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Longitudinal dependence of equatorial F region vertical plasma drifts in the dusk sector

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Abstract. The effect of solar activity on the postsunset peak of F region vertical plasma drift at Kodaikanal (77°28'E, dip 3°N) is determined as a function of season and for two levels of magnetic activity using extensive HF phase path observations and compared with that at Jicamarca (75°W, dip 2°N) reported in the literature. The postsunset peak vertical velocity V_{zp} at Kodaikanal increases linearly with 10.7-cm solar flux ($F_{10.7}$) irrespective of season and level of magnetic activity. The sensitivity of V_{zp} to solar flux changes is more at Jicamarca than at Kodaikanal during equinoxes and December solstice. This feature is virtually absent in June solstice. The seasonally averaged values of dusktime vertical velocity at Kodaikanal for moderate to high solar flux conditions and quiet magnetic conditions($Kp \leq 3$) are in reasonable agreement with those reported very recently for the Indian sector (80°E) from AE-E satellite data [*Fejer et al*, 1995]. In June solstice, the evening upward vertical velocities at Kodaikanal are, on the average, much smaller than in the Pacific sector (160°-200°E), while the postreversal downward velocities are more or less of the same magnitude in all longitude sectors except in the western American sector (230°- 310°E) where there they are higher. The present study supports the emerging view that the dusktime equatorial F region vertical plasma drifts exhibit large longitudinal variations during the June solstice.

1. Introduction

Vertical and zonal motions are a basic characteristic of the ionospheric plasma and they play an important role in determining the structure and dynamics of the coupled thermosphere-ionosphere system. In the vicinity of the magnetic equator, the F region plasma drifts affect the latitude/altitude distribution of the plasma density, the generation and evolution of equatorial spread - F (ESF) irregularities, the latitudinal variation of thermospheric winds, and the low-latitude protonospheric composition [e.g., *Kelley*, 1989]. Experimental data of plasma drifts therefore constitute a vital input for regional and global ionospheric models and also for assessment of the predictions of global atmospheric models [e.g., *Anderson et al*, 1987; *Heelis et al*, 1990; *Bailey et al*, 1993]. Detailed information of equatorial F region plasma drifts is available for the American sector, from the extensive measurements made with the incoherent scatter radar at Jicamarca (75°W, dip 2°N), Peru [e.g., *Fejer*, 1981; 1991]. Plasma drifts are also derived in recent times for other longitude zones from ground-based HF techniques like ionosonde and phase path sounder [e.g., *Batista et al*, 1986; *Namboothiri et al*, 1989; *Goel et al*, 1990; *Balan et al*, 1992; *Subbarao and Krishnamurthy*, 1994; *Sastri et al*, 1994; *Ramesh and Sastri*, 1995]. Measurements of ion drifts and vector electric fields with instrumentation aboard polar orbiting and low inclination satellites are a noteworthy addition to the studies of equatorial/low-latitude plasma drifts [e.g., *Coley and Heelis*, 1989; *Heelis and Coley*, 1992; *Fejer et al*, 1995]. Several theoretical and numerical models have been developed to explain the F- region plasma drifts in terms of electric fields generated by E and/or F - region dynamos [e.g., *Rishbeth*, 1971; *Heelis et al*, 1974; *Richmond et al*, 1976; *Farley et al*, 1986; *Crain et al*, 1993].

The equatorial F region vertical plasma drift is upward by day and downward at night with the transition occurring around sunset and sunrise [e.g., *Fejer*, 1981]. The daytime upward drift undergoes an enhancement in the dusk period before reversing to downward direction. The postsunset or prereversal increase is an important aspect of the diurnal pattern of vertical drift V_z and the peak value of the increase, V_{zp} exhibits a strong positive dependence on solar activity, as represented by the 10.7-cm radio flux or sunspot number [e.g., *Fejer et al*, 1991 and references therein; *Ramesh and Sastri*, 1995; *Fejer et al, 1995*]. The daytime up-

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ward drift in contrast is practically independent of solar activity. The response of V_{zp} to solar activity is seen even around the times of sudden and large changes in solar radiative output as for example, during March-June 1992 when the 10.7-cm solar radio flux decreased by 40 percent [*Sastri*, 1995a].

