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Observations of the generation of eastward equatorial electric fields near dawn

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Abstract. We report and discuss interesting observations of the variability of electric fields and ionospheric densities near sunrise in the equatorial ionosphere made by instruments onboard the Communications/Navigation Outage Forecasting System (C/NOFS) satellite over six consecutive orbits. Electric field measurements were made by the Vector Electric Field Instrument (VEFI), and ionospheric plasma densities were measured by Planar Langmuir Probe (PLP). The data were obtained on 17 June 2008, a period of solar minimum conditions. Deep depletions in the equatorial plasma density were observed just before sunrise on three orbits, for which one of these depletions was accompanied by a very large eastward electric field associated with the density depletion, as previously described by de La Beaujardière et al. (2009), Su et al. (2009) and Burke et al. (2009). The origin of this large eastward field (positive upward/meridional drift), which occurred when that component of the field is usually small and westward, is thought to be due to a large-scale Rayleigh–Taylor process. On three subsequent orbits, however, a distinctly different, second type of relationship between the electric field and plasma density near dawn was observed. Enhancements of the eastward electric field were also detected, one of them peaking around $3\,\mathrm{mV\,m^{-1}}$, but they were found to the east (later local time) of pre-dawn density perturbations. These observations represent sunrise enhancements of vertical drifts accompanied by eastward drifts such as those observed by the San Marco satellite (Aggson et al., 1995). Like the San Marco measurements, the enhancements occurred during winter solstice and low solar flux conditions in the Pacific longitude sector. While the evening equatorial ionosphere is believed to present the most dramatic examples of variability, our observations exemplify that the dawn sector can be highly variable as well.

Keywords. Ionosphere (electric fields and currents; equatorial ionosphere)

1 Introduction

The pre-reversal enhancement (PRE) in the eastward electric field component near sunset in the equatorial ionosphere is a phenomenon that has been well reported and studied (see Kelley, 2009). Several theories have been proposed to explain the PRE. Rishbeth (1971) first suggested that the PRE would be a result of charge accumulation below and above the equatorial ionospheric F region that would result from the disappearance of conjugate E region conductivities, and an eastward thermospheric wind. Farley et al. (1986) explained the PRE as a result of a gradient in the off-equatorial Hall conductivity, coupled with the action of eastward thermospheric neutral winds, which would result into a polarization eastward electric field near sunset. Haerendel and Eccles (1992), on the other hand, proposed that the PRE is an enhancement in the dayside (electrojet) eastward electric field created to close the wind-driven vertical current at equatorial F region heights.

Here, we report new observations of a similar phenomenon occurring at dawn. The observations are presented in the next section, followed by a discussion of the results and suggestions as to the origin of upward drifts (eastward electric field structures) near dawn.

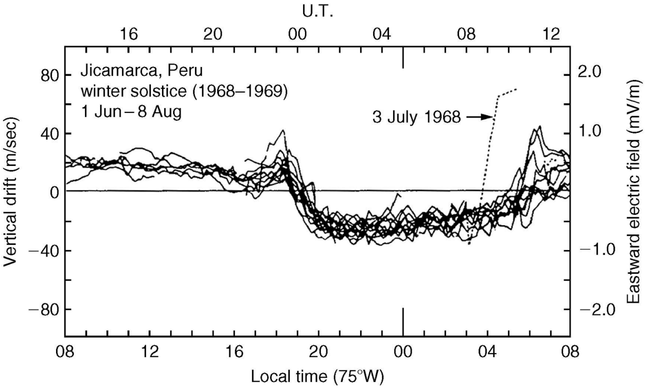

Figure 1. Superimposed vertical drifts (eastward electric fields) measured at Jicamarca, Peru. (After Woodman, 1970. Reproduced with permission of the American Geophysical Union.)

