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Dependence of equatorial Fregion vertical drifts on season and solar cycle

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Dependence of Equatorial *F* Region Vertical Drifts on Season and Solar Cycle

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Vertical drift measurements have been made at Jicamarca for more than half a solar cycle. The data from periods of high and low activity are appreciably different. Daytime drift velocities during sunspot minimum are usually larger than during the maximum, while the opposite is true for nighttime periods. The evening reversal occurs earlier during sunspot minimum than during the maximum, but the morning reversal is not altered. The period of eastward electric field (upward drift) is thus shortest during sunspot minimum and local winter. By integrating the drift velocity data with respect to time, one can obtain a measure of the total potential drop between reversal points (near the terminators). This drop is largest at solar maximum. There is also a pronounced seasonal variation, with a minimum in mid-December during both solar minimum and maximum. The general features of the data cannot be explained solely on the basis of tidal winds driving an *E* region dynamo; polarization fields related to the *F* region dynamo are of major importance, particularly in helping to explain the enhancement of the daytime upward drift which often occurs shortly before the drift reverses to downward in the evening. In order to account quantitatively for the observed variations, however, numerical models considerably more sophisticated than those presently available are needed.

INTRODUCTION

At the magnetic equator the motion of the *F* region plasma is controlled by the vertical and zonal electric field. In particular, the east-west electric field determines the vertical drift velocity, and the latter can be conveniently and accurately measured with the incoherent scatter radar of the Jicamarca Observatory in Peru. A large quantity of such observations have now been made, over a period of more than half a solar cycle. Some aspects of some of these measurements have been discussed in earlier papers by *Woodman* [1970], *Balsley* [1973], and *Woodman et al.* [1977]. Here we shall consider all the Jicamarca data and concentrate on the substantial seasonal and solar cycle variations.

The electric fields which control the drifts are the result of a complicated interaction between the *E* and *F* regions which changes markedly from day to night. The *E* region dynamo fields are created by tidal winds in the *E* layer and are coupled to the *F* region via the nearly equipotential magnetic field lines. There are also *F* region dynamo fields, driven by *F* region winds. These are largely shorted out by the conducting *E* region during the day, but can be important at night [e.g., *Rishbeth,* 1971]. At times the equatorial field is also strongly influenced by high latitude and magnetospheric phenomena driven ultimately by the solar wind. These latter effects are discussed in two companion papers [*Fejer et al.,* 1979; *Gonzales et al.,* 1979]. A number of models of the *E* and *F* region dynamos have been developed [e.g., *Maeda,* 1968; *Stening,* 1969; *Tarpley,* 1970; *Volland,* 1971; *Schieldge et al.,* 1973; *Heelis et al.,* 1974; *Richmond et al.,* 1976; *Forbes and Lindzen,* 1976*a*, *b*, 1977]. As we shall see, some features of our data can be explained using the available theories, but many cannot.

MEASUREMENT TECHNIQUES

The experimental procedure used for measuring *F* region vertical drifts at Jicamarca has been described in detail by *Woodman and Hagfors* [1969] and *Woodman* [1970]. The vertical drifts are obtained by pointing the incoherent scatter antenna perpendicular to the magnetic field and measuring the mean Doppler shift of the backscattered signals. The integration time is typically about 5 min and the accuracy of the measurement is of the order of 1–2 m/s. The measurements are most commonly made from 275 to 500 km, and in the absence of spread *F* the results are nearly independent of altitude [*Woodman,* 1970]. Most of the results to be discussed were obtained by averaging the drifts between 300 and 400 km, where the measurements are usually most accurate.

RESULTS

We have examined all the available data from 1968 to 1976. The drifts changed very little from 1968 to 1971, and so we have taken the data from this whole period as representative of the drifts during sunspot maximum. This permitted us to study monthly variations. The measurements from 1972 to 1974, which were less frequent and were unevenly spaced in time, will not be discussed here. The drifts during sunspot minimum consist of 45 days of data taken during 1975–1976.

