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Zonal/meridional wind and disturbance dynamo electric field control of the low-latitude ionosphere based on the SUNDIAL/ATLAS 1 Campaign

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Abstract. We present an evaluation of global-scale equatorial and low latitude ionospheric disturbances in response to the weak-to-moderate disturbed conditions that marked the SUNDIAL/ATLAS1 twelve-day campaign of March 22 to April 2, 1992. Ionosonde data from South American and Indian-Asian longitudes are analyzed to examine first the climatological (the average) pattern of the critical *F* region parameters (the layer peak density and height) in comparison with the empirical International Reference Ionospheric model, and then to characterize the day-to-day variabilities aiming at identifying potential causal contributions from either disturbance zonal and meridional winds or magnetospheric and disturbance dynamo electric fields. Included in this analysis are data from South American midlatitude locations which are used to determine meridional winds using an adaptation of the servo analysis technique in the Field Line Integrated Plasma (FLIP) model. We have made an assessment of the causal mechanism of the day-to-day variabilities as arising from latitude dependent disturbance meridional winds, and from electric fields produced by disturbance zonal winds and disturbance dynamo. While the contribution from disturbance meridional winds decreases from middle to equatorial latitudes, that of the electric fields maximizes around the equator. In particular, first-time evidence based on ionosonde data is provided for a disturbance dynamo electric field in the equatorial ionosphere. It is found that there are two time intervals of maximum ionospheric variability resulting from the weak to moderate magnetospheric disturbance conditions that prevailed during the campaign: one near the evening/postsunset hours and the other in the postmidnight-sunrise hours over low latitudes. At midlatitudes a broad maximum of the response occurs from premidnight to morning hours. We provide a comparison of results for the South American and Indian-Asian longitudes and a discussion of the competing roles of the disturbance zonal and meridional winds, and magnetospheric and disturbance dynamo electric fields as a function of latitude.

1. Introduction

Ionospheric climatology reflects the response of the ionospheric-thermospheric system to a quasi-steady input of solar, magnetospheric, and lower atmospheric energy. Day-to-day variabilities (weather) are produced by fluctuations in these inputs, resulting in perturbation electric fields and thermospheric winds and, ultimately, in fluctuating *E* and *F* layer heights and densities. Equatorial to low-latitude ionospheric responses to magnetospheric disturbances have received some attention in recent years for moderate to intense storm events, and a tentative understanding of such cases in terms of a cause-effect relationship seems to be emerging [e.g., *Forbes*, 1989; *Fesen et al.*, 1989; *Abdu et al.*, 1991, 1993, 1995; *Batista et al.*, 1991b; *Greenspan et al.*, 1991; *Huang and Cheng*, 1993; *Fuller-Rowell et al.*, 1994; *Fejer et al.*, 1995]. In the case of the more frequent and weaker disturbances of magnetospheric origin, the low-latitude ionospheric response remains almost undefinable. This is also true of the widely observed variabilities in the "quiet" time low-latitude ionosphere. An example is the day-to-day variability in the intensity of the evening prereversal electric field (*F* layer vertical drift) enhancement that has direct implication on the equatorial spread-*F* development conditions in the postsunset hours. In fact, a major focus of current research is to achieve a better understanding of the causes of the observed day-to-day and seasonal variabilities in the equatorial spread-*F* phenomenon. Therefore it is important to investigate and identify the salient features of the variabilities of the low latitude ionosphere under quiet and weakly disturbed conditions if we are to identify them either as manifestations of the coupling process within the system or the response of the system to external forcing. The SUNDIAL-ATLAS 1 twelve-day campaign (March 22 to April 2, 1992) has provided an opportunity to examine some prominent

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Table 1. Stations From Which Data Were Obtained for This Study

STATION	COORDINATES		
	Latitude, deg N	Longitude, deg E	Dip Angle, deg
Fortaleza	-4	322	-9
Cachoeira Paulista	-22.6	315	-28
Buenos Aires	-34.6	301.7	-36
Ushuaia	-54.8	281.7	-50.2
Waltair	15.0	80.0	14.0
Chung Li	-24.9	121.5	35.2

global features of the day-to-day variability of the low-latitude ionosphere, including causalities due to the competing roles of the electric field/zonal wind versus that of meridional wind as a function of latitude. The variabilities are presented and discussed with respect to the climatological (average) behavior of the ionosphere. Detailed discussion of the global climatology that prevailed during the campaign and comparisons with the specifications of the International Reference Ionosphere (IRI), and the predictions of first principle codes (Thermosphere-Ionosphere General Circulation Model (TIGCM) and the Fieldline Integrated Plasma Model (FLIP) are carried out by *Szuszczewicz et al.* [this issue].

The results presented in this paper are based on data from six ionosonde and two magnetometer stations distributed in the Indian-Asian and American longitude sectors as listed in Table 1. The critical frequency of the layer, f_0F_2, (that represents the peak density of the layer, NmF_2), the height of the base and the peak of the layer, $h'F$ and hpF_2/hmF_2, respectively, are analyzed, and the results are compared with the predictions from the IRI [e.g., *Bilitza et al.*, 1992] and the FLIP [*Richards and Torr*, 1985; *Torr et al.*, 1990]. The FLIP model has been run for the midlatitude stations Buenos Aires and Ushuaia to obtain the meridional winds over these stations to evaluate (by extrapolation) the possible effects of such winds on aspects of the climatology and the day-to-day variabilities of the ionosphere in the middle to equatorial latitude regions in the American sector. This approach is used because no model presently exists that could provide winds (from ionosonde data) for low-latitude regions where the electric field effects dominate the ionospheric processes. The results for the American longitude sector are compared with those for the Indian-Asian longitudes.

The solar and geomagnetic activity conditions of the SUNDIAL-ATLAS 1 campaign are detailed in the paper by *Szuszczewicz et al.* [this issue]. Briefly, the period covered the recovery phase of a weak-to-moderate storm that had onset at about 2300 UT on March 21, as indicated by the *Dst* values of Figure 1, which was predominantly more positive than -50 nT with an initial decrease to values reaching -60 nT. The geomagnetic activity index *Kp* also suggested weak to moderately disturbed conditions with values remaining generally less than 5 except for a few isolated periods. Using the local magnetograms in Brazil we conclude that the most disturbed intervals were the nights of March 21-22, 23-24, and 29-30. This characterization was generally valid for the Asian sector as well.

