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The November 2004 superstorm: Comparison of low-latitude TEC observations with LLIONS model results

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We investigate the effects of penetration electric fields, meridional thermospheric neutral winds, and composition perturbation zones (CPZs) on the distribution of low-latitude plasma during the 7–11 November 2004 geomagnetic superstorm. The impact on low-latitude plasma was assessed using total electron content (TEC) measurements from a latitudinally distributed array of ground-based GPS receivers in South America. Jicamarca Radio Observatory incoherent scatter radar measurements of vertical $\mathbf{E}\times\mathbf{B}$ drift are used in combination with the Low-Latitude IONospheric Sector (LLIONS) model to examine how penetration electric fields and meridional neutral winds shape low-latitude TEC. It is found that superfountain conditions pertain between ~1900 and 2100 UT on 9 November, creating enhanced equatorial ionization anomaly (EIA) crests at $\pm 20^\circ$ geomagnetic latitude. Large-amplitude and/or long-duration changes in the electric field were found to produce significant changes in EIA plasma density and latitudinal location, with a delay time of ~2–2.5 h. Superfountain drifts were primarily responsible for EIA TEC levels; meridional winds were needed only to create hemispherical crest TEC asymmetries. The $[O/N_2]$ density ratio (derived from the GUVI instrument, flown on the TIMED satellite) and measurements of total atmospheric density (from the GRACE satellites), combined with TEC measurements, yield information regarding a likely CPZ that appeared on 10 November, suppressing TEC for over 16 h.

1. Introduction

Geomagnetic storms have long been known to cause strong effects at high latitudes. Particle precipitation in this region ionizes neutral particles, heats the thermosphere, and excites outer shell electrons of some neutral particles into higher energy levels. Consequently, thermospheric heating alters neutral wind patterns, and relaxation of excited electrons to lower energy levels releases energy in the optical range; these emissions are known as the aurora. Furthermore, electric fields also map to low altitudes here from the magnetosphere, driving ionospheric convection cells and joule heating.

In recent years, it has become increasingly apparent that storms play an important role in mid- and low-latitude ionospheric plasma dynamics. Electric fields are one means by which high-latitude processes couple to lower latitudes. Both prompt penetration electric (PPE) fields (Fejer et al., 1979, 1990; Fejer and Scherliess, 1995; Kelley et al., 1979) and disturbance dynamo (DD) generated electric fields (Blanc and Richmond, 1980; Fejer and Scherliess, 1995; Richmond et al., 2003) at times map all the way to the geomagnetic equator. These fields in turn alter the existing seasonal and diurnal plasma $\mathbf{E}\times\mathbf{B}$ drifts, thereby redistributing plasma, most significantly in latitude and altitude. In particular, electric fields that penetrate to low latitudes may add vectorially to existing dynamo-generated zonal electric field to either reinforce or suppress what is known as the fountain effect. In the fountain effect (Kelley, 1989), an Eastward electric field, combined with the nearly horizontal geomagnetic field at very low latitudes (approximately $\pm 5^\circ$ geomagnetic latitude), will cause ionospheric plasma to $\mathbf{E}\times\mathbf{B}$ drift vertically upwards. Subsequently, gravity and pressure gradients cause the plasma to drift down along magnetic field lines to higher latitudes, resulting in two regions of enhanced plasma density together known as the equatorial ionization anomaly (EIA), or simply the "equatorial anomaly". For historical reasons, the EIA is also known as the Appleton anomaly. When strong PPE or DD electric fields reinforce the nominal daytime Eastward field, plasma is driven to very high altitudes. Magnetic field lines at higher altitudes have footpoints at higher latitudes; thus, ionization crests form at higher latitudes. During strong storms, when the Eastward field is substantially reinforced, the phenomenon is known as the "superfountain effect" (Tsurutani et al., 2007). It also sometimes

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happens that a Westward electric field penetrates to low latitudes and suppresses the fountain effect. In this case, the EIA crests move to correspondingly lower latitudes. PPE electric fields typically affect the low-latitude plasma distribution in a symmetric manner. However, DD electric fields, meridional neutral winds, and other effects may introduce TEC asymmetries between hemispheres.

Meridional neutral winds may induce asymmetries in the low-latitude total electron content (TEC) distribution in two ways. First, through ion-neutral collisional processes, they directly change the transport of plasma parallel to the magnetic field. This effect dominates at higher altitudes near the geomagnetic equator, where the dip angle is small and a horizontal meridional wind acts essentially parallel to the geomagnetic field. A northward wind will thus act to push plasma along field lines to the leeward/Northern Hemisphere, resulting in an enhanced northern anomaly crest. While it is true that plasma on the southern arc of the equatorial fountain will have a horizontal velocity component in the southern direction, acting in opposition to a northward wind, its horizontal velocity component is small relative to the vertical fountain drift, especially at higher altitudes. Thus, a meridional neutral wind of the order of tens of m/s will overwhelm this flow and redistribute plasma to the leeward hemisphere. Second, again through ion-neutral collisional processes, meridional winds drive plasma up along magnetic field lines on the windward side and down field lines on the leeward side (Hargreaves, 1992). This effect dominates at lower altitudes near the footpoints of geomagnetic field lines, where the angle between the horizontal wind vector and the field lines is significant (i.e., dip angle $>20^{\circ}$). Because recombination reactions are proportional to concentration (i.e., inversely proportional to altitude), the leeward side will experience a faster loss of ionization relative to the windward side, creating a TEC deficit in the leeward hemisphere. This effect is most important during the evening and night, when solar ionization and interhemispheric transport effects weaken or cease entirely. Conversely, as will be seen in the LLIONS (Low-Latitude IONospheric Sector) model results, interhemispheric transport of plasma and solar ionization dominate loss processes during the day.

