Ionosphere model experiment using ensemble techniques

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Abstract

The Sheffield University Plasmasphere-Ionosphere Model is a physics-based model computer code describing the distribution of ionization with time in the ionosphere. Ensemble forecasting is an approach for evaluation the uncertainty in models, improving the prediction. This technique have been used in different domain of applications. Since the atmosphere can be seen as a chaotic system, small errors in the model initial conditions can lead to large prediction errors. The evaluation for the SUPIM predictability is done by ensemble techniques. The numerical experiment is performed considering two selected days: one with low solar radio flux (January 30th, 1991), and a second one with low solar radio flux (July 2nd, 2011). An ensemble with 24 members was generated. Our experiments have showed a prediction with high reliability (low uncertainty), which is measured by the decrease of the variance along time.

Keywords: Ensemble forecasting, Ionosphere, SUPIM.

1. Introduction

The prediction using mathematical models in numerical methods is a remarkable scientific achievement. Such framework has been developed initially for weather forecasting in the mid-twentieth century [1], and became a methodology adopted to forecast ocean circulation [2], air pollution [3], electronic content of the atmosphere [4].

Space Weather embraces solar physics coupled with Earth system, mainly magnetosphere and ionosphere dynamics. The National Institute for Space Research (INPE), Brazil has adapted the Sheffield University Plasmasphere-Ionosphere Model (SUPIM) computer code for producing maps of electronic content in the atmosphere [4] 24 hours ahead. This activity is part of the Brazilian Space Weather Program, officially started in 2007. However, our models are only an approximation of reality. Errors are also present: the initial condition is not described with precision, some stochastic forcing are not computed and/or known, the numerical method contains errors. In addition, [5] has shown that some dynamical chaotic systems can be extremely sensitive to initial conditions. For those systems there is a necessity to previously evaluate the prediction's reliability. Such study is called predictability, where we want to establish or quantify the degree of uncertainty in a numerical prediction. One strategy to quantify such uncertainty is to employ the ensemble prediction [6], which is a Monte Carlo technique [7].

Several methods has been applied to compute the ensemble. One of them deals with different initial conditions. This is the approach used here. The ionosphere model is executed under different initial conditions, in order to evaluate some statistical properties as ensemble mean and variance. The variance can be understood as the uncertainty measure.

2. Ensemble Methods

The ensemble members can be obtained using different strategies: with a set of different initial conditions [8], different numerical values for model parameters, or by employing different models [9], [10], [11].

The method named *multimodel-superensemble* [10] is an ensemble-based approach, where the response from several models is combined, and a weighting average is calculated. Cane and Milelli [12] applied this method to predict the precipitation on the Piemonte (Italy) region. The precipitation forecasting was improved. Similar approach was used by [13] for predicting the precipitation field on the Amazon region, with better response with BRAMS model.

The ensemble forecasting method often employed by the operational prediction centers is a form of Monte Carlo analysis dealing with slightly different initial conditions. Therefore, the numerical prediction is performed considering all initial condition [8], generating a set of predictions is obtained, where an individual prediction is called *member* of the ensemble.

The dynamical system under analysis can drop on different scenarios:

- unstable dynamical system, where even a very small difference on initial conditions can produce strong divergence between two orbits;
- stable dynamical system, where very different initial conditions converge to a small region in the phase space.

As already mentioned, the ensemble technique allows to evaluate the system response under an imperfect model, observational errors, some forcing terms badly treated or even neglected, quantitatively evaluating the reliability of the forecast. Thus, the ensemble process result is more robust prediction and more fault-tolerance [14].

3. The ionosphere dynamics prediction system

Our focus is a forecasting system of ionospheric dynamics based on SUPIM, which is a first principles model for the Earths ionosphere and plasmasphere. This model has been developed in the last three decades [15], [16], and the equations of continuity, momentum, and energy are time dependent. To estimate the values for density, temperature, and flow of electrons and ions O^+, H^+, N^+,He^+, N_2^+, O_2^+, NO^+, all equations are solved along the magnetic field lines. The model also considers a number of physical and chemical processes [4].

The outputs of this model are given in a 2-dimensional plane aligned with Earth magnetic field lines, with fixed magnetic longitude coordinate. The code was adapted to provide the output in geographical coordinates.

The system is operationally executed since March 2011 in a cluster of computers at the Southern Regional Space Research Center (CRS/INPE), Santa Maria (RS), Brazil.

