Equatorial disturbance dynamo vertical plasma drifts over Jicamarca: Bi-monthly and solar cycle dependence

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Key Points:

- The equatorial disturbance dynamo vertical drifts have very strong temporal and solar cycle dependence.
- The strongest disturbance dynamo variations occur near dusk.
- Previous studies significantly underestimate the variability of equatorial disturbance dynamo vertical plasma drifts.

Abstract

We use extensive incoherent scatter radar observations from the Jicamarca Radio Observatory to study the local time and bi-monthly dependence of the equatorial disturbance dynamo vertical plasma drifts on solar flux and geomagnetic activity. We show that the daytime disturbance drifts have generally small magnitudes with largest values before noon and an apparent annual variation. Near dusk, they are downward throughout the year with largest values during the equinoxes and smallest during June solstice. These downward drifts increase strongly with solar flux, and shift to later local times. They also increase with increasing geomagnetically active conditions with no apparent local time shift. The equinoctial evening downward disturbance drifts are larger during the autumnal equinox than during the vernal equinox. The nighttime disturbance drifts are upward and have small seasonal and solar cycle dependence but increase strongly with geomagnetic activity, particularly in the late night sector. Our results are in general agreement with those from previous theoretical and experimental studies, except near dusk where our results show much stronger seasonal and solar cycle dependence.

1 Introduction

The first theoretical description of the ionospheric disturbance dynamo process was presented by Blanc and Richmond (1980). They pointed out that enhanced energy deposition into the high latitude thermosphere (mostly through Joule heating) during geomagnetic storms produces significant disturbances in the thermospheric neutral wind field and conductivity distribution, which lead to large departures of the middle and low latitudes thermospheric neutral winds, ionospheric electric fields and currents from their quiet-time values.

The basic features of this mechanism consist of high latitude Joule heating driving a meridional thermospheric wind circulation and westward zonal winds that extend from high to low latitudes. These disturbance winds drive equatorward Pedersen currents that accumulate positive charges at the geomagnetic equator establishing a poleward electric field and eastward Hall currents. These currents build up polarization charges at the dawn and dusk terminators and set up a dusk-to-dawn electric field. This process gives rise to polar and equatorial anti-Sq current vortices. In the equatorial region, this process drives westward (eastward) current and F region downward (upward) plasma drift disturbances on the dayside (nightside), which reduce or reverse the quiet time drift and current patterns.

Equatorial disturbance dynamo plasma drifts and currents were the subjects of several studies. Fejer et al. (1983) used incoherent scatter radar vertical plasma drifts from the Jicamarca Radio Observatory (12˚S, 76.9˚W; magnetic dip 2˚N) in Peru to show that the equatorial vertical disturbance dynamo drifts were opposite to the normal quiet patterns in agreement with the Blanc-Richmond model. In this study, the time delay between the onset of high latitude energy deposition (inferred from AE indices) was consistent with the characteristic time for the establishment of a steady circulation pattern (e.g., Richmond & Matsushita, 1975). They also noted that for most storms, there is an inherent difficulty in the separation of equatorial disturbance dynamo and prompt penetration electric field (electrodynamic plasma drift) effects (e.g., Wolf, 1995; Fejer, 1997).

Mazaudier and Venkateswaran (1990) studied the effects of the March 22, 1979 geomagnetic storm on middle and low latitude meridional winds and east/northward drifts using Saint Santin incoherent scatter radar and equatorial magnetic field measurements. They reported the generation of a meridional equatorward circulation one day after the onset of the storm, which appeared first at F-region altitudes and then descended to lower altitudes. They also observed northward electric fields from postmidnight to early afternoon. The time delay between the storm and the largest equatorial disturbances was about 15 hours. These results were also in agreement with the predictions from the Blanc-Richmond model.

Fejer and Scherliess (1995) used Jicamarca vertical drift observations and a binning technique to successfully separate prompt penetration and disturbance dynamo electric field effects. The derived disturbance dynamo disturbances were used to determine the time delays between geomagnetic activity enhancements, as indicated by AE indices, and the equatorial electrodynamic responses. They reported that the disturbance dynamo electric fields reach the equator 2-4 hours after the increase in high latitude magnetic activity. Scherliess and Fejer (1997) developed the first empirical model of equatorial disturbance dynamo vertical drifts using very extensive Jicamarca observations and AE indices. They showed that the disturbance dynamo vertical drifts are downward with small values during the day, and upward at night with largest magnitudes near sunrise. The time delays between the high latitude current enhancements and the corresponding equatorial disturbance dynamo disturbances are about 1-12 hours and 12-28 hours. The initial response is associated with fast traveling atmospheric disturbances, and the later response with changes in the thermospheric circulation and ionospheric composition (Fuller-Rowell et al 2002; Fejer, 1997; Fejer et al., 2017).

Fejer (2002) showed that after 6 hours of enhanced geomagnetic activity, the Jicamarca disturbance dynamo downward drifts near dusk were larger during equinox than during June solstice. The postmidnight upward disturbances did not show much seasonal dependence. Jensen (2007) used global vertical drift measurements from the ROCSAT-1 satellite to show that the equinoctial downward disturbance dynamo drifts near dusk increase strongly from moderate to high solar flux conditions. Fejer et al. (2008) used ROCSAT-1 satellite vertical drift measurements at an altitude of about 600 km to study the seasonal dependence of longitudinally averaged disturbance dynamo drifts resulting from 4 hours of enhanced geomagnetic activity. The evening downward dynamo drifts were largest during equinox and smallest during June solstice; the nighttime upward drifts were largest during December solstice and nearly identical during equinox and June solstice.