Before describing new data, we review previous observations that may be similar. Woodman (1970) reported on zonal electric field/upward drift data taken at the Jicamarca Radio Observatory in the summer of 1968, as reproduced in Fig. 1. At sunset, the pre-reversal enhancement of the zonal electric field occurred every night. In addition, these superimposed plots show that nearly half of the days studied also had a post-sunrise enhancement of the zonal electric field, whereas the other days did not. Long-term averages of the Jicamarca zonal field (Fejer et al., 1991; Kelley, 2009) may wash out this effect. However, it is the case that the summer averages in those references at least indicate a more precipitous decrease of the westward-directed nighttime zonal component between 04:00 and 05:00 LT than in the other seasons. This could be due to an occasional contribution of a sunrise pre-reversal enhancement of the eastward component (SrPRE) to the averages.

Using electric field data from the San Marco Satellite, Aggson et al. (1995) reported enhanced eastward electric fields at dawn, and showed nine cases of enhanced meridional (upwards) drifts occurring when the nightside zonal eastward drifts diminished significantly. Using five years of ROCSAT satellite data of ion drifts measured near 600 km altitude, Fejer et al. (2008) constructed climatological curves of vertical plasma drifts. Their results (their Fig. 4) seem to indicate the occurrence of enhanced upwards drifts during the June solstice in the longitude sector of −100 to −160° east, despite the averaging. Finally, using C/NOFS satellite data, Pfaff et al. (2010) reported vector electric fields measured during the 2008 solar minimum, which also revealed signatures of enhanced meridional $\boldsymbol{E} \times \boldsymbol{B}$ drifts near dawn. Similar to the Aggson et al. (1995) study, these authors pointed out that the vertical drift enhancements occurred where the zonal eastward drift terminated, and emphasized the geographical/seasonal variation between the angle of the magnetic declination and the sunrise terminator to explain the variability in the electric field.

Finally, we note that a high-speed stream (HSS) encountered the Earth during the period when our measurements were made (17 June 2008), as discussed by Burke et al. (2009). The associated and highly variably electric fields in the interplanetary medium are likely due to Alfven waves, which can penetrate to equatorial latitudes (e.g., Tsurutani and Gonzales, 1987; Kikuchi et al., 2008; Kelley, 2009). Kelley and Dao (2009) studied a fortuitous event in which simultaneous data existed from the ACE interplanetary satellite and the Jicamarca radar during such an event. This allowed them to determine definitively the local time dependence of the penetrating electric fields. Given that the signals discussed in the Kelley and Dao (2009) study displayed a very peaked spectrum at periods of one hour, which is quite a bit lower than the large-scale depletions, we note that the fine structure in the drifts and fields could well be associated with the HSS.

2 Data presentation

Figure 2 shows a series of plasma drift and density measurements made in situ by instruments onboard C/NOFS in June 2008. Figure 2 consists of a series of three-panel plots for each of six orbits (914 through 919) of the C/NOFS satellite on 17 June 2008. For each orbit, the upper panel shows the meridional (black) and zonal (blue) $\boldsymbol{E} \times \boldsymbol{B}$ plasma drifts. Note that the meridional plasma drift is associated with zonal electric fields, and the zonal plasma drift is associated with meridional electric fields. (Even though the measurements were gathered with an electric field instrument, we will usually refer to their corresponding $\boldsymbol{E} \times \boldsymbol{B}$ drifts, as calculated using the measured magnetic field values (see Pfaff et al., 2010) when discussing the data.)

The middle panel of each set shows the ion plasma density (N_i). Note that the scale for this component has been changed for Orbit 915 in order not to clip the deep density depletion, discussed below. Beneath the middle panel, the black bar indicates when the satellite was in eclipse. The lowest panel provides a map of the Earth's low latitude region with the satellite ground trace superposed (black line). The grey shaded region represents the Earth's shadow on the ground, and the red and blue lines indicate the satellite altitude and magnetic equator, respectively. Orbit 918 was also presented in Pfaff et al. (2010).

The regular quasi-sinusoidal oscillation in the plasma drift data is at the orbital period of the satellite, and is due to the dominant diurnal variation of these parameters (Kelley, 2009). For example, the meridional plasma drift is, to first order, upward during the day and downward at night, and the zonal plasma drift is westward during the day and eastward at night. Similarly, the ambient plasma density is highest in the daytime and lowest at night, leading to its quasi-diurnal behavior.

