The Equatorial Ionosphere: A Tutorial

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CEDAR Meeting
Seattle, WA
June 2015

The Equatorial Ionosphere

Outline

Introduction
The geomagnetic field
Unique equatorial phenomena
Low latitude transport processes
Measurement techniques
Low latitude quiet-time electrodynamics: climatology
Equatorial plasma instabilities
Longitudinal effects
Outstanding questions
Summary

Introduction

The Earth's equatorial/low latitude ionosphere is host to some of the most complex phenomena in the upper atmosphere.

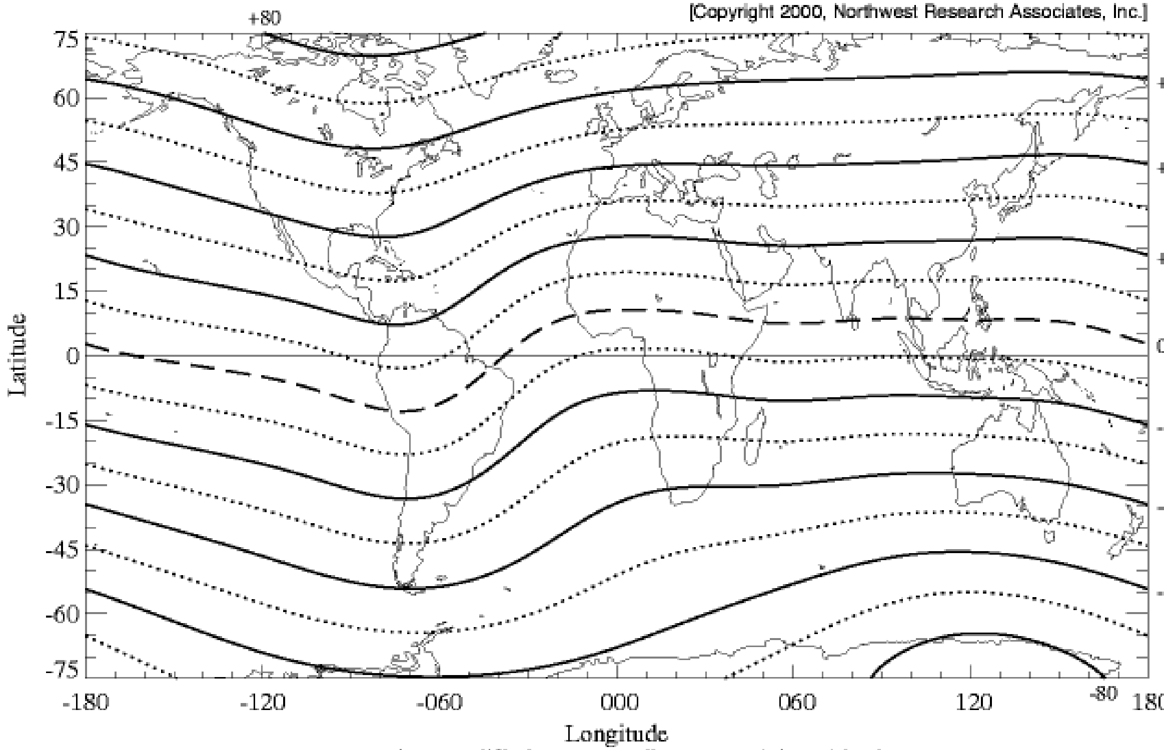
The quiet-time low latitude ionosphere is significantly affected by a large number of local and lower atmospheric processes including solar and lunar tides, planetary and gravity waves, el nino, earthquakes, tsunamis, lightning, and high latitude sudden stratospheric warmings.

This region can also be significantly disturbed by solar wind/magnetosphere/high latitude ionospheric processes including high speed streams associated with solar coronal mass ejections, corrotating interactions regions, substorms, solar wind velocity and dynamic pressure changes, solar flares, and Joule heating.

These driving processes lead local time, season, solar cycle, longitude and magnetic activity dependent ionospheric variations over about 30% of the globe

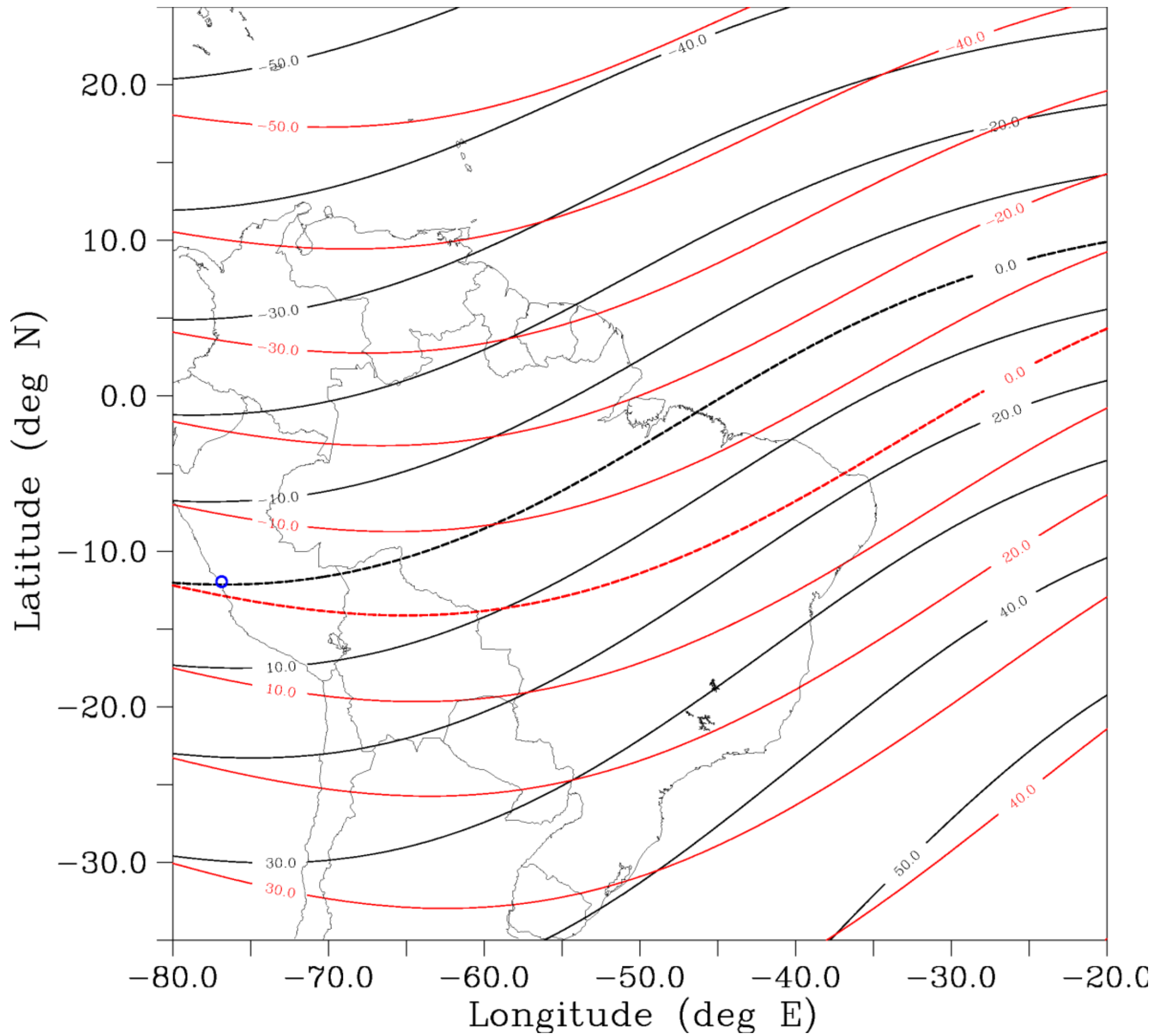
In this presentation, we will focus mostly on the main properties of equatorial of the equatorial/low latitude ionosphere, and specially with on electrodynamic processes.

Geomagnetic (350km Apex) Latitudes



Based on modified apex coordinates at 350km altitude

Variation of the Earth's magnetic field over South America in about 50 years



The low latitude/equatorial ionosphere has several unique phenomena.
Some of the most important ones are:

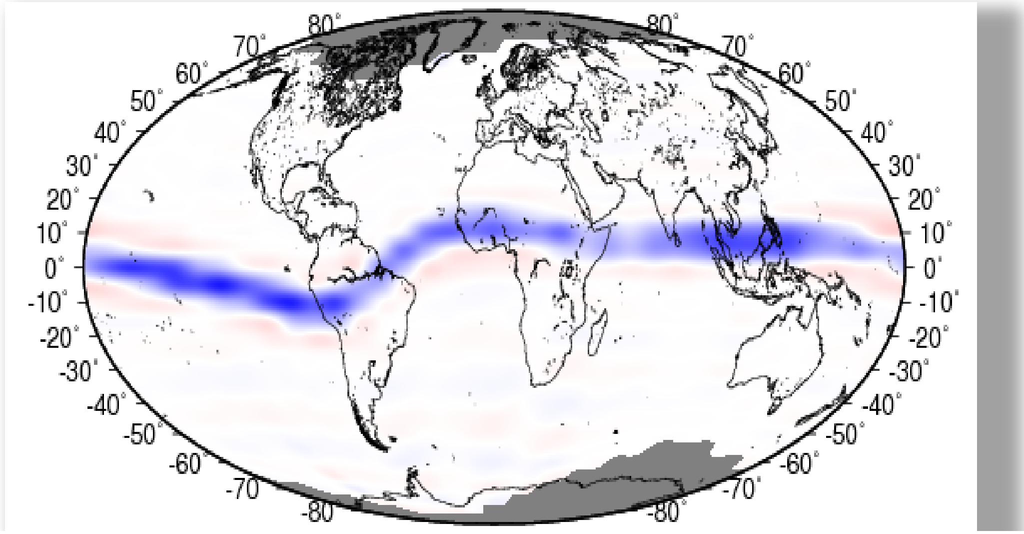
The equatorial electrojet and their plasma instabilities

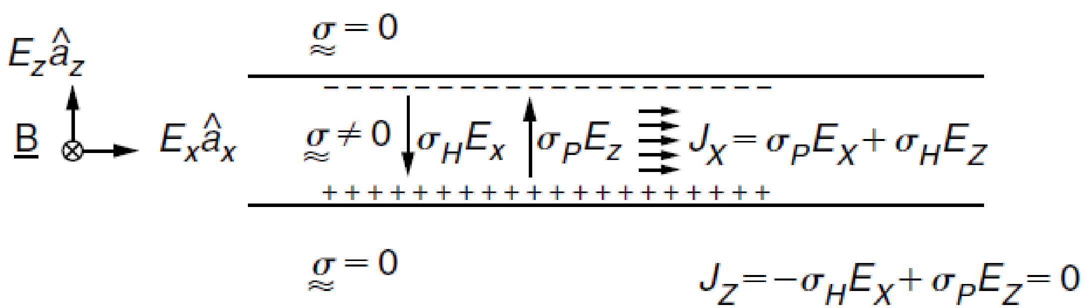
The Appleton anomaly

Plasma depletions, enhancements (blobs), and Spread F

These phenomena are strongly latitude, longitude, season, solar flux and geomagnetic activity dependent

Equatorial Electrojet

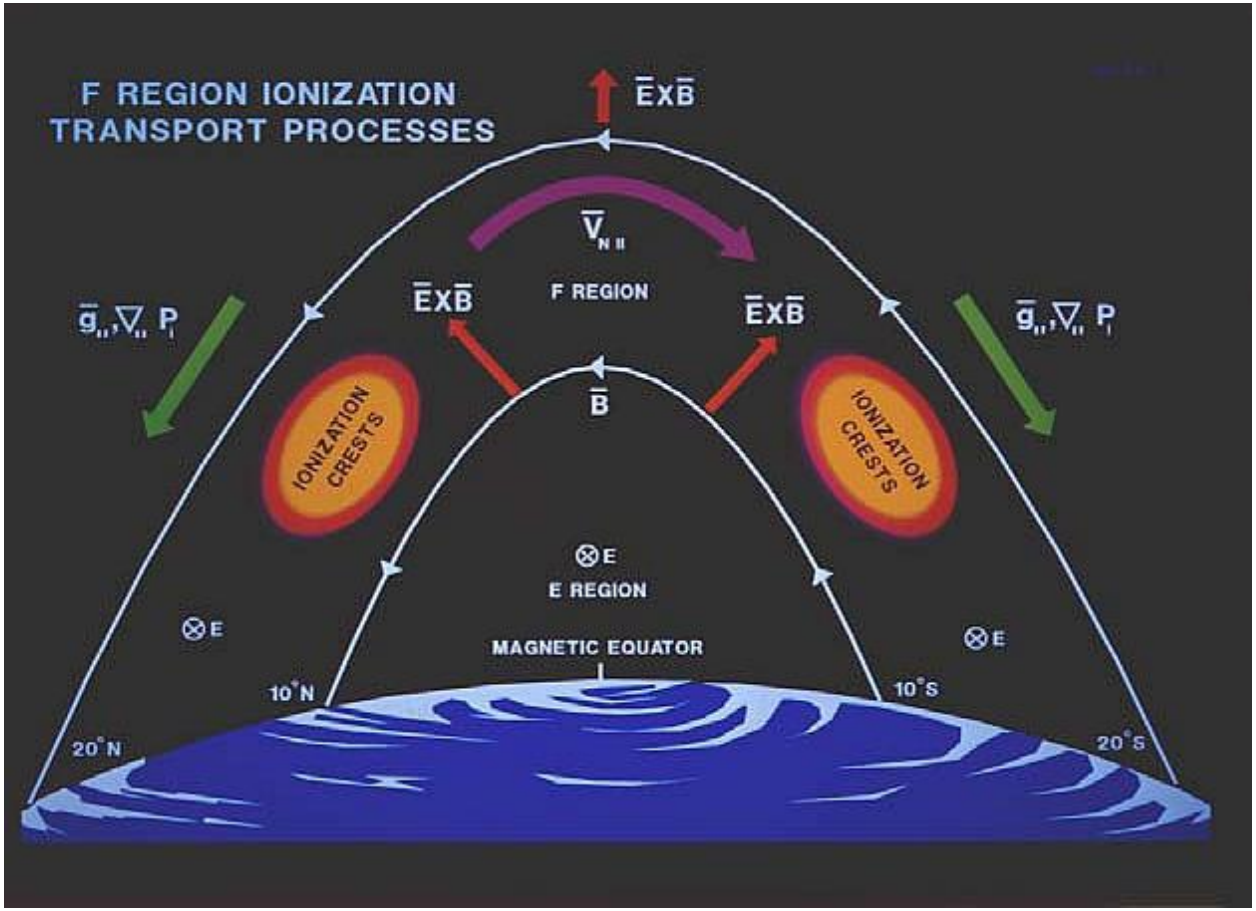




$$J_x = \left(\sigma_P + \frac{\sigma_H^2}{\sigma_P}\right) E_x = \sigma_c E_x$$

The equatorial electrojet region is highly turbulent with strong plasma waves

Appleton ionization anomaly



Meridional thermospheric neutral winds cause asymmetric anomaly peaks

Nighttime equatorial arcs (optical signatures of the Appleton anomaly)

