Real-time Neural Network Predictions of Magnetospheric Activity

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ABSTRACT

.The Boyle potential or the Boyle Index (BI), Φ (kV)=10^{-4} (V/(km/s))^2 + 11.7 (B/nT) sin^3(θ/2), is an empirically-derived formula that can characterize the Earth's polar cap potential, which is readily derivable in real time using the solar wind data from ACE. The BI has a simplistic form that utilizes a non-magnetic "viscous" and a magnetic "merging" component to characterize the magnetospheric behavior in response to the solar wind. We have investigated its correlation with two of conventional geomagnetic activity indices in the Kp, the AE and the Dst index. We have shown that the logarithms of both 3-hr and 1-hr averages of the BI correlate well with the subsequent Kp: Kp = 8.93 $\log_{10}$(BI) - 12.55. We have developed a new set of algorithms based on Artificial Neural Networks (ANNs) suitable for short term space weather forecasts with an enhanced lead-time and better accuracy in predicting these indices; the algorithms omit the time history of its targets to utilize only the solar wind data. Inputs to our ANN models benefit from the BI and its proven record as a forecasting parameter since its initiation in October, 2003. We have also performed time-sensitivity tests using cross-correlation analysis to demonstrate that our models are as efficient as those that incorporates the time history of the target indices in their inputs. Our algorithms can predict the upcoming full 3-hr Kp, purely from the solar wind data and achieve a linear correlation coefficient of 0.830, which means that it predicts the upcoming Kp value on average to within 1.3 step, which is approximately the resolution of the real-time Kp estimate. Also, when predicting an equivalent "one hour Kp", the correlation coefficient is 0.86, meaning on average a prediction within 0.99 step. Our model is also successful in predicting AE in its original 1-hr cadence format to achieve a linear correlation of 0.83. However, live results of the BI plot and Kp prediction can be obtained from http://space.rice.edu/ISTP/wind.html while members of the Rice Space Institute's free **spacalrt** system will receive email alerts whenever the value of the predicted Kp reaches 6 or higher, or when the 10-minute BI exceeds 200 kV.

Introduction

The Boyle index (BI) is an empirically derived formula that approximates steady polar cap potential and has an empirically derived functional form given by where, v is the solar wind in km/sec, B is the magnitude of the IMF in nT [Boyle et al., 1997]. Besides its simple scalar functional form, the IMF "merging" term and solar wind dependent "viscous" term makes it a good indicator as to the state of the magnetosphere system [see similar functions in Newell et al., 2007]. Its simplicity combined with IMF and solar wind dependent scalar functional form makes it a good indicator as to

$$\Phi = 10^{-4}\nu^2 + 11.7B\sin^3(\theta/2)\ kV;\ \theta = \cos^{-1}(B_z/|B|)$$

the state of the magnetosphere system. In general, during the periods when solar wind and IMF are steady for several hours, an hourly-averaged BI is a good predictor of the polar cap potential drop provided BI is less than 160kV. In general, during the periods when solar wind and IMF are steady for several hours, an hourly-averaged BI is a good predictor of the polar cap potential drop provided BI is less than 160 kV. However, it overestimates the PCP when the BI exceeds 160 kV. Theoretical studies have suggested that polar cap potential drop reaches saturation during periods of strong and southward IMF [Hill et al., 1976]. Recently, Hairston et al., [2003], using the DMSP spacecraft observations of the October and November 2003 superstorms, showed that saturation of the polar cap potential generally follows the Hill-Siscoe model, with saturation potential in the range 160-250 kV.

Kp is a geomagnetic activity index representing midlatitude regions (48^0 and 60^0) based on a quasi-logarithmic scale. It varies from 0 (signifying a quiet period) to 9 (severe activity) in 28 quantized levels and therefore take values from 0, 0+, 1-, 1, 1+, 2-, ...9.

AE index, measured in nT, is used to characterize the global electrojet activity in the auroral zone based on observatories located between 62^0 and 77^0 N latitudes.

Dst index, calculated using ground based magnetometers, measures the energy in the ring current as a function of the horizontal component of the Earth's magnetic field around the equatorial region.

The BI plot is available in real time from http://space.rice.edu/ISTP/wind.html. Subscribers to the "spacalrt" mailing list receive free email notices whenever the 10-minute BI average exceeds 200 kV (red alerts). In addition, they will also receive email notices whenever the Kp is predicted to be 6 or higher. Currently, two of our Kp prediction models are running in real time.

Data

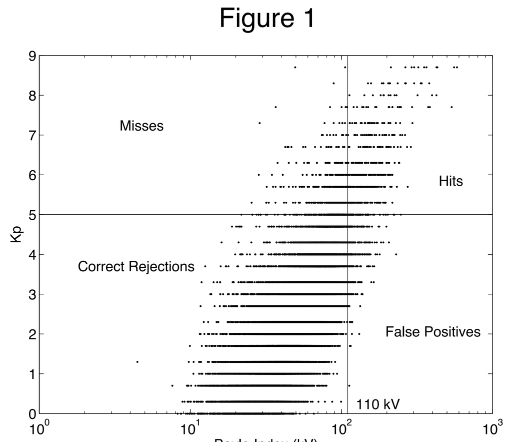
The BI's used in this study were computed using archived data from ACE (1998-2007) and official values of 3 hour averaged Kp were obtained from GeoForschungsZentrum (GFZ), Postdam, Germany. The AE and the Dst indices were downloaded from SPDF-CDAWeb.

