Daytime, low latitude, vertical ExB drift velocities, inferred from ground-based magnetometer observations in the Peruvian, Philippine and Indian longitude sectors under quiet and disturbed conditions

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Abstract

Recent studies have demonstrated that ground-based magnetometer observations can be used to infer realistic, daytime vertical ExB drift velocities in the Peruvian longitude sector. It has also been demonstrated that under certain conditions the time variability of the Interplanetary Electric Field (IEF) – minutes to hours – is reflected in the daytime, prompt penetration of high latitude electric fields to low latitudes. In this paper, we incorporate magnetometer-inferred ExB drift techniques to extend this study to include the Philippine and Indian sector ExB drift velocities and to investigate the relationships between IEF conditions and daytime, low latitude electric field observations under both geomagnetically quiet and disturbed conditions. This paper addresses two basic questions: 1.) How well do the quiet-time, ΔH-inferred ExB drift velocities compare with the Fejer-Scherliess, quiet-time, climatological model (Scherliess and Fejer, 1999) in the Peruvian, Philippine and Indian sectors and 2.) What are the relationships between the Interplanetary Electric Fields (IEF) and low latitude electric fields during disturbed periods? We address the above questions by analyzing magnetometer-inferred ExB drift velocities between January, 2001 and December, 2004 when there exists more than 450 quiet days and more than 235 geomagnetically disturbed days, defined by daily Ap values greater than 20. It is demonstrated that the neural network approach that provides realistic ExB drift velocities based on magnetometer observations in the Peruvian sector can be applied at all longitudes where appropriately placed magnetometers exist. It is found that 1.) The average quiet, daytime upward ExB drift velocity vs LT is comparable to the Fejer-Scherliess climatological model and 2.) During disturbed conditions, it is observed that promptly penetrating electric fields occur, simultaneously, in the Philippine, Indian and Peruvian sectors.

Index Terms: Equatorial electrojet, Interplanetary electric fields, Low latitude ExB drifts, Magnetometer observations

1. Introduction

In a paper by Anderson et al. (2002) it was demonstrated that there exists quantitative relationships whereby the vertical ExB drift velocity in the equatorial F-region can be estimated using ground-based magnetometer observations. Such quantitative relationships were developed for the South American sector, during the Solar Maximum period, 1998-1999. This represented the first time such a unique relationship had been quantitatively established. The Jicamarca Incoherent Scatter Radar (ISR) provided the daytime, vertical ExB drift velocities in conjunction with magnetometers at Canete and Piura in Peru. However, the data sets were only available for a total of 11 days between 1998 and 1999. A more recent paper, Anderson et al. (2004) has determined, quantitatively, the relationships over a much longer period of time, using a significantly larger database of vertical ExB drift velocities and magnetometer observations. The vertical ExB drifts were obtained from 150 km echoes at Jicamarca, Peru (Chau and Woodman, 2004).

Based on the validated ΔH vs ExB drift relationships described by Anderson et al. (2004) that provide realistic, vertical, daytime ExB drift velocities between 0700 and 1700 LT in the Peruvian longitude sector, important and unanswered questions can now be addressed. 1.) How well do the quiet-time, ΔH-inferred ExB drift velocities compare with the Fejer-Scherliess, quiet-time, climatological model (Scherliess and Fejer, 1999) in the Peruvian, Philippine and Indian sectors and 2.) What are the relationships between the Interplanetary Electric Fields (IEF) and low latitude electric fields during disturbed periods?

In the present paper we 1.) Review briefly the physics of the electrodynamics associated with the equatorial electrojet, 2.) Provide a brief description of the ΔH vs ExB techniques that are employed, 3.) Present quiet-time comparisons with the Fejer-Scherliess model, 4.) Relate IEF conditions with low latitude, ΔH-inferred electric fields under quiet and disturbed conditions, and 5) Summarize the results and present the significance and implications of our findings from a space weather perspective.

2. Low latitude electrodynamics

It is well known that the effect of neutral winds together with diurnal and semi-diurnal tidal components in the atmosphere cause currents to flow in the 100 to 120 km altitude region. This is the so-called Sq (Solar quiet) wind dynamo current system in the E region. Resulting from this current system is an electrostatic field directed eastward from dawn to dusk at low latitudes. The strength of this electric field is about 0.5 mV/m and is responsible for the upward ExB drift velocities of ~ 20 m/sec measured by the Jicamarca ISR. As a result of this electric field, within ± 2° of the magnetic equator, an enhanced eastward current flows (between 100 and 110 km altitude) known as the equatorial electrojet (see Richmond, 1989 and Reddy, 1989 for in-depth reviews of the neutral wind dynamo and the equatorial electrojet, respectively).

