

Space environment (natural and artificial) — Methods for estimation of future geomagnetic activity

Élément introductif — Élément central — Élément complémentaire

Warning

This document is not an ISO International Standard. It is distributed for review and comment. It is subject to change without notice and may not be referred to as an International Standard.

Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

Copyright notice

This ISO document is a working draft or committee draft and is copyright-protected by ISO. While the reproduction of working drafts or committee drafts in any form for use by participants in the ISO standards development process is permitted without prior permission from ISO, neither this document nor any extract from it may be reproduced, stored or transmitted in any form for any other purpose without prior written permission from ISO.

Requests for permission to reproduce this document for the purpose of selling it should be addressed as shown below or to ISO's member body in the country of the requester:

[Indicate the full address, telephone number, fax number, telex number, and electronic mail address, as appropriate, of the Copyright Manager of the ISO member body responsible for the secretariat of the TC or SC within the framework of which the working document has been prepared.]

Reproduction for sales purposes may be subject to royalty payments or a licensing agreement.

Violators may be prosecuted.

Contents

Page

1	Scope	1
2	Terms and definitions	1
3	Prediction	7
3.1	Short-term prediction	7
3.2	Middle-term prediction	9
3.3	Long-term prediction	9
4	Types of prediction method	9
4.1	Prediction based on statistical model	9
4.1.1	Regression analysis	9
4.1.2	Neural network model	9
4.1.3	Prediction filter	10
4.2	Prediction based on physical principle	10
5	Evaluation of prediction efficiency	10
5.1	Definition of prediction error	10
5.2	Methods of evaluation	10
6	Compliance criteria	10
6.1	Rationale	10
6.2	Reporting	10
6.3	Documenting	10
6.4	Publishing	11
6.5	Archiving	11
	Annex A (informative) Web sites where geomagnetic indices are available	12
	Annex B (informative) Web sites where the space weather predictions and/or now casting are presented	13

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16698 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

This International Standard provides guidelines for specifying the process of estimating future geomagnetic activity. Geomagnetic indices describe the variation of the geomagnetic field over a certain time period, and provide a measure of the disturbance of the magnetosphere.

The accuracy and method of prediction of geomagnetic indices depend on a time scale of prediction. This fact introduces some of existing works with 3 classifications of their focusing time scales:

- a) short-term (1 hour to a few days) prediction
- b) middle-term (a few weeks to a few months) prediction
- c) long-term (half year to one solar cycle) prediction

They are required as input parameters for magnetospheric magnetic field (ISO 22009), upper atmosphere (ISO 14222), ionosphere, plasmasphere (ISO/TS 16457), magnetosphere charged particles, and other models of the near Earth space environment. They are also used as the input parameters for orbital lifetime prediction and worst case environment analysis of electrostatic charging.

The Earth magnetic field is provided by three standards including internal magnetic field (ISO 16695 – under development), magnetospheric magnetic field (ISO 22009), and this standard.

Space environment (natural and artificial) — Methods for estimation of future geomagnetic activity

1 Scope

This International Standard specifies the process for estimating geomagnetic indices for time intervals from the short-term (days-a few months) to the long-term (months-years).

Geomagnetic indices are used to describe the activity levels of the disturbance of the geomagnetic field. These indices are applicable to estimate upper atmospheric and plasmaspheric densities and many other space environment models. They are also used as the input parameters for orbital lifetime prediction and worst case environment analysis of electrostatic charging.

2 Terms and definitions

2.1

geomagnetic field variations

variations in internal and external magnetic fields

NOTE 1 Internal (main) magnetic field is produced by the source currents mostly inside the Earth's core and the induced currents in the solid Earth and the ocean caused by the temporal variation of external magnetic fields. External magnetic field is produced by the magnetospheric and the ionospheric currents.

NOTE 2 The magnetosphere is highly dynamic with time scales of minutes to days. The solar wind is the ultimate source of magnetospheric dynamics. The role played by the IMF north-south component, B_z , is particularly important, and its southward component, B_s , plays a fundamental role in substorm and magnetic storm activity through the process of magnetic field line reconnection. The solar wind speed also plays essential role in the dynamics.

2.2

quiet level and disturbance fields

the five days in every month that are selected as the "Five International Quietest Days" by using the Kp index

NOTE 1 A selection of the five quietest days is made regardless of the absolute level of quietness. Thus, in a disturbed month, the quietest days may not be very quiet.

NOTE 2 Derivation: The selection of the quietest days (Q-days) of each month is deduced from the Kp indices on the basis of three criteria for each day: (1) the sum of the eight Kp values, (2) the sum of squares of the eight Kp values, and (3) the maximum of the eight Kp values. According to each of these criteria, a relative order number is assigned to each day of the month, the three order numbers are averaged and the days with the first to fifth lowest mean order numbers are selected as the five international quietest days.

NOTE 3 Reference: Website of Deutsches GeoForschungsZentrum (http://www-app3.gfz-potsdam.de/kp_index/qddescription.html)

NOTE 4 Once the quiet level is determined by using the five international quietest days, disturbance fields can be obtained as deviations from the quiet level of geomagnetic field.

2.3
K index (local 3-hour range index)

a number in the range 0 (quiet) to 9 (disturbed) that classifies locally the observed variations of the geomagnetic field after subtraction of the regular daily variation (Sq)

NOTE 1 Each activity level relates almost logarithmically to the corresponding disturbance amplitude of the horizontal field component during a 3-hour UT interval. In a day, eight K indices are given in successive 3-hour UT intervals (0-3 hr, 3-6 hr, ... , 21-24 hr UT).

NOTE 2 Derivation: The ranges R for the H and D (or X and Y) components are defined as the difference between the highest and lowest deviation, within the three-hour interval, from a smooth curve (a regular daily variation) to be expected for that element on a magnetically quiet day. Only the larger value of R, that is, R for the most disturbed element, is taken as the basis of K. In conversion from R to K, a permanent scale prepared for each observatory is used. Table 1 is an example of the permanent scale for Niemegek observatory.

