Equatorial ionospheric electrodynamic perturbations during Southern Hemisphere stratospheric warming events

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[1] We use ground-based and satellite measurements to examine, for the first time, the characteristics of equatorial electrodynamic perturbations measured during the 2002 major and 2010 minor Southern Hemisphere sudden stratospheric warming (SSW) events. Our data suggest the occurrence of enhanced quasi 2 day fluctuations during the 2002 early autumnal equinoctial warming. They also show a moderately large multi-day perturbation pattern, resembling those during arctic SSW events, during 2002 late equinox, as the major SSW was weakening. We also compare these data with extensive recent results that showed the fundamentally important role of lunar semidiurnal tidal effects on low latitude electrodynamic perturbations during arctic SSW events.

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1. Introduction

[2] Large lower and upper atmospheric transient changes associated with sudden stratospheric warmings (SSWs) have been the subject of extensive studies for over five decades. SSWs are large-scale meteorological phenomena in the winter polar atmosphere characterized by strong rapid increases and decreases in the stratospheric temperatures and the mean zonal winds, respectively, that last for several days or even a few weeks [e.g., *Andrews et al.*, 1987; *Liu and Roble*, 2002; *Holton*, 2004]. These phenomena are driven by the sudden growth of upward propagating planetary waves from the polar troposphere and their interaction with the mean circulation [e.g., *Matsuno*, 1971].

[3] Recently, several studies have reported large electrodynamic and ionospheric perturbations at low latitudes during Northern Hemisphere SSW events [e.g., *Vineeth et al.*, 2009; *Chau et al.*, 2009; 2011; Sridharan et al., 2009; *Goncharenko et al.*, 2010; *Fejer et al.*, 2010, 2011; *Yue et al.*, 2010; *Liu et al.*, 2011; *Park et al.*, 2012; *Yamazaki et al.*, 2012a, 2012b]. These include large changes in equatorial mesospheric winds, temperatures, vertical plasma drifts, daytime equatorial electrojet, ionization anomaly, and enhancements on the low latitude semidiurnal ionospheric currents. The low latitude electrodynamic response to these events shows typical multi-day perturbation patterns that shift to later local times which have been associated with enhanced lunar semidiurnal tidal effects [e.g., *Fejer et al.*, 2010, 2011; *Liu et al.*, 2011; *Park et al.*, 2012; *Yamazaki et al.*, 2012a, 2012b]. This is consistent with simulation results reported by *Stening et al.* [1997] which indicated that high latitude winds during SSWs lead to enhanced lunar tides. *Yamazaki et al.* [2012a] suggested that during December and January warmings, the lunar tidal amplitudes tend to be positively and negatively correlated, respectively, with stratospheric temperatures and winds. Several numerical simulation studies examined the dynamical relationships between the lower atmosphere and the upper atmosphere and ionosphere during these warmings [e.g., *Liu et al.*, 2010; *Fuller-Rowell et al.*, 2011; *Fang et al.*, 2012; *Yamazaki et al.*, 2012a]. Recently, *Pedatella et al.* [2012] used the Whole Atmosphere Community Climate Model (WACCM) for a detailed study of solar and lunar tidal variability in the mesosphere and lower thermosphere based on 23 moderate to strong Northern Hemisphere SSWs. This work confirmed the importance of lunar semidiurnal tidal effects on the low latitude electrodynamic perturbations during these SSWs. In particular, they showed that the observed low latitude electrodynamic perturbations are no longer apparent when the lunar tide is removed from the simulations.

[4] Major SSW events are observed primarily in the Northern Hemisphere and are far less common in the Southern Hemisphere [e.g., *Holton*, 2004] due to the significantly weaker topographically forced planetary wave energy. In August to September 2002, a series of minor SSWs was followed by the first major Southern Hemisphere SSW ever recorded. These minor and major events were subject of extensive studies [e.g., *Orsolini et al.*, 2005; *Manney et al.*, 2005; *Liu and Roble*, 2005]. Satellite measurements during the August 2002 minor events showed stratospheric warming and mesospheric cooling, which were compared with

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modeling results [e.g., *Coy et al.*, 2005; *Siskind et al.*, 2005]. Airglow mesospheric temperature measurements from the South Pole showed evidence of amplification of 4 day planetary wave activity before the mesospheric cooling which preceded the onset of the major SSW event [*Azeem et al.*, 2005].

