# Processes in the quiet and disturbed equatorial-low latitude ionosphere : SUNDIAL campaign 1984

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ABSTRACT. A network of ionospheric diagnostic instruments was operated on a world wide basis during the October 5-13, 1984 SUNDIAL campaign. The network provided a unique opportunity for a truly multiple technique global analysis of the equatorial-low latitude ionospheric behaviour during the campaign period. The SUNDIAL equatorial-low latitude data set included electric field and spread *F* data from Jicamarca radar, ionosonde data from 15 stations and magnetograms from 5 stations operated in the American, African, Asian and Indian sectors. Also included are data from electronic polarimeters at Brazilian low-latitude sites. The data analysis has focused attention on the global scale steady state ionospheric behaviour and its predictability by global theoretical model of Sojka and Schunk (1985) and by the International Reference Ionospheric (IRI). The results are suggestive of the need to modify existing quiet time electric field and neutral wind models in varying degrees for different longitude sectors. The analysis also concerns global scale ionospheric transient behaviour in response to exo-ionospheric variabilities under disturbed conditions, in an approach towards a better understanding of the factors that effect short-term prediction schemes. Among the important outcomes of this study is the possibility of using longitude chains of equatorial region ionosondes (and magnetometers) for investigation of equatorial ionospheric response to magnetospheric electric field penetration events and disturbance dynamo effects.

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## 1. INTRODUCTION

During the 8-day SUNDIAL October 5-13, 1984 campaign extensive observations of the equatorial-low latitude ionosphere were conducted at different longitudes including the American, African, Indian and Asian sectors. The principal objectives and approaches of the SUNDIAL program are discussed in detail in the paper by Szuszczewicz *et al.* (1988).

Accordingly, analyses of the different data sets have been carried out having focus on two main SUNDIAL objectives. The first of these objectives addresses the question of developing a truly predictive capability concerning the average ionospheric behaviour for specific geographic or geomagnetic location and local time and for quiescent solar activity level. The methodology adopted for achieving this objective is to carry out detailed comparative study of the observational data, representative of typical quiet, or quiescent, ionospheric conditions with theoretical (or « first principle ») and empirical ionospheric models. The second objective concerns the predictability of short-term or day-to-day variabilities of the ionosphere and foresees, for this purpose, development of qualitative as well as quantitative relationships between ionospheric and exo-ionospheric parameters that could eventually be incorporated into modelling schemes projected for more accurate short-term predictive capability. As a subset within the entire SUNDIAL campaign the equatorial-low latitude observational network consisted of 15 ionosondes operated at 5-15 min data resolution ; the Jicamarca incoherent radar that provided a rather detailed picture of the dynamic conditions of the equatorial ionosphere over Peru ; TEC (Total Electron Content) and scintillation measurements at locations in Asian and Peruvian stations ; and spaced VHF electronic polarimeters (base line of 110 km) and angular scanning photometers operated in Brazil. In addition the SUNDIAL low latitude data set included also magnetograms from five locations covering the different longitude sectors.

Towards the first of the above-mentioned objectives the steady-state equatorial-low latitude ionospheric behaviour, represented by quiet conditions are compared with results from the global theoretical ionospheric model of Sojka and Schunk (1985) as well as with the results from the International Reference Ionosphere (IRI) model (Rawer, 1981). Results of these comparative studies are presented and discussed in Section 2 of this paper. Departure from the quiescent behaviour could occur under different geophysical conditions. Day-to-night transition induces changes in electrodynamic processes, which, depending upon the season and solar activity cycle, produce evening *F*-region vertical ionization drift enhancements and triggering of irregularity generation leading to the composite spread-*F* events in the equatorial-low latitude ionosphere (Abdu *et al.*, 1985*a* ; Heelis *et al.*, 1974 ; Fejer *et al.*, 1979*a* ; Rishbeth, 1971 ; Tsunoda, 1985 ; Woodman, 1970). There is evidence that these events are often accompanied by atmospheric waves (Röttger, 1978), or upwellings (Tsunoda, 1983), resembling, in this respect, the circumstances frequently associated with midlatitude spread-*F* events (Bowman and Dunne, 1984). Marked changes in the electrodynamic processes of the equatorial-low latitude ionosphere are induced also from global ionospheric response to magnetospheric disturbances triggered by the chain of events envolving solar, solar wind and interplanetary disturbances. Such global scale responses are manifested in simultaneous effects, as in the case of magnetospheric electric field penetration to low latitudes (Fejer *et al.*, 1979*b* ; Gonzalez *et al.*, 1979 ; Rastogi and Patel, 1975 ; Rastogi *et al.*, 1978), or delayed effects, as in the case of disturbance dynamo or storm effects (Blanc and Richmond, 1980 ; Prölss, 1981 ; Fejer *et al.*, 1983 ; Rishbeth, 1975), at all longitudes, and coupled with high latitudes ionospheric processes (some of these effects will be discussed later in Section 3). There is a close relationship between spread-*F* generation and anomalous nighttime reversal of equatorial electric fields during these magnetospheric disturbances (Fejer *et al.*, 1979*b*). Most of the previous global ionospheric studies have been restricted mainly to ionospheric storm effects however (e.g., Richmond, 1979 ; Rishbeth, 1975 ; Prölss and von Zahn, 1977). Better understanding of the different aspects of the ionospheric response characteristics as well as that of the day-to-day variability in the ionospheric dynamics are essential for achieving progress towards the second SUNDIAL objective. Towards this end, equatorial-low latitude ionospheric transient response to magnetospheric disturbances is analysed using selected stations and data sets for the SUNDIAL campaign period, and Section 3 of this paper discusses the results of these studies.

The stations and data sets included in the present work are : Jicamarca (76.9° W, 12° S, 2° dip) incoherent scatter radar data ; Ionosonde data from Huancayo (74° W, 13° S, − 1° dip), Cachoeira Paulista (45° W, 22.6° S, − 26° dip), Ahmedabad (72.6° E, 23.02° N, 34° dip), Hong Kong (114° E, 22 N, 30.5° dip), Dakar (15° W, 12.5° N), Vanimo (141.3° E, 2.7° S), Ouagadougou (0° W, 5° N), Chung-Li (121° E, 25° N, 34° dip), Manila (12° E, 15° N, 12° dip), Pameung Peuk (108° E, − 8° N, − 35° dip) ; Magnetometer data from Huancayo, Vassouras (43.7° W, 22.4° S, − 26° dip), Lunping (120° E, 23° N, 34° dip), Kodaikanal (77.5° E, 10.2° N, 0.9° dip), Davao (125° E, 7.1° N, − 2° dip) and VHF polarimeter data from São José dos Campos (45.8° W, 23.2° W, − 26° dip) and Cachoeira Paulista. It might be recalled here that a global ionosonde chain was operated during the 1957-59 IGY period and numerous studies on the low latitude ionosphere have resulted from that campaign. The SUNDIAL campaign has a uniqueness in that it involves more diverse observational techniques permitting more detailed diagnostics of the ionospheric processes.