The *F* region vertical drifts from sunspot maximum and minimum are compared in Figures 1 and 2. Each curve represents the average of all the drifts available during the period

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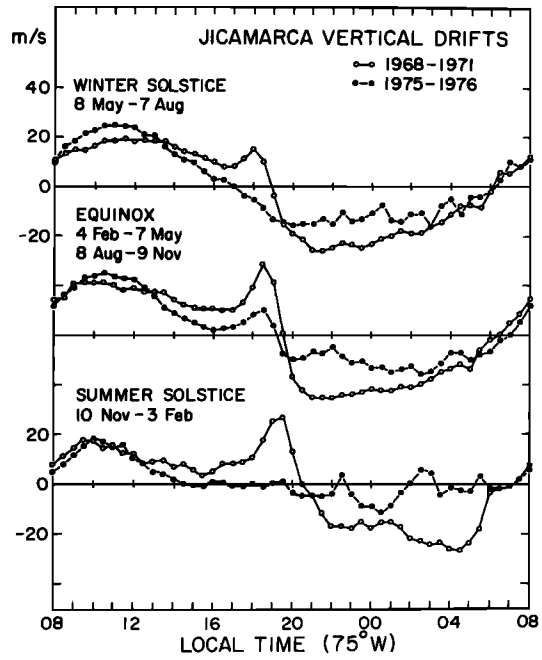

Fig. 1. Seasonal variation of the equatorial vertical drifts during sunspot maximum (1968–1971) and sunspot minimum (1975–1976).

indicated. The data shown in Figure 1 correspond mostly to quiet magnetic conditions, except for the 1975–1976 summer data, which are representative of moderate magnetic activity. A vertical drift velocity of about 40 m/s corresponds to an east-west electric field of 1 mV/m.

The main differences between the sunspot minimum and sunspot maximum drift data shown in Figure 1 are as follows:

1. The evening pre-reversal enhancement is much more common and pronounced at sunspot maximum.

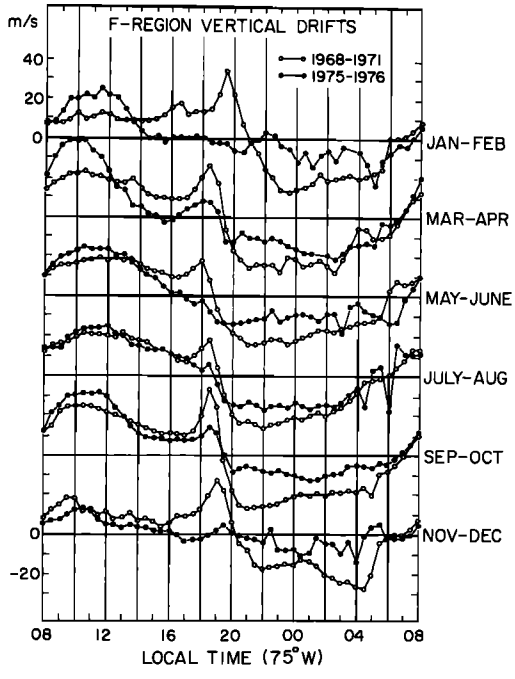

Fig. 2. Bimonthly averages of the equatorial F region drifts during solar maximum and minimum. The morning and afternoon averages for March–April 1975–1976 were obtained from a small number of measurements.

2. The time of reversal from upward daytime drifts to downward nighttime drifts occurs up to 2 hours earlier at sunspot minimum than at the maximum, while the morning reversal time is essentially unaffected by the solar cycle and changes only moderately with season.

3. The magnitudes of the evening and nighttime downward drifts are significantly smaller during sunspot minimum than during the maximum, while the daytime prenoon drifts are a little larger, except in the summer.

More detailed comparisons are shown in Figure 2. We should caution the reader that the daytime average drifts prior to 1600 for March–April 1975–1976 were obtained using a small number of measurements, and the average morning and afternoon drifts of November–December and especially January–February were significantly affected by measurements during magnetically disturbed days.