NOTE 3 References: Bartels et al. [1939], Mayaud [1980], Menvielle et al. [2011]

Table 1 — A permanent scale to convert from R to K for Niemegek observatory

Range (nT)	0-5	5-10	10-20	20-40	40-70	70-120	120-200	200-330	330-500	500-
K value	0	1	2	3	4	5	6	7	8	9

2.4
Kp, ΣKp, ap, and Ap indices (planetary indices)

indices from 13 selected mid-latitude observatories (Table 2) that contribute to the Kp index

NOTE Derivation scheme for each index is described in the corresponding subsection.

Table 2 — Thirteen observatories that contributed to the Kp index

Observatory, Country	Code	GLat (°N)	GLon (°E)	MLat (°)	Notes
Meannook, Canada	MEA	54.617	246.667	62.5	
Sitka, USA	SIT	57.058	224.675	60.0	
Lerwick, Shetland Is.,UK	LER	60.133	358.817	58.9	
Ottawa, Canada	OTT	45.400	284.450	58.9	replaced Agincourt in 1969
Uppsala , Sweden	UPS	59.903	17.353	58.5	replaced Lovo in 2004
Eskdalemuir , UK	ESK	55.317	356.800	54.3	
Brorfelde, Denmark	BJE	55.625	11.672	52.7	replaced Rude Skov in 1984
Fredericksburg , USA	FRD	38.205	282.627	51.8	replaced Cheltenham in 1957

Wingst, Germany	WNG	53.743	9.073	50.9	
Niemegk, Germany	NGK	52.072	12.675	48.8	replaced Witteveen in 1988
Hartland, UK	HAD	50.995	355.517	50.0	replaced Abinger in 1957
Canberra, Australia	CNB	-35.317	149.367	-45.2	replaced Toolangi in 1981
Eyrewell, New Zealand	EYR	-43.424	172.354	-50.2	replaced Amberley in 1978

2.4.1

Kp index (planetary 3-hour range index)

successive 3-hour UT intervals (0-3 hr, 3-6 hr, ... , 21-24 hr UT) giving eight values per UT day and ranges in 28 steps from 0 (quiet) to 9 (disturbed) with intermediate values denoted by -, o, or +, resulting in 0o, 0+, 1-, 1o, 1+, 2-, 2o, 2+, ..., 8-, 8o, 8+, 9-, and 9+

NOTE 1 Derivation: The K indices at the 13 observatories given in Table 2 are standardized by means of conversion tables that have been established through the rather complicated procedure introduced by Bartels [1940]. The standardized K indices, called the Ks index, are averaged with weighting factors to derive the Kp index.

NOTE 2 References: Bartels [1949], Mayaud [1980], Menvielle et al. [2011]

2.4.2

Σ Kp index (planetary daily range index)

sum of 8 Kps of the day.

2.4.3

ap index (planetary 3-hour equivalent amplitude index)

index that is roughly proportional to the geomagnetic disturbances

NOTE 1 The Kp index is not linearly related to the geomagnetic disturbances measured in the unit of nT. One ap unit corresponds to ~2 nT of geomagnetic variations.

NOTE 2 Derivation: The ap index is derived directly from the Kp index by using the conversion table shown in Table 3.

NOTE 3 References: Bartels and Veldkamp [1954], Mayaud [1980], Menvielle et al. [2011]

Table 3 — Conversion table from the Kp index to the ap index

Kp	ap	Kp	ap	Kp	ap
		0o	0	0+	2
1-	3	1o	4	1+	5
2-	6	2o	7	2+	9
3-	12	3o	15	3+	18
4-	22	4o	27	4+	32

5-	39	5o	48	5+	56
6-	67	6o	80	6+	94
7-	111	7o	132	7+	154
8-	179	8o	207	8+	236
9-	300	9o	400		

2.4.4

Ap index (planetary daily equivalent amplitude index)

average of the 8 values of the ap index in a UT day.

2.5

aa index (antipodal amplitude index)

a simple measure of global geomagnetic activity, which can be continuously back to 1868.

NOTE 1 Derivation: The aa index is produced from the K indices of two nearly antipodal magnetic observatories in England and Australia, which are listed in Table 4. The K indices at the two observatories are converted back to amplitudes by using Table 5. The aa index is computed as an average of the northern and southern values of amplitude with weighting factors, λ , shown in Table 4.

NOTE 2 References: Mayaud [1971]

Table 4 — Observatories in England and Australia contributing to the aa index

Observatory, Country Code	Period	GLat (°N)	GLon (°E)	MLat (°)	λ
Greenwich, England	1868-1925				1.007
Ablinger, England ABN	1926-1956	51.18	359.62	53.4	0.934
Hartland, England HAD	1957-	50.97	355.52	54.0	1.059
Melbourne, Australia	1868-1919				0.967
Toolangi, Australia TOO	1920-1979	-37.53	145.47	-45.6	1.033
Canberra, Australia CNB	1979-	-35.30	149.00	-42.9	1.084

Table 5 — Conversion table from the K index at the aa observatories to amplitudes

K index	0	1	2	3	4	5	6	7	8	9
Amplitude	2.3	7.3	15	30	55	95	160	265	415	667

2.6**Dst index (storm time disturbance index)**

a measure of the axially symmetric part of the H component along geomagnetic equator on the ground, and the main physical source is a combination of the equatorial ring current, the plasma sheet current and the magnetopause current

NOTE 1 Derivation: The Dst index is defined as the average of the disturbance variations of the H component, D_i , at the four observatories ($i=1-4$), which is listed in Table 6, divided by the average of the cosines of the dipole latitudes at the observatories for normalization to the dipole equator. Dst is computed for each UT hourly interval from the four observatories.

