainly during the depression in the average EEJ profile. Higher occurrence is seen close to the evolutionary phase of CEEJ, which indicates the strong linkage between CEEJ and Esb during high solar activity period. We then decided to check if early onset of CEEJ has any noticeable effect on Esb occurrence. For this we selected the Esb days with strong morning CEEJ events, that is, $EEJ_{min} \leq -15$ nT before 11.5 IST and $EEJ_{min} > -10$ nT after 11.5 IST, during summer season. There were only few such events across all solar activity levels. Hence, the percentage occurrence of Esb as a function of IST and corresponding EEJ profiles have been combined for all days with different solar flux and shown in Figure 11b. Early occurrence of Esb is noticed for these strong morning CEEJ days as compared to the category I days shown in Figure 11a. Even the peak Esb occurrence is about an hour earlier. It indicates that the days with prenoon CEEJ have a tendency to assist earlier formation of Esb.

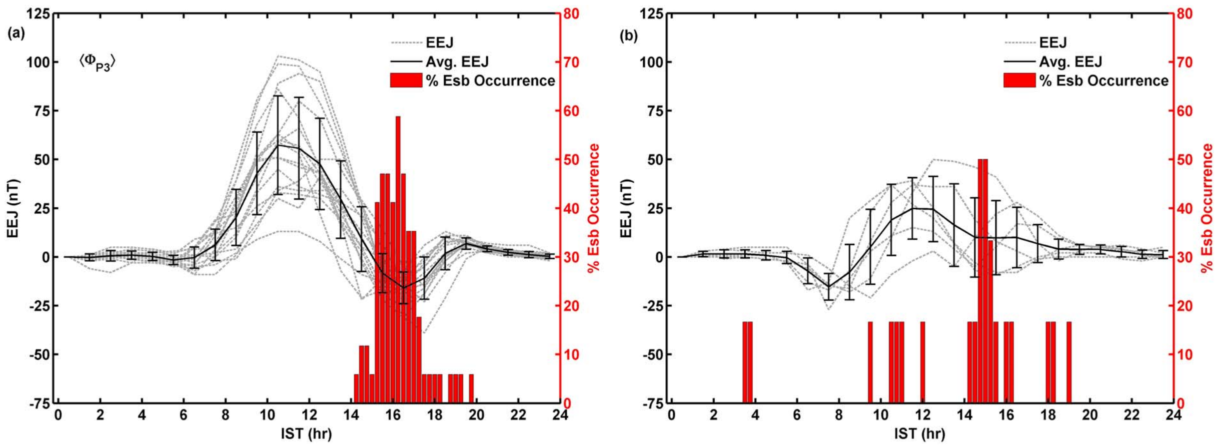

Figure 11. Percentage occurrences of Esb as a function of IST during summer (MJJA) months of 1996–2006 for (a) high solar activity days under category I with corresponding EEJ profiles and (b) all strong morning CEEJ days ($EEJ_{min} \leq -15$ nT) with corresponding EEJ profiles for all solar activity levels combined.

4. Discussion

There have been few studies on Esb occurrence over a complete solar cycle close to the dip equator. In the present study we have investigated Esb characteristics like occurrence, blanketing frequency, duration, and its type as a function of local time, season, solar flux, and magnetic activity. In general, the results obtained here are in agreement with earlier studies (Chandra & Rastogi, 1975; Devasia et al., 2006) with some new important features, which are discussed here. Frequent occurrence of CEEJ and Esb during afternoon hours in summer have been reported in previous works (Bhargava & Subrahmanyan, 1964; Chandra & Rastogi, 1975; Devasia et al., 2006; Sen Gupta & Krishna Murthy, 1975). According to Devasia et al. (2006), higher occurrence of Esb during solar minimum periods is associated with CEEJ events of lesser intensity. On the other hand, less frequent occurrence of Esb during solar maximum periods is associated with stronger CEEJ events. However, these studies have not looked at Esb occurrence on non-CEEJ days. For the first time, Yadav et al. (2014) examined the occurrence of Esb on CEEJ and non-CEEJ days separately and showed that their association is not as straightforward as reported in earlier studies; rather, it varies seasonally. These authors found that the association of Esb and CEEJ is the weakest during summer and strongest during winter (November–December) during the extremely low solar activity period of 2007–2009. Hence, there was a need to examine this association for different solar flux conditions. In the present study, we have shown that the association between Esb occurrence and CEEJ becomes stronger with increase in solar activity. It means that Esb occurrence is most likely on CEEJ days during high solar activity period.

