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An investigation of ionospheric responses, and disturbance thermospheric winds, during magnetic storms over South American sector

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[1] This paper presents the results of a study of the ionospheric and thermospheric response to magnetic storm disturbances for four stations covering a wide range of latitude in the South American region. The study is based on the F layer critical frequency (f_oF_2) and the peak height (h_mF_2) from Fortaleza (FZ), which is equatorial, Cachoeira Paulista (CP), which is low latitude, Concepción (CON), a midlatitude site, and King George Island (KGI), a middle to high latitude site. Equivalent neutral winds are extracted from the measured h_mF_2 by employing the Field Line Interhemispheric Plasma (FLIP) model. The Equatorial Ionization Anomaly (EIA) can undergo enhancement due to magnetospheric disturbance electric field that penetrates to low latitudes during the growth phase of a storm/substorm, whereas EIA inhibition occurs more often under disturbance dynamo (DD) electric field. Season-dependent meridional/transequatorial winds can significantly alter the EIA response to disturbance electric fields. Large amplitudes of DD electric field is observed during evening and morning hours in equinoctial, but not in winter, months. Over the Brazilian low latitude of large westward magnetic declination angle, large equatorward meridional wind surges seem to be helped by the presence of disturbance zonal (westward) winds. The low latitude disturbance can, in some cases, be traced to specific disturbance fronts originating promptly from auroral activity enhancements. This study confirms earlier studies that show that the quiet time meridional wind increases with increase of latitude and that over midlatitude it shows decreases with increase of solar flux due to the effect of the ion drag force. This study further shows that the disturbance meridional wind and the intensity of DD electric field increase with increasing intensity of high latitude energy input. The negative ionospheric storm phase over middle latitude, observed in equinox and not in winter, is also intensified with the increasing intensity of high latitude energy input. *INDEX TERMS:* 2411 Ionosphere: Electric fields (2712); 2415 Ionosphere: Equatorial ionosphere; 2435 Ionosphere: Ionospheric disturbances; 2437 Ionosphere: Ionospheric dynamics; 2443 Ionosphere: Midlatitude ionosphere; 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); *KEYWORDS:* electric field, meridional wind, equatorial anomaly, gravity waves, ionospheric response to storms, disturbance dynamo

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1. Introduction

[2] In this paper we have analyzed ionosonde data from a latitudinal chain of stations extending from Antarctic to equatorial regions in the South American sector during a few magnetic storm intervals. The objective of this study is to investigate some outstanding aspects of ionospheric and thermospheric response features, as a function of latitude, focusing attention on specific effects arising from disturbance electric fields, disturbance magnetic meridional wind and thermospheric circulation. The thermospheric meridional wind patterns under quiet and disturbed conditions were determined by using the Field Line Interhemispheric Plasma (FLIP) model [*Richards and Torr*, 1985; *Richards et al.*, 1994].

[3] The energy and particle injection that takes place during magnetospheric disturbances produces multiple changes to the Earth's high latitude ionosphere–thermosphere system. Through different dynamic and electrodynamic processes the effect of this excess energy deposition significantly influences the ionosphere–thermosphere system at all longitudes and latitudes. Prompt penetration (PP)

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magnetospheric electric fields have been observed during times of sudden changes in high latitude convection as evident in ionospheric response features observed at low and equatorial latitudes associated with development and decay of substorms [e.g., *Fejer and Scherliess*, 1998; *Abdu et al.*, 1995; *Sobral et al.*, 1997]. These electric fields have also been observed at midlatitudes [e.g., *Blanc*, 1983]. Thermospheric heating that takes place from processes such as particle precipitation, Joule dissipation, etc., sets pressure gradient forces that produce gravity waves/TIDs, global scale disturbed thermospheric circulation and associated disturbances in thermospheric winds and composition changes reaching the middle, low, and equatorial latitude regions with a delay of a few hours from the onset of a magnetospheric disturbance event. The disturbance neutral winds can be produced also by increased ion drag due to rapid plasma convection [*Fuller-Rowell et al.*, 1994; *Prölss*, 1997]. These perturbation winds could penetrate to middle and low latitudes more efficiently in the postmidnight sector in which the pressure gradient and ion drag forces mobilize the neutral air in the same direction [*Buonsanto et al.*, 1990]. Also, the thermospheric disturbance winds produce, through dynamo action, electric fields, widely known as disturbance dynamo (DD) electric field that usually persists well after the response to PP electric field of magnetospheric/high latitude origin subsides [*Blanc and Richmond*, 1980; *Scherliess and Fejer*, 1997; *Abdu et al.*, 1997].

[4] Simulations of coupled thermosphere–ionosphere dynamics using a global general circulation model showed interesting response features of the thermosphere and ionosphere as a unique system [*Fuller-Rowell et al.*, 1994, 1997]. Vertical upwelling of the air through vertical winds could cause enhanced abundance of molecular species at higher altitudes establishing cells of air rich in N_2 at ionospheric heights (especially at F region) as modeled by *Fuller-Rowell et al.* [1994]. Such air cells expand in latitude and longitude through disturbance thermospheric circulation and wind patterns subject to Coriolis effect, and, influenced by the prevailing quiet time winds, substantially perturb the ionospheric density and height at all latitudes, giving rise to the ionospheric storm responses, characterized by positive and negative phases in these parameters [*Matsushita*, 1959]. Using satellite data, *Richards* [2001] found that both atomic oxygen and molecular nitrogen were well represented by hydrostatic or diffusive equilibrium during storms in September 1974. However, the column density of atomic oxygen was a factor of 2 lower than predicted by the MSIS model. The ionospheric response that involve effects of the winds, electric fields and changes in the neutral atmospheric composition presents a complex dependence with latitude, longitude, season of the year, intensity of the magnetic storm, solar activity, hour of the storm onset, etc. For example, *Field and Rishbeth* [1997] have shown in global terms that the storm response over midlatitude depends on season with the negative phase being more common in summer and positive phase in winter. The coupled and self-consistent models widely used in recent years provide important information on global scale response features, but they often do not address adequately the problems in terms of a specific longitude sector or on a regional basis. No model seems to have addressed so far the complex problem of low latitude ionospheric response to magnetic disturbances. This paper presents the first study of the ionospheric response to magnetic storms over a wide range of latitude in the South American longitude sector, where the phenomenology varies from one dominated largely by zonal electric field to one dominated by meridional winds of thermospheric circulation. In the equatorial–low latitude region the ionization distribution is strongly controlled by the zonal electric field of ionospheric dynamo, in such a way that the equatorial plasma fountain driven by this electric field causes an ionization trough of lower densities along the dip equator that is flanked by two crests of enhanced densities at approximately ±15° latitude, thus forming the Equatorial Ionization Anomaly (EIA), also known as Appleton Anomaly. It should be noted that the two Brazilian stations, Fortaleza (FZ) and Cachoeira Paulista (CP) are located close to the trough and crest, respectively, of the EIA. The large westward magnetic declination angle (~22°W) in the low latitude region in the Brazilian sector produces a magnetic meridional component of a zonal wind, which could cause a NS hemispheric asymmetry in low latitude ionospheric responses to disturbance winds. A further complication is the possibility of ionospheric modification due to energetic particle precipitation in the South Atlantic Magnetic Anomaly (SAMA), which is characterized by the occurrence of a global minimum in the total intensity of the geomagnetic field in southern Brazil [*Abdu*, 2001], but this phenomena will not be specifically addressed in this paper.

Table 1. Ionospheric Stations

Station	Code	Geographic coordinates		Dip angle
Fortaleza	FZ	4°S	38°W	−8.3°
Cachoeira Paulista	CP	23°S	45°W	−30.4°
Concepción	CON	37°S	73°W	−37.1°
King George Island	KGI	62°S	59°W	−56.5°

2. Modeling and Methodology

[5] The four stations for which the data were analyzed are King George Island (KGI), Concepción (CON), CP, and FZ representing, respectively, middle, low, and equatorial latitudes whose coordinates are given in Table 1. The ionospheric dynamics is implicit in the F layer critical parameters, f_oF_2, which is a measure of the F layer peak electron density, and h_mF_2, the height of the peak density. We have modeled these parameters, using the FLIP model [*Richards and Torr*, 1985; *Richards et al.*, 1994], to yield the magnetic meridional component of the thermospheric wind. The FLIP model is a one-dimensional model for thermosphere and ionosphere, which has been thoroughly validated for midlatitudes studies [*Buonsanto et al.*, 1997; *Dyson et al.*, 1997; *Richards*, 2001]. The FLIP model is a comprehensive ionosphere–plasmasphere model that solves the equations of continuity, momentum for the all important ionospheric species. It also solves the two-stream photoelectron flux equations and the electron and ion energy equations to provide electron temperatures. The neutral atmosphere is provided by the MSIS model which is known to be very reliable during quiet periods but may under-

estimate neutral temperatures and overestimate atomic oxygen densities during magnetic storms (P. G. Richards, Ion and neutral density variations during ionospheric storms in September 1974: Comparison of measurement and models, submitted to *Journal of Geophysical Research*, January 2002). The MSIS model values are solar and magnetic activity dependent. The FLIP model allows the determination of the magnetic meridional component of the thermospheric wind by means of the method of *Miller et al.* [1986], which is based on a linear relationship between the vertical displacement of $h_{\max}$ and the meridional wind responsible for such displacement. The technique has been described in detail by *Richards et al.* [1994] and *Dyson et al.* [1997]. Calculations in those papers found good agreement between the winds from h_mF_2 and measured winds from optical and radar methods. The excellent agreement between winds from h_mF_2 and optical winds found by *Dyson et al.* [1997] was obtained under similar disturbed magnetic conditions to those in this paper. The method does not work near the equator where the field lines are almost horizontal and at high latitudes where the field lines are almost vertical.