It is increasingly being realized in recent times that the morphology of equatorial F region vertical plasma drift (and hence of the causative zonal electric field) is longitude dependent [e.g., *Schieldge et al*, 1973; *Abdu et al*, 1981; *Deminov et al*, 1988; *Fejer et al*, 1991; *Ramesh and Sastri*, 1995]. The most recent study of Fejer et al [1995] based on AE-E satellite data shows that the longitudinal variations of F region vertical velocity are largest near the June solstice peaking near dusk and dawn and are virtually absent during equinoxes. The earlier work of *Coley et al* [1990] also shows the lack of any longitudinal effect in the equinoctial pattern of F region vertical drift. The conclusion that Jicamarca plasma drifts do not represent drifts in other longitude sectors, particularly during southern winter (June solstice) was also reached earlier by *Fejer et al* [1991]. Our recent studies showed that the behavior of the prereversal peak in vertical velocity, V_{zp}, over Kodaikanal in the Indian sector (75°E) is different in certain respects from that evidenced at Jicamarca in the American sector (75°W). For example, the sensitivity of the average V_{zp} to 10.7-cm solar flux (as represented by the slope of the line of best fit to data) is higher at Jicamarca than at Kodaikanal [*Ramesh and Sastri*, 1995]. In addition, during high solar activity conditions, there is no significant seasonal variation in V_{zp} at Kodaikanal, unlike at Jicamarca where V_{zp} is higher in equinoxes and December solstice by a factor of 2 or more than in June solstice [*Sastri et al*, 1994]. These results are based on measurements with the HF phase path technique at Kodaikanal over the period February 1991 to February 1993, corresponding to moderate to high solar activity epochs ($98 < F_{10.7} < 297$ flux units). we have now extended our database to the low solar activity epoch with the measurements made up to December 1994. In the present study, we use this large database to derive empirical formulae of the dependence of V_{zp} at Kodaikanal on solar flux as a function of season and for two levels of magnetic activity. The basic objective is to arrive at a more accurate definition of the longitudinal dependence of the solar flux variation of the dusktime peak of equatorial F region vertical velocity, through a comparison of our results with those reported by *Fejer et al.* [1991] for Jicamarca. We also attempt a comparison of the dusktime variation of vertical velocity over Kodaikanal with those reported by *Fejer et al.* [1995] for the four longitude zones from AE-E satellite data.

2. Experimental Technique and Data Analysis

The HF pulsed phase path sounder at Kodaikanal provides continuous information on the changes in phase path (P) of reflections from discrete ionospheric regions at normal incidence [*Sastri et al*, 1985]. The sounder consists of a broadband pulse transmitter, phase coherent receiver(s) with quadrature detection, a frequency synthesizer, timing and logic circuitry, and analog recording facilities. The system is rendered phase coherent by generating all the signals required for the transmitter and the receiver from a single 16.0-MHz temperature-controlled crystal oscillator with a frequency stability of better than 1 part in 10^7. The transmitter radiates pulsed RF energy (pulse width, 100 μs; pulse repetition rate, 50 Hz; peak power, 3 KW) on any chosen frequency in the band 2-20 MHz. In the receiver the phase of the ionospheric echo is compared at the intermediate frequency (IF) with two reference signals in phase quadrature (derived from the frequency synthesiser unit) in two separate phase detectors. The outputs of the two phase detectors are separately amplified and bandlimited by using low-pass filters. A gate pulse (width, 10 μs ; pulse repetition rate, 50 Hz) whose delay with respect to the transmitter pulse can be varied is generated in the frequency synthesizer unit and is fed to the receiver to activate the sample and hold (S/H) circuits in the quadrature channels. The quadrature channel outputs ($A \sin \phi$, $A \cos \phi$) of the receiver are used in a logic scheme (which essentially identifies the $2n\pi$ phase condition) to provide data on the sense and magnitude of the changes in phase path to the limit equivalent of a total phase path change of a wavelength, λ, of the probing radio waves. The time delay of the S/H gate pulse is adjusted to select the reflecting region (height resolution, 1.5 km) of interest. Data are recorded continuously on a strip chart recorder run at a speed of 10 cm/min, which gives a basic time resolution of 6 s. The sounder is operated on 4 MHz, and the phase path measurements at this frequency correspond to the bottomside F region during the evening period dealt with here.

The present work is based on the measurements made on 444 days over the period February 1991 through December 1994. The continuous data run varied from 3 to 14 hours on individual days over the time interval 1600-0600 IST(IST=UT+5.5 hours) depending on the ionospheric conditions. Recordings are discontinued if equatorial spread - F (ESF) conditions are seen on 4 MHz. The data thus correspond to bottomside F layer and under no-ESF conditions. There is a fairly uniform distribution of the observations over the seasons during the 47-month period, which covered high, moderate and low solar activity epochs. The 10.7-cm solar flux ($F_{10.7}$) varied in the range 70.3 to 296.6 flux units over the period. It is pertinent to mention here that the solar radiative output (as seen in conventional indiactors of solar activity such as 10.7-cm radio flux, 1-8 A° X - ray flux, Mg II core/wing index and Ca II K index) underwent a large and rapid reduction begining in March 1992 that resulted in a symbiotic response in the characteristics of the Earth's upper atmosphere [see *White et al*, 1994 and references therein; *Sastri*, 1995a]. Geomagnetic conditions varying from quiet (Ap = 2) to highly disturbed (Ap = 179) were encountered during the period of our plasma drift measurements.