The Evening Reversal

The evening pre-reversal enhancement is observed throughout the year during solar maximum, but its amplitude is smallest from May to August. For solar minimum conditions this enhancement is almost completely absent except during the equinoctial months. Additional data in Figure 3 illustrate the rapid change in the enhancement in more detail. It is clearly observed in September, but has disappeared by mid-October. The times at which the enhancement and evening reversal occur show considerable variation, as is shown in more detail in Figure 4, which also includes the E region sunset times. The sunset time is quite close to the time of the enhancement at solar maximum. Only in local winter does the evening drift reversal occur early during solar minimum.

The rare occurrence of the pre-reversal enhancement at solar minimum has already been reported by *Woodman et al.* [1977], who also discussed the variation of the reversal times with solar cycle. They showed that the yearly average of the evening reversal time is about 1 hour earlier during sunspot minimum than during the maximum, but the morning reversal time does not vary. Our results show that the earlier evening reversal times at solar minimum are essentially restricted to winter, a result which is lost in the averaging process.

Day-to-Day Variability

The variability of the F region vertical drifts is illustrated in Figures 5 and 6. The bars in Figure 5 represent the scatter of the observations (twice the standard deviation). Figure 5 also shows that the average May drifts change very little from 1968–1969 to 1970–1971. The nighttime drift data show a significantly larger variability during sunspot minimum than during the maximum, especially during local winter. This may be a real effect, but it may also be at least partly due to the low signal-to-noise ratio often encountered after midnight. The 1975 winter drift data are shown in Figure 6. Note the relatively short period of upward daytime drifts and the small and irregular nighttime drifts.

Drift Magnitudes

The prenoon drifts during solar minimum are slightly larger than at the maximum, but the evening and especially the nighttime drifts are considerably smaller. The daytime drifts maximize during equinox and decrease in magnitude from September to mid-December during both phases of the sunspot cycle. The maximum daytime drifts occur earliest during

November–December and latest during May–June. These observations are consistent with the results of *Woodman et al.* [1977], the *E* region horizontal drift measurements using the spaced receiver technique [*Chandra and Rastogi,* 1969; *Oyinloye and Onolaja,* 1977, 1978], and electrojet current and electric field variations [e.g., *Matsushita,* 1962; *Chapman and Raja Rao,* 1965; *Tarpley,* 1973].

Total Potential Drop

The *F* region vertical drifts are well correlated with the horizontal *E* region electron drifts, especially during daytime. Since the equatorial east-west electric field must be nearly irrotational, the line integral of this electric field along the equator must be zero. Let us consider the potential drop between the reversal points. If we assume (possibly incorrectly, see below) that the longitude and local time coordinates are interchangeable, we can calculate this potential by integrating the *F* region vertical drift velocity with respect to time. That is

$$\Delta\phi = B\int_{t_1}^{t_2} v_z\, dt$$

where B denotes the equatorial magnetic field strength (~0.25 wb/m^2), and t_1 and t_2 represent the morning and evening drift reversal times. Figure 7 shows the variation of both the daytime voltage and the nighttime-to-daytime ratio obtained by integrating the nighttime and daytime drifts, respectively. This ratio should be unity if our assumptions are valid and the data are accurate. The ratio is less accurate during solar minimum than during solar maximum because of the smaller number of days of observation and larger variability of the data. The typical standard deviation of these ratios is about 15–20%.

The daytime voltage is just slightly smaller during sunspot minimum than during the maximum and is largest during equinox in both cases, as might be expected from the preceding results. Figure 7 also shows large potential decreases from mid-September to December during both sunspot maximum and minimum. The ratio between the nighttime and daytime voltages is appreciably larger during solar maximum than during solar minimum.

THEORIES

The equatorial electric field in the *F* region is controlled by atmospheric tides, *F* region polarization effects (particularly at night), and high latitude and magnetospheric effects (during disturbed periods). All of these interactions may vary with season and solar cycle.