[6] The meridional wind from h_mF_2 is an equivalent or effective wind because it can include a contribution from zonal electric field. It is well known that vertical displacements of h_mF_2 over a station close to the magnetic equator, such as FZ, are predominantly controlled by the strong equatorial zonal electric field [e.g., *Souza et al.*, 2000] and winds have little effect because the field lines are almost horizontal. On the other hand, over CP (which is further away from the magnetic equator) displacements of h_mF_2 arise from both zonal electric fields and magnetic meridional winds. We have separated from the $u_{\|}$ calculated by the FLIP model over CP a contribution arising from the zonal electric field as determined for FZ. This procedure is similar to that adopted by *De Medeiros et al.* [1997] and *Batista et al.* [1997] who used the well-known servomechanism of the F_2 layer [*Rishbeth*, 1967; *Rishbeth et al.*, 1978] to determine the meridional wind over CP by correcting for the effect of zonal electric field. The correction for the electric field effect in the present case was carried out using the relationship:

$$u_{\|real} = u_{\|} - \frac{E}{B\sin I} \tag{1}$$

where E is the zonal electric field over the equatorial station Fortaleza, which is field line mapped on to the F layer over CP, B is the magnetic field intensity, and I the inclination. (The height variation of E over FZ has been taken into account as per *De Medeiros et al.* [1997].) The diurnal variation pattern of E used was that based on Jicamarca radar data [*Fejer et al.*, 1996] except for the evening to premidnight hours when it is known that the zonal electric field (vertical plasma drift) over Jicamarca is different from that observed over FZ [*Abdu et al.*, 1981]. During these hours we have determined the zonal electric field from ionosonde data over FZ based on the calculation of vertical drift as given by $W_{FZ} = \Delta h'F/\Delta t = E/B$. The vertical drift so determined is valid for $h'F \geq 300$ km. For lower values of $h'F$ a correction to $\Delta h'F/\Delta t$ arising from an apparent drift due to recombination needs to be applied [*Bittencourt and Abdu*, 1981].

Table 2. Perturbed Events

Month and year	Storm days	$(\Sigma Kp)_{\max}$
September 1986	11–15	45
October 1986	13–17	32
November 1986	4–7	45
April 1989	25–29	46
May 1989	23–27	46
August 1989	27–31	38
September 1989	17–20	36
October 1989	20–24	47
November 1989	17–20	48
June 1990	12–15	44

[7] We may note that FZ and CP are located at the trough and crest of the EIA, which is basically driven by the equatorial plasma fountain, but also controlled by meridional/transequatorial winds. As a result, the f_oF_2 and h_mF_2 variations at these stations are intimately coupled. The interpretation of the relevant results needs to be based on the following basic considerations:

1. The vertical drift due to a zonal electric field (which is field line mapped) should vary with latitude as cos I, where I is the magnetic field inclination. Its value being $-9°$ and $-28°$, respectively, for the two stations, the mapping factor varies from 0.987 to 0.88 from FZ to CP. Thus the response of h_mF_2, could show up in-phase with "comparable" amplitudes at the two stations. On the other hand the meridional wind effect on vertical ionization drift varies as sin I cos I that has values of 0.15 and 0.41, respectively, for the two stations, and therefore the associated h_mF_2 deviations over the two stations could be of different amplitude and phase.
2. The f_oF_2 response to a disturbance zonal electric field (or a disturbance plasma fountain) could be anti phase at the two stations, a positive deviation over CP (FZ) associated to a negative deviation over FZ (CP) being indicative of EIA enhancement (inhibition/contraction). A disturbance meridional wind could modify such a simple picture, however. The EIA has a prompt response to an imposed perturbation electric field, but depending upon local time the maximum effect on f_oF_2 to such an imposed electric field/meridional wind perturbation, could often involve some delay of 1–3 hours, as described by *Abdu et al.* [1991] and *Souza et al.* [2000].
3. The f_oF_2 values over CP can undergo significant modification due to meridional wind at conjugate point of CP whereas the h_mF_2 values responds directly to local meridional wind [*Souza et al.*, 2000].

3. Data Analysis and Presentation of Results

[8] The 10 storm intervals shown in Table 2 were selected for analysis because they were the only events for which simultaneous data over the four stations were available. Based on the maximum D_{st} values these storms are considered to be of moderate to weak intensity. They represent winter and equinoctial months of low and high solar activity epochs. Of the 10 storms four representative storms with consistent response features were selected for this study. These storms occurred during October 1986 and 1989, May 1989, and June 1990. In Figures 1–4 we have presented the data for 4/5 day intervals covering the disturbed periods of

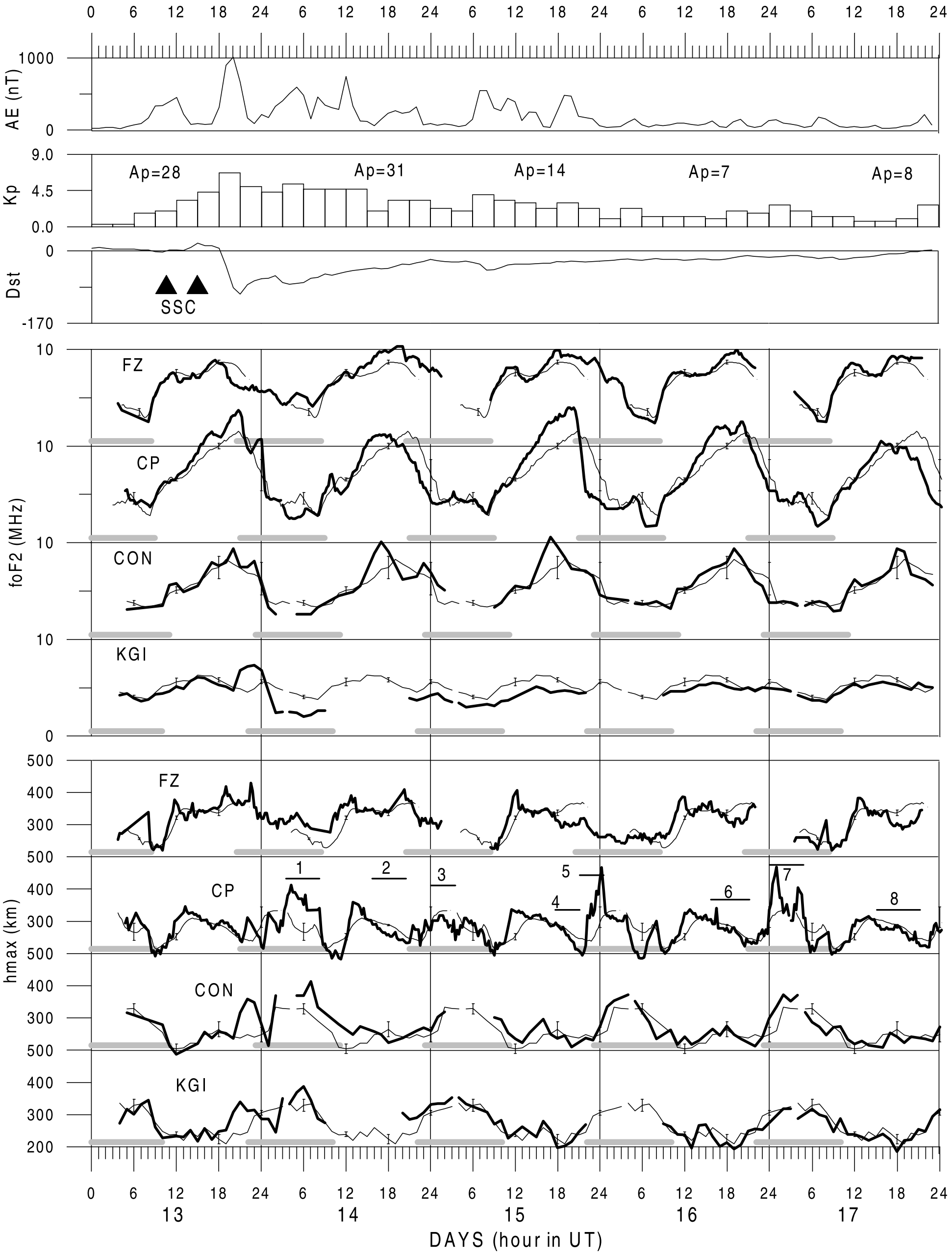

Figure 1. The auroral activity index AE, the three hourly planetary index Kp, and the D_{st} values during 13–17 October 1986 corresponding to the magnetic storm disturbance that had onset at 1054 UT and a second SSC at 1454 UT on 13 October plotted in the first top three panels. The two bottom panels show the variations of f_oF_2 and h_mF_2 during these days for the four locations FZ, CP, CON, and KGI. Thick lines represent the day-to-day values and thin lines represent five quiet day mean values used as reference. The vertical bars on these curves represent the standard deviation. Horizontal patches indicate night hours for each of the stations. Horizontal lines with identification numbers, 1, 2, 3, etc., along the h_mF_2 plot over CP indicate intervals when positive and negative disturbances in meridional winds occurred as marked in Figure 6a. (The D_{st} values hourly and they are plotted at the beginning of the hour.) Vertical bars on the thin curves are the standard deviation.

these storms. Also shown are the magnetic activity indices, Kp and D_{st}, as well as the auroral AE activity index (for the solar minimum epoch of 1986) and the asymmetric indices, that is, Asy-H and Asy-D values (for the solar activity maximum epoch of 1989 and 1990). The AE indices were not available for this latter epoch. *Iyemori* [1990] have shown that the asymmetric indices can be used as a proxy to AE indices. In section 4 the storm time response features in h_mF_2 and f_oF_2 are discussed with reference to their quiet time reference curves represented by the mean of the 5 quietest days of the month. (The thin lines in the respective figures are the reference curves. The discontinuity during