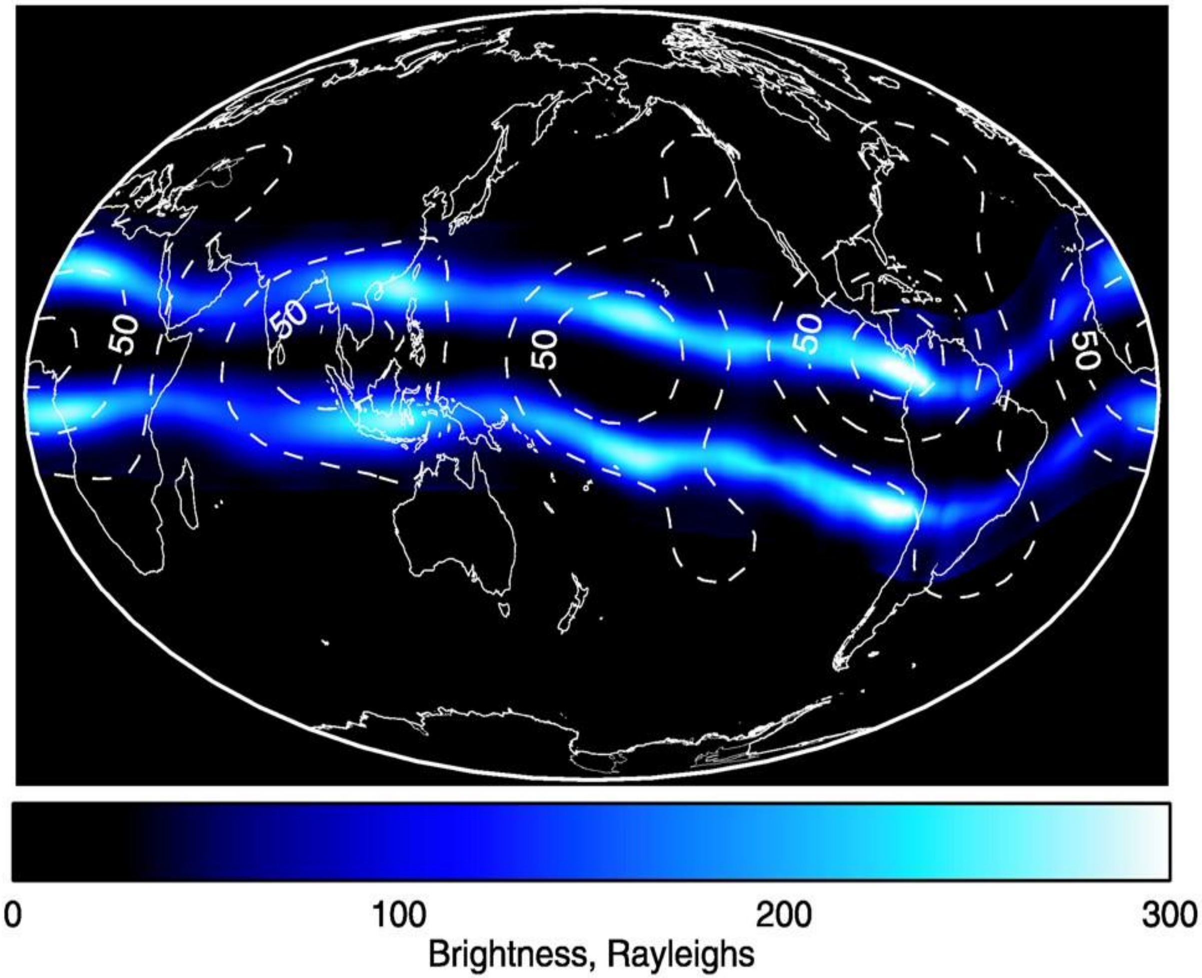
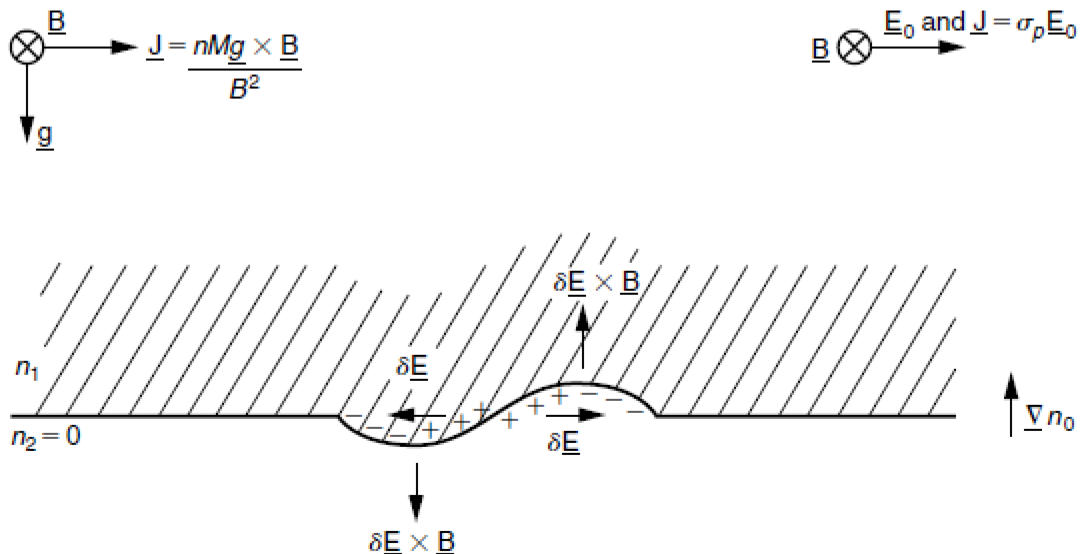
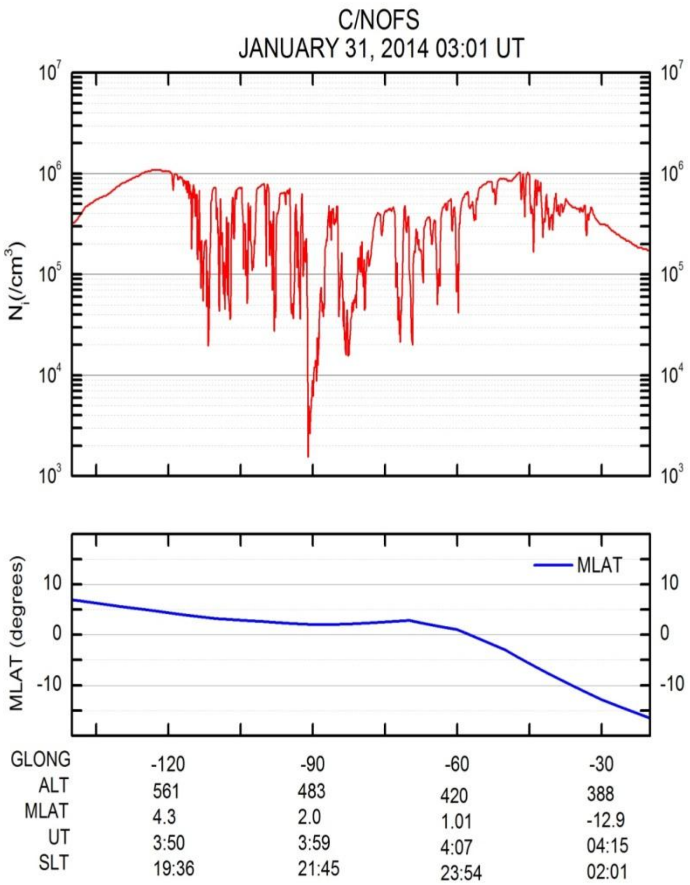


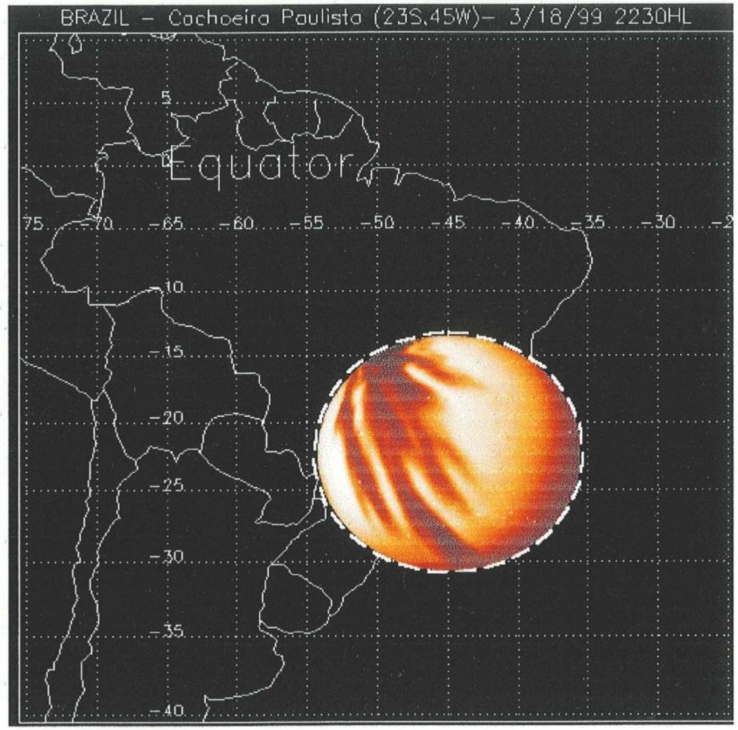
IMAGE composite of 135.6-nm O airglow (350-400 km) for March-April 2002 and temperature oscillations at 115 km (Immel et al., 2006).

Rayleigh-Taylor instability in the magnetic equator



Signatures of equatorial plasma depletions

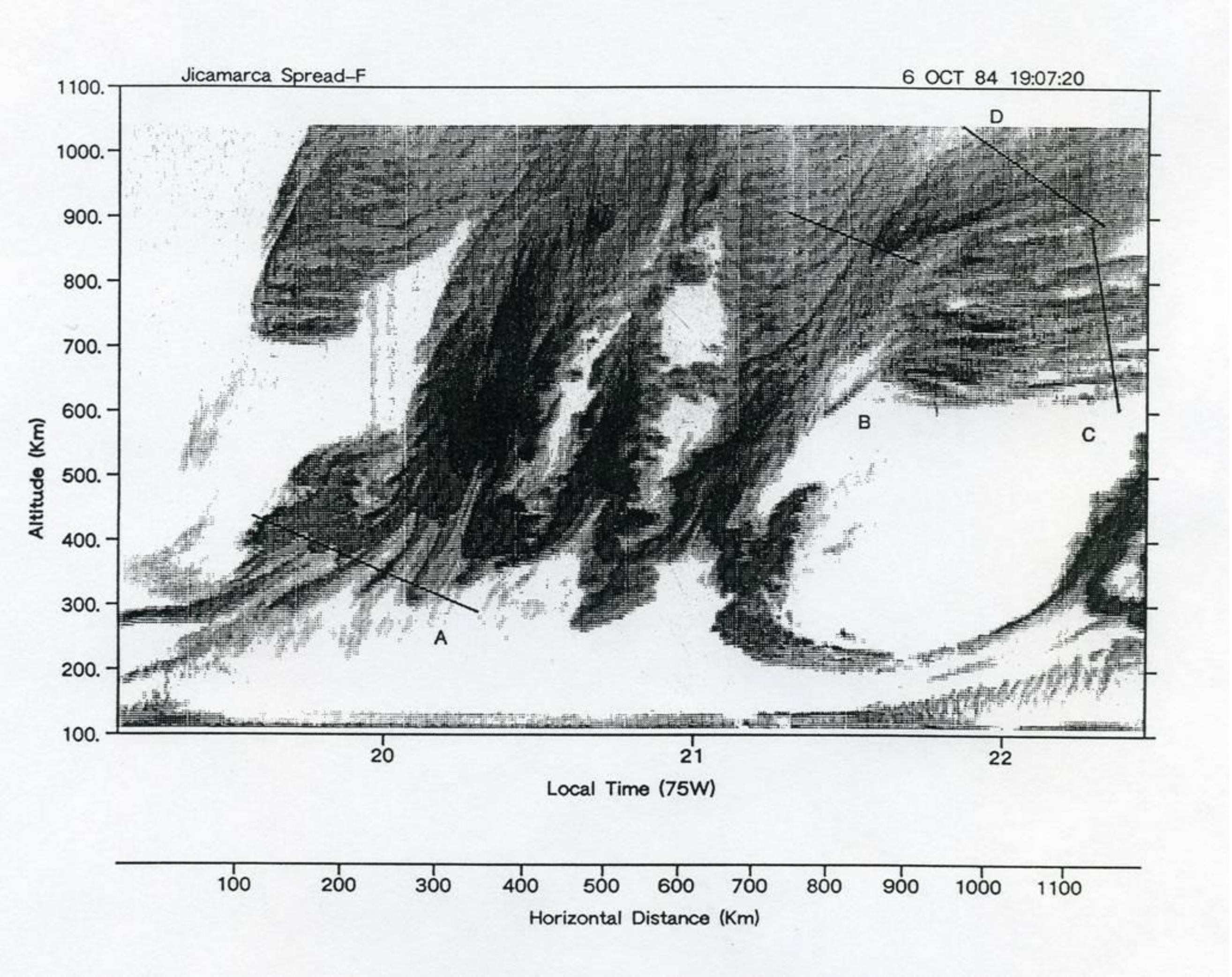




Courtesy of INPE (Brazil) researchers

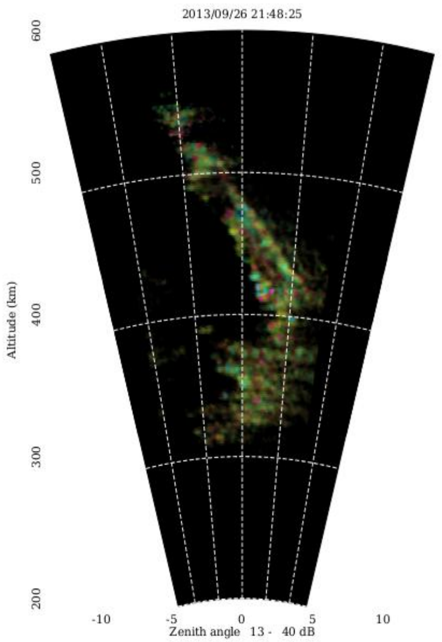
These plasma depletions have large upward and westward drift velocities. Smaller scale irregularities associated with these depletions can significantly affect navigation and communication systems, including GNSS.

