Data-driven numerical simulations and forecasts of equatorial spread *F* in the Peruvian sector

D. L. Hysell[1] *and M. A. Milla*[2]

[1]Cornell University, 2122 Snee Hall, Ithaca, NY, USA, (david.hysell@cornell.edu)

[2]Jicamarca Radio Observatory, Lima, Perú, (marco.milla@jro.igp.gob.pe)

Abstract

Ionospheric state parameters including plasma number density and vector drift profiles were measured at the Jicamarca Radio Observatory during campaigns throughout 2013. Neutral winds were measured by the red-line Fabry Perot interferometer at Jicamarca. Coherent radar backscatter from plasma irregularities associated with equatorial spread F (ESF) was also recorded. Radar imagery of the morphology of the large-scale ESF irregularities is also available from simultaneous measurements. A 3D numerical simulation of ionospheric irregularities, initialized and forced using parametrizations derived from a combination of measurements and empirical models, has been used to reproduce the ESF activity that occurred on a number of different, representative campaign nights. The simulations were able to recover many of the most salient features of the irregularities that formed in each case. The campaign data, numerical simulations, and protocols used to associate them are presented.

1. Introduction

Equatorial spread *F* (ESF) is a manifestation of space weather characterized by broadband plasma density irregularities that occur in the equatorial *F* region ionosphere. The source of free energy is unstable stratification after sunset. The resulting irregularities affect radio wave propagation and pose a hazard for critical communication, navigation, and imaging systems (see recent reviews by [10, 5]). Being detectable by a wide variety of diagnostics, they also provide investigators with a laboratory for studying plasma dynamics in a laboratory free of walls.

ESF was discovered by [2] using ionospheric sounding over 75 years ago and remains the focus of intense experimental and theoretical research. However, progress in understanding the most important processes in ESF do date prompted [10] to inquire if the ESF problem had been, in the main, solved. For many applications, the problem is solved when ESF can be forecast.

Here, we attempt to simulate ESF regionally using data from the Jicamarca Radio Observatory operating in campaign mode. The simulation code itself is an updated version of the one described by [1]. The simulation output is compared with coherent scatter radar observations of ESF irregularities also observed at Jicamarca. A successful simulation is one in which the observed level of irregularity evolution is recovered.

2. Methods

Ionospheric observations were made at the Jicamarca Radio Observatory during multiple campaigns in 2013. Three different experiments were run simultaneously using time-division multiplexing and by subdividing the main facility antenna. Plasma number density, temperature, and composition were measured with the Faraday rotation double-pulse incoherent scatter experiment, making use of the north and south quarters of the antenna array for transmission and reception. Vertical and east-west plasma drifts were measured using the east and west quarters of the main array for transmission and reception, with the beams of the two linear polarizations directed eastward and westward along the magnetic locus of perpendicularity, respectively. Finally, coherent backscatter from field-aligned irregularities was observed in Jicamarca imaging mode. This involves the transmission of short pulses toward the locus of perpendicularity and the reception of coherent scatter using 8 distinct submodules (64ths) of the antenna array.

The Jicamarca data, including red-line Fabry Perot wind measurements, were used to initialize and force a 3D numerical simulation of equatorial ionospheric irregularities and instabilities. The ESF simulation solves for the three-dimensional abundances of four ion species (O^+, NO^+, O_2^+, and H^+) in time starting from initial conditions. The first computation required is the solution of the potential equation which arises from the quasineutrality condition. The second computation required is the time advance of the ion continuity equations. We employ a flux assignment scheme based on the total variation diminishing (TVD) condition of [3] (see [8]). That reference describes monotone upwind schemes for conservation laws (MUSCLs) applicable to the ion continuity problem. Our method combines upwind differencing schemes, flux limiting (e.g. [9]), and second order TVD schemes, extended to 3D using a dimensional splitting technique [7].