Measurements of F region height changes in the Indian equatorial region near dusk suggested that the largest disturbance dynamo vertical drifts occur about 0.5-4 hours and 16-23 hours after enhanced geomagnetic activity, and that the disturbance lifetimes decrease with increasing solar flux (Kakad et al., 2011). Storm-driven electrojet disturbances derived from magnetometer measurements in the Indian and Peruvian equatorial regions, presented by Yamazaki and Kosch (2015), showed that the disturbance dynamo effects are dominant during the recovery phase of geomagnetic storms. The disturbance dynamo currents in the Peruvian sector exhibit a semidiurnal variation, which resembles the pattern in Scherliess-Fejer empirical model (Fejer et al., 2017). The derived current disturbances increase with solar flux activity, most likely as a consequence of the increased ionospheric conductance. Pandey et al. (2018) reported that the largest disturbance dynamo effects on the equatorial electrojet over India occur during equinox and high solar activity periods.

Fejer and Emmert (2003) used incoherent scatter radar observation from Jicamarca and Arecibo and wind measurements from the Upper Atmospheric Research Satellite (UARS) for the first detailed study of low latitude disturbance dynamo effects during the recovery of a major geomagnetic storm. These observations showed large latitudinal variability of the disturbance drifts. They also reported that although the characteristics of the measured disturbance dynamo drifts were generally consistent with climatological and theoretical patterns, their amplitudes were initially much larger than the expected values. Xiong et al. (2016) used CHAMP and ROCSAT-1 satellite observations to study the local time and longitudinal dependent response of the equatorial electrojet, vertical plasma drifts and zonal winds to the solar wind parameters using the 3 hours integrated merging electric fields proposed by Newell et al. (2007) to represent the energy input to the magnetosphere-ionosphere-thermosphere system. They showed that the nighttime disturbance dynamo drifts are upward and have the largest magnitudes in the postmidnight sector after 4.5 hours and gradually decrease to their quiet time values after 24 hours. The daytime disturbance drifts are downward and small in agreement with results from earlier studies. Zhang et al. (2017a) examined the storm-time evolution of middle and low latitude ionosphere disturbance dynamo drifts during three long-lasting geomagnetic storms using ROCSAT-1 and C/NOFS satellite measurements. They showed that the local time dependence of the equatorial disturbance dynamo vertical drifts can be affected by the shift of the disturbance winds to later local times.

Huang and Chen (2008) and Huang (2013) used the National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamics General Circulation Model NCAR/TIEGCM to study seasonal and solar cycle dependence of the equatorial disturbance dynamo vertical plasma drifts. These simulations reproduced the observed decrease of the magnitudes of the disturbance dynamo drifts with decreasing solar flux, and the occurrence of larger magnitudes during equinox than during June solstice.

In this study, we use extensive vertical plasma drifts observations from the Jicamarca Radio Observatory incoherent scatter radar to examine in more detail the bi-monthly, solar cycle and geomagnetically active condition dependence of the equatorial disturbance dynamo vertical plasma drifts. We show that these drifts have strong solar cycle and bimonthly variations. In the following sections, we first describe our database and then present and discuss our results.

2 Data and Methodology

The vertical plasma drifts used in this study were obtained from incoherent scatter radar measurements at the Jicamarca Radio Observatory from April 1968 to February 2018. The experimental procedure was described by Woodman (1970). The data acquisition and signal processing techniques were described by Kudeki et al. (1999). The drifts were measured usually at altitudes from about 250 to 800km with a height resolution of 20-45km and with an integration time of 5 min. These measurements are available at the Jicamarca website. The values used in this study represent 15-min averages at altitudes from about 250 to 400km, where the signal to noise ratios are highest. However, during periods of strong equatorial spread F, the height range of drift was extended sometimes up to 850km to minimize the effects produced by these echoes. The error of these measurements is about 1m/s during the day and somewhat larger at night.

We used 10525 hours of drift measurements and complementary AE and decimetric solar flux indices. We have determined the disturbance dynamo vertical drifts by removing solar cycle dependent bimonthly quiet time values (expressed by hourly AE indices smaller than 300nT for at least 28 hours prior to the observation) derived by Scherliess (1997). These quiet values, which have standard errors of the means of about 2 m/s correspond to an average AE of about 130 nT, were removed from the 15-min averaged drifts. Then, following Fejer and Scherliess (1995) and Fejer et al. (2008), we selected the disturbance drifts following an average increase in the last 6 hours of geomagnetic activity of at least 100 nT in AE relative to the quiet value mentioned before i.e. ΔAE(0-6 hrs)>100nT, and minimized prompt penetration electric fields effects by excluding disturbance drifts when the hourly AE changes were larger than 250 nT i.e. when the absolute differences of both the current and the previously hourly value and the previously hourly value and the value two hours before were larger than 250 nT. We note that it is not possible to completely separate prompt penetration and disturbance dynamo electric field effects. Since these processes have opposite local time dependent polarities (e.g., Fejer, 2011), we estimate that, on the average, residual prompt penetration electric fields effects decrease the magnitudes of our inferred disturbance dynamo drifts only slightly (by about 2-3 m/s). We also tested other more stringent criteria to further minimize these magnetospheric effects with no significant differences in the results. We have deleted observations related to the solar flare events (e.g., Zhang et al., 2017b).