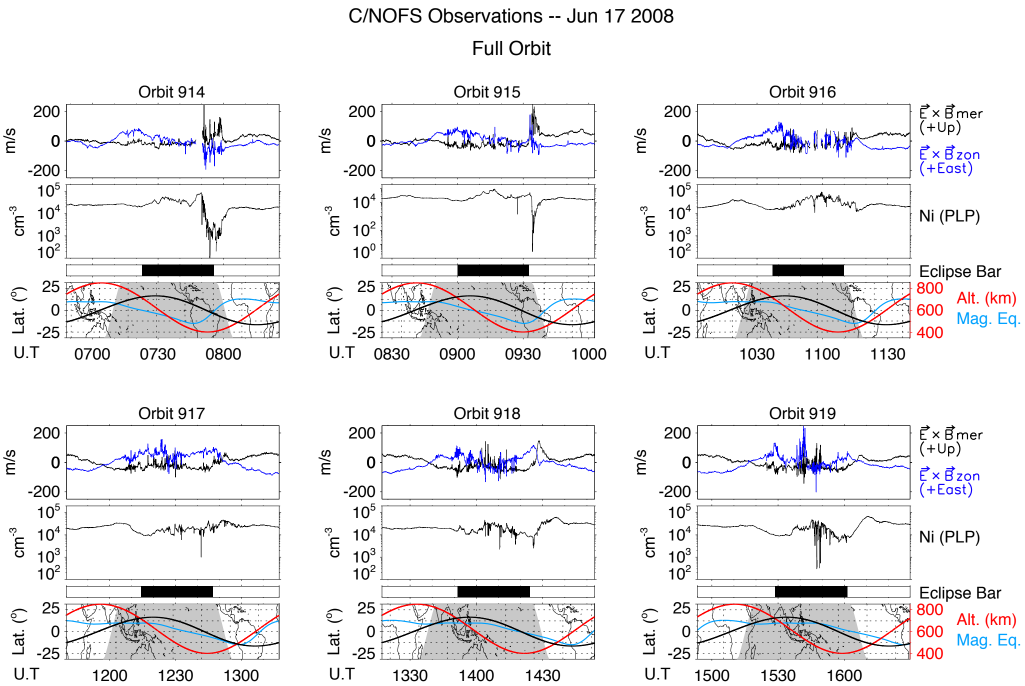

Figure 2. Meridional and zonal plasma drifts measured by VEFI and ion density measured by PLP for six consecutive orbits of the C/NOFS satellite on 17 June 2008. The eclipse bar below the middle panel shows when the satellite was in the Earth's shadow. The lowest panel shows the C/NOFS geographic location and altitude, the magnetic equator, and the Earth's shadow on the ground.

Figure 3 shows expanded plots of the data centered on the dawn region for the local times of 3 to 8 a.m. The panels are the same as before, although here, the grey shadow overlaid on the Earth in the lowest panel corresponds to where the terminator occurs at 100 km altitude. Inspection of these six orbits reveals two different general relationships between the electric field and plasma density near dawn.

The event near 09:36 UT on Orbit 915 is one of the collocated, deep depletion/high zonal electric field events reported by de La Beaujardière et al. (2009) and Su et al. (2009). The large electric field enhancement and deep plasma depletion were found before E region sunrise and were anti-correlated; that is, the upward drift had a waveform similar to the density depletion. The previous pass (Orbit 914) had a deep density depletion, but a fluctuating electric field that was not organized into a recognizable enhancement until the east wall of the depletion. In the subsequent orbit (916), there is a weak event with little evident correlation, although the depletion is very modest compared to that of the preceding two orbits.