NOTE 2 References: Sugiura [1964], Sugiura and Kamei [1991]

Table 6 — Four observatories contributing to the Dst index

Observatory, Country	Code	GLat (°N)	GLon (°E)	Dipole Lat (°)
Kakioka, Japan	KAK	36.230	140.190	26.0
San Juan, USA	SJG	18.113	293.850	29.6
Honolulu, USA	HON	21.320	201.998	21.1
Hermanus, South Africa	HER	-34.425	19.225	-33.3

2.7**ASY and SYM indices (mid-latitude disturbance indices)**

the asymmetric and symmetric disturbance fields in mid-latitudes with the high-time of 1 min resolution [longitudinally asymmetric (ASY) and symmetric (SYM) disturbance indices] derived for both the H and D components

NOTE 1 The disturbance fields in mid- and low-latitudes are generally not axially symmetric, in particular, in the developing phase of a magnetic storm. The SYM-H index is approximately the same as the Dst index, while its time resolution is 1 minute.

NOTE 2 Derivation: The ASY/SYM indices are derived from 6 selected mid-latitude observatories (Table 7) in the following four steps: (1) subtraction of the geomagnetic main field and the Sq field to obtain the disturbance field component, (2) coordinate transformation to a dipole coordinate system, (3) calculation of the longitudinally symmetric indices, SYM-H and SYM-D, by taking averages of disturbance fields of the 6 stations, and (4) calculation of the asymmetric disturbance indices, ASY-H and ASY-D, by computing the range between the maximum and the minimum asymmetric fields.

NOTE 3 References: Iyemori et al. [1992], Menvielle et al. [2011]

Table 7 — Four observatories contributing to the SYM/ASY indices

Observatory, Country	Code	GLat (°N)	GLon (°E)	MLat (°)	MLon (°E)	Rotation angle (°)
Memambetsu, Japan	MMB	43.9	144.2	34.6	210.2	-16.1
Honolulu, USA	HON	21.3	202.0	21.5	268.6	0.5
Tuscon, USA	TUC	32.3	249.2	40.4	314.6	2.7
Fredericksburg, USA	FRD	38.2	282.6	49.1	352.2	0.4
Hermanus, South Africa	HER	-34.4	19.2	-33.7	82.7	-10.1
Urmuqu, China	WMQ	43.8	87.7	34.3	162.5	7.7

2.8

AU, AL, AE, and AO indices (auroral electrojet indices)

measures of the intensity of the auroral electrojets and consist of four indices, AU, AL, AE and AO

NOTE 1 The AU and AL indices are intended to express the strongest current intensity of the eastward and westward auroral electrojets, respectively. The AE index represents the overall activity of the electrojets, and the AO index provides a measure of the equivalent zonal current.

NOTE 2 Derivation: The auroral electrojet indices are derived from geomagnetic variations in the H component observed at 12 selected observatories along the auroral zone in the northern hemisphere (Table 8). The AU and AL indices are respectively defined by the largest and the smallest values so selected. The symbols, AU and AL, derive from the fact that these values form the upper and lower envelopes of the superposed plots of all the data from these stations as functions of UT. The difference, AU minus AL, defines the AE index, and the mean value of the AU and AL, i.e. $(AU+AL)/2$, defines the AO index.

NOTE 3 References: Davis and Sugiura [1966], Kamei and Maeda [1981]

Table 8 — Twelve (and obsolete three) observatories contributing to the AE index

Observatory, Country	Code	GLat (°N)	GLon (°E)	MLat (°)	MLon (°E)	Notes
Abisko, Sweden	ABK	68.36	18.82	66.06	114.66	
Dixon Island, Russia	DIK	73.55	80.57	64.04	162.53	
Cape Chelyuskin, Russia	CCS	77.72	104.28	67.48	177.82	

Tixie Bay, Russia	TIK	71.58	129.00	61.76	193.71	
Pebek, Russia	PBK	70.09	170.93	63.82	223.31	Opened in 2001/04
Barrow, USA	BRW	71.30	203.25	69.57	246.18	
College, USA	CMO	64.87	212.17	65.38	261.18	
Yellowknife, Canada	YKC	62.40	245.60	68.87	299.53	
Fort Churchill, Canada	FCC	58.80	265.90	67.98	328.36	
Sanikiluaq, Canada	SNK	56.5	280.8	66.6	349.7	Opened in 2007/12
Narssarssuaq, Denmark	NAQ	61.20	314.16	69.96	37.95	
Leirvogur, Iceland	LRV	64.18	338.30	69.32	71.04	
<hr/>						
Cape Wellen, Russia	CWE	66.17	190.17	62.88	241.36	Closed in 1996
Great Whale River, Russia	GWR	55.27	282.22	65.45	351.77	Closed in 1984/07
Poste-de-la-Baleine, Canada	PBQ	55.27	282.22	65.45	351.77	Opened in 1984/09
						Closed in 2007/11
<hr/>						

NOTE Time lag in the derivation and temporal resolution (sampling): Some of the indices have different class (generation) for operational use. That is, for quasi-real time derivation, different naming is used for them to distinguish from original definition with quality controlled data. For example, in the case of the Dst index, Real-Time (Quick-Look) Dst, Provisional Dst and Final Dst exist, Attempts to increase the temporal resolution of the indices are also made (e.g., Gannon and Love, 2011). (See Annex A).

3 Prediction

The accuracy and method of prediction of geomagnetic indices depend on a time scale of prediction. This section introduces some of existing works with 3 classifications of their focusing time scales: short-term (1 hour to a few days), middle-term (a few weeks to a few months), and long-term (half year to one solar cycle). Some of them are actually used and the results are put online (See Annex B).

3.1 Short-term prediction

Stimulated by the space weather programs, there are many proposed methods and related research papers to predict geomagnetic indices in a time scale of 1 hour to a few days. They are categorized into 4 types: (1) Linear prediction technique, (2) Neural network model, (3) Probabilistic prediction with solar wind data, and (4) MHD simulation. Most of recent techniques need real-time solar wind parameters and near real-time geomagnetic observations as the input. Prediction of the solar wind disturbance from solar surface observation may be a key to improve the geomagnetic index prediction.

