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Evidence for OI 630.0 nm dayglow variations over low latitudes during onset of a substorm

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[1] Observations of OI 630.0 nm dayglow intensity from Mt. Abu (magnetic latitude (MLAT): 16.2°N; magnetic longitude (MLONG): 148°E) at two different directions corresponding to two different magnetic latitudes ($\text{MLAT}_{\text{Zenith}}$: 16.2°N and $\text{MLAT}_{20°\text{Elevation}}$: 22.2°N) revealed nearly simultaneous intensity enhancements on 2 February 2002 (Ap = 19) during 0554–0635 universal time (UT) (1124–1205 Indian Standard Time (IST); IST = UT + 5.5 h). This feature is found to be absent on a typical control day (3 February 2002; Ap = 4). The dayglow enhancements were concomitant with enhancements in the *E*-region zonal electric field inferred from deviations of the northward component of magnetic field (ΔH) obtained from a meridional chain of magnetometers encompassing the dip equatorial and low-latitude regions. Simultaneous positive bay signatures in ΔH were also recorded at all stations along the 210° magnetic meridian (MM) in the afternoon sector (~1454–1535 magnetic local time). The changes in the solar wind parameters including the dawn-to-dusk component of IEF and ram pressure are found negligible during 0554–0635 UT. However, the variations in the auroral electrojet and ring current indices indicate the presence of a substorm during 0554–0635 UT. Sudden enhancements in the energetic particle fluxes measured by the Los Alamos National Laboratory (LANL) 1991–080 satellite at geosynchronous altitude provide evidence for the onset of the expansion phase of a magnetospheric substorm. Therefore, the present investigation adduces the response of 630.0 nm dayglow intensities over low latitudes corresponding to the onset of the expansion phase of an auroral/magnetospheric substorm.

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1. Introduction

[2] The ionosphere-thermosphere system (ITS) over low latitudes behaves as a mutually coupled system and, as a consequence, many characteristic low-latitude ionospheric processes have been found to leave their footprints on the neutral thermospheric airglow emission. Neutral (OI) 630.0 nm thermospheric airglow is one of the most widely studied emissions that is believed to act as a reliable tracer to the coupling processes pertaining to ITS. Although nighttime OI 630.0 nm airglow measurements [e.g., *VanZandt and Peterson*, 1968; *Kulkarni and Rao*, 1972] have been used extensively to investigate the low-latitude ITS, evidence for the effects of interplanetary electric field (IEF) on OI 630.0 nm nightglow emission over low latitude was obtained only recently [*Chakrabarty et al.*, 2005]. This result showed that a neutral thermospheric airglow emission over low latitude could be affected by plasma processes occurring as far as in the interplanetary medium and provided an impetus to investigate the low-latitude ITS during disturbed space weather conditions using daytime measurements of 630.0 nm airglow. Although measurements of 630.0 nm dayglow emission were carried out from satellite platform a long time ago [e.g., *Hays et al.*, 1978], systematic ground-based observations of 630.0 nm dayglow are sparse mainly due to the difficulty of detecting the faint emission buried in bright background continuum [e.g., *Chakrabarti*, 1998 and references cited therein]. In the past couple of decades, remarkable progress has been made in this regard to address the coupling aspects of ITS using 630.0 nm dayglow emission as tracer [e.g., *Sridharan et al.*, 1991, 1992a, 1992b, 1994;

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Chakrabarty et al., 2002; *Pallamraju et al.*, 2002]. Many of those results highlighted the importance of zonal electric field over the dip equator in the plasma distribution throughout the low-latitude ionosphere.

[3] It is now known that the zonal electric field over low latitudes is affected by the global electric field perturbations that arise due to (i) prompt penetration and overshielding effects of IEF [e.g., see *Chakrabarty et al.*, 2006 and references cited therein], (ii) substorms [e.g., *Huang et al.*, 2004; *Sastri et al.*, 2003; *Kikuchi et al.*, 2003], (iii) storm sudden commencement (SSC) [e.g., *Sastri et al.*, 1993], and (iv) disturbance dynamo (DD) [*Blanc and Richmond*, 1980]. Among these effects, transient electric field perturbations due to SSC would occur just prior to the main phase of a geomagnetic storm and electric field perturbation due to DD at least several hours after the onset of a storm/substorm. On the other hand, prompt penetration and overshielding electric field effects over low latitudes are known to be nearly simultaneous. Disturbances in the zonal electric field may also occur during auroral/magnetospheric substorms within or without a geomagnetic storm. The ionospheric effects of a substorm are multifaceted, depending on the substorm phase [e.g., *Kamide et al.*, 1996 and references cited therein] and prevalent ionospheric conditions. A number of favorable solar wind conditions like polarity reversals in IMF Bz and By, changes in solar wind ram pressure, discontinuities in the solar wind, and so on, are known to trigger substorms [*Lyons*, 1996], although the mere presence of these conditions does not guarantee the occurrence of substorms [*Lee et al.*, 2007]. On many occasions, substorms occur even without any comprehendible trigger [*Henderson et al.*, 1996].

[4] It is generally agreed on that substorm-induced impulsive electric field perturbations over low latitudes occur due to the reconfiguration of the magnetic field during growth and expansion phases when the shape of the nightside magnetosphere becomes more tail-like and dipolar respectively [e.g., *Sastri*, 2002]. This, in turn, changes the magnetic field flux inside the inner magnetosphere inducing an electric field. Substorm is primarily a nightside phenomenon. However, the effects are also observed on the dayside although an unambiguous phenomenological understanding of the daytime effects is yet to evolve. The effects of substorm on low-latitude ionosphere were addressed previously in several studies [*Reddy et al.*, 1979; *Somayajulu et al.*, 1987; *Kikuchi et al.*, 2000; *Sastri et al.*, 2001; *Huang et al.*, 2004]. Nevertheless, a comprehensive understanding on the effects of substorms on low latitude TIS remains elusive. This is due to the fact that substorm and geomagnetic storms may both get triggered/modulated by changes in the solar wind parameters like IEF, ram pressure, and so on. Therefore, it is difficult to isolate the contributions of storm and substorm in the electric field disturbances over low latitudes. An attempt in this regard was made by *Chakrabarty et al.* [2008] wherein it was shown, based on a case study, that the fast fluctuations in the zonal electric field over nightside dip equator are controlled by IEF, whereas the slow variation in the ionospheric height was governed by substorms thus enabling unambiguous identification of substorm-induced electric field perturbations.

