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PRELIMINARY EVALUATION WITH ENSEMBLE PREDICTION FOR THE SUPIM MODEL

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Abstract. An operational version from the Sheffield University Plasmasphere-Ionosphere Model (SUPIM) was developed to the Brazilian Space Weather program in INPE - Brazil (`http://www2.inpe.br/climaespacial/`). The SUPIM is a physics-based model computer code describing the distribution of ionization. The model applies electric-magnetics coordinates, where a conformal map is employed to transform the geographic (Cartesian) coordinates into electric-magnetics ones. On this transformed coordinate, the computation is performed in a 2-dimensional plane aligned with Earth magnetic field lines, with fixed magnetic longitude coordinate. The SUPIM is executed at different longitudes. Several adaptations were developed to the operational version to run daily, including: parallel version for the code (better CPU-time performance), adding an artificial exponential decay for ion–neutral collisional frequency for high altitudes (better code stability), a module for data assimilation (by Newtonian relaxation method). The operational system runs every day, forecasting almost 24 h ahead for the VTEC (vertical total electronic content) values on the South America. Preliminary tests by using an ensemble prediction scheme are under investigation. Ensemble forecasting belongs to the class of Monte Carlo approach, where multiple numerical predictions are carried out. There are several techniques to calculate the ensemble members. Our approach adopts one strategy to employ slightly different initial conditions. The ensemble forecasting allows to identify zones of

low and high predictability, as well as to compute a confidence interval. The latter issue is a quantification of uncertainty associate to the prediction.

1 INTRODUCTION

The prediction using mathematical models by using numerical methods is a remarkable scientific achievement. Such framework has been developed initially for weather forecasting the mid-twentieth century (see [14]), and became a methodology adopted to forecast ocean circulation [9], air pollution [7], electronic content of the atmosphere [15].

Space weather embraces solar physcis coupled with Earth system, mainly magnetosphere and ionosphere dynamics. The INPE (National Institute for Space Research, Brazil) has adapted the SUPIM (Sheffield University Plasmasphere-Ionosphere Model) computer code for producing maps of electronic content in the atmosphere [15] 24 hours ahead (see also: `http://www2.inpe.br/climaespacial/portal/tec-supim-previsao/`). The latter activity is part of the Brazilian Space Weather Program, officially starting since 2007.

However, our models are only an approximation of reality. Other errors are also present: the initial condition is not described with precision, some stochastic forcings are not computed and/or known, the numerical method contains errors. In addtion, Lorenz has shown that some dynamical systems can be extremely sensitive to initial conditions (these are called *chaotic systems* [13]). There is a necessity to previously evaluate the prediction reliability. This study is called predictability, in other words, we want to establish or quantify the degree of uncertainty of the numerical prediction. One strategy to quantify such uncertainty is to employ the *ensemble prediction*.

Ensemble prediction is a Monte Carlo technique.

Several methods has been aplied to compute the ensemble. One of them deals with different initial conditions. This is the approach used here. The SUPIM is executed under different initial conditions, allowing to calculte some statistical properties as ensemble mean and variance. The variance can be understood as the uncertanty measure. Few words about ensemble prediction are expressed in the next section. Section 3 presents a brief description on the SUPIM. The methodology employed and the numerical experiments carried out are in Section 4. The final section addressed some final remarks and conclusion.

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 [5, 11, 12].

The method named *multimodel-superensemble* [11] is an ensemble-based approach, where the response from several models is combined, and a weighting average is cal-

culated. Cane and Milelli [4] applied the latter method to predict the precipitation on the Piemonte (Italy) region. The precipitation forecasting was improved. Similar approach was used by Santos et al. [16] for predicting the precipitation field on the Amazon region, with better response with BRAMS model.

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

The dynamical system can drop on different scenarios:

(i) unstable dynamical system, where even very small difference on initial conditions can produced strong divergence between two orbits.

(ii) 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 that deals with imperfect model, observational errors, some forcing terms badly treated or even neglected, for quantitatively measuring the reliability of the forecast. Thus, the ensemble process gives more robust prediction and more fault-tolerant [3].

3 THE SUPIM PREDICTION SYSTEM

The SUPIM-DAVS is a forecasting system of ionospheric dynamics based on SUPIM model. The SUPIM is a model from the first principles for the Earth ionosphere and plasmasphere. This model has been developed in the last three decades [1, 2, 17].

