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ORIGINAL ARTICLE

Coupled nature of evening-time ionospheric electrodynamics

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Abstract The F region evening electrodynamics in the equatorial region is characterized by a pre-reversal enhancement (PRE) in the zonal eastward electric field. Although the theoretical mechanisms for PRE are known, its variability, particularly day-to-day variability is not fully resolved. PRE is a large scale phenomenon driven by the F region dynamo after the sunset hours. This paper investigates whether the variability of the E region conductivity (particularly the one associated with the sporadic E, Es) has any influence on the F region dynamo and hence on the PRE of zonal electric field. Interestingly, ionosonde observations have indicated a higher occurrence of the blanketing type Es (Esb) over the low latitude on days with highly suppressed PRE of zonal electric field in comparison with the days with significantly larger PRE. Observational evidences presented in this paper suggests that the formation of the Esb in the evening hours is a sovereign process, not always controlled by the sheared F region vertical electric field of equatorial origin, mapping along the magnetic field line on to the low latitude E region. Model computations of the PRE suppression based on the measured Es densities have further substantiated the observational findings presented in this paper. These results clearly indicate that the low latitude Es has the potential to suppress the PRE of zonal electric field and possibly can play a vital role in explaining the PRE variability, particularly the day-to-day variability. Results have been discussed in light of earlier reports on PRE mechanisms and E-F region coupling processes.

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1 Introduction

Pre reversal enhancement (PRE) of the equatorial zonal electric field has been studied extensively over the last several decades (e.g., Woodman 1970; Rishbeth 1971; Farley et al. 1986; Fejer et al. 1991; Haerendel and Eccles 1992; Fesen et al. 2000; Richmond and Fang 2015; Chen et al. 2017). PRE of equatorial zonal electric field plays the dominant role in the genesis of the equatorial plasma bubbles (EPB) (Anderson and Haerendel 1979; Akala et al. 2011; Kelly et al. 2014), which have the potential to cause outages in the satellite based navigation (Anderson and Haerendel 1979; de Lima et al. 2014; Gardner et al. 2014; Oladipo et al. 2014; Tiwari and Strangeways 2015; Akala et al. 2016; Yue et al. 2016). Although mechanisms exist to explain the cause of the PRE of zonal field, still the causes of its variability are not fully understood. PRE displays solar cycle, seasonal, as well as day-to-day variability.

Rishbeth (1971) hypothesized the PRE to be an outcome of the F region dynamo itself. Vertical F region electric field over the magnetic equator has a zonal gradient in the evening hours due to the zonal conductivity gradient in the low latitude E regions. Under constant magnetic field, curl free electric field requires the zonal component to enhance. Rishbeth (1971), however, has only qualitatively explained this mechanism. His explanation basically deals with the "edge effect" of the vertical electric field near the sunset terminator. Heelis et al. (1974) based on a quantitative assessment, reported that the zonal wind driven F region dynamo can cause the vertical plasma drift to enhance and manifest in the form of the PRE. Their explanation also included the enhancement in the electric field due to the horizontal gradient in the F region conductivity across the sunset terminator sector. Considering the vertical plasma drift and the zonal sheared flow, the net flow in the post sunset hours manifest in the form of a plasma vortex (e.g., Rodrigues et al. 2012). Heelis et al. (2012) studied the current system associated with the evening F region dynamo (current being more fundamental as its divergence leads to a charge build up and electric field generation). Their model indicated an enhancement in the zonal F region current at E region terminator time which further led to an enhancement in the zonal electric field caused by the zonal gradient in the F region conductivity.

Farley et al. (1986) proposed an altogether different mechanism for the PRE of the zonal field being generated by the westward conductivity gradient in the low latitude E regions around evening hours. The vertical F region electric field being enhanced during the evening hours due to the reduction in the E region conductivity maps down to the conjugate low latitude E regions. There exists a westward conductivity gradient which causes a divergence in the Hall current in the low latitudes. Polarization field that gets generated in the low latitude E regions maps along the magnetic field lines to the equatorial F region. Although the vertical F region electric field itself is enhanced due to the reduction in the E region conductivity in the evening hours, however, the fact that the conductivity in the E region decreases much faster than that in the F region signifies that the source of the enhanced zonal electric field is in the E region. The proposed mechanisms for the PRE of zonal field have always been debated in several investigations. For example, Eccles (1998) based on modeling investigation has reported that the primary mechanism responsible for PRE is the one proposed by Rishbeth (1971), while the other mechanisms proposed by Farley et al. (1986) and one by Haerendel and Eccles (1992) can influence the PRE magnitude. Fesen et al. (2000) have simulated the PRE using the TIEGCM model. Their simulation of PRE was based on the mechanism proposed by Farley et al. (1986) and they have reported that an enhancement of the night time E-region conductivity/plasma density is reducing the PRE.

Recent modeling investigation by Richmond et al. (2015) have reproduced several interesting aspects pertaining to the evening PRE. They have suggested that the eastward electric field transport the ionosphere to higher altitude where the zonal neutral flow is larger due to the reduced ion drag. As per their model calculations it is the zonal wind flow reasonably above the shear flow node that drives the F region dynamo which produces the PRE of the zonal electric field. Another report by Richmond and Fang (2015) has indicated that E region conductivity can influence both meridional as well as zonal convection in the F region by imposing a drag to the meridional convection due to Cowling current. Thus a large conductivity in the E region in the post sunset hours can suppress the PRE.