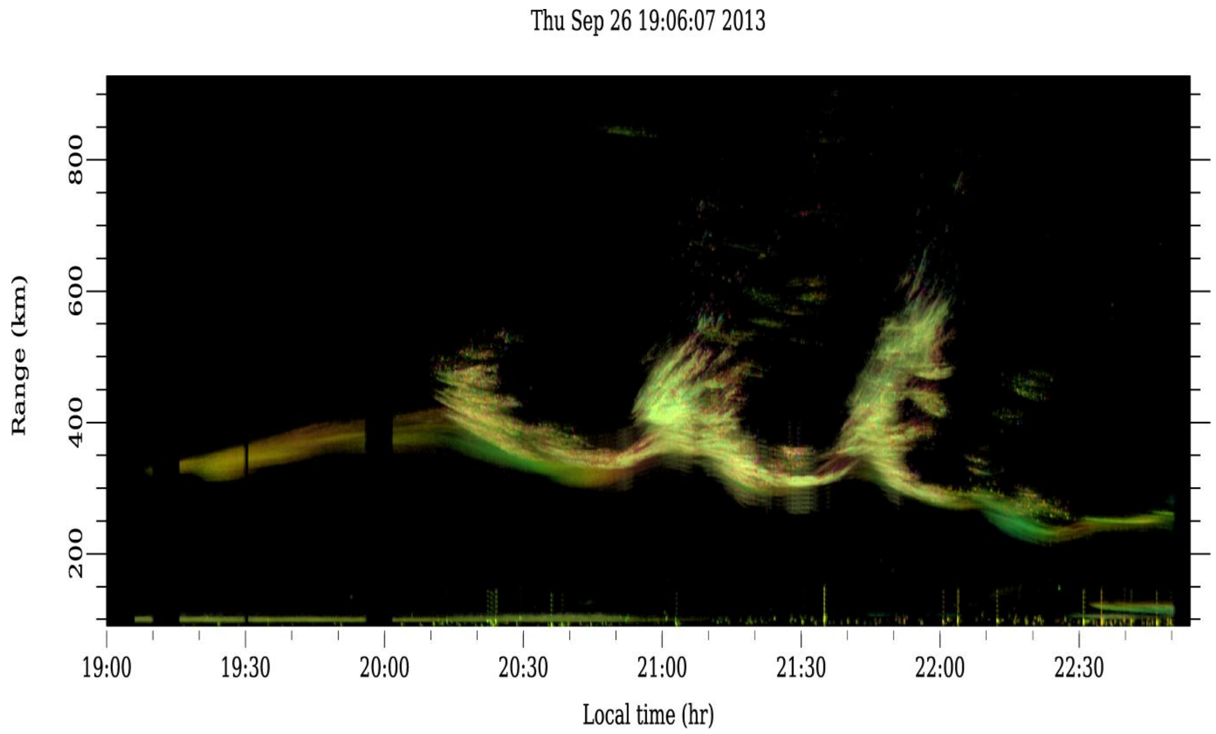
Backscatter power from 3-m plasma irregularities over Jicamarca, Peru



Kelley et al., 1981

Radar imaging of ionospheric irregularities





Hysell et al [2014]

Equatorial ionospheric electric fields and plasma drifts

The equatorial electrodynamic (**E**x**B)** plasma drift play a fundamental role on the distribution and composition of low latitude ionospheric plasma and on the generation of plasma waves and density structures.

Low latitude quiet-time ionospheric electric fields, plasma drifts and currents result mostly from the dynamo action of E and F region neutral winds driven by solar and lunar tides, but can also be significantly affected by atmospheric gravity and planetary waves with time scales from tens of minutes to about a month.

Low latitude ionospheric plasma drifts have been studied using ground based measurements mostly from the Jicamarca Radio Observatory in Peru and India, and also inferred from magnetometer and ionosonde data from Peru, Brazil, India, and Africa.

They have also been measured on board the AE-E, DE-2, DMSP, ROCSAT-1, C/NOFS, and SWARM satellites, and inferred from magnetic field measurements from the CHAMP and SWARM satellites.

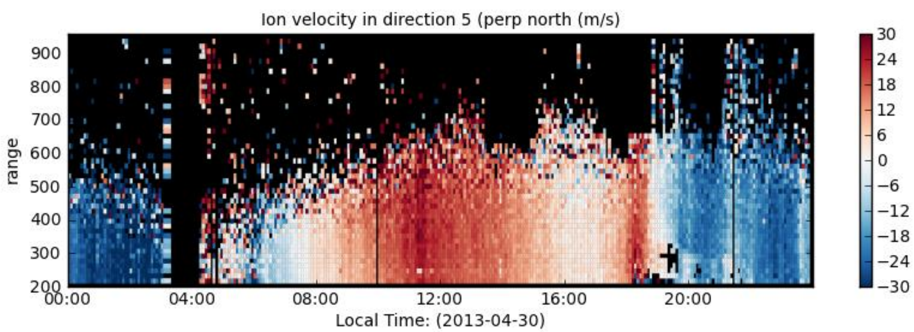
Plasma drift measurements

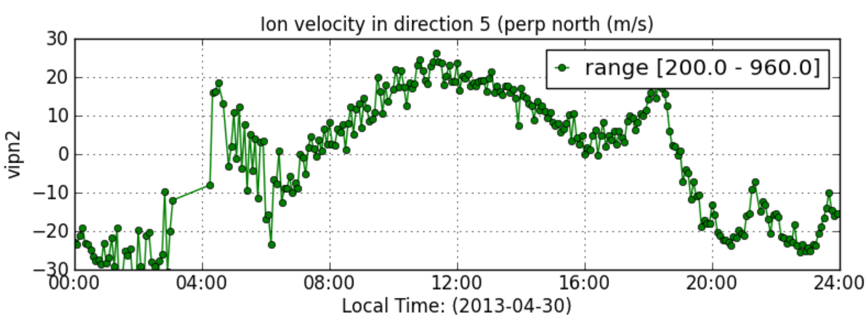
- Equatorial vertical and zonal plasma drifts have been measured extensively at the Jicamarca Radio Observatory near Lima, Peru. The vertical and zonal plasma drifts can be measured with accuracies of about 1-2 m/s and 10 -15 m/s, respectively.

Over Jicamarca, an electric field of 1mV/m corresponds to a plasma drift of about 40 m/s.

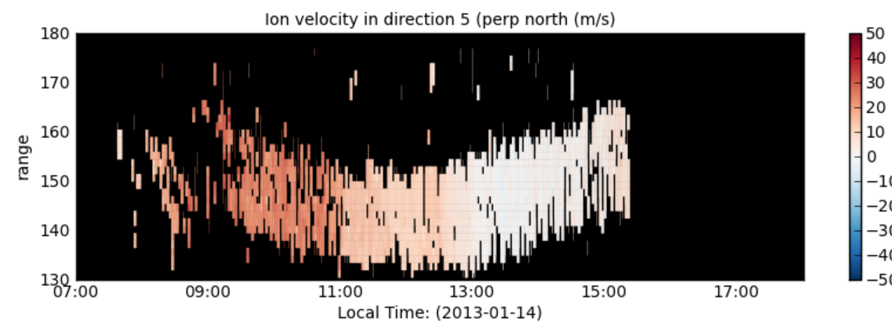
Jicamarca Radio Observatory

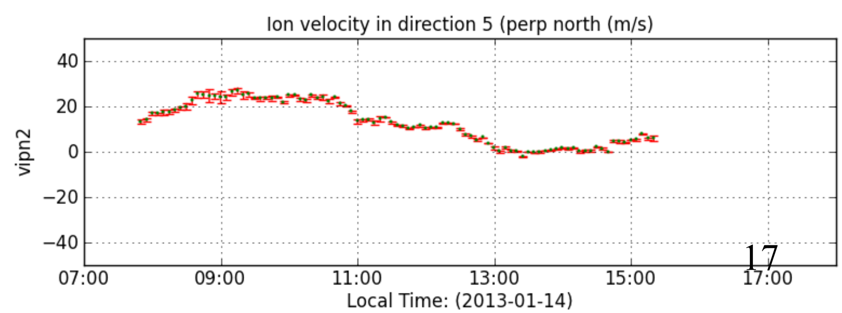
Incoherent Scatter Radar



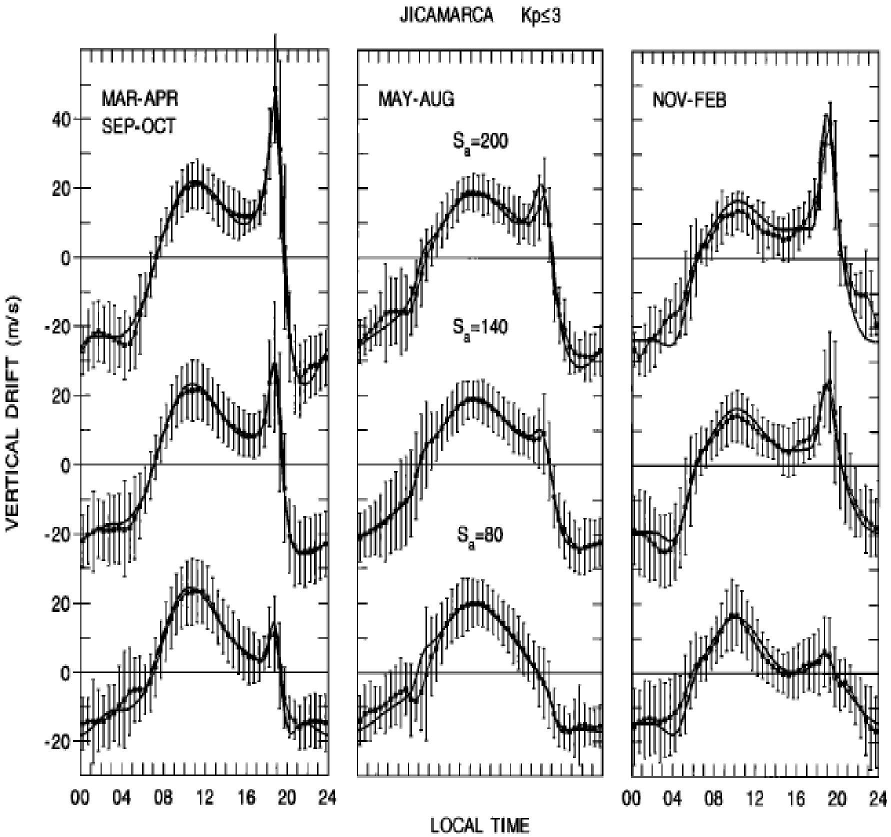


Jicamarca Unattended Long-term Ionosphere and Atmosphere (JULIA)

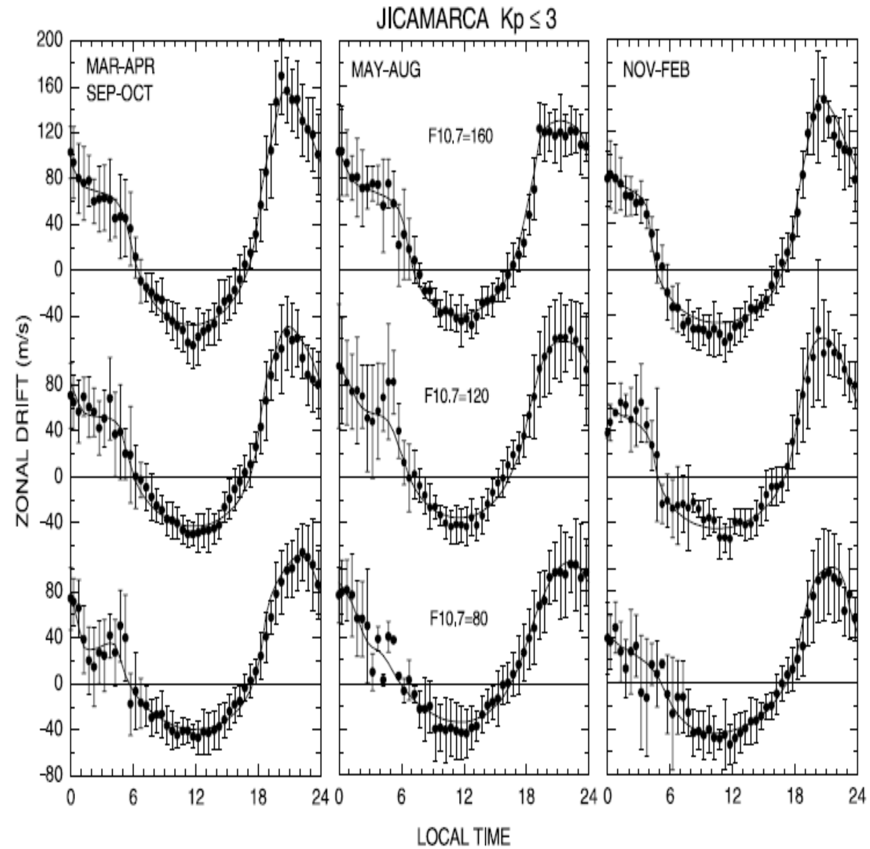




Equatorial quiet-time F region plasma drifts
(average between about 250 and 600 km)