Our database of disturbance drifts consists of 3118 hours of observations. Table 1 shows the number of hours of disturbance drifts in bimonthly bins. The smallest number of observations is from November-December with 374 hours, and the largest number from September-October with 700 hours. In general, they have fairly even distributions from low and high solar flux conditions. This is also the case for the disturbance levels, as measured by the time averaged AE indices, except for the July-August high solar flux period, where the average disturbance levels are smaller than during the other periods.

Figure 1 shows the local time and seasonal distribution of our disturbance dynamo drifts. We note that these disturbance drifts include quiet time variability effects, which are largest during low solar flux periods (e.g., Fejer & Scherliess, 2001), since these cannot be removed by subtracting average quiet time values. The relatively small number of nighttime measurements during December solstice is mostly due to the frequent occurrence of equatorial spread over the entire nighttime period during this season (e.g., Fejer et al., 1999) and to the removal of measurements during sudden stratospheric warming events (e.g., Fejer et al., 2011; Siddiqui et al., 2015).

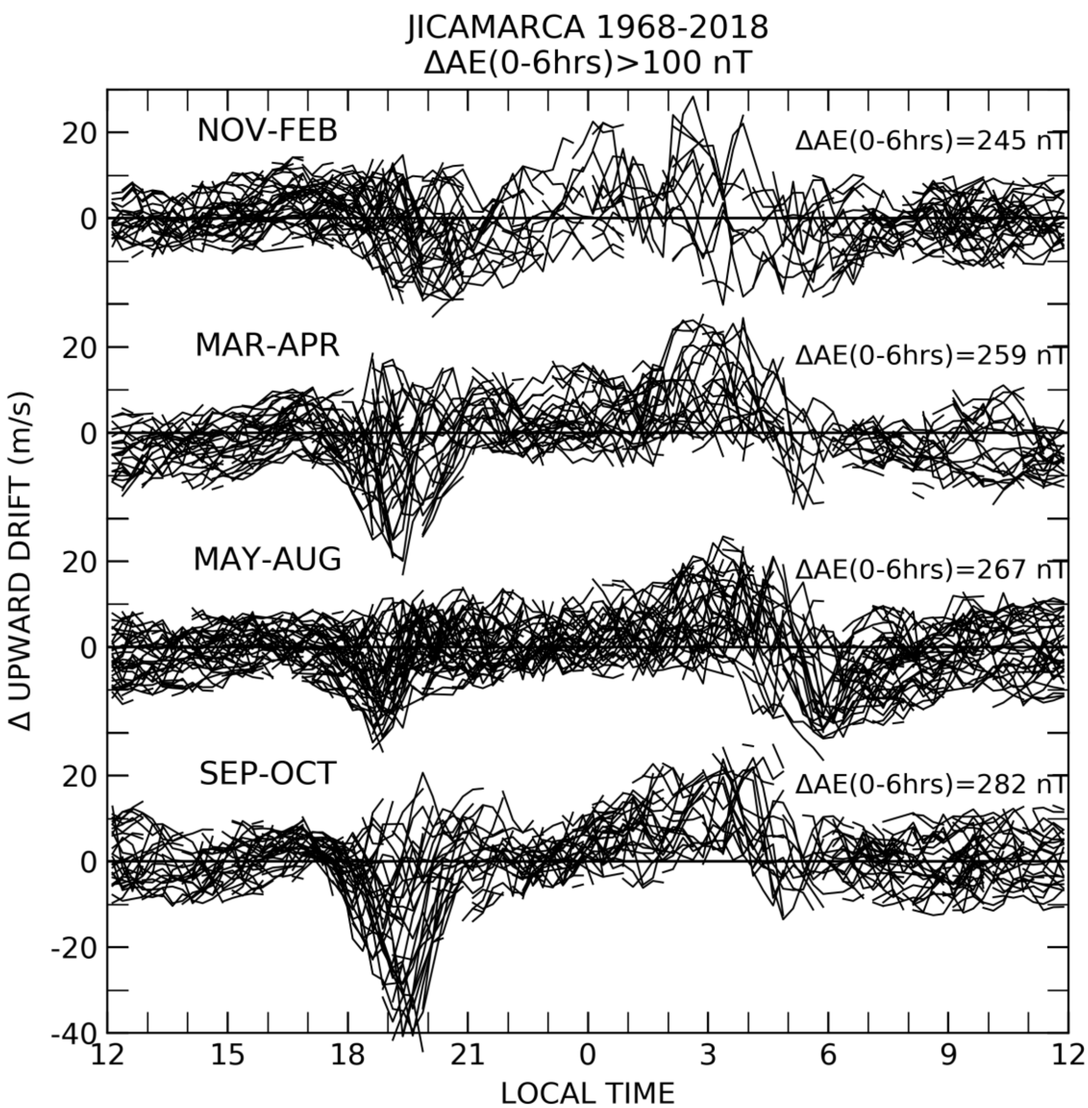

Figure 1. Scatter plot of season dependent disturbance dynamo drifts after 6 hours of enhanced geomagnetic activity.