There exist several experimental challenges in the investigation of the causes of the PRE of zonal field. While it is common to measure the vertical PRE drift (using incoherent scatter radar and ionosonde), measurement of the F region zonal neutral wind and the low latitude E region conductivity is not commonly carried out to study the cause of the PRE. There also exist experimental limitations in the measurement of the F region neutral winds and the low latitude E region conductivity. While the F region thermospheric neutral winds are likely to vary significantly with the solar forcing, E region conductivity in the dusk hours can be expected to significantly vary on a day-to-day basis depending upon the nature of the low latitude sporadic E (Es). Field line integrated Pedersen conductivity of the E region during the daytime can be comparable to that of the F region. During evening hours, due to the chemical recombination, in the absence of Es, field line integrated Pedersen conductivity of E region becomes less than the field line integrated Pedersen conductivity of F region. However, if the Es is present in the low latitude during dusk hours, E region integrated conductivity can significantly increase. Fesen et al. (2000) based on TIEGCM model investigations have found that the E region plasma density $>$ 3300–7500 electrons/cc precludes the PRE development by short circuiting the F region vertical electric field. Interestingly, this electron density is much less than the daytime E region density. Thus, the variation in the E region conductivity on a day-to-day basis during the evening hours, owing to the variation of metallic ion layers (night time Es) can be expected to significantly influence the F region dynamo characteristics. However, Fesen et al. (2000) examined the nighttime variation of the background E region conductivity, whereas, the present work deals with the local effects on the E region conductivity related with the formation of Es. Stephan et al. (2002) have examined the E region field line integrated Pedersen conductivity in the evening hours and its important role in suppressing the growth of the RT instability. They have also hypothesized that lower is the field line integrated Pedersen conductivity of the E region, higher is the PRE of the zonal electric field. Although the modeling investigations have already revealed the potential role of the low latitude E region conductivity in determining the day-to-day variability of the PRE, observational investigations to support that has been quite scarce. Particularly the role of the low latitude Es activity in influencing the PRE of zonal field needs to be investigated, as after sunset, Chapman type E layer disappears due to recombination and the E region exist in the form of Es only (Joshi et al. 2013b). Es after sunset is mainly composed of metallic ions of meteoric origin. Investigations in the past carried out using the powerful Arecibo incoherent scatter radar have already revealed the presence of thick metallic ion layers in the E region during the nighttime having plasma densities comparable to that in the daytime (Earle et al. 2000). Thus the metallic ion layer in the low latitude is likely to alter the E region conductivity which can be an important constituent of the day-to-day variability of the F region dynamo. The role of the low latitude Es in the evening hours in short circuiting the F region dynamo, thus inhibiting the PRE development is being investigated in this paper utilizing the ionosonde observation over Sriharikota, a low latitude station and spaceport of India. Model computation of the F layer height rise with and without the presence of Es in the low latitudes will also be presented.

In this investigation the mechanism proposed by Farley et al. (1986) has been adopted to study the PRE based on the observation of E region density over the Indian region. However, the variability in the low latitude E region density can be equally important from the point of views of other PRE mechanisms, as high Pedersen conductivity of low latitude E region can suppress the F region dynamo, the primary driver of the PRE (Rishbeth 1971; Heelis et al. 2012). Results will also be discussed vis-a-vis some of the previous works on PRE-Es relationship and detailed explanation will be drawn as to why these results do not directly contradict earlier observations.

2 Brief theoretical overview of evening electrodynamics associated with low latitude zonal hall current divergence

As indicated earlier, the PRE in being studied based in the mechanism of Farley et al. (1986) which is related with the divergence of Hall current. A brief theoretical description of the F region electrodynamics in the evening hours linked with the E region conductivities is being presented in this section, so as to place the observational results in a proper context, later. During the post sunset period, neutral wind driven F region dynamo controls the vertical electric field. A simplified expression of the vertical electric field in the post sunset period can be written as (Kelley 2009)

$$E_Z = -UB\frac{\sum P^F}{\sum P^F + \sum P^E} \tag{1}$$

Here E_Z represents the vertical F region electric field, U represents zonal thermospheric wind, B is the earth's magnetic field and $\frac{\sum P^F}{\sum P^F+\sum P^E}$ represents the ratio of the field line integrated Pedersen conductivity in F region to the total field line integrated Pedersen conductivity (i.e. F region + E region). E region Pedersen conductivity during the day time is many times larger than that of the F region. As a consequence, the vertical electric field during the day time originates in the E region. After the sunset, however, the production of ionization in the E region ceases and E region Pedersen conductivity reduces drastically. Now the zonal wind U becomes the primary driver of the vertical electric field (as in (1)). This vertical field in the post sunset hours can map to the low latitude E regions via magnetic field lines and drive zonal Hall current.