[5] In the present investigation, an attempt is made to highlight the changes that occurred in the low-latitude ITS during a storm-time substorm occurring under steady IEF. The investigation brings out, for the first time, the effect of substorm-induced eastward electric field on OI 630.0 nm dayglow.

2. 630.0 nm Dayglow Emission Over Low Latitudes

[6] The excited $O(^1D)$ atoms that emit 630.0 nm dayglow emission are produced by three main processes over low latitudes [*Hays et al.*, 1978, 1988; *Solomon and Abreu*, 1989; *Pallamraju et al.*, 2004]. They are the photoelectron (energy > 1.96 eV) impact (PE) of oxygen atom (O), photodissociation (PD) of molecular oxygen (O_2) by Schumann-Runge continuum (135.0–175.0 nm) of solar radiation, and dissociative recombination (DR) of O_2^+ ions with ambient ionospheric electrons. However, as indicated by *Sridharan et al.* [1992b], contributions from PE and PD channels do not vary in a short temporal scale (~1–2 h) unless the photoelectron flux and solar radiation change drastically within that timescale. On the other hand, the DR process predominantly contributes to the temporal variability of the 630.0 nm dayglow intensity over low latitudes as this process is dependent on the ambient ionospheric plasma. As the ionospheric plasma distributions over low latitudes during magnetically quiet periods vary primarily due to the ionospheric processes like equatorial ionization anomaly (EIA), passage of travelling ionospheric disturbances (TID) or the transport of plasma due to meridional wind, 630.0 nm dayglow emission is expected to capture these processes.

[7] The 630.0 nm dayglow observations reported in the present work are made with a photometer that can isolate faint OI 630.0 nm thermospheric dayglow emission buried in bright background continuum. Comprehensive details of the photometer are available elsewhere [*Narayanan et al.*, 1989; *Sridharan et al.*, 1992a]. The detection technique involves a front-end optics comprising of a narrow band (0.3 nm) interference filter centered at 630.0 nm that isolates the signal and limits the background to within 0.3 nm. A bipolar thermoelectric temperature controller is used to keep the filter temperature steady within 0.1°–0.2°C under tuned conditions. The spectral passband is then transmitted through a low-resolution Fabry-Perot etalon that is pressure tuned to 630.0 nm. The spectral fringe pattern is then focused onto a plane that houses a dual mask assembly. The mask assembly consists of a stator and a rotor. The chopping mask system attached with the rotor enables quick (within ~10 ms) sampling of two successive spectral zones. Pressure-tuning of the etalon and the mask assembly allow picking up the signal (emission feature) along with background in one spectral zone and only the background in the successive zone 0.07 nm away. Photon counts corresponding to these two spectral zones, gated and synchronously detected by a photomultiplier tube, are obtained and the difference between the counts now corresponds to the 630.0 nm dayglow intensity. The photometer is equipped with a mirror scanning arrangement that facilitates scanning of the sky both in elevation and in azimuth. In the present case, the temporal resolution of the 630.0 nm intensity time series in a given direction is ~15 s. The dayglow photometer discussed here has *f*/11 optics and ~2.2° field of view. With this field of view, the photometer covered a spatial region of ~8.5 km over zenith (16.2°N magnetic latituted (MLAT)) and ~25 km over a place at

22.2°N MLAT (20° elevation angle) considering the centroid of the emission region to be at 220 km. As the photometer could not be easily calibrated due to the presence of Fabry-Perot etalon, only relative intensity variations can safely be addressed.

[8] During February 2002, this photometer was operated for a few days in a campaign mode from Mt. Abu to measure 630.0 nm dayglow intensity in two different directions. One of those directions included zenith that represented the dayglow intensity variation over Mt. Abu and the other direction covered a place north of Mt. Abu. As Mt. Abu is strategically located near the crest of the equatorial ionization anomaly (EIA), the scientific objective was to investigate the behavior of the ionosphere-thermosphere system (ITS) at the EIA crest region and at a place beyond the crest region for different zonal electric field conditions over the dip equator. The present investigation addresses a salient observational feature obtained during that period.

3. Results

[9] Figure 1a depicts the OI 630.0 nm dayglow intensity variations over zenith as observed from Mt. Abu (MLAT: 16.2°N; magnetic longitude (MLONG): 148°E) on 2 February 2002 (star) and 3 February 2002 (solid line) respectively. Similarly, Figure 1b depicts the OI 630.0 nm dayglow intensity variations at a low elevation (20°) in the northern direction on 2 February 2002 (star) and 3 February 2002 (solid line) respectively. These measurements at two different directions from a single location provide the dayglow intensity variations at two different magnetic latitudes ($\mathrm{MLAT}_{\mathrm{Zenith}}$: 16.2°N and $\mathrm{MLAT}_{20^\circ\mathrm{Elevation}}$: 22.2°N) respectively from regions in the thermosphere around 220 km. It is to be noted here that the background intensity levels on 2 and 3 February 2002 differ substantially. This may be due to the reduced electron density on 3 February 2002 as a consequence of negative ionospheric storm effect occurring after the main phase of the geomagnetic storm on 2 February 2002. As ionosonde measurements from a nearby location were not available, and this aspect is pursued no further in this communication.

