Ann. Geophys., 32, 553–562, 2014
www.ann-geophys.net/32/553/2014/
doi:10.5194/angeo-32-553-2014
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Annales Geophysicae
Open Access

# Occurrence of blanketing $E_s$ layer ($E_{sb}$) over the equatorial region during the peculiar minimum of solar cycle 24

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Received: 2 December 2013 – Revised: 29 March 2014 – Accepted: 7 April 2014 – Published: 26 May 2014

**Abstract.** A thin and highly dense sporadic E layer, which can occasionally block the upper ionospheric layers, is called blanketing sporadic E ($E_{sb}$). We present the statistical seasonal local time occurrence pattern of $E_{sb}$ at equatorial station Tirunelveli (8.7° N, 77.8° E, dip latitude 0.7° N) during the extended minimum of solar cycle 24 (2007–2009). In spite of nearly the same average solar activity during both 2007 and 2009, considerable differences are noticed in the seasonal occurrence of $E_{sb}$ during this period. The percentage of $E_{sb}$ occurrence is found to be the highest during the summer solstice ($\geq 50\,\%$) for both 2007 and 2009, which is in general accordance with the earlier studies. The occurrences of $E_{sb}$ during the vernal equinox ($\sim 33\,\%$) and January–February ($\sim 28\,\%$) are substantial in 2009 as compared to those during the same seasons in 2007. We find that, during winter (January–February), $\sim 75\,\%$ of $E_{sb}$ occurred during or just after the period of sudden stratospheric warming (SSW). We suggest that enhanced $E_{sb}$ occurrence during winter (January–February) and the vernal equinox of 2009 could be associated with SSW-driven changes in the E region ambient conditions. Furthermore, the close association of $E_{sb}$ with counter equatorial electrojet (CEEJ) suggested by earlier studies is re-examined carefully using the scenario of $E_{sb}$ occurrence on non-CEEJ days. Such an exercise is crucial as we are unaware whether the physical mechanisms driving $E_{sb}$ and CEEJ are linked or not. We find that, of all the seasons, the association of $E_{sb}$ and CEEJ is strongest during winter (November–December).

**Keywords.** Ionosphere (equatorial ionosphere; ionospheric irregularities)

## 1 Introduction

The ionospheric E region is characterized by the presence of thin layers of enhanced ionization at heights of 100–120 km, known as sporadic E ($E_s$). At equator, $E_s$ is patchy and transparent to the radio waves reflected from layers at higher altitudes (Rishbeth and Garriott, 1969). However, sometimes these layers are highly dense, known as blanketing type sporadic E ($E_{sb}$), which effectively blocks the upper ionospheric layers to the radio waves. Occasionally, $E_{sb}$ can be very strong, causing scintillations in VHF radio signal (Rastogi and Mullen, 1981). $E_{sb}$ at the equator, mid- and high-latitudes has been studied for over half a century, yet its seasonal occurrence pattern globally remains a puzzling feature. Whitehead (1989, 1997a, b) has discussed unsolved problems in understanding the formation of $E_{sb}$ at different latitudes.

Most of the $E_{sb}$ observations at mid-latitudes are addressed by the well known wind-shear theory (Whitehead, 1961; Axford, 1963). However, this theory fails at the dip equator where the Earth's magnetic field is nearly horizontal. It is reported that $E_{sb}$ is observed at equatorial latitudes as well but its occurrence is less than that away from the equator (Oyinloye, 1971; Abdu et al., 1996). Reddy and Devasia (1973) proposed theories to explain the formation of $E_{sb}$ at equatorial latitudes, which are based on the horizontal convergence of ions. The most widely observed features of $E_{sb}$ are its seasonal occurrence, which indicates a peak during the local summer (Bhargava and Subrahmanyan, 1964; Oyinloye, 1969; Chandra and Rastogi, 1975; Devasia, 1976; Devasia et al., 2006), and its anti-correlation with equatorial electrojet (EEJ) intensity (Tsunoda, 2008). The theories proposed for the formation of $E_{sb}$ do not explain its seasonal dependence and the role of EEJ. Based on long-term observations of meteors from mid-latitude stations, it is shown that the strength and occurrence of $E_s$ layer are closely related to the meteor influx (Haldoupis et al., 2007; Haldoupis, 2011). Tsunoda (2008) suggested the transport mechanism for the formation of $E_{sb}$ at the equator and established the dependence of EEJ for the first time.

Many observational and theoretical studies of low-latitude $E_{sb}$ were carried out during 1960s but there have been very few since the 1980s. The present work is motivated by two observational aspects of equatorial $E_{sb}$ reported earlier: (i) the occurrence of $E_{sb}$ is higher during low solar activity periods (Devasia, 1976; Devasia et al., 2006) and (ii) the occurrence of $E_{sb}$ is likely on a counter equatorial electrojet (CEEJ) day (Bhargava and Subrahmanyan, 1964; Chandra and Rastogi, 1975; Sen Gupta and Krishna Murthy, 1975; Devasia et al., 2006).

The minimum of solar cycle 24 is extremely low as compared to those of the previous few solar cycles and also peculiar due to several reasons. Many interesting observations are reported during this minimum (Echer et al., 2012). More than 500 sunspot-less days were observed during this solar minimum (de Toma et al., 2010). Recent studies have shown that the background ionospheric conditions were different during this solar minimum as compared to the previous solar minimum (Solomon et al., 2013). The occurrence of $E_{sb}$ has not yet been investigated during this peculiar low solar activity period (2007–2009).