978-1-4673-5225-3/14/$31.00

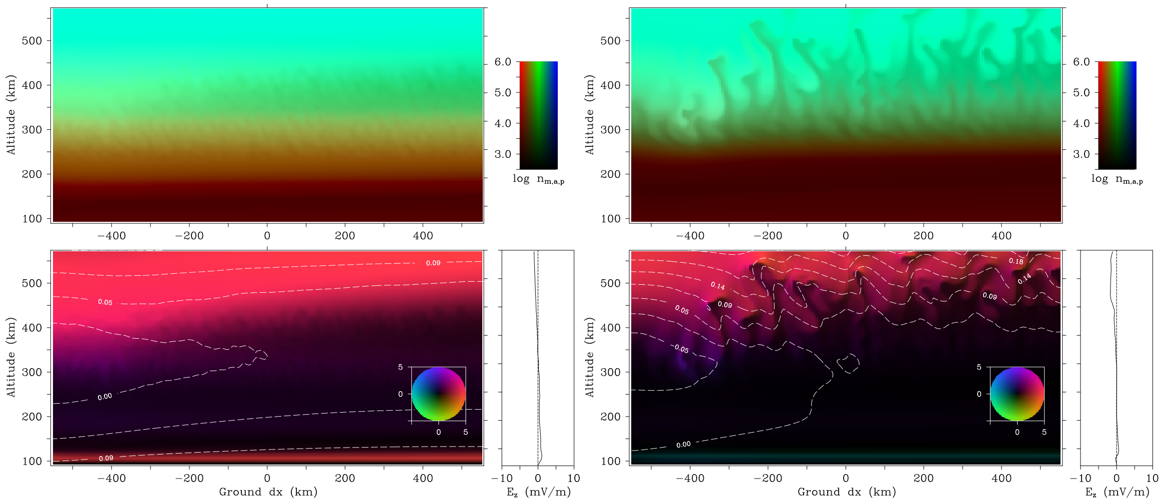

Figure 1: Numerical simulations of active ESF conditions over Jicamarca Panels on the left and right reflect conditions 25 and 75 min. after the simulation start time of 2345 UT. Top panels indicate ion abundances, with red, green, and blue hues representing molecular, atomic, and proton contentrations, respectively. Bottom panels show current density in the plane perpendicular to B according to the legend shown in μA/m^2. White contours are equipotential curves. The vertical electric field through the horizontal center of the simulation is shown in the narrow panels to the right.

3. Findings

Numerical simulations were run for cases of low, moderate, and high ESF activity. The simulation space was centered on the magnetic equator at Jicamarca's longitude in every case. Simulations were begun at 2345 UT, just prior to *F*-region sunset in the center of the simulation. Different parametrizations for the initial plasma density and the local time-varying background zonal electric field and neutral wind profiles were used according to a specific protocol The simulation was cognizant of local time variation with longitude in all state variables. Simulations were run forward in time for 90 min. Overall, the simulation was able to reproduce the degree of irregularity development observed in the coherent backscatter observations. See Fig. 1 for representative results from a high-activity simulation.

Bottom-type scattering layers occur very frequently around twilight over Jicamarca except during June solstice [11]. These thin irregularity layers, which form low in the ionosphere at the transition from the valley to the bottomside, appear to be the manifestation of pure collisional shear instability [4, 6]. The sheared plasma flow and implied vertical currents that accompany them seem also to be common features of the twilight equatorial *F* region. Collisional shear instability likewise appears in our simulations as a rule to some degree, depending on the conductivity distribution and neutral wind forcing. The resulting irregularities do not propagate far outside the strata where vertical currents flow, however.

The expansion of ESF irregularities to higher altitudes requires collisional interchange instability which grows relatively slowly but which operates at all altitudes below the *F* peak in the linear regime. Since the background zonal electric field is the dominant driver of zonal currents below the *F* peak, and since it is generally only eastward (destabilizing) for a finite amount of time, strong, long-lived, eastward electric fields coincident with periods of sheared plasma flow seem to be the key to forming bottomside spread *F* with significant vertical development. The higher the irregular layers, the more important the destabilizing role of gravity, and the greater the chances of producing topside ESF depletions. In the topside, gravity can sustain irregularity growth after the evening electric field reversal. This behavior, found in nature, is captured in our simulations.

References

[1] H. C. Aveiro, D. L. Hysell, J. Park, and H. Luhr. Equatorial spread F-related currents: Three-dimensional simulations and observations. *Geophys. Res. Lett.*, 38, L21103, 2011.

[2] H. G. Booker and H. W. Wells. Scattering of radio waves by the *F* region. *Terres. Magn.*, 43:249, 1938.

[3] A. Harten. High resolution schemes for hyperbolic conservation laws. *J. Com. Phys*, 49:357, 1983.

[4] D. L. Hysell and E. Kudeki. Collisional shear instability in the eqautorial *F* region ionosphere. *J. Geophys. Res.*, 109:(A11301), 2004.

[5] M. C. Kelley, J. J. Makela, O. de la Beaujardiere, and J. Retterer. Convective ionospheric storms: A review. *Rev. Geophys.*, 49(RG2003):doi:10.1029/2010RG000340, 2011.

[6] E. Kudeki, A. Akgiray, M. A. Milla, J. L. Chau, and D. L. Hysell. Equatorial spread-F initiation: post-sunset vortex, thermospheric winds, gravity waves. *J. Atmos. Sol. Terr. Phys.*, 69 (17-18):2416–2427, 2007.

[7] G. Strang. On the construction and comparison of difference schemes. *SIAM J. Num. Anal.*, 5:506–517, 1968.

[8] H. Trac and U. L. Pen. A primer on Eulerian computational fluid dynamics for astrophysicists. *Astrophysics*, 115:303–321, 2003.

[9] B. Van-Leer. Towards the ultimate conservation difference scheme. II. Monotonicity and conservation combined in a second-order scheme. *J. Comp. Phys.*, 14:361, 1974.

[10] R. F. Woodman. Spread F- An old equatorial aeronomy problem finally resolved? *Ann. Geophys.*, 27:1915–1934, 2009.

[11] R. F. Woodman and C. La Hoz. Radar observations of *F* region equatorial irregularities. *J. Geophys. Res.*, 81:5447–5466, 1976.