3 Results

Figure 2 shows the bimonthly averaged disturbance vertical drifts corresponding to 6-hours of enhanced magnetic activity and to an average solar flux index of about 120 units. For the November-December and January-February bins, we have included measurements 15 days before and after these nominal periods to overcome low statistics. The average increases in the 6-hours AE indices over our quiet time value (about 130 nT) varied from 230nT to 260nT, except for January-February, which had an average increase of about 180nT. The residuals were averaged in hourly bins, except around sunset where half-hour bins were used. The standard deviations on the average disturbance drift varied from about 3 m/s to 10 m/s, except for the December solstice nighttime data where it was up to about 15 m/s.

Figure 2 shows that the daytime drifts are typically downward with values of about 5 m/s from January to June, and close to zero for the rest of the year. Near dusk, the disturbance drifts are downward throughout the year with largest values during the autumnal equinox and smallest during May-June. The evening disturbance dynamo downward peak drifts, and the reversals from downward to upward drifts, occur earliest during May-June and latest during January-February. There is a clear equinoctial asymmetry in the disturbance dynamo drifts near dusk with autumnal equinoctial values about twice as large as the vernal equinoctial values. The nighttime disturbance drifts are upward throughout the year with smallest values during May-June. The magnitudes of the December solstice nighttime disturbance drifts have much larger uncertainties than during the other seasons due to poor statistics. The morning drift reversals from upward to downward occur latest during December and earliest during June solstice.

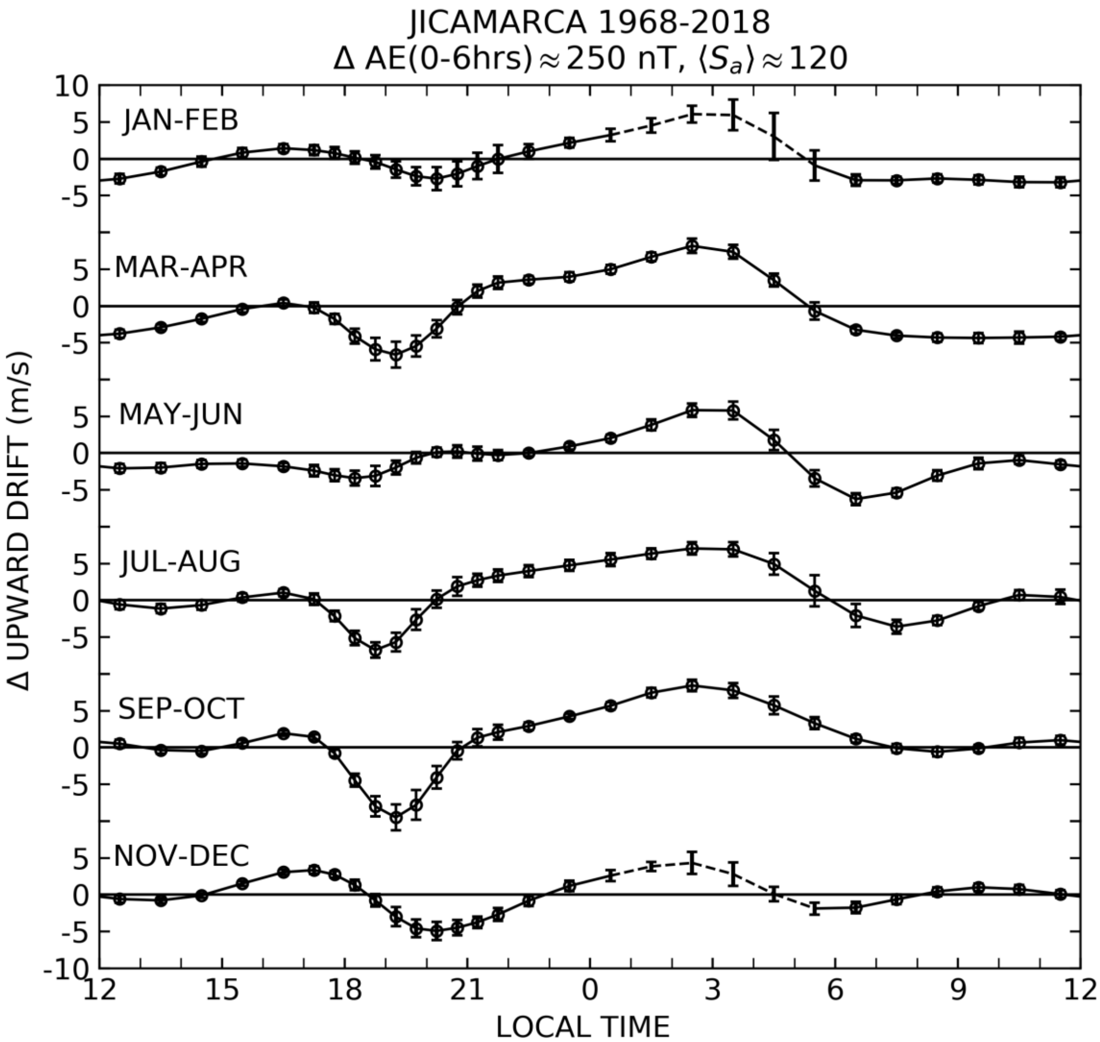

Figure 2. Bimonthly averages of disturbance vertical drifts for moderate flux conditions. The error bars denote the standard errors of the means. The dotted lines denote periods of low statistics.