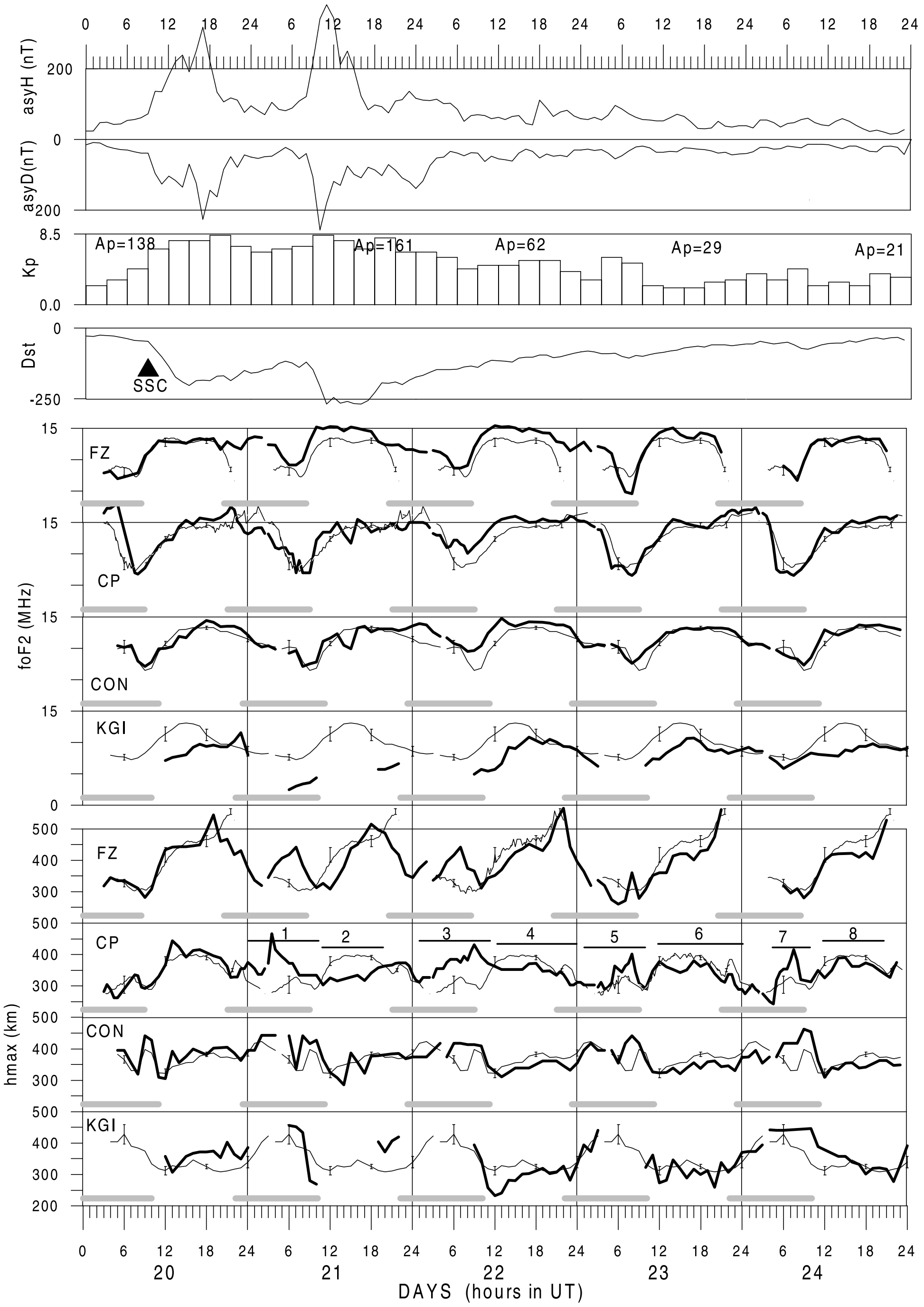

Figure 2. Similar data as in Figure 1, but plotted for the disturbance interval of 20–24 October 1989.

night hours in the curves for f_oF_2 and h_mF_2 over FZ and CP is due to the occurrence of spread *F* in the ionograms that makes the determination of these parameters uncertain). In sections 5, 6, and 7 we present the results on quiet and disturbed thermospheric winds, discussion and conclusions, respectively.

4. Storm-Dependent Responses of f_oF_2 and h_mF_2

4.1. 13–16 October 1986

[9] The 5 panels in Figure 1 show from top to bottom the AE index, the three hourly planetary disturbance index (Kp), the storm time disturbance ring current activity index (D_{st}), and the f_oF_2 and h_mF_2 values for the four stations, from 13 to 17 October 1986. This was a period of low solar flux with monthly mean F10.7 = 82.4 (the monthly mean sunspot number was 35.4). The sudden commencement for this storm (SSC) occurred at 1054 UT followed by another SSC at 1454 UT (the corresponding local times lag behind UT by 2.5, 3, 5, and 4 hours at the four station respectively starting at FZ). The main phase development that produced a maximum D_{st} of −90 nT classifies this storm as moderate [e.g., *Szuszczewicz et al.*, 1998]. The D_{st} index showed an initial phase positive deviation starting at 1300 UT of day

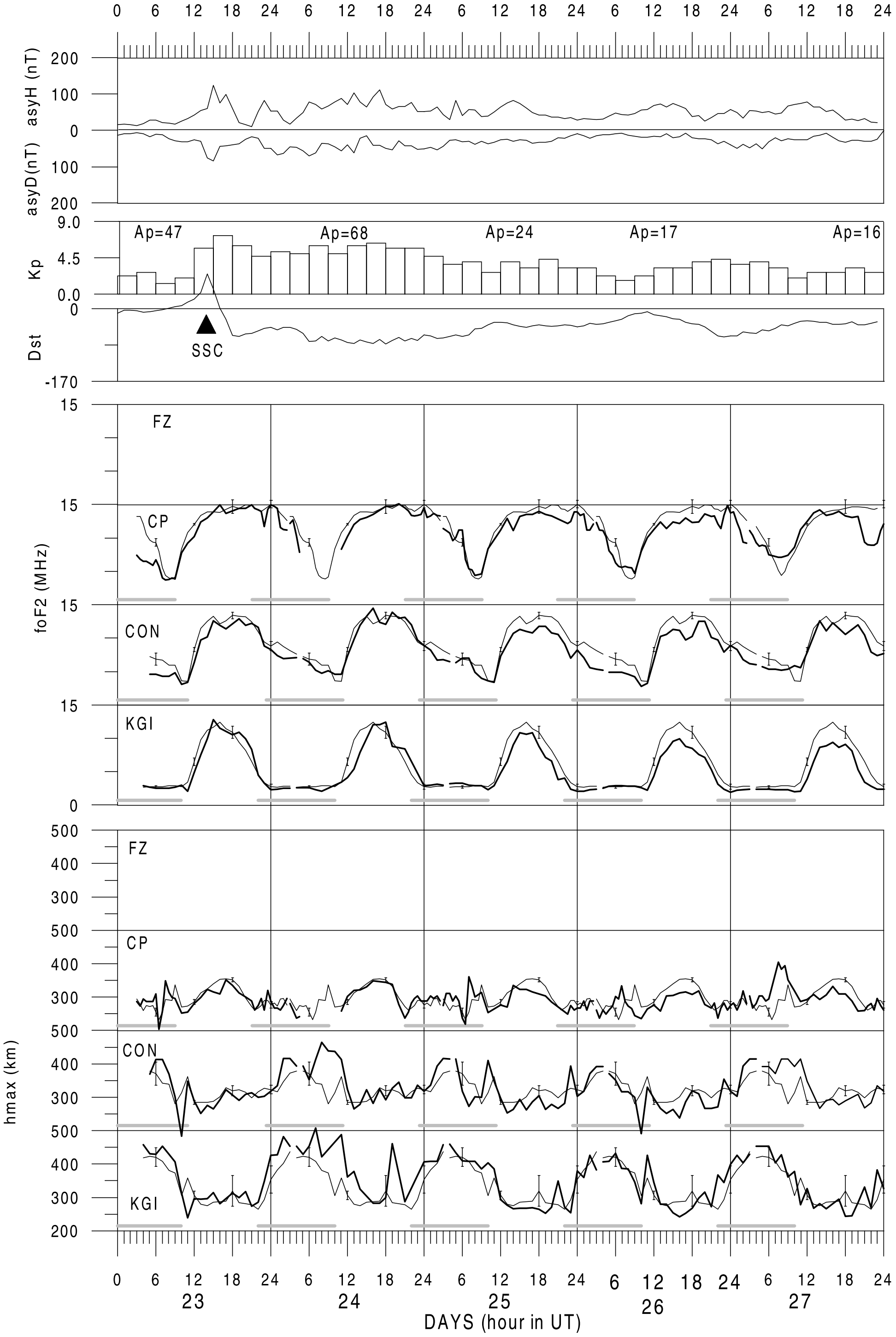

Figure 3. Similar data sets as in Figures 1 and 2, but plotted for the disturbance interval of 23–27 May 1989.

13 that was followed by the storm main phase development starting at 1800 UT. The D_{st} reached its minimum value of -90 nT at ~2100 UT and remained at less than -50 nT up to 0800 UT of the day 14. The AE index remained perturbed until 2400 UT of day 15. A second enhancement in AE that occurred starting at ~0600 UT of this day seems to be responsible for keeping the ionosphere perturbed until the day 17.

[10] The response characteristics of f_oF_2 and h_mF_2 during these disturbances are, in general, very complex, although their disturbance variations (that is, the deviation with reference to the quiet day curve) seem to present comparable amplitudes at these stations, with the exception of CP where fluctuation amplitudes are often larger. In a broad sense, however, it seems possible to identify them as belonging to two types: thermospheric–ionospheric