2. F Region Climatology

The climatological behavior of the *F* region, manifested by the average magnitudes of the critical parameters f_0F_2 and hpF_2 over the South American stations, Fortaleza, Cachoeira Paulista, Buenos Aires, and Ushuaia, is presented in Figure 2. We have used here the parameter hpF_2, instead of hmF_2, and it represents the height of the peak density for a parabolic approximation of the layer that is directly read from the ionograms [*Piggot and Rawer*, 1978]. A comparative study by *Batista et al.* [1991a] of the hpF_2 with the hmF_2 from the true height Polinomial Analysis (POLAN) code [*Titheridge*, 1985] has shown that for equinoctial night conditions the two values are practically the same, whereas during the day the hpF_2 coud be higher than hmF_2, the difference being generally less than, but seldom exeeding 10%. The f_0F_2 and hmF_2 values obtained from the FLIP runs are also included in Figure 2 for Buenos Aires and Ushuaia. With reference to Figure 2 we will discuss the day-to-day variabilities and extend the results to Indian-Asian longitudes for which the f_0F_2 and hpF_2 diurnal patterns are presented in Figure 3. Our comparison here covers all local times but is restricted to a few stations in the South American and Indian-Asian longitudes. We note that there is very good general agreement between the observed mean and

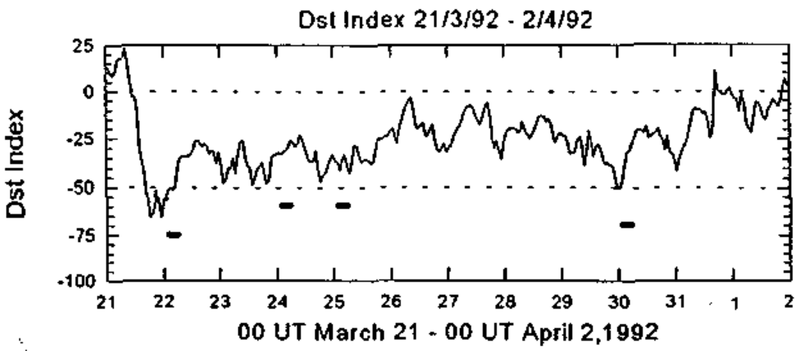

Figure 1. *Dst* values from March 22 to April 2, 1992. Solid rectangles represent the local time intervals of *F* layer height increases over Fortaleza due to the disturbance dynamo electric field on March 22, 24, 25, and 30.

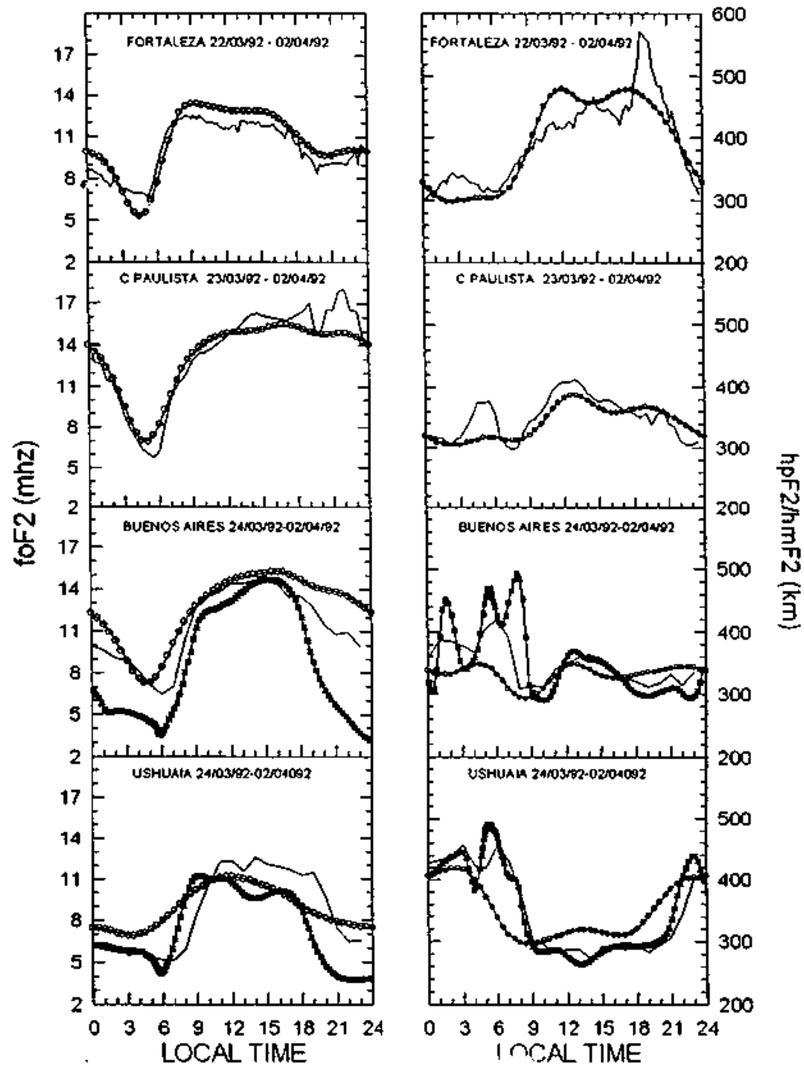

Figure 2. The average diurnal pattern of f_0F_2 and hpF_2 for Fortaleza, Cachoeira Paulista, Buenos Aires, and Ushuaia (solid lines) compared with their IRI specifications (circles). The f_0F_2 and hmF_2 from the FLIP runs (stars) are included for Buenos Aires and Ushuaia.

the predicted IRI values. However, some notable differences are as follows:

1. The evening F layer uplift (around 1800-1900LT, Figure 2, right panel) over Fortaleza produced by the prereversal enhancement electric field, and the corresponding postsunset resurgence of the equatorial ionization anomaly over Cachoeira Paulista (f_0F_2 values around 2100-2200LT, Figure 2, left panel) are not adequately represented by the IRI [see also *Abdu et al.*, 1996].

2. There is an indication that the postmidnight-morning hpF_2 increases over Buenos Aires and Ushuaia and the corresponding (small) decrease of f_0F_2 are not adequately represented by the IRI. We will show that such differences, however, are likely produced by equatorward meridional winds resulting from the disturbed conditions that characterized the SUNDIAL-ATLAS campaign interval.

3. The morning height increase over Fortaleza that appears as a departure from the IRI representation is, in fact, in response to the disturbed conditions, but as will be explained, it seems to be produced by a disturbance dynamo electric field.

4. Both the disturbance sources in points 2 and 3 seem to be responsible for the morning height rise over Cachoeira Paulista.

5. The FLIP model results for hmF_2 show very good agreement with the observations over Ushuaia and Buenos Aires (except for its structured feature in the morning hours over the latter site), whereas the f_0F_2 values present some desagreement marked by low model values for night conditions over Buenos Aires and for noon-to-midnight conditions over Ushuaia.