Figure 3 shows a color map of the annual variation of the disturbance dynamo drifts for moderate solar flux conditions. It is an extension of the results shown in Figure 2 using a sliding bimonthly window every two weeks. This window was one month longer for December solstice when less data was available and, as a result, it is often difficult to estimate accurately the disturbance drifts due to the frequent occurrence of plasma irregularities and strong sudden stratospheric warming events. In this case, the average disturbance increases over the quiet value (about 130nT) ranged from 200nT to 290nT, except from mid November to mid February when they ranged from about 170nT to 190nT. The average solar flux conditions ranged from 110 to 130 solar flux units. The overall standard deviations are comparable to those reported in Figure 1 (i.e., between about 5 and 10 m/s and somewhat larger, especially at night, during December solstice).

Figure 3 shows in more detail the strong annual variation of the equatorial disturbance dynamo vertical drifts. The magnitude and peak times of the downward drifts near dusk, in particular, change strongly throughout the year. These peak drifts are largest around the autumnal equinox and smallest around June solstice. There is also a pronounced asymmetry on the equinoctial drifts near sunset where the downward disturbance drifts are larger during the autumnal equinox than during the vernal equinox. The same is true for the late night upward drifts. In addition, the postmidnight upward disturbance drifts extend further into the dayside during the autumnal equinox than during the vernal equinox. The daytime and nighttime disturbance drifts are smallest during May-June, except near sunrise. There is also an apparent annual variation on the morning disturbance drifts, which are generally downward from December to July, and close to zero for the rest of the year. Except for June solstice, the late afternoon drifts are upward with largest values around December solstice.

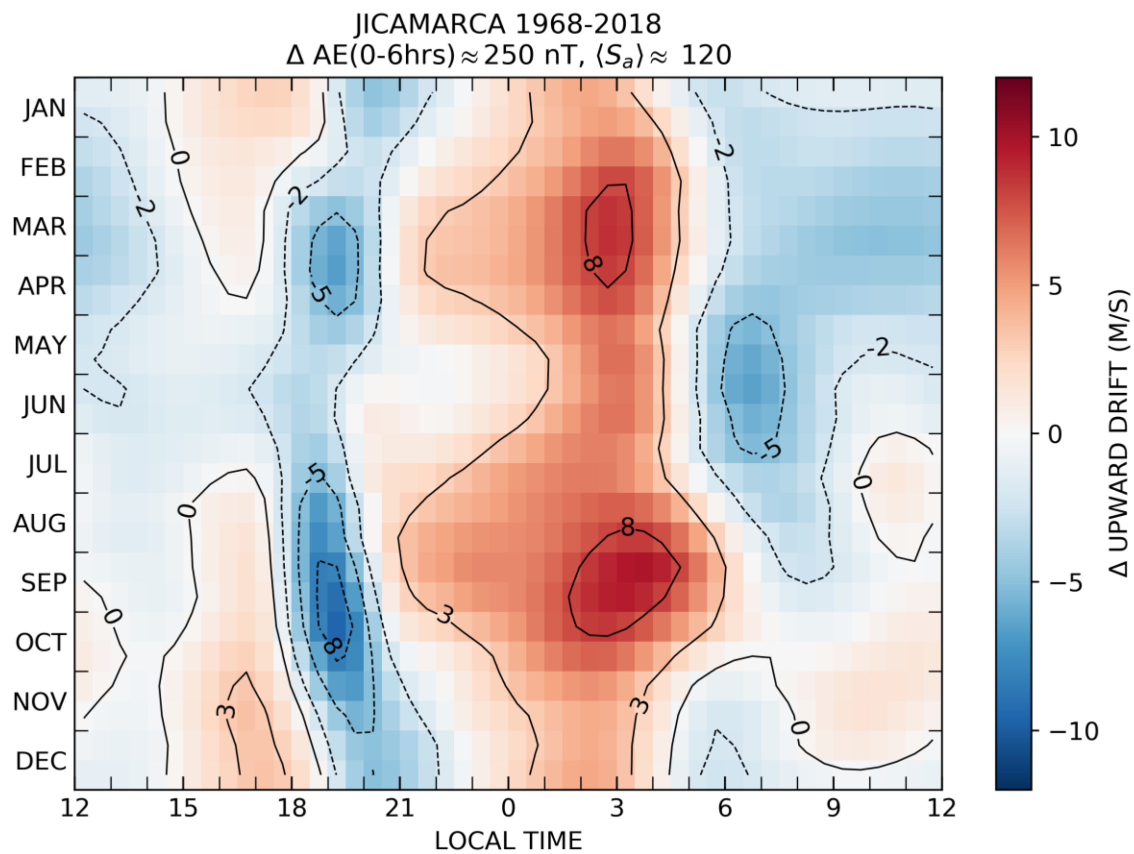

Figure 3. Annual variation and local time dependence of disturbance vertical drifts for moderate flux conditions.