[10] The relevant variation for the present investigation is the simultaneous enhancements in 630.0 nm dayglow intensities at the two dip latitudes during 1124–1205 IST (0554–0635 universal time (UT)) on 2 February 2002 (Ap = 19). It is to be noted that this feature in the airglow intensity variation is conspicuously absent on a control day (3 February 2002; Ap = 4). In order to highlight this short-duration dayglow intensity variation and address its origin in the context of other measurements, this interval (0554–0635 UT) is marked by the hatched box here and on subsequent plots, wherever applicable. It is to be noted here that the intensity variations at other times are not addressed further as the amplitudes of the small-scale dayglow intensity variations are not sufficiently prominent in the northern direction.

[11] In order to determine whether the dayglow intensity variations over low latitudes during 0554–0635 UT are due to electric field disturbances, the variations in $\Delta H_{\mathrm{TIR}} - \Delta H_{\mathrm{VSK}}$ on 2 February 2002 (solid line) and 3 February 2002 (dashed line), respectively are depicted in Figure 1c. Here, TIR and VSK represent Tirunelveli (MLAT = 0.57°S) and Visakhapatnam (MLAT = 8.2°N) in the Indian zone. Those values of $\Delta H_{\mathrm{TIR}} - \Delta H_{\mathrm{VSK}}$ are representative of the strength of the Equatorial Electrojet (EEJ) [*Rastogi and Patil*, 1986] and consequently act as a proxy to the zonal electric field that drives the EEJ. The hatched box in Figure 1c indicates an enhancement of zonal electric field during 0554–0635 UT on 2 February 2002 when there is prompt response in the intensity variations of 630.0 nm dayglow at both the latitudes. In order to identify the corresponding signatures, if any, in the ΔH variations over India during 0554–0635 UT on 2 and 3 February 2002, available data from three Indian stations, TIR, Pondicherry (PND, MLAT: 2.7°N), and VSK are analyzed. Figures 1d, 1e, and 1f represent the variations in ΔH for TIR, PND, and VSK on those 2 days. Enhancements are found to be present on 2 February 2002 in all three stations during 0554–0635 UT with the amplitude of the enhancement decreasing with increasing latitude (~36, 15, and 8 nT enhancements in TIR, PND, and VSK respectively) from the magnetic equator.

[12] In order to facilitate the assessment of the prevalent conditions in solar wind-magnetosphere-ionosphere system on 2 February 2002, variations in the solar wind parameters and a few storm and/or substorm indices on this day are presented in Figure 2. Figures 2a–2c present the variations in *x*, *y*, and *z* components (in GSE coordinates) of the interplanetary magnetic field (IMF). The *x* component of solar wind velocity, proton density, and ram pressure are shown in Figures 2d–2e, while the *y* component (dawn-to-dusk) of the interplanetary electric field (IEFy) and polar cap (PC) index [*Troshichev et al.*, 2000] are shown in Figure 2f. These are taken from NASA GSFC CDAweb (http://cdaweb.gsfc.nasa.gov/istp_public/), where all the above-mentioned parameters have been corrected for propagation time to the nose of the bow shock. In order to account for the additional propagation lag owing to the magnetosheath and Alfven transit times, each datum point in these parameters is additionally shifted in time following the methodology described in *Chakrabarty et al.* [2005]. Though all the parameters described in Figures 2a–2f exhibit insignificant changes during 0554–0635 UT, the PC index in Figure 2f stands out with ~40% variation during this interval. Interestingly, the IEFy in Figure 2f is found to be devoid of any large fluctuations during 0330–0730 UT and is persistently in the dawn-to-dusk direction during this interval. Figure 2g depicts the development of the auroral electrojet (AU/AL/AE indices) on 2 February 2002. Large changes are noticed in AU, AL, and AE during 0554–0635 UT although an enhancement in AL is delayed by ~12 min. Sharp changes are also observed in the ring current indices [*Iyemori and Rao*, 1996] like the *H* component of the asymmetric ring current (ASY-H) (Figure 2h), *D* component of the asymmetric ring current (ASY-D) (Figure 2i), and *H* component of symmetric ring current (SYM-H) (Figure 2j) during 0554–0635 UT.

[13] In addition to the changes in the solar wind parameters and the storm/substorm indices, as revealed in Figure 2, enhancements in the deviations of the *H* component (ΔH) are also observed on 2 February at all the magnetometer stations along the 210° magnetic meridian (MM) chain (*Yumoto et al.*, 2001) in the afternoon sector (0554–0635 UT or 1454–1535 magnetic local time, MLT). Figure 3a depicts the variations in ΔH at some of the representative magnetometer stations ranging from the northern station, Magadan (MGD, MLAT 53.6°N) to the southern station, Adelaide (ADL, MLAT 46.5°S). It is interesting to note that enhancement in

