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Multi-longitude case studies comparing the interplanetary and equatorial ionospheric electric fields using an empirical model

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Abstract

Electric fields have been determined at three longitudes corresponding to Peru, India, and the Philippines. We compare these fields to applying a frequency-dependent linear transfer function (TF) to the dawn-to-dusk component of the interplanetary electric field (IEF). The TF is based on four years of simultaneous observations of the IEF and equatorial data. The model gives good results for the prompt penetrating electric field (PPE) in the case of an oscillatory IEF with a period in the 1–2 h range, when the interplanetary magnetic field remains southward for a long period and, to a lesser extent, when the IEF can be described as a square wave. There is evidence that a disturbance dynamo (DD) effect contributes on the dayside, where it leads to suppression of the normal quiet time pattern. A very strong counter-electrojet was seen at two locations during a time of persistent B_z south and was not predicted by the model or a linear scaling of the IEF. This suggests that suppression (and even reversal) of the *E*-region dynamo can occur in a large storm. Both the data and the model yielded a long-lived response to a sustained southward interplanetary magnetic field. Previously suggested B_y effects on equatorial electric fields are confirmed by a sequence of three distinct spikes in the B_y component of the IMF, one of which had no associated B_z change and yet was reproduced by two independent ground magnetometer-based electric field determinations. The sometimes remarkable agreement of a linear relationship between the equatorial and interplanetary electric fields shown here and elsewhere remains somewhat mysterious for such an apparently complex system.

Keywords: Middle atmosphere–composition and chemistry; Equatorial ionosphere; Ionosphere–atmosphere interactions; Turbulence

1. Introduction

Interest in solar wind effects on the ionosphere has remained high for decades. The shear number of papers in this special issue of the *Journal of*

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Atmospheric and Solar-Terrestrial Physics is evidence that, at equatorial latitudes, these effects are not at all well understood. The purpose of this paper is to examine two case studies for which we have simultaneous observations of electric fields at widely differing longitudes and to relate them to a linear model that predicts the amplitude and phase of the equatorial field based on the dawn-to-dusk component of the interplanetary electric field (IEF).

For both case study dates (in March 2001 and April 2002), we have data from the Philippines (122°E), Peru (283°E), and India (75°E). The specific dates were chosen as follows. We have four years of Peruvian magnetic field data in hand as well as Jicamarca data for a key event in April 2002. A number of papers have already been published on the April 17, 2002 event, one of our case study dates. We thus requested data from colleagues in India and the Philippines for that day. The March 31, 2001 period has also been heavily studied, so similar data from India and the Philippines for the entire month were requested and we concentrated on the days surrounding that date.

We use the magnetic field measured at three longitudes (Philippines, Peru, and India) and two stations (at each longitude), one on the magnetic equator and one off the equator but not so far away that the ring current contribution to the observations is significantly different. The geographic locations of each site are listed in Table 1. The concept is that magnetic fields resulting from the ring current will affect both sites equally whereas the equatorial electrojet magnetic field is confined to the near-equatorial site. This idea was first used by Gonzales et al. (1979), who pioneered the comparison of measured equatorial electric fields at the equator with interplanetary phenomena. These authors used the Jicamarca incoherent scatter radar (ISR) to directly determine the electric field in the South American sector and the two-site magnetometer method to qualitatively gauge the electric field at other locations. Recently, Anderson et al. (2002, 2004, 2006) validated this technique by showing that the electric field can be determined quite well during the daytime by developing a neural network that learns from the simultaneous direct observations of the vertical drift and hence the electric field at Jicamarca. This idea has been successfully extended to other longitudes. Any remaining ring current effects are removed from the neural network output since it learns from the measured electric field at Jicamarca.

For April 2002 we also have direct determination of the plasma drift and hence the electric fields over Peru (using the ISR technique) and India by using the time derivative of the ionospheric layer height to determine the electric field.