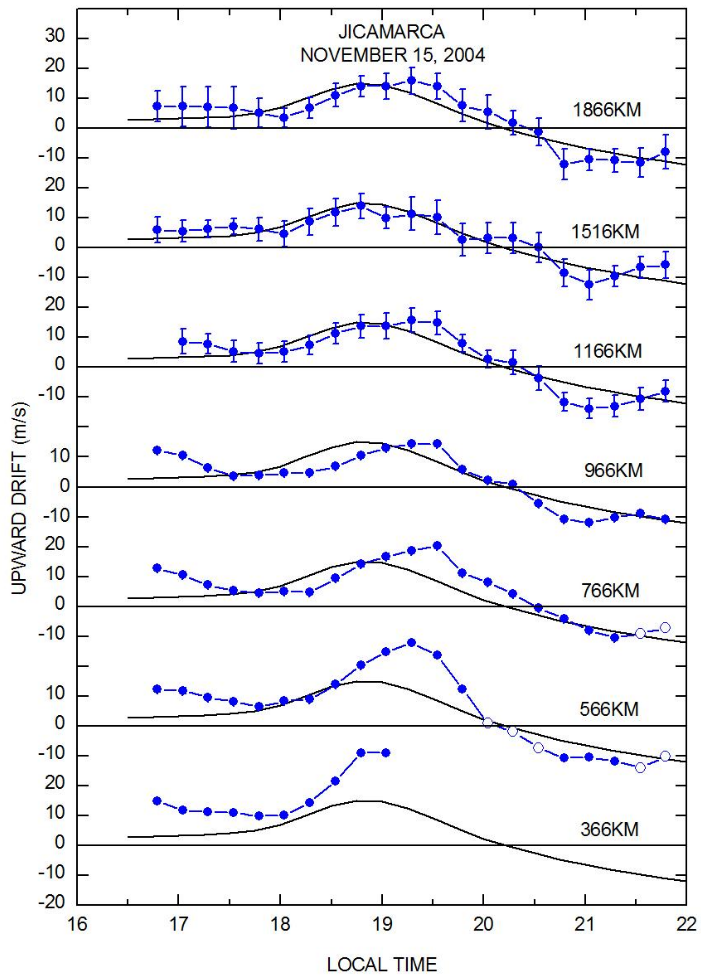
Scherliess and Fejer, 1999

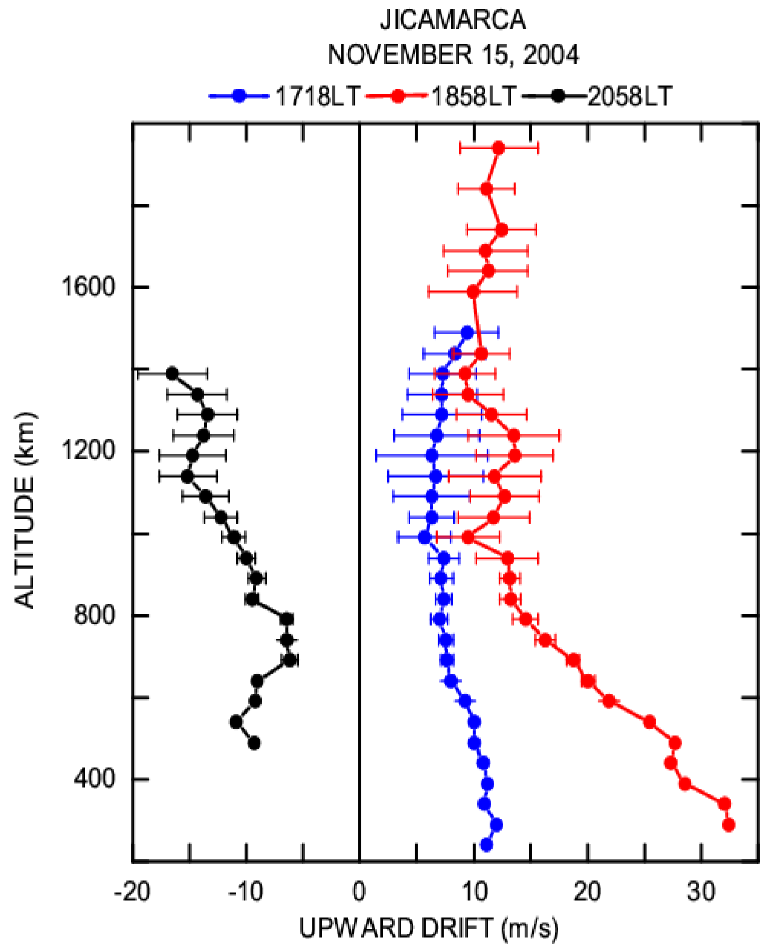


Fejer et al., 2005

The equatorial F region plasma drifts change very little with altitude, except near sunrise and sunset

Altitudinal variation of equatorial evening vertical drifts

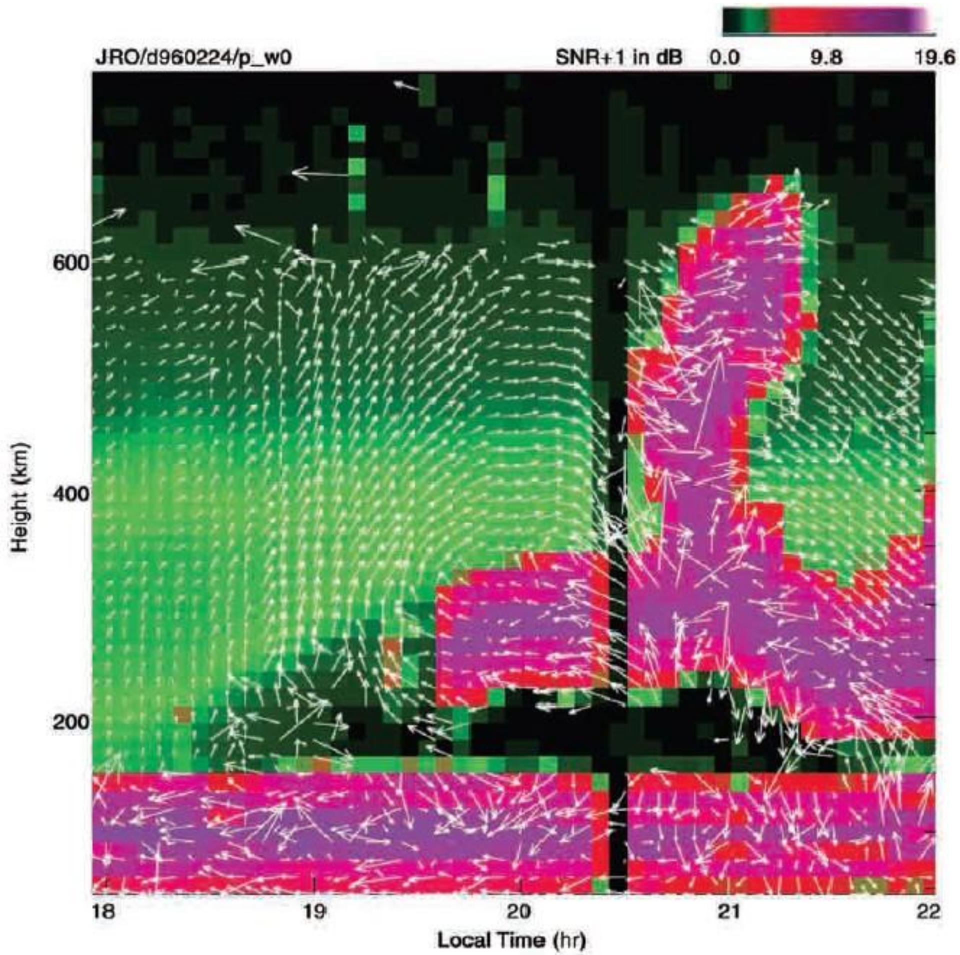




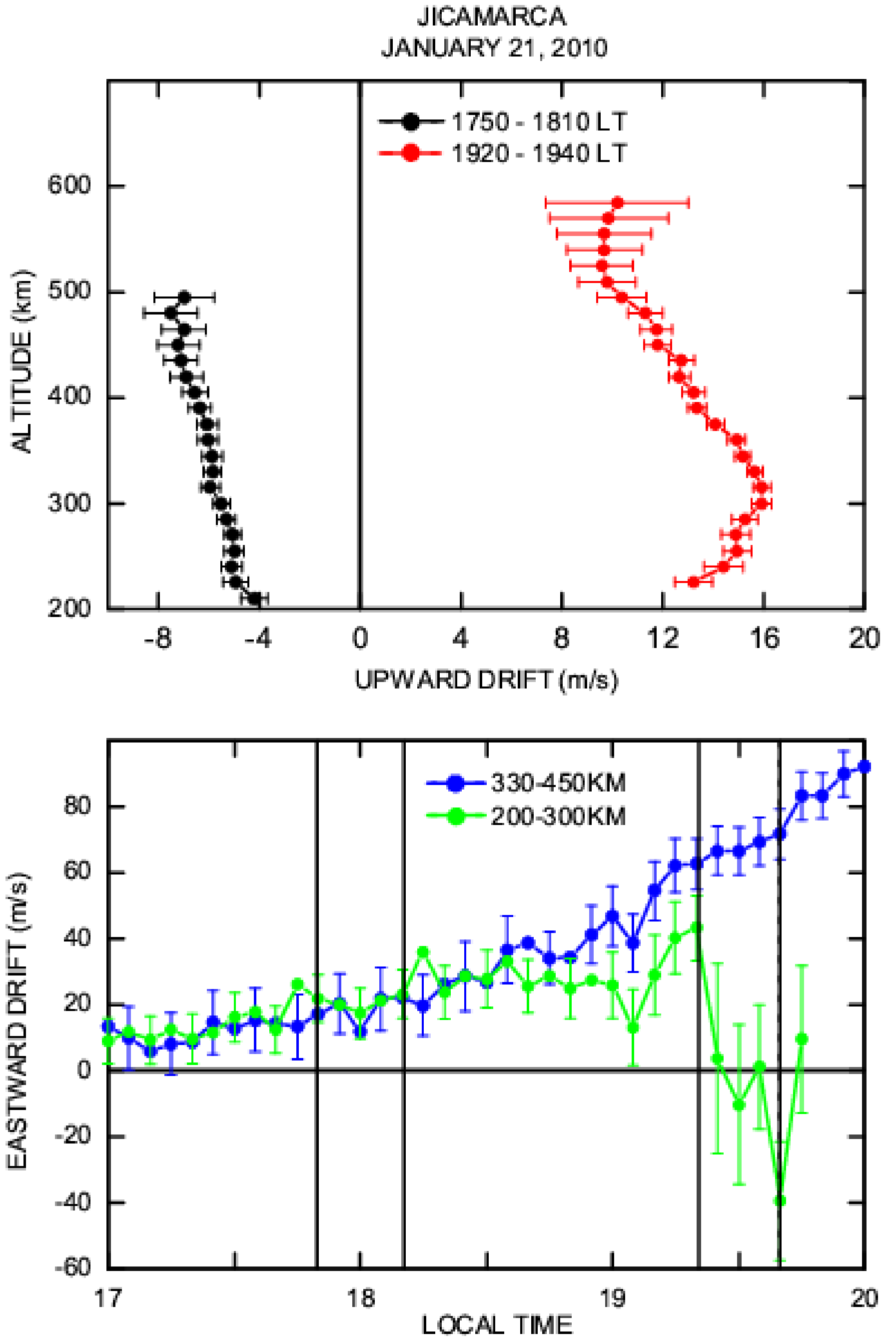
Fejer et al., 2014

The evening vertical plasma drifts play a fundamental on the occurrence of equatorial spread-F and depletions

Equatorial evening plasma drift vortex plays a fundamental role on the generation of equatorial plasma depletions