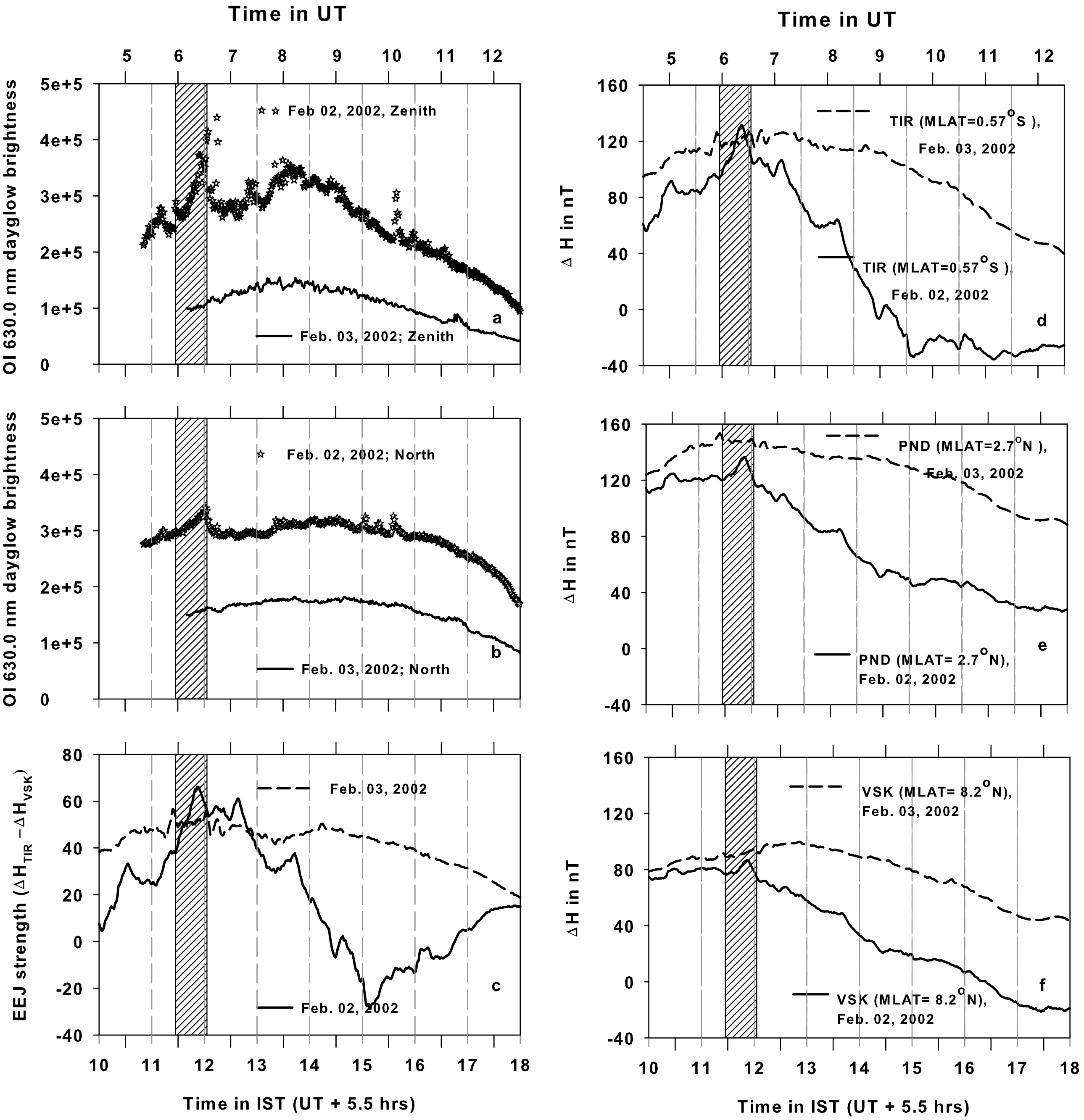

Figure 1. (a) The OI 630.0 nm dayglow intensity variations observed from Mt. Abu on 2 February 2002 (star) and 3 February 2002 (solid line) respectively corresponding to zenith (dip latitude: 16.2°N), and (b) northern direction (dip latitude: 22.2°N); (c) ($\Delta H_{TIR} - \Delta H_{VSK}$) variations that represent the Equatorial Electrojet strength on 2 February 2002 (solid line) and 3 February 2002 (dashed line), respectively. (d), (e), and (f) The variations in ΔH recorded at Tirunelveli (TIR), Pondicherry (PND), and Visakhapatnam (VSK) respectively on 2 February 2002 (solid line) and 3 February 2002 (dashed line). The importance of enhancements during 0554–0635 UT marked by hatched box is discussed in the text.

ΔH (positive bay) is seen during 0554–0635 UT irrespective of whether the station is situated in the northern or southern hemisphere. Figure 3b presents the energetic electron fluxes measured by Los Alamos National Laboratory (LANL) 1991–080 satellite at geosynchronous orbit at multiple energy channels on 2 February 2002. Sudden increases in the electron fluxes are found to occur in all the energy channels at 0554 UT. It is also verified that similar 210°MM and LANL signatures are not seen on the control day (3 February 2003) during 0430–0930 UT (not shown here).

[14] In order to ascertain the concurrence of the enhancements in 630.0 nm dayglow intensity on 2 February 2002