Examples of prediction:

Kp, ap, and Ap indices

- McPherron, Predicting the Ap index from past behavior and solar wind velocity, *Phys. Chem. Earth (C)*, 24, 45-56, 1999. (Type 1)
- Boberg et al., Real time Kp predictions from solar wind data using neural networks, *Phys. Chem. Earth (C)*, 25, 275-280, 2000. (Type 2)
- Costello, Moving the Rice MSFM into a real-time forecast mode using solar wind driven forecast models, Ph.D. dissertation, Rice Univ., Houston, Texas, 1997 (<http://hdl.handle.net/1911/19251>). (Type 2)
- Thomson, Non-linear predictions of Ap by activity class and numerical value, *PAGEOPH*, 146, 163-193, 1996. (Type 2)
- Wing et al., Kp forecast models, *J. Geophys. Res.*, 110, A04203, doi:10.1029/2004JA010500, 2005. (Type 2)
- Detman and Joselyn, Real-time Kp predictions from ACE real time solar wind, *Solar Wind Nine*, edited by Habbal et al., *AIP Conf. Proc.*, 271, 729-732, 1999. (Type 2)
- McPherron, Probabilistic forecasting of the 3-h ap index, *IEEE Trans. Plasma Science*, 32, 1425-1438, 2004. (Type 3)

Dst index

- Balikhin et al., Terrestrial magnetosphere as a nonlinear resonator, *Geophys. Res. Lett.*, 28, 1123-1126, 2001. (Type 1)
- Boaghe et al., Identification of nonlinear processes in the magnetospheric dynamics and forecasting of Dst index, *J. Geophys. Res.*, 106, 30047-30066, 2001. (Type 1)
- Iyemori, T. and H. Maeda, Prediction of Geomagnetic Activities from Solar Wind Parameters Based on the Linear Prediction Theory, in *Solar-Terrestrial Predictions Proceedings*, Vol. IV, ed. by R.F. Donnelly, Apr.23-27, 1979, Boulder, 1980. (Type 1)
- Lundstedt, Solar origin of geomagnetic storms and prediction of storms with the use of neural networks, *Surveys in Geophysics*, 17, 561-573, 1996. (Type 2)
- Stepanova et al., Prediction of Dst variations from polar cap indices using time-delay neural network, *J. Atmos. Solar-Terr. Phys.*, 67, 1658-1664, 2005. (Type 2)
- Burton et al., An empirical relationship between interplanetary conditions and Dst, *J. Geophys. Res.*, 80, 4204-4214, 1975. (Type 3)
- O'Brien and McPherron, Forecasting the ring current Dst in real time, *J. Atmos. Solar Terr. Phys.*, 62, 1295-1299, 2000. (Type 3)
- Temerin and Li, A new model for the prediction of Dst on the basis of the solar wind, *J. Geophys. Res.*, 107, 1472, doi:10.1029/2001JA007532, 2002. (Type 3)
- Fok et al., Comprehensive computational model of the Earth's ring current, *J. Geophys. Res.*, 106, 8417-8424, 2001. (Type 4)

AE indices

- Iyemori, T. and H. Maeda, Prediction of Geomagnetic Activities from Solar Wind Parameters Based on the Linear Prediction Theory, in *Solar-Terrestrial Predictions Proceedings*, Vol. IV, ed. by R.F. Donnelly, Apr.23-27, 1979, Boulder, 1980. (Type 1)
- Palocchia et al., AE index forecast at different time scales through an ANN algorithm based on L1 IMF and plasma measurements, *J. Atmos. Solar Terr. Phys.*, 70, 663-668, 2008. (Type 2)

Takalo and Timonen, Neural network prediction of the AE index from the PC index, *Phys. Chem. Earth (C)*, 24, 89-92, 1999. (Type 2)

Li et al., Prediction of the AL index using solar wind parameters, *J. Geophys. Res.*, 112, A06224, doi:10.1029/2006JA011918, 2007. (Type 3)

Kitamura et al., Properties of AE indices derived from real-time global simulation and their implications for solar wind-magnetosphere coupling, *J. Geophys. Res.*, 113, A03S10, doi:10.1029/2007JA012514, 2008. (Type 4)

3.2 Middle-term prediction

There are only a few research papers which use recurrences of geomagnetic disturbances in a time scale of a few weeks to a few months.

Example of prediction:

Zhou and Wei, Prediction of recurrent geomagnetic disturbances by using adaptive filtering, *Earth Planets Space*, 50, 839-845, 1998. (prediction of the Kp index)

3.3 Long-term prediction

For prediction of geomagnetic indices in a time scale of half year to one solar cycle, proposed technique and/or research papers are very few comparing with those of solar activities such as sun spot numbers or F10.7 flux. There could be a possibility to combine the technique of solar activity prediction with solar-geomagnetic disturbance relationship.

Examples of prediction:

Niehuss et al., Statistical technique for intermediate and long-range estimation of 13-month smoothed solar flux and geomagnetic index, *NASA Technical Memorandum 4759*, 1996. (prediction of the Ap index)

Cliver et al., A prediction of geomagnetic activity for solar cycle 23, *J. Geophys. Res.*, 104, 6871-6876, 1999. (prediction of the aa index).

4 Types of prediction method

The prediction methods would be categorized mainly to (1) those based on statistical model and (2) those based on physical principle.

4.1 Prediction based on statistical model

4.1.1 Regression analysis

This method is based on the periodicity of geomagnetic disturbances such as the sun spot cycle, annual or semi-annual variation [see Joselyn, 1995]. For long time scale (one to 10 years) prediction, we need a prediction of sun spot number. [see Feynman and Gu]. Similar technique used in the prediction of F10.7 flux and the Ap index [e.g., Niehuss et al., 1996] would be available.

4.1.2 Neural network model

There exist several models with neural network. This method is applicable for the time scale of several days to sun spot cycle. It has been concluded that the interplanetary magnetic field and solar wind plasma data are significant components for any of the models [see Thomson, 1996; Wing et al., 2005].

4.1.3 Prediction filter

This prediction method uses the data of precedent interval having the length similar to (or longer than) the period to be predicted. The precision of prediction depends, in general, the temporal distance between most recent data and the epoch when we want to predict. There are two types of prediction: One is to use the index of precedent interval as the input data [see Zhou and Wei, 1998] and another is to use the solar wind parameters [see Iyemori and Maeda, 1980; McPherron et al., 2004; Li et al., 2007].