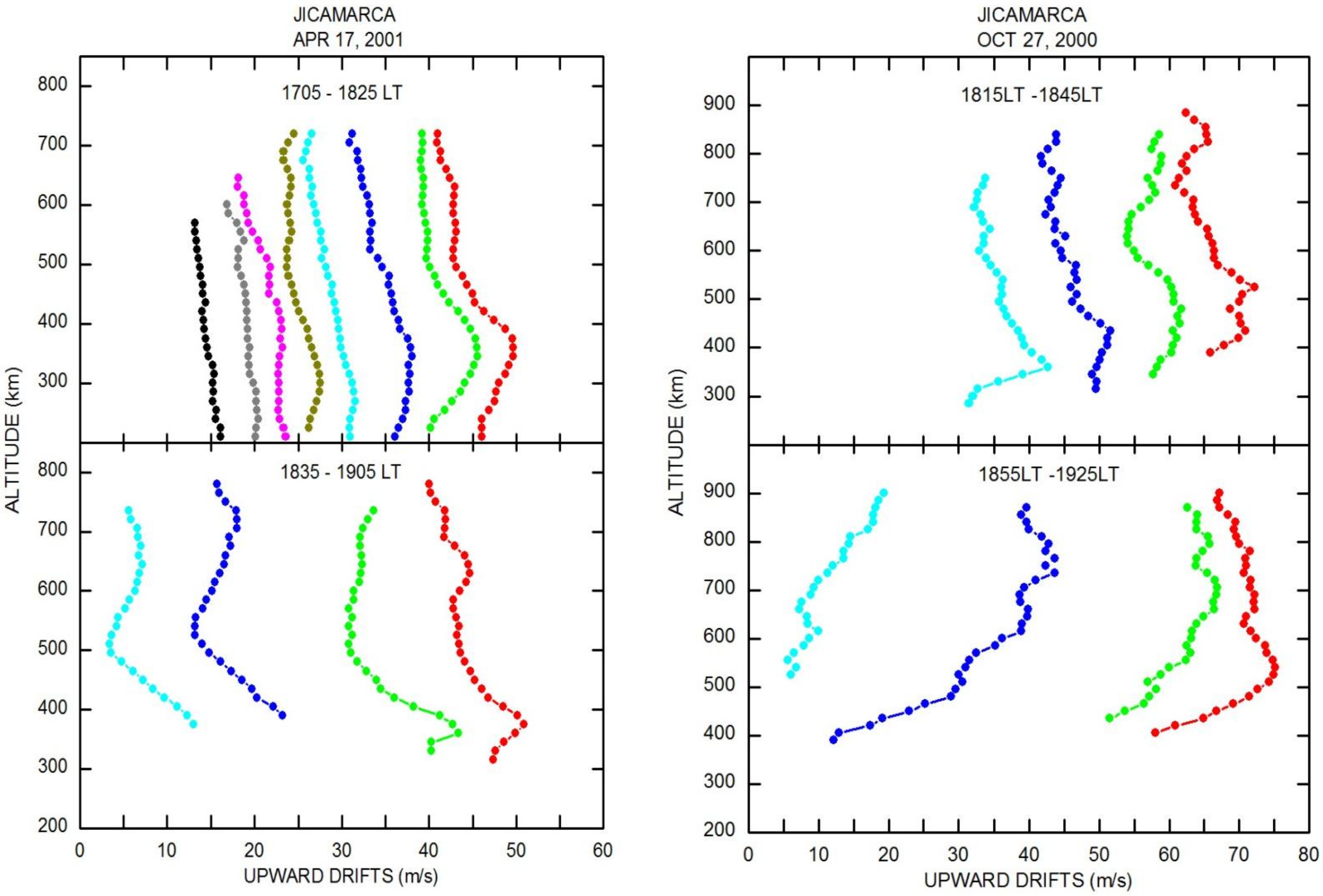


Kudeki et al., 1999



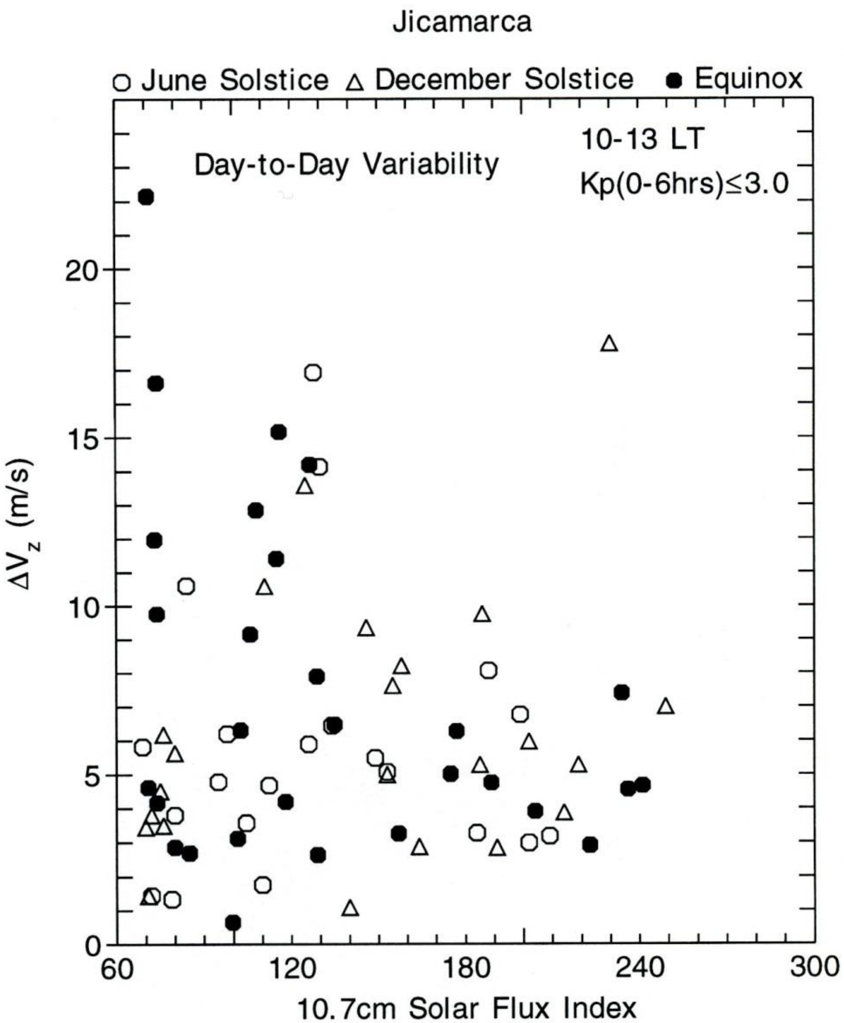
Fejer et al., 2014

The altitudinal variation of the evening prereversal velocity enhancements can be highly variable



Fejer at al., 2014

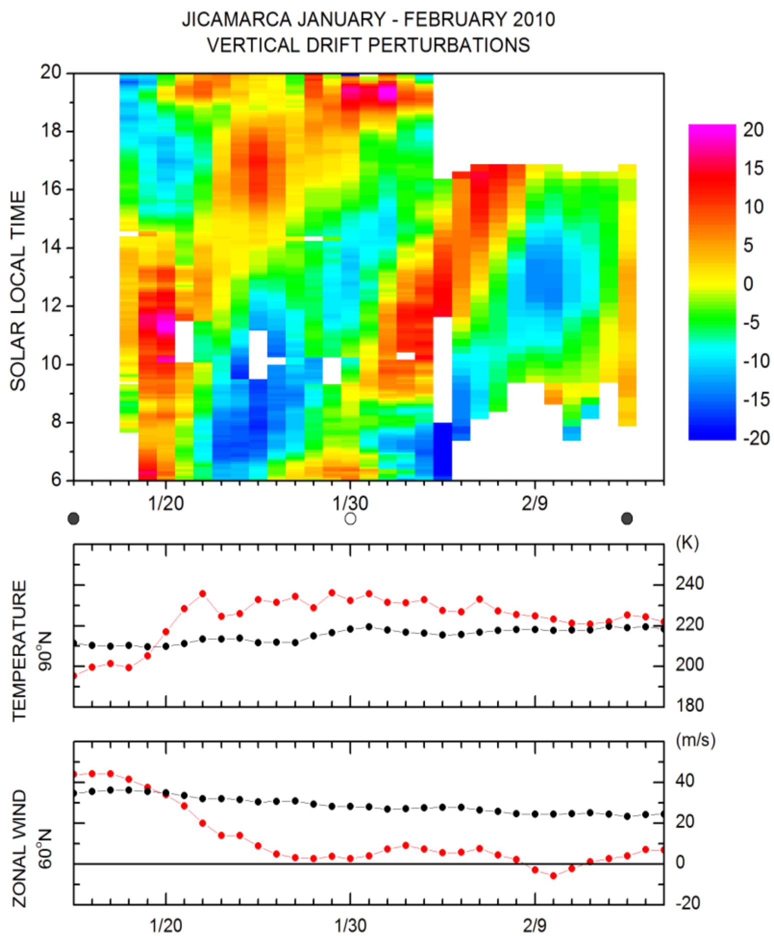
The vertical drift variability is largest near solar minima



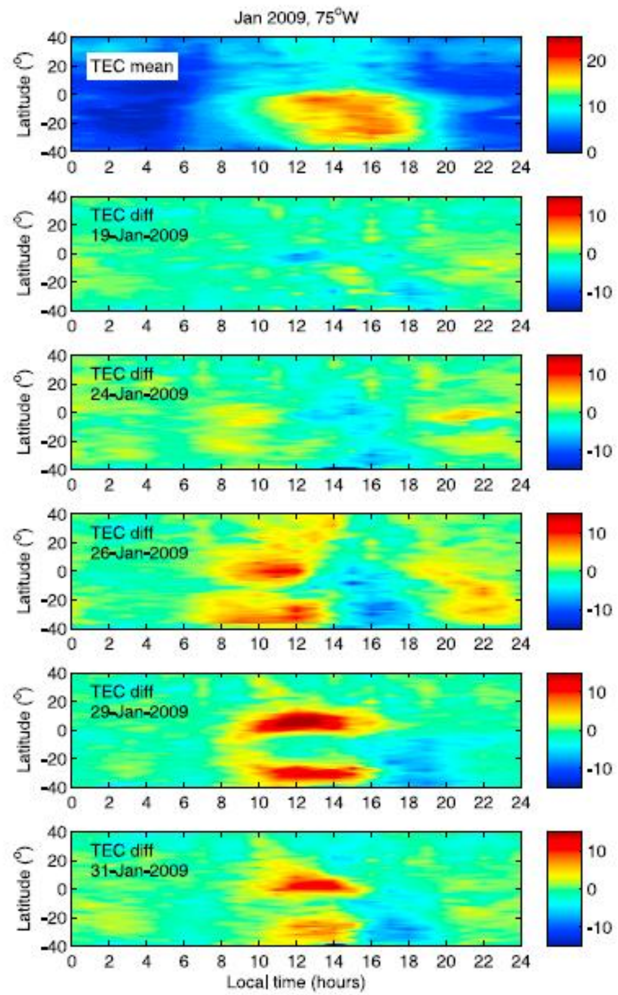
Fejer and Scherliess, 2001

The large day-to-day variability of the equatorial vertical drifts is probably due to short-term changes in tidal forcing of global winds, effects of planetary waves and irregular winds in the dynamo region, and changes in the dynamic conditions at the base of the thermosphere.

Response to Sudden Stratospheric Warming Events



Fejer and Tracy, 2012



Goncharenko et al., 2010

Sudden stratospheric warmings give rise to large perturbations in the equatorial aionosphere and Appleton anomaly lasting for several days. These drift perturbations are partly due to strongly enhanced lunar semidiurnal tidal effects.

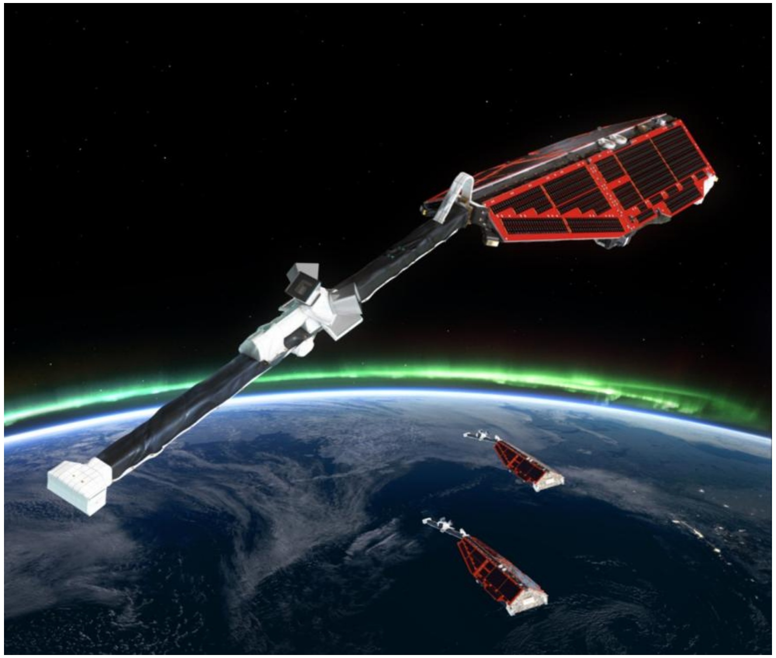
Extensive Global measurements of low latitude ionospheric currents, plasma densities and drifts have been made on board the AE-E, DE-2, DMSP, ROCSAT-1, C/NOFS, CHAMP, GOCE, and SWARM satellites

Satellite ionospheric electrodynamic measurements

C/NOFS (Communication Navigation Outage Forecasting System) launched April 2008

The current apogee is about 475 km and the perigee is about 345 km.

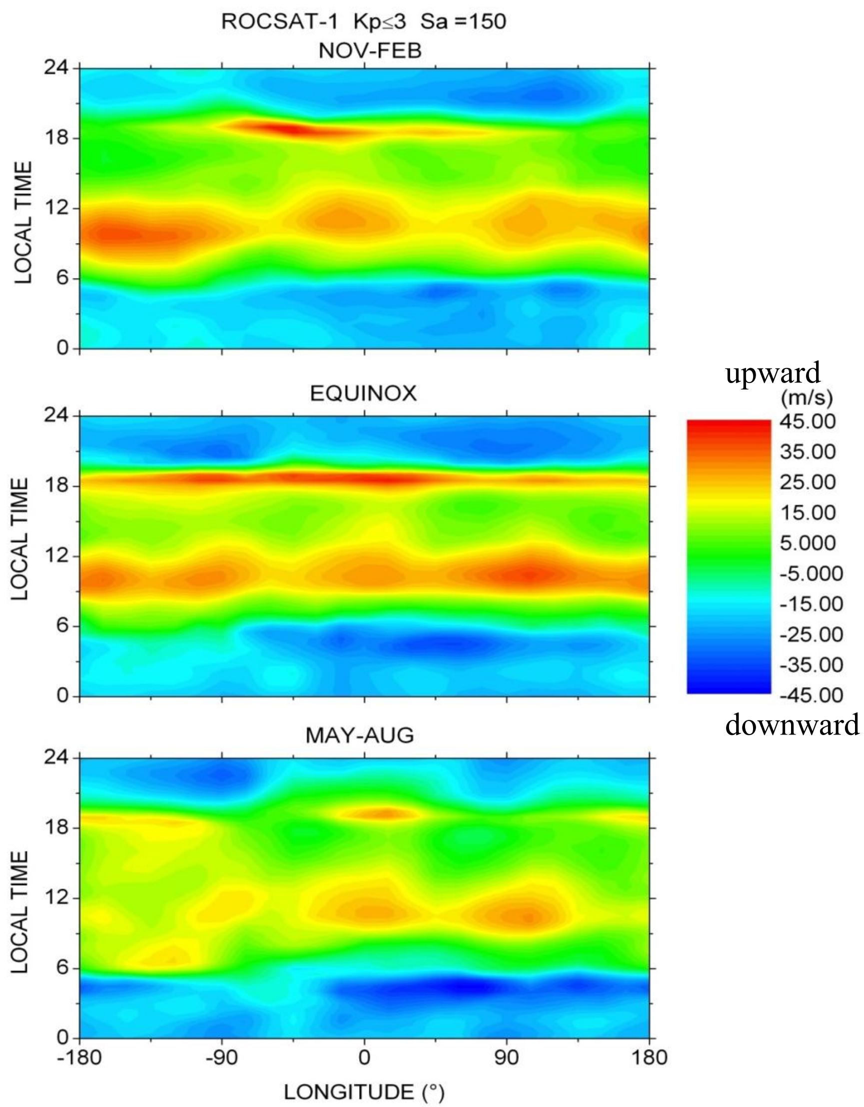
SWARM 3-satellite Constellation launched November 2013



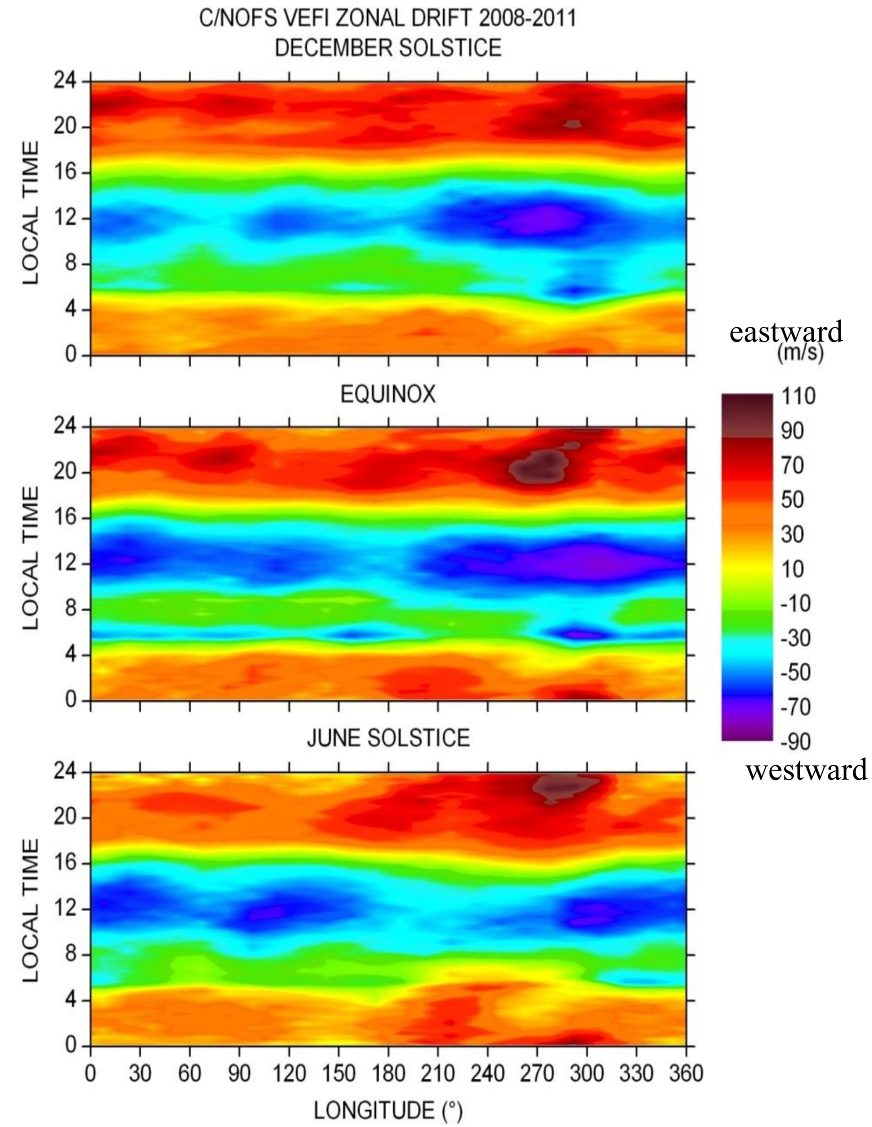
Satellite A and C: Initial altitude 480km
Side-by-side flying (Δlon: 1.4°, ΔLT: 6 min, 160km distance (at equator)), Inclination 87.4°.
Satellite B:
Initial altitude 520km, Inclination 86.8°