4. Experiment and Result

The ensemble forecasting experiment were run on two selected days. The first was January 30th, 1991, that showed the higher solar radio flux in the considered period, from 1990 to 2014, according to OmniWeb from NASA. The SUPIM execution with the lowest solar radio flux day showed code instability in some cases. The second day used here was July 2nd, 2011. The latter day presented solar radio flux similar to the lowest, but without convergence problems.

For the experiment, the average values of Vertical Total Electron Content (VTEC) in the South America region were evaluated over time for the selected days of simulation. There were 6 selected locations, geographically spaced over South America map (as shown in Figure 1), where used to track ionosphere variability in specific regions. Therefore, we would be able to identify anomalies that would be unnoticed by the average values of VTEC.

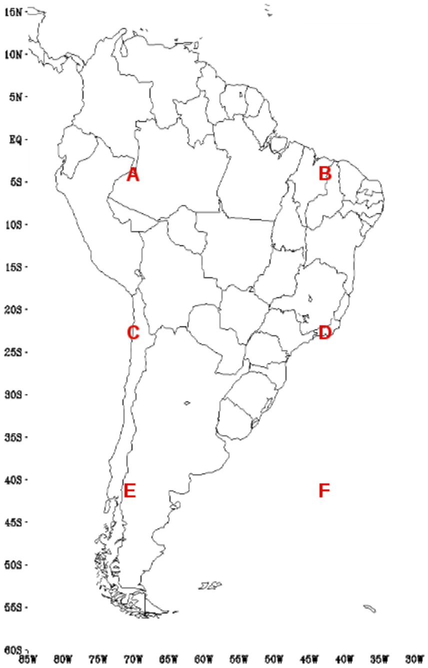

Figure 1 - Sample locations in the South America.

Figure 2 illustrates the procedure used in experiment. We start with the ionosphere simulation in the previous day of interest, and store the output data for each hour. After, it is applied noise in a specific hour of the stored output data, and this simulation is evolved from that noisy hour until the end of the day, in order to generate a initial condition (ensemble member) for the simulation in the day of interest. This process is repeated for each hour, generating 24 different ensemble members. In even hours the noise used was 30% positive and in odd hours the noise was 30% negative. The noise was applied in ionic and electronic contents. The final step is to evaluate the simulation evolution in the day of interest using different ensemble members.

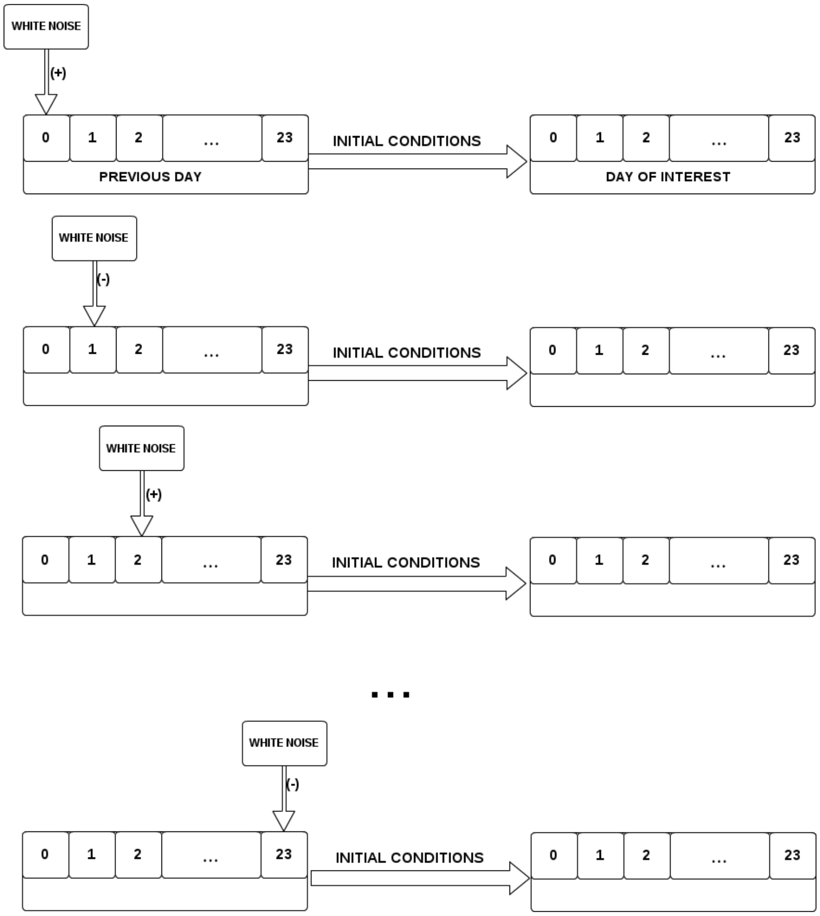

Figure 2 - Fluxogram of experiment.