## 2. COMPARATIVE STUDY OF SUNDIAL QUIET TIME OBSERVATIONAL DATA SET WITH THEORETICAL AND EMPIRICAL IONOSPHERIC MODELS

In comparative studies involving observational data and modelling results, it is necessary and convenient to distinguish quiet ionospheric conditions from disturbed conditions. For representing the quiet conditions it is desirable to obtain a mean behaviour of the ionospheric parameters, such as the critical plasma frequencies and heights of the different layers, as well as electron density height profiles, for a few quietest days of a specific period (say, a given month). Such a procedure is called for due to the ionization variabilities caused by « quiet » day neutral atmospheric dynamics. This mean behaviour, in the case of low latitude ionosphere, will be a function mainly of a representative mean solar ionizing radiation flux, geographic location and local time. Departure from this behaviour, that could be identified with variabilities in the exo-ionospheric parameters as the cause, is then recognized as a disturbed day. Ionospheric behaviour on a given day could be classified either as typical of a quiet day or of a disturbed day depending upon the magnetic index values for that day. For convenience we shall define $K_p \leqq 2+$ and $\sum K_p \leqq 21.3$ to represent a quiet day. The data coverage for the SUNDIAL period was not sufficiently long to construct a mean quiet day behaviour as per the above procedure since a solar wind disturbance had triggered global scale ionospheric disturbances starting at ~ 20 : 15 UT on the second day (6 October 84) of the SUNDIAL observational window. All preceding data on the 5th and 6th represent typical quiet ionospheric conditions, the 5th being magnetically quieter ($\sum K_p = 13.9$) than the 6th. Short-term exceptions to the above defined quiet condition prevailed from 03-06 UT on 6th, when $K_p$ varied from 3 + to 4 +, but $\sum K_p$ in the 24-h period prior to the 20 : 15 UT onset of the disturbance was 21.7 which indicated overall quiet conditions. We will use the data on both these days as reference to carry out comparative studies with the global theoretical ionospheric model of Sojka and Schunk (1985) and with the IRI model (Rawer, 1981). The IRI model uses a set of empirical codes based on observational and extrapolated data points for obtaining height profiles of key ionospheric parameters and is considered as a useful reference source for comparison with the SUNDIAL observational data set (see

Schunk and Szuszczewicz, 1988, for more details on these models). Titheridge's (1985) program code has been adopted for true height analysis of all SUNDIAL ionograms.

The $F$-layer critical parameters, namely, the peak plasma frequency of the layer represented by $f_o F_2$ and its height *hmF*2, or the representative height *hpF*2 (deduced on the basis of a parabolic layer approximation), for locations selected in the American and Asian sectors of the equatorial-low latitude ionosphere, are compared with results from the global theoretical model of Sojka and Schunk (1985) computed for conditions representative of the October, 1984 SUNDIAL period. The input electric field model used in the calculation was that of Richmond *et al.* (1980) while the neutral wind model resembled the low latitude wind pattern described by Sterling *et al.* (1969) and Anderson (1973). Zonal wind is not included in the calculations. In the comparison plots given in figures 1 and 2 for $f_o F_2$ and *hpF*2 (and in some cases for *hmF*2) respectively, the data for the 6th (solid line) and, where available, for the 5th (crosses) are presented and the onset of the magnetospheric disturbance at 20 : 15 UT is indicated. It should be pointed out that the *hpF*2 values are generally higher than the real peak height *hmF*2 obtained from true height analysis of the ionogram using the method of Titheridge (1985), or that of Paul (1967). This difference, seen clearly in the data plotted for

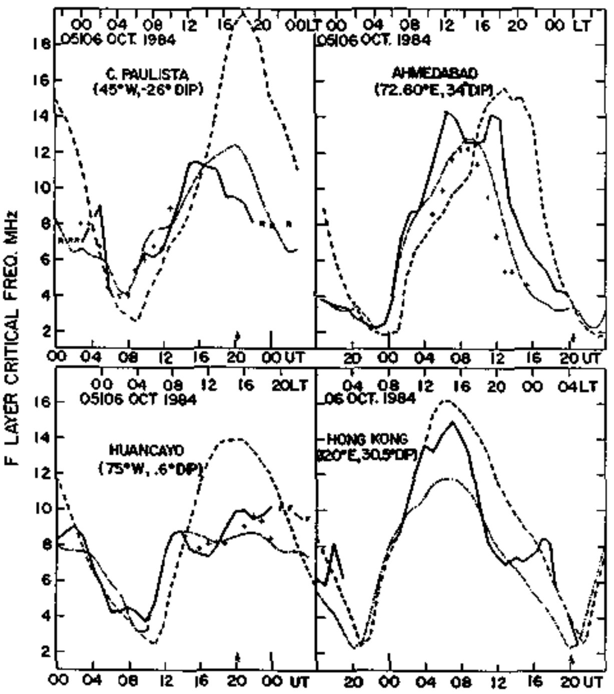


Figure 1

*Comparison of the F-layer peak densities (represented by $f_o F_2$) observed on 6th (solid line) and 5th (crosses) October 1984, the quiet day of the SUNDIAL period, with the results obtained from the global theoretical ionospheric model of Sojka and Schunk (1985) run for October conditions of low solar activity period. Also shown for comparison are the results of the International Reference Ionosphere (IRI) model. The comparative plots are presented for Cachoeira Paulista and Huancayo in the American sector and Ahmedabad and Hong Kong in the Asian sector. (Range and frequency types of spread-F are indicated by R and F respectively).*

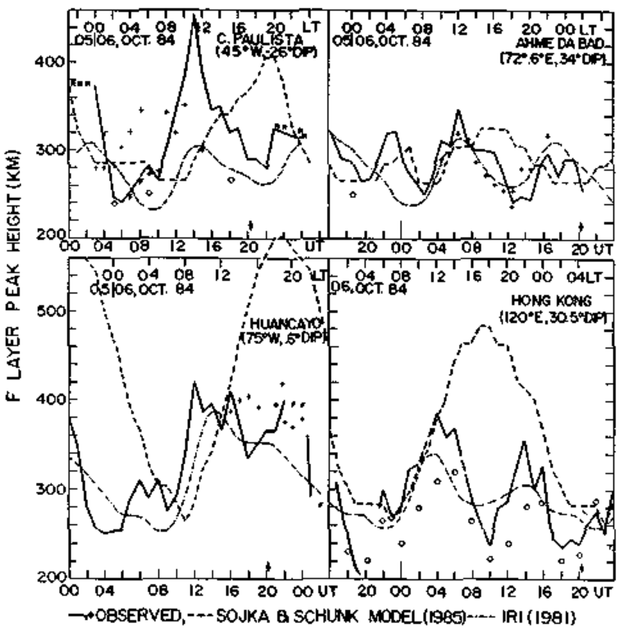


Figure 2

*Results of comparative study similar to that in figure 1, but for the layer peak height parameter hpF2, and, in some cases, for hmF2 (open circles).*