DMSP satellites (at 840 km) are also providing equatorial ionospheric electrodynamic data

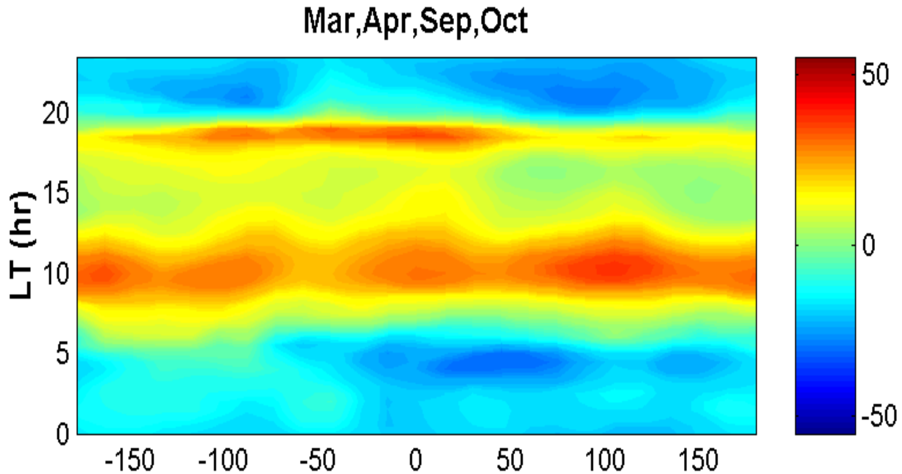
The equatorial vertical and zonal drifts have large seasonal and longitudinal dependence



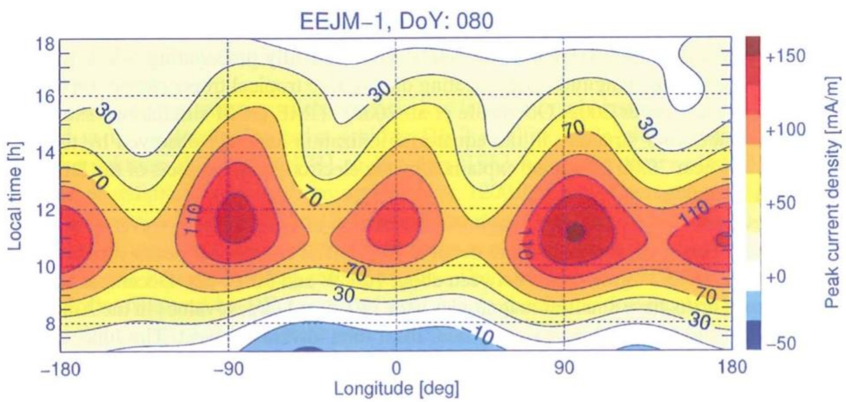
Fejer et al., 2008



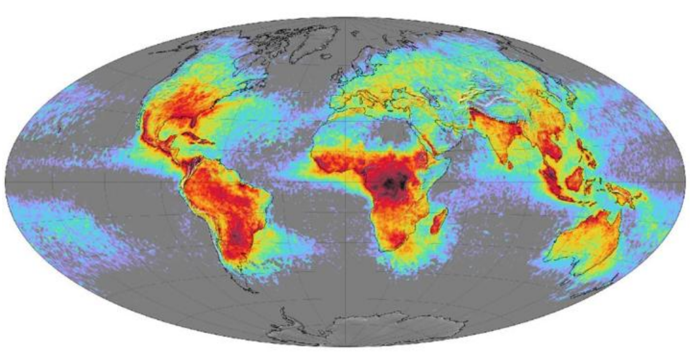
Fejer et al., 2013



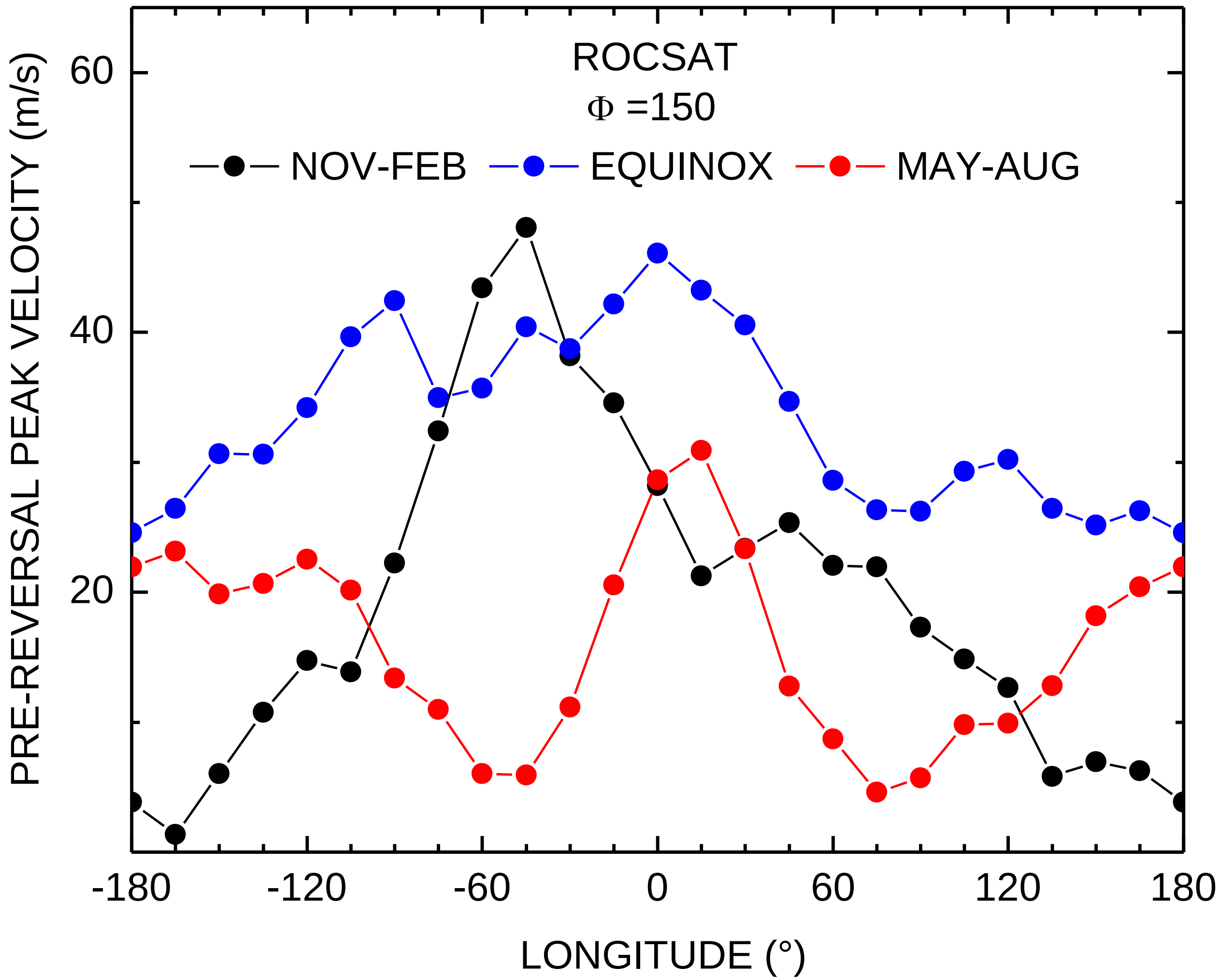
ROCSAT-1
Fejer et al., 2008



CHAMP
Luhr et al., 2008

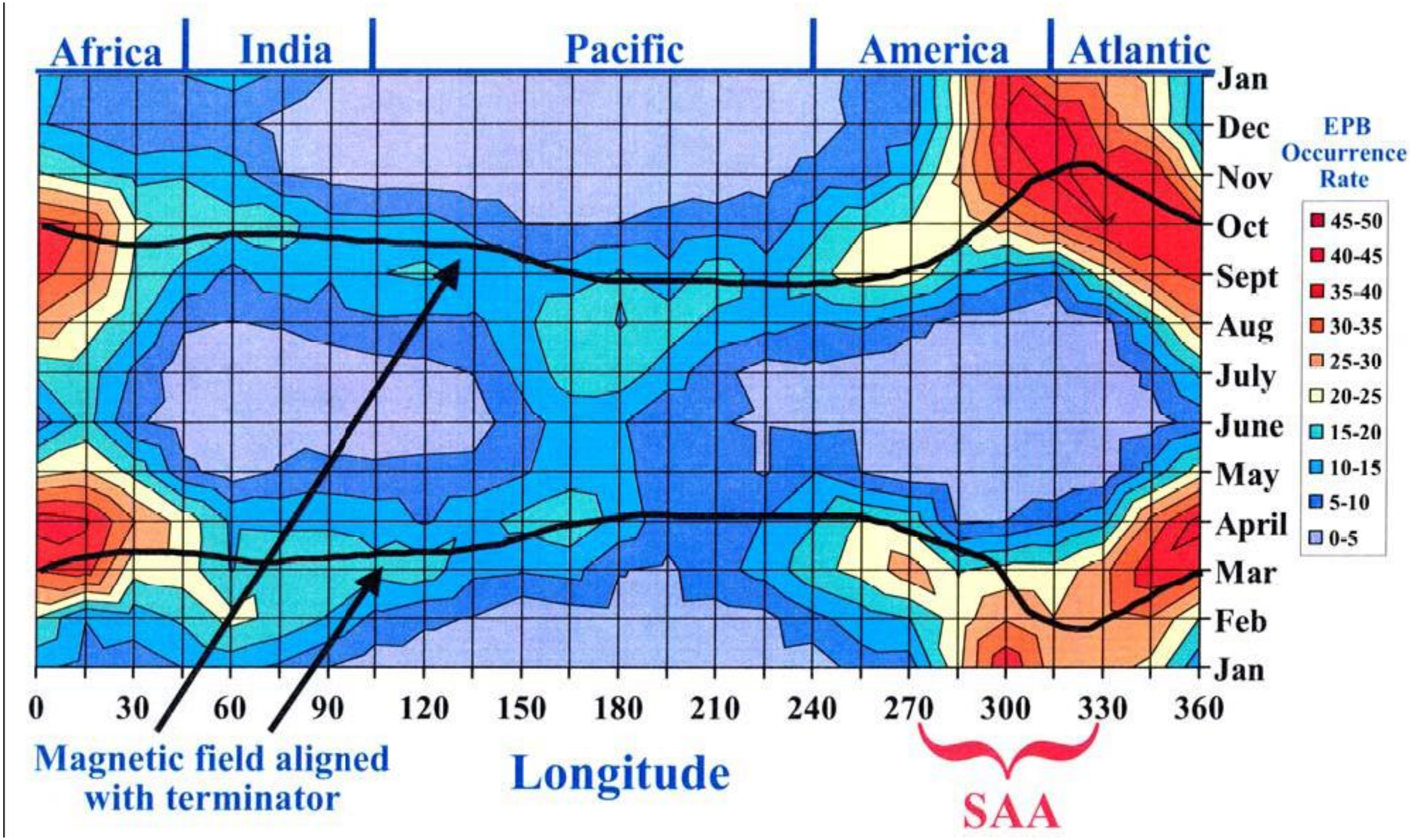


The prereversal enhancements of the evening vertical drifts vary strongly season and longitude. These drift play an important role on the occurrence of equatorial spread F