The equatorial disturbance dynamo drifts vary strongly with the level of energy deposition into the high latitude ionosphere, as measured by the time-averaged AE indices, and with solar flux. Figure 4 illustrates the annual and local time dependent increases of the disturbance dynamo drift magnitudes for an increase in the time-averaged AE indices by about 270 nT for moderate solar flux conditions. In this case again, we combined the results from November to February in order to obtain statistically more meaningful results. Figure 4 shows that increased geomagnetic activity leads to large increases in the magnitudes of the disturbance drifts near dusk and in the late night sector, with no significant effects on the daytime drifts. The downward disturbance drifts near dusk increase strongly during the equinoctial months and very weakly between May and August. The rate of increase of the nighttime upward disturbance drifts is largest near 03 LT and does not change much throughout the year.

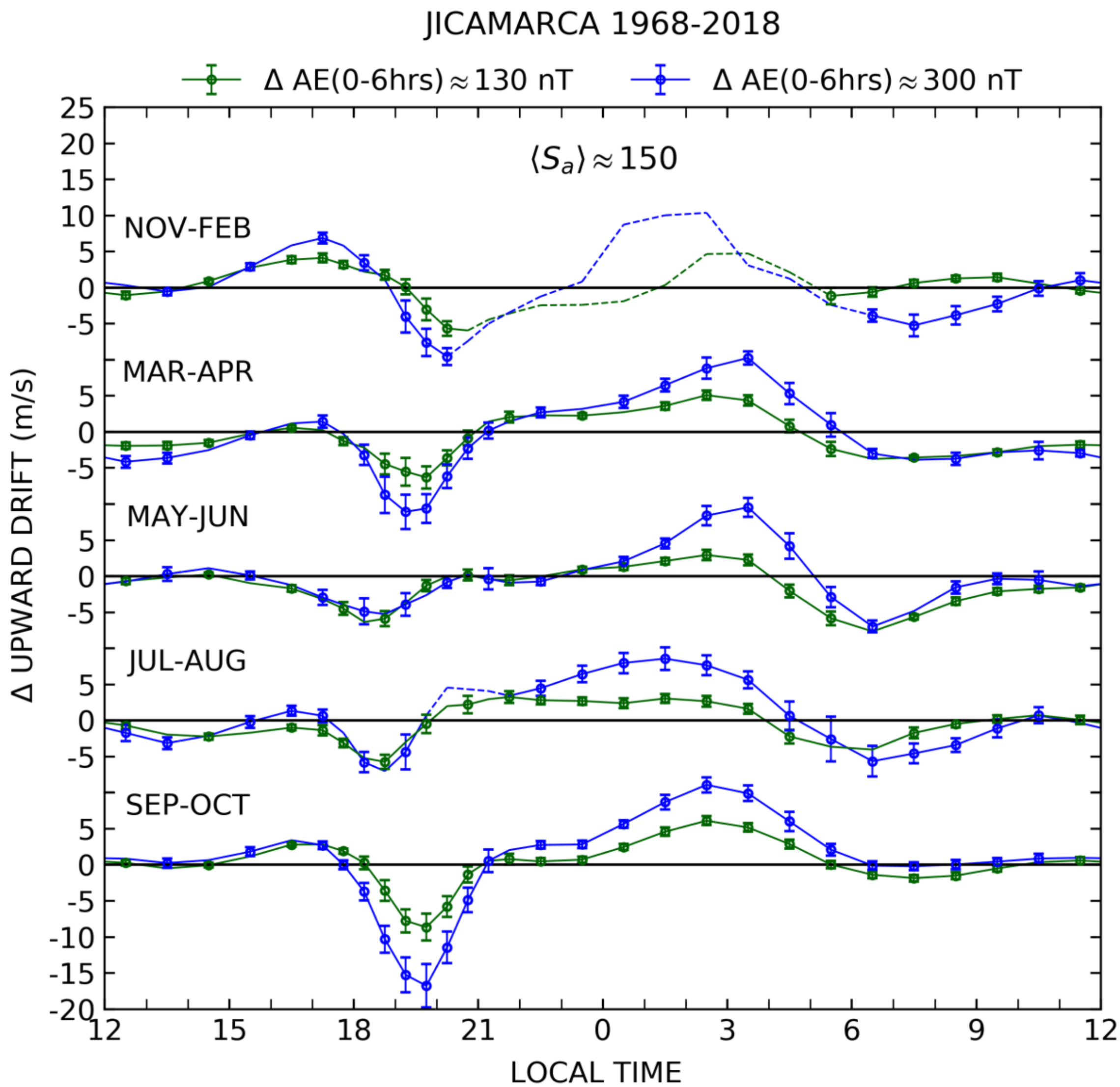

Figure 4. Annual variation of the disturbance dynamo vertical drifts for low (green) and high (blue) magnetically active conditions. The scatter bars denote the standard errors of the means. The dotted lines indicate periods of low statistics.

Figure 5 shows the annual variation of the disturbance drifts with solar flux. We used three solar flux levels only near dusk where they vary most strongly with solar flux, and have omitted the high solar flux results for July-August since they are not statistically significant due the small number of observations. These average disturbance drift patterns were obtained by binning the data in variable overlapping solar flux ranges. The resulting average values ranged from 90 to 100 s.f.u. and 175 to 185 s.f.u. for low and high solar flux conditions respectively, except for

November-February high solar conditions when this value was 150 s.f.u. The 6-hour average increase in the AE indices ranged from about 240 nT to 250nT for low solar flux conditions, and from about 260 nT to 270 nT for medium and high solar conditions respectively, except for Nov-Dec where the average increase was about 200nT. The standard deviations were generally about 5 m/s for the daytime and premidnight sectors, and about 8 m/s for the rest of the day. These standard deviations were smallest for May-June and largest for November-December.

