CLIMATOLOGY OF MIDDLE AND LOW-LATITUDE F-REGION
PLASMA DRIFTS FROM SATELLITE MEASUREMENTS

by

John W. Jensen

A dissertation submitted in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

in

Physics

UTAH STATE UNIVERSITY
Logan, Utah
2007
We used ion drift observations from the DE-2 satellite to study for the first time the longitudinal variations of middle and low latitude F-region zonal plasma drifts during quiet and disturbed conditions. The daytime quiet-time drifts do not change much with longitude. In the dusk-premidnight period, the equinoctial middle latitude westward drifts are smallest in the European sector, and the low latitude eastward drifts are largest in the American-Pacific sector. The longitudinal variations of the late night-early morning drifts during June and December solstice are anti-correlated. During geomagnetically active times, there are large westward perturbation drifts in the late afternoon-early night sector at upper middle latitudes and in the midnight sector at low latitudes. The largest westward disturbed drifts during equinox occur in the European sector and the smallest in the Pacific region. These results suggest that during equinox, Subauroral Polarization Streams (SAPS) events occur most often at European longitudes. The low latitude perturbation drifts do not show significant longitudinal dependence.
We have used five years of measurements on board the ROCSAT-1 satellite to develop a detailed local-time, season, and longitude-dependent quiet-time global empirical model for equatorial F-region vertical plasma drifts. We show that the longitudinal dependence of the daytime and nighttime vertical drifts is much stronger than reported earlier, especially during December and June solstice. The late night downward drift velocities are larger in the eastern than in the western hemisphere at all seasons, the morning and afternoon December solstice drifts have significantly different longitudinal dependence, and the daytime upward drifts have strong wavenumber-four signatures during equinox and June solstice. The largest evening upward drifts occur during equinox and December solstice near the American sector. The longitudinal variations of the evening prereversal velocity peaks during December and June solstice are anti-correlated, which further indicates the importance of conductivity effects on the electrodynamics of the equatorial ionosphere. We have shown that disturbance dynamo largely does not affect daytime drifts. The upward perturbations during the nighttime are largely season independent, but near the prereversal enhancement, the downward perturbation drifts are largest during equinox and smallest during December.
I would like to thank my advisor, Dr. Bela Fejer, for his guidance, patience, and encouragement. I would also like to thank the members of my committee, Drs. Eric Held, Robert Schunk, Charles Swenson, and Michael Taylor, for their support and suggestions. I am grateful to Dr. Shin-Yi Su for providing the ROSCAT-1 data and to Drs. Roderick Heelis and Robin Coley for providing the DE-2 data.

I would also like to thank the staff of the Physics Department and the Center for Atmospheric and Space Sciences, especially Melanie, Shawna, Sharon, Karalee, and Shelley, for their support and assistance.

I am grateful to my parents for instilling in me a desire to learn and explore the world around me. Lastly, I would like to express my deepest gratitude to my wife, Stacey. Without her loving support and encouragement, I would have never reached this point.

John W. Jensen
CONTENTS

ABSTRACT .................................................................................................................. iii

ACKNOWLEDGMENTS ................................................................................................. v

LIST OF FIGURES .......................................................................................................... viii

CHAPTER

1. INTRODUCTION ......................................................................................................... 1

1.1 The Earth’s Atmosphere .......................................................................................... 1

1.2 The Earth’s Ionosphere ........................................................................................... 2

1.3 Overview of This Work ............................................................................................ 5

2. LOW AND MIDDLE LATITUDE IONOSPHERIC PLASMA DRIFTS ......................... 8

2.1 Introduction .............................................................................................................. 8

2.2 Quiet-Time Dynamo ............................................................................................... 9

2.3 Equatorial Quiet-Time Plasma Drifts ...................................................................... 11

2.4 Low-Latitude Quiet-Time Plasma Drifts .................................................................. 18

2.5 Mid-Latitude Quiet-Time Plasma Drifts .................................................................. 22

2.6 Low- and Mid-Latitude Disturbed Plasma Drifts ..................................................... 27

3. LONGITUDINAL DEPENDENCE OF MIDDLE AND LOW-LATITUDE ZONAL PLASMA DRIFTS MEASURED BY DE-2 .................................................................................. 40

3.1 Introduction .............................................................................................................. 40

3.2 Data and Methodology ......................................................................................... 43

3.3 Quiet-Time Drifts .................................................................................................... 45

3.4 Disturbed Drifts ....................................................................................................... 60

4. EQUATORIAL F-REGION VERTICAL PLASMA DRIFTS FROM ROCSAT-1 OBSERVATIONS .................................................................................................................. 65

4.1 Introduction .............................................................................................................. 65

4.2 Measurements and Data Selection ........................................................................... 69

4.3 Quiet-Time Model Development and Accuracy ...................................................... 72
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Altitudinal variation of ion and electron density at noon and midnight</td>
</tr>
<tr>
<td>1-2</td>
<td>Altitudinal variation of ionospheric conductivities during daytime</td>
</tr>
<tr>
<td>2-1</td>
<td>Average vertical plasma drift velocities over Jicamarca</td>
</tr>
<tr>
<td>2-2</td>
<td>Solar flux dependency of the average vertical prereversal enhancement peak drift velocity for three seasons</td>
</tr>
<tr>
<td>2-3</td>
<td>Empirical model of quiet-time vertical plasma drifts derived from AE-E satellite data</td>
</tr>
<tr>
<td>2-4</td>
<td>Global empirical model for high and low solar flux</td>
</tr>
<tr>
<td>2-5</td>
<td>Jicamarca model zonal plasma drifts for three seasons and two levels of solar flux</td>
</tr>
<tr>
<td>2-6</td>
<td>Seasonal dependence of quiet-time perpendicular/northward drifts for two values of solar flux</td>
</tr>
<tr>
<td>2-7</td>
<td>Seasonal dependence of quiet-time perpendicular/eastward drifts for two values of solar flux</td>
</tr>
<tr>
<td>2-8</td>
<td>Quiet-time perpendicular/northward plasma drifts over Saint Santin</td>
</tr>
<tr>
<td>2-9</td>
<td>Quiet-time perpendicular/northward plasma drifts over Millstone Hill</td>
</tr>
<tr>
<td>2-10</td>
<td>Quiet-time zonal plasma drifts over Saint Santin</td>
</tr>
<tr>
<td>2-11</td>
<td>Quiet-time zonal plasma drifts over Millstone Hill</td>
</tr>
<tr>
<td>2-12</td>
<td>A typical 48-hour period during disturbed conditions above Jicamarca</td>
</tr>
<tr>
<td>2-13</td>
<td>Comparison of local time variation of empirical prompt penetration electric fields for various storm times with the Rice convection model</td>
</tr>
<tr>
<td>2-14</td>
<td>Local time variation of the vertical disturbance dynamo perturbation drifts</td>
</tr>
<tr>
<td>2-15</td>
<td>Seasonal and solar flux dependency of zonal plasma drifts over Jicamarca</td>
</tr>
</tbody>
</table>
2-16 Seasonal dependence of the quiet and disturbed zonal plasma drifts over Arecibo .................................................................37
2-17 Average zonal plasma drifts as a function of magnetic local time for 5 latitudinal regions under geomagnetically quiet and disturbed conditions .........38
2-18 Comparison of long lasting zonal disturbance drift perturbations from Millstone Hill and Saint Santin radar measurements and DE-2 zonal drift data .................................................................39
3-1 Number of DE-2 zonal drift measurements in three latitudinal sectors during geomagnetically quiet and active times .........................................................45
3-2 Examples of latitudinal profiles of quiet-time average zonal drifts measured by DE-2 during 1982 ........................................................................47
3-3 Longitudinally averaged quiet-time DE-2 zonal drift velocities in five latitudinal sectors ..................................................................................48
3-4 Longitudinal variations of early night northern and southern hemisphere quiet-time average relative zonal drift velocities in five longitudinal sectors ......50
3-5 Longitudinal and latitudinal dependence of average quiet-time relative zonal plasma drifts in the early night sector .............................................................52
3-6 Latitudinal and longitudinal dependence of relative zonal drifts obtained by averaging the northern and southern hemisphere quiet-time relative drifts (upper panel). Latitudinal and longitudinal variations of the zonal drift velocities obtained by adding the relative drifts shown in the upper panel and the longitudinally averaged values at 22.5 LT (lower panel) ...........................................53
3-7 Longitudinal variation of the late night-early morning quiet-time relative zonal drifts during June and December solstice in five latitudinal sectors .........55
3-8 Latitudinal and longitudinal dependence of quiet-time zonal drifts at 5.5 LT during December and June solstice ...............................................................57
3-9 Longitudinal variation of the early morning-noon quiet-time relative zonal drifts during equinox in five latitudinal sectors .................................................58
3-10 Longitudinal variation of the noon-early evening quiet-time relative zonal drifts during June and December solstice in five latitudinal sectors ..............59
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-11</td>
<td>Longitudinally averaged zonal drift velocities during geomagnetically quiet and disturbed conditions</td>
</tr>
<tr>
<td>3-12</td>
<td>Longitudinal dependence of quiet and disturbed zonal drift velocities at upper middle latitudes</td>
</tr>
<tr>
<td>3-13</td>
<td>Scatter plot of longitudinal dependence of upper middle latitude zonal plasma drifts under disturbed conditions for 18-22 MLT</td>
</tr>
<tr>
<td>3-14</td>
<td>Percentage of occurrence of early night large westward drifts upper middle latitudes for Kp &gt; 4</td>
</tr>
<tr>
<td>4-1</td>
<td>Examples of scatter plots of quiet-time equatorial vertical drift velocities over a 30° longitudinal sector measured by ROCSAT-1 for three plasma density thresholds</td>
</tr>
<tr>
<td>4-2</td>
<td>Longitude integrated equatorial zonal electric fields</td>
</tr>
<tr>
<td>4-3</td>
<td>Local time and longitude dependence of quiet-time equatorial vertical drifts in eight longitudinal sectors for moderate solar flux conditions</td>
</tr>
<tr>
<td>4-4</td>
<td>Local time, seasonal and longitudinal dependent equatorial quiet-time vertical drift velocities for moderate solar flux conditions</td>
</tr>
<tr>
<td>4-5</td>
<td>Longitudinal variations of morning and afternoon averaged quiet-time vertical drifts</td>
</tr>
<tr>
<td>4-6</td>
<td>Seasonal and longitude dependence of quiet-time evening prereversal velocity peaks</td>
</tr>
<tr>
<td>4-7</td>
<td>Seasonal and longitude dependence of quiet-time equatorial model drift velocities for two decimetric solar flux values</td>
</tr>
<tr>
<td>4-8</td>
<td>Seasonal and longitudinal variations equatorial evening prereversal velocity peaks for two decimetric solar flux values</td>
</tr>
<tr>
<td>4-9</td>
<td>Comparison of ROCSAT-1 and Jicamarca model vertical plasma drifts for two solar flux values</td>
</tr>
<tr>
<td>4-10</td>
<td>Comparison of quiet-time equinoctial evening prereversal vertical velocity peaks obtained from the ROCSAT-1 data and from the numerical simulation by Vichare and Richmond</td>
</tr>
</tbody>
</table>
4-11  Seasonal dependence of vertical plasma drifts during quiet and disturbed conditions..................................................................................................................91

4-12  Seasonal dependence of residual vertical drift calculations for a difference in AE of 300 nT ..................................................................................................................92

4-13  Solar flux variation of longitudinally averaged residual vertical plasma drifts during equinox .................................................................................................................93

4-14  Longitudinal dependence of residual vertical plasma drifts for equinox.........95

A-1  Quiet-time model values for December solstice at 150 units of flux ..........111

A-2  Quiet-time model values for Equinox at 150 units of flux .........................112

A-3  Quiet-time model values for June solstice at 150 units of flux......................113

B-1  Quiet-time model flux variation for December solstice at two levels of flux ....115

B-2  Quiet-time model flux variation for equinox at two levels of flux.................116

B-3  Quiet-time model flux variation for June solstice at two levels of flux..........117

C-1  Longitudinal variation of quiet-time vertical plasma drifts during the day ....119
1.1 The Earth’s Atmosphere

The Earth’s atmosphere extends from the surface of the Earth to many thousands of kilometers. The neutral atmosphere can be classified into different regions based on its temperature profile. The region from the ground to about 10 km in which the temperature steadily decreases with altitude is called the troposphere. The height of the tropopause, the upper boundary of the troposphere, varies from about 8 km at the equator to about 18 km at the geographical poles. The temperature then quickly rises in the stratosphere, the region above the tropopause, due in part to the relatively large amount of ozone which absorbs solar radiation. The stratopause, located at about 45 km, defines the end of this temperature increase and the start of the mesosphere, which is characterized by a large decrease in temperature. The mesopause which is located at 95 km is the upper boundary of the mesosphere; it is the coldest region of the atmosphere with temperatures as low as 180 K. The higher altitude region is the thermosphere which extends from 95 km to about 500 km. The temperature in this region quickly reaches and maintains a maximum value of 1000 K.

The neutral atmosphere is well mixed below about 100 km, which constitutes the homosphere, with a composition of 78% N₂, 21% O₂, and 1% Ar, as well as many minor constituents. Above 100 km (heterosphere) the various gases begin to separate into different layers according to their masses with heavier molecules dominating at
lower altitudes and lighter atoms dominating at higher altitudes. Above 500 km, in the exosphere, the neutral densities are so low that collisions are no longer important; the neutral particles follow ballistic motions and can often gain enough energy to exit the Earth's atmosphere.