During the evening hours, the zonal conductivity gradient in the low latitude is westward. Hence in the low latitude E region there also exists a zonal divergence of the Hall current which is being generated by the field line mapping of the F region vertical electric field. The divergence in the Hall current will lead to a charge pileup given by (2), basically continuity equation.

$$\nabla . J_H = -\frac{\partial q}{\partial t} \tag{2}$$

where J_H indicates the Hall current density and q indicates the charge. Negative sign on the right hand side of (1) signifies that the charge pileup will lead to the production of electric field to oppose the divergence of the Hall current. The divergence will tend to become zero under the steady state. Thus the magnitude of the divergence of the Hall current in the low latitude must decide the magnitude of the generated electric field. The current density and electric field is related by (Ohm's law)

$$J = \sigma E \tag{3}$$

Under the steady state equation (2) can also be written as

$$\nabla J_H = -\nabla(\sigma_P E) \tag{4}$$

where σ_P is the Pedersen conductivity in the E region. This can be explained as, Pedersen current will flow in the E region under steady state to make the overall current divergence free. Additional electric field must develop for such Pedersen current to flow. Considering only the zonal component of the current density and Pedersen conductivity variation in (4), we get

$$\frac{\partial J_{Hx}}{\partial x} = -\sigma_P \frac{\partial E_x}{\partial x} - E_x \frac{\partial \sigma_P}{\partial x} \tag{5}$$

Simplifying for ∂E_x,

$$\partial E_x = -\frac{\partial J_{Hx}}{\sigma_P} - E_x \frac{\partial \sigma_P}{\sigma_P} \tag{6}$$

In (6), ∂E_x is the additional zonal electric field which gets generated in the E region to make the total current divergence free. From (6) it can be understood that the ∂E_x will be positive (negative) if the conductivity gradient (Hall as well as Pedersen conductivity) is westward (eastward). This additional electric field generated in the E region maps along the field line to the F region and add up to the background zonal field. Farley et al. (1986) have considered the divergence in the hall current in the low latitude E regions driven by the vertical electric field as the main cause of the PRE of the zonal electric field. However, the conductivity of the low latitude E region in the evening hours is also expected to vary on a day-to-day basis due to the day-to-day variability of evening time Es in low latitudes. Earlier investigations have indicated that the presence of Es in the low latitudes can cause a significant reduction in the F region vertical field (as in (1)), thereby suppressing the PRE (e.g. Stephan et al. 2002; Fesen et al. 2000).

3 Ionosonde observations over Sriharikota

Ionosonde installed at Sriharikota (13.7° N, 80.1° E, 7° N dip latitude), which is a low latitude station in India has been used to observe the rise of F layer and the low latitude Es conditions. Figure 1 presents the $h'F$ during the evening/post-sunset hours over Sriharikota for 48 consecutive days (15 February 2004 to 02 April 2004). In Fig. 1 IST indicates the Indian Standard Time (UT + 5:30). In Fig. 1 cases indicated in red color represent the 12 days on which the peak $h'F$ was highest of the entire 48 days observational period, while the cases indicated in blue color represent the 12 days on which the peak $h'F$ was the lowest of the entire 48 days observation period. In simple words, red and blue color represents the upper quartile (Q4) and lower quartile (Q1) in the peak $h'F$, respectively. Q4 cases indicate relatively larger PRE of the zonal electric field and the associated post sunset height rise of the F layer. On the other hand Q1 cases indicate highly suppressed PRE, as indicated in blue color in Fig. 1. The vertical plasma drift corresponding to the low and high PRE cases is presented in Fig. 2. Figure 2(a) and (b) shows the vertical plasma drift V_z ($V_z = dh'F/dt$) calculated for Q1 and Q4 cases, respectively. One can see that the peak vertical drift are quite different in the two categories. The average peak V_z in Q4 cases is ~ 27 m/s, while the peak V_z in Q1 cases was < 5 m/s.

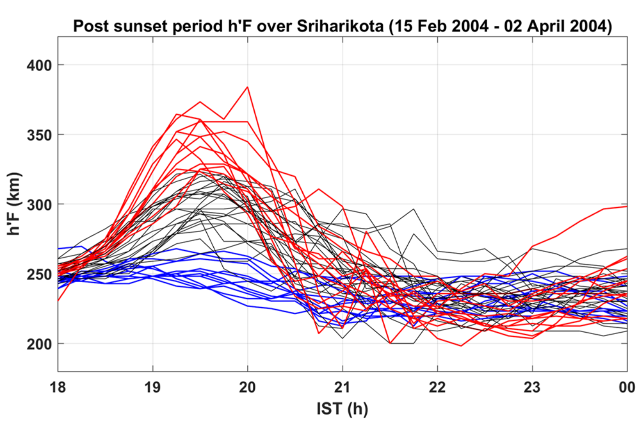

Fig. 1 $h'F$ variation over Sriharikota. Cases indicated in red are the 12 cases with highest peak $h'F$ (upper quartile, Q4). Cases indicated in blue are the 12 cases with lowest peak $h'F$ (lower quartile, Q1)

Thus the Q1 represents cases with highly suppressed PRE. During the entire observational period, the average F10.7 was 110 solar flux units. Thus the observation belongs to the moderate solar activity condition. Of all the nights of observation, one night belonged to geomagnetically active period, 11 March. A moderate geomagnetic storm has also occurred on 09 March. However, these two nights does not belong to Q1 or Q4 category. Thus the geomagnetic and space weather related factors are not the likely cause of the remarkable difference in the post sunset height rise in Q1 and Q4 cases. Electrodynamical factors pertaining to the low latitude ionosphere needs to be investigated to understand the difference in the Q1 and Q4 cases. The low latitude Es conditions corresponding to the Q1 and Q4 cases have also been investigated to figure out whether or not the low latitude Es had any possible role in suppressing the PRE in Q1 cases. It needs mention here that the vertical drift presented in Fig. 2 is the apparent rise velocity of the F layer which is reasonably close to equal but not exactly equal to the actual vertical EXB drift. Due to the ion recombination after the sunset period, apparent rise velocity is an overestimation of the actual vertical EXB drift. Proxies like the magnetic data on and off equator also represent an efficient way to derive the vertical EXB drift, however, such technique has its own limitation in the post sunset period when Equatorial electrojet strength