Fig. 1 depicts the eastward electric field (yellow arrow), the consequent vertical electric field (red arrow) and the current systems that are associated with the electrojet. The view is to the north at the magnetic equator viewing the dayside region. If an eastward electric field exists and is perpendicular to B, then a Hall current is generated in the downward direction. Because of the particular geometry at the magnetic equator where magnetic field lines are horizontal, the Hall current, carried by upward moving electrons, quickly polarizes the ionospheric E layer so that an upward directed polarization electric field is produced. This electric field (red arrow) is about 5 to 10 times stronger than the eastward electric field (yellow arrow) that produced it. It is this vertical electric field that is responsible for the eastward equatorial electrojet current. This current produces the strong enhancement in the H component observed by magnetometers within ± 10° of the magnetic equator.

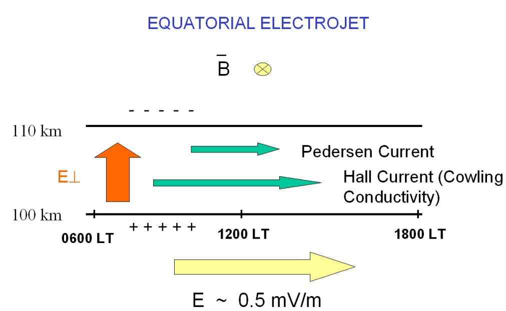

Fig.1. Schematic diagram of equatorial electrojet electric fields and current systems

Fig. 2 is a schematic plot of noontime magnetometer H component observations as a function of magnetic latitude. This figure is based on observations of the H component during September and October 1958 from a latitude chain of magnetometers at 75 ^{o} W. geog. long. (Onwumechilli, 1967). Note the 100 nanoTesla (nT) increase near the dip equator superimposed on the "global" Sq current magnetometer observations. When the H component observations from a magnetometer 6 to 9 degrees away from the magnetic equator are subtracted from the H component values measured by a magnetometer on the magnetic equator, the difference is related only to the electrojet contribution that, in turn, is directly related to the eastward electrostatic field that created the electrojet current. Carrying out this subtraction to provide a ΔH value is necessary in order to eliminate both the "global" Sq current system and the Dst ring current component in H, resulting in a ΔH value that is only related to the ionospheric electrojet current and hence the east-west electric field. This eastward electric field might originate from the Sq wind dynamo mechanism or be associated with a penetration electric field from high latitudes, or a disturbance dynamo electric field. It is emphasized that the currents are ionospheric in origin and are not associated with the Dst "ring" currents, or the tail currents.

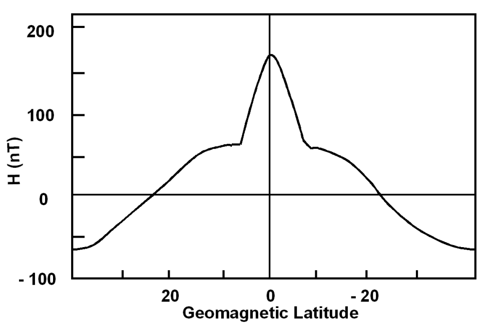

Fig. 2. Schematic plot of typical noontime magnetometer H component observations as a function of latitude

3. ΔH vs ExB Drift Relationships

In order to establish the relationships between ΔH and vertical ExB drift velocities, Anderson et al. (2004) utilized the magnetometer H component observations at Jicamarca and Piura, Peru and the vertical, daytime ExB drift velocities obtained from the JULIA (Jicamarca Unattended Long-term Ionosphere Atmosphere) 150 km radar echo observations. This investigation covered the period from August, 2001 through December, 2003. The neural network technique developed by Anderson et al. (2004) to give the ΔH vs ExB drift relationships is described in more detail in the next section. Here we briefly describe the JULIA radar and its ability to measure daytime, vertical ExB drift velocities from the Doppler shift of 150 km echo returns..

The JULIA radar at Jicamarca, Peru provides the daytime, vertical ExB drift velocities that have been related to the ground-based magnetometer observations. The JULIA radar is a low power 50 MHz coherent scatter system located at the Jicamarca Radar Observatory near Lima, Peru. The JULIA system is intended for uninterrupted and very cost effective observations of equatorial ionospheric field aligned irregularities (electrojet, spread F and 150-km echoes) and atmospheric irregularities (troposphere and lower stratosphere).