1.2 The Earth’s Ionosphere

The ionosphere, the ionized portion of the upper atmosphere, is formed by ionization of atmospheric gases by solar UV and X-ray radiation. Ions and electrons are constantly being generated on the sunward side of the Earth and lost by recombination with other particles or diffusion to other regions. The ions and electrons that make up the plasma in the ionosphere have number densities that are generally less than 1% of typical neutral densities, but the currents and electric fields that are produced can have a profound impact on the region.

The ionosphere can be classified into different altitudinal layers or regions based upon the plasma density profile as illustrated in Figure 1-1. The D-region extends from about 60 to 100 km and is heavily dominated by chemical processes and collisions with the neutral atmosphere. The major ions in this region are both positive and negative molecular ions as well as water cluster ions; due to their complex chemical processes, this region is the most difficult to model. The E-region (100 to 150 km) is also dominated by chemical loss processes and collisions. The major ion constituents in this region are \( NO^+ \) and \( O_2^+ \), and the major loss process is dissociative recombination. Both the D- and E-region loss processes are quite fast and therefore lead to rapid decreases of the lower ionospheric plasma densities after sunset.
The F-region extends from 150 to about 800 km and is usually divided into three sub-regions. The F1 region (150 to 250 km) is still dominated by chemical loss processes; the F2 region is a transition region where both chemical and diffusion loss processes are important. Diffusion loss processes dominate in the topside ionosphere (from about 500 to 800 km). The daytime peak in the plasma density occurs generally in the altitudinal range of about 300 to 500 km where it can have values larger than \(10^6 \text{ cm}^{-3}\) near noon. At night the altitude of the peak can range from 200 to 600 km, and the peak densities can be as low as \(10^4 \text{ cm}^{-3}\) in the postmidnight period. Relatively large F-region plasma densities are maintained throughout most of the night because of much
slower loss processes and small additional sources of ionization from an even higher region of ionization known as the protonosphere (800 km to well above 1000 km).

This work deals only with mid- and low-latitude (below 60° geomagnetic latitude) ionospheric processes which are mostly shielded from high-latitude effects during geomagnetically quiet conditions. During disturbed periods, however, high latitude electric fields and currents can significantly affect the lower latitude ionosphere.

The dynamics of the quiet-time upper atmosphere is driven mostly by solar heating tidal forces. On the dayside, solar radiation sets up a global system of neutral winds that tend to flow toward the colder regions on the nightside. When these neutral winds push the ionospheric plasma across magnetic field lines, electric fields and currents are generated, which play a major role on the distribution of ionization.

Ionospheric conductance, especially the field-line integrated values, plays a fundamental role on the electrodynamics of the region. The conductivity parallel to the electric field and perpendicular the magnetic field is called the Pedersen conductivity. The Hall conductivity is in a direction perpendicular to both the electric and magnetic field, and the parallel conductivity is parallel to the geomagnetic field. The parallel conductivity is more than six orders of magnitude larger than the other two, and thus ionospheric electric fields can be transferred along these lines virtually uninhibited. Figure 1-2 shows the values of the Pedersen, Hall, and parallel conductivities as a function of altitude. As can be seen from Figure 1-2, the Pedersen and Hall conductivities decrease with increasing altitude. The parallel conductivity, on the other hand, increases with increasing altitude. More detailed information on ionospheric
Ionospheric Conductivities

Figure 1-2. Altitudinal variation of ionospheric conductivities during daytime (Courtesy Christian Wohlwend, Center for Atmospheric and Space Sciences, Utah State University, 2007).

processes is given in the textbooks by Kelley [1989], Tascione [1994], Schunk and Nagy [2000], and others.

1.2 Overview of This Work

The main focus of this thesis is a detailed study of longitudinal, latitudinal, seasonal, and solar flux dependency of mid- and low-latitude F-region plasma drifts using extensive databases of satellite observations. We will consider these drifts during mostly geomagnetically quiet conditions but will also examine the main characteristics of disturbance drifts. We used middle and low-latitude zonal drift measurements from the
polar orbiting Dynamics Explorer 2 (DE-2) as well as equatorial vertical drift observations from the low inclination Republic of China Satellite 1 (ROCSAT-1). For equatorial latitudes, we have developed a quiet-time, global, solar flux dependent, empirical model with longitudinal resolution of 15° over solar flux values ranging from 100 to 200 units.

In Chapter 2 of this work, we first review briefly the basic ionospheric electrodynamic processes including the E- and F-region dynamos which are responsible for the mid- and low-latitude quiet-time and disturbed plasma drifts. Then we overview the main results on quiet and disturbed plasma drifts at mid- and low-latitudes derived from radar and satellite observations. We also give observations and an overview of previous attempts of global satellite studies of seasonal, solar flux, latitudinal, and longitudinal dependency of mid- and low-latitude plasma drifts.

In Chapter 3 we present for the first time the study of longitudinal and seasonal dependence of zonal plasma drifts derived from the DE-2 satellite for mid- and low-latitudes during quiet and disturbed conditions. Our results indicate that the longitudinal variation is strongly seasonal dependent. Chapter 4 initially describes a detailed description of the data selection and methodology for the study of the longitudinal dependence of the ROCSAT-1 equatorial vertical drifts. Then, it presents the first time that longitudinal, seasonal, and solar flux variation of the average vertical plasma drifts have been inferred from the satellite data. Finally, it discusses the main properties of seasonal and longitudinal dependent disturbance dynamo drifts and compares them with
earlier results. In Chapter 5 we present a summary of our results and present suggestions for future work on global studies of ionospheric electrodynamics.
CHAPTER 2
LOW AND MIDDLE LATITUDE IONOSPHERIC PLASMA DRIFTS

2.1 Introduction

Ionospheric electric fields and currents play an important role in the dynamics of the Earth’s thermosphere and magnetosphere. Low-latitude ionospheric electrodynamic (ExB) plasma drifts strongly affect various ionospheric and thermospheric phenomena such as the Appleton anomaly, the global distribution of low-latitude ionization, the equatorial electrojet and the generation of equatorial plasma structures, spread F, and radio wave scintillations. These processes have been discussed in detail by several authors [e.g., Kelley, 1989; Schunk and Nagy, 2000].

The climatology and characteristics of mid- and low-latitude F-region plasma drifts have been studied extensively over the last few decades. This is especially the case over the American sector where there have been extensive ground based measurements. These experimental results have been used in numerous comparisons with theoretical and numerical electrodynamic models as well as for the development of empirical plasma drift models. Recently there have been an increasing number of experimental studies of the global distribution of plasma drifts using satellites such as the Dynamics Explorer 2 (DE-2) [Heelis and Coley, 1992; Coley and Heelis, 1989], Atmospheric Explorer E (AE-E) [Fejer et al., 1995], and Defense Meteorological Satellite Program (DMSP) [e.g., Hartman and Heelis, 2007]. Global numerical models such as Thermosphere-Ionosphere

\footnote{All figures in this chapter are copyrighted by the American Geophysical Union and reproduced here with permission.}
electrodynamics General Circulation Model (TIEGCM) [Fesen et al., 2000; Vichare and Richmond, 2005] and the Coupled Thermosphere-Ionosphere-Plasmasphere model (CTIP) [e.g., Millward et al., 2001] have also been used extensively to study the middle and low latitude ionosphere-thermosphere system.

In this chapter we will first give a brief overview of the E- and F-region dynamos which are the primary generation mechanisms of quiet-time ionospheric electric fields, plasma drifts, and currents; after which we will review the main characteristics of low- and mid-latitude plasma drifts derived from both ground based and satellite measurements. Then, we will briefly outline the main generation mechanisms of plasma drifts during disturbed conditions and will describe some of their main signatures.

2.2 Quiet-Time Dynamo

The basic dynamo processes responsible for the generation of ionospheric plasma drifts and currents have been known for several decades [e.g., Rishbeth, 1971; Heelis et al., 1974; Kelley, 1989; Richmond, 1995]. In this section we will briefly discuss the quiet-time E- and F-region dynamos; after which we will give an overview of the characteristics of quiet-time plasma drifts in the low- and mid-latitude F-region ionosphere.

The solar diurnal (1, -2) tide, caused by solar heating of the sunward atmosphere, drives the dominant low-latitude E-region neutral wind system. This heating occurs mostly in the stratosphere and troposphere, and these tidal oscillations propagate upward to ionospheric heights. Above about 30° latitude, since the semidiurnal tide becomes dominant, the diurnal tide cannot propagate upward and remains trapped in the
stratosphere. The lunar semidiurnal tide (2, 2) (period of about 24.8 hours) creates the next strongest neutral wind system, but its strength is one order of magnitude smaller than those of the solar tides [e.g., Schunk and Nagy, 2000].

The solar generated neutral wind field drives a global scale current system known as the solar quiet (Sq) current system. The Sq current system covers altitudes from about 90 to 200 km and has largest values at about 150 km at noon, where the Pederson conductivity maximizes. The Sq current falls off rapidly to very low values during nighttime when the Pederson conductivity is very low due to low plasma densities. The wind system increases in strength with increasing latitude while the ionospheric conductivity weakens, so the Sq currents maximize at about 30° latitude and decrease at higher and lower latitudes.

The electric fields generated by the E-region dynamo are mapped along magnetic field lines (which act as equipotentials due to their large parallel conductivity) to F-region heights. In the nighttime mid- and low-latitude ionosphere, the dynamo effects of F-region thermospheric neutral winds, which also force plasma across magnetic field lines, generate electric fields and currents. During the day, the high E-region conductivity shorts out these polarization electric fields; therefore, daytime E- and F-region plasma drifts are driven mostly by E-region electric fields. At night, the local F-region dynamo is the dominant plasma drift generation mechanism.

At the equatorial dusk terminator, the F-region dynamo is no longer completely shorted out by the E-region due to low E-region conductivity. In this case, the F-region eastward neutral wind drives a downward electric field that is mapped down to the off-
equatorial E-region. This electric field now has an equatorward component that produces a westward current. Since no current may flow on the nightside E-region due to the reduced conductivity, negative charges develop at the terminator, which drive an eastward polarization electric field. This eastward electric field is then mapped back up to the F-region where it drives large upward $\mathbf{E} \times \mathbf{B}$ plasma drift velocities on the dayside of the terminator and downward drifts on the nightside. This large evening upward drift is commonly known as the prereversal velocity enhancement [Kelley, 1989; Schunk and Nagy, 2000].

2.3 Equatorial Quiet-Time Plasma Drifts

The majority of information about plasma drifts at equatorial latitudes has come from observations at the Jicamarca Radio Observatory near Lima, Peru (11.95° S, 76.87° W; magnetic dip 2° N). Ionosonde and spaced receiver observations over Brazil and India have also been used to study nighttime equatorial plasma drifts. Recently satellite measurements have provided information on F-region plasma drifts in other longitudinal sectors. Equatorial plasma drift results observed using other measurement techniques will be discussed in Chapter 4.

The 50 MHz incoherent scatter radar (ISR) at the Jicamarca Radio Observatory in Jicamarca, Peru, has been used extensively to study the characteristics of low-latitude F-region vertical and zonal plasma drifts [e.g. Woodman, 1970; Fejer et al., 1979, 1991, 2005]. For an integration time of 5 minutes, the accuracy of the daytime measurements is typically about 2 m/s for vertical drifts and about 15-20 m/s for zonal drifts. The nighttime measurements are less accurate due to lower signal-to-noise
ratios. Over Jicamarca, an F-region upward (eastward) plasma drift velocity of 40 m/s corresponds to an eastward (downward) electric field of 1 mV/m.

Figure 2-1 shows the seasonal and solar flux (10.7 cm) dependence of the average vertical plasma drifts over Jicamarca. These plasma drifts are upward during the day and downward during the night. The daytime drifts are typically solar flux independent and peak at about 1100 LT with magnitudes around 20 m/s during equinox and June solstice, with slightly smaller magnitudes during December solstice. A large prereversal enhancement is seen in the evening during equinox and December solstice while there is a much smaller enhancement during June solstice. The prereversal enhancement has clear solar flux variation during all seasons with higher fluxes producing higher upward drifts. The nighttime downward drifts have typical values from 10 to 30 m/s, and their magnitudes increase with solar flux. The evening reversal times show significant solar flux variation during the solstices whereas the morning reversal times are largely flux independent for all seasons.

Figure 2-2 shows the solar flux dependency of the prereversal drift enhancements in greater detail. Drift velocity peak values increase linearly during Equinox to values well above 50 m/s for F10.7 cm solar flux indices larger than 200 units. In June solstice these drift values seem to saturate around 20 m/s above a solar flux of 150 units, and the dependency is best fit with a quadratic curve. During December solstice the prereversal enhancement reaches 50 m/s for high flux, and both a quadratic and linear function fit the data well. A detailed study of the solar flux variation of the Jicamarca vertical plasma drifts was presented by Scherliess [1997].
Figure 2-1. Average vertical plasma drift velocities over Jicamarca for equinox (March-April, September-October), southern hemisphere winter (May-August), and southern hemisphere summer (November-December) (after Fejer et al., 1991).
Figure 2-2. Solar flux dependency of the average vertical prereversal enhancement peak drift velocity for three seasons. The number of points used in the average is listed next to each point (after Fejer et al., 1991).
Fejer et al. [1995] used vertical plasma drift data from the ion drift meter (IDM) onboard the AE-E satellite to study longitudinal dependency of plasma drifts in the equatorial F-region. Their results for the Brazilian (300°-360° E), American (210°-300° E), Pacific (150°-210° E), and African/Indian (0°-150° E) longitudinal sectors are shown in Figure 2-3. They show no appreciable longitudinal variation in December solstice and equinox, but they indicate large variations during June solstice. The prereversal enhancement peak velocities reach about 40 m/s during equinox, 30 m/s during December solstice, and range from 10 m/s in the Brazilian (320°) and Indian (80°) sectors to 30 m/s in the Pacific (180°) sector during June solstice. Morning reversal times during June are earliest in the Brazilian and American (260°) sector and latest in the Pacific sector, with a larger pre-morning peak in the Indian sector. Peak daytime values range from 20 to 30 m/s with largest longitudinal variation again in the June solstice. The December AE-E results are in excellent agreement with Jicamarca drifts whereas the equinoctial and June solstice AE-E drifts are smaller during the evening and at night. This discrepancy is due either to instrumental effects or the large longitudinal bins in this satellite study.