[5] In this paper, we use daytime equatorial ionospheric data derived from ground-based and CHAMP satellite measurements to examine, for the first time, the equatorial electrodynamic responses to Southern Hemisphere SSW events. Our results that suggest both enhanced short-term quasi-wave activity and large amplitude multi-day ionospheric low latitude electrodynamic perturbations resembling those observed during Northern winter SSWs also occur during Southern Hemisphere warmings.

2. Results and Discussion

[6] We used daytime measurements of the equatorial electrojet over Peru determined from the difference of the horizontal (H) magnetic fields measured at Jicamarca (11.9°S, 76.8°W, 0.8°N magnetic) and Huancayo (12.1°S, 75.2°W, 0.6°N magnetic), very near the magnetic equator, and at the off-equatorial Piura station (5.2°S, 80.6°W; 6.8°N magnetic). The Huancayo and Jicamarca magnetic field data are essentially identical, but their coverage has different gaps. We also used vertical plasma drifts over Peru derived from electrojet magnetic field data using the methodology described by *Anderson et al.* [2002]. In addition, we also examined global equatorial electrojet current densities estimated from high resolution magnetic field data (accuracy of about 0.1 nT) measured by the polar-orbiting Challenging Minisatellite Payload (CHAMP) satellite. CHAMP had a 93 min orbital period and a 23° westward precession from July 2000 until reentry in September 2010. Height and geometry-independent electrojet current densities were derived from CHAMP data by first removing magnetic fields from other sources and then using a general current model to fit the full latitudinal profile of the geomagnetic field data [e.g., *Lühr et al.*, 2004; *Alken and Maus*, 2007].

[7] Figure 1 shows, in the first to third panels the 3 h Kp indices, the mean zonal temperatures at 90°S temperatures, and the 60°S zonal winds (positive eastward) at 10 hPa (about 32 km altitude) from mid-August to late October 2002, and the corresponding 30 year mean temperatures and zonal winds, obtained from the National Center for Environmental Prediction (NCEP). The standard deviations of the temperatures and wind data are about 6 K and 8 m/s. The fourth and fifth panels show the ΔH (Huancayo-Piura) data, which are indicative of the strength of the equatorial electrojet, and the late afternoon/mid-morning electrojet current densities derived by linear interpolation of the CHAMP measurements to 5° longitudinal bins. The slant line in the ΔH (Huancayo-Piura) data indicates the satellite magnetic equator crossing times in the Peruvian sector, and the horizontal line in the CHAMP data denotes the longitude of Jicamarca. Over this period, the average daily F10.7 solar flux index was about 160.

[8] Figure 1 shows that from mid-August through mid-September 2002, there were three minor Southern Hemisphere SSW events with small short-lived increases in the high latitude stratospheric temperatures and small decreases in the eastward winds, and periods of strong geomagnetic