Since its deployment in 1996, it has been used extensively in observing equatorial plasma density irregularities, particularly from the *E* and *F* regions [e.g., Hysell et al*.,* 1997, Hysell and Burcham, 1998, Hysell and Burcham, 2000] and neutral atmospheric waves. In this study, JULIA vertical ExB drifts were obtained from the 150 km echoes (Chau and Woodman, 2004). It has been shown that these drifts are in excellent agreement with the F-region vertical drifts.

As described by Anderson et al. (2004), for each of the magnetometer data sets at Jicamarca (11.9^{o} S. geog. lat., 283.1^{o} E. geog. long., 0.8^{o} dip lat.) and Piura (5.2^{o} S. geog. lat., 279.4^{o} E. geog. long., 6.8^{o} N. dip lat.), the nighttime baseline in H was first obtained for each day and then subtracted to give the daytime values. This produced daytime H component values at each of the stations for all of the days we will be considering. The Jicamarca and Piura magnetometer H component observations for this study were available from January, 2001 through December, 2004.

Neural Network Approach

In general, neural networks provide a very powerful technique for mapping complex functions related to a wide variety of systems and are particularly suited for real-time applications.

Similar to the method described by Anderson et al. (2004), a multilayer feedforward neural network has been employed in estimating the daytime equatorial vertical ExB drift velocities from Jicamarca and Piura magnetometer H component observations. The network architecture, its inputs and output are depicted in Fig. 3. The eight inputs to the network are named on the left side of the Fig. 3 and on the right side is the network's output, the vertical ExB drift velocity. In the Anderson et al. (2002) paper, the authors investigated the relevance of each network's input on the output using a stepwise discriminant analysis method, showing that the most significant input parameter is ΔH and the next most important input is the F10.7 cm solar radio flux. They also concluded that the other inputs are less significant in affecting the daytime ΔH vs ExB drift relationships within the considered training domain.

Anderson et al. (2004) validated the trained neural network by comparing the ΔH-inferred ExB drift velocities with the independent ExB drift velocities obtained from the Jicamarca ISR observations. Between April, 2001 and November, 2003, there were 38 days when the Jicamarca Incoherent Scatter Radar (ISR) in Peru was measuring the vertical ExB drift velocities. Extracting the ISR ExB drift velocities between 10 and 16 LT for each of the 38 days, gave 2254 samples to validate the realism of these relationships. In each case the neural network approach (with 8 inputs) gave the lowest RMS error of the three approaches described in their paper. Over the 38 days, the average RMS error for the multiple regression method was 4.59 m/sec and for the neural network approach it was 4.21 m/sec. The reader is referred to their Figure 9 which compares, graphically, the Jicamarca ExB drifts with the three approaches for April 17, 2002 and September 25, 2003.

For the present study, 463 quiet and disturbed days of observations covering a period from August, 2001 to February, 2005 between 0700 and 1700 LT, were used to train a MATLAB 3-layer feedforward network with 15 hidden neurons and 8 input neurons (Demuth and Beale, 2001). The training set consisted of 31,858, 5 minute-averaged samples of combined magnetometer _H component observations and vertical ExB drift velocities, from the Jicamarca 150 km echoes and the ISR observations. The RMS error over the training set was 3.36 m/sec. The neural network accurately learned the nearly linear ΔH vs. ExB drift relationship for each one of the days included in the training set. The network itself can be looked at as a collection of nearly linear ΔH vs. ExB drift relationships with a large day-to-day variability. After being trained with observations from Jicamarca and Piura, the network is presented with new input observations from the Peruvian, Philippine and Indian longitude sectors to estimate the daytime vertical ExB drift velocities. This is discussed in the next section.

4. Quiet Time Studies

In this study, we investigate quiet-day ΔH-inferred ExB drift velocities vs Local Time in three longitude sectors, the Peruvian sector, the Philippine sector and the Indian sector. In the Peruvian sector, we obtain data from the magnetometers at Jicamarca and Piura, which have already been described. In the Philippine sector, Prof. K. Yumoto, Director of the Circum-Pan Pacific Magnetometer Network (CPMN), has supplied magnetometer observations from Davao (7^o N., 125.4^o E, 1.4^o S dip lat.) and Muntinlupa (14.4^o N, 121^o E, 6.3^o N dip lat.) (Yumoto, 2001). In the Indian sector, Dr. Bhatacharyya has provided magnetometer data from Thirunelveli (8.7^o N, 76.9^o E., 0.5^o S dip lat.) and Alibag (18.6^o N, 72.9^o E, 10^o N dip lat.)