3. Day-to-Day Variabilities

In Figure 4 we present the hpF_2 values for all four stations for March 30, a day which started with a short duration (5-6 hours) *Dst* decrease to about -50 nT (see Figure 1). The following salient features may be noted. Over Fortaleza (1) there is a 60-km presunrise increase of the *F* layer height and (2) there is a large uplift of the layer around sunset produced by the well-known evening prereversal enhancement electric field, which on this night was interrupted at 1915 LT by

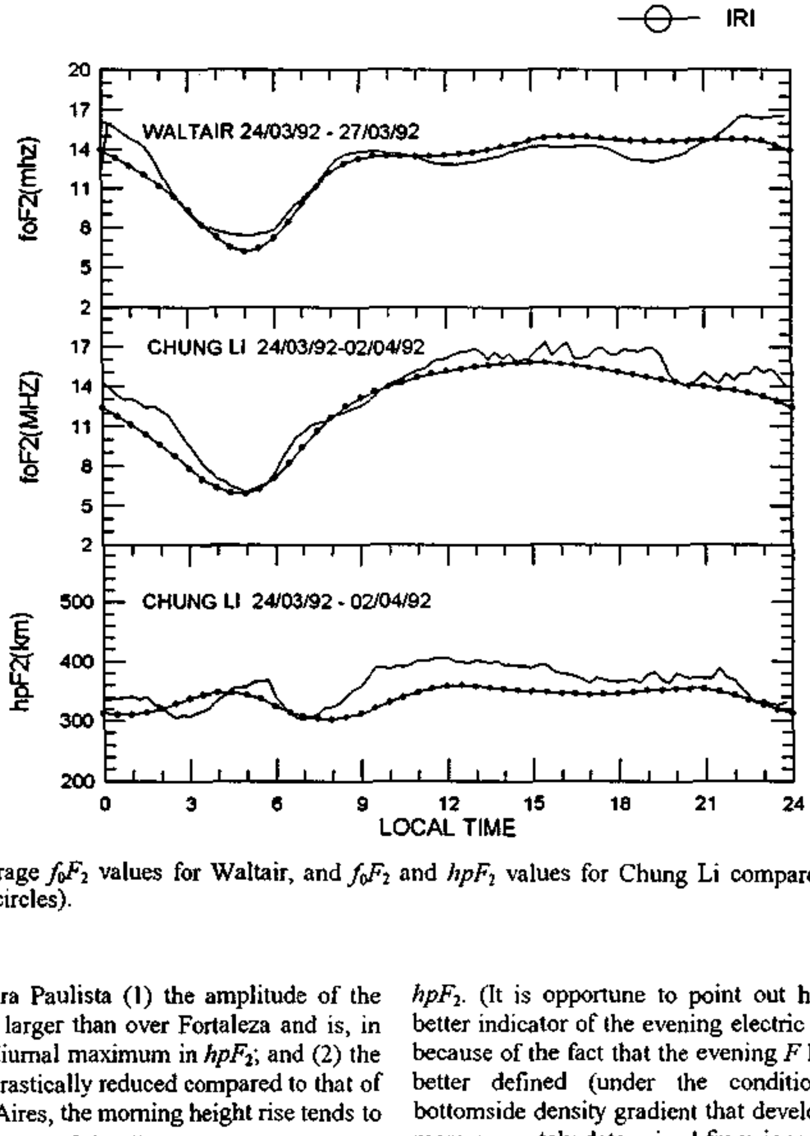

Figure 3. Average f_0F_2 values for Waltair, and f_0F_2 and hpF_2 values for Chung Li compared to their IRI specifications (circles).

spread *F*. Over Cachoeira Paulista (1) the amplitude of the presunrise height rise is larger than over Fortaleza and is, in fact, comparable to the diurnal maximum in hpF_2; and (2) the evening height uplift is drastically reduced compared to that of Fortaleza. Over Buenos Aires, the morning height rise tends to become the dominant feature of the diurnal pattern, and over Ushuaia the morning height rise is the most dominant feature of the diurnal pattern. In fact, the morning height rise over Ushuaia starts from near midnight and lasts to well after the sunrise. Thus there is clear evidence here of a postmidnight-morning height enhancement and of a latitudinal dependence in its amplitude and duration (i.e., its amplitude and duration decrease with decreasing latitude from midlatitude to the equator). By contrast, the evening/sunset enhancement decreases rather rapidly with increasing latitude from the equator.

Figure 5 presents superimposed daily plots, covering the campaign period, of the *F* layer height parameters, hpF_2 and $h'F$, for the same four south American stations as in Figure 4. All points mentioned above can be verified while presenting perspective of the day-to-day variability in the *F* layer characteristics and their latitudinal dependence. The variability in the *F* layer peak density parameter f_0F_2 is similar, being a consequence of the variability in the peak height. A separate figure on f_0F_2 is therefore not presented here. The sunset-associated prereversal electric field enhancements seen as the *F* layer uplift that dominates the diurnal pattern over Fortaleza (in Figure 5) seems to be better defined in *F* layer base height, $h'F$, rather than in peak height, hpF_2. (It is opportune to point out here that $d(h'F)/dt$ is a better indicator of the evening electric field than is $d(hpF_2)/dt$ because of the fact that the evening *F* layer lower boundary is better defined (under the condition of the steepening bottomside density gradient that develops at these times), and more accurately determined from ionograms, than is the peak height. Further, with the diffusion coefficient increasing exponentially with height, the layer peak height variation $d(hpF_2)/dt$ receives significantly more of a contribution from the diffusion factor than in the $d(h'F)/dt$). There is a large day-to-day variability in the reversal time of the electric field, that is, in the local time of the evening maximum of the $h'F$. This is an indication of the variability in the intensity of the *F* layer dynamo electric field . The weaker (stronger) the *F* layer dynamo is, the earlier (later) will be the reversal of the evening electric field. Since the *F* layer dynamo electric field intensity is dependent on the eastward thermospheric zonal wind [*Rishbeth*, 1981; *Heelis et al.*, 1974; *Farley et al.*, 1986; *Batista et al.*, 1986] the observed variability of the evening $h'F$ (and hpF_2) is an indicator of a corresponding day-to-day variability in the amplitude of the thermospheric zonal wind. We will come back to this point.