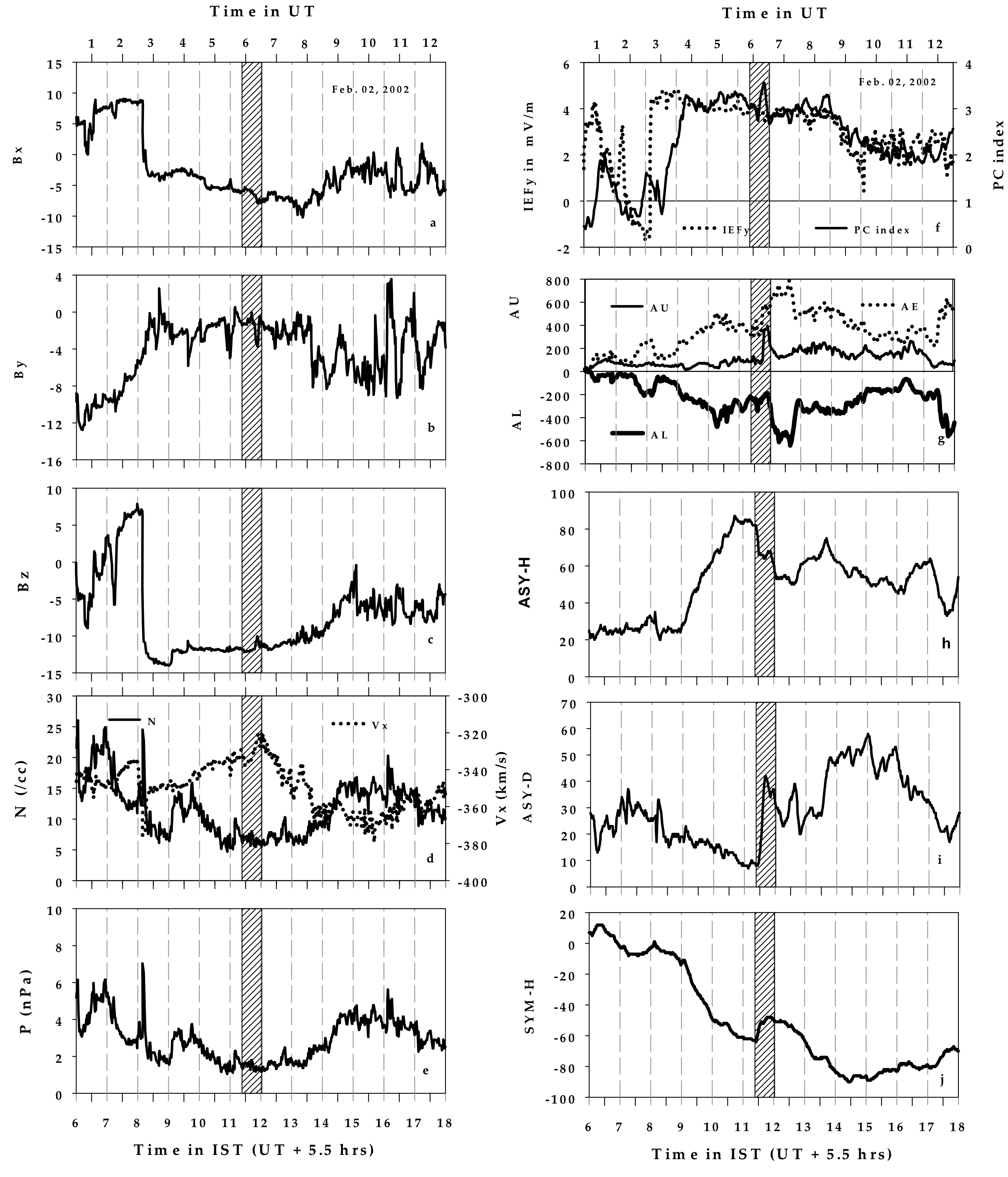

Figure 2. Variations in (a) IMF Bx; (b) IMF By; (c) IMF Bz; (d) proton density (N) and *x* component of solar wind velocity (Vx); (e) solar wind ram pressure (P); (f) IEFy and Polar Cap (PC) index; (g) AU, AL, and AE; (h) and (i) ASY-H and ASY-D respectively; (j) SYM-H, all on 2 February 2002 during 0030–1230 UT. The period during 0554–0635 UT is marked in all the subplots to highlight the changes.

with the onset of the substorm under consideration, Figure 4 is plotted. The zoomed-in subplots of Figure 4 selectively depict the variations in the electron flux at 225–315 keV energy channel, the SYM-H indices, and the EEJ strength during 0500–0700 UT (1030–1230 IST) in the upper panel (Figure 4a) and 630.0 nm dayglow intensity variations in two directions during the same interval in the lower panel (Figure 4b). The choice of the energetic electron channel is