Secondly, if we assume that CEEJ and $E_{sb}$ are two independent processes occurring predominantly in local summer, then it is likely that both the phenomena will be observed on the same day. However, this does not imply that there is a cause and effect relationship between the two. Though unlikely, it could well be a coincidence. Thus, we re-examine the dependence of $E_{sb}$ on CEEJ by taking into account the occurrence of $E_{sb}$ on non-CEEJ days. Such an exercise is extremely important to establish their relation, which is not addressed in earlier studies. The data used and results are elaborated in Sects. 2 and 3 respectively. The present observations are discussed in the light of existing theories in Sect. 4. The results are discussed and conclusions presented in Sects. 5 and 6 respectively.

## 2 Data and instrument description

CADI ionosonde data recorded at Tirunelveli (8.7°N, 77.8°E, dip latitude 0.7° N) during 2007–2009 is used in the present study. The ionograms are recorded at every 15 min and occasionally at every 5/10 min. These ionograms are manually examined to note the occurrence of $E_{sb}$ and its blanketing frequency ($fbE_s$), which is the minimum frequency at which the F region trace starts appearing in the ionograms. The events with $fbE_s \geq 4$ MHz are considered in the present study. The days with $\sum Kp \geq 24$ are taken as magnetically disturbed days and $E_{sb}$ events occurring on these days are excluded from the analysis. Magnetically disturbed days and non-availability of ionosonde data are represented by blue and white patches respectively in Fig. 1. Sometimes the F layer trace is completely invisible in the ionograms due to the presence of a strong $E_s$ layer known as total blanketing $E_s$. For the present study, $E_{sb}$ events with $4\,\text{MHz} \leq fbE_s \leq 8\,\text{MHz}$ are chosen as partial blanketing $E_s$, and $E_{sb}$ events with $fbE_s \geq 8$ MHz are chosen as total blanketing $E_s$. We also utilize ground-based observations of the geomagnetic field's H-component with 1-minute resolution, recorded by digital fluxgate magnetometer (DFM) at Tirunelveli and Alibag (18.6° N, 72.9° E, dip latitude 14.1° N). These $H$ observations are used to estimate EEJ during 2007–2009 (Patil et al., 1990a, b; Chandra et al., 2000). To verify whether the observation station is within the EEJ belt, we compute the magnetic inclination ($I$) at Tirunelveli using hourly magnetic field measurements during the period January 2007 to December 2009. For better temporal representation of the occurrence of $E_{sb}$, we divide a day into 15 min intervals, so we get 96 cells per day. If $E_{sb}$ is observed during the 15 min interval under consideration, then that cell is marked as a cell with $E_{sb}$. Sometimes more than one value of $fbE_s$ is present during a 15 min interval due to the availability of ionograms with 5/10 min sampling interval. In such cases, the largest $fbE_s$ value during that 15 min interval is assigned to the corresponding cell.

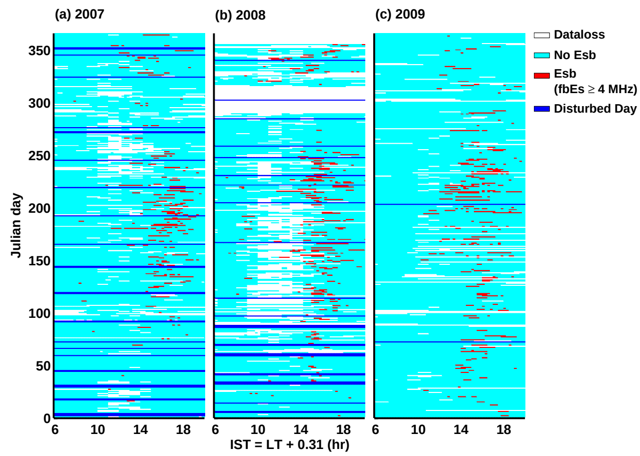


**Figure 1.** Occurrence of blanketing $E_s$ ($E_{sb}$) as a function of IST during **(a)** 2007, **(b)** 2008 and **(c)** 2009. Disturbed days ($\sum Kp \geq 24$) and data loss are shown by blue and white colour respectively.

## 3 Results

The results based on the $E_{sb}$ information retrieved from ionograms are presented and discussed in this section. We discuss the seasonal local time occurrence of $E_{sb}$ and their dependence on EEJ/CEEJ in Sects. 3.1 and 3.2 respectively. The duration of $E_{sb}$ are detailed in Sect. 3.3. Here, the figures are plotted as a function of Indian Standard Time (IST), where local time of the observation site LT = IST − 0.31 (hours).

### 3.1 Seasonal variation of the $E_{sb}$ occurrence

Daily information on the occurrence of $E_{sb}$ obtained from ionograms at 15 min resolution is compiled for each year and graphically presented in Fig. 1 for 2007–2009. A red patch indicates a 15 min interval where $E_{sb}$ with $fbE_s \geq 4$ MHz is observed on the ionogram during that time interval. White and blue patches in the figure represent loss of ionosonde data and magnetically disturbed days respectively. It should be noted that the occurrence of $E_{sb}$ is primarily seen between 10:00 and 20:00 IST, thus we calculate the seasonal local time percentage occurrence of $E_{sb}$ for this period. While computing percentage occurrence for a given 15 min bin, we make sure that the bin contains $E_{sb}$ information from at least 75 % of magnetically quiet days of the corresponding season. It should be noted that we encountered frequent data loss in 2008. Hence, for many of the 15 min bins in each season of 2008, the percentage occurrence of $E_{sb}$ is not computed. As we could not get a meaningful information on the occurrence of $E_{sb}$ during 2008, we discuss the results for 2007 and 2009 hereafter. For the winter season, we compute the percentage occurrence of $E_{sb}$ separately for January–February and November–December, as these months correspond to the same year and combining them together is not appropriate.