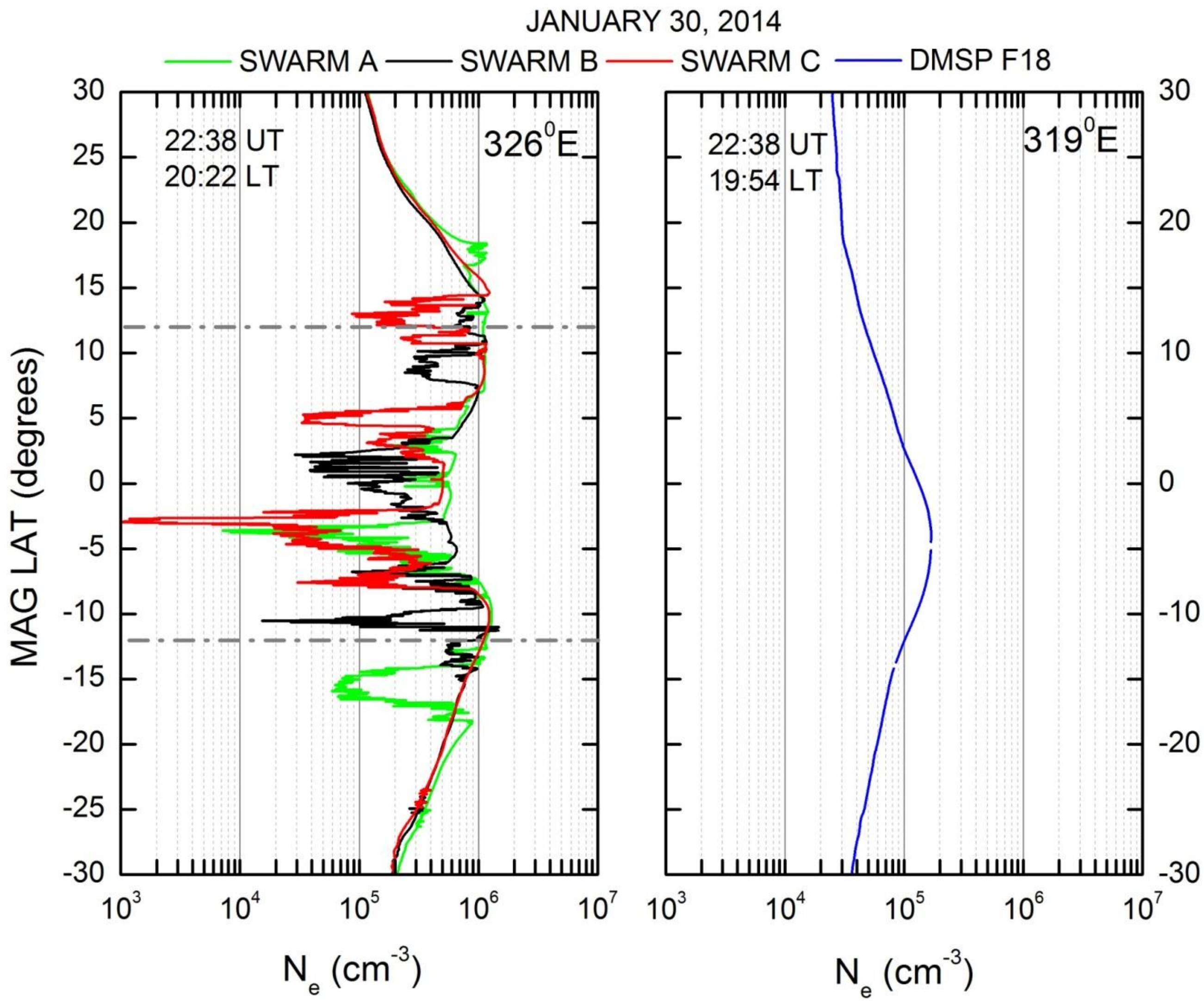
Fejer, et al. 2008

Equatorial plasma depletions from DMSP satellite measurements at about 840 km near solar maximum



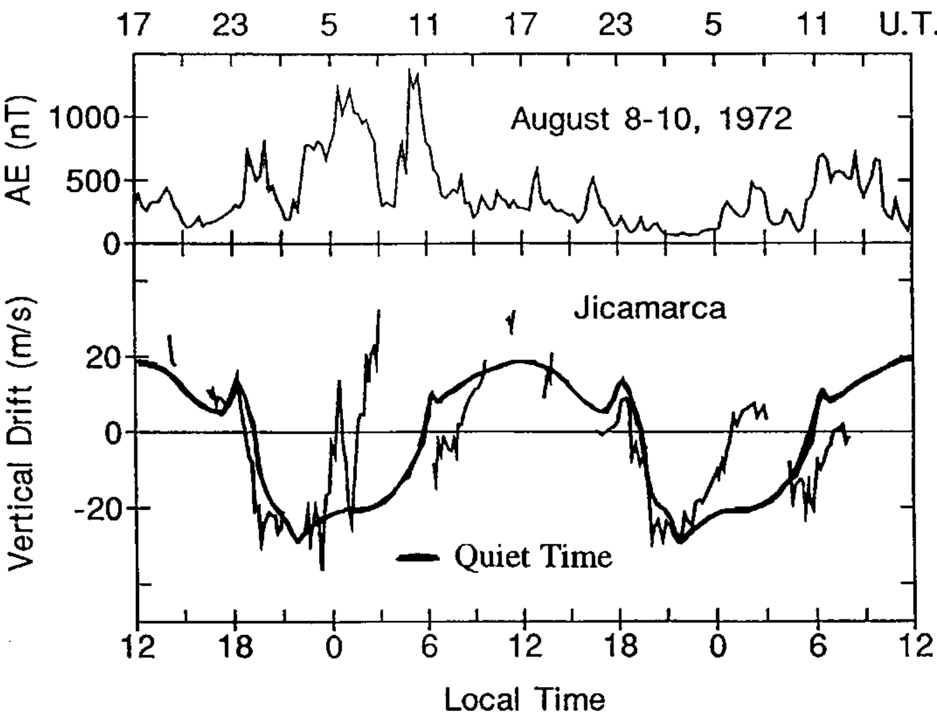
Burke et al., 2004

The climatology of equatorial plasma depletions and spread F depends on the observational probe



Response to enhanced geomagnetic activity

Equatorial prompt penetration and disturbance dynamo ExB plasma drift perturbations



Over Jicamarca 40 m/s = 1 mV/m

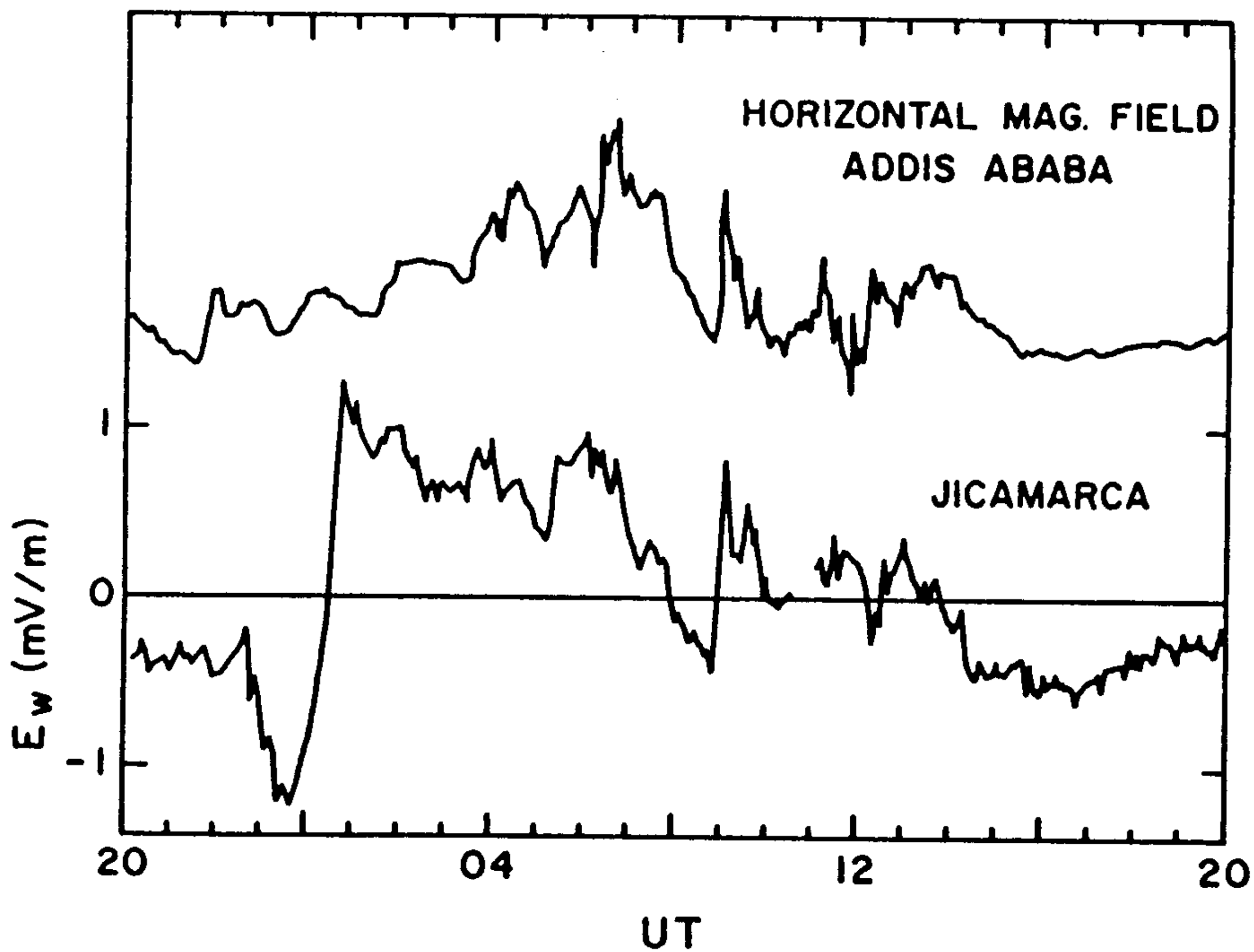
There are often relatively large vertical plasma drift (zonal electric field) perturbations in the low latitude ionosphere during and after geomagnetic active conditions.

These disturbance electric fields occur globally and cover a broad range of time scales (from minutes to a few days).

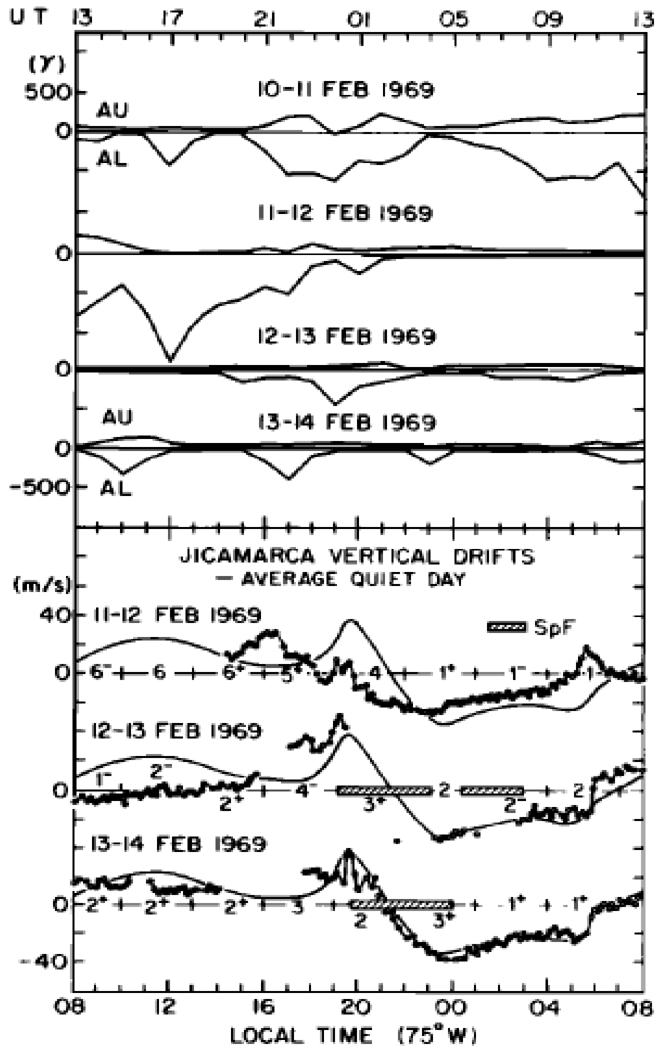
The short-lived (time constant of up to a few hours) are due to the prompt penetration of solar wind driven high latitude electric fields into the low latitude ionosphere.

Longer lasting perturbations are due to ionospheric disturbance dynamo electric fields driven by enhanced energy deposition into the high latitude ionosphere.

Prompt penetration electric fields occur simultaneously at all longitudes but with different amplitudes



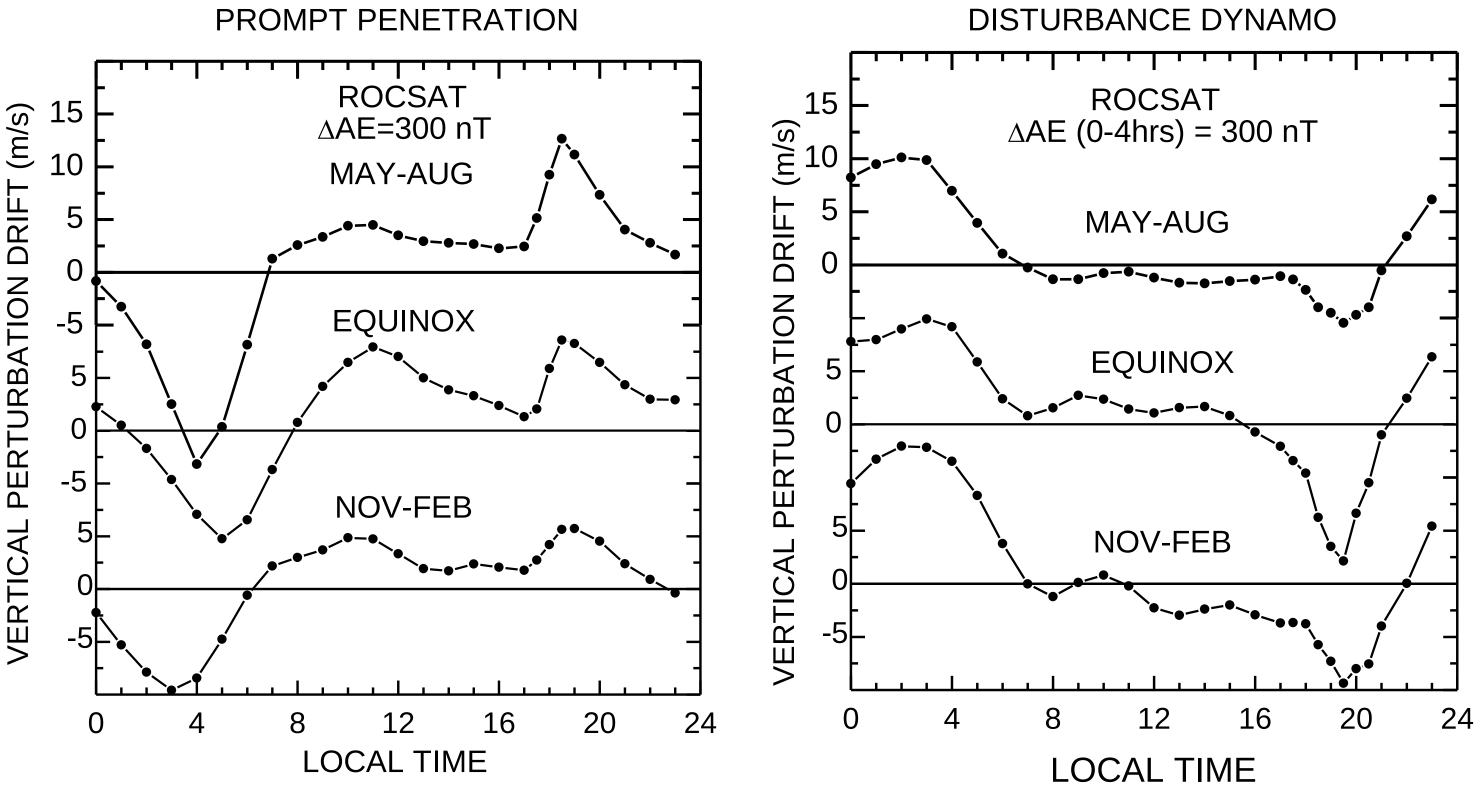
Westward electric field at Jicamarca and horizontal component of the magnetic field at Addis Abbaba on October 10-11, 1980 (after *Gonzales et al.,* 1983).