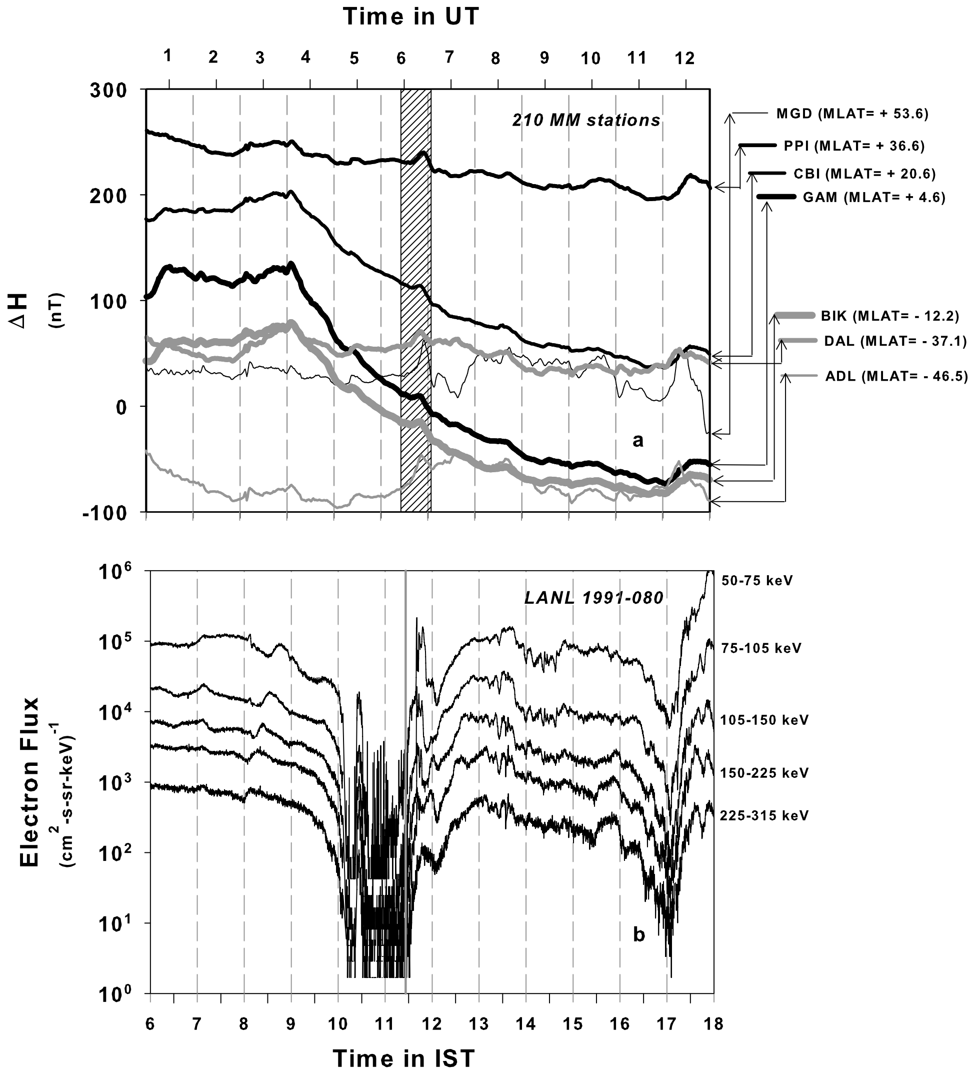

Figure 3. (a) Variations in ΔH on 2 February 2002 at Biak (BIK), Dalby (DAL), Adelaide (ADL), Guam (GAM), Chichijima (CBI), Popov Island (PPI), and Magadan (MGD) in the 210 MM chain. The "+" and "–" symbols in MLAT stand for northern and southern stations, respectively. The hatched box (0554–0635 UT or ~1454–1535 magnetic local time, MLT) highlights the presence of small positive bay disturbances at all the stations; (b) Energetic electron fluxes as measured by Los Alamos National Laboratory (LANL) 1991–080 satellite at geosynchronous orbit at 50–75, 75–105, 105–150, 150–225, and 225–315 keV energy channels respectively (top to bottom) on 2 February 2002. The vertical line denotes the sudden increase in the electron fluxes at 0554 UT in all the energy channels, indicating the onset of the expansion phase of the substorm.

arbitrary and one can use other channels also for comparison. Significant changes in ring current (SYM-H) and zonal electric field over dip equator (EEJ strength) seem to occur in unison at 5.93 UT (or 0554 UT) with the onset of enhancement in the energetic electron flux at the geosynchronous orbit. A conspicuous change in the 630.0 nm dayglow intensity over zenith is observed at this time. At the same time, only a small but noticeable enhancement in the dayglow intensity along the northern direction is observed. The amplitude of the intensity enhancement and the rate of increase in intensity over zenith are considerably larger compared to the corresponding observations from the northern direction. This is due to the smearing-out effect as a consequence of the larger atmospheric volume covered by the slanted view. After 0554 UT and till 0635 UT, mean variations in the airglow intensities from both the directions increase with the gradual increase in the zonal electric field.

4. Discussion

[15] The prompt occurrence of the OI 630.0 nm dayglow intensity fluctuations nearly simultaneously over two latitudes in the Indian zone during 0554–0635 UT on 2 February 2002 and the simultaneous occurrence of the positive bay in ΔH over a range of latitudes over India as well as at the stations along the 210°MM chain clearly suggest an