Figure 2 illustrates the percentage occurrence of $E_{sb}$ as a function of IST for summer solstice (May–August), winter solstice (January–February, November–December), vernal equinox (March–April) and autumnal equinox (September–October) of 2007 and 2009. We also compute the number of days with partial and total blanketing $E_s$ for each season, which is shown in Fig. 3 for 2007 and 2009. We put the condition that total duration of $E_{sb}$ event should be ≥ 30 min between 10:00–20:00 IST for a day to qualify as a day with $E_{sb}$. The percentage of number of days with $E_{sb}$ is mentioned over each bar in Fig. 3, except for autumnal equinox of 2007, as its estimated percentage is not reliable due to data loss of more than 25 %. Figures 2 and 3 yield the following important features of the $E_{sb}$ observations:

1. The occurrence of $E_{sb}$ is higher during 2009 as compared to 2007, which is particularly due to the enhanced $E_{sb}$ occurrence during winter (January–February) and vernal equinox of 2009.

2. It is observed that the occurrence of $E_{sb}$ is maximum during the summer solstice of both 2007 and 2009. This is in general agreement with the earlier studies on $E_{sb}$ (Bhargava and Subrahmanyan, 1964; Chandra and Rastogi, 1975; Devasia, 1976; Devasia et al., 2006).

3. The occurrence of $E_{sb}$ shows a larger spread over local time during the summer solstice of 2009 as compared to 2007.

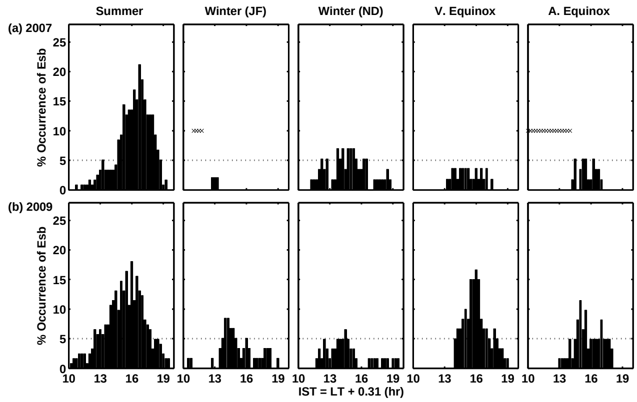


**Figure 2.** Seasonal percentage occurrence of $E_{sb}$ events as a function of IST during **(a)** 2007 and **(b)** 2009. The cross symbols indicate data loss on more than 25 % quiet days during that time bin. Horizontal dotted line represents 5 % occurrence of $E_{sb}$.

4. $E_{sb}$ is more likely to occur during 13:00–18:00 IST with a peak occurrence at around 16:00 (16.75) IST during the summer solstice of 2009 (2007). For the winter solstice (January–February, November–December) of 2009, the peak $E_{sb}$ occurrence is seen at around 14:00 IST.

5. Total blanketing $E_s$ events are predominantly seen during 2009 as compared to 2007. Their percentage occurrence is found to increase from ∼ 25 % in 2007 to ∼ 42 % in 2009.

Devasia et al. (2006) have shown that the $E_{sb}$ occurrence in the equatorial region is higher during low solar activity than that during high solar activity. Also, at Indian equatorial stations, the maximum $E_{sb}$ occurrence is predominantly reported during the summer solstice with a minor secondary peak during the winter solstice (Bhargava and Subrahmanyan, 1964; Devasia, 1976). There are no reports of significant $E_{sb}$ occurrence during the vernal equinox in the Indian sector. Nevertheless, there is a report of an equinoctial peak $E_{sb}$ occurrence at American and African sectors during a high solar activity period (Oyinloye, 1971). The past investigations of $E_{sb}$ at low-latitude stations provide two important observational aspects of $E_{sb}$ occurrence: (i) the occurrence decreases as we move from low latitude to equatorial stations where EEJ current is stronger (Oyinloye, 1971; Abdu et al., 1996) and (ii) $E_{sb}$ at equatorial regions is mainly seen during periods of CEEJ or weak EEJ (Bhargava and Subrahmanyan, 1964; Chandra and Rastogi, 1975; Sen Gupta and Krishna Murthy, 1975; Devasia et al., 2006). The average monthly sunspot number during 2007 and 2009 was 7.5 ± 5.0 and 3.1 ± 2.9 respectively. Thus, both 2007 and 2009 were under the influence of nearly the same solar activity, but the seasonal local time occurrence pattern of $E_{sb}$ is found to be considerably different during the two years. Specifically, the enhanced $E_{sb}$ occurrence during