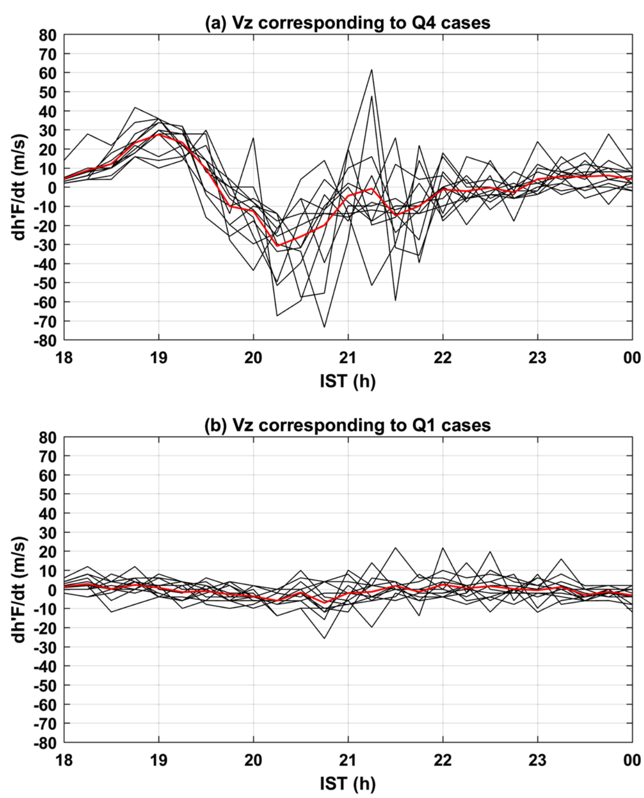

Fig. 2 The vertical PRE drift ($dh'F/dt$) in (**a**) Q4 and (**b**) Q1 cases. The red line indicates the average value

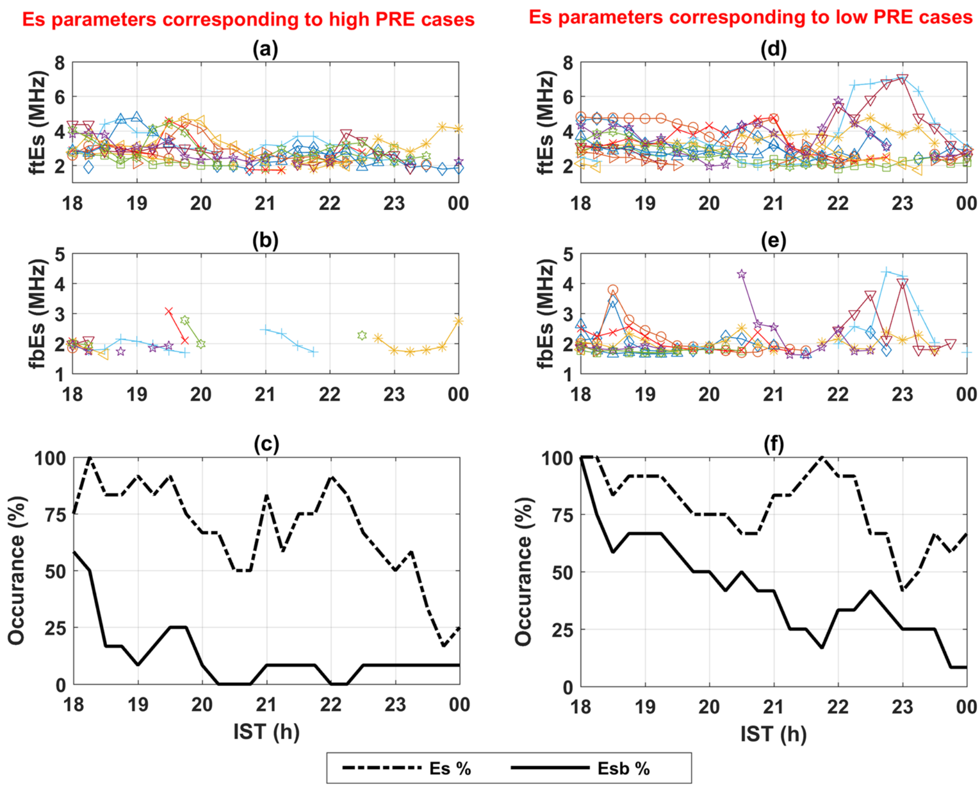

Fig. 3 Es parameters corresponding to high (Q4) and low (Q1) PRE cases. (**a**–**c**) indicates top frequency of Es (ftEs), blanketing frequency of Es (fbEs), and the occurrence % of the Es/Esb, respectively, for high (Q4) PRE cases. (**d**–**f**) indicates the same but corresponding to low (Q1) PRE cases. Details are given in the text

reduces. Thus the vertical drift of the F layer have been calculated using the apparent height rise measurement.