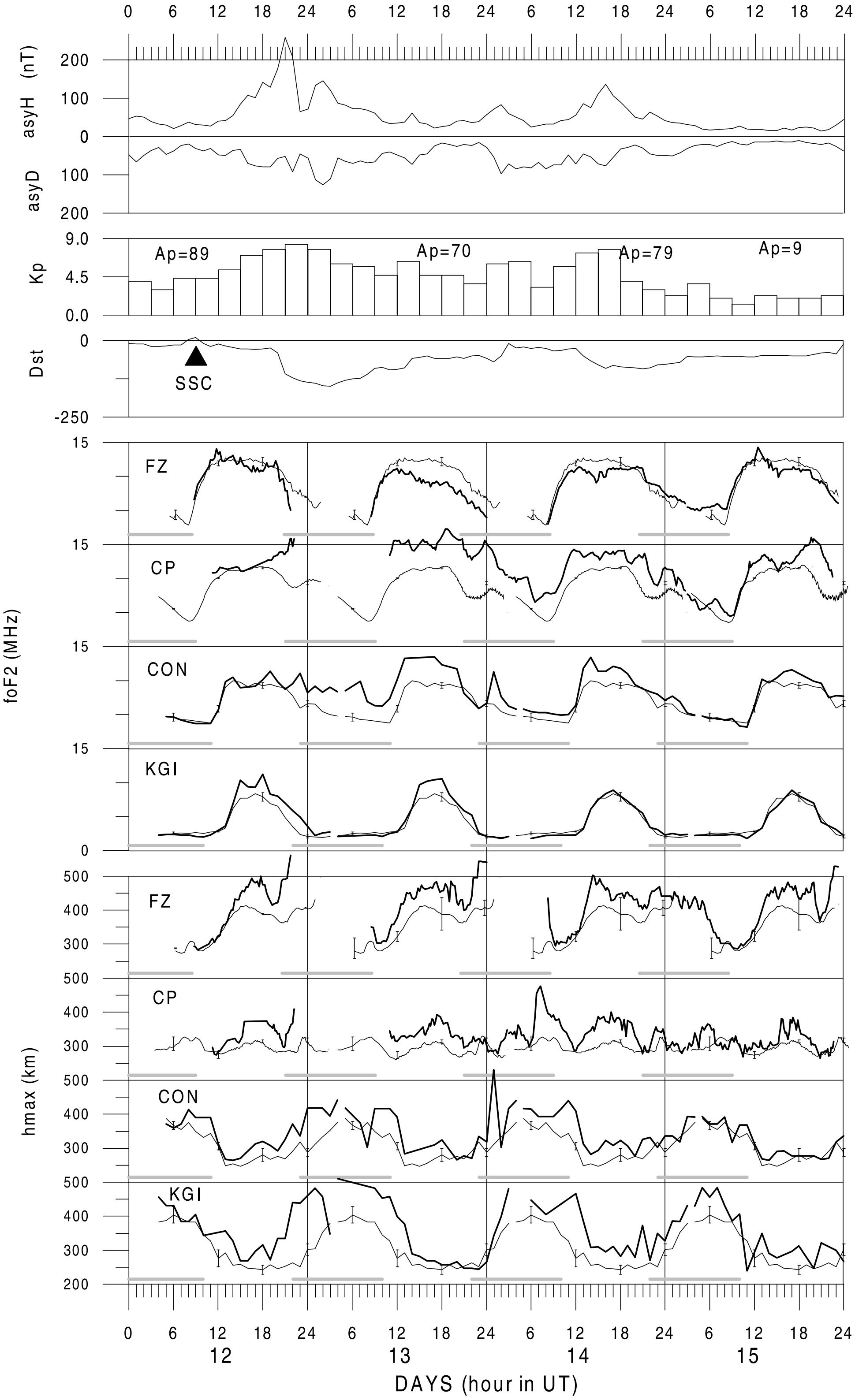

Figure 4. Results similar to those of Figures 1, 2, and 3, but plotted for the disturbance interval 12–15 June 1990.

disturbances propagating equatorward due to forcing from high latitude sources (see, for example, a disturbance onset in h_mF_2 at ~1800 UT on 13 October over KGI that propagates equatorward), on the one hand, and the responses at low latitudes, through modifications of the EIA, arising from the disturbance electric fields and disturbance winds originating from magnetospheric and high latitude processes, on the other.

[11] Minor disturbances in AE and Kp were present before and during the SSC on the day 13 that seem to have produced responses in h_mF_2 and f_oF_2 over FZ and CP. An auroral activity enhancement (in the form of a substorm) and the onset of the D_{st} main phase decrease, that set in by ~1800 UT, produced a large increase in h_mF_2 (~70 km) over FZ (Figure 1, panel 5, top section) with a smaller increase at CP. This is a clear indication of the presence of a disturbance zonal (eastward) electric field, marking the penetration of a magnetospheric electric field to equatorial latitudes. Starting at this time the f_oF_2 over FZ shows a decrease accompanied by a marked enhancement over CP (fourth panel from top). Since these two stations are located at the trough and crest of the EIA, respectively, this antiphase f_oF_2 deviations would indicate an enhanced EIA produced by the disturbance eastward electric field. There is reason to suspect that the small increase in f_oF_2 observed at the same time over CON might indicate a latitudinal expansion of the EIA under disturbed condition as was pointed out by *Abdu et al.* [1991]. This EIA response feature is recognizable only until ~2200 UT when the auroral substorm enhancement and the D_{st} main phase decrease were past their peak values.

[12] Starting at ~1900 UT, immediately following the auroral activity enhancement, a disturbance front onset can be seen as an increase in h_mF_2 over KGI which propagates equatorward hitting first CON and then CP involving delay of ~1 hour for successive stations (bottom panel of Figure 1). A corresponding disturbance (dominantly positive) is observed also in f_oF_2 at all these stations (panel 2 from bottom of Figure 1). The increase in h_mF_2 near 2200 UT over FZ represents the prereversal electric field enhancement (PRE) that characterize the postsunset *F* layer dynamics over FZ, which, on this evening, seems to have been enhanced by superposed action of an additional penetration electric field arising from the auroral substorm recovery (sudden decrease in high latitude convection) occurring at this time. This feature has been noted before [*Fejer et al.*, 1979; *Abdu et al.*, 1995]. Over CP the perturbation seems to result in a gravity wave type oscillation (clearly seen in h_mF_2). A second surge of disturbance has onset over KGI at ~0200 UT whose effect appears to propagate to CON and CP with a larger delay. The larger amplitude of disturbance in h_mF_2 over CP on the 14th (from near midnight to near midday) as compared to that over FZ would indicate dominating role of meridional wind over CP as compared to the electric field effect, that dominates over FZ. It is to be noted that the amplitude of the disturbances over CP is also larger than those over CON and KGI. Such a feature, present also on the nights of 15–16 and 16–17, is likely to be aided by the large westward magnetic declination angle of CP, a point that we shall return to later. Other major response features observed are the following:

1. The negative storm effect in f_oF_2 that set in near midnight of 13–14 over KGI, and that prevailed till the end of the storm does not seems to be caused by disturbance winds, based on the observed h_mF_2 disturbance pattern. The possibility of this being caused by thermospheric composition changes, characterized by increase in the ratio of [N_2]/[O], is being investigated [e.g., *Prölss*, 1977; *Fuller-Rowell et al.*, 1994].

2. A predominantly positive storm effect in f_oF_2 is present during most of the daytime hours over CON, CP, and FZ until nearly the end of the recovery. The f_oF_2 deviation over CON could indicate the role of a meridional wind. Presence of such wind is suggested from the disturbance variations in h_mF_2 as well. The positive deviation in f_oF_2 over FZ is possibly an indicator of a westward-directed disturbance electric field that could inhibit the EIA causing negative change in f_oF_2 over CP. But positive deviations in f_oF_2 are observed over CP (during daytime on 14–16 October) which might indicate the presence of disturbance meridional wind over this station. Thus the complex interplay of the response features emphasize the role of disturbance meridional wind in shaping the anomaly response primarily driven by disturbance electric field. It should be noted that a disturbance meridional/transequatorial winds could cause latitudinal displacement or deformation of the trough and crest of the EIA with respect to its quiet time pattern which could result in complex variation in the f_oF_2 values over the two stations. The reader is therefore cautioned that the characterization as EIA enhancement/inhibition of a given situation of the f_oF_2 variations observed over the two stations may be subject to significant uncertainty when there is uncertainty on the relative dominance of the disturbance electric field and wind which characterize that situation.

3. The influence of a DD electric field (which is westward in the evening to postsunset hours) is particularly evident in the large negative deviation in h_mF_2 observed around these hours on the 15th over FZ which appears to last until at least 0400 UT/0100 LT (in comparison with previous two nights). A comparison of this with the two previous nights would suggest that westward electric field was present until at least 0200 UT/2300 LT on this night. (Further discussion on the DD electric field will follow in the presentation of the other storm results and in the discussion part). The corresponding change in f_oF_2 over CP is seen as a rapid fall in its value, starting around 2100 UT/1800 LT, producing a negative deviation from a strong positive effect that prevailed before, thus bringing about a severe EIA inhibition. (It is pertinent to point out here that EIA responses could involve a time delay of 1–3 hours which is the time required to adjust itself to an applied forcing [*Abdu et al.*, 1991; *Souza et al.*, 2000].) This striking decrease seems to be further helped by a surge of meridional wind (indicated by increased h_mF_2 over CP starting at ~2100 UT/1800 LT). Although such wind surge did occur on the next night as well (from 2400 UT/2100 LT to 0600 UT/0300 LT) it did not cause a severe f_oF_2 decrease on this night since the intensity of the disturbance electric field was apparently much weaker at these times.

4.2. 20–24 October 1989

[13] Figure 2 shows similar parameters as in Figure 1 but for the storm interval that started on 20 October 1989. As judged from the Asy-H/Asy-D, Kp and D_{st} values, this storm is significantly more intense than that of October 1986. The monthly mean F10.7 and sunspot number were 207.4 and 159.4, respectively, indicating, also, a higher solar activity level compared to that of the October 1986 storm. There were two main auroral activity enhancements

and associated D_{st} developments within an interval of ~24 hours. The maximum D_{st} reached was <-260 nT during this storm as compared to <-90 during the storm of October 1986.

[14] The main response features during this event can be summarized as follows:

1. Following the SSC (at 0916 UT) and during the first of the two major auroral activity events, the effect of the disturbance is seen as increases in h_mF_2 over FZ peaking around 1200 UT/0900 LT and 1900 UT/1600 LT that seem to correspond to specific auroral activity enhancements and therefore may be considered as events of PP (eastward) electric field. CP also shows increases in h_mF_2, which are possibly modulated by meridional winds. (The corresponding responses over CON and KGI are unclear). The EIA enhancement, indicated by the f_oF_2 increase over CP (starting around 1900 UT) followed that the 1900 UT h_mF_2 increase over FZ was very similar to the afternoon event of October 1986. We note further that EIA enhancement involved a response time of 1–3 hours (for peak effect) in both cases, as noted before.

2. An abrupt decrease in h_mF_2 starts at ~1900 UT/1600 LT on 20 October over FZ, which seems to mark the beginning of a strong westward disturbance electric field that persisted till midnight, after which the polarity changed to eastward, as indicated by the conspicuous increase in h_mF_2 that lasted till ~1000 UT/0700 LT. The 1900 UT onset of the westward electric field seems to be caused by development of a DD that usually follows, after a delay of a few hours (5–8 hours) from the onset of an auroral disturbance [*Blanc and Richmond*, 1980; *Scherliess and Fejer*, 1997; *Abdu et al.*, 1997]. The time difference between the first Asy-H/Asy-D enhancement and the onset of the westward electric field in the present case is compatible with such delay. The DD electric field polarity that was eastward in the morning of 21st turned westward again by 0700 UT of the same day.

3. The usual F layer uplift in the evening (arising from the PRE), over FZ is totally inhibited on the evening of the 20th and 21st with recovery established by the evening of the 22nd. Such inhibition of the evening F layer uplift is a clear manifestation of the westward DD electric field at these hours. (PRE inhibition can result also from a disturbance westward wind as discussed by *Abdu et al.* [1995].) An associated postsunset f_oF_2 decrease over CP (that could suggest an EIA inhibition) such as that seen during the October 1986 storm (on the 14th and 15th) was not evident in theses cases. This is likely to be due to the meridional wind pattern that ruled on these evenings, as we shall see later.