Earlier studies have attributed the formation of CEEJ to superposition of Sq current system with other current systems reported to be generated by combination of the solar semidiurnal and diurnal tides (Gurubaran, 2002; Hanuise et al., 1983; Marriott et al., 1979; Stening, 1977). Others have ascribed it to local or global changes in zonal winds (Reddy & Devasia, 1981; Somayajulu et al., 1993; Stening et al., 1996). However, how quiet time CEEJ and electric field favor the formation of Esb can be understood in light of recent study by Resende et al. (2016). They have shown that wind shear mechanism is also operative close to the dip latitude, and it forms Esb in the presence of weaker polarization electric fields. For Brazilian sector, a threshold of 3.85 mV/m is suggested for the vertical polarization electric field. It is known that EEJ has solar activity dependence and a semiannual variation with solstitial minima and equinoctial maxima (Yadav et al., 2014, and references therein). Additionally, EEJ strength increases during high solar activity years. Both these effects have been shown in Figure 12 for the period considered under the present study. EEJ strength is an indicator of the vertical polarization electric field associated with EEJ. This means that the polarization electric field is weaker during solstices and solar minimum as compared to equinoxes and solar maximum periods, respectively. Presence of weaker electric field during CEEJ period can help the formation of Esb through wind shear. As Trivandrum is not exactly over dip equator, the wind shear mechanism can be still weakly operative over there. The formation of Esb exactly over dip equator is still an open question though.

Tsunoda (2008) has explained occurrence of Esb at dip equator by "transport mechanism." It proposes that Esb from off-equatorial region is transported to the dip equator by neutral winds having speeds greater than a

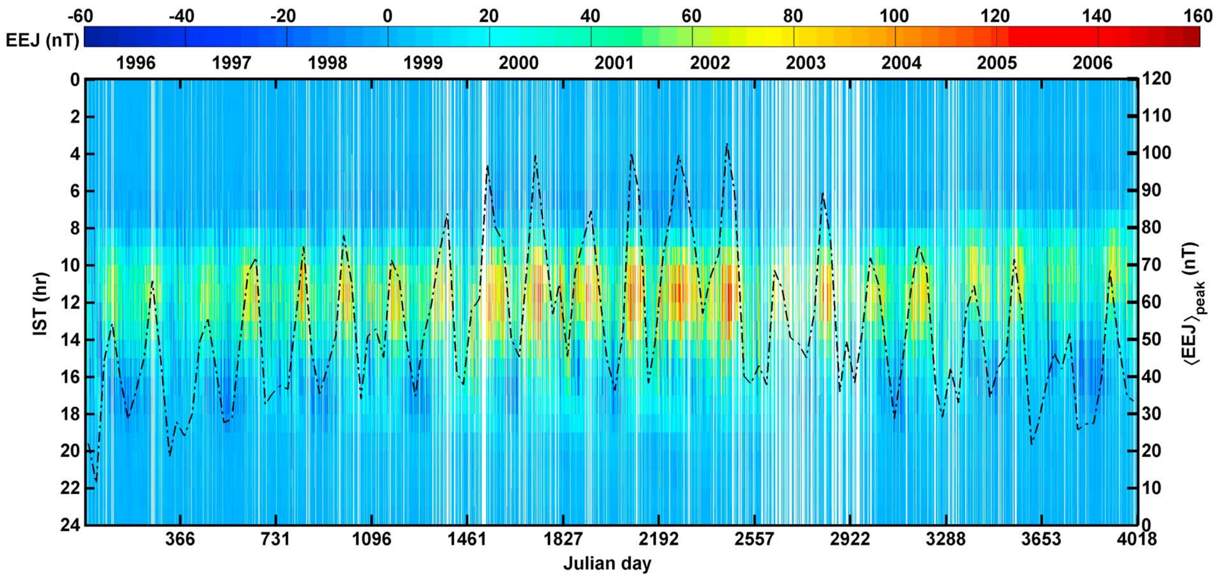

Figure 12. Daily temporal variation of EEJ for the period 1996–2006. The dotted line represents the maximum of monthly averaged EEJ.

threshold speed determined by the polarization electric field. Thus, Esb observed at a low-latitude/equatorial station like Trivandrum can have some contribution from Esb transported from mid latitudes, in addition to their local generation as suggested by Resende et al. (2016, 2017) at quasi equatorial stations. They have also shown that when EEJ reverses during nighttime at São Luís in Brazil, Esb layers formed by wind shear are observed. On the other hand, nighttime Esb at Trivandrum is observed only during low solar activity periods and the occurrence is much lower as compared to the daytime hours. This could indicate that wind shear mechanism over Trivandrum generates fewer Esb layers and the larger contribution is by the transport mechanism. However, whether an observed Esb is transported or locally generated is not known, as their identification is not straightforward. Thus, for a better understanding of Esb dynamics close to the dip latitude, local wind observations at *E* region altitudes are essential.