Cachoeira Paulista and Hong Kong in figure 2, is usually smaller for night hours (a few km) when the low lying ionization is smaller than during daytime hours (when it reaches a few tens of km). For comparative studies the results from IRI model are also presented in these figures. Over Cachoeira Paulista the diurnal peak in $f_o F_2$ (fig. 1) obtained from theoretical model is around 70 % higher than the observed value, namely, the theoretical electron density is approximately 3 times higher than the observed values, the difference continuing till midnight hours. Differences to a lesser degree between the theoretical and observed values are present over the magnetic equatorial location of Huancayo. At these two stations the diurnal minima in the theoretical model are delayed by about one hour with respect to the observations. The diurnal shape of the electron density also presents some difference and this difference over Huancayo seems to be more significant since the daytime equatorial electron density should normally present morning and afternoon maxima with a noon bite-out, whereas the global theoretical model predicts a broad afternoon peak centered around 15 LT. The height variation in figure 2 for Huancayo shows significant differences both in amplitude and in local time of occurrence of the $F$-layer peak. These differences with the theoretical model are present whether we consider the data for the 6th or the 5th. It looks that, in the case of Huancayo, the global electric field model of Richmond *et al.* (1980) which provides an essential input for the numerical calculation of Sojka and Schunk (1985) does not conform to the quiet days the SUNDIAL period. On the other hand, the results of comparison of electron densities and heights for Cachoeira Paulista (which is a low latitude station), also in the American sector, would point towards the need for improving the east-west electric field as well as the neutral wind models used in the computation. Results for the Indian and Asian low latitude stations, namely, for Ahmedabad and Hong Kong respectively, in general, suggest better agreement between the theoretical results and observations although there exists significant difference between the theoretical model and the observed $f_o F_2$ values on the 5th evening over Ahmedabad. While the results for Ahmedabad might suggest mainly a certain phase shift for the adopted electric field and/or wind pattern, the results for Hong Kong point out the need for modification of the amplitudes of the two input parameters, for obtaining better agreement with the observational data.

The observational data in figures 1 and 2 are indicative of possible presence of a longitudinal asymmetry in the Appleton anomaly development, as the three stations, Cachoeira Paulista, Ahmedabad and Hong Kong are in fact located close to the anomaly crest. This problem has been addressed in the review paper by Walker (1981) who pointed out the cause of the asymmetry as partly due to magnetic meridional wind component arising from zonal wind in the presence of longitude dependent magnetic declination angle. It should be pointed out that the zonal wind influences also the east-west electric field through the *F*-region dynamo action (Rishbeth, 1971) resulting in the occurrence of the pre-reversal evening enhancement in the *F*-region ionization drift (Heelis *et al.*, 1974 ; Woodman, 1970 ; Fejer *et al.*, 1979*a*) which in turn controls in a significant way the post sunset anomaly ionization distribution (Anderson, 1981 ; Sojka and Schunk, 1985). Since the *F*-region dynamo development takes place under the combined action of zonal neutral wind and conjugate *E*-layer conductivity longitudinal gradient at sunset hours (the latter being dependent on the angle between the sunset terminator and the magnetic meridian of the conjugate *E*-layers) a longitude dependent magnetic declination angle together whith the zonal winds (Batista *et al.*, 1986) could provide additional means to explain the observed longitudinal asymmetry of the anomaly ionization features. Thus in order to obtain a more realistic simulation of equatorial-low latitude electron densities for different locations, it seems necessary to adopt as input to the global model an *F*-region electric field model, as well as meridional and zonal wind models, that are representative not only of a specific season but of longitude (including the magnetic declination angle effect) as well, of the location being modelled. For example calculations using regional models of vertical drifts values such as those based on Jicamarca radar measurements seem to reproduce better the noon bite-out feature of Huancayo electron densities (Anderson, 1981). Other possible causes of longitudinal differences, namely, the position of the magnetic equator relative to geographic equator and strength of the magnetic field in the different longitude sectors are already incorporated into the global model (Sojka and Schunk, 1985).

The IRI model results for the *foF*2 and *hmF*2 presented in the figures 1 and 2 show varying degrees of agreement with the observational results. Considering the fact that our data represent only one or two days of observations, whereas the IRI represents a mean behaviour it is satisfying that the SUNDIAL « quiet » day is generally in very good agreement with the averaged IRI representation. However, certain systematic difference has been noted from comparison of the height profiles obtained from IRI model with those deduced from true height ionogram analyses over Cachoeira Paulista (not shown here). The IRI profiles show subpeak densities (i.e. *F*1 densities) generally higher than those obtained from the ionograms, a difference which reflects important effects in flux-tube integrated conductivities and attendant polarization fields.

A true height-local time cross section of plasma frequency contours in steps of 1 MHz obtained from ionogram analysis on 6 October, 1984 for Dakar (14° 46′ N, 12° 27′ W) is compared in figure 3 with the results from the global theoretical model. A minor local disturbance, indicated by height oscillations in electron density, mainly between 08 to 12 LT approximately, seems to be present over Dakar on this day ; however, the *hmf*2 values predicted by the model are reasonably close to the observed values from early morning till late aternoon hours. Departure from observed values dominates from near sunset till after midnight. The electron densities predicted from the model, on the other hand, are significantly smaller than observed at most of the local times and heights. This contrasts with the situation in the American low latitude sector where the comparison showed, as mentioned above, higher peak densities (for a significant part of the day) predicted by the model as compared to observations.

Thus, the present preliminary comparative study using the prediction from theoretical model of Sojka and Schunk (1985) and the equatorial-low latitude observational data set seems to point towards the need for more realistic values of the low latitude electric field and neutral wind patterns to be used as model inputs, in order to achieve a better predictive