4.2 Prediction based on physical principle

This type of prediction is based on numerical MHD simulation of magnetospheric process or energy principle. These methods need the solar wind parameters as the input. For example, see Burton et al. (1975), Kitamura et al [2008].

5 Evaluation of prediction efficiency

5.1 Definition of prediction error

For a simple time series, the most popular definition of prediction error would be an average of square of differences between the predicted values and the observed values. It is reasonable to adopt this as a measure of prediction error.

5.2 Methods of evaluation

It has been reported that the accuracy of prediction is different for the sun spot maximum and minimum period. It has been also reported that the accuracy is different for different solar cycle. (see Feynman and Gu, 1986) Accuracy is also different for the time scale of prediction. Therefore the prediction efficiency should be shown with specification of various conditions applied for evaluation.

Evaluation of the prediction can be measured by the skill score. In case of a dichotomous forecast, the true skill statistics, the Gilbert skill score, the Heidke skill score, and others can be used (Detman and Joselyn, 1999). In case of prediction of continuous variables, the mean square skill score can be used. (Murphy, 1988). As a method of evaluation, the mean square skill score without "reference model" (see Murphy, 1988) is recommended because the reference (i.e., quiet condition) is normally set zero for geomagnetic indices.

6 Compliance criteria

6.1 Rationale

Prediction principle and scheme should be concisely and clearly described. It is highly required to be published as scientific articles in refereed/peer-review international journals. References of the published articles should be given to public. Otherwise, journal style documents suitable for international journals should be accessible from public.

6.2 Reporting

Prediction results of geomagnetic indices should be open to public for evaluation and application by the third party. Digital values of the prediction results should be given, at least, in the same data format as the corresponding geomagnetic indices, such as the WDC exchange format.

6.3 Documenting

Information of the following items regarding prediction should be clearly documented or displayed.

Input: (1) Types of data, (2) Source of data, (3) Time resolution of data, (4) Number of data points, (5) Time of data acquisition

Output: (1) Types of predicting data, (2) Time of predicting data, (3) Time of prediction performed

Miscellaneous: (1) Types of prediction method (choose one/some from the 4 types listed in section 4, otherwise describe briefly), (2) Point of contact

6.4 Publishing

When the geomagnetic index becomes available, comparison with the prediction results should be conducted. The comparison includes calculation of prediction error, skill score, correlation coefficients, and so on, as listed in section 5.

6.5 Archiving

Results of prediction should be archived and open to public for evaluation.

Annex A (informative)

Web sites where geomagnetic indices are available

(1) GFZ-Potsdam

http://www-app3.gfz-potsdam.de/kp_index/ (Kp)

(2) Service International des Indices Geomagnetiques (ISGI)

<http://isgi.laatos.ipsl.fr/lesdonne.htm> (aa, am, Kp, AE, Dst, PC)

(3) WDC for Geomagnetism, Kyoto

<http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html> (AE, Dst, ASY/SYM)

(4) Arctic and Antarctic Research Institute

http://www.aari.nw.ru/index_en.html (PCS)

(5) WDC for Geomagnetism, Copenhagen

<ftp://ftp.space.dtu.dk/WDC/indices/pcn/> (PCN)

(6) US Geological Survey

<http://geomag.usgs.gov/dst/> (RT-Dst)

Annex B (informative)

Web sites where the space weather predictions and/or now casting are presented

(1) NOAA Space Environment Center

<http://www.sec.noaa.gov/>

(2) Magnetospheric Specification and Forecast model (MSFM)