Figure 5 shows that the strongest solar cycle effects on the disturbance dynamo drifts occur near sunset. In this local time sector, the downward disturbance drifts increase with solar flux during all seasons and have largest increases during equinox. The high solar flux evening peak disturbance drifts in Figure 5 are largest and smallest during September-October and May-June with values of about -20 m/s and -5 m/s, respectively. The evening peak of the disturbance drifts also shift to later local times from low to high solar flux periods. The low solar flux disturbance drifts near sunset are typically smaller than about -5 m/s for all seasons, and have largest magnitudes during the autumnal equinox. The nighttime upward disturbance drifts generally do not change much with solar flux. The solar flux dependence of the December solstice nighttime drift cannot be determined from our limited data. The morning westward drifts generally decrease weakly with increasing solar flux, particularly during June solstice, and the late afternoon drift becomes increasingly eastward prior to turning downward.

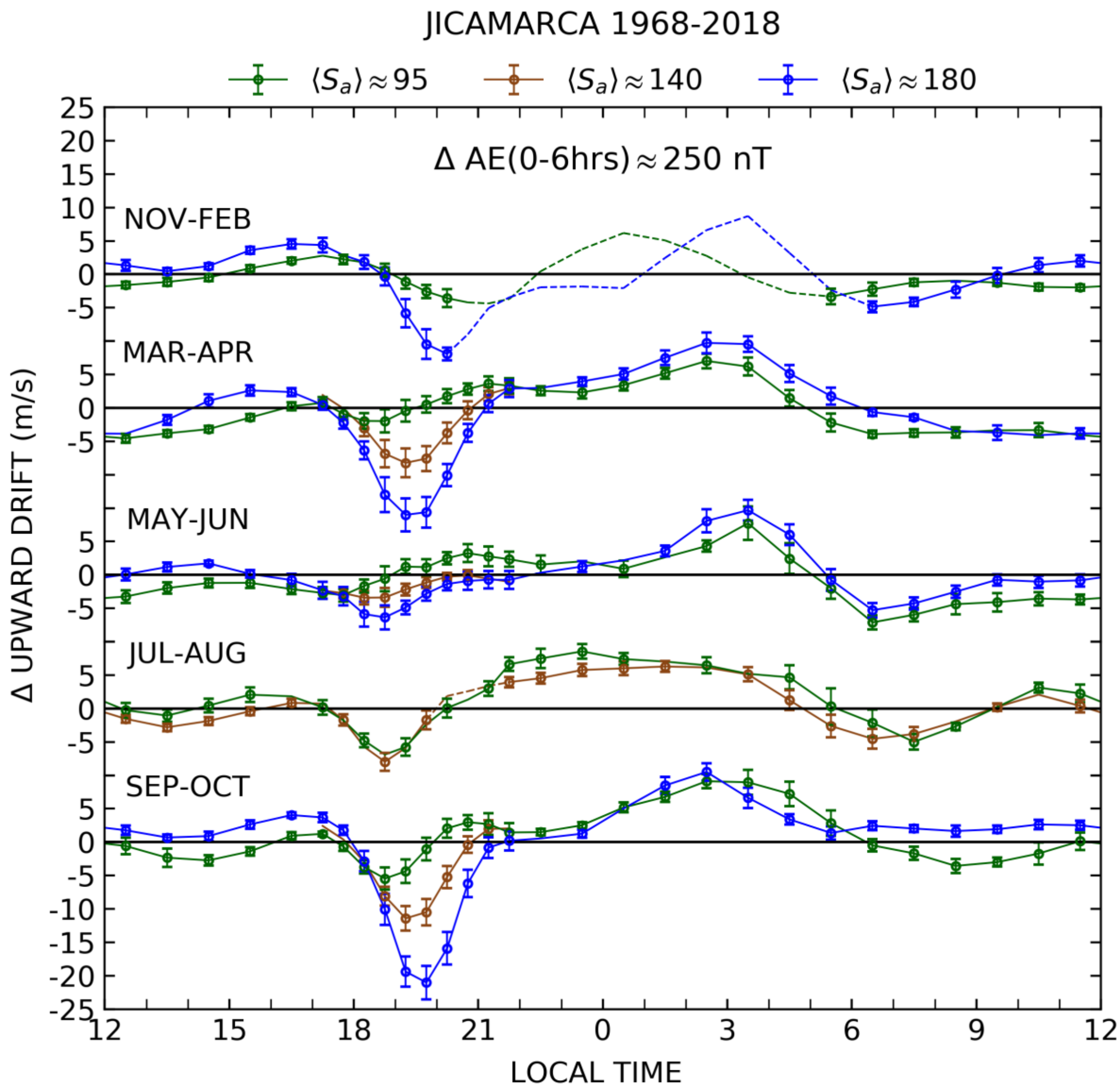

Figure 5. Annual variation of disturbance dynamo vertical drifts for low (green), medium (brown) and high (blue) solar flux conditions. The scatter bars denote the standard errors of the means. The dotted lines indicate periods of low statistics