4. The DD electric field polarity, being clearly eastward/positive during postmidnight to morning hours (as seen in the large increases in h_mF_2 at these hours over FZ on the 21st and 22nd) and westward/negative during most of the daytime and evening hours, (clearly seen on 20th and 21st) is in good agreement with the statistical results based on Jicamarca radar vertical drift data presented by *Scherliess and Fejer* [1997].

5. The f_oF_2 over FZ showing generally positive deviation on 21, 22, and 23 is somewhat consistent with a westward electric field dominating for much of the daytime and evening hours as seen in the predominantly negative h_mF_2 variation, which is expected to cause an EIA inhibition. (The effect of the enhancement in the eastward electric field of the postmidnight to morning hours is not clear in the f_oF_2 variation over FZ). However, only on the night of 20–21 the f_oF_2 over CP shows a negative deviation, (though of small magnitude), as to be expected from a basically electric field induced EIA inhibition. The fact that there are significant positive excursions in the disturbed f_oF_2 values over CP for much of the time would suggests the influence of meridional wind in the EIA development, as was pointed out also in case of the October 1986 storm response.

6. A strong negative phase in f_oF_2 that set in over KGI soon after the initiation of the auroral disturbance continued till 24 October. This negative phase was significantly more severe than that which marked the October 1986 storm. These results are in excellent agreement with other observational results [e.g., *Szuszczewicz et al.*, 1998] as well as the model results of *Fuller-Rowell et al.* [1994] and *Codrescu et al.* [1997].

7. It may be noted that the increase in h_mF_2 over FZ that was large during the postmidnight to morning periods (0300–0900 UT) on the first 2 days (21st and 22nd) of this storm was weak or absent during the October 1986 storm, thus suggesting a strong positive dependence of DD electric field on solar flux for these hours.

4.3. 23–27 May 1989

[15] Figure 3 presents the parameters as in Figures 1 and 2 but for the 23–27 May 1989 storm. No data were available for FZ for this storm. This is a weak-to-moderate disturbance in a period of moderate to high solar activity (monthly mean F10.7 = 194.4, sunspot number = 138.5) and winter conditions. The maximum value of D_{st} index reached was -85 nT. On 23 May an SSC occurred at 1346 UT which was followed, after a short-lived initial phase, by the main phase development with some modulation that lasted until ~0300 UT of the 24 May followed by rather steady value lasting till midnight of the 24th after which there was a recovery phase. A weaker activity started at ~1200 UT of the 26th that prevailed through the 27th. Auroral electrojet activity also continued until day 27 with sign of a partial recovery toward the end of the day. The following response features may be noted:

1. It is difficult to evaluate to what degree the EIA has been modified during this disturbance because of lack of data from FZ. However, there is indication of a dominantly negative f_oF_2 deviation over CP that might possibly suggest a general EIA inhibition. The disturbance component of the h_mF_2 over CP appears relatively weaker compared to the previous two storms, suggesting a weaker disturbance meridional wind as will be discussed later.

2. The f_oF_2 values show predominantly negative disturbances at the three locations on all 5 days, with the effect appearing more pronounced during the day than during night, (with the exception of the nights of 25–26 over CON when the effect appears more pronounced). Over KGI the negative storm effect in f_oF_2 is significantly weaker than during the previous storms.

3. The disturbance associated h_mF_2 deviation (from reference) appears more pronounced during morning hours, of the 24th and 27th, the effect apparently not extending to CP in the former case and not being observed over KGI in the latter case. Both cases had enhanced magnetic activity

preceding them by a few hours. Such cases were present during the previous storms as well.

4.4. 12–15 June 1990

[16] Figure 4 shows the 12–15 June 1990 data sets in the same format as those of Figures 1, 2, and 3. This corresponds to winter conditions as was the previous case, but represents a more intense storm as indicated by the magnetic indices (the D_{st} reaching <-135 nT as compared to -85 nT that characterized the May 1989 event). The solar activity levels were a bit lower than during May 1989 with monthly mean F10.7 = 176.3 (sunspot number equal to 105.4). The SSC onset was at 0820 UT on 12 June. Auroral disturbance intensified starting at ~1400 UT, and reached a peak at ~2100 UT followed by a rapid recovery. A second enhancement had onset at ~0000 UT, a peak around 0200 UT, and a slow recovery that continued till ~1800 UT of the same day. Enhancements in Asy-H/Asy-D and in Kp and D_{st} occurred again maximizing around 0200 and 1600 UT of the day 14. The associated ionospheric responses can be synthesized as follows:

1. A PP disturbance eastward electric field seems to be responsible for the increase in h_mF_2 (notably over FZ) starting at the first increase in auroral activity near 1400 UT. Simultaneous positive disturbances observed over CP seems to be modulated by disturbance meridional winds. Over CON and KGI the disturbance in h_mF_2 driven mainly by winds (as we shall see later) seem to be present even at earlier local times due perhaps to some previous minor auroral disturbances. The rapid recovery in the auroral activity (that is, a decrease in the polar cap potential drop) starting at 2100 UT seems to have produced a concurrent rapid rise in the h_mF_2 over FZ and CP (just before the interruption of the data due to spread *F* over both locations). Over FZ this rise is clearly seen superposed on the PRE that was in development at this time (~2100 UT/1800 LT) as it happened also during October 1986 storm. A corresponding increase over CON and KGI is not defined.
2. The f_oF_2 over CP indicates a gradual enhancement of the EIA that starts around 1600 UT (1300 LT over CP), which got intensified by sunset at 2100 UT/1800 LT. But spread *F* in the ionograms interrupted the data. The EIA remains clearly modified (suggestive of possible intensification) on the days 13–15. In contrast to the EIA inhibition that appears to have often marked the response features of the previous storms, in this case the EIA seems to be intensified.
3. Presence of daytime DD electric field (expected to be of westward polarity) is not obvious during this storm as judged from the positive deviation of h_mF_2 over FZ that dominated the entire interval (with some data breaks). If it is typical characteristics of the solstice conditions need to be clarified from further studies.
4. The KGI and CON data show large increases in h_mF_2 indicating the presence of disturbance equatorward winds predominantly during night hours, and correspondingly the f_oF_2 show positive storm effects. In contrast to the equinoctial results that were marked by predominantly negative storm effects in f_oF_2 over KGI the mainly positive storm effects in this case seems to characterize the winter season [*Codrescu et al.*, 1997; *Field and Rishbeth*, 1997; *Lu et al.*, 2001].

5. Thermospheric Meridional Winds

5.1. Quiet Time Meridional Wind

[17] The results of meridional winds calculated by the FLIP model based on 5 quiet day mean values of h_mF_2 for the four storms studied here are plotted for the three stations in Figure 5, wherein they are compared with the meridional winds as per the HWM [*Hedin et al.*, 1991]. There are some agreements between the two results in a gross way, but also some significant differences that are note worthy.

[18] Agreements are noted regarding the following features: (1) The diurnal amplitudes obtained from the two methods are nearly comparable at all the three stations. (2) The amplitude of the wind increases toward higher latitudes in both results. Such a tendency is present in all the seasons/epochs studied here. (3) In May and June months the winds are generally poleward over CP, whereas in October they tend to be equatorward during the night.

[19] The most notable differences between the FLIP model/h_mF_2 results and the HWM description are the following: (1) During the equinoctial month of October (during both 1986 and 1989) the HWM yields equatorward winds generally in the night and morning hours, whereas the FLIP model also produces such winds at these hours, but the poleward reversal of the wind occurs much earlier than in HWM (clearly seen over KGI). Additionally, over CP during October 1989 the FLIP model calculates weaker equatorward wind than during October 1986, the HWM tending to suggest an opposite trend; (2) Largest amplitudes of the wind, as obtained from the FLIP model and observational data, occur generally during postmidnight hours over KGI and CON, whereas the HWM has maximum amplitude shifted somewhat to later hours, (by 3–4 hours). A similar phase shift is apparent over CP also (not being defined in October).

[20] Based on the excellent agreement between the h_mF_2 winds and optical winds found by *Dyson et al.* [1997] the disagreement seen in Figure 5 is likely due to the inadequacy of the HWM model. Our previous study based on simultaneous f_oF_2 and h_mF_2 over CP and FZ that utilized the Sheffield University Plasmasphere– Ionosphere Model (SUPIM) also pointed to the aspect of inadequacy of the HWM model for precise representation of winds over Brazilian sector [*Souza et al.*, 2000]. An interesting point is that the amplitude of the wind variation decreases with increase in solar flux, as clearly noticable in the wind patterns for October 1986 and 1989. This behavior is well explained by the slowing down of the winds by the increased ion drag at solar maximum.

5.2. Disturbance Meridional Winds

5.2.1. Equinoctial Pattern of the Meridional Wind

[21] Figure 6a shows equivalent meridional winds during the 5 days that covered the disturbance interval of 13–17 October 1986 (thick lines). The thin lines are the "quiet time" meridional winds from Figure 5. There are significant departures in the amplitude of the disturbance wind from the reference curve at all the three stations. There is a time delay in some of these features, (which are identified by vertical