<http://space.rice.edu/ISTP/dials.html>

(3) International Space Weather Service

<http://www.ises-spaceweather.org/>

(4) NiCT Space Environment Information Service

http://www2.nict.go.jp/y/y223/sw_portal/sw_portal-e.html

(5) Belgium SIDC

<http://sidc.oma.be/>

(6) The Australian Space Weather Agency

http://www.ips.gov.au/Space_Weather

(7) WINDMI model

<http://orion.ph.utexas.edu/~windmi/>

(8) Lund space weather model

<http://www.lund.irf.se/rwc/>

(9) CISM forecast model

<http://www.bu.edu/cism/>

<http://lasp.colorado.edu/cism/>

Bibliography

- Akasofu, S. I., and C. F. FRY (1986), A 1st Generation Numerical Geomagnetic Storm Prediction Scheme, *Planetary and Space Science*, 34, 1, 77-92.
- Baker, D. N., L. F. Bargatze, and R. D. Zwickl (1986), Magnetospheric Response to the Imf - Substorms, *Journal of Geomagnetism and Geoelectricity*, 38, 11, 1047-1073.
- Baker, D. N., R. S. Weigel, F. Rigler, R. L. McPherron, D. Vassilladis, C. N. Arge, G. L. Siscoe, and H. E. Spence (2004), Sun-to-magnetosphere modeling: CISM forecast model development using linked empirical methods, *Journal of Atmospheric and Solar-Terrestrial Physics*, 66, 15-16, 1491-1497.
- Bargatze, L. F., D. N. Baker, R. L. Mcpherron, and E. W. Hones (1985), Magnetospheric Impulse-Response for Many Levels of Geomagnetic-Activity, *Journal of Geophysical Research-Space Physics*, 90, NA7, 6387-6394.
- Bartels, J. (1949) The standardized index, Ks, and the planetary index, Kp, IATME Bulletin 12b, 97.
- Bartels, J., N. H. Heck, and H. F. Johnston (1939), The three-hour-range index measuring geomagnetic activity, *Terr. Magn. Atmos. Electr.*, 44(4), 411-454, doi:10.1029/TE044i004p00411.
- Bartels J, and J. Veldkamp (1954) International data on magnetic disturbances, first quarter, 1954. *J. Geophys. Res.*, 59, 3, 423-427.
- Blanchard, G. T., and R. L. Mcpherron (1995), Analysis of the Linear-Response Function Relating AI to Vbs for Individual Substorms, *Journal of Geophysical Research-Space Physics*, 100, A10, 19155-19165.
- Boaghe, O. M., M. A. Balikhin, S. A. Billings, and H. Alleyne (2001), Identification of nonlinear processes in the magnetospheric dynamics and forecasting of Dst index, *Journal of Geophysical Research-Space Physics*, 106, A12, 30047-30066.
- Boberg, F., P. Wintoft, and H. Lundstedt (2000), Real time Kp predictions from solar wind data using neural networks, *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science*, 25, 4, 275-280.
- Burton, R. K., R. L. Mcpherron, and C. T. Russell (1975), Empirical Relationship between Interplanetary Conditions and Dst, *Journal of Geophysical Research-Space Physics*, 80, 31, 4204-4214.
- Clauer, C. R. (1986), The technique of linear prediction filters applied to studies of solar wind-magnetosphere coupling, in *Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, pp. 39-57, Terra Scientific Publishing Co. .
- Clauer, C. R., R. L. Mcpherron, C. Searls, and M. G. Kivelson (1981), Solar-Wind Control of Auroral-Zone Geomagnetic-Activity, *Geophysical Research Letters*, 8, 8, 915-918.
- Detman, T., and J. A. Joselyn (1999), Real-time Kp predictions from ACE real time solar wind, in *Solar Wind Nine*, edited by S. R. Habbal et al., *AIP Conf. Proc.*, 471, 729-732.
- Detman, T. R., and D. Vassiliadis (1997), Review of techniques for magnetic storm forecasting, in *Magnetic Storms*, edited by B. T. Tsurutani, A. L. C. Gonzalez, Y. Kamide and J. K. Arballo, p. 253, American Geophysical Union, Washington D. C.
- Doggett, K. A. (1993), An operational forecast verification at the Space Environment Laboratory, in *Solar-Terrestrial predictions, IV, Proceedings of a Workshop*, edited by J. Hruska, Ottawa, Canada.
- Doggett, K. A. (1994), Verification of NOAA Space Environment Laboratory Forecasts: 1 January-31 December 1994, in *NOAA Tech. Memo*, edited, p. 64, Boulder, CO. .

- Doxas, I., and W. Horton (1999), Magnetospheric dynamics from a low-dimensional nonlinear dynamics model, *Physics of Plasmas*, 6, 5, 2198-2204.
- Doxas, I., W. Horton, and J. P. Smith (1999), A physics based nonlinear dynamical model for the solar wind driven magnetosphere-ionosphere system, *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science*, 24, 1-3, 67-71.
- Doxas, I., W. Horton, and J. P. Smith (1999), A physics based nonlinear dynamical model for the solar wind driven magnetosphere-ionosphere system, *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science*, 24, 1-3, 67-71.
- Dryer, M., S. I. Akasofu, H. W. Kroehl, R. Sagalyn, S. T. Wu, T. F. Tascione, and Y. Kamide (1986), The solar/interplanetary/magnetosphere/ionosphere connection: a strategy for prediction of geomagnetic storms, *Advances Astro. Sci.*, 58.
- Echer, E., M. V. Alves, and W. D. Gonzalez (2004), Geoeffectiveness of interplanetary shocks during solar minimum (1995-1996) and solar maximum (2000), *Solar Physics*, 221, 2, 361-380.
- Fay, R. A., C. R. Garrity, R. L. McPherron, and L. F. Bargatze (1986), Prediction filters for the Dst index and polar cap potential, in *Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, pp. 111-117, Terra Scientific Publishing Co.
- Foti, M. A., and C. M. Arizmendi (1997), Randomness in geomagnetic storms: Chaos or noise?, *Fractals-an Interdisciplinary Journal on the Complex Geometry of Nature*, 5, 1, 169-173.
- Francoq, C., and M. Menvielle (1996), A model for the am (Km) planetary geomagnetic activity index and application to prediction, *Geophysical Journal International*, 125, 3, 729-746.
- Freeman, J., A. Nagai, P. Reiff, W. Denig, S. Gussenhoven-Shea, M. Heinemann, F. Rich, and M. Hairson (1993), The use of neural networks to predict magnetospheric parameters for input to a magnetospheric forecast model, in *Proceedings of Artificial Intelligence Applications in Solar-Terrestrial Physics Workshop*, edited by J. A. Joselyn, H. Lundstedt and J. Trolinger, pp. 167-181, Lund, Sweden.
- Freeman, J. W., R. A. Wolf, R. W. Spiro, B. A. Hausman, B. Bales, and R. Lambour (1994), *A real time magnetospheric specification model: Magnetospheric Specification and Forecast Model (MSFM) final report*, Rice Univ., Houston, Texas.
- Gannon, J. L., and J. J. Love (2011), USGS 1-min Dst index, *J. Atmos. Solar-Terr. Phys.*, 73, 323-334.
- Gannon, J.L., Love, J.J., Friberg, P.A., Stewart, D.C. & Lisowski, S.W., 2011. U.S. Geological Survey Near Real-Time Dst Index, USGS Open-File Report, 2011-1030, 10 p.
- Gavrishchaka, V. V., and S. B. Ganguli (2001), Support vector machine as an efficient tool for high-dimensional data processing: Application to substorm forecasting, *Journal of Geophysical Research-Space Physics*, 106, A12, 29911-29914.
- Gavrishchaka, V. V., and S. B. Ganguli (2001), Optimization of the neural-network geomagnetic model for forecasting large-amplitude substorm events, *Journal of Geophysical Research-Space Physics*, 106, A4, 6247-6257.
- Gehred, P. A. (1996), Wang and Sheeley medium-range planetary A index forecast verification statistics, in *NOAA Technical Memorandum ERLSEL-91*, edited, Space Environment Center, Boulder, CO. .
- Gholipour, A., C. Lucas, and B. N. Araabi (2004), Black box modeling of magnetospheric dynamics to forecast geomagnetic activity, *Space Weather-the International Journal of Research and Applications*, 2, 7, -.
- Gleisner, H., and H. Lundstedt (1997), Response of the auroral electrojets to the solar wind modeled with neural networks, *Journal of Geophysical Research-Space Physics*, 102, A7, 14269-14278.