The empirical model assumes that the equatorial electric field in the ionosphere is linearly related to the external IEF. This idea, outlined in a companion paper (Nicolls et al., 2007), is based on four years of simultaneous IEF and daytime electric field observations over Peru. The input is the dawn-to-dusk component of the IEF and the output is the eastward electric field in the daytime equatorial ionosphere. The result of this study is an average transfer function (TF amplitude and phase) as a function of frequency that we apply to the IEF data to predict the equatorial field. There is a broad peak in the transfer function (TF) which maximizes near a 2 h period and admits signals with periods as high as 8 h. Other case studies of these two events yielded a constant (independent of frequency) value of 7% for April 17, 2002 (Kelley et al., 2003) and near 10% for March 31, 2001 (Huang et al., 2005). Note that an eastward field in the noon equatorial ionosphere and a westward field at midnight are both in the dawn-to-dusk direction when viewed from a sun-fixed system. The direction of the perturbation ionospheric field near noon and midnight has been shown to be in the same direction as the IEF dawn-to-dusk component (Gonzales et al., 1979). A more detailed study in the companion paper suggests that strong transitions are not reproduced by the average TF due to a scale size dependence of the coupling (Nicolls et al., 2007).

Table 1
Locations of the magnetometers used in this study

	Philippines	Peru	India
On equator	Davao	Jicamarca	Tirunelveli
	7°N, 125.4°E, dip 1.4°S	11.9°S, 283.1°E, dip 0.8°N	8.7°N, 76.9°E, dip 0.5°S
Off equator	Muntinlupa	Piura	Alibag
	14.4°N, 121°E, dip 6.3°N	5.2°S, 279.4°E, dip 6.8°N	18.6°N, 72.9°E, dip 10°N

2. Data and model presentation

2.1. April 17, 2002

These data were reported previously (e.g., Kelley et al., 2003). Fig. 1 shows the equatorial electric field measured using the incoherent scatter technique over the Jicamarca Radio Observatory in Peru (283°E), which is about one degree off the magnetic equator. Also shown is the quiet time equatorial eastward component and 10% of the dawn-to-dusk component of the IEF. The latter is delayed by the transit time from the ACE satellite to the magnetopause using the measured solar wind velocity. The study referenced above found a factor of 0.075 for this ratio whereas Huang et al. (2007) found an average ratio of 0.1 for 75 events, as used in the figure. Kelley et al. (2003) showed that during the daytime period on April 17, 2002, the equatorial field was correlated with the IEF with an 86% correlation coefficient. The eastward component of the fluctuating equatorial field is positively correlated with the IEF dawn-to-dusk component in the daytime and anti-correlated with the IEF component at night. Both southward and northward transitions of the interplanetary magnetic field (IMF) B_z component, corresponding to dawn-to-dusk and dusk-to-dawn IEF components, are seen at the equator for as long as 2 h with little decay. In some periods, the IEF provides a square wave input and at others a more oscillatory one.

In Fig. 2 we have plotted the downward drift component measured over India and the simultaneous upward drift measurements over Peru. The Indian data are determined from the time derivative of the *F*-layer height as measured by an ionosonde, which has been shown to be a reasonable estimator of the vertical drift if the ionosphere is high (e.g., Bittencourt and Abdu, 1981). The two curves lie on top of each other, showing that the magnitudes of the daytime and nighttime penetration fields are comparable and hence are of global large scale. Also, in a geomagnetic coordinate system, the zonal component has the opposite sign in the dayside relative to the nightside. The light black curve is the prediction of the average linear TF method for the dayside (Nicolls et al., 2007), to which the quiet time drift has been added. The oscillations in the latter have an amplitude of about half of the observed signal. The average TF was determined from four years of daytime magnetometer data taken in Peru simultaneously with IEF data and hence includes events of varying efficiency. This event and the ones studied by Huang et al. (2007) have higher efficiency than the average does by about a factor of 3.