On the other hand, on Orbit 917, there is an increase in the upward drift very close to E region sunrise, but with a weak F region density enhancement. In the subsequent two orbits (918 and 919), large $\boldsymbol{E} \times \boldsymbol{B}$ enhancements and modest density depletions were detected, but the enhanced $\boldsymbol{E} \times \boldsymbol{B}$ occurred well after (later local time) the depletion event, and just as the F region plasma density began to build up on the dayside. The $\boldsymbol{E} \times \boldsymbol{B}$ enhancements were comparable to the drifts near noon and, on Orbit 918, the component reached $150\,\mathrm{m\,s^{-1}}$ ($\sim 3\,\mathrm{mV\,m^{-1}}$), certainly among the larger upwards drift amplitudes (zonal equatorial fields) ever measured in the low-latitude ionospheric F region not associated with a density depletion.

We now explore a possible relationship between the zonally eastward plasma drift near dawn and the vertical drifts. The former is plotted in blue and the latter in black. Most notable is the event labeled Orbit 918, which exhibited very large drifts around E region sunrise, and we have blown this up in Fig. 4 and added an arrow plot (top panel) to emphasize the changing directions and magnitudes of the changing $\boldsymbol{E} \times \boldsymbol{B}$ drifts. The large eastward drift near sunrise indicates that the neutral wind was also eastward, since the F region dynamo dominates the eastward plasma drift at night. After crossing the terminator, the control of the zonal plasma drift depends upon both the E and F region dynamos. We believe, due to the inertia in the wind field, that the neutral wind remained eastward (but weaker) across the terminator, creating a similar situation to that which commonly occurs at dusk. Several examples in the data in Fig. 1 show a similar structure in the upward drift at dawn as seen here. Unfortunately, there are very few neutral wind observations near dawn, since optical instruments have very low signal strength. An exception is the DE-2 data reproduced in Fig. 3.6b of Kelley (2009), which shows that the wind, occasionally, stays east through 06:00 LT.

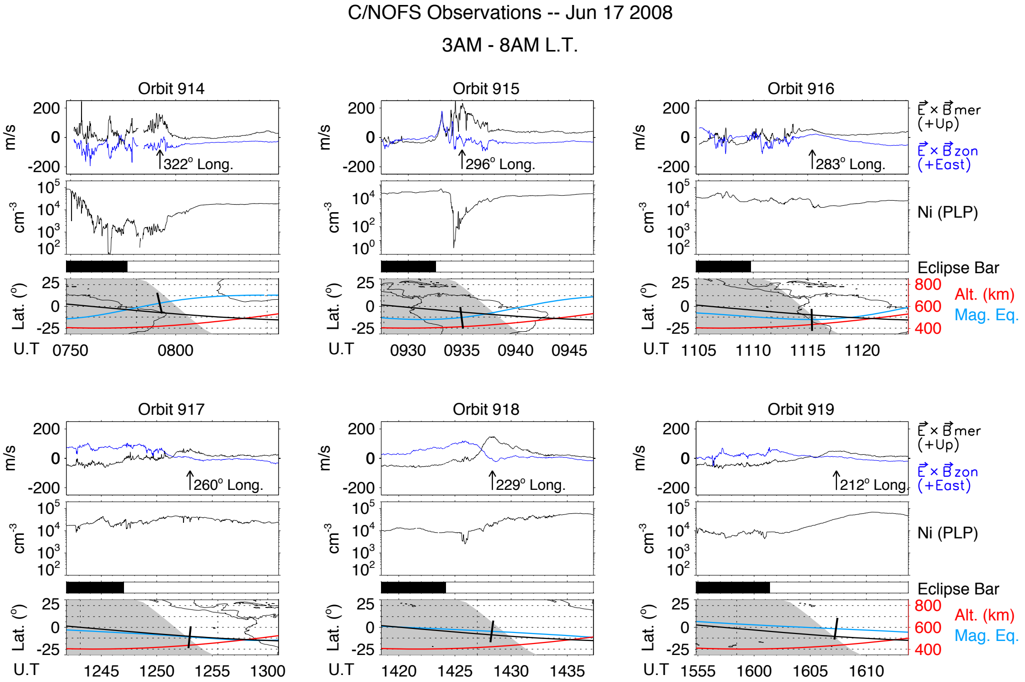

Figure 3. Same as Fig. 2, except that the data are enlarged for the periods of 03:00–08:00 LT. Furthermore, the grey shading in the lowest panel corresponds to the shadow of the Earth at 100 km altitude.