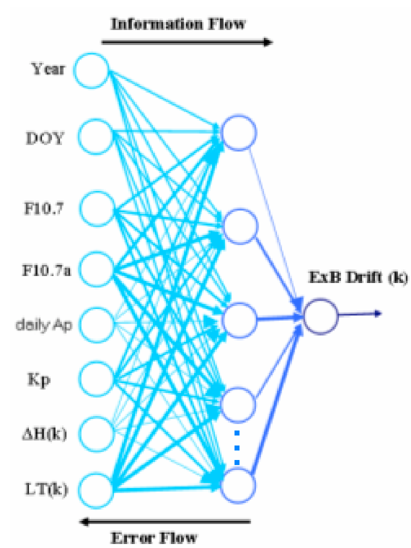

Fig. 3. Schematic of MATLAB 3-layer feedforward network

In order to compare the ΔH-inferred daytime, vertical ExB drift velocities with the Fejer-Scherliess quiet time, climatological model, we have adopted the same constraints that were employed by Scherliess and Fejer (1999) when they developed the model. We define a "quiet" day as one where the 3-hour Kp value never exceeded a value of 3 for the entire day. In addition, we choose only those days when the daily Ap value is less than 10. Between January, 2001 and December, 2004, there are more than 450 days that meet these conditions.

The Scherliess and Fejer (1999) paper outlines the procedures that were used to bin the satellite (AE-E) and ground-based radar observations by longitude, season and solar cycle activity. Briefly, three seasons were chosen 1.) June solstice (May-August), 2.) December solstice (November-February) and 3.) Equinox (March-April, September-October). Scherliess and Fejer combined all of the satellite and radar observations for low and high solar activity, together, between 0600 and 1500 LT. We have binned the "quiet" day observations into the same 3 seasonal periods and for each season, combined all of the observations from January, 2001 to December, 2004. There are fewer days in the Philippine sector because the available magnetometer observations from Davao and Muntinlupa extended only from January, 2001 through May, 2004 rather than December, 2004. In the Indian sector, magnetometer data covers the January 1, 2001 to December 31, 2002.

Fig. 4 displays all of the 165 days for the equinox season in the Peruvian longitude sector. The red line is the average of the ΔH-inferred ExB drift velocities while the blue line is the Fejer-Scherliess climatological values. During the Equinox season in the Peruvian longitude sector, the daytime variability in ExB drift velocities is less than the June Solstice variability ~ 25 m/sec versus 30 m/sec, while the average value at 1100 LT is slightly greater ~ 23 m/sec versus 20 m/sec. This matches the Fejer-Scherliess value very well. In fact, the overall daytime comparison with the Fejer-Scherliess model is excellent during the Equinox period as it is during the June Solstice period. During Equinox, the minimum value at 1100 LT is 10 m/sec, compared with 0 m/sec for both June and December solstice.

Fig. 5 displays the 129 days for the equinox season in the Philippine sector. The equinox season displays excellent agreement between the ΔH-inferred average ExB drift pattern and the climatological pattern with the climatological pattern slightly higher throughout the day.

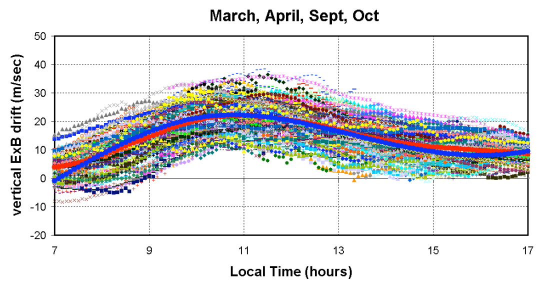

Fig. 4. ExB drift velocity vs local time in the Peruvian sector under Equinox conditions

During this season, the variability in ExB drift at 1000 LT is about 20 m/sec and the maximum average value is 25 m/sec, slightly higher than the 23 m/sec for the equinox period in the Peruvian sector.