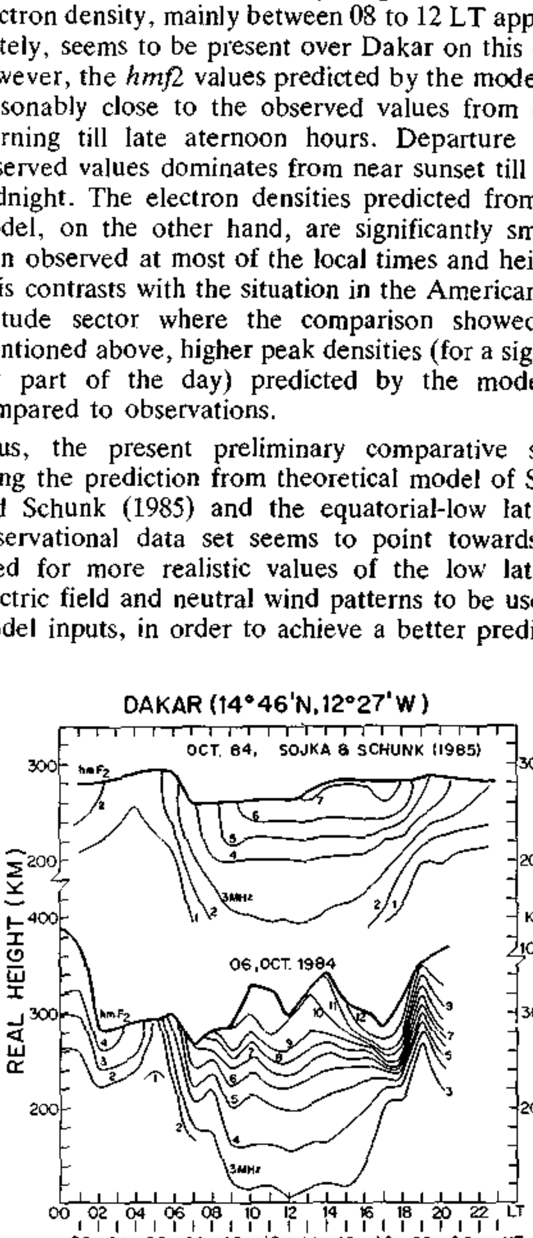


Figure 3

*A true height* versus *local time cross section of the plasma frequency contours in steps of* 1 MHz, *deduced from ionograms taken over Dakar on* 6th *October* 1984, *(lower part), compared with the corresponding results from the global theoretical ionospheric model by Sojka and Schunk* (1985).

capability for the « quiet time » low latitude ionospheric behaviour as observed during the SUNDIAL period.

## 3. EQUATORIAL-LOW LATITUDE IONOSPHERIC TRANSIENT RESPONSE TO MAGNETOSPHERIC DISTURBANCES

In this section we focus attention on the observed equatorial-low latitude ionospheric transient response to the magnetospheric disturbance, that characterized the SUNDIAL campaign period following the initial quiet conditions, with a view to examine to what extent these results have furthered the second of the stated SUNDIAL objectives. Such responses manifest coupling processes between the magnetospheric, auroral and low latitude current systems involving : *a*) penetration of electric field to low latitude during rapid changes in magnetospheric convection ; *b*) partial closure of the auroral and ring current systems at low latitude during substorms ; *c*) disturbance dynamo electric fields and ; *d*) storm sudden commencements and sudden impulses (Gonzalez *et al.*, 1979 ; Fejer, 1986). Observations of anomalous changes in the equatorial electric fields correlated with IMF $B_z$ polarity changes and auroral current intensity variations have provided evidences on direct penetration of magnetospheric electric field to equatorial ionosphere (Rastogi and Patel, 1975 ; Rastogi *et al.*, 1978 ; Kelley *et al.*, 1979 ; Fejer *et al.*, 1979*b* ; Gonzalez *et al.*, 1979, 1983). Important characteristics of these penetration electric field have been identified from analysis of data from incoherent scatter radars (especially from Jicamarca radar), equatorial and high latitude magnetograms and interplanetary magnetic field data (see Fejer, 1986 for a review). A northward turning of $B_z$, marking the end of a substorm event, often causes westward and eastward electric field changes on the day- and nightside, respectively, of the equatorial ionosphere, while, somewhat less frequently, southward $B_z$ changes produce electric field changes with the same polarity as the ambient fields. These effects have local time dependence such that the former class of events are observed at all local times with largest and smallest amplitudes between 02-05 LT and 20-24 LT sectors respectively, while the latter cases are observed predominantly in the midnight-noon local time sectors. More commonly near the solar minimum large amplitude coherent DP-2 like electric field fluctuations with time scale of about one hour are sometimes observed in the sunrise noon sector apparently with polarity dependence similar to the southward $B_z$ cases. Also, large equatorial electric field perturbations with predominantly westward polarity during the day and eastward polarity during the night are observed during period of asymmetric ring current development and high substorm activity. The longitude dependence of these different effects are not known at present due to the scarcity of data. While these effects occur almost simultaneously over the different longitude sectors as well as at middle and high altitude locations, the stormtime disturbances also affect the low latitude through the generation of disturbance dynamo electric field and associated neutral winds and thermospheric composition changes with time delays of a few hours and longer (Blanc and Richmond, 1980 ; Fejer *et al.*, 1983 ; Prölss and von Zahn, 1977 ; Rishbeth, 1975). The SUNDIAL data set has provided additional information and some new questions regarding the different coupling processes.

The magnetospheric and ionospheric disturbances that had onsets at the end of the second day of SUNDIAL observation (6 October) had their origin in the passage of a transequatorial solar coronal hole that was associated with high speed low density solar wind plasma. Associated storm level disturbances were present on 7th and 12th with the rest of the days witnessing lightly disturbed, or quiet, conditions ($\sum K_p$ varying from 24 to 31.8). The magnetospheric disturbance on the 6th started with the southward turning of IMF $B_z$ component at 20 : 15 UT as indicated in the IMP-8 data (see fig. 6 of Szuszczewicz *et al.*, 1988). The ground magnetic variation at different longitude sectors are shown in figure 4 where magnetogram $H$ components at one pair of stations, Huancayo and Vassouras, located in the American sector are compared together with data from another pair, Lunping and Kodaikanal, located in the Asian sector. It may be noted that the magnetograms at all the four stations showed brief fluctuations (kinks) simultaneous with the 20 : 15 UT IMF southward turning (indicated in the figure). In general, the $H$ variations of about 1 h or more at a given pair of stations are out of phase with those at the other pair independent of whether the stations are strictly on the day or nightside. Since the nighttime magnetograms respond most to the ring current perturbations the identification of these out-of-phase oscillations with possible DP-2 current systems (Nishida, 1968) is not clear. However, the opposite polarity relationship is

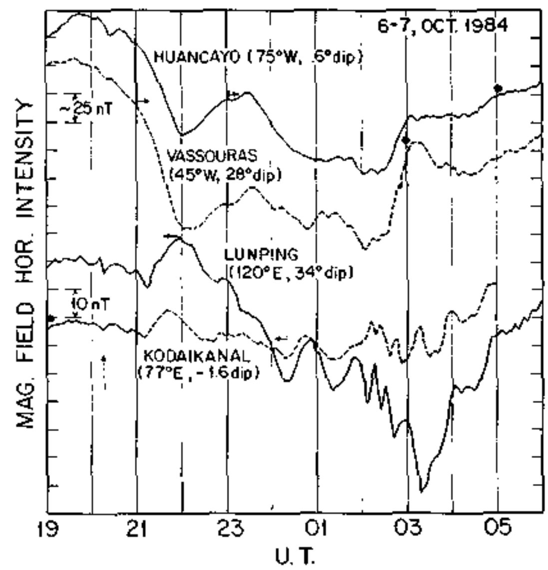


Figure 4

*Magnetogram H-component plotted versus universal time for four stations, namely, Huancayo and Vassouras in the American sector and Lunping and Kodaikanal in the Asian sector, during the period that covers the onset and development of the magnetic disturbance on 6-7 October 1984. The horizontal arrows point towards nightside on earch curve where local midnight is also indicated. The vertical arrow around 20 : 15 UT indicates a kink on each magnetogram that coincided with the southward turning of the IMF $B_z$ component.*

an interesting aspect so that analysis of more such cases involving ionospheric data should be carried out for possible identification with a DP-2 current or asymmetric ring current system. (It is significant to note that this period was also marked by ionospheric height oscillations at the different longitude sectors, to be discussed later). The presence of a somewhat stronger fluctuating component (with period of a few tens of minutes) in the dayside magnetograms having opposite polarities at Kodaikanal and Lunping separated by only 3 h, from 02 : 00 to 03 : 00 UT and afterwards getting in phase, suggests a certain longitude asymmetry in the ionospheric current system responsible for these modulations.