2.2. March 31, 2001

We have no direct electric field measurement for this day and so use the Gonzales/Anderson method. Unlike the day discussed above, the Philippine and

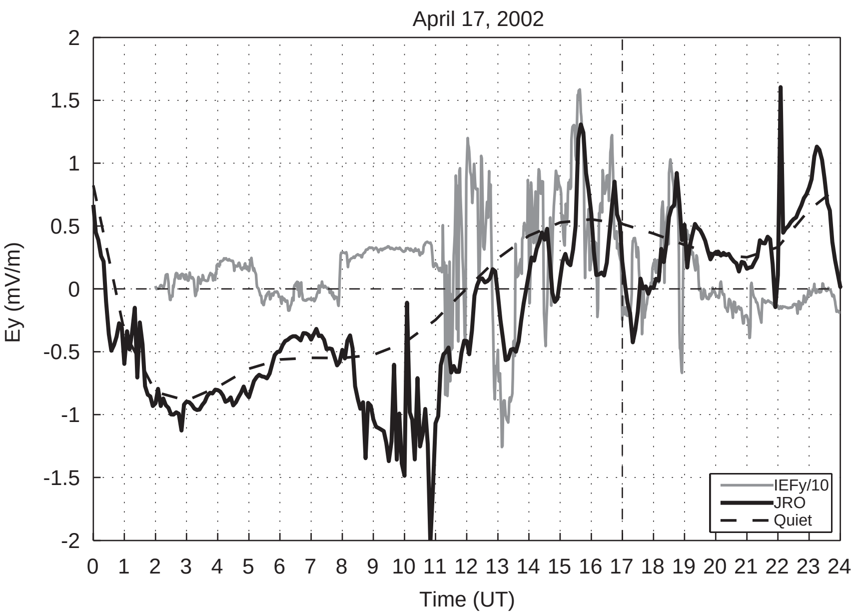

Fig. 1. The *y* component of the IEF measured by ACE divided by 10 (gray), the Jicamarca measured electric field (black), and the Scherliess and Fejer (1999) quiet day curve (dashed). The vertical dashed line corresponds to local noon at Jicamarca.

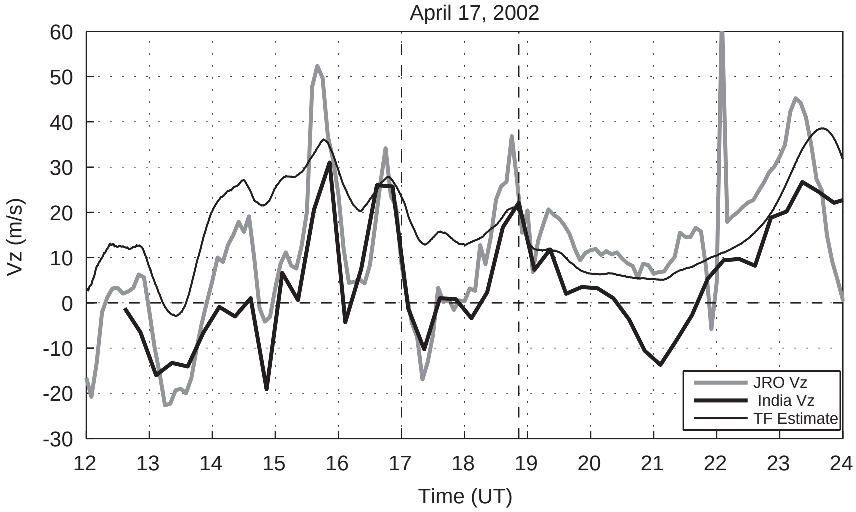

Fig. 2. V_z from Jicamarca measurements (daytime), Indian measurements (nighttime), and from the transfer function estimate. The negative of the Indian measurements has been plotted. The vertical dashed line at 1700 UT corresponds to local noon at Jicamarca and the vertical dashed line at 1900 UT corresponds to local midnight at the Indian station.