3 Analysis

The data gathered on the C/NOFS satellite orbits discussed above reveal a complex sunrise electrodynamics similar to that observed at sunset. We discuss these different types of events below.

3.1 A large-scale Rayleigh–Taylor process – Orbit 915

De La Beaujardière et al. (2009) presented the data, previously, for Orbit 915, and Su et al. (2009) simulated it. Their conclusion is that the density depletion/electric field enhancement is a large-scale Rayleigh–Taylor instability. The anti-correlation of vertical velocity and plasma density is not perfect, but this production is based on a simple model of current continuity (Kelley, 2009), which does not include any effects of two-dimensional turbulence. That instability is independent of scale (Kelley et al., 1981) if a seed depletion or electric field initially exists. Huang et al. (2012) further commented that these large depletions are caused by a merging of smaller-scale “bubbles”. We use quotation marks since the structures are really more akin to wedges similar to orange slices, but usage of the quoted term is very common. We note here that such a merging is expected, since the western edge of a wedge/bubble is positively charged, whereas the adjacent one to the west is negatively charged, causing the resulting electric field in the uplift of low-density plasma. Merging of vortices in a two-dimensionally turbulent plasma is a common component of two-dimensional theory, which supports an inverse cascade from intermediate to large scales, finally filling the available volume (Kraichnan, 1967, Seyler et al., 1975). Although not yet fully proven in convective ionospheric storms, it has been conjectured that two-dimensional turbulence occurs when wedges/bubbles extend to apex altitudes above about 500 km (Kelley and Ott, 1978; Ott, 1978).

3.2 Post-sunrise electric field enhancements – orbits 917–919

The data in orbits 917–919, and most pronounced in Orbit 918, suggest that, at times, an enhancement of the zonal electric field (and vertical $\boldsymbol{E} \times \boldsymbol{B}$ drifts) occurs around sunset times. The sunrise enhancement resembles the pre-reversal enhancement (PRE) of the vertical drifts that is commonly observed by ground- and space-spaced instrument near sunset hours in the equatorial ionosphere. The satellite tracks (thick black line) shown in the bottom panel of Fig. 4 indicates that the measurements were made very close to the magnetic equator, which is indicated by the blue line. Figure 4 also shows that the measurements were made around 400 km altitude.

The PRE has been studied extensively, and theoretical and experimental investigations have attempted to characterize its magnitude, its longitudinal and seasonal variability, as well as its dependence on solar flux and day-to-day variation (e.g., Fejer et al., 1979; Abdu et al., 1981, 1992; Eccles, 1998; Kil et al., 2009). The sunrise enhancement has been

