FORECASTING SPACE WEATHER AND EFFECTS USING KNOWLEDGE-BASED NEUROCOMPUTING

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ABSTRACT

Space Weather refers to conditions in space that can influence technological systems and endanger human health and life. In this article we discuss real-time predictions, of solar and geo space weather, and the effects. Our predictions are based on knowledge-based neurocomputing. A presentation is given of the forecast service prototype, that we have developed within the ESA Space Weather Programme Study and Alcatel Space consortium. The prototype is user oriented, updated in real-time and written in Java. For further information please visit Lund Space Weather Center (www.irfl.lu.se). Plans are now outlined for how to implement the prototype for specific users. First out will be users within the Swedish power industry. Plans for future basic research are also briefly discussed.

1. HOW IT ALL STARTED IN LUND

The first contacts with Swedish power companies were taken already in 1980. At that time they were mainly interested in post analysis of solar caused geomagnetic disturbances and effects on power systems. They wanted to know whether or not the power system problems were internal technical or external solar caused. After that they started to ask if predictions were possible. We started in late 1980 to use AI-techniques for modelling and predicting space weather and effects. First we used inductive expert systems [1]. However, we quickly realized that neural networks are much more powerful [2]. The first prediction of Dst, using a neural network and based only on solar wind data as input, was presented 1991 [3].

At that time we outlined a program for predicting the space weather and effects, based on various AI-techniques using mainly neural networks. That became the “Lund Space Weather Model” [4,5].

John Freeman introduced the term “space weather” to focus us on applications within space physics.

The word “Space Weather” was first mentioned in Swedish media in 1991 (Fig. 1). Today it’s mentioned regularly in media and TV. Even space weather forecast service on TV is now discussed.

Fig. 1. The first time space weather (rymdväder in Swedish) was mentioned in Swedish media was in 1991.

The work on the “Lund Space Weather Model” has by now resulted in three Ph.D. Thesis: “Space Weather Physics: Dynamic Neural Network Studies of Solar Wind-Magnetosphere Coupling” by Jian-Guo Wu [6]. “Space Weather Physics: Prediction and classification of solar wind structures and geomagnetic activity using artificial neural networks” by Peter Wintoft [7]. “Solar Wind and Geomagnetic Activity: Predictions using Neural Networks” by Hans Gleisner [8].

Two workshops on “Artificial Intelligence Applications in Solar-Terrestrial Physics” have been held in Lund 1993 and 1997.

Lund will participate in the Alpach summer school 2002 “Space Weather: Physics, Impacts and Predictions.

2. KNOWLEDGE-BASED NEUROCOMPUTING (KBN)

The basis of using neural networks [9] as mathematical models is ”mapping”. Given a dynamic system, a neural network can model it on the basis of a set of examples encoding the input/output behavior of the system. It can learn the mathematical function underlying the system operation (generalize), if the network is designed (architecture, weights) and trained properly (learning algorithm).

Both architecture and weights can be determined from differential equations which describe the causal relations between the physical variables (solution of differential equations is approximated by a Radial-Basis-Function network [10]). The network is then trained with observations.

The architecture (number of input and hidden nodes) can also be determined from dynamic system analysis (reconstruction of the attractor from time series gives dimension).

Neural networks can discover laws from regularities in data (e.g. Newton’s law) [11]. Neural networks can also adapt laws to a changing environment. A solar wind magnetosphere coupling function might e.g. change with time. If one constructs a hierarchy of neural networks where networks at each level can learn knowledge at some level of abstraction, then even more advanced laws can be discovered.

3. ESA/LUND FORECAST SERVICE PROTOTYPE

Fig. 2. Lund Space Weather Forecast Service front web page. At this time a halo CME has occurred on the Sun (red light), a warning (yellow light) for the CME to arrive at L1 is turned on and the conditions are quiet (green light) at Earth.