Scherliess and Fejer [1999] combined the AE-E satellite data with Jicamarca incoherent scatter radar observations to produce the first global empirical model for quiet-time equatorial F-region vertical plasma drifts. Their results for low and high solar flux conditions are presented in Figure 2-4. This figure shows that equinoctial plasma drifts are largely independent of longitude with upward prereversal enhancement drift values of about 15 to 20 m/s and 30 to 40 m/s during low and high solar flux conditions,
Figure 2-3. Empirical model of quiet-time vertical plasma drifts derived from AE-E satellite data for four longitudinal sectors under moderate to high solar flux conditions. Vertical plasma drifts over Jicamarca (solid line) for similar conditions are also shown (after Fejer et al., 1995).

respectively. During June solstice low solar flux conditions, there is no significant prereversal enhancement; during high solar flux conditions, the evening prereversal enhancement drifts range from 15 m/s at 300° E to 35 m/s at 180° E. The prereversal enhancement during December low solar flux conditions is also quite small (less than 10 m/s) except for at 240° E and 300° E where it reaches about 10 m/s. During high solar flux conditions, these prereversal upward peak drifts are about 35 m/s in the same longitudinal sectors and about 25 m/s elsewhere. The low solar flux June solstice
Figure 2-4. Scherliess and Fejer [1999] global empirical model for high (solid line) and low (dashed line) solar flux (after Scherliess and Fejer, 1999).
morning and evening reversal times and December solstice evening reversal times appears to be highly dependent upon longitude, while the high solar flux morning and evening reversal times are longitudinally independent for all seasons. Daytime drifts are largest (25 to 30 m/s) at 120° E during June and at 180° E during equinox and December. We will discuss additional experimental results of equatorial vertical plasma drifts in Chapter 4.

Figure 2-5 shows the seasonal and solar flux dependency of the F-region zonal plasma drifts above Jicamarca as given by Fejer et al. [2005]. During the day these drifts are westward and reach values of about 40 m/s; at nighttime they become eastward and have much larger magnitudes (from 40 m/s to above 160 m/s). There is virtually no daytime solar flux dependence, as well as no flux dependence for the evening reversal times. Shortly after the evening reversal, the zonal drifts have a large eastward peak near 2100 LT after which they slowly decrease throughout the night. The nighttime eastward drift velocities increase strongly with solar flux, especially during December solstice and the equinoxes. The morning reversal times for June solstice occur later with increasing solar flux. More detailed description of equatorial plasma drifts is presented by Fejer [1997], Scherliess [1997], and Fejer et al. [2005].

2.4 Low-Latitude Quiet-Time Plasma Drifts

The low-latitude plasma drifts have been studied extensively using incoherent scatter radar at Arecibo, Puerto Rico (18° N, 67° W; magnetic latitude, 30° N), and at the Middle and Upper Atmosphere radar (MU) at Shigaraki, Japan (34.9° N, 136.1° E,
Figure 2-5. Jicamarca model zonal plasma drifts for three seasons and two levels of solar flux, positive eastward (after Fejer et al., 2005).
magnetic dip 29.3°). These radars are located at middle geographic latitudes but fairly low geomagnetic latitudes.

The incoherent scatter radar at the Arecibo Observatory has been used for many decades to study the low- and mid-latitude F-region [e.g., Burnside et al., 1983; Ganguly et al., 1987; Berkey et al., 1990]. The ISR at Arecibo operates at a frequency of about 430 MHz. Over this site an F-region plasma drift velocity of 27 m/s corresponds to an electric field of about 1 mV/m.

Fejer [1993] used plasma drift data from the incoherent scatter radar at the Arecibo Observatory to determine the characteristics of the low-latitude F-region ionosphere. Some of the results of this study are shown in Figures 2-6 and 2-7. The perpendicular/northward drifts (driven by zonal electric fields) are mostly upward/poleward from early morning to afternoon hours with maximum values of about 25 m/s. From afternoon to midnight the drifts are generally westward with values less than 15 m/s. During December solstice there is a clear large poleward peak near 0400 LT during low solar flux periods, and during June solstice there is a clear equatorward peak under the same conditions. The perpendicular/eastward drift velocities are clearly diurnal with westward velocities from the pre-sunrise period to afternoon with peak values ranging from 10 m/s during June to 60 m/s during December. The plasma drifts are eastward from afternoon to the post-midnight period with large solar flux dependency over the entire eastward period. During low solar flux conditions, peak eastward drifts have values of about 25 m/s while during high solar flux conditions, the drift values are on the order of 75 m/s during equinox and June solstice and 50 m/s in December.
Figure 2-6. Seasonal dependence of quiet-time perpendicular/northward drifts for two values of solar flux (after Fejer, 1993).

Figure 2-7. Seasonal dependence of quiet-time perpendicular/eastward drifts for two values of solar flux (after Fejer, 1993).
solstice. The afternoon reversal time is earliest in June (1400 LT) and latest in December (1800 LT).

Oliver et al. [1993] studied perpendicular/northward and zonal plasma drifts using MU radar observations. They showed that the perpendicular/northward drifts do not change significantly with solar flux while the evening and nighttime eastward drifts increase with solar flux. This solar flux dependence is in good agreement with Arecibo measurements. The perpendicular/northward daytime drifts are largest above the MU radar during the daytime winter and smallest during summer. The nighttime drifts are mostly equatorward with eastward velocities near 2000 and 0400 LT. Zonal plasma drifts above the MU radar are semidiurnal with eastward drifts between about 1600 and 0300 LT with peak values of about 60 m/s. The westward plasma drifts are largest near dawn during summer and do not have a dawn peak during winter but have a gradual increase from midnight to dawn. This seasonal dependence is largely opposite that of Arecibo [e.g., Fejer, 1993].

2.5 Mid-Latitude Quiet-Time Plasma Drifts

The mid-latitude plasma drifts have been studied extensively using incoherent scatter radar at Millstone Hill and Saint Santin and more recently also with polar orbiting satellites.

The French incoherent scatter radar at Saint Santin (45° N, 2° E; magnetic latitude, 40°) collected ExB plasma drifts from 1973 to 1986 which have been studied by several authors [e.g. Blanc and Amayenc, 1979; Scherliess et al., 2001]. The ISR at
Saint Santin operated at a frequency of about 935 MHz. Over this site, a plasma velocity of 25 m/s corresponds to an electric field of 1 mV/m. The incoherent scatter radar at Millstone Hill (42.6° N, 288.5° E; Apex magnetic latitude, 54°) has been used to study the Earth’s ionosphere since 1974 [e.g. Wand, 1981; Buonsanto et al., 1993; Buonsanto and Witasse, 1999; Scherliess et al., 2001]. The radar operates at a frequency of about 440 MHz.

Figure 2-8 presents the F-region perpendicular/northward drifts above Saint Santin which have a semidiurnal appearance. The northward drifts are poleward during morning with peak values near 20 m/s for all cases except for June solstice low flux and December solstice high flux conditions, where the poleward values are much smaller.

**Figure 2-8.** Quiet-time perpendicular/northward plasma drifts (positive northward) over Saint Santin for high and low solar flux. The thick solid lines correspond to an empirical model (after Scherliess et al., 2001).
(less than 10 m/s). The June and December solstice low flux post-sunset drifts are poleward as well. Higher solar flux conditions generally cause larger northward drifts except during December solstice. However, Scherliess et al. [2001] pointed out that the December high flux perpendicular/northward data may have large instrumental errors.

Figure 2-9 shows the F-region perpendicular/northward plasma drifts above Millstone Hill, where a plasma velocity of 22 m/s corresponds to an electric field of 1 mV/m. These drifts also show mostly semidiurnal effects. The perpendicular/northward drifts are largely poleward in the early morning to pre-noon sector, and equatorward during the afternoon to midnight sector. There are short poleward excursions in the

![Figure 2-9. Quiet-time perpendicular/northward plasma drifts (positive northward) over Millstone Hill for high and low solar flux. The thick solid lines correspond to an empirical model (after Scherliess et al., 2001).](image-url)
afternoon of equinox and June solstice low flux conditions. Maximum poleward velocities are about 20 m/s in the morning, and peak equatorward values are smaller at about 10 m/s in the evening. There is large solar variation shortly after sunset in equinox and June solstice and shortly before sunrise during equinox, with higher flux values producing larger poleward drifts. During December solstice there is very little solar flux variation.

Zonal plasma drifts above Saint Santin (Figure 2-10) show a clear diurnal pattern and are eastward from late afternoon until the post-midnight sector. Maximum eastward values occur during post-sunset and have magnitudes that range from about 30 m/s to 40

![Figure 2-10](image)

**Figure 2-10.** Quiet-time zonal plasma drifts (positive eastward) over Saint Santin for high and low solar flux. The thick solid lines correspond to an empirical model (after Scherliess et al., 2001).
m/s in low solar flux to 40 m/s in June solstice and almost 80 m/s in the other two seasons. Westward drifts generally peak near sunrise and show little solar flux variation for December solstice and equinox with peak values near 40 m/s. June solstice increases from 20 m/s to almost 40 m/s for high flux.

The zonal plasma drifts at Millstone Hill (Figure 2-11) are mostly diurnal but appear to have some semidiurnal effects. These drifts are eastward near noon during equinox and December solstice but remain westward for all local times during June solstice, with largest westward values near midnight. Peak eastward velocities are about 20 m/s during December and equinoctial low solar flux conditions, whereas during high

![Figure 2-11. Quiet-time zonal plasma drifts (positive eastward) over Millstone Hill for high and low solar flux. The thick solid lines correspond to an empirical model (after Scherliess et al., 2001).](image)
flux in equinox, the drift values approach 40 m/s. Maximum westward velocities occur near midnight and range from 40 m/s during equinox and June solstice, to 60 m/s during December solstice. There appears to be very little solar flux variation for zonal drift velocities with the exception of equinox eastward values and the June post-midnight sector.

2.6 Low- and Mid-Latitude Disturbed Plasma Drifts

During disturbed conditions other dynamo processes must be taken into account, namely, prompt penetration of magnetospheric dynamo electric fields into lower latitudes and high latitude ionospheric disturbance dynamo wind effects that travel equatorward and change the nature of the quiet-time dynamo winds and electric fields. These disturbance phenomena can significantly modify the quiet-time drift patterns.

In this section we will first give a short introduction to the geomagnetic indices to be used. Then, we will briefly discuss the disturbance driving mechanisms and illustrate the general characteristics of disturbed plasma drifts in the mid- and low-latitude ionosphere.

2.6.1 Geomagnetic Indices

Several geomagnetic indices have been used to monitor the response of the Earth’s magnetic field to magnetic activity. The Kp index, introduced by Bartels in 1932, is the most common index for mid- and low-latitudes. The Kp index is calculated by combining geomagnetic disturbance levels from 13 selected subauroral stations located from 42° to 62° latitude (mostly located in the northern hemisphere) over a three-hour
period [e.g., Mayaud, 1980]. We have obtained these indices from the World Data Center (http://swdcwww.kugi.kyoto-u.ac.jp/).

The auroral electrojet (AE) index is a measure of the magnetic disturbance in the auroral region and is widely used in geomagnetism to classify magnetic conditions. This index was introduced by Davis and Sugiura [1966], and it is derived from measurements of the horizontal component of the high latitude magnetic field from an array of 12 generally auroral stations. The largest value in the array is named AU and the smallest AL. The difference of the two is the AE index, and the simple mean of the two is called the AO index. The stations range from 60° to 72° latitude, so during especially intense magnetic storms when the auroral is extended equatorward of most stations, this index underestimates the effect of auroral activity.

2.6.2 Plasma Drift Generation under Disturbed Conditions

Prompt penetration of magnetospheric dynamo electric fields affect lower latitudes following large sudden changes in the cross-polar cap potential. During steady state conditions, the ring current, typically located between 3 and 6 Earth radii, shields the lower latitude ionosphere from magnetospheric electric fields. During quick changes in the cross polar cap potential, there will be a leakage of magnetospheric electric fields into lower latitudes for a short time (time scales of roughly 1 hour). A quick increase in the polar cap potential will result in undershielding conditions while a quick decrease will result in overshielding. The undershielding (overshielding) perturbations produce eastward (westward) perturbations during the day and opposite polarity at night.
The leaked electric fields propagate to lower latitudes almost instantly and can be seen over a large longitudinal and latitudinal extent [Kelley, 1989]. Prompt penetration electric fields will not be a focus of this dissertation.

During disturbed conditions, large amounts of energy are deposited in the high latitude ionosphere, mostly due to Joule heating by increased Pederson current. The hotter neutral winds in the upper latitudes can then propagate to lower latitudes where they will affect the quiet-time dynamo process. Disturbance dynamo perturbations have longer lifetimes (a few hours) than prompt penetration electric fields but reach lower latitudes multiple hours after the onset of magnetic activity [Blanc and Richmond, 1980; Kelley, 1989]. Disturbance dynamo effects are a major focus of this dissertation and will be discussed in more detail in Chapters 3 and 4.