Statistical Correlations

BI vs Kp

A steady BI for a few hours is a good predictor of the polar cap potential drop, which in turn is a predictor of magnetospheric activity [Boyle et al., 1997]. Although the BI is an overestimation of the polar cap potentials if it is above 160kV, nevertheless and surprisingly, the correlation is still valid, possibly because Kp is logarithmic as well but also because perhaps, even though the polar cap velocity may saturate, the overall magnetospheric response may not. In figure 1 [Bala et al., 2009], the vertical and horizontal lines within the plot represents one possible BI cutoff (discriminator level, here 110 kV) and corresponding Kp index (5) cutoff. The cut-off shown here has been deliberately chosen to illustrate the result that the likelihood of a storm having a Kp index of 5 or higher exceeds 95% when the average BI over the previous three hours is over 110 kV.

Figure 1



Cross-correlations

Cross-correlation analysis is one of the fundamental forms of time series analysis performed in the time domain that can offer clues about characteristic time scales of small- or large-scale processes. From the cross-correlation analysis between BI vs Kp, AE and Dst we infer that with Kp, AE and Dst trailing BI, the prediction lead-times are in essence decided by the positive time lags; therefore, forecasts can be made accurately within a time range of 1-4 hours where the correlations are still higher (> 0.75).

We have also investigated whether the solar wind coupling function in the BI can also represent, and hence predict, other geomagnetic activity indices such as the AE and the Dst when coupled to an artificial neural network.

ANN Algorithm

We use the standard feedforward multilayer perceptron network proven to be well suited for non-linear time series prediction [Haykin 1999]. The network was trained using backpropagation procedure by applying Leverberg-Marquardt routine. We subdivided out data set for the purpose of training and testing the network, and are independent of each other.

Results and Analysis

We have explicitly developed our prediction algorithms to run at different time granularities (1-hour and 3-hour) and inputs. All our models uses only the time history of solar wind in their inputs.

Our two years (2006 and 2007) of test data was not included in our training.

Kp Prediction

Since Kp is a three-hour index, we construct a new 1-hour cadenced time series using quadratic interpolation through splines, a technique preferred over oversampling. For example, corresponding to a certain three hour period say between 0600 and 0900 UT, centered at 0730, the new 1-hour Kp index will have points centered at 0630, 0730 and 0830.

Figure 2

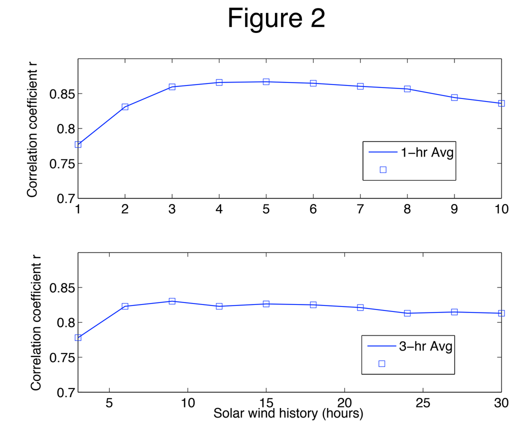


Figure 2 show the results from "time sensitivity" tests. Kp predictions (linear correlation r) from 1-hour and 3-hour models are plotted against length of time of the BI used in inputs. In the 1 hour-average study, correlation peaks at 5 hour before becoming less sensitive to time.

Kp can be predicted in the 1-3 hour time range, fairly well and just from solar wind only. Our results are "significantly" better than persistence predictions, which is vital for a space weather forecaster.

Qualitative "Real-time" Results: An unexpected activity

Our success in predicting Kp during a recent unexpected event (22 July '09) is shown in figures 3, 4 and 5.