In SUPIM code, the equations of continuity, momentum, and energy are time dependent. To calculate the values for density, temperature, and flow of electrons and ions O^+, H^+, He^+, N_2^+, O_2^+, NO^+, all equations are solved along the magnetic field. The model also encodes several physical and chemical processes [15].

The SUPIM-DAVS is operationally executed since March 2011 in a computer system (clusters) from the South Regional Center for Space Research (CRS/INPE), Santa Maria (RS), Brazil. Figure 1 shows a flow-chart of the SUPIM-DAVS execution.

The first procedure performed by the SUPIM-DAVS system is obtaining solar flux data. Eletroctronic content observations, used for data assimilation, can be obtained from different sources like ionograms from the National Oceanic and Atmospheric Administration (NOAA) web-page, INPE Space Weather webservice, or from the local server. The next step is to validate the solar flux data through SOLAR2000 code.

Using the obtained solar flux data, and setting up parameters that define the model for Earth's magnetic field, thermospheric winds, and the simulation date, the SUPIM is executed. The DAVS is divided into 3 parts: data assimilation, temporal adjustment on

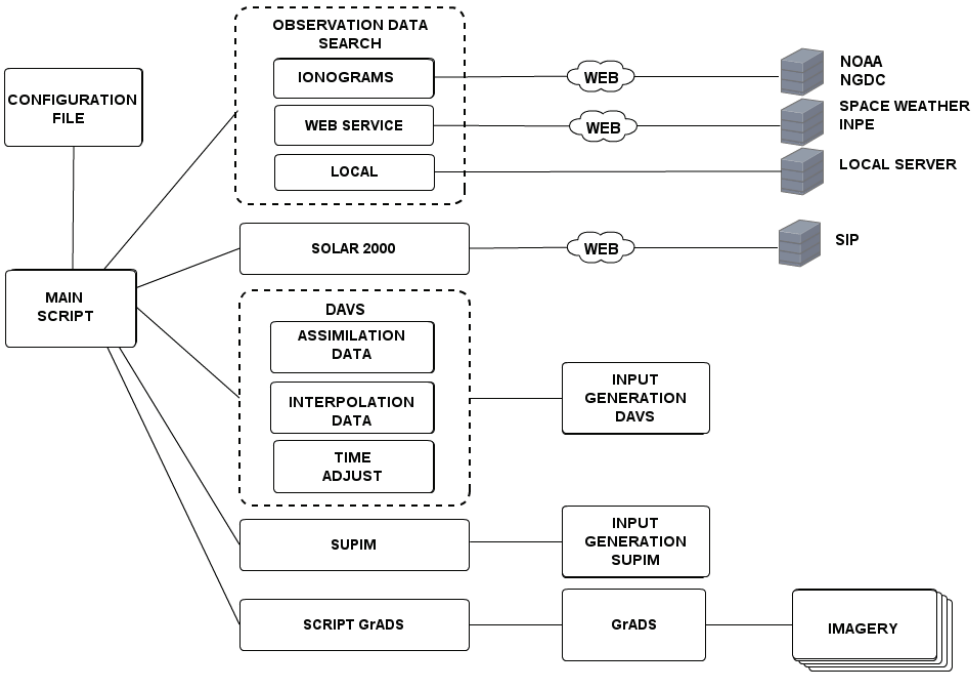

Figure 1: SUPIM-DAVS structure.

simulation results based on longitudinal offset, and post-processing (including homogeneous grid interpolation). Finally, frames of images are generated using GrADS (Grid Analysis and Display System) software.

The SUPIM is prepared to use prior forecast data. Such data register 5 different properties: electron concentration and its temperature, ionic concentration and its temperature, and thermospheric wind. The latter 3 properties are indexed to each of the 7 simulated ions. If there is no previous data of electronic concentration, the system performs an iterative process to determine an equilibrium condition. After reaching convergence for the latter iteration, the system is ready to perform the simulation.

4 EXPERIMENTS AND RESULTS

All experiments were carried out for the day 12/Dec/2014. Two types of experiments were performed. Firstly, looking at the average of the VTEC (Vertical Total Electron Content) over the whole South America map. Another one, VTEC values at 6 points geographically spaced over South America map, as shown in Figure 2. For type-2 experiment, 6 sampled points were selected to evaluate local behavior, just because the global average could hide a local anomalous behavior.