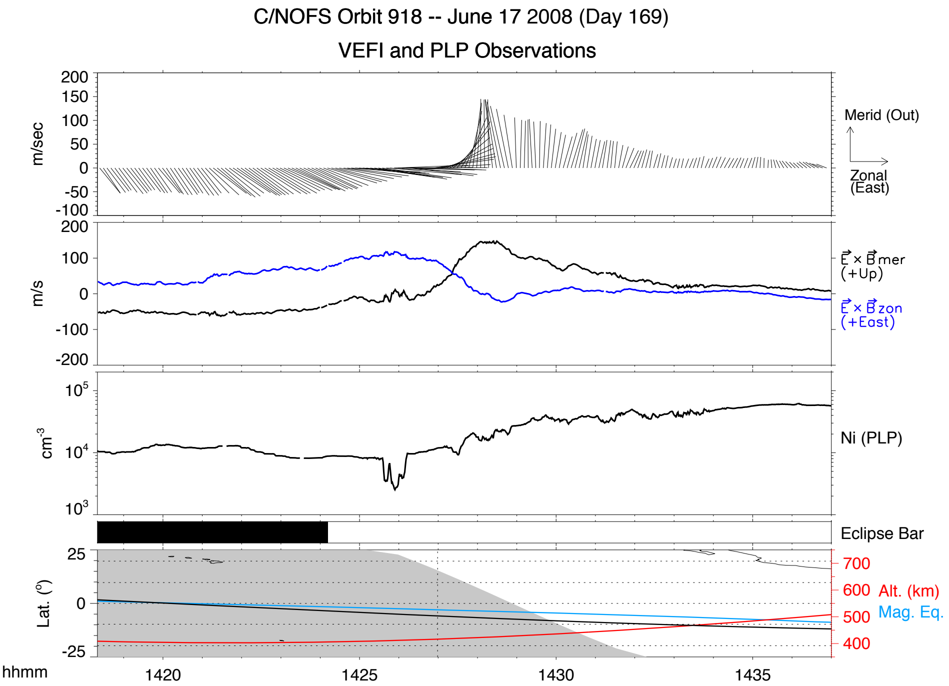

Figure 4. An enlargement of the data shown in Fig. 3 for Orbit 918. The top panel shows the $\boldsymbol{E} \times \boldsymbol{B}$ vector plasma drifts. The grey shading refers to the shadow on the ground.

studied in the past, but to a much lesser extent (e.g., Agsson et al., 1995), which has motivated us to report and discuss the observations made by C/NOFS.

Three theories (Rishbeth, 1971; Farley et al., 1986; Haerendel and Eccles, 1992) have often been invoked to explain the development of the PRE as reviewed by Eccles (1998). While the mechanism most effective at producing the PRE is the subject of discussion, the most widely referenced mechanism is, arguably, that proposed by Farley et al. (1986).

Figure 5a is used to illustrate the PRE mechanism, and to explain the enhancement of the vertical drifts around dawn. Farley et al. (1986) suggested that an eastward wind, in the evening sector and across the terminator, would produce an upward Pedersen current density ($\boldsymbol{J}_{\mathrm{p}} = \sigma_{\mathrm{P}} \boldsymbol{U} \times \boldsymbol{B}$) and, as a consequence, a downward polarization electric field (E_1) in the equatorial F region. This electric field would map, along equi-potential magnetic field lines, to the conjugate E region at low latitudes. The polarization electric field is stronger on the eastern side of the terminator because of the reduced E region densities (and conductivities) compared to the western side. The downward electric field (equatorward at low latitudes) drives a westward Hall current ($\boldsymbol{J}_{\mathrm{H}}$). The divergence of the Hall current across the terminator creates an accumulation of negative charges and a secondary polarization electric field (E_2), which points in the eastward direction to the west of the terminator, and in the westward direction to the east of the terminator. This polarization electric field would then map back to equatorial F region heights and produce the PRE pattern.

The enhancement of the zonal electric field around dawn can be explained following the same mechanism proposed by Farley et al. (1986). Again, eastward F region winds blowing in the eastward direction across the sunrise terminator are the source of the sunrise enhancement. Figure 5b illustrates the creation of the polarization electric field in the equatorial F region and its mapping to the low-latitude E region. In this case, however, the divergence of the Hall current creates an accumulation of positive charges across the sunrise terminator. As a consequence, an enhancement of the vertical (upward) drift develops to the east (dayside) of the terminator.

Considering that, at nighttime, the zonal F region plasma drifts are highly coupled to the thermospheric winds via an F region dynamo, our observations of zonal plasma drifts during orbits 917–919 suggest strong eastward winds near sunrise. The beginning of the sunrise is then indicated by the decrease in the magnitude of the zonal plasma drifts, a result of the activation of the E region dynamo. Therefore, the enhancement in the vertical drifts is observed after the satellite crossed the sunrise terminator when considering the solar illumination of the conjugate E regions. We must keep in mind that the shaded area represents the Earth's shadow at ground level, and is not a good representation of the effective (flux-tube integrated) terminator at F region heights.