Indian sectors were in daylight during part of the disturbed period.

In Fig. 3 we show the y component of the IEF after dividing by $20B$, where B is the ionosphere magnetic field strength, along with the results of the TF as applied to the IEF data and superimposed on the measured electric field for the Philippines and Peru. The quiet time drift has been added to the TF prediction. In the upper panel, the TF captures the transition at 0100 UT with a slight delay due to the absence of the highest frequency effects in the function. The oscillations and build-up of the vertical drift are reproduced, as is the brief counter-electrojet between 0800 and 0900 UT. Curiously, the model does not track the data between 0700 and 0800 UT when a counter-electrojet (due to a westward equatorial electric field component) is indicated. Huang et al. (2007) found the same result using their proportionality between the IEF and the equatorial drifts for southward B_z. One might be tempted to explain this discrepancy by a disturbed dynamo effect but a model including this effect for this event does not show the counter-electrojet (Maruyama et al., 2005).

In Peru (lower panel), the measured IEF and vertical drift have a square wave-shaped disturbance between 1300 and 1500 UT in which the IMF turns northward (see Fig. 3). The TF model captures the response very well. The response to a square wave in the AE index has been reported in this issue (Huang et al., 2007) using the Naval Research Laboratory's SAMI model (Huba et al., 2005). The model predicts that the equatorial electric field will rise sharply but decay away within 30 min. These authors concluded that such a response is the origin of the oft-quoted 30-min time scale for promptly penetrating electric field (PPE) effects. (The term "prompt" refers to responses within the magnetosphere that occur on time scales within the integration time of typical electric field instruments, which are minutes or less, rather than time scales corresponding to propagation times in the neutral atmosphere. Changes in the equatorial electric field due to the latter are termed a disturbance dynamo.) However, neither the data nor the TF approach presented here support such a short time scale. When the IEF reverses at 1500 UT, it stays strongly in the dawn-to-dusk direction for 7 h, only slowly decreasing in this period. The measured equatorial vertical drift has a very similar behavior, as does the TF method. This shows that long-duration PPE effects reported by Huang et al. (2005) are reproduced by the filter characteristics of the TF.

This stark divergence between observation and model predictions encouraged us to seek another data set, which was obtained in the Indian sector.

For reference, in Fig. 4 we include 18 consecutive determinations of the equatorial daytime vertical drift for the period surrounding the storm and at three different longitudes. Note the change of scale