Let us consider first the tidal effects. The diurnal trapped (1, −2) mode is the principal contributor to the *Sq* current system [e.g., *Stening,* 1969; *Tarpley,* 1970] and has only a slight phase change between the *E* and *F* regions [*Volland and Mayr,* 1972]. *Richmond et al.* [1976] have shown that several characteristics of the yearly averages can be accounted for by adding a contribution from the semidiurnal (2, 4) mode. *Forbes and Lindzen* [1976*a*, *b*, 1977] have shown that additional tidal modes are likely to be important in explaining the worldwide system of currents and electric fields and find that some aspects of the *F* region drifts are consistent with the calculated *E* region polarization fields during daytime, but not at night. In particular, the agreement between their calculations and the observed eastward field at the equator is poor except near midday, and they suggest that the most likely cause of the discrepancy is the neglect of the *F* region dynamo effect.

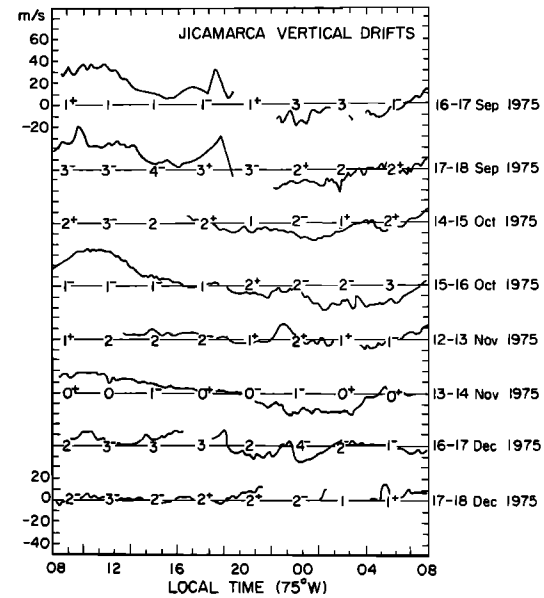

Fig. 3. Examples of the large decrease of the vertical drifts from mid-September to mid-December during solar minimum. *Kp* values are also indicated.

The importance of the *F* region dynamo has been discussed by *Rishbeth* [1971, 1977], *Heelis et al.* [1974], and *Matuura* [1974]. The latter two papers attempt to generate reasonably realistic numerical models of the fields, taking into account both *E* and *F* region winds and the day to night variation in the coupling between the layers, and they obtain improved agreement with Jicamarca observations. The results of Heelis et al. illustrate best how important the *F* region polarization fields are, particularly in explaining the nighttime pre-reversal enhancement. In their relatively simple model they assumed (1) complete symmetry about the magnetic equator, (2) *E* region winds corresponding to the diurnal (only) tidal mode of *Tarpley* [1970], (3) *F* region winds generated by pressure gradients (no Coriolis force) corresponding to observed temperature variations and the 1965 Jacchia model of the neutral atmosphere, (4) simple models of the diurnal variation of the *E* and *F* region electron densities, and (5) a two-dimensional layer conductivity model of the *E* region with no vertical current within the layer. However, they included the (crucial, as

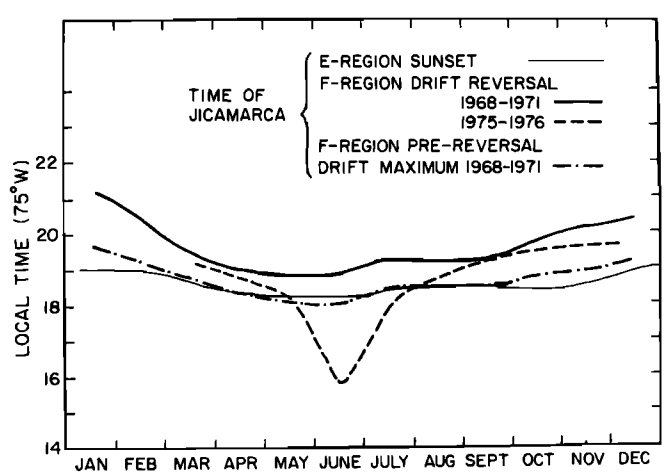

Fig. 4. Monthly variation of the characteristic times of the evening equatorial vertical drifts. Note the close correlation between the time of maximum pre-reversal enhancement and *E* region sunset.

