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Prediction of magnetic substorms using a state space model

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ABSTRACT

Nonlinear dynamical models of the magnetosphere derived from observational time series data using phase space reconstruction techniques have yielded new advances in the understanding of its dynamics. Considering the solar wind–magnetosphere interaction to be a natural input–output system its dynamical features can be reconstructed on the storm time scale by using the method of time delay embedding. Here, fourteen magnetic storm intervals belonging to low/moderate and high solar activity periods are considered and a suitable state space model has designed by performing training and validation tests, for which dawn to dusk electric field (*VBz*) is chosen as the input, and the *AL* time series as the output. The percentage of the output variations that is reproduced by the model is termed as fit_model and a higher number of fit_model means a better model. The number of components m used in the state space model is varied from 1–9 and the best prediction is obtained when $m=4$. The fit_model values of time series used for validation are 67.96, 67.2, 72.44, and 70.89, with $m=4$. In the present study most of the storms considered are having D_{st}max in between -100 and -300 nT, and they can be predicted well with this procedure. To reveal the prediction capability of the proposed state space model the 30 steps ahead outputs for the storm events are generated, which reasonably reproduce the observed values.

1. Introduction

The Sun–Earth system is a highly dynamical system in which a continuous exchange of mass, energy, and momentum occur between the solar wind and the Earth's magnetosphere through reconnection processes (Vasyliunas, 1975). However, the understanding of the magnetospheric response to the solar wind variations is still an open problem, as it involves different mechanisms of energy release and multi-scale coupling phenomena. Recently, D'Amicis et al. (2006) studied waiting-time statistics of north–south turnings of the IMF, i.e. the time interval between the end of a magnetic turning and the beginning of the next one, in order to emphasise the possible correlations between these events.

The role of the solar wind driver would be to enhance the internal fluctuations that could induce a topological transition among metastable complex topologies. In such a case the evolution of the magnetospheric system will be the result of the combined effects of local couplings of the magnetic and plasma structures, through the nonlinearities of the system (Sharma, 1997; Consolini and Chang, 2001, 2002; Vassiliadis, 2006). This point of view also supports the recent results of Sitnov et al. (2001) that the substorm activity resembles the non equilibrium (first and/or second order) phase transitions.

The theory of nonlinear, deterministic dynamical systems provides a powerful theoretical tool to characterize geometrical and dynamical properties of the attractors of such systems (Hegger et al., 1999). Along with the theoretical understanding of these systems many of the typical phenomena have been realized in laboratory experiments. Hence, nonlinear time series analysis is highly advantageous to reveal the underlying dynamics of a system. Besides the exponential divergence of trajectories the most striking feature of chaotic dynamical systems is the irregular geometry of the sets in phase space visited by the system state point in the course of time.

From the total energy transported by the solar wind, just a small fraction of 5% is able to penetrate the magnetopause or reach the terrestrial magnetosphere. These energy transfers occur by two fundamental physical processes: (a) magnetic reconnection and (b) viscous-type interaction: the magnetic reconnection implies an interaction between the interplanetary magnetic field and the terrestrial magnetic field in the day side of the magnetosphere (Dungey, 1961), as well as in other regions (Song et al., 2000). Nonmagnetic mechanisms of coupling or transport are usually referred to as interaction of viscous-type. They imply a transfer of tangential momentum through the magnetopause by means of some type of viscous drag generated by macro- or micro-instabilities in the plasma (Axford and Hines, 1961). The viscous-type interactions include two fundamental physical

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mechanisms: the diffusion of particles through the magnetopause by means of the stochastic dispersion of resonant waves (Tsurutani and Thorne, 1982). The Kelvin–Helmholtz instability at the flanks of the magnetopause which typically occurs during the evolution toward a nonlinear regime (Ojeda et al., 2005).

Recently, Unnikrishnan et al. (2006a, b) analysed the deterministic chaotic behaviour of GPS TEC fluctuations at mid-latitude, and equatorial/low latitude regions of Indian sub continent (Unnikrishnan and Ravindran, 2010) by employing the nonlinear aspects like mutual information, fraction of false nearest neighbours, phase space reconstructions, and chaotic quantifiers. Also they compared the possible chaotic behaviour of ionosphere during geomagnetic storms and quiet times, under different seasons, local times, and latitudes using dynamical and topological invariants. Their study emphasis that the influence of an external stochastic driver (solar wind) could alter the inherent dynamics of a system (ionosphere) if the coupling is powerful, and hence this could be a possible reason for the deviation of the values of Lyapunov exponent during storms from the respective quiet time values (Unnikrishnan et al., 2006a).