Over Cachoeira Paulista, the sunset height rise is rather small, but seems to be better defined in $h'F$ than in hpF_2. There is a significant day-to-day variability in both that could be produced by zonal as well as meridional wind components. As expected, the sunset associated layer rise is totally absent over Buenos Aires and Ushuaia. At these latitudes, prominent layer uplift occurs mainly during the near-midnight to

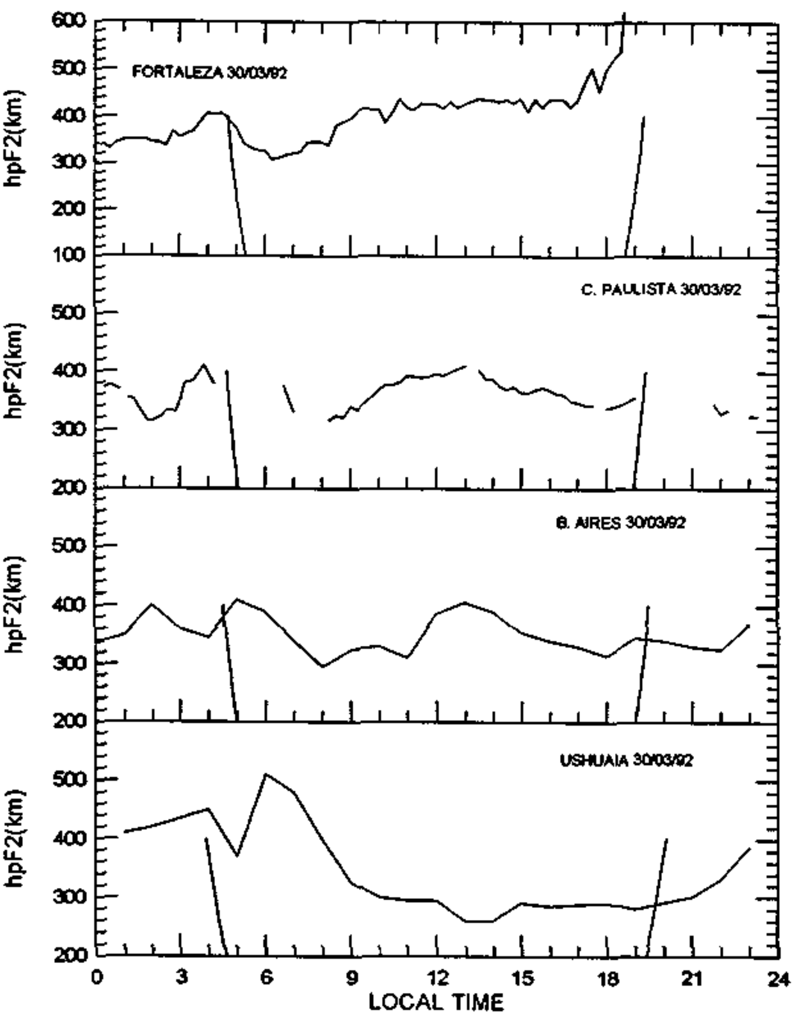

Figure 4. The hpF_2 diurnal pattern on March 30, 1992, for Fortaleza, Cachoeira Paulista, Buenos Aires, and Ushuaia. Solar terminator positions as a function of height are indicated by slant lines.

morning hours. We will show that these uplifts are produced by equatorward neutral winds.

The main point to note at this stage is that this *F* layer height rise and its variability decrease equatorward, a trend that can be clearly verified by comparing the plots for Ushuaia, Buenos Aires, Cachoeira Paulista, and Fortaleza (if we exclude from the latter two stations the curves specially identified with circles, stars, etc., for reasons to be explained below). We may note further from a comparison of the data between Cachoeira Paulista and Fortaleza that on the specially identified days the morning layer rise is significantly larger over the latter location than expected solely from response to an equatorward wind. In fact, the layer rise produced by a meridional wind (U) which is dip angle (I) dependent, as $U\cos(I)\sin(I)$, is expected to be a factor of 2.5 less over Fortaleza than over Cachoeira Paulista. However, the observed height rises over Fortaleza are significantly larger, which could possibly be caused by a disturbance dynamo electric field considering the varying degree of moderately disturbed intervals (Figure 1) that characterized these days.

Figure 6 shows the *h'F* variations on 4 days (March 24-27) over Waltair and the *h'F* and *hpF*2 for the entire campaign period over Chung Li, in the Indian-Asian longitude sector. Here, again, the dominating role of the electric field in the evening hours near the equator (Waltair) and that of meridional wind in the midnight-morning hours over low latitude (Chung Li) can be noted, in complete agreement with the results from the American longitude sector. The *h'F* increase during the presunrise hours over Waltair could be arising from meridional wind as well as possibly from disturbance dynamo electric field as mentioned in the case of Fortaleza.

4. Discussion

Our main focus in this paper has been on the day-to-day variabilities that dominated the postsunset and presunrise periods over the low-latitude ionosphere, and aspects of their coupling with midlatitudes. We will now examine the roles of the zonal and meridional winds and that of the disturbance dynamo electric field in these variabilities.

4.1. Role of the Zonal Wind

We have noted that the most outstanding feature of the *F* layer height characteristics over Fortaleza is the evening electric field enhancement manifested as a large uplift of the