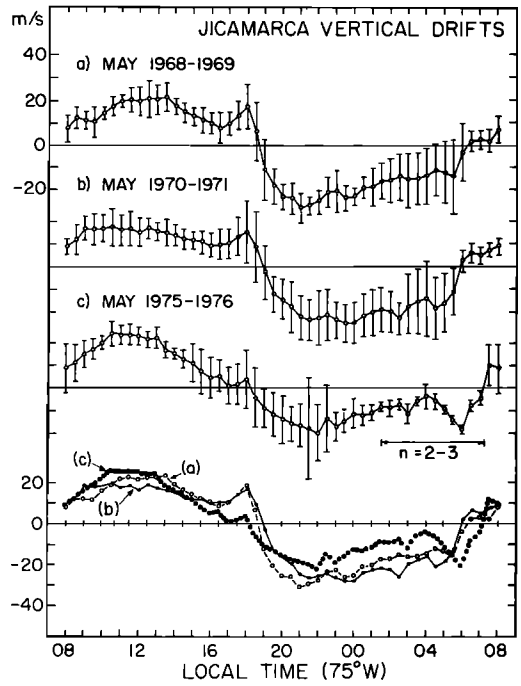

Fig. 5. Average vertical drifts during May. The bars represent scatter in the observations and not uncertainty in the measurements.

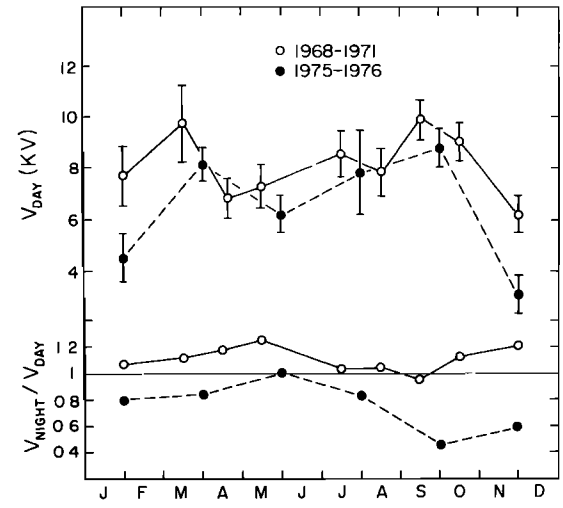

Fig. 7. Monthly variation of the total daytime voltage drop between the reversals and of the nighttime to daytime ratio. Standard deviation of the latter is about 15–20%.

it turns out) effect of a field aligned current flowing between the top of the E layer and the F region.

The procedure by which the numerical calculation is carried out also makes the physics clear. One first 'turns on' the E region tidal winds and calculates the E region currents and electric fields, assuming the field aligned coupling current to be zero. Then, from the F region pressure gradient and the electrostatic field coupled up from the E region, one calculates the winds and the motion of the F region plasma and finds the small F region current flowing perpendicular to the magnetic field. From the latter, and the fact that the divergence of the current must be zero, one calculates the field aligned current at the base of the F layer, which must equal the current at the top of the E layer. The E region currents and fields are then recalculated taking into account this additional current source (or sink), and the whole process is iterated until a steady state (self consistent) solution is found.

The results of the calculation for the magnetic equator are shown in Figure 8. The dashed curve corresponds to the case in which the coupling current is forced to be zero, whereas the solid curve illustrates the calculation discussed in the previous paragraph. There is obviously a dramatic difference and a greatly improved agreement with the Jicamarca observations. In particular, the inclusion of the F region dynamo effect accounts for the pronounced pre-reversal enhancement of the vertical drift.