Fejer et al. [1983]

Equatorial disturbance dynamo vertical perturbation drifts last up to about 30 hours after large storm-time energy deposition (mostly due to Joule heating) into the high latitude ionosphere. They have opposite polarity to the quiet time drifts and larges amplitudes at night.

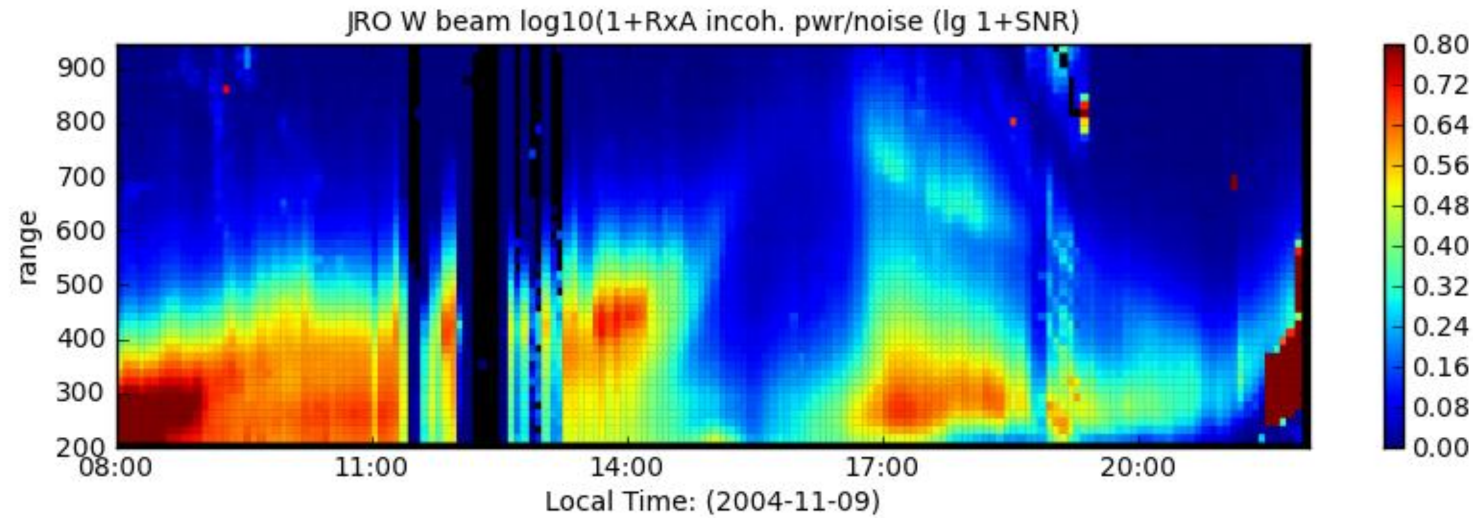
Equatorial prompt penetration are largest and the disturbance dynamo drifts are smallest during June solstice

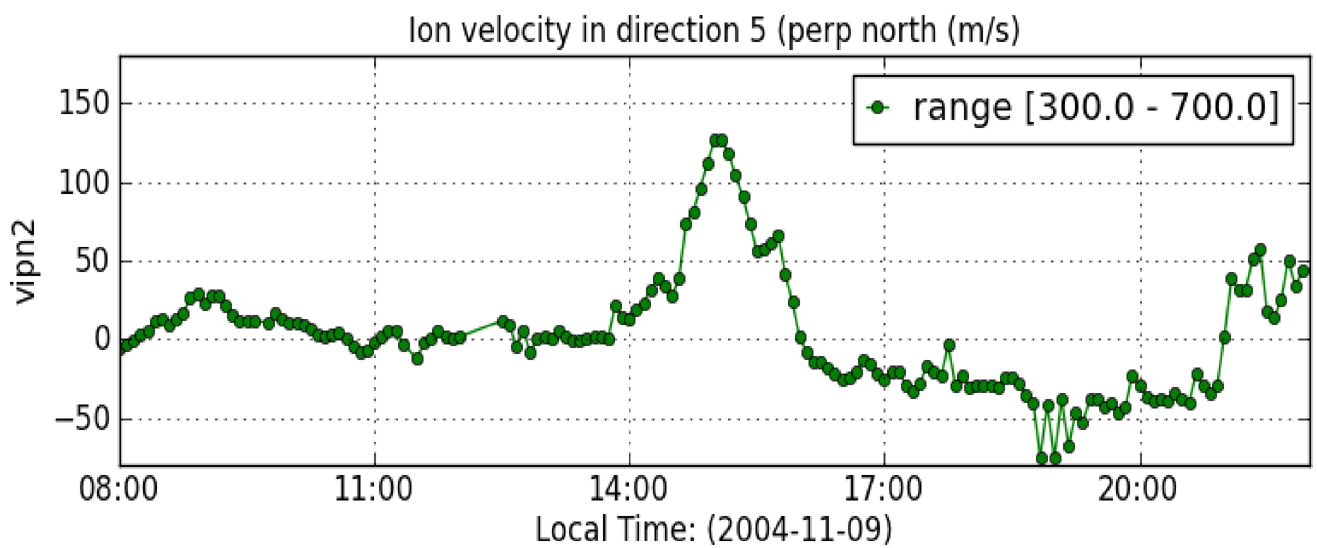


Fejer et al., 2008

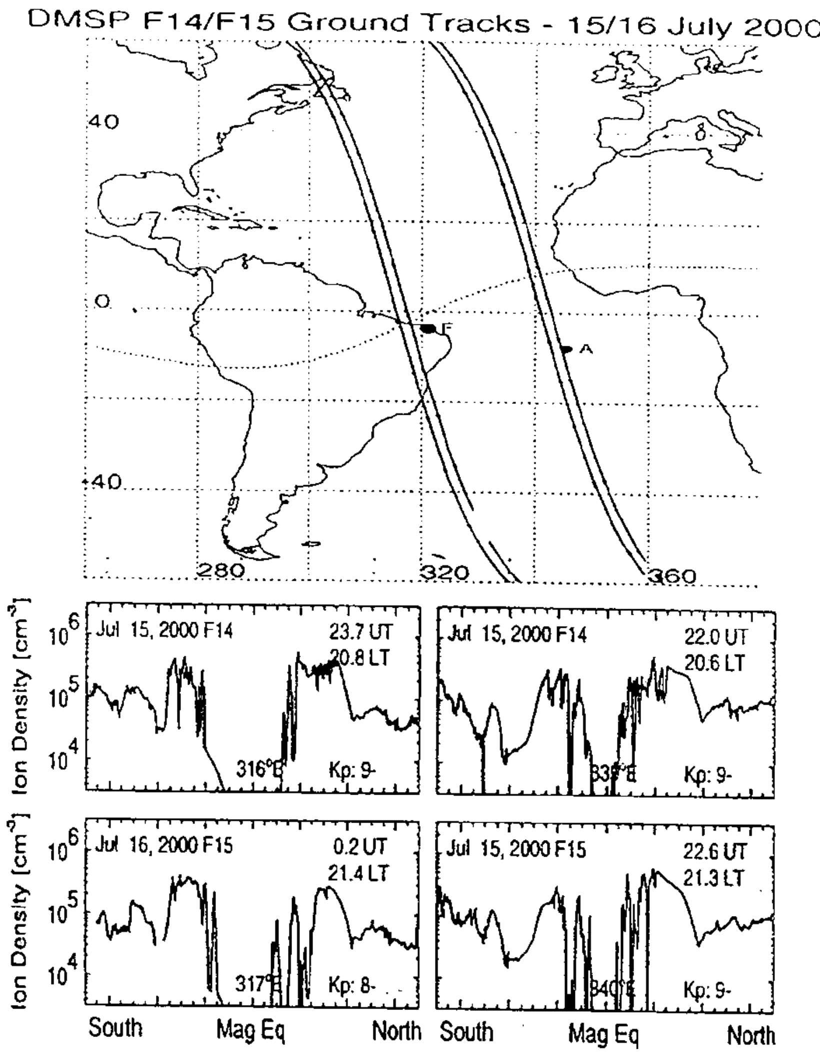
Storm-time plasma drift effect on the radar backscatter power (proportional to the electron density)

Jicamarca





Response of equatorial topside (840 km) ionosphere near dusk to storm-driven very large prompt penetration upward drifts



Prompt penetration upward drifts in the dusk sector also lead to the generation of strong equatorial spread and plasma depletions

Disturbance dynamo plasma Drift inhibit the occurrence of early night equatorial nighttime irregularities

Basu et al. 2000

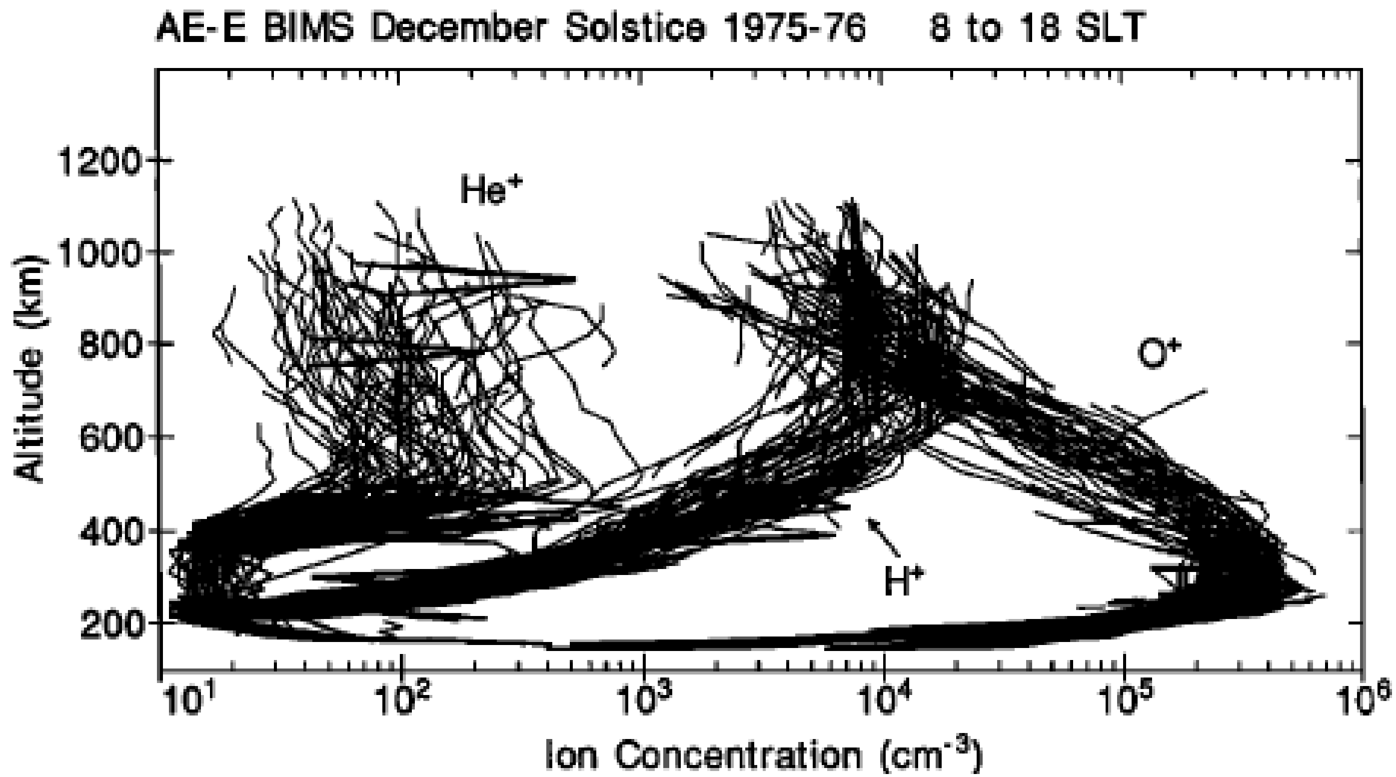
One of the challenges in the study of the equatorial ionosphere is the optimum use of a large number of very diverse ground-based measurements and data from current satellite missions (e.g., C/NOFS, DMSP, SWARM) and future missions (e.g., ICON)

Cluster of Instruments for Equatorial and Low-latitude Observations (CIELO)

- LISN (C. Valladares, BC)
- Magnetometer chain (O.Veliz, IGP)
- Ionosondes
  - Digisonde (B. Reinish, U. Mass. Lowell)
  - VIPIR (E. Kudeki, J. Makela, Illinois)
- Beacon RXs (P. Bernhardt, NRL, Tsunoda, SRI)
- GNSS RXs (J. Morton, MU)
- CIRI Huancayo (J. Urbina, PSU)
- AMISR14 (J. Arratia, UMET) (under repair)
- FPI chain (J. Meriwether, Clemson, A. Gerrard, NJIT)
- Airglow camera (C. Martinis, BU)

Small clustered probes are fundamentally useful, but the importance of complex satellite missions should not be overlooked

The AE-E satellite was in a highly elliptical (150 km by 4000 km) between December 1975 and December 1976. These measurements were made up to about 1200 km.



Gonzalez et al., 1992

Summary

The climatologies of the equatorial plasma drifts, ionospheric nighttime plasma irregularities, and Appleton are generally now reasonably well understood, but little progress has been made in the understanding of their quiet-time short-term (less than about a month) variability. This is largely due to the complex effects of lower and thermospheric parameters on both the ambient ionosphere and plasma instability conditions.

The transport processes and the corresponding plasma distribution in the lower ionosphere have not been studied in detail. There is also very little information on the electrodynamics and plasma irregularities above about 1000 km.

The evening prereversal enhancement of the equatorial quiet-time vertical drifts have large spatial and temporal variability which indicate highly variable thermospheric winds, conductivity distributions, which are not fully understood.

Several possibly important seed mechanisms for the generation of equatorial spread F and larger scale plasma irregularities have been suggested by observations and numerical studies, but their relative importance has not been determined.

The basic signatures of equatorial prompt penetration electric fields and plasma drifts are reasonably well understood and reproduced by convection models, but their longitudinal dependence still needs be better determined. In addition, the effects of various solar wind parameters (e.g., IMF By) and magnetospheric processes (e.g., substorms, dipolarization, etc.) are not well understood.

Global general circulation and convection models have explained several important empirical results. However, major progress in the study of the very complex remaining questions will require much closer interactions between the experimental and modeling communities.