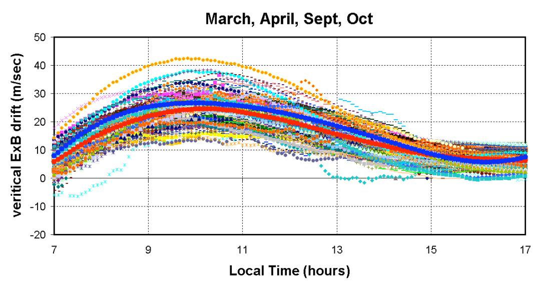

Fig. 5. Same as Fig. 4 for the Philippine sector

In the Indian sector, magnetometer data between Jan., 2001 and Dec., 2002 provided 92 days during the Equinox period and these are displayed in Fig. 6. Note that the average ΔH-inferred ExB drift pattern (red line) is in reasonable agreement with the Fejer-Scherliess climatological curve (blue line). A comparison between Fig. 5 and Fig. 6 shows that the maximum daytime ΔH-inferred ExB drift velocity occurs at 1000 LT in both the Philippine and Indian sectors and both have nearly equal maximum drift values. For all three sectors, the standard deviation in ExB drifts is +/- 5 m/sec, signifying that 90% of all quiet days fall within +/- 5 m/sec of the average curve between 0700 and 1700 LT for all three sectors and all three seasons.

5. Disturbed Time Studies

Compared with quiet time ExB drift patterns, low latitude plasma drifts and currents respond quite differently during geomagnetic disturbed periods. Under steady-state conditions, the low

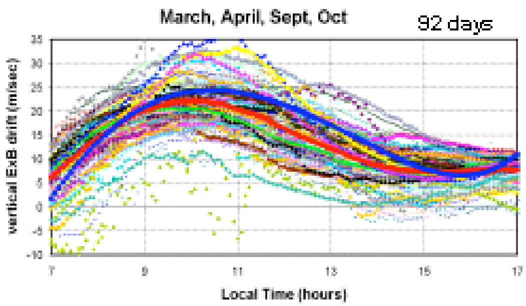

Fig. 6 Same as Fig. 4 in the Indian sector

and mid latitude ionosphere is shielded from the high latitude convection by ions at the low-latitude edge of the plasma sheet (*Wolf*, 1975; *Sakharov et al.*, 1989). During periods when the high latitude convection patterns are undergoing large changes, high latitude electric fields "leak through" the shielding layer. Evidence for this penetration of electric fields to the equatorial region are presented by *Gonzales et al.* (1983) and *Fejer et al.* (1990). *Kikuchi et al.* (1978) and *Kikuchi and Araki* (1979) have suggested that the electrostatic fields travel to the equatorial region, instantaneously, by the zeroth-order TM mode in the Earth-ionosphere waveguide.

There are two major sources of low latitude electric field disturbances during geomagnetically active periods. One originates from the magnetosphere and the other is due to the ionospheric disturbance dynamo. The latter results from the dynamo action of storm time winds as a result of enhanced energy deposition at high latitudes. *Scherliess and Fejer* (1997) have developed an empirical model that describes the storm time dependence of the equatorial disturbance dynamo electric fields.

When the cross polar cap potential suddenly increases as a result of an increase in the dawn-to-dusk, cross-tail electric field, E_y ($E_y = -V_{sw} \times B_z$), this electric field can promptly penetrate to the equatorial region (undershielding) until a shielding electric field (dusk-to-dawn) has had time to develop in the inner magnetosphere (*Wolf*, 1983; *Sazykin*, 2000). This electric field shields the inner magnetosphere from strong convection fields. When the strong convection field decreases due to a northward turning of the IMF, the dusk-to-dawn electric field can promptly penetrate to low latitudes (overshielding) until the shielding layer and overall magnetospheric configuration readjust.

In the figures that follow, we compare the IEF conditons observed by the ACE satellite, time-shifted to the magnetopause location, with the low latitude electric fields inferred from magnetometer observations in the Peruvian, Philippine and Indian longitude sectors. Fig. 7 compares the IEFy and IEFz components and the vertical ExB drift velocities in the three sectors as a function of UT for July 12, 2001.The lower portion of the figure illustrates the daytime periods for each sector (0700 – 1700 LT) as a function of UT. This is a quiet day and the ΔH-inferred ExB drift velocities are approximately 20 m/sec in each of the sectors and the maximum values occur around 1000 to 1100 LT.