- Gleisner, H., and H. Lundstedt (1999), Ring current influence on auroral electrojet predictions, *Annales Geophysicae-Atmospheres Hydrospheres and Space Sciences*, 17, 10, 1268-1275.
- Gleisner, H., and H. Lundstedt (2001), Auroral electrojet predictions with dynamic neural networks, *Journal of Geophysical Research-Space Physics*, 106, A11, 24541-24549.
- Gleisner, H., H. Lundstedt, and P. Wintoft (1996), Predicting geomagnetic storms from solar-wind data using time-delay neural networks, *Annales Geophysicae-Atmospheres Hydrospheres and Space Sciences*, 14, 7, 679-686.
- Gleisner, H., H. Lundstedt, and P. Wintoft (1996), The response of the auroral electrojets to the solar wind modelled with neural networks, *Journal of Geophysical Research*.
- Goertz, C. K., L. H. Shan, and R. A. Smith (1993), Prediction of geomagnetic activity, *Journal of Geophysical Research*, 98, 7673.
- Gonzalez, A. L. C. (1990), A unified view of solar wind-magnetosphere coupling functions, *Planetary and Space Science*, 38, 627-632.
- Gonzalez, W. D., A. Dal Lago, A. L. C. de Gonzalez, L. E. A. Vieira, and B. T. Tsurutani (2004), Prediction of peak-Dst from halo CME/magnetic cloud-speed observations, *Journal of Atmospheric and Solar-Terrestrial Physics*, 66, 2, 161-165.
- Gonzalez, W. D., and E. Echer (2005), A study on the peak Dst and peak negative Bz relationship during intense geomagnetic storms, *Geophysical Research Letters*, 32, 18, -.
- Harrison, R. A., M. A. Hapgood, V. Moore, and E. A. Lucek (1992), An Interplanetary Scintillation Activity Index, *Annales Geophysicae-Atmospheres Hydrospheres and Space Sciences*, 10, 8, 519-526.
- Heckman, G. R. (1979), A summary of the indices and predictions of the Space Environment Services Center, in *Proceedings of International Solar-Terrestrial Predictions Workshop*, edited by R. F. Donnelly, pp. 322-349, U. S. Department of Commerce, Washington D. C. .
- Heinemann, M., N. C. Maynard, D. N. Anderson, and F. Marcos (1993), Space Weather Forecasting System, in *Proceedings of Solar-Terrestrial Predictions-IV, Proceedings of a Workshop*, edited, NOAA, Environment Research Laboratories, Boulder, CO., Ottawa, Canada.
- Hernandez, J. V., T. Tajima, and W. Horton (1993), Neural net forecasting for geomagnetic activity, *Geophysical Research Letters*, 20, 2707.
- Horton, W., and I. Dexas (1998), A low-dimensional dynamical model for the solar wind driven geotail-ionosphere system, *Journal of Geophysical Research-Space Physics*, 103, A3, 4561-4572.
- Horton, W., J. P. Smith, R. Weigel, C. Crabtree, I. Dexas, B. Goode, and J. Cary (1999), The solar-wind driven magnetosphere-ionosphere as a complex dynamical system, *Physics of Plasmas*, 6, 11, 4178-4184.
- Horton, W., J. P. Smith, R. Weigel, C. Crabtree, I. Dexas, B. Goode, and J. Cary (1999), The solar-wind driven magnetosphere-ionosphere as a complex dynamical system, *Physics of Plasmas*, 6, 11, 4178-4184.
- Iyemori, T., T. Araki, T. Kamei, and M. Takeda (1992) Mid-latitude geomagnetic indices ASY and SYM (Provisional), No. 1, 1989-1990, Data Analysis Center for Geomagnetism and Space Magnetism, Kyoto Univ.
- Iyemori, T., H. Maeda, and T. Kamei (1979), Impulse-Response of Geomagnetic Indexes to Inter-Planetary Magnetic-Field, *Journal of Geomagnetism and Geoelectricity*, 31, 1, 1-9.
- Iyemori, T. and H. Maeda (1980), Prediction of Geomagnetic Activities from Solar Wind Parameters Based on the Linear Prediction Theory, in *Solar-Terrestrial Predictions Proceedings*, Vol. IV, ed. by R.F. Donnelly, Apr.23-27, 1979, Boulder.