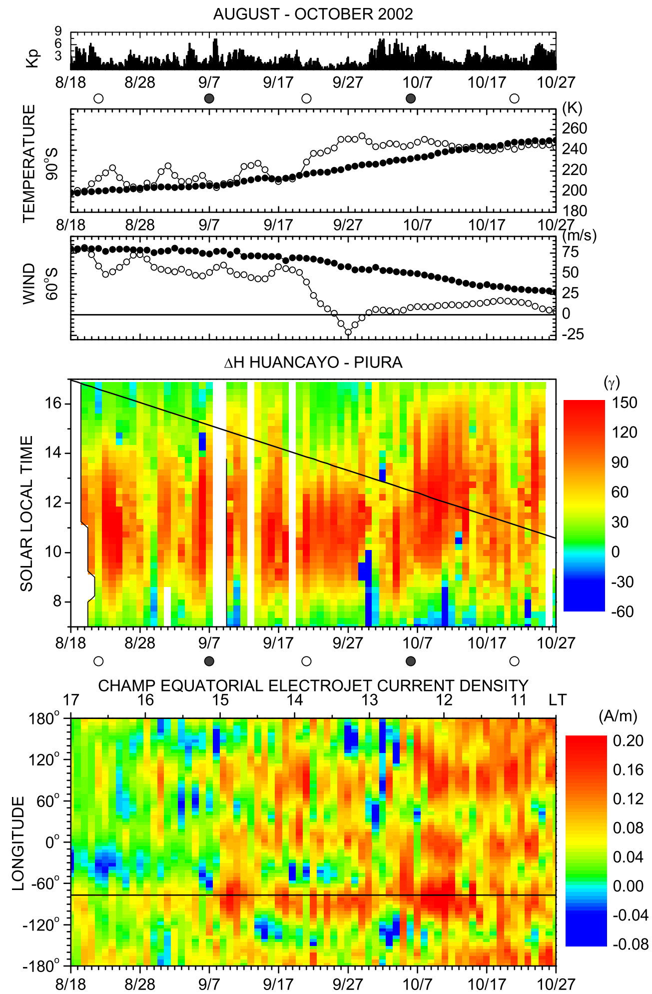

Figure 1. Geomagnetic Kp indices, Southern Hemisphere high latitude stratospheric temperatures and zonal winds (open circles), equatorial electrojet magnetic field data over Peru, and current densities measured by the CHAMP satellite around the 2002 sudden stratospheric warming. The climatological temperatures and winds are shown with closed circles. The slant line in the Peruvian magnetic field data denotes the times of the CHAMP satellite crossings, the horizontal line in the CHAMP data indicates the longitude of the Jicamarca radar, and the open and closed circles between the panels indicate the days of full and new moon, respectively.

activity especially during mid-August and early September. In this period, it is not clear if the observed electrojet short-term variability is related to the sporadic warmings. The current density peaks around 90°W, 0°, 90°E, and 180°E on the CHAMP data are indicative of the equatorial ionospheric four-wave longitudinal structure which is known to be strongest during autumnal equinox [e.g., *Lühr et al.*, 2008].

[9] A major SSW event started about 20 September, resulting in a peak temperature increase of about 30 K and a westward wind perturbation of about 80 m/s on 27 September, when these perturbations started to decrease systematically. Geomagnetic activity was relatively quiet during this period. From about the onset of the strong warming through early October, the Peruvian magnetometer data show oscillations with an approximate period of 2 days in the 1200–1400 LT

sector superposed on a local time ΔH pattern with slightly increased afternoon values that shifted to later local times. The corresponding CHAMP data also showed quasi 2 day oscillations over the South American sector. It is not clear if these oscillations are related to quasi 2 day waves. The stratospheric temperatures nearly returned to their mean levels after 15 October, but the zonal wind perturbations remained westward into November. The Kp indices indicate there were periods of strong geomagnetic activity, especially from late September to early October. Although episodes of enhanced geomagnetic activity make the identification of short-term (periods of a few days) ionospheric wave-like signatures from ground-based magnetic field measurements more difficult, SSW-driven multi-day electrodynamic perturbations can generally be identified from these measurements [*Fejer et al.*, 2010]. From about the time of the new moon on 6 October through mid-October, past the peak of the warming, the strength of the equatorial electrojet over Peru had large afternoon increases and morning decreases that appear to shift to later local times. This late equinoctial electrodynamic perturbation resembles those observed during Northern Hemisphere winter SSW events [e.g., *Chau et al.*, 2009; *Fejer et al.* 2010]. In the 2002 event, however, there were no large afternoon reversals of the electrojet current close to new and full moon. The CHAMP data do not show much change in the electrojet current densities in the early afternoon sector before 6 October, which is consistent with the Peruvian magnetometer data.

[10] Figure 2 shows the generally good agreement of simultaneous ground-based magnetometer and CHAMP measurements averaged within a 30° longitudinal sector centered at Jicamarca. These ground-based and satellite data show quasi two day wave activity during the period of quiet geomagnetic activity from about the beginning of the SSW event up to early October. We have seen in Figure 1 that during this period of strong stratospheric westward wind disturbance there was no indication of the typical multi-day electrodynamic disturbance pattern observed during Northern Hemisphere SSWs. Figure 2 shows strong increases in the electrojet currents close to noon around the time of the new moon on 7 October. We note that during strong and long-lasting geomagnetic activity, the CHAMP current densities (derived from fitting the full latitudinal current profile) give different (and probably more accurate) estimates of the electrojet strength than the geomagnetic field data based on a pair of ground-based stations. The large increase in the measured current perturbations during early October resulted partly from the shift of the measurements to local times close to that of peak electrojet currents, as shown in Figure 1. The large perturbations near 7 September and 15 October are most likely due to the effects of enhanced geomagnetic activity. Multi-day wave activity is also seen after about 18 October.