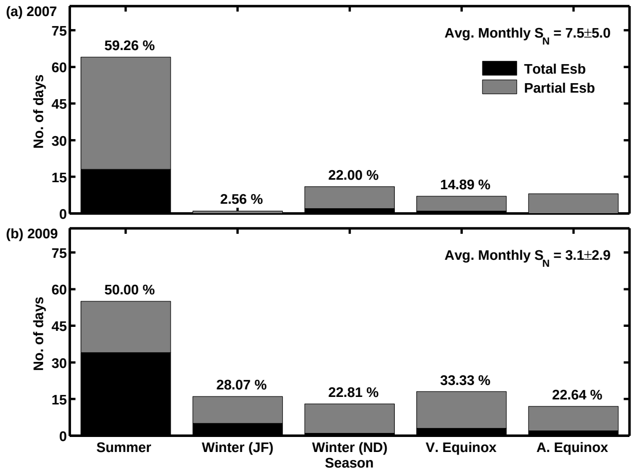


**Figure 3.** Number of days with partial blanketing $E_S$ ($4\,\text{MHz} \leq fbE_S \leq 8\,\text{MHz}$) and total blanketing $E_S$ ($fbE_S \geq 8\,\text{MHz}$) for each season during **(a)** 2007 and **(b)** 2009. The percentage of number of days with $E_{sb}$ is given over each bar corresponding to each season.

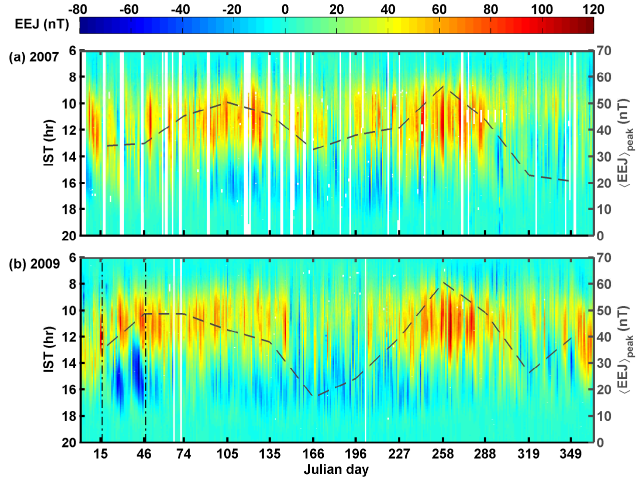


**Figure 4.** Daily EEJ during **(a)** 2007 and **(b)** 2009. The "dash-dotted" curve represents the maximum of monthly average EEJ. Standard deviation in monthly average EEJ is in the range of 11–24 nT (12–23 nT) for 2007 (2009). Vertical lines in **(b)** show the SSW period of 16 January–16 February.

winter (January–February) and vernal equinox of 2009 as compared to 2007 is an interesting observation. In order to understand this discrepancy, we examine the dependence of $E_{sb}$ occurrence on EEJ and CEEJ. The details of this investigation are elaborated in the next section.

### 3.2 EEJ/CEEJ dependence of $E_{sb}$

It is widely known that EEJ strength shows semiannual variation with a minimum during solstice periods (Tarpley, 1973; Okeke and Hamano, 2000; Chandra et al., 2000). This semiannual variation of EEJ strength is apparent irrespective of solar activity, with weaker EEJ strength during low solar activity periods. We examine the variation of EEJ strength with local time and day of the year in 2007 and 2009 under magnetically quiet conditions to find any peculiar differences in their variations during these periods. Figure 4 illustrates the daily variation of EEJ for 2007 and 2009. The dash-dotted curves indicate the peak monthly average EEJ strength. The white gaps seen in the figure represent data loss and magnetically disturbed days. The EEJ strength is found to be weaker during the summer solstice of 2009 ($\langle\text{EEJ}\rangle_{\text{peak}} = 29\pm18$) as compared to 2007 ($\langle\text{EEJ}\rangle_{\text{peak}} = 39\pm 18$). No noticeable difference between peak average EEJ activity during equinoxes of 2007 ($\langle\text{EEJ}\rangle_{\text{peak}} = 49 \pm 21$) and 2009 ($\langle\text{EEJ}\rangle_{\text{peak}} = 50 \pm 20$) is observed. However, frequent presence of strong CEEJ is observed mainly during January and February of 2009, which coincides with a period of strong sudden stratospheric warming (SSW) (Upadhayaya and Mahajan, 2013). The occurrence of CEEJ during SSWs was reported in earlier studies (Stening et al., 1996; Rastogi, 1999; Vineeth et al., 2009; Yamazaki et al., 2012). Referring to Fig. 2 of Labitzke and Kunze (2009), we note that SSWs were observed from 16 January to 16 February 2009, which are reported to be the strongest and most long-lived of the past 50 years (Manney et al., 2009). This SSW period is shown by vertical dotted lines in Fig. 4b. We find that during winter (January–February) $\sim 44\,\%$ of $E_{sb}$ events occurred during SSWs (16 January–16 February, 2009), whereas 31 % of $E_{sb}$ events occurred during the post-SSW (17–26 February, 2009) days. It is apparent that 75 % of $E_{sb}$ events, which occurred during winter (January–February) of 2009, are closely related to the SSWs. On the other hand, hardly any occurrence of $E_{sb}$ is seen during the winter (January–February) of 2007. Thus, we propose that SSW activity-related changes in the E region produce favourable ambient conditions for the generation of $E_{sb}$.