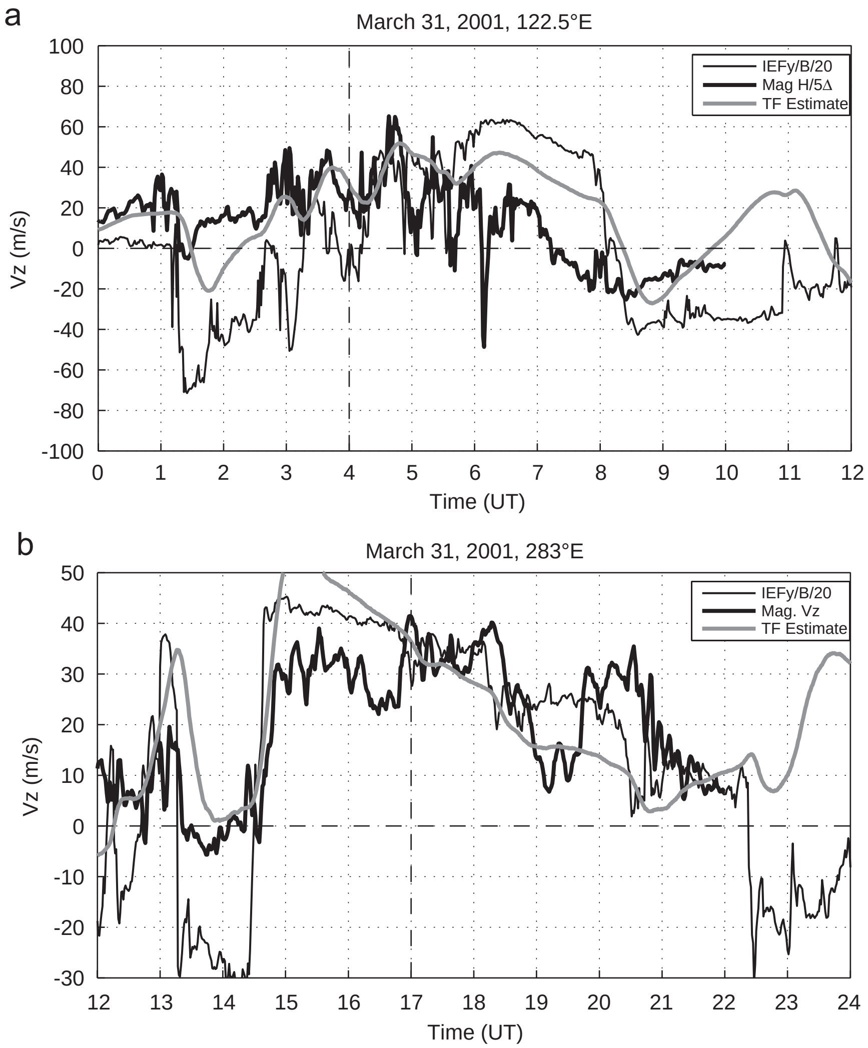

Fig. 3. The y component of the IEF divided by the equatorial B divided by a factor of 20 (light black), the transfer function model (gray), and V_z from magnetometer estimates (thick black) in the Philippines (top) and in Peru (bottom). The vertical dashed lines correspond to local noon in the Philippines (top) and in Peru (bottom). Scherliess and Fejer (1999) quiet-time curves have been added to the transfer function estimates.

by a factor of 2 on March 31. The counter-electrojet observed in the Indian sector agrees well with the Philippine data. If anything, the counter-electrojet is stronger in India and clearly is not captured by the model. The counter-electrojet occurs at about the minimum of the Dst index (about -360 nT) and hence might be a disturbance dynamo effect. The main phase of the storm began about 0400 or 0500 UT. However, Maruyama et al. (2007) do not see a counter-electrojet when both prompt and delayed effects are added, although a very weak westward electric field is seen using only the disturbance dynamo. The March 31, 2001 event has been studied by Knipp et al. (2004), who report that the joule heating on this day exceeded the dayside EUV input. This extreme case may not have been captured by the modeling and possibly is the source of the reversed electric field on the dayside. The daytime electrojet reached 300 nT in two of the sites and over 200 nT at the third. The counter-electrojet centered on 0800 UT on that day is the source of the data deviation and is clearly seen simultaneously in both India and the Philippines. On April 1, 2001 the electrojets are depressed from their typical values, which may be an interesting effect to try to reproduce with a global model.

Finally, the series of negative spikes in both the Indian and Philippines data between about 0500