3.1 Low latitude Es parameters in high and low PRE cases

Figure 3 presents the low latitude Es parameters corresponding to the two categories. In Fig. 3 panels (a), (b), and (c) indicates the top frequency of the Es (ftEs), blanketing frequency of the Es (fbEs), and the occurrence % of Es, respectively, for the Q4 cases. While right side panels (d–f) indicates similar Es parameters, but for the Q1 cases. Panels (a) and (d) presenting the ftEs indicates that the Es occurred in the low latitude on days corresponding to both Q4 and Q1 cases in the evening hours (18–20 IST). Es, however, could be either blanketing type (Esb) or non blanketing type. Panels (b) and (e) presents fbEs over Sriharikota corresponding to Q4 and Q1 cases, respectively. In comparison to the top frequency, the pattern of fbEs differed significantly in the two categories in the evening hours. In Q4 cases, except on one day Es during the evening hours was either non-blanketing or intermittently blanketing type. Except for one case indicated with light blue color there is a disruption of the fbEs in the evening hours in panel (b). Such a feature is not seen in panel (e). In panel (e) the Es is predominantly blanketing type. Based on a detailed investigation to understand the coupling between the EPB genesis and low latitude Es formation, Joshi et al. (2013a, 2013b) found the blanketing frequency of the Es to better indicate (than the top frequency of Es) the existence of highly conducting thick sporadic E layer which has the capability to short circuit the F region electric field. On the other hand the top frequency of the Es (ftEs) indicates the peak plasma density of the plasma patches located anywhere within the field of view of the ionosonde, which possesses the capability to reflect/scatter the radio waves. However, the background peak plasma density of sporadic E layer is indicated by its blanketing frequency (fbEs). Radio waves having a frequency lesser than the Es blanketing frequency will not penetrate up to the higher layers in the ionosphere and will be reflected back. As far as the Es layer conductivity is concerned, it will depend on the background plasma density of Es rather than the peak plasma density of the plasma patches within Es. It should be pointed out here that even for the cases in which only the ftEs is measured (non-blanketing Es) there are corresponding fbEs values (and therefore a background plasma density of the Es layer) that happen to be below the ionosonde sensitivity limit (thus not measurable), which is ∼ 1.6 MHz. Thus, the background peak plasma density of the Es in Q4 cases is less than that in Q1 cases.

The lesser occurrence of fbEs in panel (b) in comparison to that in panel (e) indicates that the background plasma density of the E region was significantly lower in the Q4 cases than in the Q1 cases. On the other hand top frequency of the Es (ftEs), as indicated in panels (a) and (c) in Fig. 3 was in the range of 2–5 MHz during the evening hours (18–20 IST) in both Q1 and Q4 cases. Thus the density of the plasma patches in the E region in general was identical in both Q1 and Q4 cases.

In Fig. 3 occurrence % of the Es/Esb in the Q4 and Q1 cases are indicated in panels (c) and (f), respectively. As far as the occurrence of the Es is concerned, its percentage is more or less similar in the two categories. However, the occurrence of the blanketing Es or Esb is quite different in the two categories. In Q1 cases, as shown in panel (f), the occurrence of Esb was 100% at 18 IST, while it was ∼ 60% in Q4 cases (panel c) at 18 IST. In Q1 cases (panel f) the occurrence of Esb was ∼ 70% at 19 IST, while it was much less than 25% in Q4 cases (panel c) at 19 IST. It must be noted that the 19 IST is the time of the peak in the vertical plasma drift associated with the PRE of the zonal electric field. Detailed discussions and model simulations to further substantiate the observational findings is presented next.

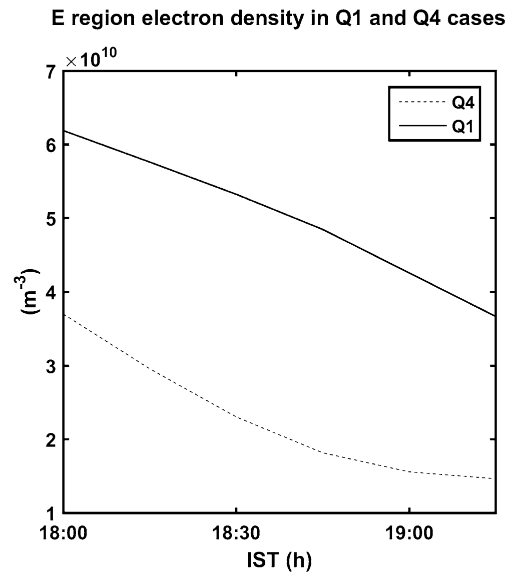

Fig. 4 Background peak E region electron densities in low PRE, Q1 (solid line) and high PRE, Q4 (dotted line) cases

4 Model computation based on observed Es density

Although the theoretical basis of the PRE suppression due to short circuiting of the F region dynamo by conducting E layer has been known for long, its observational evidence linked with the low latitude Es has seldom been presented before. Fesen et al. (2000) based on TIEGCM model investigation reported that the E region plasma density > 3300–7500 electrons/cc precludes the PRE development by short circuiting the F region vertical electric field. This electron density is in fact much lesser than the sensitivity limit of an ionosonde. However, Fesen et al. (2000) considered the E region to be in the form of a slab extending between 100 to 125 km altitudes with uniform electron density. In practice the E region is in the form of layer with Es often making it more structured. Formation of the Es in the low latitudes during the post sunset hours depends on the transport of the metallic ions of meteoric origin (in the absence of photo production after sunset). Formation of the Es is primarily governed by the variability of the tidal winds. Observations over Sriharikota have indicated a much lesser occurrence of the blanketing Es or Esb on high PRE days (Q4) than on low PRE days (Q1). Thus the observations presented in this paper further corroborate the theoretical findings of Fesen et al. (2000). To further understand the observational results, model computation of the F layer height rise based on the observed Es electron densities in the Q1 and Q4 cases is being presented next.