The Lund Solar and Space Weather Research Group has developed a very extensive prototype [12] in Java, which forecasts, warns and informs about ongoing activity and explains the space weather and effects. The prototype is based on ideas from the work on the Lund Space Weather Model, as mentioned in the introduction, that goes back to the late eighties.

The stoplights, on the front page, show the activity at the Sun, L1 and Earth. The status is updated every 5 minutes. The front page gives the user a fast general overview of what is happening and herewith the basis whether or not actions should be taken. It informs about if activity is ongoing (red), if there is a warning for activity (yellow) or if it’s quiet (green) at the Sun, at L1 or at Earth. The latest SOHO solar images are available by clicking on the Sun. The latest ACE data by clicking at L1 region and the latest Polar images by clicking on Earth.

An introduction to what space weather is and which effects it can cause, are given in the “User Guide” frame. Both a visual dictionary and a glossary are available. The “User Guide” also contains information about what a specific user (Public and Science Tourists, Scientists, Satellite Launch and Operators, Space Agencies (Man in Space), Aircrews, Communication Operators and Power Operators) can learn from the Lund Space Weather Forecast Service.

3.1 The Sun Stoplight Applet

By clicking on each stoplight the three applets, Sun, L1 and Earth, start to run. Real-time data, historical data and forecasts are fetched from the database. This very large database has also been written in Java [13].

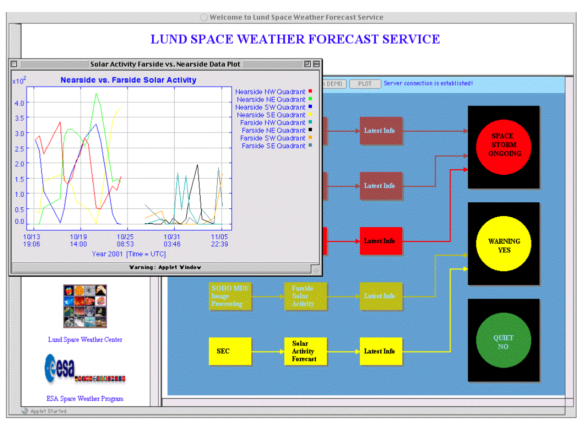

Fig. 3. The plot shows the near and far side solar activity.

The Sun applet produces nowcasts (red and green stoplight) of X-ray solar flares, proton events, partial and halo coronal mass ejections (CMEs) and coronal holes. Forecasts (yellow light) are produced of solar activity 1-3 days and 7-14 days ahead.

Using helioseismological techniques and MDI/SOHO images scientists at Stanford University have managed to construct images of Sun's farside activity. The images are available at the site (http://soi.Stanford.EDU/data/farside/). We have included these images in the database of our prototype. Using these images we can warn for quiet/high activity times 7-14 days ahead.

We have also included forecasts and warnings of solar activity 1-3 days ahead from the Space Environment Center in Boulder in the prototype. These forecasts will however later be replaced with warnings and forecasts from IRF-Lund based on SOHO/MDI solar magnetic field data.

In [14] we decomposed the solar activity in its oscillations and periodicities by using wavelet transforms of the solar mean magnetic field. We used both solar data from Wilcox Solar Observatory and MDI/SOHO. It seems as if oscillations are caused by CMEs, which would facilitate an early detection of CMEs. Today they are detected in SOHO/LASCO and EIT images. We also hope to predict other times of enhanced solar activity by training KBNs the discussed periodicities.

3.2 The L1 Stoplight Applet

The L1 applet produces nowcasts (red/green lights) of whether or not halo CMEs, shocks or fast solar wind have arrived at L1.