Another important aspect of this study is Esb occurrence on disturbed days. During disturbed periods, both electric field and ambient neutral winds in the ionosphere (both *E* and *F* regions) get affected due to the magnetic disturbances (Abdu et al., 2013; Blanc & Richmond, 1980; Kikuchi et al., 1996). Present study indicates that the occurrence of Esb is marginally affected by magnetic activity during periods of low solar activity. However, characteristics of Esb like its duration and blanketing frequency are significantly affected by magnetic activity linked changes in *E* region. Previous studies have reported no significant effect of magnetic activity on blanketing frequency fbEs or occurrence of Es layers using observations from various stations located at mid to low latitudes (Awe, 1971). Higher blanketing frequencies are reported during the recovery phase of a geomagnetic storm (Denardini et al., 2016). It is worth noting that Esb layers are intense form of Es layers at mid latitudes, which are formed by the wind shear mechanism. Present observations are attributed to the modulations in tidal winds and electric field in the *E* region that strengthen the wind shear mechanism.

Lastly, we find increased postmidnight (00–06 IST) occurrence of Esb during low solar activity period and nearly no nighttime occurrence with increase in solar activity. This is in contrast to the postmidnight occurrence at Trivandrum reported earlier during high solar activity period by Devasia (1976). Previous studies examining night time Esb occurrence and fbEs at mid latitude locations give varying conclusions. Some of these studies suggest no clear dependence of occurrence of Esb on solar activity, whereas some suggest a negative correlation between the two. However, most of these studies agree on nighttime fbEs being independent of solar activity (Awe, 1971; Sastri & Murthy, 1975, and references therein).

5. Summary and Conclusion

This work is a detailed statistical investigation of seasonal Esb occurrence during solar cycle 23 (1996–2006), using data from digisonde at dip equatorial station Trivandrum in Indian longitudes. Solar flux and seasonal dependence of Esb occurrence has been investigated for both quiet and disturbed periods thoroughly.

The results of the study are in general agreement with the earlier works on Esb. Earlier study by Yadav et al. (2014) reported that Esb and CEEJ association is weaker during summer (May – August) as compared to other seasons. However, this study was based on the observations from extremely low solar activity period (2007 – 2009). The new finding of the present study is that the association of Esb and CEEJ during summer season strengthens as solar flux increases. It indicates that the Esb observed during summer in high solar activity periods are most likely to be associated with CEEJ. It supports the finding of Resende et al. (2016, 2017) that suggest vertical polarization electric field as a key factor in the formation of Esb through wind shear mechanism. Second important outcome of the study is that magnetic activity affects Esb occurrence marginally, but its influence on Esb duration and frequency is noticeable. In addition, we present a detailed statistics of types of Esb for solar cycle 23. The main findings of the present study are summarized as follows:

1. Occurrence of Esb is highest during afternoon hours in summer and increases with decreasing solar activity. This is in general agreement with earlier studies (Bhargava & Subrahmanyan, 1964; Chandra & Rastogi, 1975; Devasia, 1976; Devasia et al., 2006; Yadav et al., 2014).
2. Temporal variation of Esb occurrence is slightly wider on disturbed days as compared to that on quiet days. It indicates that the duration of Esb on magnetically disturbed days is larger as compared to those on quiet days. Also, the percentage of total blanketing is found to be significantly larger during disturbed periods in summer for low solar flux.
3. Blanketing frequency and duration of Esb tend to be larger during low solar activity periods for both quiet and disturbed periods.
4. Association of Esb and CEEJ gets stronger with increase in solar activity. It clearly indicates that there are some common source drivers assisting their physical mechanism.
5. Prenoon CEEJ assists the formation of Esb at an earlier time than the usual peak Esb occurrence in the postnoon period.
6. Almost all the postmidnight (00 – 06 IST) occurrences of Esb are seen during low solar activity period. However, the cause for its generation needs to be explored with observations and theoretical studies.
7. We find that dip latitude influences the peak occurrence time of Esb, and it is manifested through the local dynamics of ambient tidal winds.

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