Figure 3

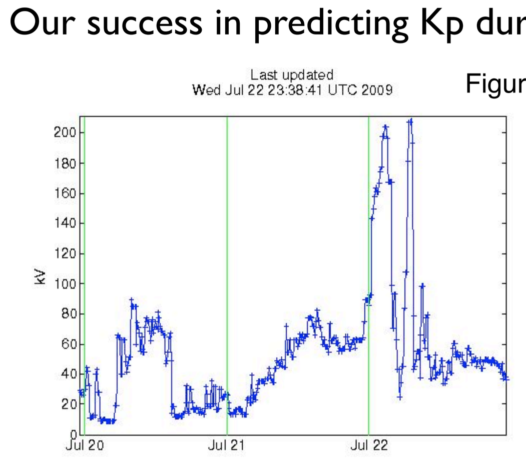


Figure 4

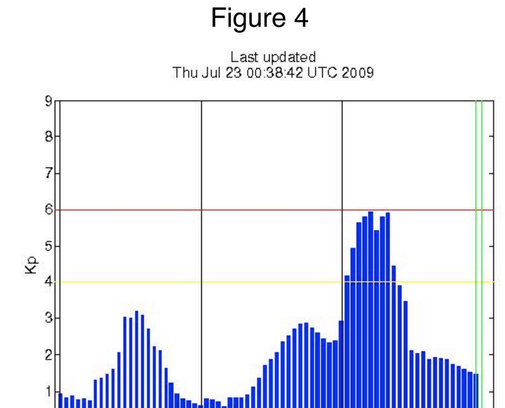
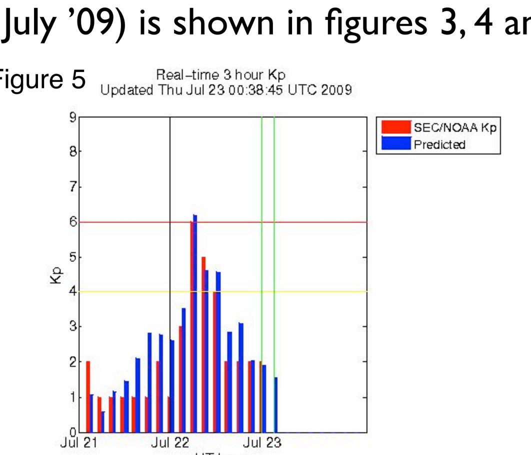


Figure 5



AE Prediction

Figure 6 show the results of our ANN predictions for the AE index covering 14-15 Dec. 2006 during a geomagnetic storm. Predictions are shown in red and the measured value is given in blue.

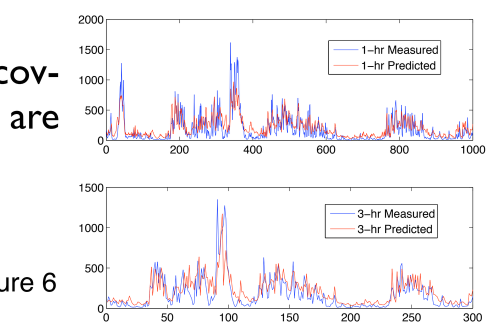


Figure 6

Dst Prediction

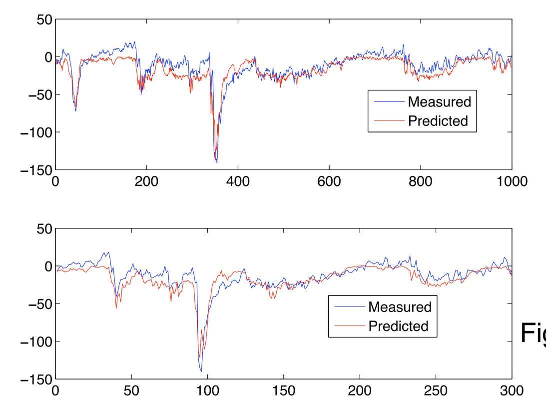


Figure 7

A similar result, covering 14-15 Dec. 2006, is shown for the Dst index in figure 7. Here, the measured Dst index has been corrected for the dynamic pressure according to the BMR equation [Burton et al., 1975].

Persistence Forecasting

As an example, from Bala et al., 2009, at zero lag, the autocorrelation is of the data stream with itself and so is always exactly unity. At the next time step of 3 hours, it shows an autocorrelation at 3 hours of 0.80, defining the persistence (figure 8). In other words, any prediction algorithm that uses prior knowledge of Kp must have a correlation coefficient of greater than 0.80. Conversely, for those that do not use prior Kp data, an 80% correlation coefficient is good.

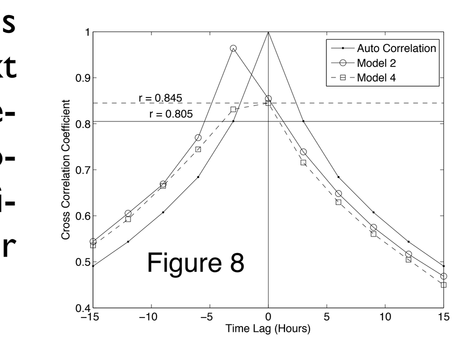


Figure 8

Prediction Summary

Forecast Model	r	RMS Error
Kp: ANN 1-hr using the BI	0.866	0.656
Kp: ANN 3-hr using the BI	0.830	0.741
AE: ANN 1-hr using the BI	0.835	90.86 nT
AE: ANN 3-hr using the BI	0.819	85.66 nT
Dst: ANN 1-hr using the BI	0.778	10.46 nT
Dst: ANN 3-hr using the BI	0.777	9.15 nT

Conclusions

- We can give a reliable Kp forecast with a lead-time of 1-hour (r = 0.866, RMS Error < 1) when using the BI only; for predictions with a lead-time of 3 hour, the correlation coefficient between the predicted and official Kp is found to be 0.830.
- The BI is also good in predicting the AE and Dst indices
- Significantly, our models does not include the history of the target indices instead only use the history of the BI, and therefore do not suffer the problem of "persistence contamination".

References

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