It is appropriate to recall here the limitations of the HF phase path (Doppler) technique for study of F- region dynamics. The temporal changes in the phase path of ionospheric echoes during daytime are determined by the changes in the reflection height brought about by plasma transport processes as well as by changes in the electron density profile upto the reflection level. The latter depend in a complex way on ion production, chemical recombination and plasma transport. On the other hand, during nighttime, there is no plasma production and the *F*- region usually remains at high altitudes where the chemical recombination effects are not very significant. Under these physical conditions, the plasma density throughout *F*- region and the plasma density contours collectively come under the influence of transport mechanisms, permitting thereby straightforward derivation of information on plasma vertical drifts from observations of the temporal changes in the phase path. Direct experimental support for these arguments based on simple physical considerations has been provided by the comparative study of the simultaneous measurements of *F*-region vertical drift with the incoherent scatter (IS) radar and HF Doppler radar(modified version of digital ionosonde) at Arecibo [*Gonzales et al*, 1982]. The study amply demonstrated a good agreement between the IS radar and HF Doppler radar measurements of vertical drift throughout the evening-nighttime period but not during daytime. It is because of these limitations of the phase path technique that we restrict our measurements of *F*- region vertical plasma drifts to the evening-nighttime period.

For each night, the time rate of change of phase path, $\Delta P/\Delta t$ of the *F*- region reflections is calculated at 1-min intervals and then converted to vertical plasma drift V_z $(=1/2\Delta P/\Delta t)$. The data are analysed for information on steady vertical drift by computing the running averages of 1-min interval V_z with a 65-min window. This is done to suppress very short - period random fluctuations(if any) and the large amplitude (peak-to-peak amplitude 4-12 m/s) quasi-periodic variations of 5 - to 60 - min periods, which manifest quite commonly in the *F*- region V_z near the dip equator during the evening hours. These are believed to be due to zonal electric field variations associated with atmospheric gravity waves at *E/F* region heights [e.g., *Nair et al.*, 1992; *Subbarao and Krishnamurthy*, 1994, *Sastri*, 1995b]. The peak value of the prereversal enhancement in V_z (V_{zp}) is determined for each night for evaluation of its dependence on season and solar and geomagnetic activity. It is to be noted that the F-region vertical drift V_z derived from the time rate of change of phase path represents an apparent vertical drift as it includes the contribution due to the layer decay arising from chemical loss. *Bittencourt and Abdu* [1981] have shown that the effect due to layer decay is significant only when the height of reflecting layer is < 300 km. In the database used here, the height of bottomside *F*- region as ascertained from the ionograms of a colocated ionosonde as well as group delay (on 4 MHz) notings is < 300 km during the evening hours on 252 days out of the total 444 days. The values of V_{zp} for these 252 days are determined after applying the correction for layer decay. For this purpose, the expression given by *Titheridge and Buonsanto* [1983] is used to calculate the loss coefficient β, while the concentrations of neutral species are taken from the MSIS-86 model [*Hedin*, 1987] for the prevailing solar and geomagnetic conditions. The correction term $V_\beta = \beta L$ for the vertical drifts is computed for an assumed electron density scale length (L) of 10 km which is a fairly representative value for the evening equatorial *F* region [e.g., *Somayajulu et al*, 1991]. The correction to V_{zp} due to chemical loss is < 5 m/s on 238 out of the 252 days for which such corrections are made.

3. Results and Discussion

Figure 1 shows the variation of the average V_{zp} as a function of 10.7-cm solar flux separately for the three seasons: equinoxes (March-April, Sepetmber-October), northern summer (May-August) and northern winter (November- February). The patterns are derived by binning the daily values of V_{zp} according to the solar flux levels of 60-80, 80-100, 100-120,...,240-260, and computing for each bin the average values of the flux and the corresponding V_{zp}. The standard deviation of each average V_{zp} and the number of values used for the purpose are shown in Figure 1. The solid curves in Figure 1 represent the least squares linear fits to the data. Bins in which the total number of paired values of V_{zp} and $F_{10.7}$ are less than three are not used in the regression analysis but are shown in the figure for completeness. The empirical relationships between V_{zp} and 10.7-cm solar flux derived by *Fejer et al* [1991] for Jicamarca are also shown (as dashed lines) in Figure 1 to highlight, by comparison, the longitudinal differences in the solar flux variation of V_{zp} at the two dip equatorial stations.

It is quite evident from Figure 1 that V_{zp} at Kodaikanal bears a positive linear relationship to solar flux in all the seasons. The slope (b) of the lines of best fit indicates that the degree of dependence on solar flux is slightly more in equinoxes (b=0.1119) than either in December solstice (b=0.088) or June solstice (b=0.09). Though a similar positive dependence of average V_{zp} on the solar flux prevails at Jicamarca, the sensitivity of V_{zp} to solar flux changes is significantly higher in equinoxes and December solstice than at Kodaikanal. This longitudinal difference can be gauged from the fact that the slope of linear fit to Jicamarca data is higher by a factor of 2.6 and 2.8 in equinoxes and December solstice respectively than the corresponding values at Kodaikanal. It follows therefore that during epochs of high solar activity ($F_{10.7} > 180$ flux units), the prereversal peak of upward vertical velocity is significantly higher at Jicamarca than at Kodaikanal as can clearly be seen from Figure 1. At a solar flux level of 200 units for example, V_{zp} at Jicamarca is higher, on the average, by 82 and 86 per cent in equinoxes and December solstice respectively. This longitudinal effect is of immediate relevance to theoretical modeling studies of the equatorial ionosphere for which the vertical velocity is an important input [e.g., *Anderson et al*, 1987; *Bailey et al*, 1993]. During the June solstice, on the other hand, while a linear dependence of V_{zp} on solar flux prevails at Kodaikanal, a quadratic fit is found to better represent the data at Jicamarca [*Fejer et al*,

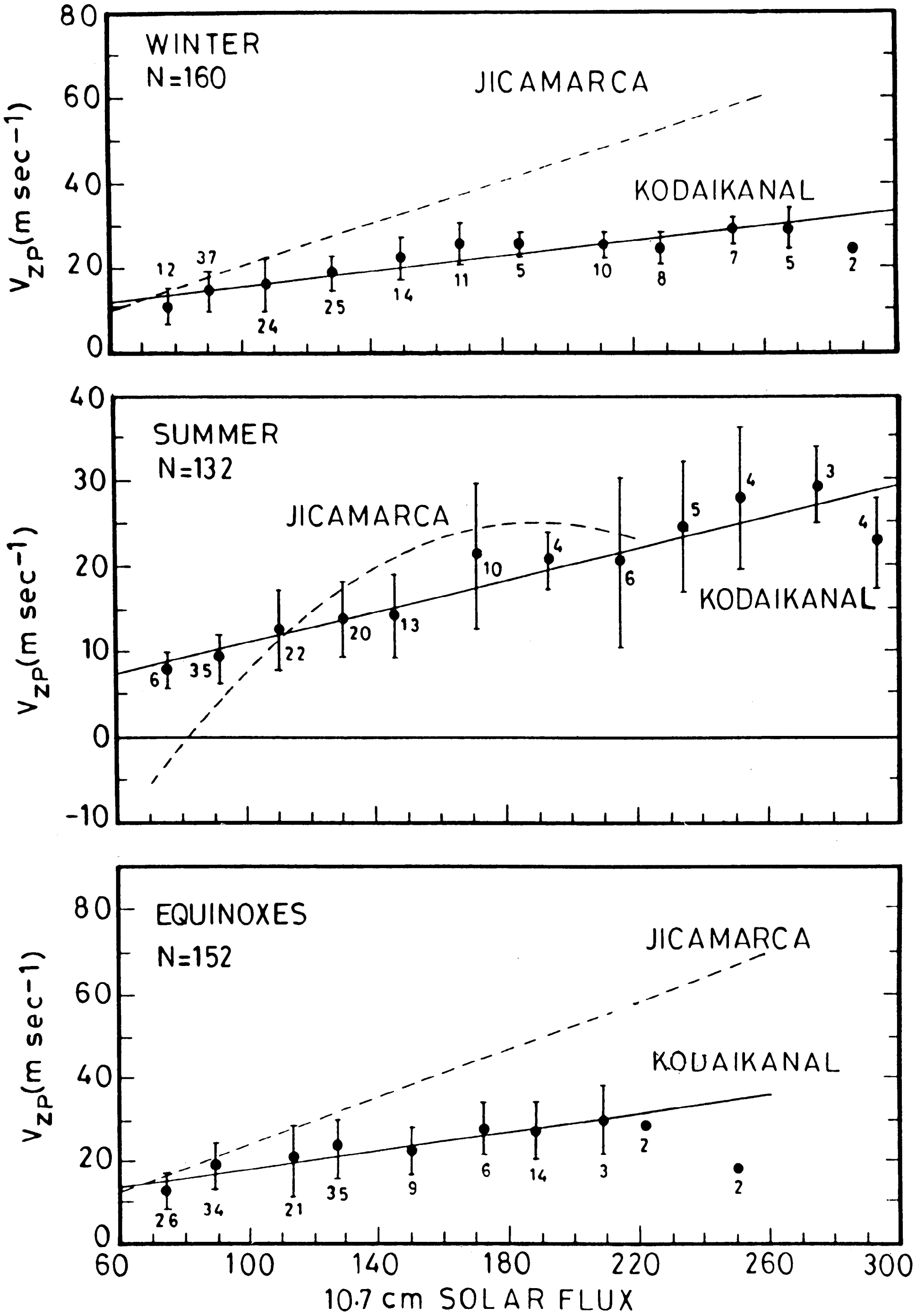

Figure 1. Variation of the average postsunset peak vertical velocity (V_{zp}) over Kodaikanal with 10.7-cm solar radio flux for the three seasonal groups of months: equinoxes (March-April), summer (May-August) and winter (November-February). Also shown are the standard deviation and the number of values used for each average and the lines of best fit to the data. The dashed lines represent the solar flux variation of V_{zp} over Jicamarca, Peru adopted from *Fejer et al,* [1991].

1991]. However, the important point here is that for moderate to high solar activity conditions($120 < f_{10.7} < 220$ flux units), the average values of V_{zp} are more or less the same at Kodaikanal and Jicamarca, unlike in equinoxes and December solstice as can be seen from the middle panel of Figure 1 (note the enlarged scale of V_{zp} in the middle panel). This indicates that the difference in the response of V_{zp} to solar activity between the Indian and Peruvian equatorial regions is depends on season.

The solar flux variation of V_{zp} at Kodaikanal is also studied for two levels of magnetic activity represented

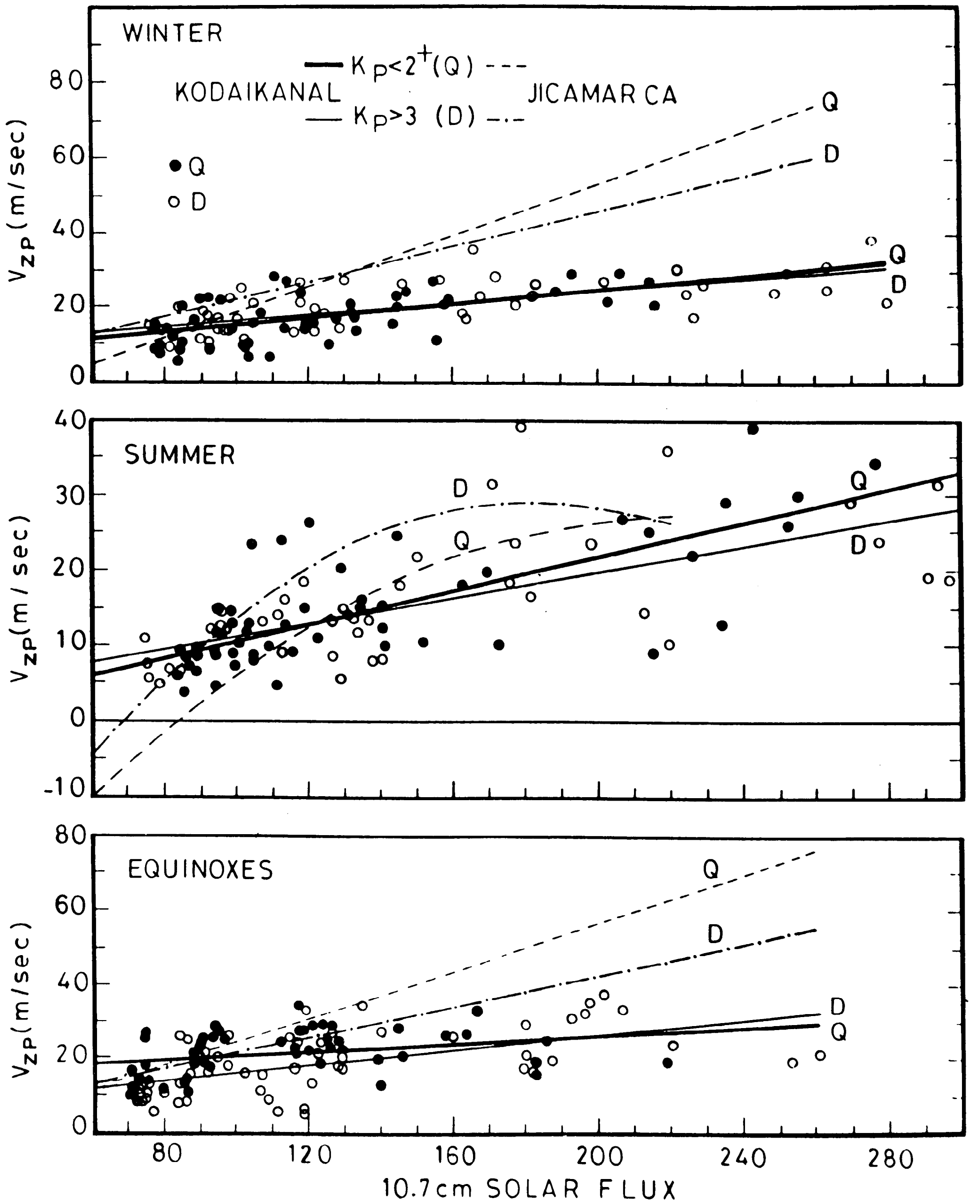

Figure. 2. Postsunset peaks of vertical velocity over Kodaiknal as a function of solar flux on individual days during the three seasons and for two levels of magnetic activity. The solid lines represent the best fits to data. The corresponding fits to Jicamarca data adopted from *Fejer et al*, [1991] are also shown for comparison.

by conditions with Kp index $\leq 2^+$ and > 3. The result is presented in Figure 2 in the same format as of Figure 1. Here we have used V_{zp} values on individual days rather than binning the velocity data according to the solar flux level. This is done to facilitate a direct comparison with the results of *Fejer et al* [1991] for Jicamarca. The following are the noteworthy features in Figure 2. At Kodaikanal, there is no significant effect of magnetic activity on V_{zp} at any level of solar flux in December and June solstices. In equinoxes there is a trend of a decrease in V_{zp} with magnetic activity but only during moderate solar activity periods ($F_{10.7}$ 100-120 flux units) as can be seen from the lower panel of Figure 2. These results are consistent with our recent recent studies which showed the absence of a systematic and significant effect of magnetic activity on V_{zp} at Kodaikanal, except during equinoxes of moderate solar activity [*Sastri et al*, 1994; *Ramesh and Sastri*, 1995]. It is therefore not surprising that V_{zp} at Kodaikanal exhibits a positive dependence on solar flux more or less independent of magnetic activity in all the seasons as evidenced in Figure 2. At Jicamarca, on the other hand, V_{zp} is more sensitive to magnetic activity. As can be seen from Figure 2, while V_{zp} tends to decrease with magnetic activity in equinoxes of high solar activity periods, it tends to increase in June solstice (local winter) of low to moderate solar activity conditions [see *Fejer et al*, 1989; 1991]. The net result of these differing geomagnetic activity effects on V_{zp} at Jicamarca and Kodaikanal is that the average V_{zp} persists to be significantly higher at Jicamarca compared to Kodaikanal, during equinoxes and December solstice of moderate to high solar activity epochs independent of magnetic activity. In other words, the difference in the solar flux variation of V_{zp} in the Indian and Peruvian sectors manifests irrespective of magnetic activity.

Fejer et al [1995] developed a global model of equatorial F region vertical plasma drifts valid for moderate to high solar activity (average $F_{10.7}$ 160-180 flux units) and for magnetically quiet conditions ($Kp \leq 3$), using AE-E satellite data between January 1978 and December 1979. Excellent agreement is noticed during the December solstice between the radar measurements of vertical drifts at Jicamarca and the satellite measurements for the western American (260°E) sector. Very good agreement is also seen in equinoxes except that the satellite data show larger upward drifts in the forenoon and reduced downward drifts in the postmidnight hours. It is only in the June solstice that significant discrepancies are found between the two data sets in the form of larger (smaller) daytime (nighttime) drifts in satellite data. We have attempted a comparison of the dusktime vertical plasma drifts at Kodaikanal with the AE-E satellite measurements for the Indian sector (80°E). The outcome is presented in Figure 3 separately for the three seasonal groups of months. We have ensured the similarity in the prevailing solar-geophysical conditions between the two data sets. In our data sample, the average values of 10.7-cm solar flux for equinoxes, December and June solstices are 176, 178, and 167 respectively, which are within the range of 160-180 flux units used by *Fejer et al.* [1995]. As can be seen from Figure 3, the average values of vertical velocity at Kodaikanal in the evening hours are marginally lower (higher) than the satellite measurements in equinoxes and December solstice (June solstice). The time span of comparison between the two sets of measurements is rather limited in equinoxes and December solstice due to lack of enough observations at Kodaikanal caused in part, by the occurrence of spread -F conditions in the postsunset hours (we discontinue observations once spread -F condition sets in on the probing frequency as mentioned earlier). Bearing in view the spatial averaging procedures used in the analysis of the satellite data, we do not attach much significance to these small differences and consider the agreement between Kodaikanal drifts and the satellite drifts as reasonably good for the dusk period in the Indian sector.

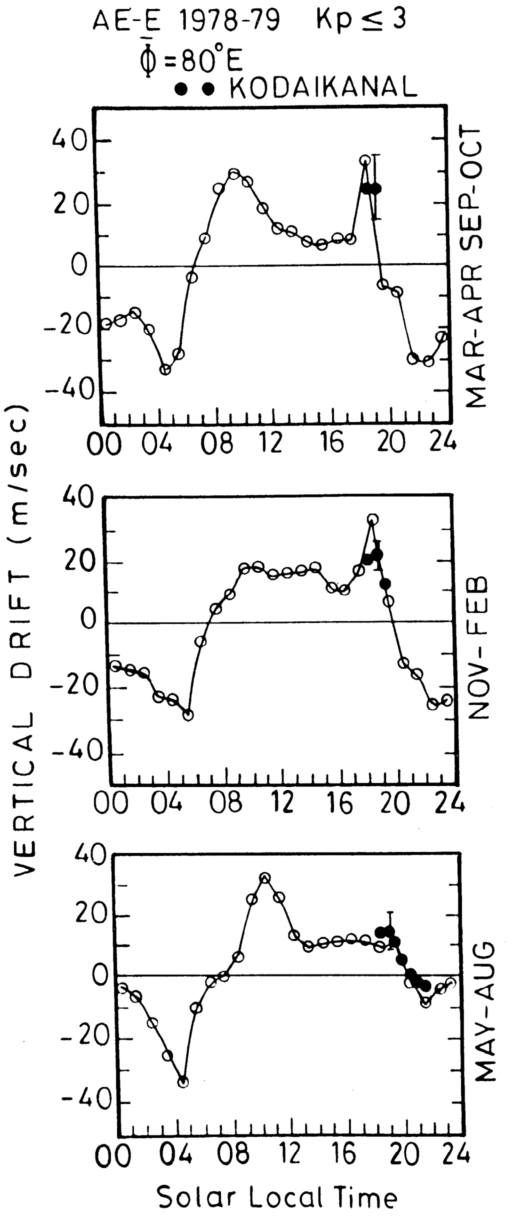

Figure. 3. Empirical model of vertical velocity for the Indian zone (80°E) for moderate to high solar flux conditions and magnetically quiet conditions derived from AE-E satellite data [after *Fejer et al*, 1995]. The evening pattern of vertical velocity over Kodaikanal for similar solar and geophysical conditions is also shown.

We have also examined the dusktime pattern of vertical velocity at Kodaikanal during the June solstice against the patterns reported by *Fejer et al* [1995] from AE-E satellite measurements for the other longitude zones. Their results which pertain to moderate to high solar activity epochs and magnetically quiet conditions are reproduced in Figure 4. That the average prereversal upward vertical velocity exhibits marked longitudinal variations during the June solstice is quite evident in Figure 4. The longitudinal dependence is characterized by a relatively large prereversal enhancement of drifts in the Pacific sector (160°-200°E), and the earliest reversal of vertical drift to downward direction in the western American sector. The average vertical velocity pattern at Kodaikanal for similar solar and geophysical conditions plotted in Figure 4 clearly shows that, in June solstice, the abnormally large prereversal upward drifts are confined essentially to the Pacific sector. There is no significant difference between the drifts in the western American sector (230°-310°E) and Kodaikanal drifts which is consistent with the results presented in the previous section (see middle panel of Figure 2). The postreversal downward drifts, on the otherhand, are more or less of the same magnitude (5-

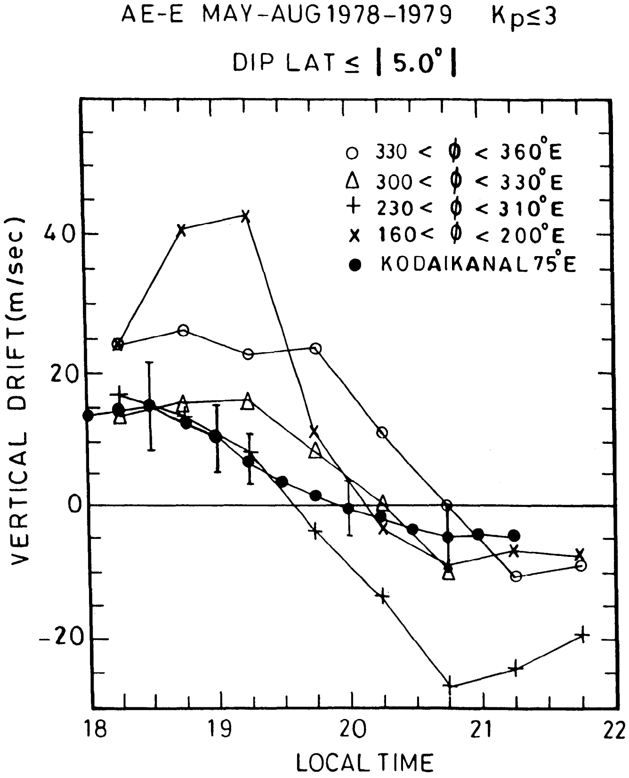

Figure. 4. Time variation of average vertical velocity in the evening hours for different longitude zones during moderate to high solar flux and magnetically quiet conditions of June solstice derived from AE-E satellite data [after *Fejer et al*, 1995]. The evening pattern of vertical velocity over Kodaikanal for similar solar and geophysical conditions is also shown.

10 m/s) at all longitudes except in the western American sector where they are significantly higher (15-27 m/s). We believe the reduced postreversal downward velocities which are seen at longitudes other than of Jicamarca (in AE-E satellite data as well as groundbased observations at Kodaikanal) to be a genuine feature of geophysical origin rather than a (unknown) bias in the satellite data.

It is generally accepted that the prereversal enhancement of *F* region upward drift in the vicinity of the dip equator is due to an increase of zonal electric fields due to the *F* layer dynamo mechanism, which gains prominence at sunset when the *E* region conductivity rapidly decreases [*Rishbeth*, 1971; *Heelis et al*, 1974; *Batista et al*, 1986; *Farley et al*, 1986; *Goel et al*, 1990 ; *Crain et al*, 1993]. The basic ingredients of the *F* layer dynamo effect are the thermospheric zonal winds, the ratio of the field-line-integrated Pedersen conductivities of *E* and *F* regions and, more importantly, the longitudinal (local time) gradients in *E* region conductivity (due to the offset between the magnetic flux tubes and the solar terminator) and in the zonal neutral wind. The theoretical simulations of *Crain et al* [1993], in fact, show that the longitudinal gradient in thermospheric zonal winds acting in conjunction with that in the *E* region conductivity is primarily responsible for the dusktime increase of *F* region vertical velocity near the dip equator.

The positive response of V_{zp} over Kodaikanal and Jicamarca to solar flux changes may therefore be understood in terms of changes in the longitudinal gradient of *E* region conductivity, as it is estimated to decrease by a factor of 2 from high to low solar activity [*Goel et al*, 1990]. There may also be an important contribution from the solar flux related changes in thermospheric zonal winds, particularly in their longitudinal(local time) gradients. Using the published results of F region zonal plasma drifts at Jicamarca [*Fejer et al*, 1985; 1991], we have shown very recently that the dusktime temporal gradient in F region zonal plasma drift increases with solar activity [*Sastri*, 1995a]. This implies a similar variation in the temporal gradient of thermospheric zonal wind as well, because the gross diurnal pattern of the equatorial *F* region zonal plasma drifts agrees well with that of the zonal neutral winds [*Fejer et al*, 1985; *Herrero et al*, 1985]. It is not unreasonable, therefore, to attribute the positive dependence of the dusktime peak in equatorial *F* region vertical drift to corresponding changes in the longitudinal (local time) gradient of *E* region conductivity as well as of *F* region zonal neutral wind. The significant differences in the magnitude of the solar activity effect on prereversal peak in vertical velocity between the Indian and Peruvian dip equatorial regions may then be due to differences in the dusktime gradients of zonal winds and E region conductivity. Systematic and extensive observations of thermospheric zonal winds and/or *F* region zonal plasma drifts at equatorial stations in the various longitude sectors will help ascertain the origin of the longitudinal dependence of dusktime *F* region vertical plasma drifts discussed here.

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