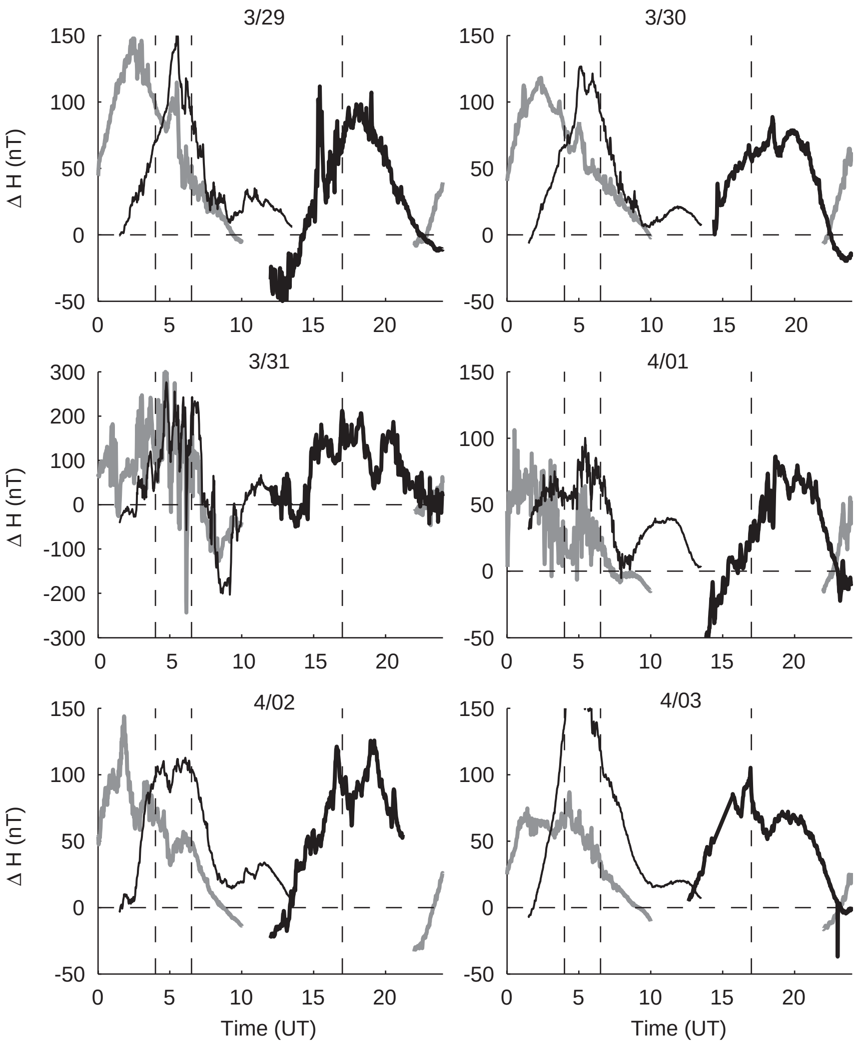

Fig. 4. ΔH for a series of days around March 31, 2001 from Peru (thick black), the Philippines (gray), and India (light black). Note the different *y*-axis limits on the March 31 plot. The vertical dashed lines correspond to local noon in the Philippines (~0400 UT), India (~0630 UT), and Peru (~1700 UT).

and 0615 UT are not seen in the dawn-to-dusk component of the IEF and hence are not detected by the TF. However, as shown in Fig. 5, examination of the IMF shows three spikes in the B_y component (upper panel). Note that B_y has not been shifted (time delayed) here. The series of spikes occur about 30 min prior to the magnetometer signatures, which are also plotted in the lower panel. The last of these spikes was not accompanied by any disturbance in B_z and yet was clearly detected at the magnetic equator. The implication seems to be that interplanetary currents flowing perpendicular to the ecliptic plane can partially close through the ionosphere (Kelley and Makela, 2002), and are the dominant effects during this time period.

3. Summary

One of the most striking results of this study and of the one by Huang et al. (2007) is how well simple linear relationships between the interplonetary electric field (IEF) and the equatorial electric field work. The physics of this relationship must be related to the shielding or over-shielding of the ring current and hence only applies to the prompt penetrating electric field (PPE) component.