2.6.3 Equatorial Plasma Drifts Under Disturbed Conditions

The characteristics of equatorial F-region plasma drifts during geomagnetically disturbed conditions were studied in detail over several decades using Jicamarca data [e.g., Fejer, 1997; Fejer and Scherliess, 1995, 1997; Scherliess and Fejer, 1997]. An example of a typical disturbed day above Jicamarca is given in Figure 2-12. We can see from this figure that disturbed conditions can cause plasma drifts to vary widely from the quiet-time average. Between 0500 and 1000 UT on August 10 we can see a large perturbation in the plasma drifts for relatively small values of AE. This perturbation is largely due to ionospheric disturbance dynamo electric fields associated with
Figure 2-12. A typical 48-hour period during disturbed conditions above Jicamarca. The thin solid line is the average quiet-time pattern. The value of the AE index is plotted in the top panel (after Scherliess and Fejer, 1997).

Geomagnetic activity occurring about a day earlier. Figure 2-12 also shows both disturbance dynamo and prompt penetration effects from 0700 to 1000 UT on August 9.

Fejer and Scherliess [1995] were able to separate the effects of disturbance dynamo plasma drifts from prompt penetration effects. Briefly, this involves binning data according to an idealized history of the AE index during a magnetic storm (Figure 2-13 top panel) in which a large jump in AE will generate prompt penetration electric field effects, and large AE values for the previous few hours will generate disturbance dynamo perturbations. Using data found at the beginning of the idealized storm will give prompt
penetration effects, and using data found near the middle of the idealized storm will give disturbance dynamo effects.

An empirical model describing equatorial prompt penetration zonal electric fields was obtained by Fejer and Scherliess [1997] using Jicamarca vertical drift data. Their comparison of prompt penetration electric fields with the Rice convection model (RCM) is presented in Figure 2-13.

Figure 2-13 shows that prompt penetration electric fields at the beginning of the storm (undershielding) are largely upward during the day and downward during the night. During the evening, the prompt penetration electric field is downward with peak magnitudes of about 15 m/s directly after the onset of geomagnetic activity, and about 10 m/s one hour afterwards. In the daytime, perturbation drifts are positive with peak values above 5 m/s. The initial equatorial disturbance dynamo drifts study using Jicamarca data was published by Fejer et al. [1983]. Their results were consistent with the theoretical predictions by Blanc and Richmond [1980]. Scherliess and Fejer [1997] studied the storm time dependence of disturbance dynamo zonal electric fields using a very extensive database of Jicamarca ISR data. They presented an empirical model of the local time variation of vertical disturbance dynamo drifts for different storm time conditions. Their results for disturbance dynamo drift perturbations from quiet-time drifts are shown in Figure 2-14.

We can see from Figure 2-14 that the vertical disturbance dynamo drifts are largely opposite the prompt penetration electric fields shown in Figure 2-13. During the
Figure 2-13. Comparison of local time variation of empirical prompt penetration electric fields for various storm times (top panel) with the Rice convection model (RCM). The empirical model (solid line) is given for storm times of 7.5 and 60 minutes (after Fejer and Scherliess, 1997).
Figure 2-14. Local time variation of the vertical disturbance dynamo perturbation drifts with scatter bars for three different idealized storm times shown in the top panel (after Scherliess and Fejer, 1997).
night, the perturbation drifts are upward and have largest values near 0500 LT. At t1, peak upward values are more than 5 m/s and increase to 10 m/s at t2 because of the continual energy input at high latitudes. During the day, disturbance dynamo effects are mostly negative and very small except for downward values of about 5 m/s at 2000 LT during t2. Six hours after the decay of magnetic activity (t3), the disturbance dynamo perturbations are mostly gone. On the other hand, there are additional drift perturbations that occur about 24 hours after the initial period of enhanced geomagnetic activity as shown in Figure 2-12 and modeled by Scherliess and Fejer [1997].

Zonal equatorial plasma drifts during disturbed conditions were empirically modeled by Fejer et al. [2005] using Bernstein polynomials as base functions. Figure 2-15 shows their results. They found that zonal drifts are westward and largely season and solar flux independent during the day with very little perturbation during disturbed conditions. Nighttime drifts were more westward for disturbed conditions during high solar flux for equinox and December solstice. June solstice has little perturbation from quiet-time averages during disturbed conditions except for some small perturbations during nighttime.

2.6.4 Low- and Mid-Latitude Plasma Drifts under Disturbed Conditions

The perpendicular north low- and mid-latitude plasma drifts do not show large geomagnetic effects except during strong and short-lived prompt penetration events [Fejer, 1997; Scherliess et al., 2001]. Therefore, we will discuss only the zonal disturbed drift patterns. These will also be discussed further in the next chapter.
Figure 2-15. Seasonal and solar flux dependency of zonal plasma drifts over Jicamarca (after Fejer et al., 2005).
Fejer [1993] presented both the quiet and disturbed plasma drift patterns over Arecibo, which are shown in Figure 2-16. We can see that disturbed zonal drift perturbations are westward at all local times with largest amplitudes during the night. During equinox and December solstice there are some significant perturbations in the late afternoon, whereas during June there are small perturbations during the day.

DE-2 satellite measurements were used by Heelis and Coley [1992] to examine latitudinal dependence of zonal plasma drifts under quiet and disturbed conditions. Their results can be seen in Figure 2-17. We can see that the disturbed data (right column) differs from the quiet-time data (left column) at high latitudes with large westward perturbations during the nighttime. At 55° and 65° there are eastward perturbations during the post-midnight to early morning periods. At lower latitudes the disturbed drifts have smaller perturbations that are mostly confined to the nighttime sector.

Scherliess et al. [2001] compared mid-latitude disturbance zonal plasma drifts from Millstone Hill and Saint Santin radar measurements with longitudinally averaged DE-2 disturbed zonal plasma drifts. Their comparison of long lasting zonal disturbance drifts can be seen in Figure 2-18. The radar perturbation drifts are westward at all local times except during a short eastward excursion at Millstone Hill during the morning. Westward maximum values occur near midnight at above 80 m/s for Millstone Hill and about 50 m/s for Saint Santin. DE-2 drifts have consistently smaller amplitudes, especially from 1800 LT to midnight. This discrepancy could be due to the fact that the
Figure 2-16. Seasonal dependence of the quiet and disturbed zonal plasma drifts over Arecibo (after Fejer, 1993).
Figure 2-17. Average zonal plasma drifts as a function of magnetic local time for 5 latitudinal regions under geomagnetically quiet (left column) and disturbed (right column) conditions. The solid line is generated by an empirical model based on the DE-2 data (circles) (after Heelis and Coley, 1992).
satellite data are longitudinally averaged and that, in the DE-2 data, season and local time are locked together.

In the next chapter we will present a more detailed study of middle and low-latitude DE-2 zonal plasma drifts during quiet and disturbed times.

Figure 2-18. Comparison of long lasting zonal disturbance drift perturbations from Millstone Hill and Saint Santin radar measurements and DE-2 zonal drift data (after Scherliess et al., 2001).
3.1 Introduction

Ionospheric plasma drifts perpendicular to the Earth’s magnetic field are driven by E- and F-region dynamo electric fields during geomagnetically quiet times, and also by solar wind-magnetospheric and ionospheric disturbance dynamo electric fields during periods of enhanced geomagnetic activity [e.g. Blanc and Richmond, 1980; Kelley, 1989; Richmond, 1995; Fejer, 1997]. Since these plasma drifts (electric fields) play important roles on the distribution of ionization from middle to equatorial latitudes, the understanding of their driving mechanisms and spatial and temporal variations is essential for the development and validation of realistic models of the ionospheric weather. In this study, we focus on the global characteristics of F-region zonal drifts.

Middle and low-latitude ionospheric zonal plasma drifts have been routinely measured with incoherent radar observations from Millstone Hill (42.6° N, 66.5° W; apex magnetic latitude 54°), Saint-Santin (45° N, 2° E; magnetic latitude 40°), Arecibo (18° N, 67° W, dip latitude 31° N), Shigaraki (34.9° N, 136.1° E, dip latitude 29.3° N), and Jicamarca (11.9° S, 76.8° W; dip latitude 1° N). These measurements have determined the local time, season, solar cycle, and magnetic activity dependent climatologies of the zonal plasma drifts over the regions sampled by the radars [e.g., Blanc, 1983; Fukao et al., 1991; Fejer, 1991, 1993, 1997; Oliver et al., 1993; Takami et al., 1996; Buonsanto and

---

This chapter is largely comprised of the publication Jensen, J. W., and B. G. Fejer, Longitudinal dependence of middle and low-latitude zonal plasma drifts measured by DE-2, submitted to Annales Geophysicae, 2007.
At equatorial latitudes, nighttime zonal drifts have also been frequently studied with zonal drift measurements of ionospheric plasma irregularities using ground-based spaced receiver and optical imaging techniques [e.g., Sobral et al., 1999; Martinis et al., 2003; Sheehan and Valladares et al., 2004].

Global F-region zonal plasma drifts have been studied using ion drift meter (IDM) measurements on board of the polar orbiting Dynamics Explorer-2 (DE-2) satellite. Coley and Heelis [1989] used DE-2 data to study the local time and altitudinal variations of low-latitude zonal drifts. Heelis and Coley [1992] determined the average middle and low-latitude DE-2 zonal drift patterns during quiet and magnetically disturbed conditions and studied their dependence on dynamo and high latitude electric fields. Coley et al. [1994] used DE-2 IDM and wind and temperature spectrometer (WATS) data to show that both the superrotation and the diurnal components of ion and neutral zonal velocities flows are strongly peaked at the dip equator. Scherliess and Fejer [1998] and Fejer and Scherliess [1998] determined the average response of middle latitude DE-2 zonal drifts to prompt penetration and disturbance dynamo electric fields during moderately disturbed conditions. They also showed that these perturbation drift patterns are in good agreement with results from incoherent scatter radar measurements and global convection models.

There have been only a few studies of the longitudinal variation of the ambient quiet-time F-region zonal drifts. Fejer [1993] and Takami et al. [1996] have discussed the relationship of the F-region drift velocities over Arecibo and over the MU radar at Shigaraki. Immel et al. [2004] showed that the zonal drifts of nighttime equatorial
plasma depletions observed on board the high apogee IMAGE satellite during March-May 2002 were largest in the Indian sector. Fejer et al. [2005] suggested that longitudinal variation of the equatorial F-region zonal drifts in the dusk-premidnight sector should be strongly controlled by the season dependent prereversal enhancement of the vertical plasma drifts.

Satellite and incoherent radar observations at subauroral and middle latitudes during strongly enhanced geomagnetic conditions have shown that the occurrence of very strong, highly localized, northward electric fields (westward electric fields) are due to the extension of the auroral zone to lower latitudes and the formation of very large polarization electric fields near the equatorward extent of the pre-midnight sunward convection [e.g., Galperin et al., 1974, 1997; Burke et al., 2000; Anderson et al., 2001; Foster and Vo, 2002]. These electric fields generate large highly structured storm enhanced plasma densities, steep spatial gradients in plasma parameters, strong radio wave scintillations, and strongly affect the erosion and reconfiguration of the outer plasmasphere [e.g., Foster et al., 2002]. The subauroral regions of large (> 500 m/s) westward convection has recently been named Subauroral Polarization Streams (SAPS) [Foster and Burke, 2002]. The longitudinal distribution of these large westward zonal drifts has not been determined.

In this work we use the entire database of middle to equatorial latitudes DE-2 observations to study, for the first time, the longitudinal dependence of the ionospheric zonal plasma drifts. In the next sections, we first briefly describe the IDM (Ion Drift Meter) measurements on board the DE-2 satellite and our database and methodology.
Then, we describe the season and latitude dependent longitudinal variations of these plasma drifts during geomagnetically quiet and active times.

3.2 Data and Methodology

The Dynamics Explorer 2 satellite was launched in August 1981 into a 90° inclination orbit. This mission ended in February 1983. The apogee was near 1200 km and the perigee near 280 km. The ascending node (location of the northbound equatorial crossing) passed through an entire 24 hour period in 12 months. Therefore, local time and season were locked together. The data near dawn and dusk were measured during the summer and winter solstices, and the data near noon and midnight were obtained during the equinoxes. We have used 16 second averaged IDM zonal drifts. The characteristics of the instrument were described by Heelis et al. [1981]. The sensitivity of the ion drift component perpendicular to the satellite track was about 5 m/s, and the absolute accuracy was about 10 m/s. Even though the instrument measured the zonal drift in the geographic east-west direction, these drifts were dominated by the geomagnetic east-west $\text{ExB}$ ion motion [Heelis and Coley, 1992].

We have used data from the altitudinal range of 280 to 800 km to minimize the effects of light ions at upper altitudes. At the magnetic equator, these altitudes correspond to invariant latitudes of about 10° and 20°, respectively. We have also restricted our data to altitudes between 400 and 800 km for invariant latitudes smaller than 15° during 1900 and 2300 LT, to minimize the effects of the shear in the zonal drifts below the F-region peak. In order to account for the altitudinal variations, the drifts were mapped along the magnetic field lines to a height of 400 km using the procedure
presented by Jacobson et al. [1996], which assumes equipotential magnetic field lines. When ion density data were available, we restricted our database to drift measurements corresponding to densities greater than $2 \times 10^4$ cm$^{-3}$. Density measurements were not available from November 1981 to February 1982 due to a malfunction of the retarding potential analyzer (RPA).

Figure 3-1 shows that the number of measurements in three latitudinal sectors as a function of solar local time (SLT). The total number of observations during quiet ($K_p \leq 3$) and disturbed ($K_p > 3$) was about the same, but they decreased significantly with latitude. This number is smallest during 0000–0400 LT and 1200–1600 LT, which correspond to solsticial periods. Only the 0400–0800 LT period have sufficiently large number of measurements for the reliable estimates of the hourly average drifts during two different seasons (summer and winter). Therefore, this is also the only period when we have been able to determine the longitudinal dependence of the drifts during different seasons. The 16-second integration time in the DE-2 polar orbit resulted in about 12 data points in a 10° latitudinal range.