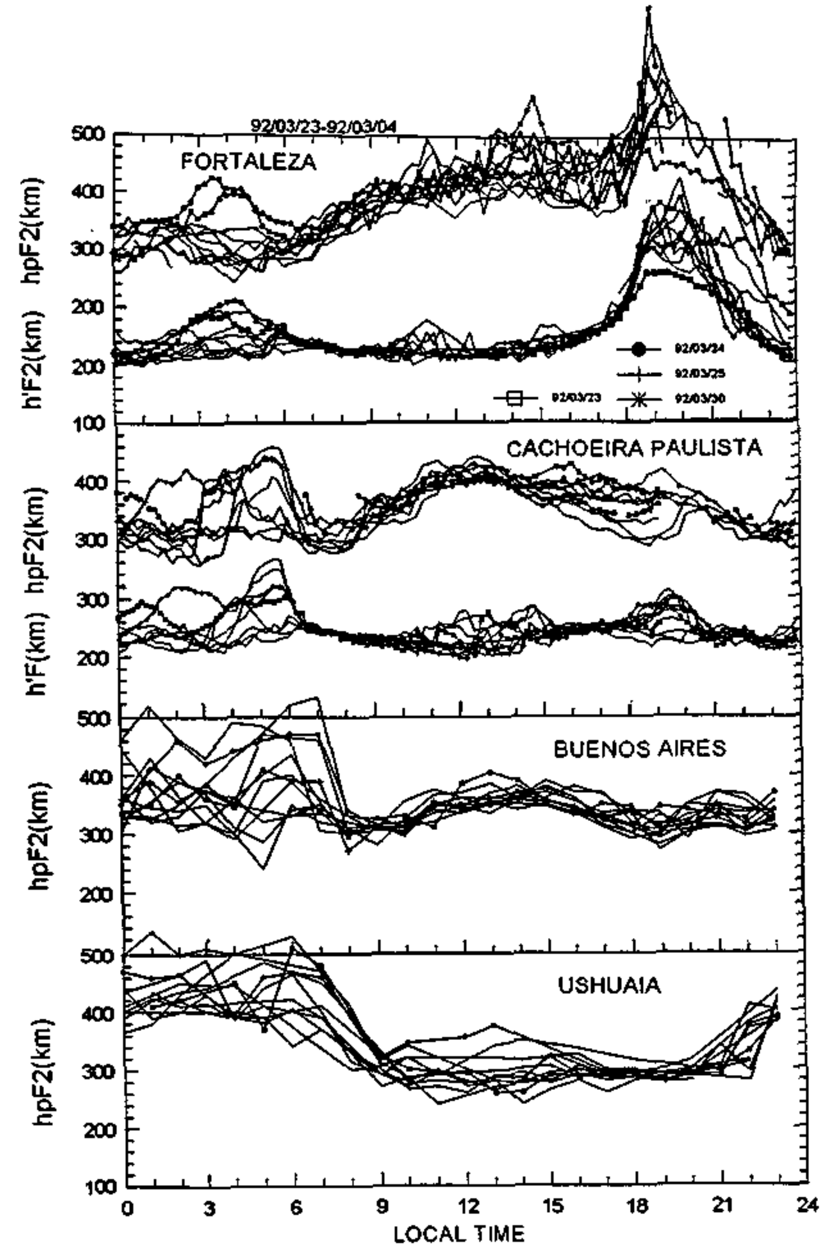

Figure 5. Superimposed plots of $hpF_2/h'F$ for the SUNDIAL-ATLAS 1 campaign interval for Fortaleza, Cachoeira Paulista, Buenos Aires, and Ushuaia. The curves identified with circles, stars, triangles, etc., represent data on four of the more disturbed days of the campaign (March 22, 24, 25, and 30), when anomalous height increases were observed over Fortaleza and Cachoeira Paulista, during the presunrise hours. The data for the remaining days are plotted in continuous lines.

layer seen both in $h'F$ and hpF_2. This is the well-known prereversal enhancement of the vertical drift (zonal electric field) amply documented in the literature based on radar data [*Woodman*, 1970; *Fejer et al.*, 1991], on ionosonde data [*Abdu et al.*, 1981; *Batista et al.*, 1986], on *hf* Doppler observations [*Balan et al.*, 1992], and theoretically explained as produced by the *F* layer dynamo [*Rishbeth*, 1971; *Heelis et al.*, 1974; *Farley et al.*, 1986; *Batista et al.*, 1986; *Crain et al.*, 1993]. Briefly, the evening equatorial zonal wind (which is eastward) interacts with the longitudinal *E* layer conductivity gradient that develops across the sunset terminator. This creates a certain negative charge accumulation at the day-to-night boundary which produces an electric field that is eastward (westward) on the dayside (nightside) of the terminator. Theoretical calculations show that the local time of the maximum of the prereversal enhancement electric field is dependent upon the time at which the steepest longitudinal gradient in conductivity occurs, while the strength of the electric field, that is, the amplitude of the vertical drift, is strongly dependent on the neutral wind velocity [*Abdu et al.*, 1995; *Batista et al.*, 1986].

It is therefore reasonable to attribute the day-to-day variability in the vertical drift/zonal electric field enhancement amplitude, to the day-to-day variability in the zonal wind

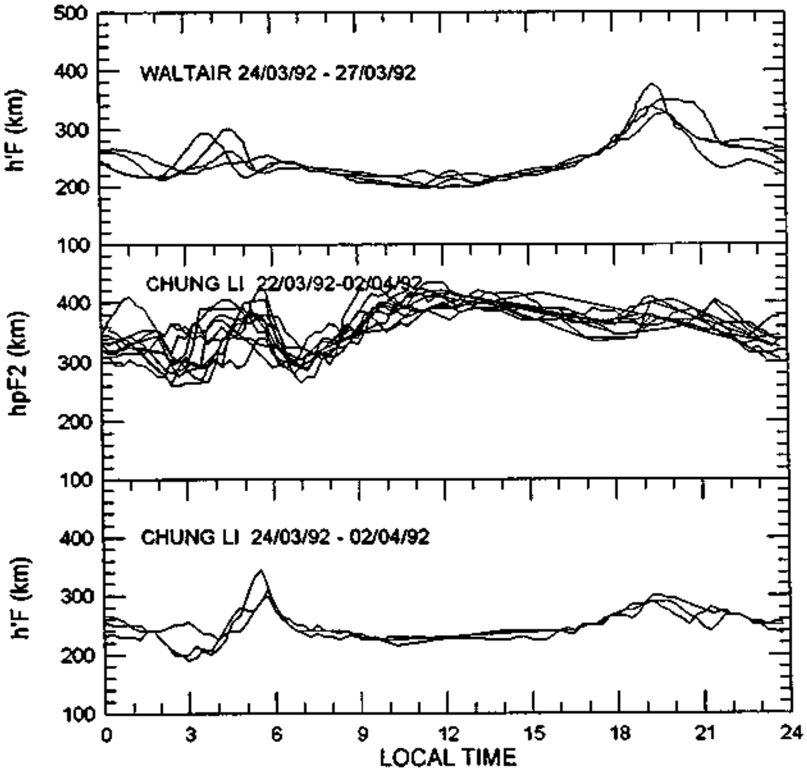

Figure 6. Plots of $h'F/hpF_2$ as in Figure 5 but for Waltair and Chung Li.

values (since the longitudinal gradient in conductivity is not expected to present such variability). In fact, the variabilities in the evening vertical drift/zonal electric field could arise also from other sources: (1) a disturbance magnetospheric electric field that penetrates to the low-latitude ionosphere, associated with substorm onset/recovery and asymmetric/*Dst* ring current developments [e.g., *Fejer et al.*, 1990; *Abdu et al.*, 1993, 1995; *Sastri, et al.*, 1992; *Tanaka*, 1986; *Somayajulu et al.*, 1991], (2) a disturbance dynamo electric field associated with disturbances in the global thermospheric circulation driven by storm energy deposition in the high latitude thermosphere [*Blanc and Richmond*, 1980; *Fejer et al.*, 1983, 1995]; (3) the disturbance zonal and meridional winds associated with item 2 interacting locally with ambient thermospheric winds in the equatorial region. Since the entire campaign interval was characterized by the recovery phase of a storm of weak-to-moderate intensity, we may consider item 1 above as having contributed only partially to the observed variabilities. The contributions from items 2 and 3 to the day-to-day variability in the evening electric field enhancement may be assessed as follows. The prereversal enhancement amplitude in the vertical drift (V_z)/eastward electric field shows a nearly linear positive dependence on the $F_{10.7}$ flux [*Fejer et al.*, 1991]. For example, a 10% change in the solar flux could cause nearly 10% change in V_z [see *Fejer et al.*, 1991, Figure 3]. The maximum variation in the $F_{10.7}$ flux values was around 10% with respect to the mean value (182 flux units) during the campaign period [*National Oceanic and Atmospheric Administration*, 1992]. However, the variability in the V_z (as judged from the slope of the $h'F/hpF_2$ curves near 1800-1900 LT in Figure 5) is significantly higher than 10% which implies that causes other than the variability in $F_{10.7}$ flux could be responsible for the observed variabilities in V_z. Another source of disturbance zonal wind arises from changing energy input at high latitudes that disturbs the global thermospheric circulation, producing a westward wind in the equatorial latitudes [*Blanc and Richmond*, 1980]. The westward wind interacting with the normal eastward wind would cause a reduced net eastward wind velocity, which in turn, could decrease the intensity of the evening electric field enhancement, as described by *Abdu et al.* [1995]. These considerations suggest (although we have not shown quantitatively) that the day-to-day variability in the evening electric field could receive a significant contribution from variability in the disturbance zonal winds besides that from disturbance electric-fields. It appears that modest variations in the high latitude energy inputs, as expected for the weak-to-moderate disturbance of the campaign period, could produce variability in the equatorial zonal wind system, since magnetospherically disturbed conditions prevailed for several hours prior to the local evenings [*Abdu et al.*, 1995] on many days of the campaign.

On the other hand, magnetospheric disturbances in the form of substorms or asymmetric ring current developments occurring in the dusk sector could produce penetration eastward electric fields, causing enhanced uplift of the layer [*Abdu et al.*, 1995]. In fact, the larger evening uplift of the layer observed on March 24 and 30, in Figures 5 and 7, accompanied by slightly higher slope of the *h'F* curve (that is, higher vertical drift) could be attributed to a disturbance electric field of this type associated with some degree of magnetic disturbances developing at these times, as verified in the local magnetograms (not shown here). The enhanced vertical uplift of the equatorial *F* layer on these two days

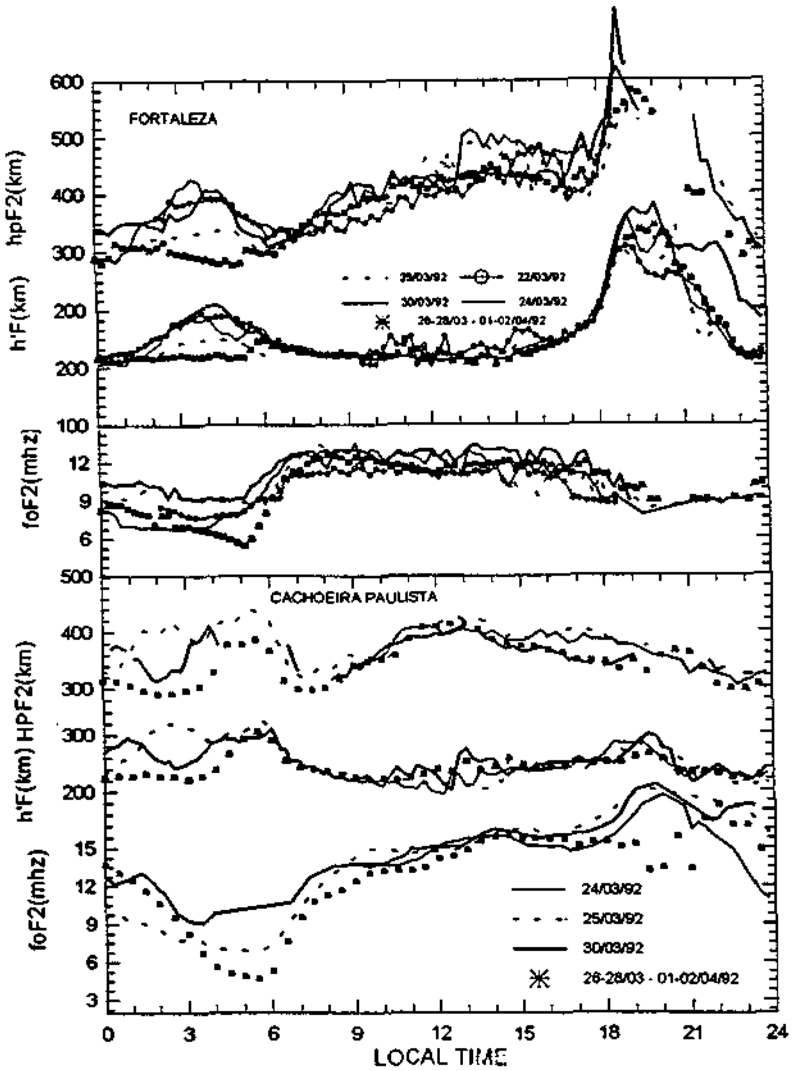

Figure 7. The $h'F$ and hpF_2 values for the relatively more disturbed days of the campaign (March 22, 24, 25, and 30), that is, the days for which the morning hours were preceded by *Dst* decreases (to ~50 nT) of a few hours duration plotted together with the mean curves for the magnetically quietest days of the campaign (stars).

seems to have produced EIA enhancements in the postsunset hours. This can be verified from the f_0F_2 plots over Cachoeira Paulista in Figure 7 [see also *Abdu, et al.*, 1995].

Therefore any explanation on the causes of the observed variabilities in the prereversal electric field enhancement should take into consideration whether an associated magnetic disturbance developed just before (at nearby local times) and/or whether such disturbances prevailed for several hours prior to, dusk. Because of the weak-to-moderate nature of the disturbance condition that characterized the SUNDIAL/ATLAS 1 campaign, unambiguous identification of a cause-effect relationship is difficult with respect to the different disturbance sources mentioned above.