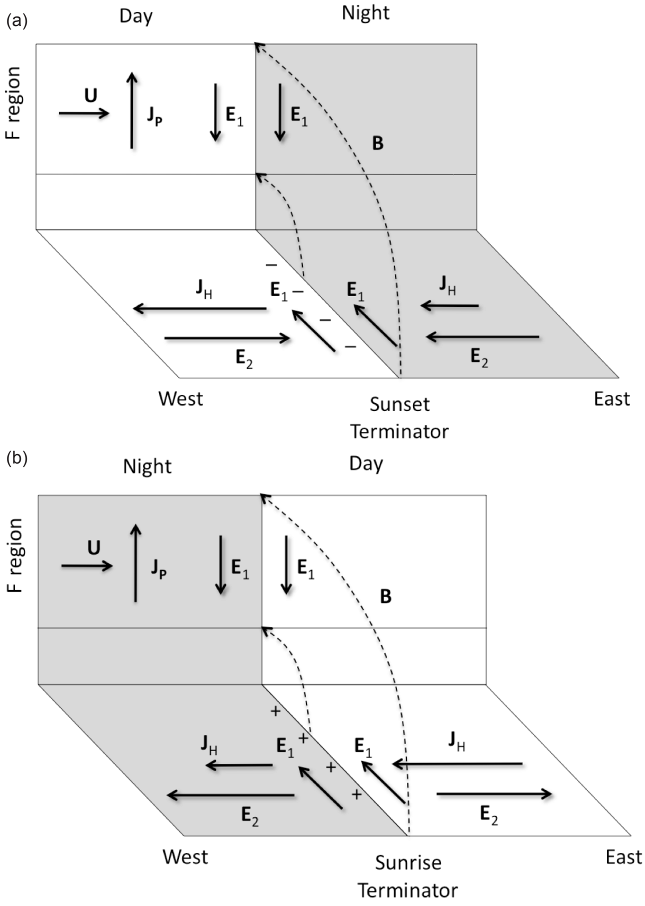

Figure 5. Sketches illustrating the processes responsible for enhancements in the vertical drifts around **(a)** sunset and **(b)** sunrise hours, following the mechanism proposed by Farley et al. (1986).

Plasma density depletions, or even irregularities, were not observed during the vertical drift enhancement or after its appearance. Only a few irregularities were observed to the west, and are thought to be reminiscent of the depletions seen in the previous orbits. The absence of plasma depletion during or after the enhanced drifts would be explained by the less-than-negligible E region shorting of any polarization electric field associated with interchange instabilities trying to develop during that time.

4 Conclusions

We have presented and discussed interesting observations of the variability of equatorial F region electric fields and ionospheric densities made by instruments onboard the C/NOFS satellite over six consecutive orbits. While the evening equatorial ionosphere is believed to present the most dramatic examples of variability, our observations show that the dawn sector can be highly variable as well.

Large ionospheric plasma depletions were observed just before sunrise on the three first orbits. These depletions were accompanied by large eastward electric fields as previously described by de La Beaujardière et al. (2009), Su et al. (2009) and Burke et al. (2009). The eastward field (positive upward/meridional drift) is thought to be associated with a large-scale interchange plasma (Rayleigh–Taylor) process. On three subsequent orbits, however, a relationship between electric fields and plasma density patterns was observed near dawn. Enhancements of the eastward electric field were also detected, one of them peaking around $3\,\mathrm{mV\,m^{-1}}$, but they were found to the east (dayside) of the terminator. These observations represent dawn enhancements of vertical drifts driven by eastward winds such as those observed by the San Marco satellite (Aggson et al., 1995). Like the San Marco measurements, the enhancements occurred during winter solstice and low solar flux conditions in the Pacific longitude sector. We explain that, under the action of an eastward, equatorial thermospheric wind, the enhancement of the vertical plasma around sunrise hours can be explained using the same mechanism proposed by Farley et al. (1986) to explain the enhancement of the vertical drifts around sunset.

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