[11] Figure 3 presents vertical plasma drifts derived from the Peruvian magnetic field measurements during 7–16 October 2002, and the corresponding season and solar flux

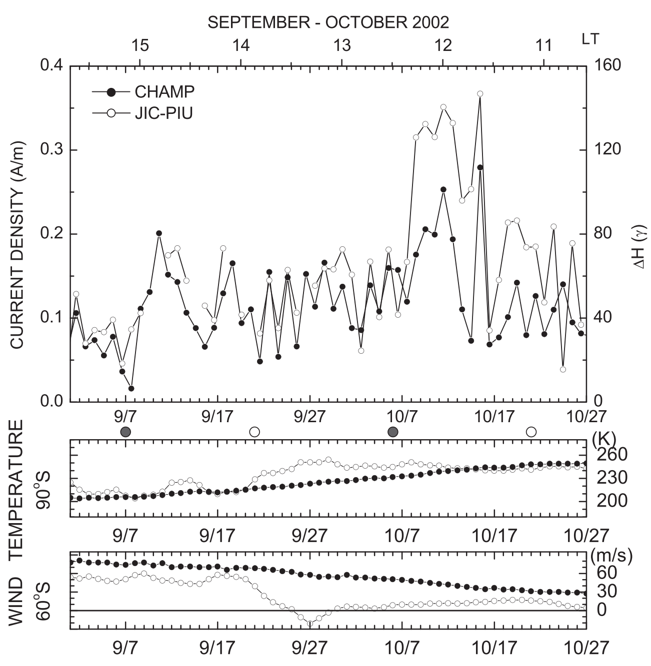

Figure 2. Equatorial electrojet current densities from CHAMP and ground-based magnetic field data over Peru, and high latitude stratospheric temperature and zonal wind data (open circles) around the 2002 sudden stratospheric warming period and their climatological values (closed circles). The days of full and new moon are indicated by open and closed circles between the panels, respectively.

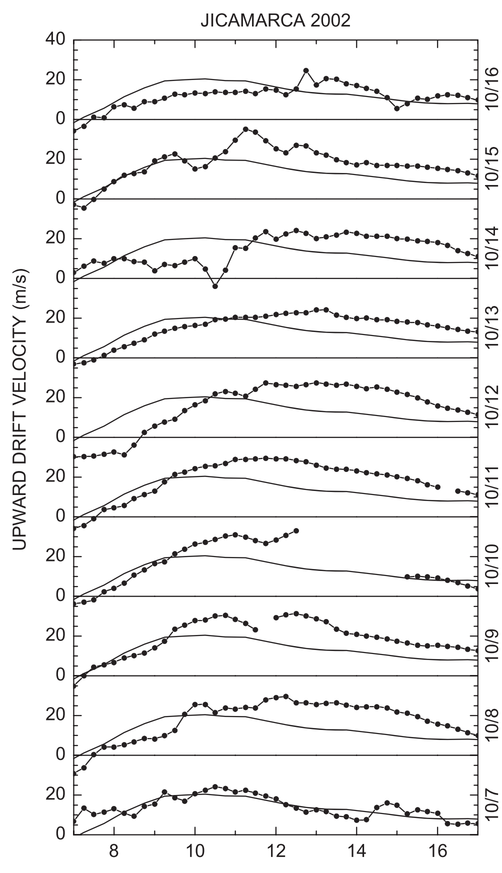

Figure 3. Equatorial vertical plasma drifts over Jicamarca derived from ground-based magnetic field data (closed circles). The smooth curves denote the climatological drifts.

dependent climatological drifts derived by *Scherliess and Fejer* [1999] from extensive radar measurements. These daytime model drifts have an accuracy of about 2 m/s. The short-lived drift perturbations (e.g., at 1100 LT on 14 October) were due to enhanced geomagnetic activity. Figure 3 indicates that from 8 October on, the early morning decreases and the late morning and afternoon upward drift enhancements generally shifted to later local times. This perturbation drift pattern is similar to, but has smaller amplitudes (particularly in the morning and later afternoon) than those, typically observed during Northern Hemisphere warmings, as indicated, for example, by the absence of afternoon electrojet current reversals.