4.1 Low latitude E region densities considered in the model computation

The E region electron density used as an input in the model computation for F layer height rise is being described in this section. Figure 4 shows the average smoothed peak electron density during post sunset hours in Q1 and Q4 cases. These densities have been calculated based on the blanketing frequency of the E region. Blanketing frequency (fbEs) has been considered as an indicator of the background peak electron density of the E region (HF frequencies below fbEs will not penetrate up into the higher regions). On the other hand top frequency indicates the density of the irregular plasma patches present anywhere within the field of view of the ionosonde. Thus, in order to calculate the average peak electron density of the E region in Q1 and Q4 cases, electron density corresponding to the blanketing frequency has been taken into account. As lower operating frequency limit of the ionosonde utilized in the present investigation is ∼ 1.6 MHz, blanketing frequency below 1.6 MHz can't be detected. In the cases where Es is non blanketing type, corresponding peak E region density has been taken from the IRI model, in order to estimate the average E region density. IRI model is a reference model for the ionosphere. In Fig. 4 one can see that the peak electron density in Q4 is significantly lesser than that in the Q1.

While the ionosonde is capable of detecting the ionospheric density in the E region, it is not possible to derive its exact profile with it particularly in the presence of Es. Es appears as a slab of varying thickness in the ionogram (e.g., Batista and Abdu 1977). For the model computation, the E region in the post sunset hours has been constructed for the Q1 and Q4 cases based on a Gaussian fitting on the peak electron densities shown in Fig. 4. The constructed E region for Q4 and Q1 cases is presented in Fig. 5(a) and (b), respectively. Here the peak electron density has been assumed to be located at 105 km with a moderate scale height of 3.5 km

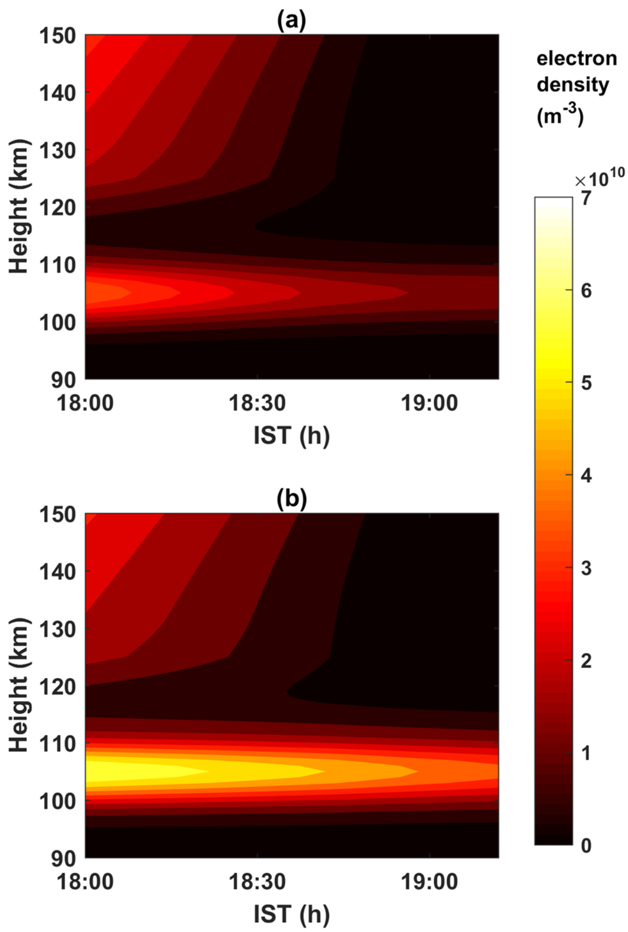

Fig. 5 E region considered in the model computation corresponding to (**a**) high PRE, Q4 cases and (**b**) low PRE, Q1 cases. Details are given in the text

It must be mentioned here that the Es layer can have a large range of thickness from a few hundred meters (thin/patchy Es) to more than 10 km (thick Es). Several previous studies have indicated the presence of thick metallic ion layers in the E region during the night time. Some reports have also indicated the observation of highly variable metallic ion layers having large plasma densities occurring during the post sunset periods (e.g., Earle et al. 2000). The formation of Es at all non-equatorial latitudes is dynamically governed by the transport of plasma in the E region by the forcing of tidal and gravity wave winds (Mathews and Bekeny 1979; Carter and Forbes 1999). Several previous reports have already indicated the nighttime occurrence of thick metallic ion layers having significant peak plasma density, even comparable to that in the daytime (e.g., Earle et al. 2000; Bishop and Earle 2003; Roddy et al. 2007). Variability of the nighttime Es density and structure still remains a subject of investigation. In Fig. 5 the electron density in 120–150 km height (valley region) have been considered in accordance with the IRI model. The relative impact of the E region presented in Fig. 5(a) and (b) on the F layer height migration has been assessed based on the model computations.