We have initially determined the latitudinal and local time dependence of the longitudinally averaged drifts by averaging the data in 1 hour and 5° latitudinal bins for $\Lambda \leq 60^\circ$, separately for the northern and southern hemisphere data. We have used both solar and magnetic local times in our analysis with essentially identical results. Most of our results are presented as a function of solar local time since this allows an easier comparison with radar data; the mid-latitude disturbed drifts are shown as a function of magnetic local time. The study of seasonal, longitudinal, and magnetic activity effects
Figure 3-1. Number of DE-2 zonal drift measurements in three latitudinal sectors during geomagnetically quiet and active times.

requires larger temporal and spatial bins to improve statistical significance. In this case, we binned the data in six 4-hour periods, three 4-month seasons (November–February, May–August, March–April and September–October), and in 10° latitudinal and 60° overlapping longitudinal bins centered 30° apart with periodic boundary conditions.

3.3 Quiet-Time Drifts

In this section, we present initially the latitudinal and local time profiles of the longitudinally averaged quiet-time zonal drifts and then examine their longitudinal dependence.
3.3.1 Latitudinal and Local Time Dependence

Figure 3-2 shows the latitudinal variations of longitudinally averaged daytime and evening and nighttime quiet-time (Kp $\leq 3$) zonal drifts. We will not show the data for $\Lambda < 10^\circ$ since they have low statistical significance due to the smaller number of measurements and to our altitudinal and density restrictions. The daytime drifts are westward and have largest values (about 80 m/s) near noon and at low latitudes; the evening drifts are small and mostly westward except at the lowest latitudes. After sunset, they are westward at the highest latitudes; they change to eastward for $\Lambda = 45^\circ$ and reach their peak values (about 150 m/s) at the lowest latitudes. The northern and southern hemisphere data are in good agreement, as expected from the conjugacy of the meridional electric fields. The results presented in Figure 3-2 are in good agreement with the latitudinal profiles derived by Scherliess [1997] from lower altitude (300 km) DE-2 IDM data. The lowest latitude ($\Lambda = 15^\circ$) drifts are also in good agreement with Jicamarca radar observations [e.g., Fejer et al., 2005].

Figure 3-3 shows the local time dependence of the longitudinally averaged zonal drifts in 5 latitudinal sectors. In this case, we smoothed the data using 3-point running averages weighted by the standard deviations. Since local time and season were locked together in the DE-2 measurements, the drifts at different local time sectors correspond to different seasons. The large standard deviation at 1030 results from an anomalous DC offset in the 1981 data, which required a 50 m/s correction. As mentioned earlier, different local time sectors correspond to different seasons. Figure 3-3 indicates that our highest latitude drifts are westward with typical magnitudes of about 30 to 50 m/s, except
Figure 3-2. Examples of latitudinal profiles of quiet-time (Kp ≤ 3) average zonal drifts (positive eastward) measured by DE-2 during 1982. The scatter bars denote the standard deviations.
Figure 3-3. Longitudinally averaged quiet-time DE-2 zonal drift velocities in five latitudinal sectors.
in the morning-noon period, when they first decrease in magnitude and then briefly reverse to eastward. At low latitudes ($\lambda \leq 30^\circ$), the drifts are westward during the day with typical values of 40 m/s, and eastward at night with largest values (up to about 170 m/s) in the premidnight sector. These latitudinal profiles are in good agreement with the results presented by Heelis and Coley [1992], and at the lowest latitudes, they are also in good agreement with the Jicamarca drifts [Fejer et al., 2005].

3.3.2 Longitudinal Dependence

The DE-2 zonal drift database is not extensive enough for the study of longitudinal variations in hourly periods. Therefore, we examined this dependence using 4-hour local time bins to improve the statistical significance of our results, which still allowed us to largely decouple longitudinal and seasonal effects. Initially, we have determined the relative zonal drifts by subtracting from each measurement the corresponding longitudinally averaged hourly value. Then, we determined the longitudinal variation of the relative drifts using 4-hour local time bins, 10° latitudinal bins, and 60° overlapping longitudinal bins centered 30° apart, with periodic boundary conditions. We should note that these residual drifts are more accurate than the absolute values, since instrumental offsets should be subtracted out through this procedure.

Figure 3-4 shows the longitudinal variation of the quiet-time ($K_p \leq 3$) northern and southern hemisphere relative drifts during 2000–2400 LT, which corresponds to equinoctial conditions. In this case, the standard deviations of the mean varied from about 10 m/s at 55° to about 30 m/s at 15°. Figure 3-4 indicates that the largest relative
Figure 3-4. Longitudinal variations of early night northern and southern hemisphere quiet-time average relative zonal drift velocities in five latitudinal sectors.
drifts occur between about $-10^\circ$ to $70^\circ$ at upper middle latitudes and between $-150^\circ$ to $-60^\circ$ at low latitudes. The peak-to-peak values are about 40–50 m/s. Notice, as shown in Figure 3-3, in this local time sector the longitudinally averaged drifts are westward at upper mid-latitudes and eastward at low latitudes. Figure 3-5 illustrates in more detail the good agreement of the northern and southern hemisphere data. In this case, we have used 13 normalized cubic b-splines at equally spaced nodes for each latitudinal bin and interpolated the resulting data to generate a grid of 20 points in latitude by 20 in longitude.

We have seen in Figure 3-2 that the northern and southern hemisphere longitudinally averaged drifts are in good agreement, and in Figures 3-4 and 3-5 the same is true for their longitudinal variations during the 2000–2400 local time period. The patterns from both hemispheres were consistent also during the other 4 hour local time periods; therefore, from now on, we show only results obtained by combining the data from both hemispheres, which further improves their statistical significance.

Figure 3-6 shows in the top panel longitudinal dependence of the quiet-time equinoctial relative drifts in the premidnight sector. The bottom panel shows their estimated latitudinal and longitudinal dependence at 22.5 LT obtained by combining the hourly and longitudinally averaged drifts given in Figure 3-3; the longitudinally dependent relative drifts are given in the top panel. At this local time, the drifts are westward at upper middle latitudes with smallest magnitudes near $60^\circ$ E, and they change to eastward at $\Lambda = 45^\circ$ near $30^\circ$ E and at $\Lambda = 40^\circ$ near $180^\circ$ E. The low-latitude eastward
Figure 3-5. Longitudinal and latitudinal dependence of average quiet-time relative zonal plasma drifts in the early night sector.
Figure 3-6. Latitudinal and longitudinal dependence of relative zonal drifts (positive eastward) obtained by averaging the northern and southern hemisphere quiet-time relative drifts (upper panel). Latitudinal and longitudinal variations of the zonal drift velocities obtained by adding the relative drifts shown in the upper panel and the longitudinally averaged values at 22.5 LT (lower panel).
drifts have largest values (up to about 180 m/s) between about 30° and 120° W. The latitudinal variations of these early night drifts are strongest (weakest) near 150° W (150° E). The zonal drifts shown in the bottom panel of Figure 3-6 are in good agreement with results from middle, low-latitude and equatorial radar drift measurements [e.g., Fejer, 1993; Scherliess et al., 2001; Fejer et al., 2005].

We have seen in Figure 3-1 that the number of measurements during 0000–0400 LT, which correspond to June and December solstice, was relatively small. Therefore, in this case, we have averaged the data from these two seasons. The resulting longitudinal dependence is generally similar to that shown in Figure 3-4 but shifted eastward by about 80° with smaller peak-to-peak variations.

The most extensive DE-2 drift measurements were made during the 2000–2400 and 0400–0800 LT. The latter period, which corresponds to the solstices, is the only one with large enough number of measurements for the study of longitudinal effects during different seasons. In this case, the June solstice data are almost exclusively from 1982, while the December solstice data are mostly from 1981 and 1982. We have determined the longitudinal variation of the relative drifts during this period using the same procedure outlined earlier. Figure 3-7 shows that during this early morning period the longitudinal variations of the June and December solstice residual drifts are mostly anti-correlated. During December solstice, the largest relative drifts occur at about 30° E at higher latitudes and near 90° W at low latitudes, while during June solstice they occur at
Figure 3-7. Longitudinal variation of the late night-early morning quiet-time relative zonal drifts during June and December solstice in five latitudinal sectors.
about 90° W and 120° E, respectively. The peak-to-peak variation of these relative drifts is about 40 m/s.

Figure 3-8 shows the derived longitudinal variations of the zonal drifts at 0530 LT, obtained by adding the longitudinally averaged and corresponding longitudinally dependent relative drifts for the solstices. Notice that the zonal drifts at 0530 shown in Figure 3-3 shows longitudinal averages of the corresponding June and December solstice values. Figure 3-8 shows the December solstice drifts are westward at middle latitudes with largest magnitudes (about 75 m/s) near 15° E and eastward at the lowest latitudes. During June solstice the region of westward drifts is shifted about 5° equatorward, with maximum values (about 55 m/s) near 170° E; the higher (lower) latitude drifts are more (less) eastward during June than during December. Late night-early morning radar observations show larger westward drifts during December solstice than during June solstice over Arecibo [Fejer, 1993] and opposite results over the MU radar [Takami et al., 1996], in good agreement with the results presented in Figure 3-8.

Figure 3-9 shows the longitudinal dependence of the relative zonal drifts during 0800–1200 LT is approximately anticorrelated to that during 2000–2400 LT (see Figure 3-4) but with peak-to-peak values about half as large. In the 1200–1600 LT period the relative zonal drifts have only small magnitudes and longitude dependence, as indicated in Figure 3-10. Finally, in the 1600–2000 LT period, the longitudinal variation of the relative drifts resembles that of the 2000–2400 LT period shown in Figure 3-4 but with smaller magnitudes since this period also includes daytime drifts.
Figure 3-8. Latitudinal and longitudinal dependence of quiet-time zonal drifts at 5.5 LT during December and June solstice.
Figure 3-9. Longitudinal variation of the early morning-noon quiet-time relative zonal drifts during equinox in five latitudinal sectors.
Figure 3-10. Longitudinal variation of the noon-early evening quiet-time relative zonal drifts during June and December solstice in five latitudinal sectors.
3.4 Disturbed Drifts

Figure 3-11 shows the latitudinal variation of the longitudinally averaged quiet and disturbed drifts, now as a function of magnetic local time. For $\Lambda > 50^\circ$, the disturbance (difference between disturbed and quiet-time) drifts are eastward from about 0200 to 1200 MLT and westward at other local times. These westward drifts are largest near 2000 MLT, where they reach average values about 300 m/s for $Kp \leq 5$. At the lower latitudes, the perturbation drifts are westward at all local times and have largest values near midnight for $30^\circ < \Lambda < 50^\circ$ and in the postmidnight sector for $10^\circ < \Lambda < 30^\circ$; the daytime disturbance drifts are very small.

The results shown in Figure 3-11 are in good agreement with the DE-2 drifts patterns presented by Heelis and Coley [1992] shown in Figure 2-17 and Scherliess and Fejer [1998]. They are also consistent with the middle, low, and equatorial perturbation drifts derived from incoherent scatter radar observations [Blanc, 1983; Fejer, 1993, 1997; Scherliess et al., 2001] and with ionosonde derived drifts over Bundoora, Australia (141.1° E, 37.7° S, 49° S magnetic) [Parkinson et al., 2001]. These earlier studies have shown that mid-latitude disturbance drifts are largely due to the equatorward extension of auroral electric fields; the lower latitude perturbation drifts are mostly due to prompt penetration and disturbance dynamo electric fields.

We have seen that the largest middle latitude perturbation drifts occur near 2100 MLT. Figure 3-12 shows the longitudinal dependence of the quiet and disturbed drifts in the 1800–2200 MLT sector for $50^\circ < \Lambda \leq 60^\circ$. This Figure shows that for $60^\circ \geq \Lambda > 50^\circ$ the European sector has the smallest westward drifts during quiet times but the largest
Figure 3-11. Longitudinally averaged zonal drift velocities during geomagnetically quiet (Kp ≤ 3) and disturbed (Kp > 4) conditions.
Figure 3-12. Longitudinal dependence of quiet (Kp ≤ 3) and disturbed (Kp > 4) zonal drift velocities at upper middle latitudes. The scatter bars denote the standard deviations.

during geomagnetic active periods. For 50° ≥ A > 40°, the magnitude of the disturbed drift is significantly smaller, but perturbation drifts are still largest in the European sector. Similar results were obtained in the 1800–2200 and 2000–2400 MLT sectors. The longitudinal dependence of the low-latitude drifts, which are eastward with largest magnitudes between 2200–0400 MLT, cannot be inferred from our data.

The DE-2 satellite often measured very large westward drifts in the late afternoon-midnight sector. Figure 3-13 shows the scatter plot of disturbed drifts for Kp > 4 in the 1800–2200 MLT sector, while Figure 3-14 shows the percentage of occurrence of the very large westward drifts. The total number of drift measurements with Kp > 4 in each of the two latitudinal bins shown in Figure 3-14 was about 2000; the number of data points with westward drifts larger than 600 (800) m/s was 411 (259) in the higher
Figure 3-13. Scatter plot of longitudinal dependence of upper mid-latitude zonal plasma drifts under disturbed conditions for 18-22 MLT.

Figure 3-14. Percentage of occurrence of early night large westward drifts upper middle latitudes for Kp > 4.
latitudinal bin and 110 (74) in the lower one. This Figure shows a large peak in the European sector, a secondary peak at about 150° E, a broad minimum in the Pacific sector in the upper latitudinal bin, and a sharp decrease in the frequency of occurrence of these large velocities with latitude. The 1900–2300 MLT data showed similar longitudinal dependence, and the 2000–2400 MLT data showed a large decrease in this frequency of occurrence in the European sector and again a significantly larger occurrence at eastern longitudes than at western longitudes.