It has already been reported that the occurrence of $E_{sb}$ is more frequent during CEEJ (Devasia, 1976; Devasia et al., 2006). However, establishing such dependence is not straightforward when we are unaware of whether the observed processes (i.e. $E_{sb}$ and CEEJ) are driven by the same cause/physical mechanism or not. Thus, it is crucial to examine the scenario of $E_{sb}$ occurrence on days without CEEJ as well, which was not investigated in earlier studies. Here, we divide the quiet days of a season into two categories based on the presence or absence of CEEJ. A day with a minimum of $\text{EEJ} \leq -10\,\text{nT}$ during 10:00–20:00 IST is considered as a day with CEEJ, otherwise it is a day without CEEJ. The occurrence of $E_{sb}$ is then verified for each quiet day of a given season for these two categories. The percentage occurrence of $E_{sb}$ for each of these categories is estimated and shown in Fig. 5. The number of $E_{sb}$ days in these categories for each season is given over the corresponding bars.

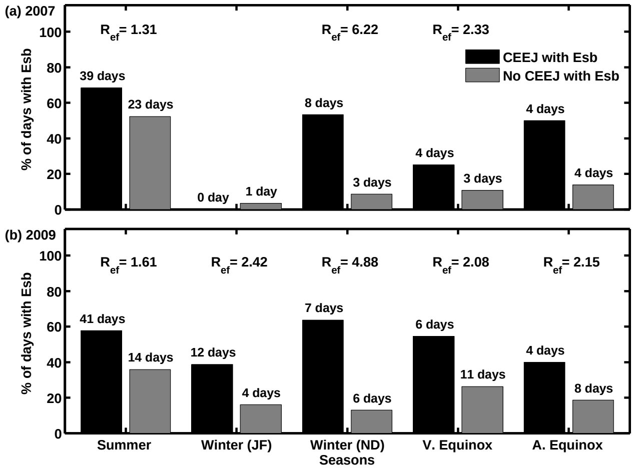


**Figure 5.** Percentage of number of $E_{sb}$ days for category I (with CEEJ) and category II (without CEEJ). The number of days displayed above each bar represents the number of $E_{sb}$ days in the corresponding category. $R_{ef}$ is the ratio of percentage of days with $E_{sb}$ for category I to that for category II. $R_{ef}$ for winter (January–February), 2007 is not calculated due to fewer $E_{sb}$ days. $R_{ef}$ for autumnal equinox in 2007 is not calculated as there was large data loss during that period.

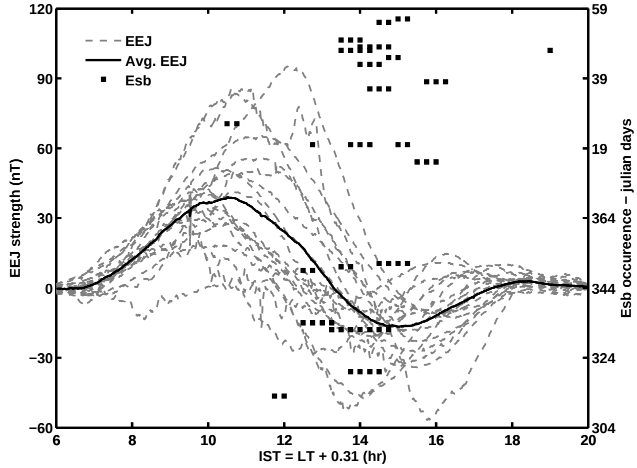


**Figure 6.** Occurrence of $E_{sb}$ and corresponding EEJ profiles as a function of IST for days under the category I of winter solstice of 2009. The EEJ profiles are represented by broken grey curves. The solid black curve represents the average of all EEJ profiles shown.

This indicates that the percentage occurrence of $E_{sb}$ for category I (with CEEJ) is found to be higher for all seasons during both 2007 and 2009. But, it is seen that the occurrence of $E_{sb}$ for category II (without CEEJ) is also not less significant during summer solstice. Even if CEEJ is absent, the occurrence of $E_{sb}$ is still likely. If we assume that $E_{sb}$ is strongly dependent on CEEJ then one expects a smaller percentage in category II. Based on this, we define a parameter $R_{ef}$ that is the ratio of percentage $E_{sb}$ occurrence of category I to that of category II. $R_{ef}$ approximately provides the efficiency of $E_{sb}$ and CEEJ association in different seasons. In general, $R_{ef}$ is found to be $> 1$ for all seasons during 2007 and 2009, indicating the association of $E_{sb}$ with CEEJ. However, the $R_{ef}$ values mentioned in Fig. 5 indicate that the $R_{ef}$ is maximum (minimum) during winter, November–December (summer) for both 2007 and 2009. This shows the tendency of stronger association between $E_{sb}$ and CEEJ during winter (November–December) as compared to the other seasons. The secondary peak in $R_{ef}$ falls during winter (January–February) 2009, which indicates that $E_{sb}$ is moderately associated with CEEJ during this season. In 2009, the peak percentage occurrence of $E_{sb}$ is observed around 14:00 IST during winter (January–February, November–December), which is nearly 2 h earlier as compared to that during the summer solstice. Thus, we examined the temporal variation of EEJ and occurrence of $E_{sb}$ for days under category I. Figure 6 shows the occurrence of $E_{sb}$ and corresponding EEJ profiles for days of category I during winter (January–February, November–December) of 2009. The solid line in the figure shows the average of all EEJ profiles. It is found that the $E_{sb}$ events have occurred mainly during the evolutionary phase of CEEJ, which confirms the close link between $E_{sb}$ occurrence and CEEJ during winter (January–February, November–December) 2009. It also explains the early occurrence of $E_{sb}$ during this season. Here, we want to point that the $R_{ef}$ value is not computed for winter (January–February) of 2007 as the number of $E_{sb}$ days is very few. For a given season, if the percentage of days with $E_{sb}$ is very low then we cannot use the estimated $R_{ef}$ value to verify the efficiency of the above-mentioned dependence.