4.2. Role of the Meridional Wind

The meridional wind contribution to ionospheric heights as a function of latitude is indicated by the F_2 peak height variations in Figure 5. At midlatitudes the hpF_2 variation is a strong function of the meridional wind. We have calculated the meridional wind for Ushuaia and Buenos Aires following the servo method used by *Miller et al.* [1986] that utilizes the Richards/Torr ionospheric model [*Young et al.*, 1980a,b; *Richards and Torr*, 1985; *Richards*, 1991]. This method involves the use of an ionospheric model to establish a relationship between meridional wind and F_2 layer height at specified locations, and then by comparing the measured hmF_2 with the modeled layer height, the meridional wind is derived. This method can produce, according to *Miller et al.* [1986] meridional winds comparable to the results from other techniques such as Fabri-Perot interferometer and incoherent scatter measurements. The acuracy of the wind calculated by this method depends upon that of the hmF_2 values reduced from the ionogram, and therefore on the precise technique used to obtain the hmF_2 values. For example, the use of the factor $M(3000)F_2$ for deducing the hmF_2 could introduce an error of up to 10% with respect to the hmF_2 calculated using the POLAN code [*Titheridge*, 1985]. In our calculation of the meridional wind, we have used hpF_2 values, and its deviation from the hmF_2 as per the POLAN code has been discussed in section 2. The results of model runs for all individual days for Ushuaia and Buenos Aires are plotted in Figure 8. Over Ushuaia, the winds are generally poleward (positive values) for most of the day and equatorward from near midnight to approximately 0800 LT. From around 2000 LT to midnight the meridional winds blow in both the directions in varying degrees on different days. Day-to-day variabilities are significantly more pronounced in the equatorward wind which dominates from around 2100 LT to the morning hours than in the poleward wind. This might point to the variable intensities at these hours of the high-latitude energy source that could be driving the equatorward disturbance winds. This is consistent with what is to be expected from the generally active nature of the ATLAS 1 period represented by the continuous negative *Dst* values (fluctuating at values mostly <50 nT, Figure 1), variable *Kp* values, and the interhemispheric power and activity index from NOAA/TIROS satellite presented by *Szuszczewicz et al.* [this issue]. It should be remembered also that under the relatively denser electron/ion densities prevailing from approximately 0900 to 2100 LT (see Figure 2) the meridional wind attenuation from ion drag force could be more significant at these local times (that is, in the poleward wind) than during the remaining hours (that is, in the equatorward wind). Over Buenos Aires, the durations of the equatorward winds are more restricted in local time than over Ushuaia, with equally significant poleward winds also registered at these times. The amplitude of the day-to-day variability in the disturbance meridional winds, indicated by the difference between the extreme values of the winds during the midnight-morning local times, are, however, nearly the same at both locations. We may point out that the degree of the day-to-day variabilities of the meridional wind, and their local time dependence, at the two stations as seen in Figure 8 can be treated as very much realistic, since they reflect almost exactly such features seen in the corresponding hpF_2 values of Figure 5. In Figure 8 we have also plotted the meridional winds for Ushuaia and Buenos Aires as specified by the HWM-90 model of *Hedin et al.* [1991]. The wind local time patterns presented are for the magnetically quietest and the most disturbed days of the campaign, i.e., April 2 (Ap=04) and March 23 (Ap=28). The HWM-90 model winds show, in general, reasonable agreement with the winds derived from the ionosonde data for both locations. The main exceptions are the poleward winds around midday over Buenos Aires and the equatorward winds in the evening hours at both locations, which the HWM-90 tends to overestimate. Higher magnetic activity produces higher equatorward winds in the HWM-90 mainly for night conditions. Such a dependence is present also in the deduced winds, but with slightly different local time dependence at the two locations. Also, the observed amplitudes of the day-to-day variabilities in the meridional winds are significantly higher than predicted by the HWM-90.

Over Cachoeira Paulista, which is at a lower latitude than Buenos Aires, the determination of the meridional wind from ionosonde data is a complex task (and no model is yet available) due to the increasing role of the electric field at equatorial latitudes. However, a comparison of the $hpF_2/h'F$ patterns over Cachoeira Paulista and Fortaleza with those over Buenos Aires and Ushuaia (Figure 5) vis-a-vis the meridional wind variations over the latter stations (Figure 8) points to a diminishing trend in the amplitude of the meridional wind from midlatitudes toward the equator in the morning hours. Such a trend becomes clearer if we exclude from Figure 5 the specially identified curves, for reasons to be explained below. Thus the results of Figures 5 and 8 clearly demonstrate the dominating role of meridional wind in the day-to-day variability of the night-sunrise sector midlatitude ionosphere

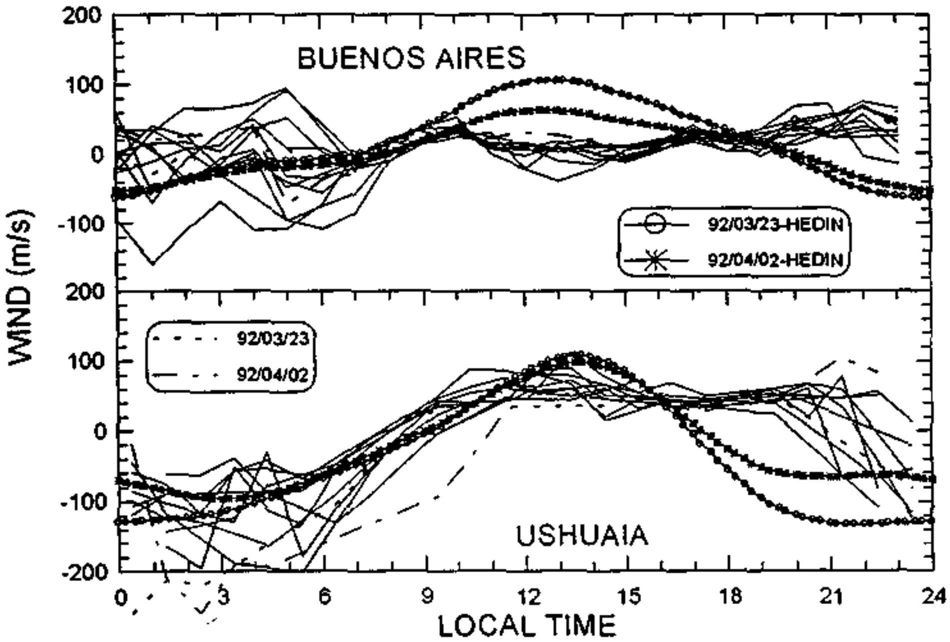

Figure 8. Meridional winds (positive poleward) obtained using the servo method by *Miller et al.* [1986] based on the FLIP model that used the $hpF2$ values for Buenos Aires and Ushuaia, plotted for all days of the SUNDIAL-ATLAS 1 campaign. The Hedin HMW-90 model meridional winds are shown for the 2 days of the lowest and highest Ap values, April 2 (stars) and March 23 (circles).

that progressively diminishes toward the equator. Such variabilities seem to result, as mentioned before, from the fluctuating magnetic activity that characterized the SUNDIAL/ATLAS 1 campaign period. The fluctuating magnetic activity seems to have produced, (in the same morning local time sector) over equatorial latitudes, to be explained below, additional F layer height increases which can be attributed to the action of disturbance dynamo electric field.