Assuming that the extension of auroral convection velocities to lower latitudes should generally be longitude independent, these data suggest the frequency of occurrence of SAPS events during equinox should be highest in the European sector. The 2000–2400 data also showed an increase in the occurrence of these large velocities for 45° < Λ ≤ 55°, which is consistent with the increase in the frequency of occurrence of SAPS events at lower latitudes with increasing magnetic local times [Foster and Vo, 2002].

At latitudes below 40°, the disturbed drifts are significantly smaller, as appears to be their longitudinal dependence. The perturbation drifts at these latitudes should mostly be due to disturbance dynamo electric fields [e.g., Blanc and Richmond, 1980]. Therefore, our results suggest that low-latitude disturbance dynamo meridional electric fields do not have strong longitudinal dependence during late afternoon-midnight equinoctial periods.
CHAPTER 4

EQUATORIAL F-REGION VERTICAL PLASMA DRIFTS
FROM ROCSAT-1 OBSERVATIONS

4.1 Introduction

Low-latitude ionospheric plasma drifts and electric fields are controlled by complex E- and F-region electrodynamic processes, which are known to vary significantly with local time, season, solar cycle, geomagnetic activity, and longitude [e.g., Fejer, 1997]. The understanding of this large variability during quiet and disturbed times is fundamental for improved forecasting of the low-latitude ionospheric weather.

Equatorial F-region vertical plasma drifts have been measured extensively using coherent and incoherent scatter radar measurements at the Jicamarca Radio Observatory (11.95°S, 76.87°W; magnetic dip 2°N), and they have also been inferred from daytime magnetometer [e.g., Anderson et al., 2004] and nighttime ionosonde observations [e.g., Abdu et al., 1981]. These measurements have been used in numerous case studies of the quiet and disturbed equatorial ionosphere and also for the development of regional empirical plasma drift models [e.g., Abdu et al., 1995; Sastri, 1996; Batista et al., 1996; Fejer, 1997; Fejer et al., 1999, Scherliess and Fejer, 1999].

Low-latitude vertical plasma drifts measurements were made by the Ion Drift Meter (IDM) probe on board the low inclination (19.96°) Atmosphere Explorer-2 (AE-E) satellite from January 1977 through December 1979. During this period, the AE-E satellite was in nearly circular orbits at altitudes from 260 to 450 km. Coley et al.

---

3 Parts of this chapter are comprised of the publication B. G. Fejer, J. W. Jensen, and S.-Y. Su, Quiet-time equatorial F-region vertical plasma drift model derived from ROCSAT-1 observations, submitted to Journal of Geophysical Research, 2007. Sections 4.1 through 4.4 are largely taken from this publication.
[1990] showed that the local time dependence of the longitudinally averaged AE-E equatorial vertical plasma drifts during equinox and December solstice high solar flux conditions was similar to that derived from Jicamarca radar measurements. They also highlighted the occurrence of large longitudinal variations during June solstice.

Equatorial vertical plasma drifts measurements by the high inclination (90°) Dynamics Explorer-B (DE-2) between August 1981 and February 1983 [Coley and Heelis, 1989] and zonal electric field observations by the equatorial San Marco satellite during April to August 1988 [Maynard et al., 1995] were also in good agreement with the Jicamarca drifts. The equatorial vertical drift databases from the DE-2 and San Marco satellites are too small for detailed studies of longitudinal effects.

Fejer et al. [1995] presented the first comprehensive study of season, solar cycle, and longitude effects on quiet-time equatorial F-region vertical ion drifts using IDM data from the AE-E satellite. They showed that the equatorial drifts have large day-to-day and seasonal variations, and solar cycle effects are most pronounced near dusk, where they increase strongly from solar minimum to solar maximum. This study also presented empirical models for the vertical drifts at four longitudinal sectors representative of the Africa-Indian (0°-150°E), Pacific (150°-210°E), Western American (210°-300°E), and Brazilian (300°-360°E) equatorial regions. Scherliess and Fejer [1999] used incoherent scatter radar observations from Jicamarca and IDM data from AE-E to develop the first global empirical model for quiet equatorial F-region vertical plasma drifts. This analytical model, which uses products of cubic-B splines to describe the temporal and
spatial variations of the equatorial vertical drifts, has extensively been used for modeling equatorial ionospheric processes.

Recent satellite studies have reported wavenumber-four longitudinal signatures on the strengths of the nighttime equatorial ionization anomaly [Immel et al., 2006] and of the noontime equatorial electrojet [England et al., 2006], which were attributed to the longitudinal modulation of equatorial zonal electric fields. Hartman and Heelis [2007] presented morning ion drift measurements made on board the Defense Meteorological Satellite Program (DMSP) in the topside equatorial ionosphere, which show that wavenumber-four longitudinal variations occur throughout the year but have most clear signatures during equinox. Kil et al. [2007] reported wavenumber-four longitudinal patterns on seasonally averaged equatorial vertical plasma drift velocities and plasma densities measured by the first Republic of China Satellite (ROCSAT-1) at an altitude of about 600 km. These longitudinal signatures are believed to be due to electrodynamic effects of a non-migrating E-region tide [e.g., Hagan and Forbes, 2002; Forbes et al., 2003]. Kil et al. [2007] also showed the seasonally averaged evening vertical drifts do not exhibit the wavenumber-four longitudinal structure. More recently, Scherliess et al. [2007] have used a very extensive database of total electron content (TEC) from the TOPEX satellite to study the evolution of wavenumber-four longitudinal effects on the low-latitude ionospheric plasma density under different geophysical conditions. They reported that these events were most clearly defined during equinox and June solstice.

Three-dimensional global coupled ionosphere-thermosphere models have increasingly been used to study the electrodynamics of the equatorial region. Fesen et al.
[2000] successfully simulated the seasonal and local time variations of the equatorial F-region vertical and zonal plasma drifts using the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM). This study showed that the E-region semidiurnal tide plays an important role on the daytime drifts. Millward et al. [2001] examined the global effects of tidal forcing on F-region equatorial vertical ion drifts using the Coupled Thermosphere-Ionosphere-Plasmasphere model (CTIP). They showed that the prereversal enhancement of the evening vertical ion drifts is not affected by tidal forcing during periods of high solar activity. Recently, Vichare and Richmond [2005] used simulations from the Magnetosphere-Thermosphere-Ionosphere-Electrodynamics General Circulation Model (MTIEGCM) and experimental observations to study the effects of various ionospheric and thermospheric parameters on the longitudinal variation of the evening equatorial vertical plasma drifts during equinox. These simulations indicate that the evening upward drifts are larger in the American-Atlantic sector than in the Indian sector, which could possibly be due to the longitudinal variation of the strength of the geomagnetic field.

In this work we present the first detailed study of the local time, longitudinal, seasonal, and solar cycle dependence of the equatorial F-region vertical plasma drifts measured by the Ionospheric Plasma and Electrodynamics Probe Instrument (IPEI) aboard ROCSAT-1. This satellite was launched on 27 January 1999 into a circular orbit at an altitude of 600 km with an orbital inclination of 35° and a period of 97 minutes. This mission, which ended early July 2005, covered 24-hour local times in 25 days. The IPEI measurements, made continuously from mid March 1999 to early June 2004, have
been used in numerous case studies of the low-latitude ionosphere [e.g., Lin et al., 2001; Su et al., 2002, 2003; Chao et al., 2003; Kil et al., 2007]. In the following sections we initially describe in detail our data selection and model development. Then, we examine the general characteristics of these equatorial vertical drifts and compare our results with those from previous studies.

4.2 Measurements and Data Selection

The characteristics of the IPEI were described by Yeh et al. [1999]. In this probe, the cross track ion velocity components were determined from the arrival angles of the ions with 1° corresponding to about 125 m/s. The error on these drift measurements were typically smaller than 10% when the ion density was larger than $10^3$ cm$^{-3}$ and the percentage of oxygen ions exceeded 85%, but as we will see later, they were much larger during late night low solar flux periods, due to the larger percentage of light ions at about 600 km. The vertical velocity is usually a combination of the ion drift components perpendicular and parallel to the geomagnetic field, but near the dip equator it corresponds basically to the electrodynamic drift driven by the zonal electric field.

We have examined the entire ROCSAT-1 database of 15-second averaged quiet-time ($Kp \leq 3$) drift measurements which span from mid March 1999 through early June 2004. We have discarded data from March to June 1999, which have very large variability, and from the end of February to mid March 2000 because of an anomalous offset. We have also deleted measurements within a few seconds from noon throughout the entire database, which were also clearly erroneous.
We selected and analyzed the ROCSAT-1 equatorial drifts using basically the methodology described by Fejer et al. [1995]. However, since this satellite was at a much higher altitude than AE-E, particularly during lower solar flux conditions, additional data analysis constraints were also necessary. We have first determined that the average drift patterns using observations within 5° and 2.5° of the dip equator were largely identical. Therefore, the results to be presented below were obtained using measurements within 5° of the dip equator, since they have higher statistical significance.

The accuracy of the drift measurements decreases markedly with decreasing ion density and increasing density of light ions. Since we have not used the ion composition data, we have tried to minimize the measurement errors by first examining the average drifts corresponding to plasma densities larger than $10^4$ cm$^{-3}$, $2 \times 10^4$ cm$^{-3}$, $5 \times 10^4$ cm$^{-3}$, and $10^5$ cm$^{-3}$. Figure 4-1 shows an example of a scatter plot of the drift measurements obtained using three plasma density thresholds. This figure indicates that the use of larger threshold plasma densities decreases the scatter and the number of late night measurements. The upward drifts after about 1900 LT are due to equatorial plasma depletions, which are most frequent in the Atlantic-American sector. The lower plasma densities in the late night sector are generally associated with larger downward velocities and also with larger scatter and errors in the measurements, especially during low solar flux conditions. Our analysis indicated the occurrence of unrealistically large late night downward velocities for plasma densities smaller than about $10^4$ cm$^{-3}$, which, as will be shown later, resulted in large departures from the curl-free condition for the longitudinally averaged zonal electric fields.
Figure 4-1. Examples of scatter plots of quiet-time equatorial vertical drift velocities over a 30° longitudinal sector measured by ROCSAT-1 for three plasma density thresholds.

We obtained our best overall results using drifts corresponding to plasma densities larger than $10^5$ cm$^{-3}$ between 0800 and 0200 LT and $5 \times 10^4$ cm$^{-3}$ from 0200 to 0800 LT. We note that the number of measurements and accuracy of our late night data decreased with solar flux, especially during June solstice. Finally, we tried to minimize the effects of upward drifts associated with plasma depletions by excluding velocities with magnitudes larger than 100 m/s, since, under geomagnetically quiet conditions ($K_p \leq 3$), they generally appear to be due to instrumental effects or, during early night periods, to equatorial plasma depletions. We will show later that these constraints seem
to give quite accurate average drifts, except for relatively low solar flux \((S_a < 130)\) late night June solstice conditions.

### 4.3 Quiet-Time Model Development and Accuracy

Our database consists of over 560,000 quiet-time \((K_p \leq 3)\) measurements. These data were grouped into 4-month seasonal bins representing December solstice (November-February), June solstice (May-August), and equinox (March-April, September-October), with 15° overlapping, 30° wide longitudinal bins. We have used 1 hour local time bins, except in the 1700–2200 LT sector, where we used 30-minute bins shifted every 15 minutes, in order to more accurately account for rapidly changing evening prereversal drift enhancements. When averaging the data, we discarded points outside two standard deviations.

We have determined that the variations of the drift velocities with solar flux were best reproduced by using bilinear relationships. This was also the case for the vertical drifts measured by the Jicamarca radar \([\text{Scherliess}, 1997]\). For each local time, season, and longitude bin, we have first grouped the drift data into three overlapping solar flux index bins: \(S_a \leq 130\), \(S_a \leq 160\), and \(S_a > 160\). The average solar flux indices in these bins were about 110, 130, and 185, respectively, with largest values during equinox and smallest during June solstice. Other solar flux groupings were also tried, but they resulted in inferior fits to the data. We have determined the variations of the drifts with solar flux for \(100 \leq S_a \leq 120\) and \(140 \leq S_a < 210\) using our binned data and the assumption of a linear drift dependence with solar flux. Between 0000–1700 and
2200–2400 LT sectors, we used 4-hour local time bins shifted every 2 hours. It is possible that these large bins have smoothed out the early morning flux dependence too much, but this was necessary since the data are sparse in this period. For the 1700–2200 LT sector, where the drift velocities often change rapidly, we have calculated the solar dependence using 60-minute local time bins shifted by 30 minutes, except for a few cases that required the use of 30-minute bins shifted by 15 minutes. The derived flux variations for \( \text{Sa} \leq 120 \), and \( \text{Sa} \geq 140 \) are generally quite similar. For \( 120 < \text{Sa} < 140 \), we have interpolated between our low and high flux variations. Finally, we have performed 3 point running averages on the longitudinal variations of the derived flux dependence.

The solar flux variations derived from our data are generally consistent with those presented by Scherliess and Fejer [1999], except near dusk where we have stronger solar flux dependence.

The empirical model derived using the procedure outlined above gives the quiet-time (\( \text{Kp} \leq 3 \)) equatorial vertical drifts at an altitude of 600 km for each season, usually in 1 hour bins shifting every 30 minutes in local time and 30° wide longitudinal bins overlapping 15° for \( \text{Sa} = 100-200 \). In the 1700–2200 LT sector, the drifts are specified in 30-minute local time bins shifting every 15 minutes. As discussed below and highlighted later, these model drifts are most accurate for equinox and December solstice.