### 3.3 Duration of $E_{sb}$

We examined the duration of $E_{sb}$ events in each season of 2007 and 2009. The number of days is displayed as a function of duration of $E_{sb}$ events in Fig. 7. Most frequent duration is found to be 0.75 h for both summer solstice and winter (January–February, November–December) of 2009. However, $E_{sb}$ events with duration $\geq 2.5$ h are predominantly seen during the summer solstice of 2009. The average time duration of $E_{sb}$ with standard deviation is mentioned in each panel. It is seen that average duration of $E_{sb}$ is higher in 2009 as compared to 2007 during summer solstice, whereas it is found to be shortest during the winter solstice of 2009.

## 4 Discussion

Here, we discuss the formation of $E_{sb}$ in the equatorial region in the light of existing theories. First, we checked the variation of dip angle (inclination) at Tirunelveli between January 2007 and December 2009 to confirm that the observations of $E_{sb}$ presented here are within the EEJ belt ($\pm 3°$) (Abdu et al., 1996). We calculate inclination by using the relation

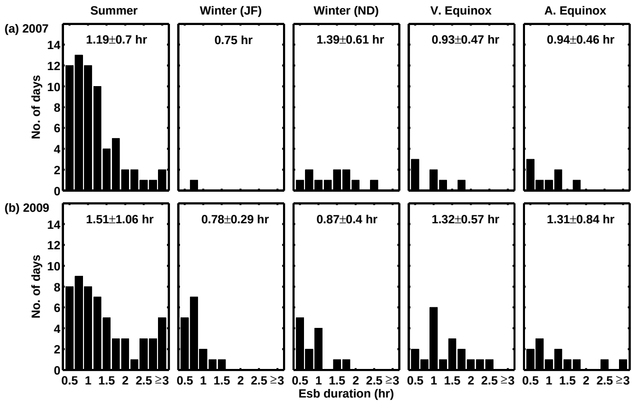


**Figure 7.** Seasonal number of days with $E_{sb}$ events as a function of duration of $E_{sb}$ events. Average duration of $E_{sb}$ along with standard deviation for each season is shown at the top in each panel.

$I = \tan^{-1}(Z/H)$, where $Z$ and $H$ are the vertical and horizontal components of the geomagnetic field respectively. Here, we use the monthly average of midnight $Z$ and $H$ values to compute inclination for the corresponding month. The inclination at Tirunelveli varies approximately from 1.25° to 1.75° during this period. This shows that the observation station is well within the influence of EEJ and observed $E_{sb}$ are associated with physical processes in the equatorial E region.

Wind shear theory is widely known and accepted as applicable for the formation of $E_s$ and $E_{sb}$ at mid latitudes (Whitehead, 1961; Axford, 1963; Whitehead, 1989, 1997b). According to this theory, if there is westward wind at higher height and eastward wind at lower height in E region at mid-latitudes, then in the presence of inclined geomagnetic field lines, ions accumulate due to Lorentz force. Electrons are unaffected by these zonal winds as they are magnetized. However, they follow the ions along the inclined field lines. This results in vertical convergence of ionization in a thin and dense layer, which is the $E_{sb}$ layer. This theory fails at the dip equator where the magnetic field is nearly horizontal (Reddy and Devasia, 1973). It should be noted that a small increase in inclination can slightly enhance efficiency of the wind shear mechanism to form $E_{sb}$. However, that will not be sufficient to explain the observed differences in $E_{sb}$ occurrence during 2007 and 2009. The equatorial $E_s$ layer is known to be associated with EEJ and its formation is explained based on two-stream instability (Farley Jr., 1963; Buneman, 1963) and gradient drift instability (Rogister and D'Angelo, 1970). The radar observations of $E_s$ are in good agreement with these theories (Phanikumar et al., 2008; Maruyama et al., 2006). However, the formation of $E_{sb}$, i.e. highly dense thin layers at the equatorial E region, requires the convergence of long-lived metallic ions. Closs (1971) proposed that a suitable electric field of appropriate magnitude can produce a convergent flow of metallic ions and cause blanketing. This theory was not given much attention as the $E_{sb}$ events were observed during weak electric fields. Later, Reddy and Devasia (1973) proposed that shear in meridional wind can cause the convergence of ionization along magnetic field lines. The common drawback of the above theories was that none of them could explain the observed peak $E_{sb}$ occurrence during the summer solstice. Reddy and Devasia (1981) proposed the formation of CEEJ due to the action of local east–west winds with vertical shear. As $E_{sb}$ and CEEJ are often observed together, the authors suggested that such winds might be playing a role in the formation of $E_{sb}$. However, how height varying zonal winds produce convergence of ionization at the equator to form $E_{sb}$ is not discussed.

