ARTICLE IN PRESS

Journal of Atmospheric and Solar-Terrestrial Physics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

The role of electric fields in sporadic E layer formation over low latitudes under quiet and magnetic storm conditions

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ARTICLE INFO

Article history:
Received 20 June 2013
Received in revised form
17 November 2013
Accepted 4 December 2013

Keywords:
Low latitude sporadic E layers
Magnetic storms
Penetration electric fields
Vertical Hall eletcric fields
Es layer formation
Es layer disruption

ABSTRACT

Sporadic E layers are formed dominantly by wind shear mechanism, but their formation and dynamics are driven also by ionospheric electric fields. Investigation of low latitude sporadic E layers under quiet conditions shows that Es layer formation during post sunset hours can be disrupted or enhanced depending upon the vertical structure of the vertical electric field arising from sunset electrodynamic processes. During magnetic storms the formation and disruption of these layers are also strongly controlled by vertical Hall electric field induced by the zonal magnetospheric electric fields that penetrates to equatorial/low latitude ionosphere. Observational results on storm time Es layer responses in the Brazilian and Indian-Asian longitudes are compared. An under-shielding prompt penetration electric field (PPEF) of westward polarity that dominate the night side ionosphere, or an over-shielding electric field also of westward polarity in the evening sector can cause formation of sporadic E layers near 100 km, while an eastward polarity electric field, (under-shielding/over-shielding depending upon local time) can lead to disruption of an Es layer in progress. Ionization convergence/divergence leading to the Es layer formation/disruption is driven by a vertical Hall electric field, induced by the primary zonal PPEF, in the presence of storm associated enhanced ratio of field line integrated Hall to Pedersen conductivity $(\sum_H)/(\sum_P)$. A downward polarity of the Hall electric field leads to Es layer formation, while an upward polarity causes the Es layer disruption. An enhancement in the $\sum_H/\sum_P$ ratio can result from E layer conductivity enhancement due to energetic particle precipitation peculiar to the longitude of the South Atlantic Magnetic Anomaly (SAMA) and/or from a drastic reduction in integrated Pederson conductivity in the form of reduced foF2 that is observed in all longitudes.

1. Introduction

Thin ionization layers of the E region, widely known as sporadic E layers, or tidal ion layers, have been investigated extensively since their early observations that started by ionosondes. Our present understanding of their phenomenology is based on observational data from diverse techniques, ionosondes, radars, measurement on board sounding rockets and satellites, and GPS occultation by LEO satellites (see for example, Abdu and Batista, 1977; Arras et al., 2008; Haldoupis et al., 2006; Heelis, 1999; Hocke et al., 2001; Narcisi, 1967; Smith, 1970; etc.). These layers occur in the height region of ~95–120 km, and depending upon the geomagnetic field line inclination they are formed by different generation mechanisms, so that they present distinct characteristics at equatorial latitudes, low-to- mid-latitudes and high latitudes. Over the low and middle latitudes the Es layers are known to be formed by the wind shear mechanism according to which ionization converges at the null points of vertical shears in meridional or zonal wind fields as per the theory originally formulated by Whitehead (1961) and Axford (1963) (for reviews on midlatitude Es layers, see Mathew, 1998, and Haldoupis, 2011). Meridional wind shear is the main driver of vertical ion convergence over mid-latitudes where it is most efficient above ~120 km, whereas the vertical shear in zonal wind becomes more efficient at lower heights. The zonal wind/wind shear becomes the most efficient driver of Es layers at lower latitudes. Depending upon the latitude, electric fields also play important roles in Es layer formation (Nygren et al., 1984). Over equatorial and high latitudes where the geomagnetic field lines are close to being horizontal or vertical, respectively, the process of ion convergence is no more controlled by meridional wind shear, but is driven basically by zonal winds and electric fields. For the low latitude conditions, focused in this paper, the roles of the zonal wind and electric fields in the Es layer phenomenology are now well

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http://dx.doi.org/10.1016/j.jastp.2013.12.003

established (see for example, MacDougall, 1974; Abdu and Batista, 1977; and Abdu et al., 2003a). In fact the role of electric fields gain importance as we approach equatorial latitudes and, especially, in the low latitude region just outside the equator, a vertical electric field has a distinct role to play in the Es layer formation/decay processes (Abdu et al., 2003a; Carrasco et al., 2007). Right at the dip equator where the ion convergence by zonal wind is inefficient, the vertical Hall electric field due to the Cowling conductivity that drives the electrojet current system further impedes the ion convergence process for the Es layer formation. The well known q-type Es layer formed there is constituted by plasma irregularities arising from gradient drift instability mechanism driven by the same Hall vertical electric field acting at the positive (upward) density gradient region below the E layer peak. Away from the dip equator the zonal wind and the vertical shear in it become dominant drivers of the ion convergence process for Es layer formation while at the same time being subject to significant modification/ modulation by vertical electric fields. The main focus in this paper is on the significant role of such electric fields in the development and evolution of low latitude sporadic E layers. This role has the following operational characteristics. (1) An ion convergence process that is in progress under a dominating background wind/wind shear, can suffer modification by an imposed electric field resulting in either enhancement or disruption of the ongoing process. This situation can occur mostly during quiet times, but sometimes also during magnetic storm conditions; (2) An Es layer formation/disruption through ion convergence/divergence processes can be caused solely by disturbance electric fields that can occur during magnetic storm conditions. We will present Es layer response dynamics under each of these characterizations and discuss their implications and significance in terms of the electrodynamic processes of the low latitude nighttime ionosphere that are also related in complex ways with the post sunset developments of the prereversal electric field enhancement and the associated spread F plasma irregularities. Our discussion will also focus on some interesting aspects of interactive processes that are peculiar to the South Atlantic/South American Magnetic Anomaly (SAMA) region (Abdu et al., 2005). We will present results showing electric field effects on Es layer development, separately during quiet times (in Section 2) and periods of magnetic storms (in Section 3), to be followed by discussion and conclusions (in Sections 4 and 5).