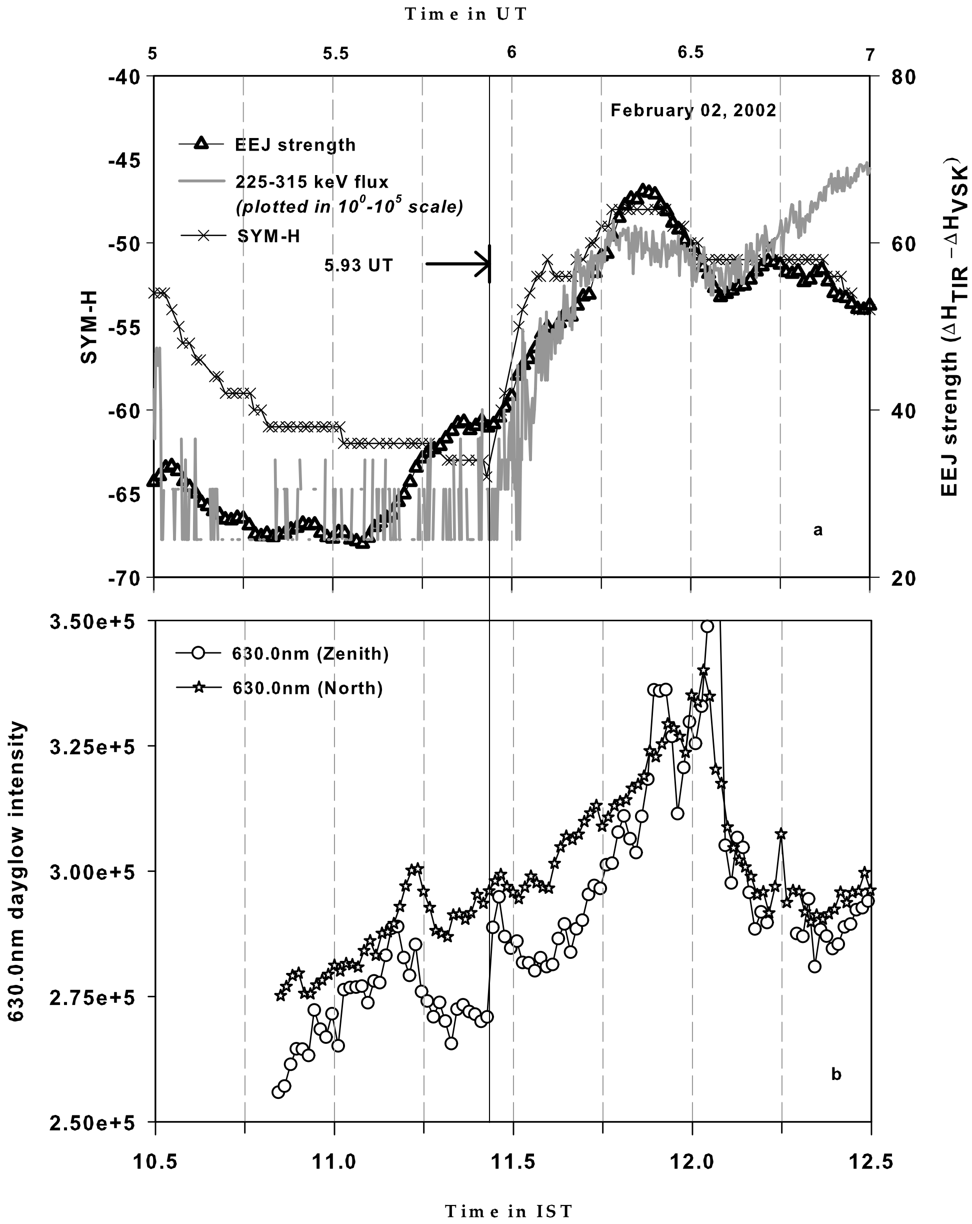

Figure 4. (a) Blown-up plots of the variations in the EEJ strength (triangles joined by line) and SYM-H ("x" symbols joined by line) with geosynchronous electron flux at 225–315 keV (grey line) during 0500 to 0700 UT; (b) 630.0 nm dayglow intensity variations over Mt. Abu (circle) and north (star) of Mt. Abu during the same interval. Corresponding changes are observed in all the parameters after 5.93 (or 0554) UT (black vertical line) indicating the onset of substorm and its effects over low latitudes at that time.

enhancement of eastward electric field throughout a wide spatial region. Such dayglow intensity fluctuations are conspicuously absent on a control day (3 February 2002). Moreover, as described by *Sastri et al.* [2003], the strong latitude dependence (decreasing amplitude with increasing latitude) of the ΔH variations over the Indian zone on 2 February 2002 is indicative of a short-lived enhancement in the daytime eastward electric field on this day.

[16] In order to find out the origin of this simultaneous enhancement of eastward electric field across wide latitude regions during 0554–0635 UT, variations in the solar wind parameters as well as various storm/substorm indices are investigated. Concurrent variations are observed in all the substorm indices (Figures 2 and 3) during 0554–0635 UT in the presence of steady solar wind conditions when, especially, dawn-to-dusk component of IEF and ram pressure did not exhibit significant changes. Moreover, it has been accepted for quite some time that impulsive injection of plasma and energetic particles at the geosynchronous altitudes is one of the trademark signatures of substorm onset [e.g., *Arnoldy and Chan*, 1969]. The sudden injection of the electrons at 0554 UT in Figure 3b clearly highlights the onset of a substorm at this time. Interestingly, the substorm does not seem to be triggered by polarity reversals of IEF,

changes in solar wind ram pressure and density as the variations in these parameters are not significant during 0554–0635 UT. It is also verified using the methodology described in *Tsurutani and Smith* [1979] that solar wind discontinuities are not responsible for the triggering of this substorm.

[17] In order to understand the complex interactions of the magnetosphere-ionosphere and thermosphere system during the substorm event under consideration, the behaviors of various solar wind parameters as well as storm/substorm indices are investigated. A combination of several observations comprising of the increase in the PC index, strengthening of the auroral electrojet current system, asymmetric ring current (ASY H/D) activities, weakening of symmetric ring current (SYM H), and the presence of simultaneous positive bays in ΔH observed over all the stations along the 210°MM chain during 0554–0635 UT have been looked into in detail. *Troshichev et al.* [2000] showed that polar cap index (PC) can be effectively considered as a proxy for ionospheric electric field in the near-pole region. The enhancement of PC index during 0554–0635 UT, therefore, indicates an enhancement of ionospheric electric field in the auroral region. The enhancement of the auroral electrojet strengths especially westward auroral electrojet strength (captured by AL) suggests the onset of a substorm expansion phase validating our earlier inference. The finite time delay between AL and AU is verified to be a consequence of the spatial separation of the AE stations and the propagation of the effects of substorm from one station to other. In addition, *Sastri et al.* [1997] also showed that high-latitude electric fields affect equatorial ionosphere during episodes of asymmetric ring current activity. Therefore, characteristic changes in asymmetric ring current indices (ASY H/D) in the present case, similar to the observations by *Sastri et al.* [1997], are indicative of electric field disturbances during 0554–0635 UT. The enhancement in SYM-H during 0554–0635 UT is believed to be related to increase in magnetic flux density in the near-Earth tail region associated with magnetic dipolarization process and also to the tail current disruption process [e.g., *Turner et al.*, 2000] that occur at the onset of substorm and affect the ring current [e.g., see *Reeves et al.*, 2003; *Huang et al.*, 2004]. The enhancement in SYM-H seems to be concurrent with the enhancements in energetic electron fluxes at the geosynchronous orbit, increase in the zonal electric field over dip equator, and enhancement in 630.0 nm dayglow intensity over low latitudes (Figure 4), suggesting the presence of nearly instantaneous effects of the substorm-induced electric field throughout the low-latitude region.