Although the IMF data were fragmentary, a sudden northward turning of IMF was noticeable at 22 UT and the high latitude magnetograms and *AE* indices (as discussed in the paper by Spiro *et al.*, 1988) suggested recovery of a substorm that had onset between 20 : 00 and 21 : 00 UT. Probably a second such event might have been responsible for a sharp increase at 23 : 45 UT on 6th October in the vertical ionization drift velocity, $V_z$, (eastward electric field) measured by Jicamarca radar. This electric field penetration occurred superimposed on the declining phase of the evening vertical drift prereversal enhancement that had its onset on this day at 18 : 00 LT (or 23 : 00 UT). These successive increases in the evening vertical drift velocity seem to have triggered the most intense 3 m irregularity plume event ever recorded by the Jicamarca radar (presented in the fig. 14 of the paper by Szuszczewicz *et al.*, 1988). In contrast to this the prereversal drift enhancement on the evening of 5th October (that was magnetically very quiet), though the data is incomplete, appears to have been much weaker (or non existent), as could be judged from comparison with the results presented by Fejer *et al.* (1979*b*) and no post-sunset irregularity event was observed as can be seen from figure 5. Numerous examples of spread-*F* irregularity generation triggered by magnetospheric electric field penetration to equatorial latitude have been presented and discussed by Fejer *et al.* (1979*a*) and Fejer (1986), but the present one is a unique case that illustrates

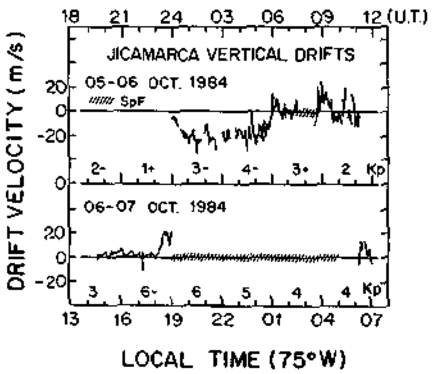


Figure 5

*Vertical ionization drift velocity of the F-region, measured by Jicamarca incoherent radar, during the afternoon morning period of 5-6 and 6-7 October 1984. Note that no evening spread-F onset took place on 5th October, and very strong irregularity plume occurrence was registered following the enhancement in the vertical drift beginning at 18 : 45 LT on 6th October.*

possible enhancement in bubble growth and 3 m irregularity development produced by an electric field penetration event that occurs under conditions that indicated an ambient unstable ionosphere.

The data on *F*-region height and spread-*F* (plotted in spread-*F* index code) for Brazilian low latitude station Cachoeira Paulista presented in figure 6 support the above conclusion. The conditions were favourable for plasma bubble generation in the equatorial ionosphere near the meridian of Cachoeira Paulista as indicated by the onset at 21 LT of the event over this station where the *F*-layer base height had passed through the prereversal evening enhancement (though seen at reduced magnitude at this low latitude station). The subsequent vertical uplift of the layer marked at 20 : 45 LT occurring almost simultaneously with the onset of the $V_z$ enhancement over Jicamarca (shown in fig. 5) seems to be responsible for the continuing higher than normal intensity of range spread-*F* (namely, plasma bubble event) which persisted till 03 : 45 on 7th. As in the case of Huancayo the night of 5-6 Ootober was characterized by a stable (or quiet) ionosphere over Cachoeira Paulista. This might suggest that the eastward electric field penetration event was responsible for the triggering, or intensification, of the plasma bubble event in an appreciably wide longitude range in the American sector.

In order to examine the global nature of this event we have compared in figure 7 the *F*-layer height response at a set of 3 stations mostly on the dayside in the Asian sector, namely, Ahmedabad, Hong Kong and Vanimo together with another set of 3 stations mostly on the nightside in the American-African sector, namely, Cachoeira Paulista, Dakar and Ouagadougou. (It should be mentioned that data from locations close to the magnetic equator which would have been better suited for studying electric field effects were not adequate for including in this comparative study). We may note that the height oscillations at the former set of stations during daytime hours from 01 UT onward are all nearly in phase which is very significant. The low latitude location of these stations might suggest possible role of neutral winds in the height oscillations. However, the large longitude separation of these stations (namely 70° between Ahmedabad and Vanimo) would make the neutral wind an unlikely candidate responsible for the in-phase height oscillations, although the *Dst* and magnetic disturbances at these times might indicate a presence of equatorward disturbance winds (see e.g., Sipler and Biondi, 1979 ; Hernandez and Roble, 1976 ; Mayr *et al.*, 1978 ; Rishbeth, 1975). The importance of a global scale electric field disturbance seems to be implied in these quasi simultaneous height oscillations in the Asian sector. It may be noted that the time of the onset of the large amplitude oscillations in this sector coincided approximately with the onset times of the effects in the American sector, namely, the eastward electric field increases over Jicamarca (fig. 5) and the *F*-layer height increases over Cachoeira Paulista marked at 23 : 45 UT, in figure 6. The polarity relationship of the electric field perturbations in the two longitude sectors near the onset of these effects is not clear, probably due to the varying degrees of sunrise related