January 30th, 1991 showed the higher solar radio flux at 10.7 cm (2800 MHz), equals to 370.1 s.f.u. Figure 3 illustrates the average of VTEC value for that day, where it is possible to observe that the noisy simulations converged after few hours to the same values of simulation without noise.

Figure 4 shows the VTEC for the locations defined in figure 1. It was possible to verify that locations (a) and (b) take more time to converge to values of simulation without noise. This behaviour was expected since they are closer to magnetic equator.

July 2nd, 2011, was chosen because it presented solar radio flux at 10.7 cm (2800 MHz) of 72.6 s.f.u, close to the lowest. Convergence difficulties in this system for low solar radio flux values were previously discussed in [4]. Figure 5 illustrates the average of VTEC value for that day. It is possible observe that the simulations behaviour were similar to the ones with high solar radio flux value.

Figure 6 shows the VTEC values variation in the selected locations. It was possible verify that simulations at locations (a) and (b) diverge significantly more on initial hours than the ones in the day of high radio solar flux value.

5. Discussion

This paper described the use of Ensemble method to evaluate ionosphere dynamics simulations. In the experiment, different initial conditions were applied to the simulations using noise in the simulation in previous day of interest. Two different days were used, that presented high and low solar radio flux values.

Our experiments have showed the system evaluated shows prediction with high reliability (low uncertainty), which is measured by the decrease of the variance along time. Even when initial conditions used were substantially different, time evolution during the day of analysis leaded ions and electron concentrations to converge. Those are characteristics usually presented in stable systems.

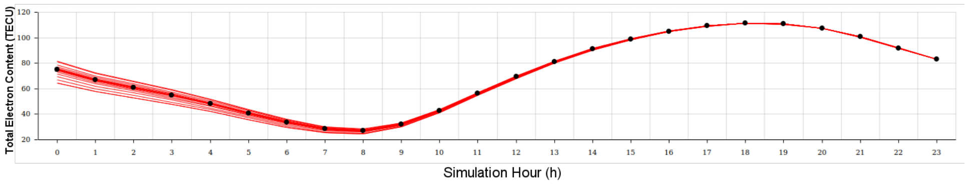

Figure 3 - Average Vertical Total Electron Content (VTEC) for January 30th, 1991.