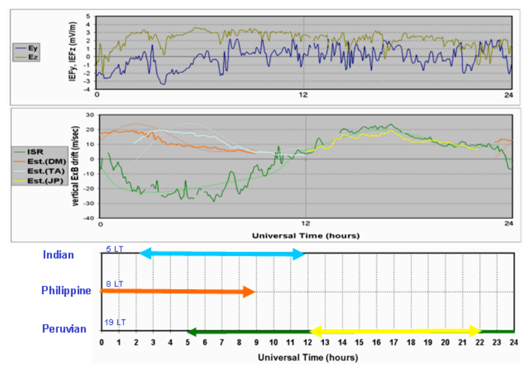

Fig. 7 IEF values and low latitude ExB drift velocities vs UT for July 12, 2001

Fig. 8 depicts the IEF conditions and the ΔH-inferred ExB drifts for April 17, 2001. For all of April 17, the IEF conditions are "quiet" and the Philippine, Indian and Peruvian sectors reflect quiet conditions. At 0100 UT on April 18, Bz suddenly turns southward leading to a strong, positive IEFy value. This occurs when the Philippine and Indian sectors are in daylight and a sudden increase in ExB drift velocity is observed in the Philippine sector. At 0430 UT, there is a sudden northward turning of IMF Bz and a sudden decrease in the upward ExB drift velocity in both the Philippine and Indian sectors. Simultaneously, in the the nighttime Peruvian sector there is a sudden increase in the upward drift velocity. This is all consistent with the idea that, for overshielding, the promptly penetrating electric fields at low latitudes are directed from dusk-to-dawn which means that the daytime ExB drifts will be downward and the nighttime ExB drift velocity will be upward.

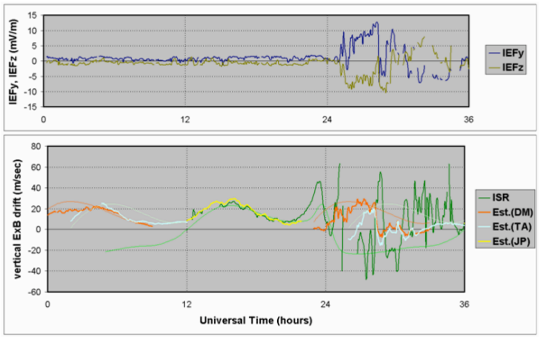

Fig. 8 Same as fig. 7 for April 17 and 18, 2001

Fig. 9 depicts the IEF conditions and the ΔH-inferred ExB drifts for April 16, 2002. This is an example where the geomagnetic storm commenced when the Peruvian sector was in daylight and the Philippine and Indian sectors were in nighttime conditions. This accounts for the lack of ExB drift observations in these two longitude sectors. However, prior to the storm onset, when IEF conditions were quiet, the quiet-time ExB signatures were observed in the Philippine and Indian sectors. In the Peruvian sector, note that the Jicamarca ISR observations of ExB drift velocities (geen line) and the ΔH-inferred velocities (yellow line) are perfectly matched and they correlate directly with the time-shifted IEFy values (Kelley et al., 2003).

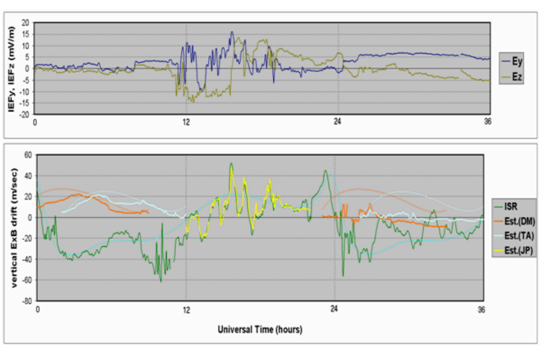

Fig. 9 Same as fig. 7 for April 17 and 18, 2002

6. Discussion and Summary

Basically, the significance of our results is two-fold:

1.) The fact that reasonable agreement with the Fejer-Scherliess, climatological, daytime ExB drift model has been achieved in three longitude sectors means that this technique can be applied to other longitude sectors where appropriately place magnetometers provide ΔH observations.
2.) Anderson et al. (2004) demonstrated that the trained neural network could be applied to both quiet and disturbed days and achieve excellent agreement with the Jicamarca ISR observed, vertical ExB drift velocities. Demonstrating that the same relationship can now be applied in different longitude sectors means, for example, that the ionospheric effects of promptly penetrating electric fields associated with geomagnetic storms can be studied, theoretically, at a number of different longitude sectors, on a day-to-day basis.

From a space weather, operational perspective, these results are also significant. The capability now exists to improve, significantly, the specification of ionospheric parameters, on a day-to-day basis, globally, by incorporating these ExB drift velocities into global ionospheric data assimilation models such as GAIM (Schunk et al., 2004) that will benefit both the DoD and civilian navigation and communication customers.

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