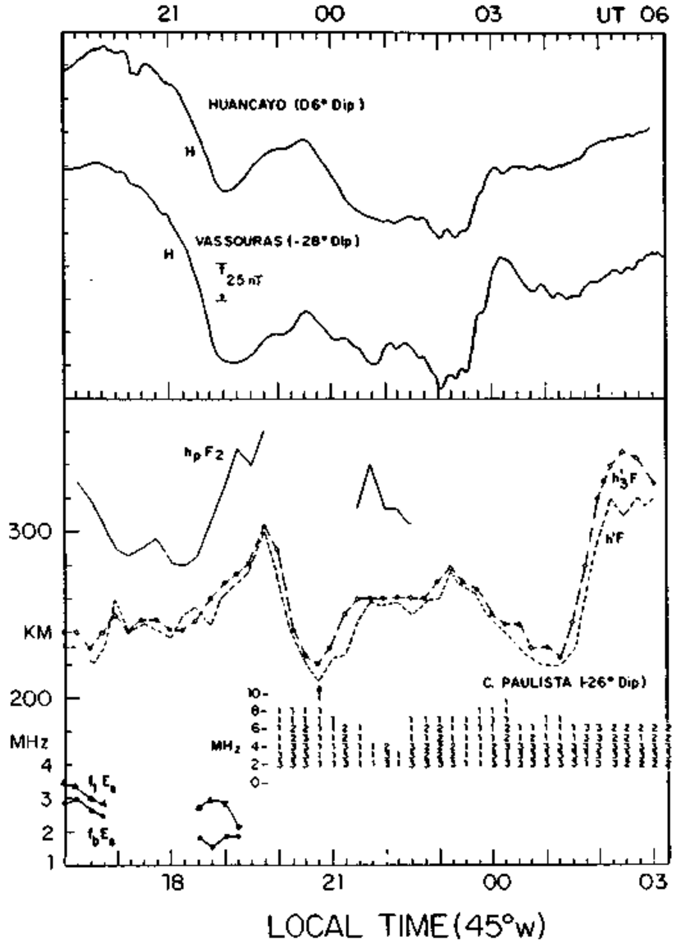


Figure 6

*Plots of magnetogram H-component variation over Huancayo and Vassouras (upper part) and h' F, $h_3F_2$ and hpF2, and spread-F index code (1, 2, 3, depending upon whether the spread range > 100 km, > 100 km < 200 km, or > 200 km, respectively) in function of ionogram frequency, over Cachoeira Paulista during the night of 6-7 October 1984. The vertical arrow (near h' F curve) indicates onset time of vertical ionization drift enhancement measured by Jicamarca radar.*

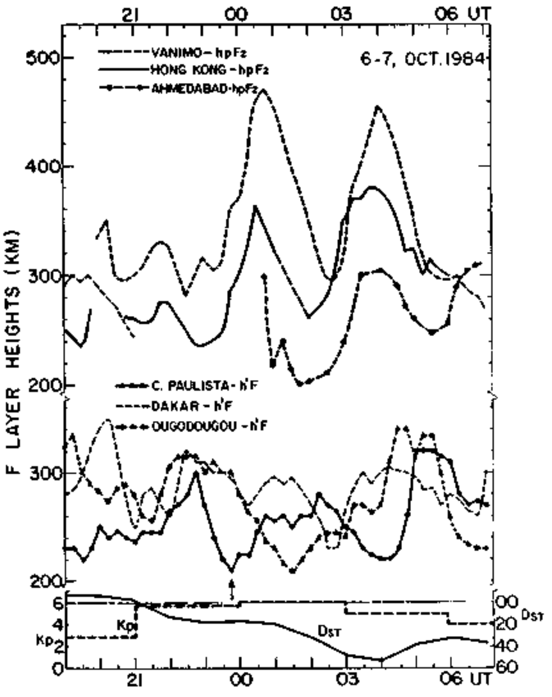


Figure 7

*Plots of hpF2 variations over Vanimo, Hong Kong and Ahmedabad in the Asian sector and h' F variations over Cachoeira Paulista, Dakar and Ouagadougou in the American and African sectors, on 6-7 October, 1984. Vertical arrow indicates the onset of the vertical drift enhancement registered by Jicamarca radar. The Dst and $K_p$ variations are shown in the bottom part of the figure.*

height variations (namely vertical ionization drifts) at the Asian sector. At later hours the oscillations over American and Asian longitudes seem to be anticorrelated suggesting that the disturbance electric field has opposite polarity in the two longitude sectors (see e.g. Fejer, 1986). The stations in the African longitude sector present ambiguous behaviours during this event. This and other complexities of this event could be arising from the varying degrees of the relative roles, possibly in function of the longitude sector, of the electric field and neutral winds. Results from stations close to the magnetic equator will be included in the follow up studies. The present results serve as an initial case study example of global coupling processes made possible by the SUNDIAL data sets. Better identification of the causal mechanism, namely, winds, or electric fields of direct penetration or that related to asymmetric ring current variations etc., should be possible from analyses of more cases which is a continuing SUNDIAL objective. Global analyses of ionosonde data are not only complementation to, but at times are useful substitutes for more costly, though more complete, radar measurements. This is an important point because Jicamarca is the only equatorial location where electric field measurements by the radar technique are presently available.

The direct electric field penetration effects discussed above were followed by after-effects in the *F*-layer densities and heights. These effects are associated with a disturbance dynamo (Blanc and Richmond, 1980) resulting from global thermospheric circulation changes and enhanced equatorward meridional winds (Rishbeth, 1975). From radar electric field measurements, Fejer *et al.* (1983) found the propagation time of the disturbance from high to equatorial latitude to vary from 16 to 24 h. Variations in $f_o F_2$ and *hpF*2 for Asian stations, Chung-Li (dip 34° N), Manila (dip 12° N) and in $f_o F_2$ for Pameung Peuk (dip − 35°) are presented in figure 8 for three days following the 6th October disturbances. Simultaneous variations in the horizontal intensity of the magnetic field over Lunping (dip 34° N) and Davao (dip 2° S) are also presented in the same figure. In each case the solid lines that represent the values for individual days are to be compared with a quiet day reference curve (broken line) in order to obtain the disturbance component in the respective parameters which, for positive disturbances, are shown by shaded region while blank region represents negative disturbances. The disturbance variation in the height is mostly positive at Chung-Li located close to the Appleton Anomaly crest and less so at Manila which is closer to the equator, where rather significant negative excursions were also observed. The peak layer density seems to show mostly negative storm effect near the anomaly crest region (Chung-Li, and Pameung Peuk) as seen clearly on 8th October, with the recovery

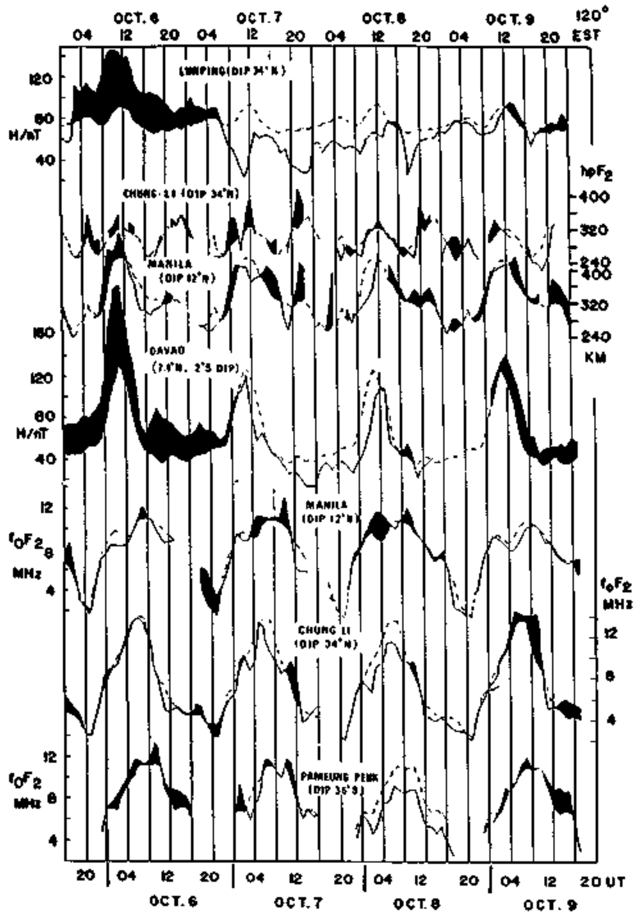


Figure 8
*hpF2 variations over Chung Li and Manila, and $f_o F_2$ values over Manila, Chung Li and Pameung Peuk and the magnetic field H-component for Lunping and Davao, all in the Asian low latitude sector, plotted in function of* 120° E *local time for* 6, 7, 8 *and* 9 *October* 1984.