4.2 F layer height rise in the model

For the computation of the height rise of the F layer, E and F region plasma densities are considered based on observation and IRI model, respectively. Thermospheric density profile is derived from NRLMSISE00 model (Picone et al. 2002). Thermospheric density profile is utilized to obtain the vertical profile of the ion neutral collision frequency (γ_{in}). Ion neutral collision frequency and plasma density values are used to calculate the Pedersen conductivity profile. In the model, an eastward neutral wind of 200 ms^{-1} is assumed to prevail in the F region. Farley et al. (1986) in their simulation of the PRE have also considered eastward thermospheric neutral wind of 200 m/s. In needs mention here that the 200 m/s wind is just a simplistic assumption, in actually scenario thermospheric winds can display large variability and even due to the complex electrodynamical process related to ion drag (e.g., Richmond et al. 2015; Richmond and Fang 2015). The vertical electric field given by (1) has been calculated by considering the above mentioned zonal wind value. For that the field line integrated Pedersen conductivity of the E region (F region) have been calculated by integrating the Pedersen conductivity along the field line in height region 90 km to 150 km (150 km to apex height). F region vertical electric field has been mapped to the low latitude E region to calculate the zonal Hall current density. The additional electric field generated due to the Hall current divergence has been calculated as in equation 6. This additional electric field has been integrated along the magnetic field line in the height region of 90–150 km (E region) to calculate the total additional electric field generated due to the Hall current divergence. This total additional electric field has been mapped with 100% efficiency to the F region as it is a large scale process (LaBelle 1985).

The height migration of the F layer over the magnetic equator in the model simulation considering the conjugate low latitude E regions to be represented by Fig. 5(a) is shown in Fig. 6(a). Here the initial profile of the F layer at 18:00 LT is taken from the IRI model. Subsequently, as the local time progresses, the F region peak plasma density and also the density gradients above and below the peak have been considered to vary in accordance with the IRI model. Variation of F region peak density and density gradients in accordance with the IRI model accounts for the loss of ionization due to the recombination process. This in turn accounts for the reduction of the F region Pedersen conductivity with time. However, the F layer height variation in Fig. 6(a) has been calculated based on the eastward electric field which is being generated due to the divergence of the Hall current in the low

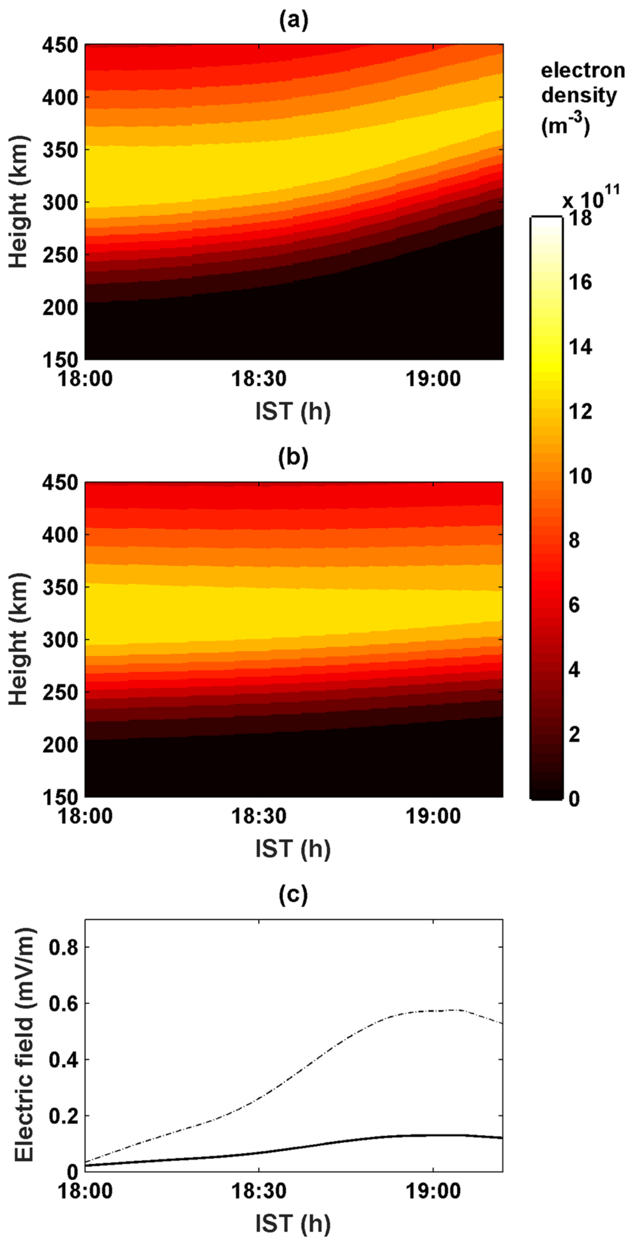

Fig. 6 F layer height rise reproduced in the model computation for (**a**) high PRE, Q4 cases and (**b**) low PRE, Q1 cases. (**c**) The enhancement of the zonal electric field brought out in the model computation in Q4 (dotted line) and Q1 (solid line)

latitude E region. As already described in the previous paragraph, eastward enhancement in the electric field has been calculated using (6). The electric field enhancement given by (6) has been integrated along the magnetic field line in the height region 90 to 150 km (model E region) to calculate the net zonal enhancement in the eastward electric field. Net zonal Electric field generated in the low latitude E region has been mapped to the F region along the magnetic field line with ∼ 100% efficiency (as PRE electric field is a very large scale electric field, LaBelle 1985). Fig. 6(a) indicates a significant height rise of the F layer in the post sunset period (when low latitude E region density is similar to Fig. 5(a)). The height rise of the F layer over equator brought out by the model computation considering the E region to be similar to Fig. 5(b) is presented in Fig. 6(b). It is interesting to note that in this case the height rise of the F layer is quite marginal as compared to that in the previous case. This happens because with increase in the E region Pedersen conductivity, the F region vertical field, as in (1), which drives the Hall current in low latitude E regions, gets suppressed. Similar suppression of the PRE due to large electron densities in the E region has been reported by Fesen et al. (2000), based on TIEGCM simulation. Thus the model computation clearly suggests that the low latitude E region densities related to the Es can play an important role in the height migration of the F layer. The eastward PRE field brought out by the model computation in the two cases is also indicated in the panel (c) of Fig. 6 (dash dotted line indicating it for Q4 and solid line for Q1). There can be seen a remarkable suppression in the PRE electric field in model computation in Q1.