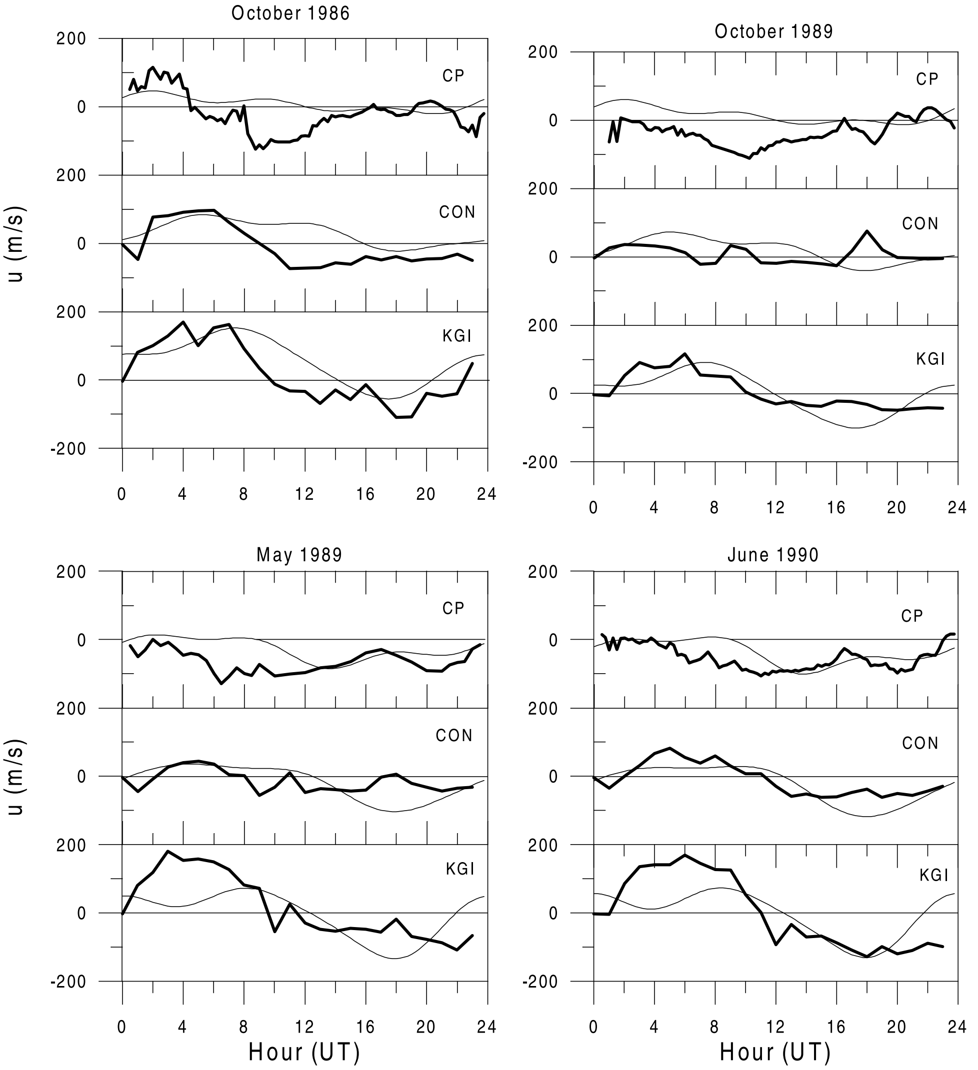

Figure 5. Meridional winds calculated using the FLIP model using h_mF_2 data (thick lines) representing the mean of five quiet days of the month in which the magnetic storm disturbance intervals were analyzed. These four quiet day values representative of the four epochs studied here are compared with their HWM descriptions (thin lines). Positive wind is equatorward.

arrows), that suggests propagation of disturbance fronts from KGI to lower latitude. We shall come back to this point later.

[22] The quarter hourly data rate for CP permits identification of shorter period structures in the disturbance wind pattern than is possible with the hourly data for CON and KGI. The amplitudes of the disturbance wind are largest over CP at the times identified by the numbers "1," "2," "3"–"8" in Figure 6a. The h_mF_2 winds calculated over CP have been corrected for the equatorial quiet time electric field, using the method adopted by *De Medeiros et al.* [1997]. There is likely to be a contribution from a disturbance component of the electric field in some of these features. Such cases can usually be distinguished from those that are unaffected by such electric fields, and their impact on the main findings from this study is very small. For example, the large equatorward wind surges identified as numbers "5" and "7" in Figure 6a occurred at a time when there was no significant auroral activity indicated by the AE index that could cause a PP electric field. However, the possibility of a DD electric field modifying the h_mF_2 cannot be ruled out. The DD electric field, which is expected to have a predominantly westward polarity at these times [e.g., *Blanc and Richmond*, 1980; *Scherliess and Fejer*, 1997], should act to reduce the h_mF_2 values leading to an underestimate of the calculated equatorward wind.

[23] The following point may be noted further: There is a tendency for the disturbance wind to be mainly poleward in the afternoon hours over CP (see the intervals marked 2, 4, 6, and 8 in Figure 6a), which is not observed over CON and KGI. At all these stations the amplitude of the disturbance winds tend to be larger during the night than during the day, which seems to agree with the model results [*Fuller-Rowell et al.*, 1994].

[24] The results for the disturbance interval of 20–24 October 1989 are presented in Figure 6b. As in October 1986, there is a tendency for the disturbance winds to be

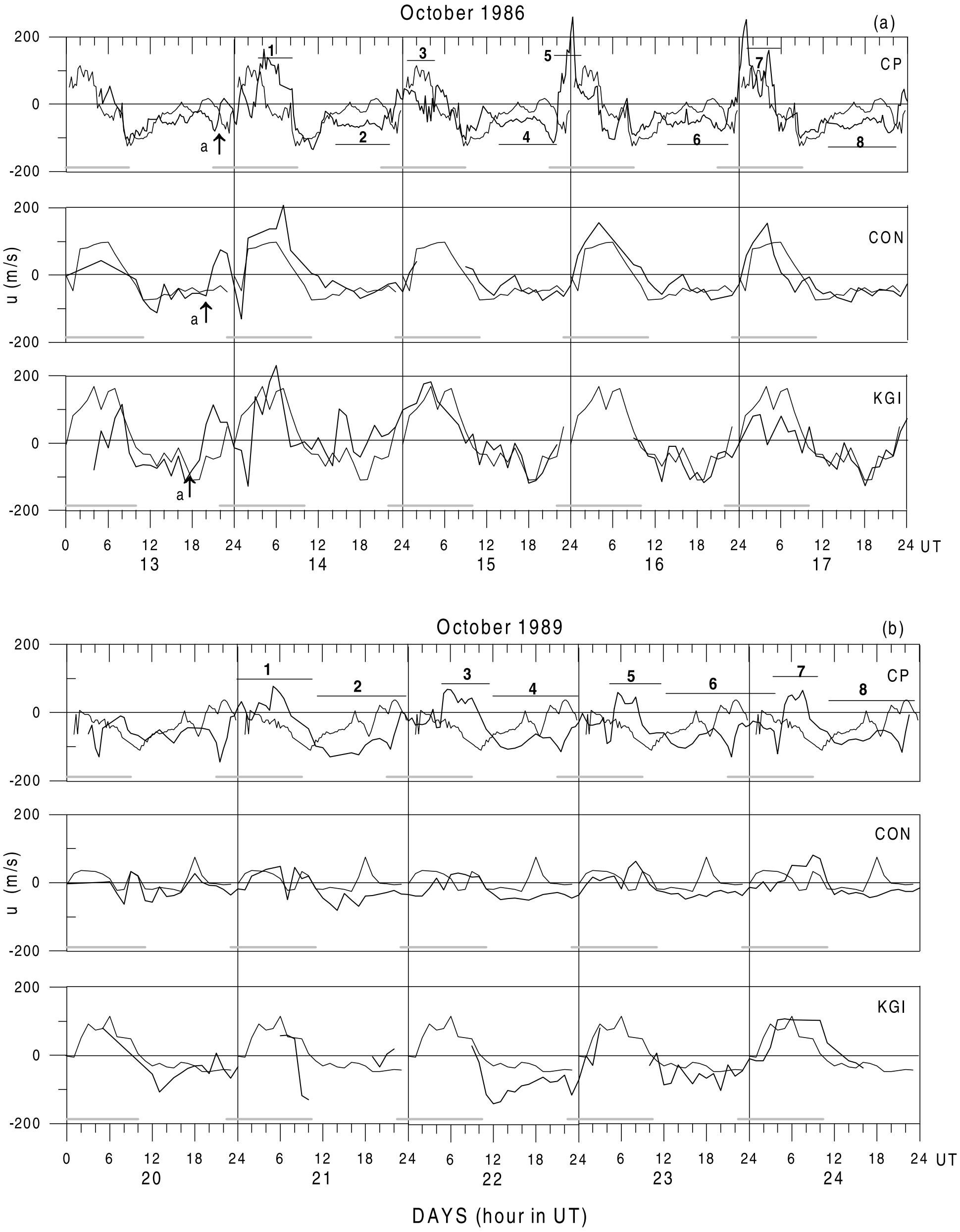

Figure 6. (a) Meridional winds calculated using the FLIP model and observational data (thick lines) are plotted for the three stations CP, CON, and KGI during the disturbance interval of Figure 1, that is, 13–17 October 1986. These values are compared with their corresponding quiet day values (of Figure 5) shown as thin lines. Horizontal line numbered 1, 2, 3, etc., indicate intervals of positive and negative disturbance winds. Vertical arrows identified by labels indicate an equatorward-propagating event. (b) Similar results as in (a), but for the disturbance interval 20–24 October 1989. Positive wind is equatorward.

equatorward in the morning hours and poleward for most of the afternoon to evening hours over CP. The amplitude of the wind variations for high solar flux values (October 1989) is generally smaller than for low solar flux values (October 1986). On the other hand the disturbance component of the wind (taken as the difference from the quiet day reference curve) is clearly larger during October 1989 than during October 1986. This is a new result that has not been seen before. The intervals of equatorward and poleward disturbance winds that are marked as "1," "2," "3"–"8" in Figure 6b are similar to those identified in Figure 6a.

5.2.2. Winter Pattern of the Meridional Wind

[25] Figures 7a and 7b presents the calculated meridional winds for the winter months of May 1989 and June 1990. Except for some short-lived equatorward excursions during disturbed conditions, the meridional winds during 23–27 May 1989 are nearly always poleward under both quiet and disturbed conditions over CP, The equatorward increase of disturbance wind occurs during early morning hours over