[12] Figure 4 shows the Kp indices, the Southern Hemisphere stratospheric temperatures and winds and the Peruvian magnetometer data during the July to September 2010 minor warming events. In this period, the average F10.7 index was about 80 and, except for 2 days in early August, geomagnetic activity was low. The main warming event lasted from about 15 July to 12 August, with a peak temperature increase of about 20 K on 31 July. The eastward winds initially increased by about 15 m/s and then decreased before increasing again toward the end of the warming period. Another short-lived warming occurred during 12–20 September, with a temperature increase of 20 K and a peak zonal wind decrease of 20 m/s. Figure 4 indicates that the main characteristic of the electrojet magnetic field data near-noon over Peru during this minor SSW was the enhancement in the multi-day fluctuations with increasing quasi-periods of a few days. Enhanced multi-day wave-like ΔH perturbations also occurred after the initial and during the mid-September short-lived warming event.

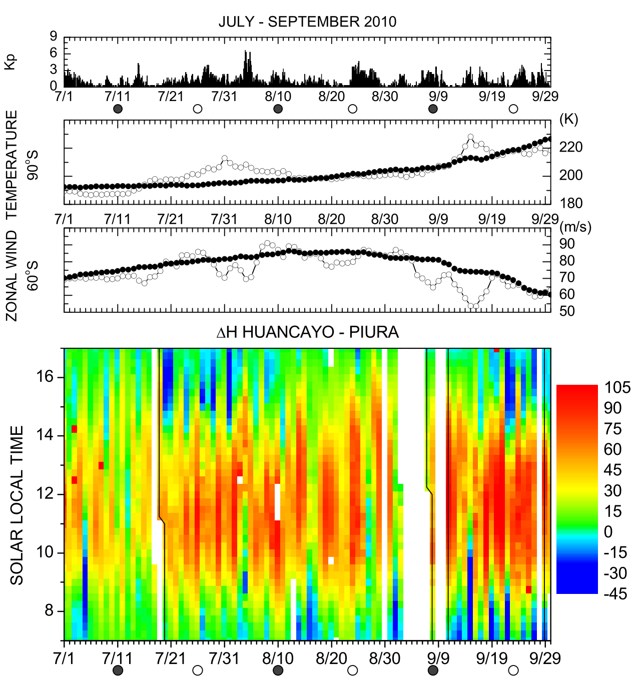

Figure 4. Geomagnetic Kp indices, southern high latitude stratospheric temperatures and zonal winds (open circles) and their climatological values (closed circles), equatorial electrojet magnetic field from ground-based data over Peru around the 2010 sudden stratospheric warming period. The open and closed circles between the panels indicate the days of full and new moon, respectively.

3. Discussion and Conclusions

[13] Low latitude ionospheric effects associated with Northern Hemisphere SSW events were attributed to various vertical coupling processes between the lower atmosphere and ionosphere [e.g., *Vineeth et al.*, 2009; *Liu et al.*, 2010; *Sridharan et al.*, 2009; *Fejer et al.*, 2010; 2011; *Fuller-Rowell et al.*, 2011; *Fang et al.*, 2012]. In particular, *Fejer et al.* [2010] suggested that enhanced lunar semidiurnal tidal effects play an important role on the multi-day equatorial electrodynamic perturbations during SSWs. This suggestion was confirmed by recent studies using CHAMP satellite and ground-based magnetometer data over periods of several years [e.g., *Park et al.*, 2012, *Yamazaki et al.;* 2012a, 2012b], and by extensive numerical simulation studies of 23 moderate to strong Northern Hemisphere SSWs using WACCM [*Pedatella et al.*, 2012]. Therefore, it is likely that SSWs during other seasons also lead to enhanced lunar tidal low latitude ionospheric effects.