marked by positive as well as negative excursions on the succeeding days not all shown here). Over Manila located equatorward the effect observed in $f_o F_2$ on 7th and 8th is relatively more positive. These effects are believed to be caused basically by the weakening of the equatorial anomaly development (Walker, 1981 ; Rajaram, 1977 ; Rush *et al.*, 1969) under the influences of the disturbance dynamo effect (Blanc and Richmond, 1980) and possibly the direct penetration electric field as well. Besides the disturbance dynamo electric field the neutral atmospheric variations associated with it affect the low latitude ionization distribution mainly in two ways. One of these arises from global circulation changes that could be accompanied by enhanced $[N2]/[O]$ ratio brought in from high latitude which in turn produces enhanced ionization loss rate giving rise to negative disturbance (Rishbeth, 1975). This factor, however, does not seem to be important in the present event since only severe storms could produce such effects at low latitude (Prölss, 1981). The other mechanism is based on equatorward meridional wind (Rishbeth, 1975) which might explain the positive height variations over Chung-Li and Manila (see also Chan and Walker, 1984). An equatorward meridional wind might explain also negative changes in density near the anomaly crest and positive change equatorward of it as follows. The anomaly latitudinal cross section is characterized by a positive latitudinal gradient in density from the equatorial trough up to the low latitude crest, after which the gradient turns negative. In the presence of such a latitudinal profile, (maintained by an $\mathbf{E} \times \mathbf{B}$ drift pattern weakened to some degree by the disturbance electric field, Woodman, 1970) an equatorward meridional wind could cause a reduction in the peak density near the crest, enhancing the densities equatorward of the crest. This occurs due to the transport of lower density ionization, across the negative gradient region, from poleward of the crest to the region of the crest in the original distribution, while transport across the positive gradient region enhances ionization equatorward of the crest. This process seems to have been at work on 8th October when $f_o F_2$ enhancement is seen over Manila (12° N) while Chung-Li and Pameung Peuk located closer to the anomaly crest registered negative density changes. On the other hand a reduced $\mathbf{E} \times \mathbf{B}$ drift could also produce similar effect on ionization densities. The negative height variations observed over Manila (for example, at the time of the positive effect in $f_o F_2$ on the 8th) would in fact suggest reduced $\mathbf{E} \times \mathbf{B}$ drift resulting possibly from a westward electric field. However, the absence of significant simultaneous height reduction over Chung-Li would imply action of an equatorward neutral wind. Thus a balancing of effects from equatorial disturbance electric field as well as disturbance neutral winds will be required to fully explain the equatorial anomaly response to storm effect. Similar analysis of storm effects has not been carried out for other low latitude stations. However, several cases analysed in detail using pre-SUNDIAL data sets for Brazilian stations, carried out with the help of tropical ionospheric model studies (De Paula, 1986), support the above explanation. Measurements using different techniques have confirmed the existence of thermospheric circulation changes and enhanced meridional winds during magnetically disturbed period (Hernandez and Roble, 1976 ; Reddy and Vasseur, 1972 ; Roper and Baxter, 1978 ; Sipler and Biondi, 1979).

On the other hand little is known about low latitude *F*-region zonal plasma motion under magnetic disturbances. Our knowledge is still more limited if we are to consider direct electric field penetration and disturbance dynamo effect in the zonal plasma motion. Zonal plasma bubble irregularity velocities measured on the nights of 5-6, 6-7, 7-8 and 8-9 October are presented in figure 9. These velocities were measured using an east-west VHF electronic polarimeter system (110 km base line) operated at the low latitude Brazilian locations, São José dos Campos and Cachoeira Paulista. It has been shown by Abdu *et al.* (1985*b*) that the velocities measured by the system represent zonal velocities of plasma bubbles with negligible contribution from their vertical motion. Further, the flux tube alignment and the vertical extension (in the equatorial plane) of the mature bubble structures, measured by the system, make their velocity approaching that of the ambient plasma velocity (see also Tsunoda *et al.*, 1981). Therefore these measurements provide an indication of the variations of the ambient plasma velocity during magnetic disturbances. On the night of 5-6 October, (quiet conditions) the eastward velocities during the pre-midnight hours were of the order of 100 m s$^{-1}$ whereas on the night of 6-7 and 7-8 (magnetically perturbed) the velocities marked significant increases reaching values of up to 170-190 m s$^{-1}$. (In the same way the early morning westward velocities also registered increases on the disturbed night). Similar results were also obtained from statistical analysis involving different, and more numerous, data sets representing a few months of 1982-83 period (Abdu *et al.*, 1985*b*).

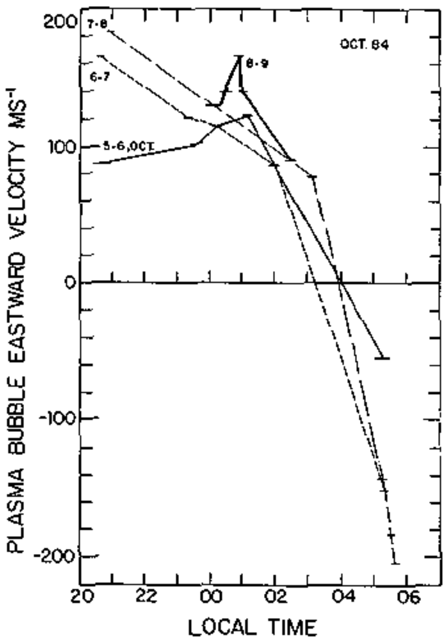


Figure 9

*Plasma bubble zonal velocities measured by the spaced* VHF *electronic polarimeter system operated in low latitude locations Cachoeira Paulista — São José dos Campos, in Brazil, plotted as a function of 45° W local time.*