Nonlinear dynamical models of the magnetosphere derived from observational time series data using phase space reconnection techniques have yielded new advances in the understanding of its dynamics. The importance of nonlinear dynamical studies to space weather arises from its ability to reconstruct the dynamics from the observational data of a limited number of variables. In the input–output studies the local linear technique has been successful in yielding simple predictive models of the global magnetospheric dynamics by using the main features of the system.

The coupled solar wind–magnetosphere system exhibits complexity, which is the characteristic of nonlinear systems, and the techniques of state space reconstruction from time series data is appropriate to study such behaviour. Among the most important aspects of nonlinear dynamical techniques is the possibility of reconstructing the dynamics from experimental data and gaining insight into the physics of complex nonlinear systems, independent of particular modelling techniques. The novelty of the nonlinear dynamical techniques is in their ability to distinguish the statistical and the dynamical characteristics of a system from time series data.

In a review paper, Kamide et al. (1998) has clarified several outstanding questions in the area of storm/substorm relationship. Recent studies reveal that basically the magnetospheric fluctuations are of internal origin though the bursts can be triggered by an external perturbation (solar wind), and there could be an interplay of the deterministic and stochastic components of a stationary out of equilibrium system (Ukhorskiy et al., 2004).

In the present study the solar wind–magnetosphere interaction is considered as a natural input–output system, and its dynamical features are reconstructed on the storm time scale by using the method of time delay embedding. Here fourteen magnetic storm intervals are considered, and a suitable state space model has been designed by performing training and validation tests for which the dawn to dusk electric field *VBz*, is chosen as the input, and the *AL* time series as the output. To reveal the prediction capability of the state space model, the 30 steps ahead outputs for the above storm events (used for final test) are generated, which reasonably reproduce the observed values.

2. Data analysis and methodology

It is known that the combination of the storm and substorm caused some unique and well-correlated phenomena in the magnetosphere and auroral–subauroral ionosphere (Huang et al., 2003). Moreover, other studies also observed that the magnetic substorm is the set of phenomena during which a reduction in topological complexity in the tail regions takes place (Chang, 2001a, b; Consolini and Chang, 2001, 2002).

It is widely believed that the main phase of a magnetic storm is the interval in which many intense substorms must take place successively. Substorms can play a role in storm development in different ways. The examples include initiating of ionospheric ion flow and injection of energetic ions into the inner magnetosphere. The strong correlation between intense substorms and the main phase of storms has suggested a cause–effect relationship between these two components of geomagnetic activity (Gonzalez et al., 1994). In the present study fourteen geomagnetic storm periods are considered (Table 1) for developing the state space model. The solar wind induced dawn-to-dusk electric field $Ey = VBz$, given by the product of the solar wind speed V and north–south component Bz of the IMF is chosen as the input (Valdivia et al., 1996) and the *AL* time series as the output.

Fig. 1a and b represents the time series of dawn-to-dusk electric field (*VBz*), and *AL*, respectively, during the period, 02–06 April 2004. According to embedding theorems, if we choose an appropriate delay based on the data, at most $2d+1$ delay coordinates are enough, where d is the fractal dimension of the attractor (Saucer et al., 1991). Mostly, the smallest integer

Table 1
List of storm events used in the present study.

Year and S 10.7 (in bracket)	Storm event (time series) T=training V=validation C=confirmation	D_{st} max value during storm period (nT), and convergence time in brackets (minutes)	Date and UT of SSC (in bracket)
2004 (106.5)	28 August–02 September 2004 (C)	−126 (200)	29 August (1004)
	06–10 November 2004 (C)	−373 (400)	07 November (1051)
	02–06 April 2004 (T)	−112(200)	03 April (0947)
	21–25 January 2004 (T)	−149 (200)	22 January (0137)
	21–25 July 2004 (T)	−101 (200)	22 July (1033)
2003 (128.5)	28 May–01 June 2003 (V)	−144 (200)	29 May (1224)
	17–21 June 2003 (V)	−141 (250)	18 June (0512)
2001 (181.4)	10–14 April 2001 (T)	−271 (250)	11 April (1343)
	16–20 August 2001 (T)	−105 (200)	17 August (1101)
	20–24 October 2001 (T)	−177 (200)	21 October (1646)
	23–27 November 2001 (V)	−221 (200)	24 November (0554)
	30 March-03 April 2001 (C)	−387 (350)	31 March (0051)
	24–28 September 2001 (C)	−102 (200)	25 September (2024)
	18–22 March 2001 (V)	−149 (200)	19 March (1112)