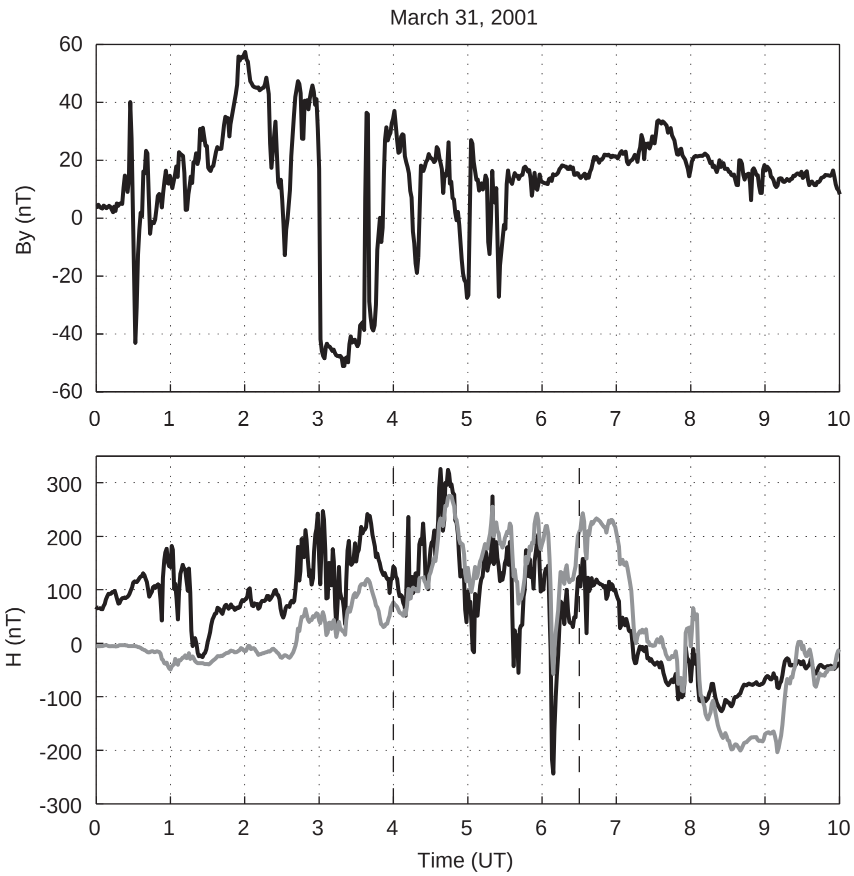

Fig. 5. The top panel shows B_y (undelayed) measured in the solar wind. The bottom plot shows ΔH from the Philippines (black) and from India (gray). The vertical dashed lines correspond to local noon in the Philippines and India.

On March 31, 2001 the long duration with B_z southward created an extended period of high vertical drift, which was predicted by the model. This stormtime condition is similar to the long-duration PPE events reported by Huang et al. (2005). This shows that the high pass filter associated with the inductance of the ring current passes IEF signals with periods of many hours.

As for high frequency components, the TF picks up the sharp edges fairly well when an abrupt change occurs in the IEF. Square wave inputs to the AE index do not seem to create corresponding square wave equatorial fields, which suggests that a direct drive by the IEF may provide a better input for models.

The large spike in the magnetometer data on March 31, 2001 was not seen in the dawn-to-dusk IEF component but there was a similar spike in the IMF B_y component. The result is similar to the event reported by Kelley and Makela (2002), in which they found a B_y-dependent effect at Jicamarca.

The strong counter-electrojet centered at 0800 UT on March 31 was seen at two longitudes and was unpredicted by the model. At this time, B_y was small. For an event with over 500 nT ring current, such as occurred on March 31, 2001, a robust disturbance dynamo component might have produced the counter-electrojet, but evidently this was not predicted by the most complete modeling study to date (Maruyama et al., 2005).

The sometimes remarkable agreement of linear relationships between the equatorial and interplanetary electric fields is shown here but remains somewhat mysterious. These results show progress toward predicting the equatorial electric field based on interplanetary parameters, particularly the IEF, but work remains to be done. From an experimental standpoint the daytime Gonzales/Anderson method could be supplemented by using high spectral resolution photometric studies (Sekar et al., 2004; Chakrabarty et al., 2005), which have been shown to act as tracers of electric fields at night. In addition, two sets of stations nearby in longitude could be used to separate PPE effects from other sources of geophysical noise.

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