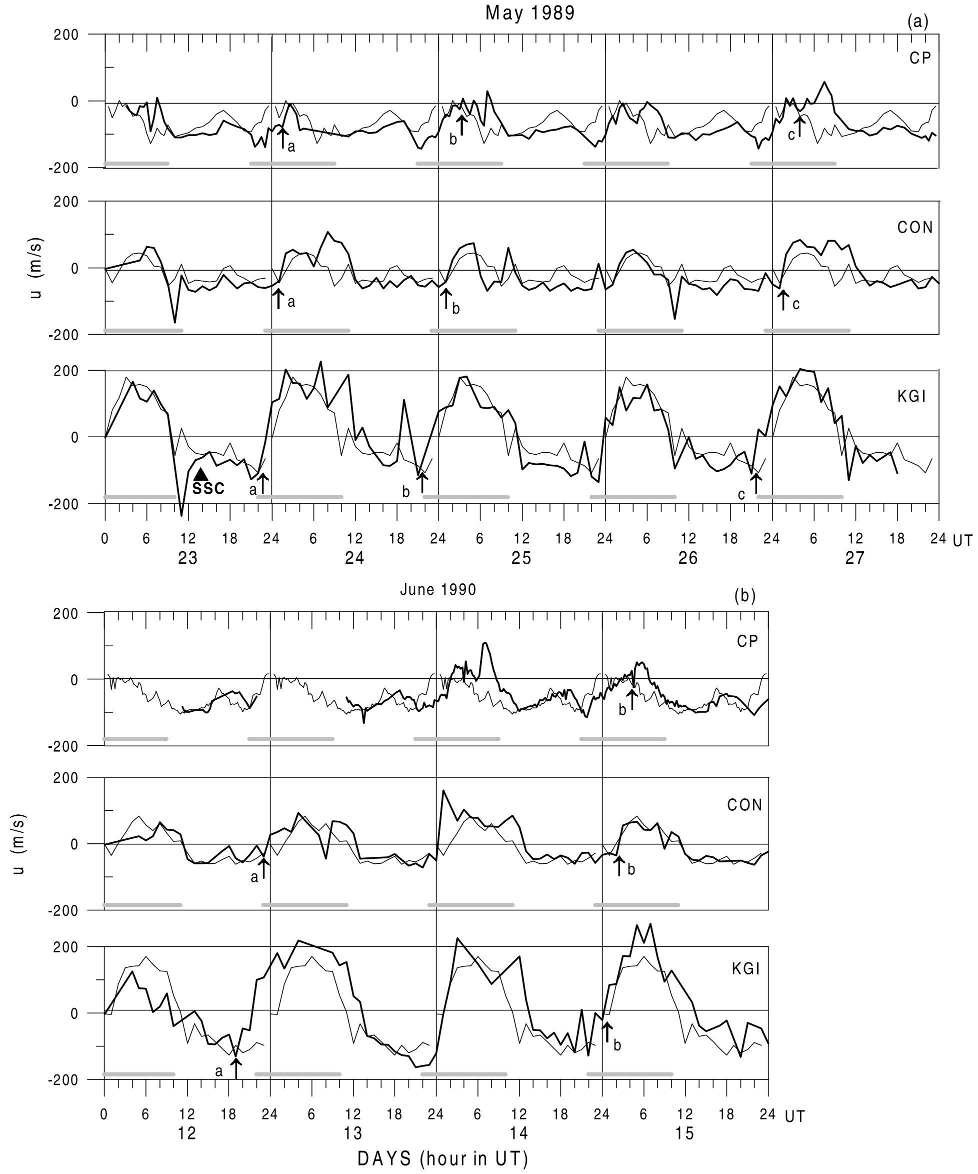

Figure 7. (a) Similar results as in Figures 6a and 6b, but for the disturbance interval 23–27 May 1989. (b) Similar results as in Figures 6a and 6b and in (a), but for the disturbance interval 12–15 June 1990. Positive wind is equatorward.

CP, as was the case in October 1986 and 1989. At all the stations the daytime disturbance wind are generally weak and blow mostly poleward. This is to be expected as the winds blow from the summer to the winter hemisphere. Rather strong equatorward wind surges are present during morning hours of the 24th over KGI and CON that do not extend to CP, whereas on the 27th such winds are present over CON and CP but not over KGI. The fact that both the cases were preceded by enhanced auroral activity as shown in Figure 3 suggests the existence of equatorward propagating disturbance cells of limited spatial extension and associated zonal (probably westward) velocity.

[26] The general wind characteristics for June 1990 are nearly the same as for May 1989. However, it may be noted that the day-to-night oscillation amplitude of the wind in general tends to be larger in this case than during May 1989.

5.2.3. Equatorward Propagating Disturbances

[27] A few cases of equatorward propagating ionospheric/thermospheric disturbance surges were noted during these intervals. Some examples are discussed below. In the results for October 1986 presented in Figure 1 we notice a minor auroral activity enhancements just before the storm onset (SSC). This was not immediately followed by any visible disturbance over KGI. However, the more intense AE, increase that marked the storm onset at ~1630 UT, was promptly followed by enhanced h_mF_2 over KGI (starting at ~1900 UT) which progressed toward lower latitudes. The enhanced h_mF_2 subsequently appeared over CON by ~2000 UT and then over CP by ~2115 UT. The corresponding increase of equatorward wind having features similar to

those of h_mF_2 can be clearly identified in Figure 6a (see vertical arrows identified by the label "a"). Equatorward surges such as this have been shown as immediate thermospheric response to storm energy input in the model results presented by *Fuller-Rowell et al.* [1994]. Some other examples can be identified for May 1989 and June 1990 disturbance intervals, as shown in Figures 7a and 7b. In general the smaller disturbance amplitudes over CP are consistent with a decrease in intensity of the propagating disturbance with decrease in latitude. In some cases they seem to have got attenuated somewhere between CON and CP, or they seem to be restricted to cells of limited longitudinal extension and significant zonal velocity component, as noted in item 2 of section 5.2.2 above. The propagating disturbance of the October 1986 has evolved into TID type gravity wave disturbances as observed over CP. Considering the latitudinal separation of these stations we can determine the meridional component of the velocity of this propagating disturbance to be of the order of 300–400 m s^{-1}, which is consistent with the results of *Fuller-Rowell et al.* [1994]. The meridional velocities in the other cases as considered between KGI and CON seem to be somewhat smaller.

6. Discussion

[28] In this paper we have focused on ionospheric and thermospheric response features during magnetic disturbances over four locations that covered a wide latitude range, in South America. The magnetic storm disturbances varied in intensity, onset local times, temporal evolution and total durations, for the four case studies presented here. Because of such wide scale variabilities of the events, a detailed evaluation of their effects is a very complex task. Nevertheless we have some success in identifying some important features of the disturbance responses for equatorial, low and middle latitude ionospheres. The discussion to follow will highlight the results in terms of (1) the disturbance component of equatorial–low latitude electric field and magnetic meridional wind and consequent EIA response features and (2) features of midlatitude disturbance meridional winds, thermospheric composition changes, and resulting ionospheric response features.

[29] An important ionospheric response feature observed over equatorial and low latitudes concerns that produced by disturbance electric fields, both the PP type electric field and delayed (that is, DD) electric field [e.g., *Abdu et al.*, 1997]. Their effects are clearly identifiable in terms of the increase (decrease) in h_mF_2 values produced by an eastward (westward) disturbance electric field. Rather clear cases of the PP electric field effect were identified as h_mF_2 increases over FZ (and to a lesser extent over CP) that nearly coincide with auroral activity increases in the early phases of these storms (e.g., the h_mF_2 increases around 1200, 1900, and 2100 UT on 13 October 1986 in Figure 1, 1200 and 1900 UT on 20 October 1989 in Figure 2, and 1400–2100 UT on 12 June 1990 in Figure 4).

[30] It appears that the intensity of the disturbance penetration electric field is not proportional to the intensity of the causative auroral disturbances. For example, the auroral activity indices, the D_{st} and Kp values were clearly weaker during the October 1986 event than during the October 1989 event but the intensity of the disturbance PP electric field effect on h_mF_2 over FZ, does not appear to be correspondingly more intense in 1989 than in 1986. However, it is well known that D_{st} and Kp are not always a precise indicators of magnetic storm severity.

[31] Nevertheless, this result would suggest that the mechanism of magnetospheric electric field penetration to equatorial latitude works more efficiently during solar minimum years that during the higher solar activity years. On the other hand the DD electric field has larger and more durable intensity during the more intense storm of October 1989. See, for example, the h_mF_2 increases in the morning hours (~0200–0900 UT) over FZ (Figure 2) on 21 and 22 October 1989 and their decreases during evening and night hours that preceded them. These are clearly more intense than the corresponding effects during the less intense storm of October 1986. This result would thus suggest that the DD electric field intensity could depend upon the strength of the causative auroral activity, which is understandable as the larger storm energy input at high latitude could cause larger thermospheric disturbance circulation [*Fuller-Rowell et al.*, 1994; *Codrescu et al.*, 1997]. We note that a larger disturbance thermospheric circulation could produce a more intense DD electric field.

[32] Model results of *Fuller-Rowell et al.* [1994] show that equatorward propagating thermospheric disturbance winds build up, under coriolis force, zonal velocity that eventually limits the meridional circulation over low latitude. Such situation could result in a larger meridional wind over CP where the magnetic declination is large and westward (21°W). It was pointed out before that there are enhancements in disturbance meridional wind (that are more often equatorward) at late night and morning hours and their amplitudes are larger over CP than over CON and KGI as seen in Figures 6a, 6b, 7a and 7b. This seems to provide evidence that a disturbance thermospheric wind with large westward amplitude over low latitudes could indeed be contributing to a larger magnetic meridional wind over CP than at CON and KGI. For the same reason the magnetic meridional wind and the corresponding ionospheric response over CP could be somewhat different from such features over CP's conjugate point in the northern hemisphere although we do not have data to verify this point.

[33] Significant modification of the EIA was observed during the storms of October 1986 and 1989 and June 1990. The degree of such modification can be judged from the f_oF_2 deviations (mainly the daytime and early night values) over FZ and CP with respect to their respective quiet time values. The larger such deviations are, the more intense the modification suffered by the EIA. Cases of what appears to be EIA enhancements and inhibitions (subject to the qualifications mentioned earlier in section 4) are interposed during the October 1986 storm as indicated by the f_oF_2 variations over CP. Such interposed occurrences can be attributed to the competing effects of disturbance electric fields and disturbance meridional wind occurring with their relative contributions varying with time. This can be verified by examining the results of Figures 1 and 6 as follows: The effect of a PP eastward electric field is evident from the h_mF_2 increase over FZ around 1800 UT of 13 October (Figure 1). This produced a straightforward EIA enhancement as seen in the decrease (increase) of f_oF_2 over FZ

(CP). On the other hand there is a significant westward DD electric field starting around 1700 UT/1400 LT on 15 October (h_mF_2 decrease) which eventually resulted in the nearly total inhibition of the usual sunset (prereversal) increase of h_mF_2 over FZ (around 2100 UT/1800 LT). This is accompanied by an inhibition of the EIA as evident in the decrease (increase) of f_oF_2 over CP (FZ). The decrease of f_oF_2 over CP in fact shows up as large and abrupt around 2100 UT/1800 LT, around the same time when a surge in equatorward wind started over CP (see Figure 6a, at ~2100 UT of 15 October). This complex response feature shows that an EIA inhibition (or what appears to be so) can be produced, depending upon the local time of the effect, by a superimposed forcing by a DD electric field as well as by an equatorward disturbance wind, which in this case seems to have a contribution also from a disturbance westward wind as explained before.