Fejer *et al.* (1985) have pointed out that radar zonal plasma velocities over Jicamarca did not show any significant change with short-term fluctuations in magnetic activity. Rastogi *et al.* (1972) found that the average *F*-region east-west drifts on disturbed days were generally reduced in magnitude with respect to quiet days. Based on Fabry Pérot interferometer wind measurements, Meriwether *et al.* (1986) suggested that the major effect of geomagnetic storms « tends to be the reversal or weakening of zonal component of the meridional wind ». These latter results seem to be in agreement with the theoretical results on disturbance dynamo effect by Blanc and Richmond (1980) predicting westward and equatorward winds over low latitude. This wind system drives equatorward Pedersen current that causes charge accumulation and generation of poleward electric field, namely, vertical field over the equator, which in turn would produce westward drift of plasma in the ionospheric reference frame. The disturbance dynamo effect, thus, would be to reduce the eastward plasma velocities. Our results in figure 9 do not seem to fit in with this picture expected from disturbance dynamo effect. However, if we assume a certain degree of hemispheric asymmetry in the strength of the disturbance meridional wind then in the region of large magnetic declination angle that characterises our measurements it is conceivable to expect a resultant downward/equatorward electric field in a given flux tube and consequently an eastward plasma drift. But the existing neutral wind data are inadequate for supporting the validity of such a hypothesis. Since the *F*-layer heights were not markedly different at these local times on the different nights the possibility of ion drag effect causing the observed velocity changes is very unlikely. Under these circumstances, we are led to believe that the results in figure 9 could be significantly influenced by magnetospheric dynamo effect. *In situ* satellite measurements by Galperin *et al.* (1978) using Cosmos 184 satellite during October-November 1967 have indicated increases in the equatorial upward and eastward plasma drift when the interplanetary magnetic field component, $B_y$, reversed from negative to positive. IMF data during the SUNDIAL were rather incomplete for attempting to examine possible dependence of these velocities on IMF parameters. Accumulated data from future SUNDIAL campaigns should be useful for further investigation of this point.

## 4. DISCUSSION AND CONCLUDING REMARKS

The analyses of the SUNDIAL low latitude data set have in the first place focused attention on the global scale steady-state behaviour of the ionosphere, especially in as far as its predictability by global theoretical and empirical models is concerned. Comparative studies using the data for two reference days of the SUNDIAL period (during which the $\sum K_p$ varied from 13.9 on one day to 21.7 on the other) and the parameters calculated using the global theoretical ionosphere model (Sojka and Schunk, 1985) lead to the following conclusions. Different degrees of agreement between the observations and theoretical predictions were obtained depending upon the longitude sectors used in the comparison. In general the results of comparison emphasized the need to improve the existing models of quiet time low latitude electric field and neutral winds used as essential inputs in the theoretical model. For the « quiet day » conditions of the SUNDIAL period the models of these input parameters seem to depart from the real values to a greater degree in the American and African sectors than in the Asian sector. It is expected that the existing models of these key input parameters to the global ionospheric model will be improved progressively as more and more observational data become available. Such improvements should be considered with respect to their validity for different longitude sectors as well.

As pointed out earlier the zonal wind in the presence of finite magnetic declination angle contributes to the equatorial-low latitude ionization distribution mainly in two ways : through *a*) generation of a meridional wind component and *b*) control of the evening *F*-region dynamo electric field, especially in longitude sector of appreciable magnetic declination angle (see e.g., Abdu *et al.*, 1981 ; Batista *et al.*, 1986 ; Maruyama and Matuura, 1984 ; Tsunoda, 1985 ; Walker, 1981). Therefore both zonal and meridional wind data should be collected in a coordinated way for different longitude sectors as these are essential for a more realistic theoretical ionospheric prediction. Equatorial electric field data are presently available only over Jicamarca. With the help of such data, and from a knowledge of the winds and complementary ionospheric data coupled with theoretical model studies of the type carried out by Heelis *et al.* (1974) and Batista *et al.* (1986), it should be possible to construct more realistic vertical drift (electric field) models for different longitude sectors.

Comparison of our observational data with the International Reference Ionosphere model showed that this model is capable of predicting reasonably well the peak densities and heights of layer for the quiet days of the SUNDIAL 1984 campaign, namely October month of a low sunspot year, nearly for all longitude sectors.

The analysis on the equatorial-low latitude transient response to magnetospheric disturbances has brought out some new points on the different processes that operate in the coupling of these regions, besides providing complementary evidences to our present understanding of them. The main outcome of these studies are the following.

The disturbance equatorial electric field (associated with the IMF $B_z$ changes), occurring very close to the evening transition of eastward to westward ambient electric field, has eastward polarity. The enhanced *F*-region vertical drift, superimposed on the ambient *F*-region dynamo induced vertical drift, produces enhanced growth of plasma bubble irregularities as judged from the unprecedented more intense and longer duration 3 m irregularity plume activity observed over Jicamarca radar. The intensified disturbance electric field induced bubble activity seems to have covered most of the American longitude sector.

Globally coupled equatorial *F*-region height oscillations that occurred during this event suggest simultaneous electric field effects at day and night longitude sectors complementing the existing evidences on the electric field effects largely known from *E*-region data for much of the longitude sectors and from *E*- and *F*-region measurements over Jicamarca. Although the normal post-sunrise height variations (in the Asian sector) might have masked the polarity of the disturbances near the onset times the later data in the course of the event indicated opposite polarity for the height oscillations in the American (nightside) and Asian (dayside) sectors. It should be mentioned however that this conclusion could be significantly modified depending upon the nature of the disturbance neutral wind oscillation and its phase coherence in wide longitude ranges which at present are unknown. However it is significant that the low latitude magnetic field *H*-component also showed out-of-phase variations at the two longitude sectors for oscillations period of ~ 1 h or more although a clear cut correlation between the *H*-variation and the height oscillations could not be established for this event. More analyses should be carried out in this direction with objective to better identify the electric field effects from the different source discussed earlier in Section 3. In any case analysis of *F*-region height oscillations using a longitude chain of equatorial ionosonde (in conjunction with magnetometer data) seems to be a very promising technique for investigation of equatorial electric field penetration events especially when such a analysis is complemented by Jicamarca radar measurements. For much of the longitude sectors, where radars do not operate, ionosonde might be used to fill the gap once a certain correspondence is established between the ionosonde and radar interpretation of a given phenomenon where both the techniques are operated. This point will be receiving attention in the course of the future SUNDIAL campaigns.

The response of the equatorial-low latitude ionosphere to disturbance dynamo (and storm effects) are produced by competing effect of the equatorial disturbance electric fields as well as that of the disturbance neutral winds, the former acting in the entire anomaly latitude range while the effect of the later being confined mainly to the region around the anomaly crest. There is need to identify the relative importance of these parameters for different storm conditions and longitude sectors. Theoretical predictions of the expected effects will depend upon the detailed knowledge of these input parameters, as function of longitude sector as well.

The disturbance effect on the plasma bubble zonal velocities representing corresponding effects on the ambient plasma and neutral velocities need to be investigated further. Further aspects of elucidation regarding this and other different aspects briefly mentioned above will be subjects of attention for the future SUNDIAL campaigns.

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