Recently, Tsunoda (2008) suggested that $E_{sb}$ is transported to the equator from an off-equatorial station where they are formed due to wind shear mechanism. The author has shown that such a transport occurs only when the neutral wind speed at the off-equatorial station is greater than a certain threshold speed (Tsunoda, 2008, see Eq. 2), which is determined by the vertical polarization electric field linked with EEJ. In the case of strong EEJ, the associated polarization electric field will also be larger resulting in a larger threshold speed. Thus, for $E_{sb}$ to be transported to the equator from the off-equatorial region, larger equatorward winds are required. In support of this theory, there are $E_{sb}$ observations reported by Chandra and Rastogi (1975). For the formation of $E_{sb}$ at the equator, the authors have also suggested the transport mechanism of ionized $E_{sb}$ layer from off-equatorial latitudes to equatorial latitudes in the presence of horizontal wind with a significant north–south component. However, they could not establish the link between weak EEJ and $E_{sb}$ occurrence, which is addressed by Tsunoda (2008) for the first time.

It should be noted that the theories discussed here assume the presence of metallic ions ($Fe^+$, $Mg^+$) rather than the usual molecular ions ($O_2^+$, $NO^+$) in the E layer due to their longer lifetime (MacDougall et al., 2000). This eliminates the possibility of neutralizing the medium by the process of dissociative recombination and helps to maintain the enhanced ionization in a thin layer. Vaporization of meteors is the major source of metallic ions in the Earth's atmosphere which takes place at a height of around 90–110 km (Aikin et al., 2004; Roddy et al., 2004). Rocket observations have confirmed the presence of metallic ions in the E region (Aikin and Goldberg, 1973; Zbinden et al., 1975; Kopp, 1997). In the past there was no evidence that could show a strong seasonal dependence of meteor input. Younger et al. (2009) used long-term VHF radar observations from high-latitude stations in both hemispheres along with a low-latitude station. They showed that the meteor counts peak around local summer at the high-latitude stations in both hemispheres, whereas the equatorial station shows a semi-annual variation with two peaks close to the local summer and winter. Similar observations are reported by Phanikumar et al. (2012) using meteor data from Thumba (8.5° N, 77° E), an equatorial station close to the $E_{sb}$ observation site. They have reported a summer maximum and equinoctial minimum in meteor counts with winter counts lying in between. Recently, using an extensive data base from both the Northern and Southern Hemispheres, it has been established that the meteoric influx peaks around May–Aug and shows a good correlation with sporadic E layer intensities (Hibbins et al., 2011; Haldoupis, 2011, and references therein). In order to assess the difference in the meteor influx during 2007 and 2009, we used the radio observations of daily meteor counts recorded at Mie (35.0° N, 136.6° E, dip latitude 29.8° N), Japan (Fig. 8). These data are obtained from the International Project for Radio Meteor Observation (http://www.amro-net.jp/radio.htm). It should be noted that Mie is a mid-latitude station and hence the seasonal distribution of meteors may differ from that of the equatorial observation station, Tirunelveli. However, the difference between average meteor activity during 2007 and 2009 can be assessed from Mie observations to get an approximation of meteor influx during this period. The average meteor count for 2009 is ∼ 46 % higher than for 2007. If we assume that metallic ions solely control the occurrence of $E_{sb}$, then the percentage occurrence of $E_{sb}$ should be nearly the same for both summer and winter solstices at equatorial latitudes. This contradicts earlier observations, as the $E_{sb}$ occurrence is predominantly seen in local summer in both hemispheres (Reddy and Matsushita, 1969). The increased meteor deposits do not produce appreciable changes in $E_{sb}$ occurrence during summer in 2007 and 2009. This indicates that although the presence of metallic ions is a prerequisite to maintain enhanced ionization in a thin layer, the local wind pattern in different seasons plays a crucial role in the initiation of the convergence process and hence the formation of $E_{sb}$. Nevertheless, the increased meteor input might be playing a major role in sustaining the ionization, hence we find that average time duration of $E_{sb}$ and number of days with total blanketing are higher during 2009 than in 2007.

In view of the theories summarized above, we understand that the $E_{sb}$ observed at the equatorial region is either formed locally (Reddy and Devasia, 1973) or transported from the off-equatorial region (Chandra and Rastogi, 1975; Tsunoda, 2008). However, the contribution from each of the above-mentioned processes to $E_{sb}$ occurrence observed in the different seasons is not known. We have attempted to gather this information based on the seasonal $E_{sb}$ occurrence, estimated parameter $R_{ef}$ and earlier proposed theories. The higher $R_{ef}$ values for winter (January–February, November–December) show the close association between $E_{sb}$ and CEEJ during this season. In earlier studies, it has been suggested that the physical process of formation of CEEJ involves the local interaction of height varying zonal wind with the electrojet plasma, which can significantly modify the polarization electric field (Richmond, 1973; Stening, 1985). Somayajulu et al. (1993) have shown that the zonal winds are considerably different on CEEJ and non-CEEJ days. We propose that the physical process involving formation of $E_{sb}$ and CEEJ are closely linked (Reddy and Devasia, 1981) and the presence of east–west winds with vertical shear assists the formation of $E_{sb}$ during