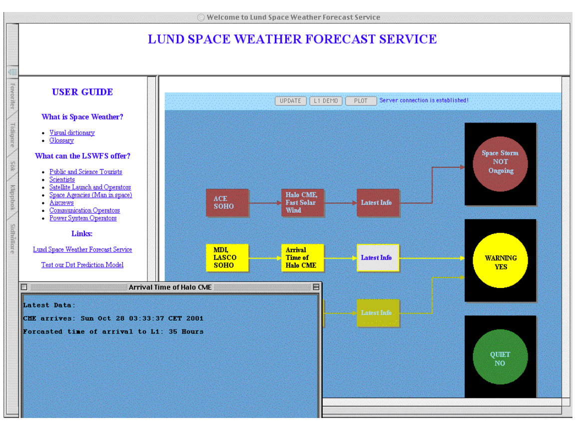

Fig. 4. The "Latest Info" informs about the halo CME, when it will arrive.

Forecasts (yellow light) are produced of the arrival time and velocity of the halo CMEs and fast solar wind at L1.

3.3 The Earth Stoplight Applet

Nowcasts (red/green lights) are produced of geomagnetic storms, communication conditions, geomagnetically induced currents.

Forecasts (yellow lights) are produced of satellite anomalies, communication condition, geomagnetic storms, GICs and aurora.

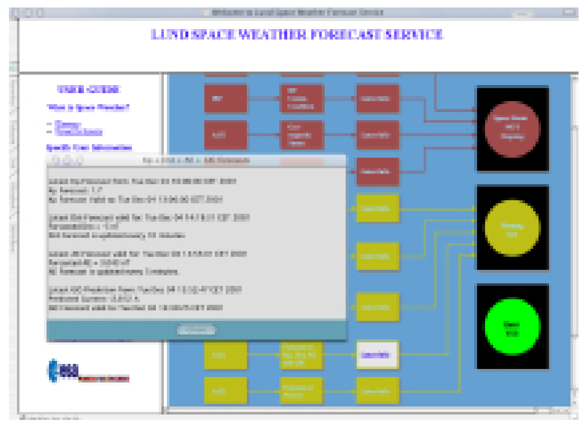

Fig. 5. The "Latest Info" informs about the forecasted Kp, Dst, AE and GIC value.

The neural network prediction model of satellite anomalies was developed within the ESA SAAPS project [15].

All the forecast models use real-time ACE solar wind data as input. Each neural network model has been tested during many years.

The forecasts of GICs are based on local measurements by the Swedish power companies. New and more advanced forecasts of GICs, based on a large set local GIC measurements and use of a model for the power grid, are planned.

The forecasts of aurora are given as probabilities of no, weak or strong. Presently, forecasts are offered for Northern Scandinavia. Forecasts for lower latitudes are planned. The forecasts are also given as SMS and voice messages for mobile phones.

3.4 Forecast models of Dst

Within the ESA Space Weather Programme Study we were asked to show for selected events how well our forecast models worked. We developed a test forecast model of Dst to fulfil that requirement. Dst is forecasted from only solar wind data as input with the use of an Elman recurrent neural network. The forecast model is available from http://sunrise.irfl.lu.se/. The user can test for the selected events. In Fig. 6 the result for the May 2 1998 event is shown. The user can also change the input values for the solar wind and learn how that affects the forecast. The solar wind magnetosphere coupling function learned by the neural network can in this way be explored.

Fig. 6. The forecast model shows a prediction of Dst 1 hour ahead for the selected main phase event May 2, 1998. The observed Dst value for minimum was –205 nT. Our model predicts –212 nT.

Recently we have also put together a web page describing different models predicting Dst and compared them (Fig. 7).

Predictions shown below in Fig. 7 are available in real-time at http://www.irfl.lu.se/rwc/dst/.