[14] Figure 5 shows the Peruvian magnetic field data during the main phase of the 2002 Southern Hemisphere warming and during corresponding 2003 and 2004 autumnal equinoctial periods. The solid and dashed lines denote the climatological times of the maximum and minimum lunar

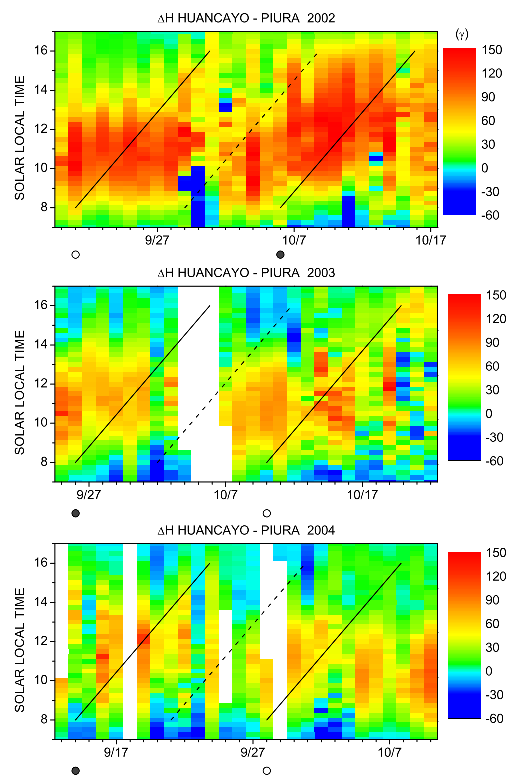

Figure 5. Equatorial electrojet magnetic field data over Peru during the 2002 major warming and two subsequent autumn periods which did not exhibit warmings. The solid and dashed lines denote the times of maxima and minima of the climatological lunar semidiurnal drifts. The open and closed circles between the panels indicate the days of full and new moon, respectively.

semidiurnal tidal drift perturbations for equinox derived extensively from Jicamarca radar drift measurements [e.g., *Stening and Fejer*, 2001]. The strong short-term variability (few hours) on the early October 2003 data is due to enhanced geomagnetic effects. Figure 5 shows the occurrence of quasi 2 day modulation on the magnetic field data during 2002, but not during the two following autumn equinoctial periods. The enhanced magnetic fields after late September 2002 follow approximately the climatological lunar semidiurnal slopes even though they were also affected by magnetic activity. The very short-lived (few hours) perturbations during mid-October 2003 and mid-September 2004 were due to enhanced geomagnetic activity. We have examined also the Peruvian magnetometer data during the 2008 and 2009 equinoctial periods, when there were no warmings. These data do not show the occurrence of quasi 2 day perturbations.

[15] Several studies showed that equatorial lunar semidiurnal effects are strongest near December solstice, and weakest near the June solstice [e.g., *Stening and Fejer*, 2001; *Pedatella and Forbes*, 2010]. Recently, *Stening* [2011] showed that over Peru the lunar ΔH tidal amplitude during January and February is about five times larger than during June solstice and about twice larger than during September–October. Therefore, if enhanced lunar tidal effects are associated with equatorial electrodynamic perturbations during non-arctic warmings as well, these perturbations should have correspondingly smaller amplitudes, as suggested by our (limited) data set. The smaller modulation of the vertical drifts by lunar semidiurnal tides during equinox, compared to December solstice, is consistent with the absence of daytime equatorial electrojet reversals (counter-electrojets) in our 2002 September to October magnetic field data and also on the 16–20 March 1998 SSW data reported by *Fejer et al.* [2010]. Of course, other processes are also likely to affect low latitude perturbations during warmings.