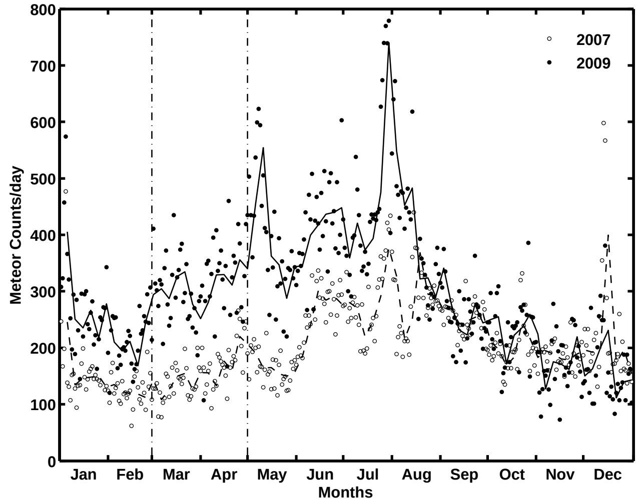


**Figure 8.** Radio observations of daily meteor counts (circles) along with 5-day average of the counts (curves) at Mie (35.0° N, 136.6° E, dip latitude 29.8° N), Japan for 2007 and 2009. Vertical lines show the beginning and end of the vernal equinoctial period.

winter (January–February, November–December). It should be noted that in winter (January–February), the CEEJs are driven by the SSW-induced changes in the E region. During winter (January–February, November–December), $E_{sb}$ is closely associated with CEEJ, which is controlled by local wind conditions. Hence, we suggest that the $E_{sb}$ observed during this season are generated locally. On the other hand, the summer solstice shows a peak occurrence of $E_{sb}$, but does not show strong dependence on CEEJ. So, we suggest that the $E_{sb}$ transport mechanism given by Tsunoda (2008) is prevalent during summer and contributes positively towards peak $E_{sb}$ occurrence in this season.

It should be noted that whether it is transported or locally generated $E_{sb}$, in both processes the local winds play a crucial role in $E_{sb}$ formation. We observe considerable $E_{sb}$ occurrence during the winter (January–February) and vernal equinox of 2009 as compared to 2007, which is attributed to the presence of appropriate wind conditions during this period. However, why such a favourable wind pattern was present during those periods is unknown. The answer to this question probably lies in the presence of SSWs during January–February 2009, which are found to be the strongest over the past 50 years (Manney et al., 2009) and caused an increase of 70 K in temperature within 7 days at 10 hPa over the North Pole (Labitzke and Kunze, 2009). The SSW activity continued for longer duration and the increase in temperature at the 30 hPa level was observed until March 2009. Thus, we speculate that the enhanced $E_{sb}$ occurrence during the winter (January–February) and vernal equinox of 2009 is a result of the appropriate ambient wind conditions at the E region, which are linked with SSWs. As various factors like solar activity, meteor deposits, strength of EEJ, CEEJ, winds and location of observation station (inclination) play an important role in the formation of $E_{sb}$, a quantitative estimation of the increase in $E_{sb}$ occurrence due to change in each of these parameters is not straightforward. For a better understanding, we need the background wind observations at E region altitudes.

## 5 Summary and conclusions

The seasonal variation of $E_{sb}$ occurrence is studied during 2007 and 2009, using data from CADI ionosonde located at equatorial station Tirunelveli in Indian longitude. The dependence of $E_{sb}$ on EEJ and CEEJ is investigated in detail. Our results are in general agreement with the earlier studies of $E_{sb}$, with a new finding, which indicates that the association of $E_{sb}$ and CEEJ is stronger during winter (November–December) and weaker during summer. Although the average solar activity during 2007 and 2009 is low, considerable differences are observed in the seasonal $E_{sb}$ occurrence during this period. The conclusions of the present study are as follows.

1. The occurrence of $E_{sb}$ is maximum during the summer solstice, when EEJ is generally weaker. This is in accord with earlier studies.

2. We find a considerable (33 %) occurrence of $E_{sb}$ during the vernal equinox of 2009 as compared to that of 2007. To the best of our knowledge, this is the first report of the distinct occurrence of $E_{sb}$ during equinoctial periods in the Indian equatorial region.

3. The enhanced $E_{sb}$ occurrence during the winter (January–February) and vernal equinox of 2009 is closely related to the strongest and long-lived SSW activity of January–February 2009. We suggest that the SSW-driven changes in the E region background winds aided the formation of $E_{sb}$ during this period.

4. The occurrence of $E_{sb}$ during winter (November–December) is strongly linked with the CEEJ. Thus, we suggest that the physical process causing generation of $E_{sb}$ and CEEJ are interlinked. However, how local east–west winds with large vertical shear (Reddy and Devasia, 1981) result in CEEJ and assist the formation of dense layer of ionization ($E_{sb}$) is an open question.

5. Average time duration of $E_{sb}$ is higher in 2009 as compared to 2007, except during winter solstice. Also, the occurrence of total blanketing $E_s$ was higher in 2009. This is partly related to the increased meteor influx, and hence the metallic ion input, that increased by nearly 46 % from 2007 to 2009.

6. Metallic ions and winds may play a crucial role in the formation and evolution of $E_{sb}$. However, to estimate the contribution of each of these parameters in $E_{sb}$ formation and for better understanding of physical processes involved in its generation, we need simultaneous $E_{sb}$, meteor influx and wind observations at the equatorial E region.

*Acknowledgements.* We thank WDC Kyoto and WDC IIG for magnetic field data. We are also grateful to GSFC and the International Project for Radio Meteor Observation for meteor data. We thank C. Selvaraj, IIG for technical help on ionosonde.

Topical Editor H. Kil thanks two anonymous referees for their help in evaluating this paper.

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