4 Discussion

We have determined the bi-monthly variation of the Jicamarca disturbance dynamo vertical drifts and their dependence on solar flux following a 6-hours AE increase of 250 nT. For moderate solar flux conditions, the daytime disturbance drifts are smaller than about 5 m/s and generally downward, except in the late afternoon sector. Near dusk, they are downward with largest and smallest magnitudes during the autumnal equinox and May-June, respectively. The early night drift reversal times from downward to upward occur earliest during May-June and latest during January-February. The nighttime disturbance drifts are upward with largest magnitudes (about 8 m/s) close to sunrise and vary weakly with season, except for slightly smaller values during May-June. The disturbance drifts reverse from upward to downward near dawn.

Our disturbance drift patterns are in good agreement with the patterns from the Blanc-Richmond numerical and the season independent Scherliess-Fejer empirical model. The seasonal variations of the disturbance drifts presented above are consistent with the results from previous (less detailed) empirical (e.g., Fejer, 2002; Fejer et al., 2008) and numerical simulation studies (e.g., Huang & Chen, 2008; Huang, 2013). However, our results show a much stronger variation of the disturbance dynamo drift throughout the year, with solar flux and geomagnetic conditions than reported previously. In particular, our data indicate very weak low solar flux disturbance dynamo effects near dusk between about March and June.

The disturbance dynamo drifts vary most strongly with solar flux near dusk, but this dependence changes significantly throughout the year. In this local time sector, an increase in the solar flux index from about 90 to 180 s.f.u. results in an increase of the peak downward drift from 5 to 20 m/s during for September-October, but only from about 3 to 5 m/s during May-June. Although our average disturbance drifts are less accurate during December solstice, they also indicate a strong increase of the peak downward drift with solar flux. Similar annual variation is found for increased geomagnetic activity, but with no shift to later local times.

The evening disturbance dynamo drifts have larger values during the autumnal equinox than during the vernal equinox, particularly during low solar flux conditions. Scherliess (1997) showed that there is a similar equinoctial asymmetry on the Jicamarca quiet time evening upward prereversal velocities with larger values during the autumnal equinox. Ren et al (2011) used ROCSAT-1 satellite data to describe the longitudinal variation of this equinoctial asymmetry under quiet time conditions, which was attributed to the action of asymmetries on different thermospheric parameters, especially in the eastward winds and in the tides related to them.

The morning and early afternoon disturbance dynamo drifts, which are predominantly downward during low solar flux periods, decrease and even turn slightly eastward during high solar flux conditions. The nighttime upward disturbance drifts do not change much from low to high solar flux periods, but they increase strongly with geomagnetic activity close to dawn. These drifts also do not change much with season, except perhaps for the early night period. The relatively large late night upward disturbance dynamo drift and the decrease of the nighttime quiet-time ambient downward vertical drifts with solar flux, makes the disturbance dynamo drifts an increasingly important driving mechanism for equatorial spread F during low solar flux geomagnetic active periods (e.g., Fejer et al. 1999). The same is the case near dusk during July-August (e.g., Rodrigues et al. 2018).

The physical processes responsible for the strong dependence of the equatorial disturbance dynamo on season and solar flux have not been studied in detail. Simulations studies presented by Huang et al (2005), Huang and Chen (2008) and Huang (2013) suggest that the disturbance dynamo electric fields are largely controlled by the same main parameters (e.g., thermospheric winds and ionospheric conductances) that are responsible for the quiet time drifts. Huang (2013) pointed out that an asymmetric energy deposition at high latitudes may also play an important role, even during equinox, but these effects have not been studied using numerical simulations.

5 Summary and conclusions

We have presented the first detailed study of the bi-monthly, solar cycle and enhanced geomagnetic conditions dependence of the disturbance dynamo vertical drifts over Jicamarca. Our results indicate that the equatorial disturbance dynamo drifts can have much stronger seasonal and solar cycle variations than previously reported. The daytime vertical disturbance dynamo drifts have small magnitudes and an apparent annual dependence, with largest downward disturbances around March-April. Near dusk, the disturbance drifts are downward and show pronounced equinoctial asymmetry with larger values during the autumnal than during the vernal equinox. These drifts increase strongly with both solar flux and enhanced geomagnetic activity but shift to later local times with increasing solar flux only. They reach much larger magnitudes than predicted by the Scherliess-Fejer empirical disturbance drift model, particularly during equinox solar maximum periods. Nighttime disturbance dynamo drifts are upward with large magnitudes in the postmidnight sector, have no significant solar cycle or seasonal dependence, except during the early night period.

Acknowledgments, Samples, and Data

This work was supported by the NASA H-LWS program through grant 80NSSC17K071 and by the Physics Department at Utah State University. The Jicamarca Radio Observatory is a facility of the Instituto Geofísico del Peru operated with support from the NSF AGS-0905448 through Cornell University. The radar data is available at the website of the Jicamarca Radio Observatory (http://jro.igp.gob.pe), and the geomagnetic indices are available from the World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp) and from the National Centers for Environmental Information of the National Oceanic and Atmospheric Administration (https://www.ngdc.noaa.gov).

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