5 Discussion and concluding remarks

Several aspects of the E-F region coupling associated with the PRE of the zonal field have been already investigated in the past (Fesen et al. 2000; Stephan et al. 2002; Abdu et al. 2003; Joshi et al. 2012, 2013a, 2013b; Joshi 2016). PRE itself is a manifestation of the E-F region coupling in the sense that electric field enhancement happens after the E region conductivity decreases reasonably in the evening hours (Rishbeth 1971; Farley et al. 1986). One of the important aspects of the E-F region coupling is the deformation of the low latitude Es structure as a consequence of the sheared vertical ion Pedersen drift driven by the sheared PRE vertical field mapping on to the low latitude E region (Abdu et al. 2003). Sudden abrupt disappearance of the Es in the low latitude at the time of the F layer attaining the peak height (peak $h'F$) have been reported from the Brazilian sector on days when the PRE vertical drift exceeded 45 m/s to 60 m/s mark. Furthermore, modeling investigations have also suggested that the deformation of the low latitude Es structure is indeed possible if the PRE vertical drift is extremely large (Carrasco et al. 2005, 2007). In the Indian longitude sector, PRE drift > 45–60 m/s can be seen during the prompt penetration of electric field (PPEF) in the active phase of the geomagnetic storms coinciding with the PRE (e.g., Joshi et al. 2016; Joshi and Sripathi 2016). Observations reported in this investigation on the other hand does not indicate a sudden abrupt disruption of Es (ftEs) close to the peak $h'F$ time (as reported by Abdu et al. 2003), and for the simple reason that the average peak PRE vertical drift was ∼ 27 m/s (which is significantly lesser than that reported against Es disruption by Abdu et al. 2003). Rather, a steep reduction in the occurrence % of the blanketing Es or Esb was seen much before the peak $h'F$ time in Q4 cases (when the PRE drift was even lesser). Although it is possible to observe the difference in the Es characteristics much before the PRE period, the PRE is affected by the current condition of the Es conductivity. Difference in the Es characteristics in the two cases merely indicates that the Es formation is independent of the PRE strength. The results (specially observations) presented in this paper seems to indicate: (a) the formation of Es is a sovereign process (particularly when peak PRE vertical drift is significantly smaller than 45 m/s to 60 m/s mark), and (b) the Es densities in the low latitude has a significant impact on the F region dynamo. On the other hand the hypothesis of Abdu et al. (2003) is also not being completely ruled out. Extremely high sheared PRE electric field may be able to deform the low latitude Es structure, however, that is a different aspect of research (not covered in this investigation).

PRE of the zonal electric field have already been studied extensively since last several decades, however, several fundamental aspects related to the PRE are still being investigated in the recent times. Richmond et al. (2015) based on a detailed model computations based on National Center for Atmospheric Research Thermosphere-Ionosphere-Electrodynamics

General-Circulation Model (TIEGCM) have investigated the PRE and the evening vortex characteristics. They found that the shear in neutral wind flow at the bottom of the F region is closely related with the shear in the zonal flow of the plasma. They have also reported that the primary driver of the PRE is the zonal neutral wind flowing above the F region altitude with apex above the F region peak over magnetic equator. That being the case, zonal wind in the EIA crest region plays a dominant role in the PRE. The model computation in the present investigation is quite simplistic in comparison with that of Richmond et al. (2015) and Richmond and Fang (2015). For example, in the present investigation a simplistic 200 m/s zonal eastward wind have been considered to prevail in the evening ionosphere. In actual scenario the thermospheric winds can display large variability which can significantly influence the variability of the PRE. It needs mention that the present investigation deals with the observation study and model computations have been carried out to further substantiate the broader aspects of the observational findings particularly the role of the low latitude Es. Very significant scope does exist to investigate the PRE using the physics based models considering the variability of the low latitude E region conductivity as well as the thermospheric winds. Also the role of the low latitude Es formation in influencing the PRE (by suppressing the F region dynamo) based on the mechanisms proposed by Rishbeth (1971), Heelis et al. (2012) and Richmond et al. (2015) can be further investigated. Considering a significant day-to-day variability in the low latitude E region conductivity due to the Es formation, F region dynamo characteristics under varying low latitude Es conditions can be further evaluated using state of the art physics based models. Although the PRE in the present investigation has been modeled based on the mechanism of Farley et al. (1986), the present investigation does not challenge at all the significance of other mechanisms through which the variation in the low latitude E region conductivities influences the PRE. For example, Richmond and Fang (2015) have found that the E region conductivity can influence the zonal and the meridional convection by drag on the meridional convection associated with the Cowling current. They have reported that if the E region plasma density is significantly high, the E region Pedersen conductivity can impose a drag on the zonal convection and thus can suppress the PRE. However, the results presented in this paper (particularly the observational results) provide a direct evidence that the Es formation can significantly influence the PRE characteristics, by modifying the properties of the F region dynamo. Thus, the variability in the low latitude Es characteristics can be a potential cause of the PRE variability.

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