4.1 Methodology

For implementing the ensemble method, it was necessary to determine different initial conditions. To generate the initial conditions, the properties calculated by SUPIM were changed by adding a random noise.

The noise were added on only two properties: eletronic content and ionic concentration for each one of 7 ions. The other properties were not changed, because their variation has no no significant impact on TEC values.

Five different simulations were performed to implement the method:

(a) Simulation without noise.

(b) Simulation with positive maximum noise level of 30%;

(c) Simulation with negative maximum noise level of 30%;

(d) Simulation with positive maximum noise level of 50%;

(e) Simulation with negative maximum noise level of 50%.

4.2 Results

Figure 3 illustrates the simulations for the time evolution of the TEC average over the South America. The red lines represent noisy simulations and black points the simulation without noise. The latter points also show the standard deviation interval (vertical lines over the points). The interval is calculated with the noisy values. This gives us a notion of dispersion among different simulations. It is clear the convergence of curves for all 5 simulations. For this simulation, the snapshot indicates a stability condition.

For the experiment using 6 points, shown in Figure [**?**], the evolution of TEC values also showed similar behavior to the previous experiment, indicating local stability for the marked points. However, the convergence rate varied for each location. In location (b), convergence was slower than in other locations evaluated. Location (c) achieved small values for standard deviation after few hours of simulation. These differences in convergence evolution can be attributed to the physical process modeled, where regions of very high electronic concentration follow the curvature of the Earth's magnetic field in the region.

5 CONCLUSIONS

The simulation for ensemble members converged for the same value. In other words, our experiments have showed a prediction with high reliability (low uncertainty), which is measured by the decrease of the variance along time.

The performed experiments are not to be considered as a representative ones. The goal is to show, by worked examples, the methodology under development applied to quantify the uncertainty linked to the prediction, indicating the degree of reliability of the forecast.

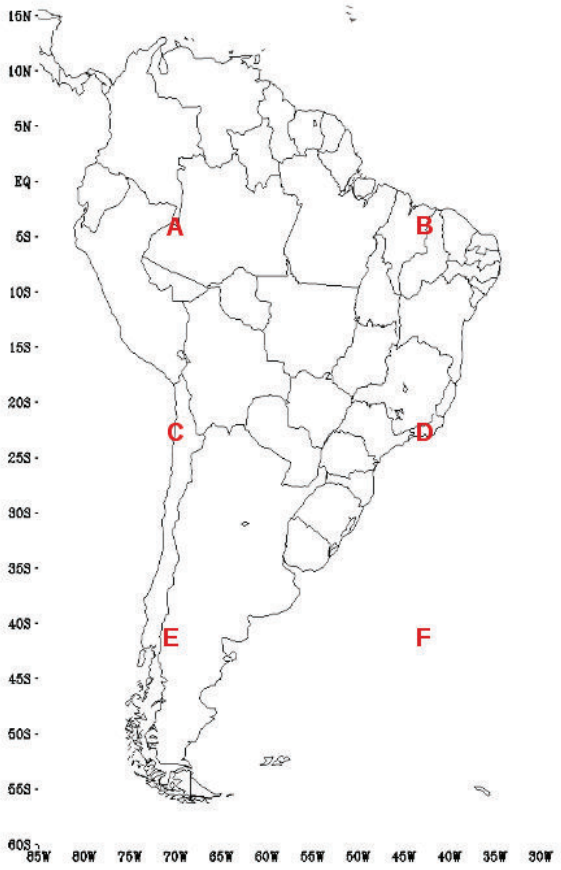

Figure 2: Sample points in the South America.