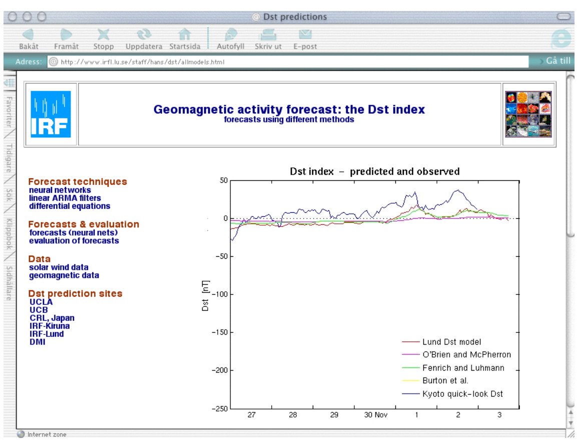

Fig. 7. The plot shows the forecasted Dst value using different methods and the observed value.

Four different models are currently run in real time using the latest solar-wind data from ACE. These models are evaluated on past solar wind-Dst data taken from the OMNI data set. Data from 1963 to 1999 were scanned for periods longer than 10 days and with no data gaps longer than 2 hours. The data set was then further reduced by the requirement that all periods should start at low geomagnetic activity (-15 nT < Dst < 10 nT), and that Dst occasionally should fall below -50 nT during the period. This search resulted in 68 periods covering 41,295 hours.

The models are initiated at the beginning of each test period, and are then run in an iterative mode with only solar-wind data as input. This means that we do not use the models to extrapolate from the latest observed Dst value, but rather to simulate the dynamics of the electrical currents that contribute to the Dst index.

For each model, we first computed the RMS errors and the linear correlations between predicted and observed Dst.

	RMSE	Correlation
Lund Dst model	10.3	0.88
O'Brian and McPherron [16]	12.3	0.83
Fenrich and Luhmann [17]	15.3	0.78
Burton et al. [18]	16.4	0.76

Table 1. Four Dst models compared.

Table 1. shows how successful the forecasts based on knowledge-based neurocomputing are. Something that is expected since the nature of the solar wind magnetosphere coupling is non-linear and multi dimensional. The coupling function might even change with time.

4. DISCUSSIONS

We now plan to implement the prototype for specific users and in a first step for the users within the power industry. However, the flexibility and module nature of the prototype makes it easy to include new and improved models. Parallel to the implementation is therefore basic research carried out within several fields: Predictions of electron flux from solar wind data [19], which is of interest for satellite anomaly forecasts; Predictions of local magnetic fields from solar wind data [20], which is of interest for GIC predictions; Predictions of solar magnetic activity, which is of interest for making long-term forecasts and forecasts of climate changes.

There is an urgent need for improved forecasts of solar activity, days, months and years ahead [21]. The existing forecasts are not very useful for forecasts of space weather effects. Helioseismological studies together with photospheric magnetic field studies, based on SOHO/MDI, may however be the breakthrough. The Sun's interior was found to be much more complex and dynamic than expected. Stanford scientists were able to study the conditions over 100 000 km below an active region. They their found numerous magnetic elements, not a single flux tube, rising to finally forming the active region with sunspots and solar flares. Even further down at the so called tachocline they found new surprises. The dynamo located their and cause of the 11 year solar cycle, showed an 1.3 year periodicity. The same periodicity we also found in our wavelet study of the photospheric mean field. It might be that we can associate the periodicities we found with circulations below the solar surface. If we train the KBN with this new knowledge about the solar activity, then we might have the improved forecast capabilities we so urgently need.

5. SUMMARY

Space weather initiatives started early in Sweden. Early started also the collaboration with the power industry. Knowledge-based neurocomputing gave us the tool to develop forecasts. However, we also needed real-time input data. Not until recently became real-time solar wind data available from ACE, which was a breakthrough for accurate real-time forecasts hours ahead. SOHO started to give us 1995 a new picture of the Sun and a much better way to warn for space weather effects days, even weeks ahead.

Today we have developed a user oriented real-time forecast service. We are now in the process of implementing the service for the user we started to collaborate in early eighties! The output of the forecast service is kept track off, so we know when to improve the service. New and better models will be developed, based on new scientific results. New better data will be available.

The space weather approach has been very successful. It proposes interesting questions of basic research. It promotes collaboration with industry. It creates fun outreach activities.

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