2. Es layering process by electric field during quiet time

The Es layers are known to be constituted mostly of metallic ions formed either by direct solar ionization of metallic atoms or by charge exchange of the latter with molecular ions (Narcisi, 1967, Mathews, 1998) produced by solar ionizing radiation or energetic particle precipitation in the E region. The ion vertical velocity (in context of low latitudes) is driven by zonal wind under neutral-ion collisional forcing and geomagnetic Lorentz forcing in such a way that the height gradients in any of these forcing factors can lead to vertical convergence of the ion velocity leading to Es layer formation. Although the Es layers are known to form at or near the descending velocity null point of tidal wind modes and thereby occurring commonly in the height region from ~150 down to ~90 km, most of the layers are observed to remain for longer time near 100 km. This characteristics can be clearly noted in Fig. 1, which shows the height distribution statistics for a typical case of September month over Fortaleza. In this height region it may be pointed out (as discussed by Abdu and Batista, 1977) that independent of the height structure of the zonal wind a significant degree of the height gradient in the ion-neutral collision frequency can, by itself, lead to Es layer formation. For this height region the ion vertical velocity v_z is given by:

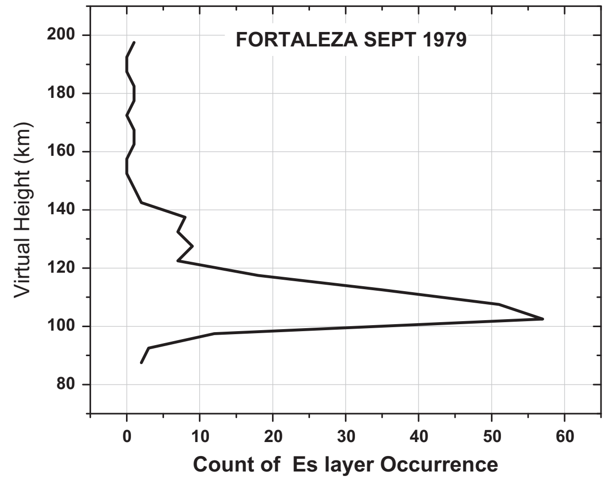

Fig. 1. Statistics of height distribution of Es layer occurrence in September month over Fortaleza, Brazil.

$$v_z = \frac{R_i}{1+R_i^2}\left[\frac{E_z}{B_0} - \frac{E_y}{B_o R_i} - U_y\right] \quad (1)$$

(See Abdu et al., 2003). Here, $R_i = \nu_{in}/\omega_I > 1$ (for the height < 120 km), where ν_{in} is the ion-neutral collision frequency and ω_I is the ion gyro frequency, U_y is zonal wind, B_0 is the magnetic field. This equation shows that vertical electric field (E_z) is more efficient than the zonal electric field (E_y) to cause the vertical ion drift, and that, depending upon its orientation it can enhance or oppose the vertical ion drift forcing by zonal wind. For example a downward (upward) forcing by a westward (eastward) wind can be opposed by an upward (downward) directed E_z, creating a situation in which the ion vertical convergence for Es layer formation can be opposed, or conversely, the vertical electric field acting in the same sense as that of the wind forcing can favor the vertical ion convergence leading to Es layer formation, as explained in detail by Abdu et al. (2003a). Inside the EEJ (Equatorial Electrojet), the normally upward direct E_z opposes any ion convergence that may lead to Es layer formation, permitting only the q-type (irregularity type) Es layer formation, while outside of the EEJ, at low latitudes, also the E_z plays an important role in the Es layering process. A specific case of interest is at sunset hours when the vertical structure of the E_z can cause latitude dependent effects on the Es layer formation. From considerations on the sunset electrodynamics processes, Haerendel et al. (1992) derived an equation for the vertical electric field as given by:

$$E_V = \frac{\Sigma_H}{\Sigma_P} E_{EW} - B_o U_{EW}^P - \frac{J_V}{\Sigma_P} \quad (2)$$

where $\sum_H$ and $\sum_P$ are the field line integrated Hall and Pedersen conductivities; B_o is the magnetic field; J_V is the field line integrated vertical (field line perpendicular) current, and U_{EW}^P field line integrated conductivity weighted zonal wind. (The E_V and E_{EW} in Eq. (2) are the same as the E_Z and E_y in Eq. (1)). The three terms of Eq. (2) correspond to (a) Hall conduction (b) neutral wind dynamo and (c) vertical currents arising from divergence of horizontal currents. The E_z vertical structure at 19 LT as obtained from two dimensional model calculations using field line integrated quantities (by Haerendel et al., 1992) is shown in Fig. 2 (top panel). As explained also by Abdu and Brum (2009) the E_z vertical structure is part of the evening plasma vortex flow such as that observed by the Jicamarca radar (Kudeki and Bhattacharyya, 1999). The evening prereversal enhancement in the zonal (eastward) electric field with the associated vertical plasma drift, the