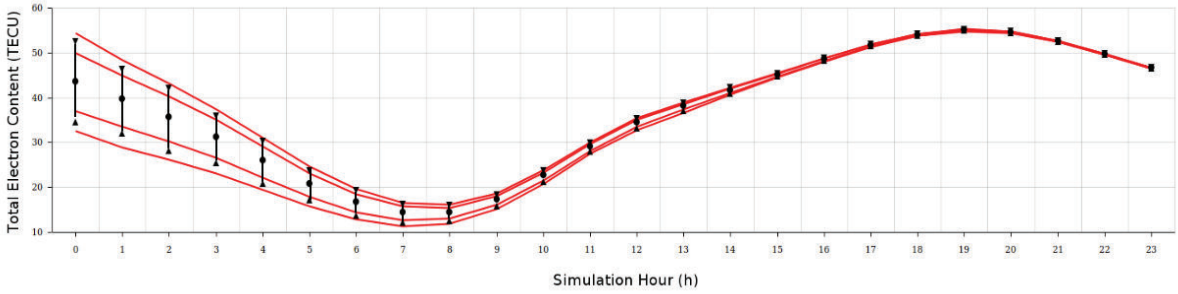

Figure 3: Mean Total Electron Content (TECU).

For all experiments, the SUPIM-DAVS performed stable simulations, even with the presence of noise in the data, generating acceptable results.

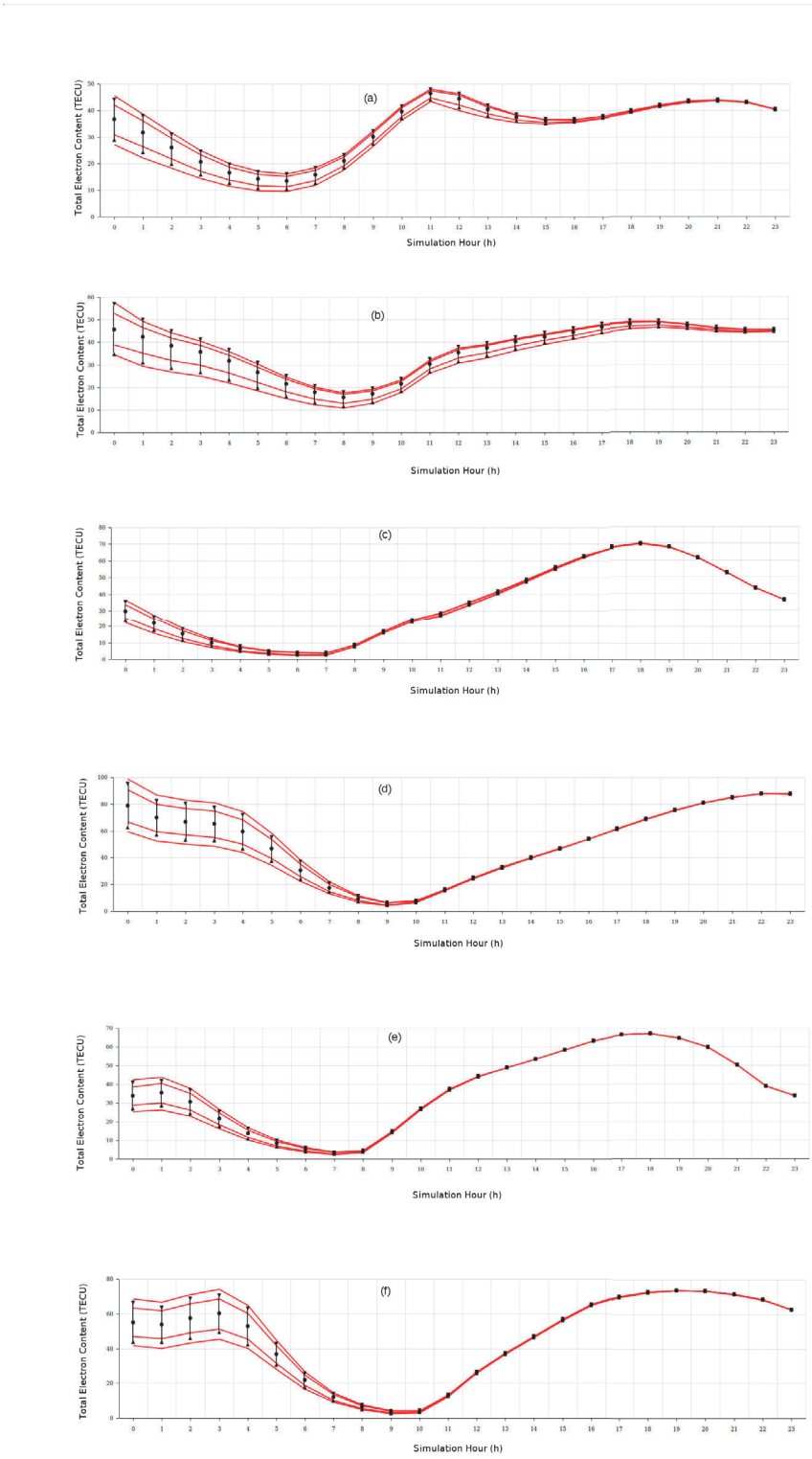

Figure 4: Ensemble TEC evolution for 6 points on South America.