Schieldge et al. [1973] showed that certain combinations of tidal modes could also produce a slight pre-reversal enhancement without an F region dynamo, but the more recent tidal models show no such effect. In any case, Figure 8 shows that the F region dynamo cannot be ignored, although refinements in the model are needed before it can account quantitatively for most of the observations we have described here. The seasonal and solar cycle variations in the pre-reversal enhancement, for example, must be due to variations in the importance of the F region dynamo. The seasonal effects are doubtless related to the fact that, except at the equinoxes, the assumption of symmetry about the equator is inadequate; if either end of a magnetic field line is sunlit, the F region dynamo will be shorted out. Solar cycle effects are probably related to changes in the neutral atmosphere and perhaps elec-

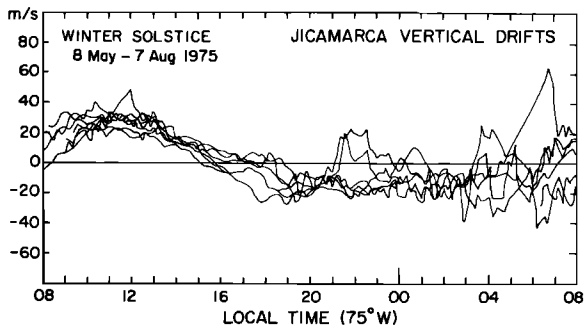

Fig. 6. F region vertical drifts observed during the 1975 winter solstice. Note the large variability of the nighttime drifts.

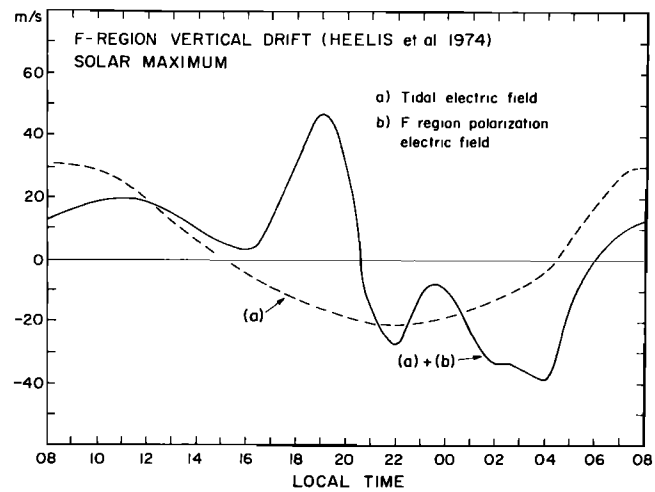

Fig. 8. Daily variation of the F region vertical drift predicted from tidal theory only and with the inclusion of the F region polarization effect [from *Heelis et al.*, 1974].

tron density profiles, both of which will affect the conductivities in the E and F regions and hence the coupling between the two. It seems quite likely that more than just the single diurnal tidal mode is important, and the absolute and relative strengths of the modes probably will vary with season, solar cycle, and perhaps even from day to day. Finally, the fact that the total potential drops corresponding to daytime and nighttime conditions do not in general have the same magnitude indicates that the assumption that longitude and local time are interchangeable is not correct, although the errors involved may not be serious for many purposes.

The effect of high latitude phenomena on the equatorial fields is considered in two companions papers [*Fejer et al.*, 1979; *Gonzales et al.*, 1979]. Here we note only that the increased variability of the nighttime drift data during solar minimum may be due to an increase in the ease of penetration of magnetospheric fields to low latitudes, as suggested by *Jaggi and Wolf* [1973].

CONCLUSIONS

The F region vertical drifts at Jicamarca, which are a measure of the east-west electric field at the equator, show large seasonal and solar cycle variations. Theories based solely on tidal winds driving an E region dynamo do not agree well with the equatorial data, even if the tidal model is quite sophisticated. On the other hand, the inclusion of F region dynamo effects drastically improves the agreement, even for quite simple tidal models. In particular, the pre-reversal enhancement of the daytime upward drift is predicted by the latter theory. In order to explain the daily, seasonal, and solar cycle variations in the data, more realistic models of the processes are needed. These must take account of additional tidal modes, asymmetries about the equator, variations in the neutral atmosphere and electron density profiles, possible variations in the E region tides (if these can be predicted), and perhaps even longitude effects. During magnetically disturbed conditions the effects of high latitude electric fields also must be included.

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