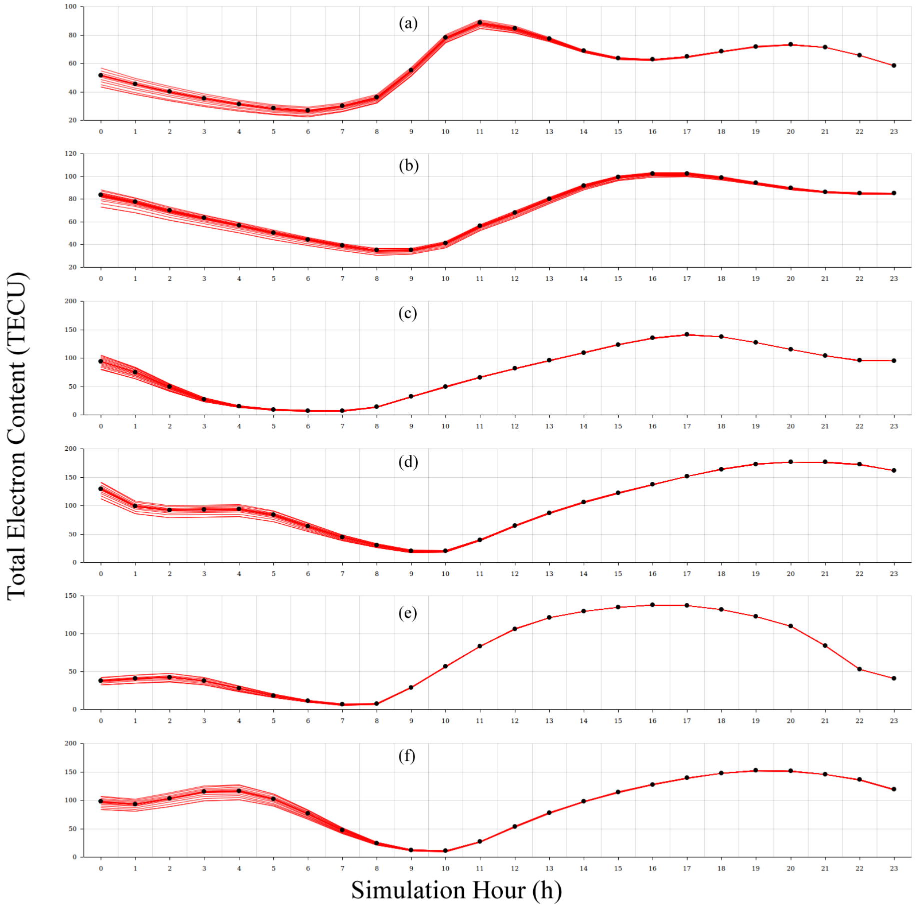

Figure 4 - Vertical Total Electron Content (VTEC) at selected locations defined in figure 1 for January 30th, 1991.

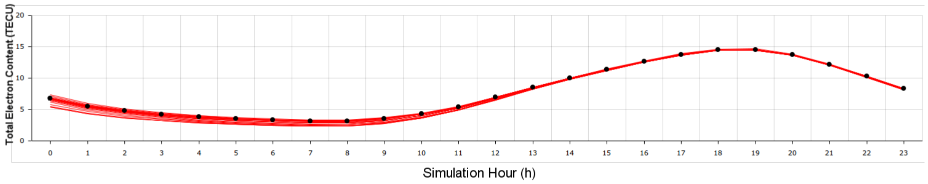

Figure 5 - Average Vertical Total Electron Content (VTEC) for July 2nd, 2011.

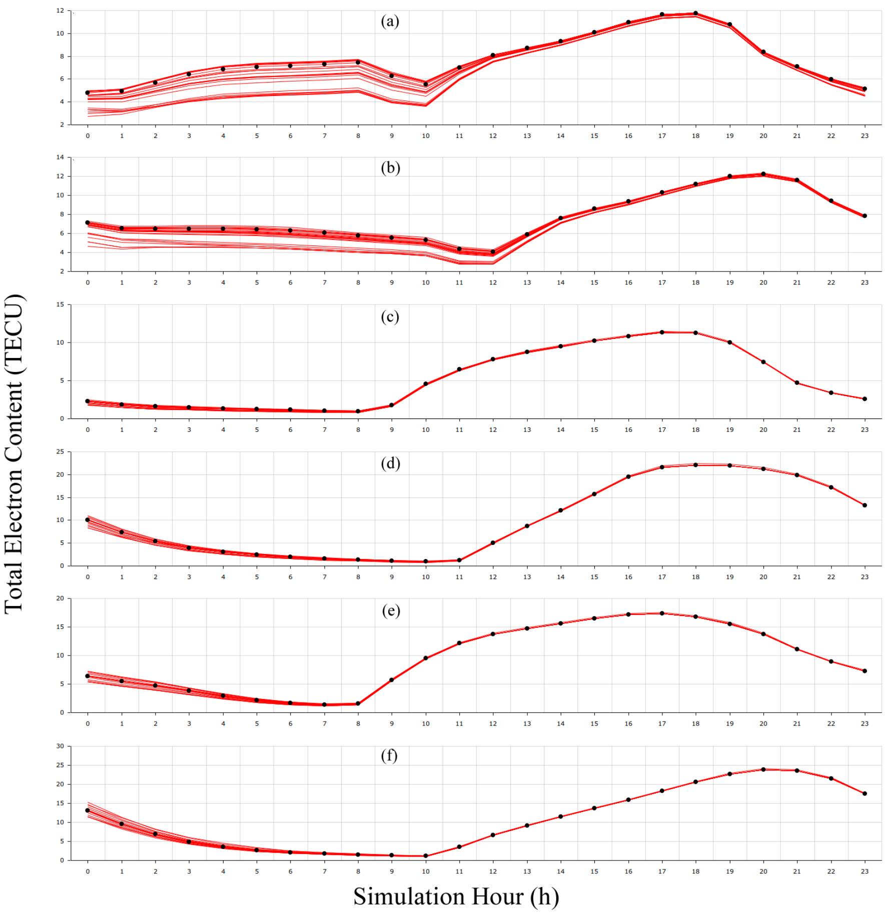

Figure 6 - Vertical Total Electron Content (VTEC) at selected locations defined in figure 1 for July 2nd, 2011.

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