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REFERENCES

[1] Bailey, G.J., and and R. Sellek. "A mathematiO foco paracal model of the earth's plasmasphere and its application in a study of He (+) at L= 3 *Annales Geophysicae*, Vol. 8 (1990).

[2] Bailey, G. J., R. Sellek, and Y. Rippeth. "A modelling study of the equatorial topside ionosphere." Annales geophysicae. Vol. 11. No. 4. Copernicus *Annales Geophysicae*, Vol. 8 (1993).

[3] Bourgin, F., et al. "Investigating the interactions between data assimilation and post-processing in hydrological ensemble forecasting." *Journal of Hydrology*, 519, 2775–2784 (2014).

[4] Cane, D., Milelli, M., Multimodel SuperEnsemble technique for quantitative precipitation forecasts in Piemonte region, *Nat. Hazards Earth Syst. Sci.*, 10, 256-273 (2010).

[5] Casanova, S., Ahrens, B., On the Weighting of Multimodel Ensembles in Seasonal and Short-RangeWeather Forecasting, *Mon. Weather Rev.*, 137, 3811–3822 (2009).

[6] Finlay, C. C., Maus, S., Beggan, C. D., et al., *International geomagnetic reference field*, 1216–1230 (2010).

[7] Freitas, S. R., Longo, K. M., Silva Dias, M. A. F., Chatfield, R., Silva Dias, P. L., Artaxo, P., Andreae, M. O., Grell, G, L. F. Rodrigues, L. F., Fazenda, A., and J. Panetta, "The Coupled Aerosol and Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System (CATT-BRAMS) ? Part 1: Model description and evaluation". *Atmospheric Chemistry and Physics*, 9, 2843–2861 (2009).

[8] Kalnay, E. Atmospheric modeling, data assimilation, and predictability. *Cambridge University Press* (2003).

[9] Kantha, L. H., and Clayson, C. A., Numerical Models of Oceans and Oceanic Processes. *Academic Press* (2000).

[10] Kent Tobiska, W. et al. The SOLAR2000 empirical solar irradiance model and forecast tool. *J. Atmos. Terr. Phys.*, 62, 1233–1250 (2000).

[11] Krishnamurti, T. N., Kishtawal, C. M., LaRow, T. E., Bachiochi, D. R., Zhang, Z., Williford, C. E., Gadgil, S., and Surendran, S.: Improved Weather and Seasonal Climate Forecasts from Multimodel Superensemble, *Science*, 285, 1548?-1550 (1999).

[12] Leutbecher, M., and Palmer, T.N. Ensemble forecasting. *Journal of Computational Physics*, 227(7), 3515–3539 (2008).

[13] Lorenz, E. N. Deterministic non-periodic flow. spectral vorticity equations *J. Afmos. Sci.*, 20(2), 130–141 (1963).

[14] Lynch, P. "Weather Prediction by Numerical Process" The Emergence of Numerical Weather Prediction. *Cambridge University Press* (2006).

[15] Petry, A., Souza, J. R., Campos Velho, H. F., and Pereira, A. G., "First results of operational ionospheric dynamics prediction for the Brazilian Space Weather program." *Advances in Space Research* 54(1), 22-36, (2014).

[16] Santos, A. F., Freitas, S. R., J. G. Z. Mattos, Campos Velho, H. F., Gan, M. A., Luz, E. F. P., Grell, G.: Using the firefly optimization method to weight an ensemble of rainfall forecasts from the Brazilian developments on the Regional Atmospheric Modeling System (BRAMS). *Advances in Geophysics*, 35, 123–136 (2013).

[17] Souza, J. R., et al. "Enhancement of the Sheffield University plasmasphere-ionosphere model: E region and new inputs." *Personal communication* (2011).