4.3. Disturbance Dynamo Electric Field

The morning (0200-0600 LT) height rise over Fortaleza in Figure 5 is significantly larger on some days (curves identified with squares and stars) than on other days. Such events of height rises seem to be associated with prior increases in magnetic disturbances, of a few hours duration (seen as *Dst* values decreasing to about -50 nT, denoted in Figure 1) that were observed on some days. These days were identified as March 22, 24, 25 and 30. The hpF_2, $h'F$, and f_0F_2 over Fortaleza and Cachoeira Paulista for these days are plotted in Figure 7 together with the mean of the magnetically quietest days (March 26, 27, 28 and April 1, 2) of the campaign (see Figure 1). It is quite evident from Figure 7 that a morning height increase is practically absent over Fortaleza in the quietest day mean curve, and significant height increases both in $h'F$ and hpF_2 are clearly present on the disturbed days during the postmidnight-morning hours with maximum effect centered around 0300-0400 LT. (The increase centered around 0500 LT observed in the quiet day average curve of Cachoeira Paulista could be produced by quiet time neutral wind). In a recent study on time-dependent responses of ionospheric electric fields to magnetospheric disturbances, *Fejer and Scherliess* [1995] have shown from statistical analysis of long-term Jicamarca vertical drift data, that maximum vertical drift disturbances from a disturbance dynamo electric field occurred within 5-6 hours from the onset of an auroral substorm event represented by *AE* indices. The corresponding maximum upward drift (eastward electric field) occurred around 0300-0400 LT (see *Fejer and Scherliess*, 1995, Figure 2]. We note that the maximum effect in hpF_2 and $h'F$ over Fortaleza also corresponds to disturbances occurring in the same local time range, in Figure 7. It is further interesting to note that the height disturbances (whose occurrence local times are indicated in the *Dst* plot of Figure 1) are preceded by short-duration *Dst* decreases (to about -50 nT). The amplitudes of these morning height increases over Fortaleza are comparable to, if not higher than, those observed during the same LT interval over Cachoeira Paulista. The action of disturbance meridional (equatorward) winds as the cause of such height increases may be discarded (even if such winds are present) owing to the fact that the effect of an equatorward wind in lifting up the F_2 layer peak height is a factor of ~2.5 less over Fortaleza (with dip angle of -8°) than over Cachoeira Paulista (with dip angle of -28°). The cause of the observed height increases over Fortaleza may therefore be attributed to the presence of a disturbance eastward electric field. The antecedence time of up to a few hours (~5-6 hours) for the disturbance source as observed in the *Dst* increases are in general agreement with the Jicamarca results of *Fejer and Scherliess* [1995]. Thus the results of Figure 7 offer evidence, for the first time based on ionosonde data, of disturbance dynamo eastward electric field manifestation in the equatorial ionosphere. The result for Cachoeira Paulista in the lower two panels of Figure 7 is in general agreement with that of Fortaleza. However, the dissimilar temporal structures at the two locations suggest that height variations over the former location were modulated by disturbance meridional wind (that seems indeed to be present). The disturbance dynamo electric field manifestations at other local times are ambiguous in the present data. Partial inhibitions of equatorial electrojet current as seen in reduced amplitudes of diurnal ranges in the geomagnetic field horizontal component, with associated ionospheric and thermospheric signatures, have been atributed to disturbance dynamo westward electric fields by *Sastri* [1988] and *Mazaudier and Venkateswaran* [1990], respectively, for the Indian and African-European longitudes. The variabilities in the evening F layer uplift seen in Figures 5 and 7 are likely to be produced more by the variabilities of the zonal wind and to some extent by the magnetospheric disturbance electric field (as explained earlier) than by the disturbance dynamo electric field. It is interesting to note that the f_0F_2 values also show generally positive modifications compared with those of the heights at both the stations, in response to the disturbance dynamo electric field, as the f_0F_2 results show in Figure 7.

5. Conclusions

In the present study, we considered the climatology of the low-latitude ionospheric F region over the American and Indian-Asian longitude sectors. A comparison of the observed averaged behavior with the IRI model representations showed that such a climatological picture is indeed describable by the model in general. Some exceptions are noted, especially in the case of the equatorial F layer heights at times of the evening electric field prereversal enhancement and the nighttime resurgence of the equatorial ionization anomaly. The main focus of the study, however, has been on the day-to-day variabilities of the ionosphere, with reference to its average behavior, during the 12-day campaign period that marked the recovery phase of a weak to moderate magnetic storm. The recovery phase in itself was marked by fluctuating magnetic indices. The identification, in terms of specific cause-effect relationship, of low-latitude ionospheric response to a weak-to-moderate intensity storm event, is a rather difficult task. We have therefore adopted an approach that focuses on salient features of the day-to-day variabilities observed during the campaign interval on global as well as regional scales. Some specific local-time and latitude-dependent characteristics attributable to disturbance zonal and meridional winds and to a disturbance dynamo electric field have been identified. The main findings are the following. Under weak-to-moderately disturbed conditions (with *Dst* of about -50 nT) the day-to-day variabilities of the equatorial and low-latitude ionosphere are produced mainly in the evening/sunset sector and in the early morning hours. The former observation is a manifestation of the variability in the electric field prereversal enhancement amplitude (that is, in the F layer uplift) that seems to be caused mainly by corresponding variability in the equatorial zonal eastward winds and penetrating disturbance magnetospheric electric field. The effects in the early morning hours, manifested as height rises produced from a disturbance dynamo electric field, occur with a delay of a few hours with respect to an increase in magnetic disturbance (seen as *Dst* decreases). It may be pointed out that this is the first evidence from ionosonde data so far reported on disturbance dynamo electric field effects in the equatorial ionosphere. These effects decrease steadily going away from the equator, becoming indistiguishable at latitudes higher than that of Cachoeira Paulista (-28° dip), close to the EIA crest. At midlatitude locations the day-to-day variabilities arise from corresponding variabilities in the meridional neutral wind, the effect being dominant from premidnight to morning hours. We may note that the servo method of height analysis gives an effective meridional wind, which under disturbed conditions could mean a combined effect of winds and electric fields. However, the indications that the amplitude of the effect decreases toward the equator (in a way consistent with the equatorward decreasing values of the geomagnetic dip angle) suggest rather strongly that the day-to-day variabilities are caused by disturbance meridional winds. The effect also gets restricted in local time toward the equator such that at the latitude of the EIA crest it is observed during post midnight-sunrise hours only. At equatorial latitudes (such as Fortaleza and Waltair) the effect from meridional wind is imperceptible as such, being significantly smaller than the disturbance dynamo electric field effect that seems to dominate the response features for these locations during presunrise hours. It may be remarked that in the morning hours no identifiable effect was observed from the direct penetration magnetospheric electric field whose presence seems to characterize some cases of the response features in the evening hours. It is suggested that further studies should be pursued, involving a larger database, aiming at elucidating further the cause-effect relationships governing the low-latitude ionospheric response to magnetic disturbances of weak-to-moderate intensity.

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