Equatorward wind surges are a mechanism by which high-latitude effects may propagate to low latitudes to create an asymmetric distribution of plasma across the geomagnetic equator. Particle precipitation and joule heating in the auroral region heat the thermosphere, which then rises and expands. Since these parcels of upwelling neutrals originate at relatively low altitudes, they are enriched with heavy neutrals compared with the background atmosphere. These parcels are then typically driven equatorward by some combination of storm winds and existing seasonal/diurnal meridional winds (Lin et al., 2005a). Due to their enriched heavy neutral content, they are termed "composition perturbation zones", or CPZs. Under the right conditions, CPZs may reach low latitudes – even the geomagnetic equator – where they can significantly alter the local recombination chemistry. Molecular Nitrogen, in particular, will accelerate loss reactions, rapidly quenching the local plasma density. A hemispherical asymmetry in the background/stormtime wind magnitude, CPZ maximum latitudinal penetration, or CPZ chemical composition/concentration will induce a corresponding asymmetry in the low-latitude TEC, provided that a CPZ reaches the latitude of at least one anomaly crest.

Until recently, it has been very difficult to measure all of the effects thus described. The large distances involved, lack of distributed instrumentation, and relative rarity of storms all have contributed to this problem. However, in recent years large-scale deployment of GPS receivers has proceeded rapidly throughout the South American sector. These distributed arrays make it possible to make maps of total electron content covering wide geographic areas. When supplemented by computer models, GPS receiver TEC measurements have been shown to be a powerful tool for mapping the three-dimensional distribution of plasma at low latitudes (Lin et al., 2005a, b; Valladares and Sheehan, 2001; Valladares et al., 2004). Early studies show that CPZs and penetration electric fields (Lin et al., 2005a, b), as well as seasonal/diurnal meridional neutral wind patterns (Valladares and Sheehan, 2001; Valladares et al., 2004), strongly influence low-latitude plasma dynamics and chemistry.

The November 2004 superstorm represents a unique opportunity to study stormtime effects. Never before have such a wide array of instruments simultaneously observed a storm of this magnitude (Kelley et al., 2009). Most significantly, this is the first time that continuous measurements of the vertical plasma drift near the geomagnetic equator have been available during a large portion of a superstorm. Previously, the best superstorm vertical drift data available were from the ROCSAT-1 satellite, for the October–November 2003 superstorm (Lin et al., 2005b). Jicamarca Radio Observatory (JRO) drift data offer improved accuracy, without the limitations imposed by satellite orbital motion and the precession of the satellite orbit. By continuously measuring the vertical plasma velocity in a single geographic sector, JRO data thus make it possible to separate out effects due to stormtime penetration electric fields from the complex array of stormtime and background drivers of the low-latitude plasma distribution.

In this work, we use TEC data from the South American array of GPS receivers, combined with Jicamarca vertical drifts to study the impact of stormtime penetration electric fields on the low-latitude plasma distribution. Additionally, we utilize other data sets to ascertain the impact of CPZs and LSTIDs. To determine the role of meridional neutral winds, we drive the Low-Latitude IONospheric Sector model with the Jicamarca vertical drift data. In this way, we determine the relative roles of the various drivers under superstorm conditions.

2. Instrumentation and data sets

Measurements of TEC were made using an array of 12 GPS receivers located in South America (Valladares et al., 2004). The receivers are situated between 70° and 80°W longitude, and span the latitude range of 9°N–40°S. Receiver locations are depicted in Fig. 1. Raw slant-TEC (STEC) measurements were converted into vertical (VTEC) values to remove TEC perturbations due to raypath length. Plots of VTEC versus geographic latitude and local time were then made by performing a two-dimensional regression analysis of the TEC values. An example of such a plot is shown in Fig. 2.

Plasma vertical drift velocities at the equator were provided by the Jicamarca incoherent scatter radar (ISR), operating in drift mode (Kudeki et al., 1999). The radar measures the plasma velocity between the altitudes of approximately 150–900 km with a 15-km vertical resolution and 5-min sample rate. F-region line-of-sight uncertainties in the drift are less than 1.0 m/s, even under the low signal-to-noise ratio conditions (SNR ≈ 0.1) typically seen away from the F-region density peak (Kudeki et al., 1999). Continuous ISR data are available from 12 UT on 9 November up through to the beginning of 11 November 2004. For the present work, the rise velocity at the geomagnetic equator was taken to be the average of the Jicamarca ISR rise velocity between 200 and 400 km altitude.

Data from the Global Ultraviolet Imager (GUVI) on the Thermosphere Ionosphere Mesosphere Energy and Dynamics (TIMED) satellite were used to examine the $[O/N_2]$ density ratio as a function of latitude, longitude, and local time. A reduced $[O/N_2]$ ratio indicates the presence of a molecular-enriched CPZ,