The equatorial zonal ionosphere electric fields, which drive F-region vertical drifts, must be irrotational on the times scales and for the quiet-time conditions considered here, so that their line integrals along the dip equator must be zero; i.e.,

\[
\oint E \, dl = \oint B \cdot v \, dl
\]
where B denotes the equatorial magnetic field strength (between 0.19 and 0.30 G at the height of the satellite) and $v_z$ is the vertical drift velocity. Scherliess and Fejer [1999] used this curl-free constraint in the development of their equatorial vertical drift model. We used this condition to estimate the longitudinally averaged accuracy of our empirical models as a function of universal time (UT). We have calculated the values of the above integrals by summing the products of the average drift velocities and corresponding magnetic field strengths at the dip equator, in hourly and half-hourly 7.5° and 15° longitudinal bins. The magnetic field values for an altitude of 600 km along the dip equator were obtained from the International Geomagnetic Reference Ionosphere (IGRF).

Figure 4-2 shows the hourly values of the zonal electric fields integrated along the magnetic equator for three solar flux values. In this case, we used a 15° longitudinal grid; nearly identical results were obtained using our higher time and spatial resolution data. Figure 4-2 indicates that for equinox and December solstice, our vertical drifts correspond to nearly curl-free electric fields. For June solstice this is the case for high solar flux conditions but not for lower solar fluxes values when there are increasing departures from the curl-free condition, which are probably due to the larger errors of the late night measurements. We note for a given UT, a shift in the drift velocities around the globe by 1.5 m/s changes the longitudinally averaged zonal electric field by about 2 mV/m. Since we do not know the exact local time and solar flux dependent accuracy of the drift measurements, we did not attempt to correct them to satisfy the curl-free condition.
4.4 Quiet-Time Model Results and Discussion

In this section, we initially describe the seasonal and longitudinal variations of the equatorial vertical drifts for the average solar flux conditions (Sa = 150) during the ROCSAT-1 mission, which correspond to our most accurate results. Then, we examine their dependence on solar flux. Finally, we compare our results with those from earlier studies.

4.4.1 General Characteristics

Figure 4-3 shows the average F-region vertical drifts in 8 longitudinal sectors for moderately high solar flux conditions derived from our ROCSAT-1 data. These drifts are upward during the day and downward at night with magnitudes up to about 40 m/s, which vary significantly with local time and longitude, particularly during the solstices. Large prereversal velocity enhancements (up to about 50 m/s) occur over a broad range of
Figure 4-3. Local time and longitude dependence of quiet-time equatorial vertical drifts (positive upward) in eight longitudinal sectors for moderate solar flux conditions.

Longitudes near dusk during equinox and close to dawn during June solstice. The evening drift reversal times do not change much with longitude during equinox but vary considerably in the American-African sector during December and June solstice. There are also large variations between the western and eastern hemisphere morning drifts and reversal times during June solstice. The full quiet-time model is given in Appendix A.

The local time, seasonal, and longitudinal dependence of the vertical drifts are illustrated in more detail in Figure 4-4. The midnight-dawn downward drifts are larger in the eastern than in the western hemisphere and have largest magnitudes near sunrise during June solstice. Figure 4-4 also shows the large longitudinal variations in the morning and afternoon daytime upward drifts at all seasons. The December solstice data
Figure 4-4. Local time, seasonal and longitudinal dependent equatorial quiet-time vertical drift velocities for moderate solar flux conditions.
show daytime velocity peaks near 10° W and 100° E at about 1100 LT, with a broad longitudinal sector of enhanced upward drifts between about 170° E and 90° W, centered at about 1000 LT. During equinox, there are four upward velocity peaks near 170° W, 100° W, 0° E, and 100° E at about 1000 LT. In this season, the daytime longitudinal drift velocity fluctuations appear to generally extend, with decreasing amplitudes, into the evening sector. The June solstice drifts have moderate to large drift peaks near 90° W, 0° E, and 100° E, a considerably smaller peak near 170° W all at about 1100 LT, and also an early morning region of enhanced upward drifts near 140° W. The latter is mostly due to the sudden drift reversal near sunrise (see Figure 4-3). Figure 4-4 also illustrates the strong seasonal and longitudinal dependence of the prereversal velocity enhancements and of the evening reversal times. The premidnight downward drifts do not show a clear longitudinal pattern.

Figure 4-5 presents in the bottom and top panels the seasonal and longitudinal dependence of the upward drift velocities averaged between 0900–1200 LT and 1300–1600 LT, respectively. The equinox, June solstice, and eastern hemisphere December solstice morning and afternoon velocity peaks are nearly identical longitudes. On the other hand, the December solstice western hemisphere morning and afternoon drifts have very different magnitudes and longitudinal dependence. The morning upward velocities are larger than the afternoon drifts by about 10-15 m/s values, except in the western hemisphere during June solstice. The dayside velocity peaks near 100°E exhibit the smallest local time and seasonal variations, which might be related to the strong geomagnetic field in this region (H. Lühr, private communication, 2007). We note that
Figure 4-5. Longitudinal variations of morning and afternoon averaged quiet-time vertical drifts.
even though the daytime longitudinal drift patterns are quiet stable, the corresponding drifts exhibit large day-to-day variability as illustrated in Appendix C.

Figures 4-3 and 4-4 show large seasonal and longitudinal variations in the evening prereversal velocity enhancements. These are illustrated further in Figure 4-6. The equinoctial peak velocity enhancements vary between 25 and 45 m/s, with largest values from 120° W to 30° E. The December solstice drifts have smallest magnitudes near 180° E and largest values in the American sector, where they occur at increasingly later local times toward the west, as shown in Figure 4-4. The June solstice evening velocity peaks have largest values near 15°E and 180°E, and smallest near to 75°E and 60°W. The longitudinal variations of the December and June solstice prereversal velocity enhancements are nearly anti-correlated. This is probably due to magnetic field line

![Figure 4-6](image)

**Figure 4-6.** Seasonal and longitude dependence of quiet-time evening prereversal velocity peaks.
integrated conductivity effects, which play a fundamental role on the magnitude of the evening prereversal velocity enhancements. It is interesting to note that, except near 60°W, the evening equinoctial peak drifts correspond approximately to the sum of the solstitial drifts.

4.4.2 Solar Cycle Effects

Figure 4-7 shows the longitudinal dependence of the vertical model drifts for Sa =130 and Sa = 200. The morning drifts do not change much with solar activity during December solstice and equinox, but the afternoon and evening upward and the nighttime downward drifts increase with solar flux. The solar flux dependence of the December solstice evening drifts varies strongly with longitude. The western hemisphere June solstice drifts show small solar flux effects in the nighttime and early morning sectors and increased upward drifts with solar flux in the noon-evening sector. On the other hand, the eastern hemisphere June solstice data show larger daytime upward and smaller nighttime downward drifts with increased solar activity. We note that the violation of the curl-freeness during moderate and low solar flux June solstice conditions shown in Figure 4-2, results from the simultaneous decrease in the upward daytime drifts and increase in the postmidnight downward drifts with decreasing solar flux, which is most pronounced in the eastern hemisphere. Therefore, we believe that the solar flux dependence indicated by the eastern hemisphere June solstice drifts in the midnight-early afternoon sector is not realistic.

Figure 4-7 also indicates the increase of the evening prereversal velocity enhancements with solar flux varies noticeably with longitude during December and June.
Figure 4-7. Seasonal and longitude dependence of quiet-time equatorial model drift velocities for two decimetric solar flux values.

Solstice. The evening reversal times do not change with solar flux, except in the American sector during June solstice. The morning reversal times generally occur earlier with decreasing solar flux during December solstice and equinox but later in the eastern hemisphere during June solstice, which is related to the solar flux dependence of these drifts, and therefore, may not be realistic. The full solar flux variability is given in Appendix B.

Figure 4-8 presents the seasonal and longitudinal variation of the evening prereversal velocity peaks for two solar flux values. The magnitudes of these drifts and their increase with solar flux are longitude dependent. The largest prereversal drift peaks occur during equinox, except near 45° W, where they are largest during December.
Figure 4-8. Seasonal and longitudinal variations equatorial evening prereversal velocity peaks for two decimetric solar flux values.
solstice. The longitudinal variation of the evening upward drift peaks is smallest during equinox solar maximum conditions, which suggests that the F-region dynamo plays an even more dominant role on the generation of high solar flux evening drifts at all longitudes. On the other hand, the longitudinal variation of the evening prereversal velocity peaks is largest during December solstice. Figure 4-8 also shows that the longitudinal variations of the December and June solstice evening peak drifts are largely anti-correlated during both high and low solar flux periods.

4.4.3 Comparison with Earlier Results

The seasonal and solar dependence of the F-region vertical plasma drifts over Jicamarca were discussed in several studies [e.g., Fejer et al., 1991; Scherliess, 1997]. These radar drifts correspond to averages generally between about 300 and 400 km during most of the day, but they correspond to higher altitudes during December solstice and equinox evening periods, and to lower heights in the postmidnight sector at all seasons as a result of the solar flux dependent evening upward and nighttime downward motions of the equatorial F-layer, respectively. On the other hand, our ROCSAT-1 drifts correspond to averages over a 30° longitudinal sector at an altitude of about 600 km. Therefore, the altitudinal variation of the vertical drifts [e.g., Pingree and Fejer, 1987; Eccles, 1998] and the relatively large longitudinal averaging of the satellite data need to be taken into account for a detailed comparison of Jicamarca and ROCSAT-1 drifts. Pingree and Fejer [1987] showed the Jicamarca equinoctial vertical drifts increase with altitude between 2100 and 1300 LT and decrease from 1300 to 2100 LT, with largest increases and decreases (about 0.15 m/s/km) at about 1000 and 1800 LT, respectively.
Similar altitudinal variations should occur during other seasons. Figure 4-9 shows the very good agreement between our results centered over the radar site and the Jicamarca drifts obtained from the Scherliess-Fejer model, even without correcting for altitudinal and longitudinal integration effects.

Our model results are generally in good agreement with the model drifts presented by Scherliess and Fejer [1999], especially during equinox. However, the large longitudinal variations of the daytime drifts shown in Figures 4-4 and 4-5, and the strong longitudinal effects shown in our solstitial evening drifts were not captured by the Scherliess-Fejer model since the relatively small number of AE-E drift measurements required the use of much larger longitudinal bins. In addition, our results show much larger prereversal velocity enhancements during December solstice and equinox. On the other hand, the solar flux variation of the midnight-morning June solstice drifts derived by Scherliess and Fejer [1999] is probably more realistic than that shown in our model.

Extensive studies of evening and early night vertical plasma drift velocities have been carried out using ground-based observations in the Brazilian and Indian equatorial regions. Our model drifts are in good agreement with the evening plasma drifts derived from ionosonde measurements over Brazil [e.g., Batista et al., 1996], especially if one considers the generally quite different altitudes and spatial integrations of the corresponding measurements. The satellite data clearly show strong longitudinal variations of the early night vertical drifts in the American sector during both June and...
Figure 4-9. Comparison of ROCSAT-1 and Jicamarca model vertical plasma drifts for two solar flux values.
December solstice, which is consistent with the ground-based data. The ROCSAT-1 drifts are also in good agreement with ground-based measurements of evening vertical drifts over India [e.g., Balan et al., 1992; Sastri, 1996].

Vertical drifts were measured by the ALTAIR incoherent scatter radar over the Kwajalein atoll (9.4° N, 167.5° E, magnetic dip 7.5° S) over a 25-day period from July to August 1990, when the solar decimetric flux index was about 200 [Sultan, 1994, 1996]. These measurements showed an evening prereversal velocity peak of about 45 m/s near 1900 LT and reversal time of about 2000 LT. In this case, our data show a peak velocity of about 30 m/s at 1900 LT and a reversal time of 2000 LT. Our model results are also in good agreement with vertical drifts measured by the electric field probe on board the San Marco D satellite between April and September 1988 [Maynard et al., 1995].

Vichare and Richmond [2005] used the MTIEGCM to simulate the longitudinal variation of the evening vertical drifts at the magnetic equator during equinox and to study their dependence on various ionospheric parameters. Figure 4-10 compares the longitudinal variations of the evening prereversal peaks obtained from the ROCSAT-1 data and from the Vichare-Richmond study. The satellite and simulation data show largest upward velocities in the western Pacific-American sector, but the magnitudes of the simulation drifts are systematically larger than the experimental values. For lower solar flux conditions, the satellite data also show a stronger longitudinal variation. Vichare and Richmond [2005] discussed the effects of the zonal wind, field integrated Pedersen conductivity, and magnetic declination on the longitudinal variation of the
evening drifts. Our evening velocity peaks appear to maximize in the region of largest field-aligned conductivities and magnetic-east zonal winds.

_Millward et al. [2001]_ studied the season, solar cycle, and longitude dependent vertical ion drift velocities using CTIP, which also included the electrodynamic coupling of the equatorial ionosphere and thermosphere. The simulations showed that the daytime vertical drifts are highly dependent on the magnitude and phase of the semidiurnal tidal component and predicted large downward velocity enhancements (typically about 40 m/s) near dawn during the solstices. The equinoctial evening prereversal velocity peaks
showed only small longitudinal variations; the December and June solstice drifts were largest in the American-Atlantic sector and in the 180°E sectors, respectively. These results, and the predicted variation of the drifts with local time, are generally consistent with our experimental results. On the other hand, the theoretical daytime drifts during high solar flux periods are often much smaller than the measured values; the prereversal enhancements are much longer lasting than observed, and the evening reversal times occur about 2 hours later than indicated by our data.