[18] During substorm onset, negative bay signatures in the ΔH in the dayside equatorial region have been reported [e.g., *Kikuchi et al.*, 2000; *Sastri et al.*, 2001]. However, occasional positive bays in ΔH at substorm onset similar to the present case were also observed earlier [e.g., *Yumoto*, 1987; *Huang et al.*, 2004; *Lyons et al.*, 2008]. Simultaneous occurrence of positive bay signatures at middle and low latitudes in both day and night sectors was reported by *Yumoto* [1987] and it was attributed to the unusual formation of a dayside current wedge. *Huang et al.* [2004], on the other hand, attributed daytime low-latitude positive bay events to substorm dipolarization process. In recent times, *Lyons et al.* [2008] found out events where daytime positive bay signatures are associated with enhancements in solar wind ram pressure. In the absence of any significant change in the solar wind ram pressure during 0554–0635 UT, the bay signatures reported here do not seem to be associated with changes in ram pressure. Recently, *Tokunaga et al.* [2007], based on independent component analyses of Pi2 pulsations data, showed that the amplitude of one component of Pi2 pulsations maximizes at nightside high latitudes and the other component gets enhanced near dip equator, suggesting instantaneous penetration of the effects of substorm from nightside high latitudes to daytime low latitudes. It is interesting to note that the eastward electric field perturbations associated with prompt penetration and overshielding effects have been detected over the years [e.g., *Kikuchi et al.*, 1996, 2000; *Fejer*, 2007]. However, as *Fejer et al.* [2007] pointed out, the relationship between the solar wind electric field and equatorial prompt penetration electric field is far more complex than the simple proportionality factors. One of the main reasons for this complexity is the additional presence of overlying electric field perturbations associated with substorms. Therefore, comprehensive, phenomenological understanding of the effects of storm-time substorms on the low-latitude ITS, especially during daytime, will require systematic and extensive investigations.

[19] The most important aspect of the present investigation is the response of OI 630.0 nm dayglow corresponding to the eastward electric field perturbations during the substorm event discussed earlier. As mentioned earlier, OI 630.0 nm dayglow emission intensity over low latitudes depends mainly on three processes, PE, PD, and DR. However, it was shown that the DR process contributes ~35% to the total dayglow intensity and nearly accounts for all the temporal variability over low latitudes [*Sridharan et al.*, 1992b]. Variations in solar flux mainly contribute to the PE and PD processes. PE and PD processes do not contribute to small-period (<1.0 h) temporal variations unless there are substantial changes in the photoelectron flux similar to local sunset and sunrise times or considerable changes in the solar radiation in the Schumann-Runge continuum during solar flare events (e.g., see *Das et al.* [2010]). As no significant solar flare event took place around 0554–0635 UT, it is unlikely that the dayglow intensity variation during 0554–0635 UT is caused by either the PE or PD process. Therefore, variations in 630.0 nm dayglow intensity in the present case is believed to be due to the changes in DR process. The production of $O(^1D)$ through DR process is dependent on ambient electron density and O_2^+ ions. Under normal circumstances, the latter is produced due to charge exchange of O^+ ions with O_2 molecules. Availability of more electrons or supply of more O_2^+ ions at the dayglow emission region can result in increased 630.0 nm dayglow emission. Electron density enhancement at the emission altitude region can occur due to increased production of photoelectrons and/or arrival of excess plasma from dip equatorial region through plasma fountain effect. As already stated, the period during 0554–0635 UT is devoid of any significant solar flare activity. Therefore, intensity enhancement in the present case is unlikely to be associated with any ephemeral electron density enhancement. Moreover, the intensity enhancements are also unlikely to be caused by the modulations in the electron density by equatorial plasma fountain effect and/or traveling ionospheric disturbances (TID) arriving from other latitudes as the time delay between the dayglow intensity enhancements over two latitudes is negligible. In addition, the transport due to plasma fountain

process is expected to affect the overall intensity level (dc level) rather than the impulsive changes in the intensity as observed in the present case. Further, it is to be noted that the zonal transport of plasma is minimal in the low-latitude ionosphere during daytime as the plasma gradient in the zonal direction is small. On the other hand, thermospheric meridional wind can affect the dayglow emission by supplying excess plasma at the emission region from other places. Meridional wind is expected to affect the dayglow intensity at a longer time scale than the timescale (~30 min) of the intensity variation addressed in this investigation. Moreover, thermospheric meridional wind is governed by ion drag, which is a slow process. Therefore, impulsive changes in the meridional wind is, in general, not expected. These considerations further indicate that the impulsive response of the dayglow over both the latitudes are due to changes in the electric field that affect globally.

[20] As OI 630.0 nm airglow intensity depends on the concentration of O_2^+, it is important to highlight the salient features of plasma composition of the low-latitude ionosphere. Based on the measurements of plasma composition over a low-latitude region [e.g., see *Narcisi and Szuzczewicz*, 1981; *Sridharan*, 1983], it is known that NO^+ is the dominant ion in the *E* region during nighttime and its concentration is more than O_2^+ concentration by an order of magnitude. However, during daytime, under normal circumstances, both the molecular ions $[O_2^+]$ and $[NO^+]$ are comparable in the *E* region. The centroid of 630.0 nm airglow emission is typically ~220 km during daytime and between 250 and 300 km during nighttime. Under these circumstances, any eastward electric field during nighttime would facilitate transport ($\nabla . NV$) of plasma from the centroid of emission and, thereby, reduce the airglow intensity. This picture is consistent with the empirical relationship on nighttime 630.0 nm airglow emission intensity put forward by Barbier [*Barbier*, 1959]. However, during daytime, in the presence of considerable O_2^+ in the upper *E* region (~150 km), when an eastward electric field is imposed, it could build up a considerable amount of O_2^+ to the centroid of emission (~220 km) compared to the transport of electrons from the centroid of emission to higher altitude. Thus, one could anticipate increase in the 630.0 nm dayglow intensity when an eastward ephemeral electric field is imposed during a substorm.

5. Summary

[21] The present investigation brings out the signature in OI 630.0 nm dayglow emission over low latitudes corresponding to the onset of the expansion phase of a magnetospheric substorm based on a number of space-borne and ground-based measurements. Enhancements in 630.0 nm dayglow intensity over low latitudes are attributed to the possible supply of O_2^+ ions by the eastward electric field induced by the onset of substorm, highlighting the complexities in the magnetosphere-ionosphere-thermosphere system.

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