[16] We have shown the occurrence of enhanced short-term oscillations with quasi-periods of about 2 days on the equatorial electrojet magnetic field data when geomagnetic activity was quiet during the Southern Hemisphere 2002, and with slightly longer periods during the 2010 minor warming. Figure 6 presents Peruvian magnetometer data during the 2010 minor warming and during the corresponding 2008 and 2009 periods when there were no warmings. This figure indicates that the multi-day perturbations during the 2010 SSW resemble those that occurred during the previous solsticial periods. Therefore, it appears that this minor warming did not significantly affect the occurrence multi-day perturbations. Figure 6 also shows the frequent occurrence of quasi 2 day perturbations up to about mid-August. This supports the hypothesis that the quasi 2 day waves during September 2002 were associated with the SSW since, as mentioned earlier, the following equinoctial data did not show the occurrence of these short-period perturbations. This was confirmed by Fourier analysis. Enhanced quasi-wave activity with periods of a few days was also reported around arctic warming events [e.g., *Fejer et al.*, 2011]. The sporadic warmings and enhancements of geomagnetic activity during the August 2002 minor event made the identification of possible enhanced multi-day oscillations more difficult.

[17] In summary, our data suggest that during 2002 Southern Hemisphere SSW event, there were quasi 2 day perturbations on equatorial ionospheric electric fields and currents. Our autumnal equinoctial data also suggest the occurrence of multi-day coherent electrodynamic perturbations with morning depression and afternoon enhancements near new moon. These perturbations resemble those observed during Northern Hemisphere warmings and which were associated with enhanced lunar tidal effects. However, additional measurements during Southern Hemisphere and also equinoctial Northern Hemisphere SSWs are clearly needed to fully characterize the response of the low latitude ionosphere during these events and to determine the importance of lunar tidal and the occurrence of enhanced wave-like fluctuations.

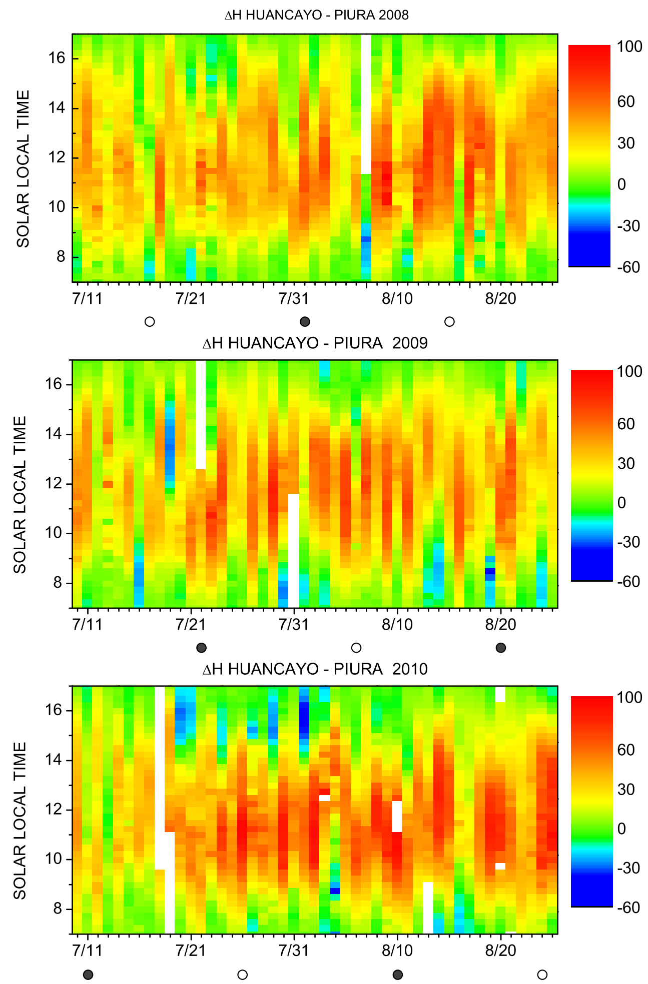

Figure 6. Equatorial magnetic field during the 2010 minor warming and during two preceding June solstice periods which did not exhibit warmings. The open and closed circles between the panels indicate the days of full and new moons, respectively.

[18] **Acknowledgments.** We thank S. Maus for processing and providing us the CHAMP equatorial electrojet magnetic field data. This work was supported by the Aeronomy Program, Division of Atmospheric Sciences of the National Science Foundation through grant AGS-1068104 and by NASA through grants NNH12C02C and NNX09ANSSG. The Jicamarca Radio Observatory is a facility of the Instituto Geofisico del Peru, Ministry of Education, and is operated with support from the NSF cooperative agreement AGS-0905448 through Cornell University.

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