[34] An interesting contrast in the EIA responses between equinoctial and winter months to storms of moderate intensity can be noticed by comparing the f_oF_2 features over CP and FZ during October 1989 and June 1990 storms. During October 1989 starting from the evening of the first day of the storm (the 20th) the disturbance h_mF_2 variation clearly indicates the DD electric field alternating between eastward and westward polarities until the 22nd followed thereafter by dominantly westward polarity. The corresponding f_oF_2 variation over FZ, showing dominantly positive deviation, would suggest a generally inhibited EIA intensity. However, the f_oF_2 variation over CP (showing more often positive than negative deviation) would suggest mild enhancement of the EIA as a dominant feature. Such a situation could arise from the disturbance meridional wind pattern that is dominantly poleward in Figure 6b. In contrast, in June 1990 (Figure 4) the reduced (enhanced) f_oF_2 over FZ (CP) suggests a likely case of an intense EIA enhancement that continued till 15 June and past the storm recovery. Unlike in October 1989 (Figure 6) the disturbance component of meridional wind over CP for this case (Figure 7b) looks too weak to affect significantly the EIA densities. Under this situation we attribute the observed strong f_oF_2 enhancement over CP to a disturbance equatorward meridional wind over the conjugate point of CP (as per the item 3 of section 2), which is in northern summer hemisphere. As explained by *Souza et al.* [2000] a latitudinal variation (in the right sense) in the intensity of a transequatorial wind can produce convergence of ionization in the concerned flux tube, the resulting f_oF_2 increase being identifiable at the conjugate point to which the transequatorial wind is directed. Thus it looks that the intensity of EIA modification due to magnetic disturbances can vary depending upon what looks to be a seasonally dependent disturbance meridional wind.

[35] A notable feature of the quiet time meridional wind as pointed before, is that the diurnal amplitude decreases with increasing solar activity as can be seen by comparing the wind patterns over CON and KGI for the October months of 1986 and 1989 in Figure 5. Such a trend is less clear over CP. The relatively smaller difference in F10.7 for the data of June 1990 and May 1989 does not permit a clear evaluation of such trend for the solstice season. *Richards* [2001] reported a global decrease in wind speed at noon and midnight as solar activity increased between 1976 and 1980. The inverse dependence of meridional wind on solar flux may be attributed to the greater ion drag effect on the wind arising from the larger *F* region plasma densities that characterize the higher solar flux conditions as suggested [e.g., *Fuller-Rowell et al.*, 1994].

[36] Although the disturbance winds for CP might contain a disturbance electric field component the general characteristics of the disturbance wind inferred over this station are likely to be correct. The effect of the electric field component, which is most likely to arise from DD electric field, is to slightly underestimate or overestimate the derived meridional winds over this station. The winds deduced for CON and KGI should be relatively free of such contamination The disturbance component of the meridional wind over these stations generally shows, a positive dependence on the intensity of the magnetic disturbance as can be verified from the results of Figures 6a and 6b (compared to the magnetic indices of Figures 1 and 2, respectively). This seems to bear added significance since the weaker disturbance winds corresponding to low solar flux condition were subject to reduced ion drag force, while the larger amplitude wind of higher solar flux conditions met with larger ion drag effect. This positive dependence of disturbance wind on magnetic activity is similar to such dependence of the DD electric field pointed out before, and it is consistent with the larger storm energy input at high latitude producing larger thermospheric disturbance circulation [*Fuller-Rowell et al.*, 1994; *Codrescu et al.*, 1997]. We may note that larger intensity of disturbance thermospheric circulation could signify correspondingly more intense DD electric field. Thus the present results seem to offer evidence (at least qualitatively) linking the intensity of thermospheric circulation effects and associated DD electric field to their causative storm energy input at high latitude.

[37] The ionospheric response features over midlatitudes are mainly controlled by disturbance meridional winds and thermospheric composition bulge of altered ratio of N_2/O, both being driven by the processes of upwelling, that takes place during the energy deposition phase of a storm, followed by downwelling that occurs during the storm recovery phase, as discussed by *Fuller-Rowell et al.* [1994]. The modeling result of these authors showed that the intensity of the ionospheric/thermosphere response is strongest in the night sector (of reduced ion drag) and in the longitude sector of the magnetic pole, such that a favorable combination of these factors could cause big surges in meridional wind extending to lower latitudes and to the opposite hemisphere, whereby poleward disturbance wind in wide areas are produced within a few hours of the storm duration. Also, under the competing/complementary forces of the ambient wind and the disturbance driven circulation the boundary of the composition bulge and the associated negative/positive storm phases get displaced equatorward (poleward) during night (day). Thus, a detailed synthesis of the response features is a highly complex task in absence of detailed information on the energy input functions for these storms. Nevertheless, an evaluation is possible as to whether or not the outstanding response features identified here are consistent with what is expected based on well-known self-consistent models and other relevant observational results. The larger (smaller) nighttime (daytime) ambient as well as

disturbed winds observed over CON and KGI are in good agreement with model results [*Fuller-Rowell et al.*, 1994].

[38] The negative phases in f_oF_2 over KGI that dominates the entire interval of both October 1986 and 1989 disturbance intervals are obviously the result of composition bulges with higher ratio of $[N_2]/[O]$, since the fluctuating disturbance wind (with both positive and negative deviations) for these cases do not appear capable of explaining such a feature by itself. The intensity of the bulge is larger during the driving phase of the storm (clearly seen during the October 1989 storm) decreasing thereafter with the storm recovery. We note that the larger intensity of the negative phase during the October 1989 storm is consistent with the larger energy input for this case, as was verified for the DD electric filed and disturbance wind as well.

[39] The storm response features over midlatitude during winter solstitial months present a striking contrast with those of equinoctial month. During the weak disturbance of May 1989 (Figure 3) the f_oF_2 over CON presents a mild negative phase which appears to be consistent with the predominantly poleward disturbance wind for this case (Figure 7a). On the other hand, for the much more intense disturbance of June 1990 there is rather intense positive phase over CON with weaker f_oF_2 enhancement also over KGI. We attribute this result to the downwelling process described by *Fuller-Rowell et al.* [1994], as also possibly to ionization convergence in flux tube due to disturbance wind from opposite hemisphere as it seems to be operating for CP (which was pointed out before). Another interesting point concerns the seasonal dependence of the negative storm phase over KGI, which is rather pronounced during equinox but very weak or turns positive during winter months. Such weaker negative/positive phase in f_oF_2 during winter months is consistent with and complements previous studies [e.g., *Field and Rishbeth*, 1997]. A careful examination of the h_mF_2 variations of Figures 3 and 4 and the meridional wind patterns (mostly equatorward wind) of Figures 7a and 7b over KGI would suggest that the weak negative or mostly positive disturbance f_oF_2 variations during these two storms could be consistent with the effect by disturbance meridional wind rather than by composition changes. The disturbance in composition (in the form of the ratio $[N_2]/[O]$ therefore does not seem to control the electron density in the winter hemisphere as model results show.

7. Conclusions

[40] Analysis of simultaneous ionospheric data sets from a meridional chain of ionosondes in South American sector, extending from Antarctic to equatorial locations, have revealed some important features of the ionospheric and thermospheric responses during a magnetic storms of moderate to weak intensity. Although a good number of cases of the ionospheric responses formed the basis of this overall investigation, and many details of the response features vary from one event to the other, we have presented here results of only four cases studies that are representative of the most outstanding storm response features. Our results show that the response of the equatorial and low latitude ionosphere to magnetic storms are dominantly controlled by disturbance electric fields with superimposed effects from disturbance winds. They also show, in broad agreement with the existing understanding, that at midlatitudes the dominant effects are due to disturbance winds with superimposed effects from modified thermospheric composition. The main specific conclusions of this study may be summarized as follows:

1. Over equatorial region daytime positive changes in h_mF_2 are often observed due to PP eastward electric field associated with auroral disturbance developments. Rapid substorm recovery occurring during evening hours also produces an eastward PP electric field that causes an additional increase of the PRE and hence increases of h_mF_2. In both the cases the EIA undergoes enhancement. There is suggestion that the PP electric field penetration to equatorial latitude could be more efficient during low solar flux, than high solar flux years. This point needs to be established from further investigations, however.
2. DD electric field that has westward polarity during evening hours inhibits the PRE resulting in reduced h_mF_2. Its polarity turns eastward after midnight and again to westward near 0700 LT in agreement with well-known model results. The overall effect of the DD electric field seems to be to inhibit EIA development, subject to the influence from disturbance meridional wind, which could produce even apparent EIA enhancement (that is, f_oF_2 increase over CP).
3. Results during June solstice appears to suggest that the low latitude f_oF_2 in the winter hemisphere could become enhanced by the effect of disturbance meridional wind of the conjugate hemisphere, an effect that is superimposed on that of the disturbance zonal electric field. This point needs to be confirmed from more case studies, however.
4. The DD electric field does not seem to be a dominant storm effect in the winter hemisphere. This point deserves further investigation.
5. The HWM winds and the winds calculated from h_mF_2 only agree qualitatively. The discrepancies noted here are similar to those found by *Dyson et al.* [1997] who found that the h_mF_2 winds agreed well with the optical winds.
6. In a gross way the quiet time winds are equatorward during nighttime, whereas daytime winds are poleward, at all locations and epochs. The diurnal amplitude of the wind variation increases with increasing latitude; at low latitude the poleward wind is dominant whereas at higher latitudes the dominant wind is equatorward. The amplitude of the quiet time meridional wind is larger during years of low solar flux than that during high solar flux years (a feature clearly verifiable for equinoctial months). Such inverse dependence on solar activity may be attributed to ion drag effect.
7. Disturbance magnetic meridional equatorward wind over CP often has larger amplitude as compared to CON and KGI, which is believed to be arising in part from a disturbance westward wind and the large westward magnetic declination of this location. This factor could introduce significant hemispheric asymmetry in the ionospheric response to magnetic disturbances. This point merits confirmation from further observational data.
8. The intensity of the disturbance wind and that of DD electric field show increase with increase in high latitude energy input represented by the intensities of auroral and magnetic activities. Such a positive dependence on energy

input is present also for the negative storm effect of equinoctial month over KGI.

9. Fronts of disturbance meridional wind propagating equatorward follow promptly after the auroral activity onset during some events.

10. Negative storm effect dominates over the high midlatitude location KGI during equinoctial months but not during winter months.

[41] Analysis is continuing aiming at further elucidation of the different aspects of stormtime ionosphere–thermosphere response features over the South American longitude sector.

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