Kil et al. [2007] showed the season averaged morning vertical drifts measured by ROCSAT-1 exhibit a clear wavenumber-four longitudinal pattern and illustrated the large variability of the morning and evening upward drifts. Our results indicate that this daytime wavenumber-four signature is observed during equinox and June solstice and is most pronounced during equinox, which is in good agreement with DMSP results presented by Hartman and Heelis [2007]. We have seen that during December solstice there is a single broad region of enhanced daytime upward drifts in the western hemisphere centered at about 150°W. The seasonal and longitudinal variations of our daytime upward drifts are fully consistent with global distribution of low-latitude TEC derived from TOPEX satellite data [Scherliess et al., 2007]. The physical processes responsible for the wavenumber-four ionospheric signatures are subjects of intense current research.

4.5 Disturbance Dynamo Drifts

In this section, we initially discuss the methodology used to determine the signature of disturbance dynamo drifts, and then we examine the seasonal dependence of
the longitudinally averaged drift patterns. Finally, we briefly discuss solar cycle and longitudinal effects on the equinoctial disturbance drifts.

We used AE indices to extract the disturbance dynamo drifts by only selecting data that had elevated AE values over the previous 4 hours. We also required that there be no large changes in the AE values near the data point. This produced an average AE pattern similar to the top panel of Figure 2-14 with an average AE value of 380 nT. We then binned the data in three seasons and averaged over longitude. We have compared initially the seasonally averaged quiet-time and disturbed patterns.

Figure 4-11 shows both the quiet and disturbed average drifts for the three seasons and for $\delta a = 150$. The average AE indices for quiet and disturbed conditions were about 130 nT and about 380 nT, respectively, with slightly lower values for December solstice disturbed conditions. Figure 4-11 shows that the disturbance dynamo electric fields do not greatly affect the daytime drifts or reversal times near dawn and dusk, but they decrease the magnitudes of the evening upward and nighttime downward drifts. This is consistent with the results from earlier studies [e.g., Blanc and Richmond, 1980; Scherliess and Fejer, 1997]. Figure 4-11 shows that the nighttime perturbations do not change much with season, and evening perturbations are largest during equinox.

Figure 4-12 shows the local time and seasonal variations of the longitudinal average disturbance dynamo drifts obtained by subtracting the quiet and disturbed drifts presented in Figure 4-11 and normalizing them to $\Delta AE = 300$ nT. We can see again that there is little seasonal variation in the post-midnight sector with upward perturbation drifts reaching about 12 m/s at 0500 LT during December solstice, and at 0400 LT during
Figure 4-11. Seasonal dependence of vertical plasma drifts during quiet and disturbed conditions.
Figure 4-12. Seasonal dependence of residual vertical drift calculations for a difference in AE of 300 nT.
equinox and June solstice. There is strong seasonal dependence near 1900 LT with downward drift perturbations of about 12 m/s during equinox and smaller perturbations of about 7 m/s and 5 m/s during June and December, respectively. The occurrence of largest disturbance dynamo drifts near 1900 LT during equinox is consistent with results from Jicamarca [Fejer, 2002]. The daytime perturbations are very small (on the order of the accuracy of our measurements).

During equinox, there was enough data to examine possible solar flux and longitudinal effects on these perturbation plasma drifts. Figure 4-13 shows the solar flux variation of longitudinally averaged equinoctial perturbation drifts normalized to $\Delta AE = 300$ nT for solar flux bins of $S_a > 150$ ($\langle S_a \rangle = 120$) and $S_a < 150$ ($\langle S_a \rangle = 180$). We can

![Figure 4-13. Solar flux variation of longitudinally averaged residual vertical plasma drifts during equinox.](image-url)
see that vertical plasma drift perturbations reach a downward maximum of about 7 m/s near 1900 LT for low solar flux conditions while for high solar flux conditions, the perturbation doubles in amplitude to above 15 m/s. The post-midnight perturbation drifts for these two solar flux values are largely identical with upward values reaching 12 m/s at 0400 LT. There are some differences between the two flux bins near 0200 LT, 0600 LT, and during the day, but it is difficult to know if these are physical or are merely due to the relatively high noise level.

Figure 4-14 shows the longitudinal variation of the residual vertical plasma drifts for equinox for $\Delta AE = 300$ nT. In this case, we have used 120° overlapping longitudinal bins shifted every 60°. Figure 4-14 shows that the drift perturbations near dusk are highly longitudinally dependent. The largest downward perturbations occur in the Indian-Pacific sector (centered at 120°) with values of about 15 m/s while the smallest values (about 7 m/s) occur in the American sector (centered at about −120°). The post-midnight perturbations are mostly longitudinally independent with upward maximum ranging from about 10 to 12 m/s near 0400 LT.

Huang et al. [2005] have used the NCAR TIEGCM to study the storm-time and longitudinal dependence of low-latitude zonal perturbation electric fields and thermospheric winds during equinox moderate solar flux conditions. The local time variation of the zonal disturbance dynamo electric fields derived from the simulations for the American and Indian sectors is in good agreement with the results shown in Figure 4-14. This simulation also predicts stronger evening disturbance dynamo effects in the
Figure 4-14. Longitudinal dependence of residual vertical plasma drifts for equinox.
Indian than in the American sector, which is also consistent with the results in Figure 4-14. On the other hand, the theoretical predictions of a strong longitudinal dependence of the reversal times of the evening disturbance dynamo zonal electric fields (vertical drifts) are not consistent with our data.

We have presented in this chapter an extensive study of equatorial vertical plasma drifts derived from ROCSAT-1 measurements. We believe that in spite of limitations of satellite measurements, our results should considerably help the detailed testing of global model results of low-latitude ionospheric electrodynamics.
CHAPTER 5

CONCLUSIONS

We have studied in detail the climatology of F-region plasma drifts using very large databases of measurements from the DE-2 and ROCSAT-1 satellites. We have discussed the climatology of longitudinal, seasonal, and solar flux dependency of middle and low-latitude zonal drifts and equatorial vertical plasma drifts. We have compared our results with ground-based observations, and have carried out a detailed analysis of equatorial vertical plasma drifts and developed a quiet-time empirical model for these drifts that can be used for more comprehensive studies of low-latitude electrodynamic processes.

This chapter summarizes our main results in detail and also presents suggestions for future work.

5.1 Summary of Results

The middle and low-latitude quiet-time zonal drifts measured by the DE-2 satellite indicate the occurrence of significant latitude dependent longitudinal variations during the evening to early morning hours at all seasons. During equinox, the quiet-time eastward relative drifts in the premidnight sector are largest in the European sector at upper middle latitudes and in the American-Pacific longitudinal sector at low latitudes. The late night-early morning relative drifts during June and December solstice have anti-correlated longitudinal variations, but the daytime drifts do not change much with longitude. The zonal perturbations drifts resulting from enhanced geomagnetic activity are westward and have largest values in the upper middle latitudes and in the evening and
early night periods. During equinox, the upper middle latitude disturbance drifts are largest in the European sector. Our results also suggest that during equinox, SAPS events occur most often in the European sector. The low-latitude disturbance drifts are largest in the midnight sector and do not appear to have strong longitudinal dependence, at least during equinox.

We have developed an empirical model for equatorial F-region quiet-time (Kp \leq 3) vertical plasma drifts using ion drift observations on board the ROCSAT-1 from March 1999 to July 2004. This model, which is most accurate during equinox and December solstice, describes in 15° latitudinal bins the diurnal, seasonal and solar cycle variations of equatorial vertical drifts at an altitude of about 600 km for moderate to high solar flux conditions (100 \leq Sa \leq 200). Our results over Peru are consistent with Jicamarca radar observations. They are also consistent with previous ground-based and in-situ measurements in other longitudinal sectors. On the other hand, they show much stronger longitudinal effects during both day and night than suggested earlier.

The daytime ROCSAT-1 model drifts show strong wavenumber four signatures, which are most clear during equinox. There are also noticeable longitudinal perturbations on the daytime drifts during the solstices. The longitudinal dependence of the daytime and nighttime drifts is largest during December solstice high solar flux periods. The evening prereversal velocity enhancements and reversal times also exhibit large longitudinal variations, particularly during the solstices. The largest prereversal velocity enhancement occurs in the American sector during December solstice. The
seasonal and longitudinal dependence of the evening drifts highlights the fundamental import ance of the ionospheric conductivity in the electrodynamics of the early night equatorial ionosphere.

This new quiet-time drift model is available from the authors as well as plotted in Appendix A. It should provide a considerably more accurate description of equatorial ionospheric processes.

We very briefly studied the disturbance dynamo effects on the ROCSAT-1 vertical plasma drifts. These effects decrease the magnitudes of the evening upward and nighttime downward drifts but do not cause significant perturbation during the day. Postmidnight disturbance dynamo perturbation drifts are roughly season independent, while near dusk they are largest during equinox. We have also shown that the equinoctial nighttime and evening disturbance dynamo perturbations vary with solar flux and longitude. Near dusk, the largest downward perturbation drifts occur in the Indian-Pacific sector and the smallest occur in the American-Brazilian sector.

5.2 Suggestions for Future Work

We have shown that during geomagnetically quiet and disturbed conditions there is large seasonal and longitudinal variation in the vertical and zonal plasma drifts. In order to fully understand the global climatology of ionospheric plasma drifts, many more measurements will be required.

The DE-2 measurements given in Chapter 3 suggest significant longitudinal variation in the seasonal dependency of the zonal plasma drifts, especially during evening
and nighttime periods. These effects could not be fully addressed in Chapter 3, since, in the DE-2 measurements, season and local time are locked together. Further measurements are also needed to understand the strong latitudinal and longitudinal dependence of the zonal plasma drifts under geomagnetically disturbed conditions. Finally, the DE-2 satellite was not able to give reliable measurements of north/south plasma drifts perpendicular to the magnetic field. Further latitudinal and longitudinal studies of this component of plasma drift will be needed to understand the global characteristics of electric fields and currents.

The ROCSAT-1 measurements have greatly increased our understanding of the climatology of equatorial quiet-time vertical plasma drifts, but this satellite was not able to give reliable zonal drift measurements. Additional measurements are needed at higher and lower solar flux values in order to have a greater understanding of the solar flux variation of quiet and disturbed plasma drifts. Finally, more extensive measurements are also needed in order to better understand the effects of prompt penetration electric fields and disturbance dynamo drifts, as well as their variations with longitude, latitude, season, and solar flux.


Sultan, P. J., Chemical release experiments to induce F region ionospheric plasma irregularities at the magnetic equator, PhD dissertation, Boston University, Boston, MA, 1994.


Wand, R. W., A model representation of the ionospheric electric field over Millstone Hill (\(\Lambda = 56^\circ\)), *J. Geophys. Res.*, 86, 5801-5808, 1981.

APPENDICES
Appendix A. Plot of Entire Quiet-Time Model Vertical Plasma Drifts at 150 Flux Units
Figure A-1. Quiet-time model values for December solstice at 150 units of flux.
Figure A-2. Quiet-time model values for Equinox at 150 units of flux.
Figure A-2. Quiet-time model values for June solstice at 150 units of flux.
Appendix B. Plot of Quiet-Time Model Solar Flux Variation
Figure B-1. Quiet-time model flux variation for December solstice at two levels of flux.
Figure B-2. Quiet-time model flux variation for equinox at two levels of flux.
Figure B-3. Quiet-time model flux variation for June solstice at two levels of flux.
Appendix C. Quiet-Time Variability of Daytime ROCSAT-1 Vertical Plasma Drifts
Figure C-1. Longitudinal variation of quiet-time vertical plasma drifts during the day. The vertical bars indicate the standard deviations.
Appendix D. Copyright Information
All figures in Chapter 2 are copyrighted by the American Geophysical Union and reproduced with permission. The following page contains the text of an e-mail sent by the American Geophysical Union outlining the permission given to use the figures in question. Page 123 includes a letter sent by Dr. Shin-Yi Su giving permission to include in Chapter 4 the paper of which he is a coauthor.
Thank you for your interest in reproducing AGU published material. AGU does not require that permission be obtained from AGU or the author(s) for the use of tables, figures, or short extracts of papers published in AGU journals or books, provided that the original publication be appropriately cited.

The standard credit line for the citation is, “Author(s), title, publication, volume number, issue number, page number(s), date. Copyright [year] American Geophysical Union.” The following must also be included, “Reproduced/modified by permission of American Geophysical Union.”

If an article was placed in the public domain, in which case the words “Not subject to U.S. copyright” appear on the bottom of the first page or screen of the article, please substitute “published” for the word “copyright” in the credit line mentioned above.

Copyright information is provided on the inside cover of our journals. For permission for any other use, please contact the AGU Publications Office at AGU, 2000 Florida Ave., N.W., Washington, DC 20009.

Michael Connolly
Journals Publications Specialist
October 4, 2007

School of Graduate Studies
Utah State University
Logan, Utah
U. S. A.

Dear Sir,

I am writing this letter to express my agreement for Mr. John Jensen to include the paper of ROCSAT model in his dissertation to partially fulfill the requirement of a Ph. D. degree from the Utah State University.

With best regard,

Sincerely yours,

Shin-Yi Su
Professor and PI of IPEI/ROCSAT project
CURRICULUM VITAE

John W. Jensen
(October 2007)

EDUCATION:
PhD in Physics, Utah State University, October 2007 (expected)
BSc in Physics, Utah Valley State College, April 2004, Cum Laude

PROFESSIONAL EXPERIENCE:
Graduate Research Assistant, Physics Dept., Utah State University, 2004-Present
Physics Tutor, Utah Valley State College, 2002-2004
REU Intern, Brigham Young University, Summer 2003

AWARDS:
Presidential Fellowship, 2004-2005 (Graduate)
Full Tuition Departmental Scholarship, 2001-2004 (Undergraduate)
“Outstanding Physics Student,” 2002

PUBLICATIONS:

PRESENTATIONS: