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Response of equatorial *F* layer vertical drift in the dusk sector to the change in the radiative output of the Sun in 1992

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Abstract. A study is made of the effect of the rapid and large decline in the solar radiative output that occurred from March through May 1992 on the postsunset maximum in *F* layer vertical drift V_{zp} over Kodaikanal (dip 3°N). Between the periods July 1991 through February 1992 and June 1992 through February 1993, there is a 35 % decrease in the mean amplitude of the postsunset peak in *F* layer vertical drift (V_{zp}) over Kodaikanal, corresponding to the 40 % decrease in the mean level of the 10.7-cm solar radio flux. Changes of the same magnitude are also seen when the comparison is restricted to a shorter interval of two local winter months preceding and following the rapid decline in the 10.7-cm flux. The results illustrate the sensitivity of equatorial *F* layer vertical drift in the dusk sector to short-term variability in the solar radiative output. Solar flux related changes in the longitudinal (local time) gradient in *E* region conductivity as well as in the *F* region zonal winds are suggested as the cause of the positive response of the dusktime peak in *F* layer vertical drift to the rapid decline in solar radiative output that occurred in early 1992.

1. Introduction

Beginning in March 1992 the radiative output of the Sun underwent a large and rapid reduction which apparently ended in June of the same year. The reality of the decline is confirmed from independent ground and space measurements of solar UV spectral irradiance and conventional indicators 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 [see *White et al*, 1994, and references therein]. Between the periods December 1991 through March 1992 and June 1992 through December 1993, the integrated intensity in Lymanα flux decreased by 15 % and the 10.7- cm radio flux by 40 %. The situation regarding the change in total irradiance is under assessment and the first indication is a reduction of the order of 0.4 W/m^2 [*White et al*, 1994]. This solar event, which occurred on the descending phase of cycle 22, is perceived to have the potential to advance our understanding of the physical mechanisms underlying the loss of radiative energy on the Sun on the one hand and of solar-terrestrial coupling on the other.

The well-documented reduction in solar radiative output that occurred in early 1992 can be expected to have affected the Earth's thermospheric density and temperature, in view of the known sensitivity of this medium to EUV radiation and the fact that both UV and EUV emissions follow the level of solar activity [e.g., *Roble*, 1987; *Lean*, 1987]. Analysis of UARS orbital data indeed showed a rapid and sustained decline in the orbital decay rate in consonance with that in the Lyman$_\alpha$ irradiance, confirming the anticipated effect of the sudden change in solar radiative output on the atmospheric drag [*White et al*, 1994].

Against this background we examine here the response of the Earth's ionosphere in particular, the equatorial *F* layer vertical drift (V_z) in the dusk sector to the change in solar radiative output that occurred in 1992. It is known that near the dip equator the *F* layer vertical drift during the evening period is strongly dependent on the degree of solar activity as represented, for example, by the 10.7-cm radio flux [*Fejer et al*, 1979, 1991; *Namboothiri et al*, 1989; *Goel et al*, 1990]. It is to be noted that the evidence for the solar flux dependence of *F* layer vertical drift is derived, for example, from analysis of incoherent scatter radar/ionosonde measurements spread over several years corresponding to different phases of the solar cycle. The solar event of 1992, on the other hand, provided an unique opportunity to assess the solar flux dependence of the equatorial *F* layer vertical drift on shorter time scales. We have used for the present work the database of evening *F* layer vertical drift over Kodaikanal (10°14'N, 77°28'E, dip 3°N), developed from regular measurements with the HF phase path sounder over the period 1991-1993. The study showed a precipitous decrease in the amplitude of the postsunset or prereversal peak in upward *F* layer vertical drift (V_{zp}) over Kodaikanal, as the radiative state of the Sun suddenly changed from that of high output to that of low output from March through May 1992.

2. Measurement Technique

The HF pulsed phase path sounder at Kodaikanal provides continuous information on the changes in

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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 ϕ, A cos ϕ) 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.

3. Results

The present work is based on phase path measurements made fairly regularly over the period July 1991 through February 1993 during the evening hours. For each day the time rate of change of phase path, $\Delta P/\Delta t$, of the F region echoes is calculated at 1-min intervals and converted to vertical drift V_z ($= 1/2\ \Delta P/\Delta t$). Running averages of 1-min V_z values are computed with a window of 65-min width to supress the short-period (T < 1hr) fluctuations, which prevail quite commonly in F region vertical drift near the dip equator and which are generally considered as the signatures of atmospheric gravity waves [e.g. *Earle and Kelley*, 1987; *Nair et al*, 1992]. The postsunset peak in upward vertical drift (V_{zp}) is determined for each day from the ambient V_z pattern thus derived. Because of the frequent occurrence of spread-F conditions, particularly in equinoctial and local summer months, V_{zp} could not be determined with any certainity on some nights. A database of 201 nightly values of V_{zp} became available over the 20-month period mentioned above for study in relation to the solar radiative output.

It is to be noted that F region vertical drift from $\Delta P/\Delta t$ represents an apparent drift because of the contribution from layer decay due to chemical loss. The upward vertical drift due to layer decay is, however, significant only when the height of reflecting layer is <300 km [*Bittencourt and Abdu*, 1981]. In the data base used here, the height of bottomside F region (h' F) scaled from ionograms of a co-located ionosonde is >300 km during the evening hours over the entire period July 1991 through April 1992. It is only from May 1992 that this physical condition is usually not met, necessitating the application of corrections for layer decay. In all, the chemical loss corrections are applied to V_{zp} on 79 days. The correction term is $V_\beta = \beta L$, where β is the loss coefficient and L is the electron density scale length. β is computed from the expression of *Titheridge and Buonsanto* [1983] with the neutral species concentrations taken from MSIS-86 model [*Hedin*, 1987] for the relevant solar and geophysical conditions. Chemical loss corrections are made with an assumed L value of 10 km, which is a fairly representative value for the evening equatorial F region [e.g., *Somayajulu et al*, 1991]. Of the 79 days, the correction term, V_β is <5 m/s on 65 days and is between 5 and 10 m/s on 12 days.

Fig.1. illustrates the sudden and significant reduction in the solar radiative output that occurred in early 1992 and the response of V_{zp} over Kodaikanal, through a display of the daily values of the 10.7-cm ratio flux and V_{zp} over the period July 1991 through February 1993. The rapid decline in the solar 10.7-cm flux begining in March 1992 and apparently ending in June 1992 can clearly be seen in Figure 1. This remarkable change is superimposed on quasi-periodic variations in the 10.7-cm flux that represent the solar 27-day rotational modulation, which continued after the decline also but with a smaller amplitude. Between the intervals July 1991 through February 1992 and June 1992 through February 1993 the mean level of 10.7-cm solar radio flux decreased by 37.4 % from 206 units to 129 units. The level of the 10.7-cm radio flux after the decline is, however, well above the values characteristic of solar minimum conditions.

The data presented in Figure 1 show some of the known features of V_{zp} at dip equatorial latitudes such as its ubiquitious day-to-day variability and seasonal dependence. The seasonal variation which is characterized in the Indian sector by higher values of V_{zp} in equinoxes compared to local summer [*Namboothiri et al*, 1989; *Goel et al*, 1990], is apparent in the 1992 data of Kodaikanal shown in Figure 1. V_{zp} is, in general, higher in September-October 1992 than in June-July of the same year, whereas the low values of V_{zp} in May could have contributions from the regular seasonal variation as well as the rapid decline in the solar 10.7-cm flux that began in March 1992.

There is indeed an unambigious change in the amplitude of V_{zp} over Kodaikanal in consonance with the sudden change in the 10.7-cm solar radio flux. In the interval prior to the decline (July 1991 through February 1992), V_{zp} varied in the range 16.1-39.0 m/s with a mean value of 25.6 ± 5.0 m/s. During the period of sustenance of low radiative output that followed the decline (June 1992 through February 1993), V_{zp} varied

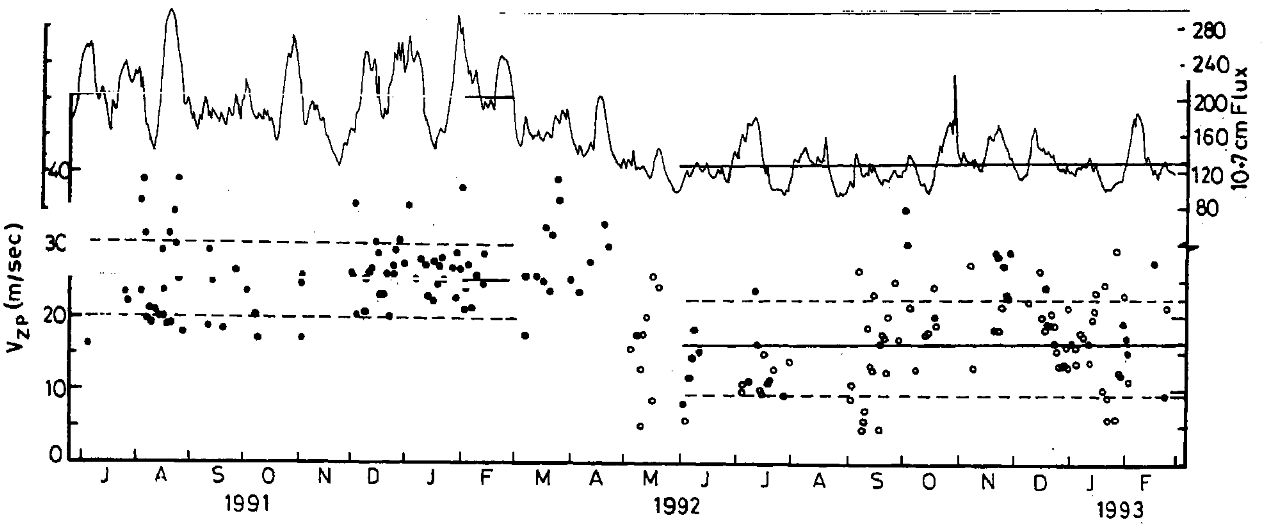

Figure 1. Daily values of the solar 10.7-cm radio flux(in units of 10^{-22} W/m^2) and the dusktime peak in F layer vertical drift (V_{zp}) over Kodaikanal(dip 3° N), India, during 1991-1993. The horizontal lines on the plots represent the mean levels of the parameters for the intervals: July 1991 through February 1992 and June 1992 through February 1993. Open circles represent V_{zp} values corrected for chemical loss effects. The standard deviations of the mean levels of V_{zp} for the two intervals are also shown(horizontal dashed lines).

over the range 2.8-35.1 m/s with a mean value of 16.7 ± 6.8 m/s. There is thus a ~ 35 % decrease in the mean level of V_{zp} in association with the ~ 40 % reduction in the 10.7-cm radio flux in the intervals before and after the sudden change in the solar radiative output. The mean level of the geomagnetic Ap index also decreased from 24.2 to 16.1 between the periods July 1991 through February 1992 and June 1992 through February 1993 (not shown here).

To bring out more clearly the transition in the mean state of V_{zp} over Kodaikanal brought about by the solar event in early 1992, which is superposed on the day-to-day and seasonal variations, we present in Figure 2 the distributions of the daily values of the 10.7-cm radio flux, V_{zp} over Kodakiakanl and the geomagnetic Ap index for the intervals December 1991 through January 1992 and December 1992 through January 1993. This is done because of the availability of a rather large and equal number (N = 34) of V_{zp} measurements only in these winter months preceding and following the solar event. The solar flux values are considered here only for those days for which plasma drift measurements are available at Kodaikanal. The definite shift in the distribution of the 10.7-cm flux to lower values after the solar event in early 1992 is quite obvious in Figure 2a. The mean va;ues of the 10.7-cm flux are 213 and 143.9 units respectively during the periods December 1991 through January 1992 and December 1992 through January 1993, constituting a reduction by ≈ 41 % between the two epochs. A similar shift in the distribution of V_{zp} over Kodaikanal to lower values is apparent in Figure 2b. While V_{zp} is >20 m/s throughout the period December 1991 through January 1992, it is <20 m/s on ≈ 71 % of the days during December 1992 through January 1993. The mean values of V_{zp} are 26.6 m/s and 17.2 m/s in the two intervals representing a 35.4 % decrease in V_{zp} corresponding to the ≈ 41 % reduction in the 10.7-cm flux. The result is thus the same as the one obtained from a comparative study of V_{zp} over a longer interval of 8-9 months (June/July- February) presented earlier. This feature indicates that the transition in the mean state of V_{zp} over Kodaikanal in reponse to the solar event in 1992 is a genuine one and is not significantly affected by the day-to-day and seasonal variations. It is pertinent to add here that there is no marked change in the mean level of Ap index in local winter months that preceded and followed the solar vent as can be seen from Figure 2c. Ap is <30 throughout the interval December 1991 through February 1992 with a mean value of 14.3, and during December 1992 through January 1993 it is <30 on 91 % of the days with a mean value of 14.5.

4. Discussion

The dusktime enhancement of F region upward drift in the vicinity of the dip equator is widely accepted as due to an increase of the 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]. The very recent work of *Crain et al* [1993], in fact, highlights the importance of F region dynamo as a source of low-latitude electric fields at all local times from self-consistent calculations of the plasma distribution and the dynamo-generated potential distribution. The basic ingredients of the F layer dynamo effect are the F region zonal winds, the ratio of the field-line-integrated Pedersen conductivities of E and F regions and, more important, the longitudinal (local time) gradients in E

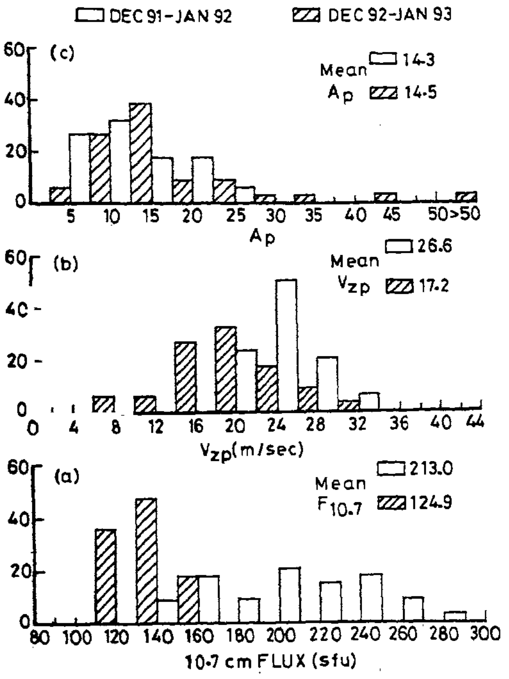

Figure 2. Distribution of the daily values of the 10.7-cm radio flux (1 sfu=10^{-22} W/m^2), V_{zp}, and geomagnetic *Ap* index for the periods: December 1991 through January 1992 and December 1992 through January 1993, representing respectively the epochs before and after the sudden and significant decline in solar radiative output in early 1992. Mean levels of the physical parameters are also given for the two periods.

region conductivity due to the offset between the magnetic flux tubes and the solar terminator, and the zonal neutral wind.

According to the current understanding of the electrodynamics of the evening equatorial ionosphere, the seasonal variation of V_{zp} over Kodaikanal may be attributed, at least in part, to seasonal changes in the longitudinal gradient of field-line-integrated *E* region conductivity. The times of sunset at the two conjugate *E* regions corresponding to *F* region over Kodaikanal are nearsimultaneous around the equinoxes and differ by up to about 35 min during local winter and summer months (see Figure 9 of *Goel et al*, [1990]). The duration of sunset (which represents the longitudinal gradient in *E* region conductivity) thus varies through the year, modulating, in turn, the buildup of vertical polarization electric fields and the associated enhancement of zonal electric field to cause higher values of V_{zp} in equinoxes compared to winter and summer.

The response of V_{zp} over Kodaikanal to the rapid decline in solar 10.7-cm flux in early 1992 may be understood in terms of changes in the logitudinal 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 *F* region zonal winds. The recent work of *Biondi et al* [1991] indeed provided the experimental evidence for a positive dependence of equatorial thermospheric zonal winds (at Arequipa, Peru) on solar activity. But the observed increase in zonal winds from solar minimum to maximum is rather modest, indicating the prevelance of damping mechanisms such as ion drag (which increases with solar activity) as well as other factors such as upward propagating waves from the middle atmosphere which are difficult to assess. Moreover, what is important is not just the absolute magnitude of the wind but its longitudinal gradient. The simulations of *Crain et al*, [1993], in fact, showed that the longitudinal gradient in zonal winds acting in conjunction with that in the *E* region conductivity is primarily responsible for the dusktime increase of *F* region vertical drift near the dip equator. Optical measurements of the type reported by *Biondi et al* [1991] are not particularly suitable for evaluation of the dusktime temporal gradients in the zonal winds as they typically cover the period after local sunset. It is known that 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]. We have therefore examined the variation of the temporal gradients in *F* region zonal plasma drifts at Jicamarca(dip 2°N) with the level of solar activity from the published work. *Fejer et al* [1985] documented the average patterns of zonal plasma drifts at Jicamarca for the periods 1974-1977,1970-1971, and 1978-1981, with average sunspot numbers (during the months of observations) of 25, 80, and 170, respectively. The longitudinal(local time) gradient in zonal plasma drift at 18 hours LT(19 hours LT) estimated from Figure 2 of *Fejer et al* [1985] showed a systematic increase from ~ 50 m/s/hour (~ 47m/s/hour) during 1974-1977 to ~ 60m/s/hour(~ 58m/s/hour) during 1970-1971 to ~ 105m/s/hour(~ 92m/s/hour) during 1978-1981. A similar increase in the zonal wind gradient with solar activity is also evident in the results of *Fejer et al* [1991] exclusively for the equinox season (see Figure 7 of their paper). Between the epochs of moderate solar acitivity ($100 < F_{10.7} < 150$ units) and high solar activity($F_{10.7} > 150$ units), the temporal gradient in zonal plasma drift at 18 hours LT (19 hours LT) increased from ~ 58m/s/hour (~ 68m/s/hour) to ~ 95m/s/hour(~ 94m/s/hour). These numerical values estimated from experimental data clearly demonstrate a positive dependence of the dusktime temporal gradient in *F* region zonal plasma drift and hence in the thermospheric zonal neutral wind on solar activity. It is not unreasonable,therefore, to attribute the observed positive dependence of the dusktime peak in *F* layer vertical drift over Kodaikanal to the rapid decline in the solar radiative output in early 1992, in terms of corresponding changes in the longitudinal (local time) gradient of *E* region conductivity as well as of *F* region zonal neutral wind.

The equatorial *F* layer vertical drift is known to depend on the level of geomagnetic activity. The nature of dependence, however, seems to be complex from the results available in the literature. At Jicamarca, Peru, the dusktime peak in *F* layer vertical drift(V_{zp}) is found to decrease with geomagnetic activity in equinox but to increase in local winter [*Fejer et al*, 1989;1991]. At Trivandrum(dip 0.6°N), India, *Namboothiri et al* [1989] noticed V_{zp} to decrease as geomagnetic activity changes from quiet to moderate conditions ($Ap \sim$ 15-20) but to increase well above the quiet time values for high geomagnetic activity. They did not evaluate the seasonal pattern(if any) in the dependence of V_{zp} on geomagnetic activity. Since the mean level and distribution of Ap index clearly showed no significant change (in local winter months, see Figure 2c) or a decrease (June/July-December) in the level of geomagnetic activity, after the rapid and significant reduction in the solar radiative output than before, the observed response of V_{zp} over Kodaikanal to the solar event in 1992 is unlikely to be influenced by geomagnetic activity related disturbances in equatorial *F* layer vertical drift. It would be interesting to evaluate the response of the dusktime *F* layer vertical drift over dip equatorial stations in other longitude sectors, particularly the American sector(75°W), to the solar event discussed here.

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