- Jankovicova, D., P. Dolinsky, F. Valach, and Z. Voros (2002), Neural network-based nonlinear prediction of magnetic storms, *Journal of Atmospheric and Solar-Terrestrial Physics*, 64, 5-6, 651-656.
- Joselyn, J. A. (1986), Real-time prediction of global geomagnetic activity, in *Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, pp. 127-138, Tokyo, Japan.
- Joselyn, J. A. (1995), Geomagnetic-Activity Forecasting - the State-of-the-Art, *Reviews of Geophysics*, 33, 3, 383-401.
- Kamei, T., and H. Maeda (1981) Auroral electrojet indices (AE) for January-June 1978, World Data Center C2 for Geomagnetism Data Book, No. 3, Data Analysis Center for Geomagnetism and Space Magnetism, Kyoto Univ.
- Kamide, Y., W. Baumjohann, I. A. Daglis, W. D. Gonzalez, M. Grande, J. A. Joselyn, R. L. McPherron, J. L. Phillips, E. G. D. Reeves, G. Rostoker, A. S. Sharma, H. J. Singer, B. T. Tsurutani, and V. M. Vasyliunas (1998), Current understanding of magnetic storms: Storm-substorm relationships, *Journal of Geophysical Research-Space Physics*, 103, A8, 17705-17728.
- Kane, R. P. (2005), How good is the relationship of solar and interplanetary plasma parameters with geomagnetic storms?, *Journal of Geophysical Research-Space Physics*, 110, A2, -.
- Klimas, A. J., D. Vassiliadis, and D. N. Baker (1997), Data-derived analogues of the magnetospheric dynamics, *Journal of Geophysical Research-Space Physics*, 102, A12, 26993-27009.
- Klimas, A. J., D. Vassiliadis, and D. N. Baker (1998), Dst index prediction using data-derived analogues of the magnetospheric dynamics, *Journal of Geophysical Research-Space Physics*, 103, A9, 20435-20447.
- Klimas, A. J., D. Vassiliadis, D. N. Baker, and D. A. Roberts (1996), The organized nonlinear dynamics of the magnetosphere, *Journal of Geophysical Research-Space Physics*, 101, A6, 13089-13113.
- Klimas, A. J., D. Vassiliadis, D. N. Baker, and J. A. Valdivia (1999), Data-derived analogues of the solar wind-magnetosphere interaction, *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science*, 24, 1-3, 37-44.
- Kugblenu, S., S. Taguchi, and T. Okuzawa (1999), Prediction of the geomagnetic storm associated D-st index using an artificial neural network algorithm, *Earth Planets and Space*, 51, 4, 307-313.
- Lathuillere, C., M. Menvielle, J. Liliensten, T. Amari, and S. M. Radicella (2002), From the Sun's atmosphere to the Earth's atmosphere: an overview of scientific models available for space weather developments, *Annales Geophysicae*, 20, 7, 1081-1104.
- Li, X., M. Temerin, D. N. Baker, E. G. D. Reeves, D. Larson, and S. G. Kanekal (2003), The predictability of the magnetosphere and space weather, *Eos Transactions of American Geophysics Union*, 84, 37, 369-370.
- Love, J. J. & Gannon, J. L., 2009. Revised Dst and the epicycles of magnetic disturbance: 1958-2007, *Ann. Geophys.*, 27, 3101-3131.
- Luhmann, J. G., S. C. Solomon, J. A. Linker, J. G. Lyon, Z. Mikic, D. Odstrcil, W. B. Wang, and M. Wiltberger (2004), Coupled model simulation of a Sun-to-Earth space weather event, *Journal of Atmospheric and Solar-Terrestrial Physics*, 66, 15-16, 1243-1256.
- Lundstedt, H. (1992), Neural Networks and Predictions of Solar Terrestrial Effects, *Planetary and Space Science*, 40, 4, 457-464.
- Lundstedt, H. (1992), A trained neural network, geomagnetic activity and solar wind variation, in *Proceedings of Solar-Terrestrial Workshop*, edited by M. A. Shea, pp. 607-610, NOAA, Ottawa, Canada.

- Lundstedt, H. (1996), Solar origin of geomagnetic storms and prediction of storms with the use of neural networks, *Surveys in Geophysics*, 17, 5, 561-573.
- Lundstedt, H. (1997), AI techniques in geomagnetic storm forecasting, in *Magnetic Storms*, edited by B. T. Tsurutani, A. L. C. Gonzalez, Y. Kamide and J. K. Arballo, pp. 243-252, American Geophysical Union, Washington D. C. .
- Lundstedt, H. (1998), Lund Space Weather Model: Status and Future Plans, in *Proceedings of the 2nd Workshop on AI applications in Solar-Terrestrial Physics*, edited, pp. 107-112, ESA WPP-148, Paris, Lund, Sweden.
- Lundstedt, H. (2002), Forecasting Space Weather and Effects Using Knowledge-Based Neurocomputing in *Proceedings of ESA Workshop on Space Weather: Looking Towards a European Space Weather Programme*, edited, ESA, Noordwijk, the Netherlands.
- Lundstedt, H., H. Gleisner, and P. Wintoft (2002), Operational forecasts of the geomagnetic Dst index, *Geophysical Research Letters*, 29, 24, -.
- Lundstedt, H., and P. Wintoft (1994), Prediction of Geomagnetic Storms from Solar-Wind Data with the Use of a Neural-Network, *Annales Geophysicae-Atmospheres Hydrospheres and Space Sciences*, 12, 1, 19-24.
- Lundstedt, H., P. Wintoft, J. G. Wu, and H. Gleisner (1995), AI methods and space weather forecasting, in *Proceedings of Artificial Intelligence and Knowledge Based System for Space, 5th Workshop, 10-11, Oct.*, edited, ESTEC, ESA.
- Macpherson, K. P., A. J. Conway, and J. C. Brown (1995), Prediction of Solar and Geomagnetic-Activity Data Using Neural Networks, *Journal of Geophysical Research-Space Physics*, 100, A11, 21735-21744.
- Marubashi, K. (1989), The Space Weather Forecast Program, *Space Science Reviews*, 51, 1-2, 197-214.
- Maruyama, T. (1986), Coupling function between the solar wind and the Dst index, in *Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, pp. 119-126, Terra Scientific Publishing Co. .
- McAllister, A. H., S. F. Martin, N. U. Crooker, R. P. Lepping, and R. J. Fitzenreiter (2001), A test of real-time prediction of magnetic cloud topology and geomagnetic storm occurrence from solar signatures, *Journal of Geophysical Research-Space Physics*, 106, A12, 29185-29194.
- McPherron, R. L. (1999), Predicting the Ap index from past behavior and solar wind velocity, *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science*, 24, 1-3, 45-56.
- McPherron, R. L., D. N. Baker, and L. F. Bargatze (1986), Linear filters as a method of real time prediction of geomagnetic activity, in *Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, pp. 85-92, Terra Scientific Publishing Co. .
- McPherron, R. L., R. A. Fay, C. R. Garrity, L. F. Bargatze, D. N. Baker, C. R. Clauer, and C. Searls (1984), Coupling of the solar wind to measures of magnetic activity, in *Proc. Conf. Achievement of the IMS*, edited, pp. 161-170, ESA SP-217, Graz, Austria.
- McPherron, R. L., G. Siscoe, and N. Arge (2004), Probabilistic forecasting of the 3-h ap index, *IEEE Transactions on Plasma Science*, 32, 4, 1425-1438.
- Meng, C. I., and B. T. Tsurutani (1973), Cross-correlation analysis of the AE index and the interplanetary magnetic field Bz component, *Journal of Geophysical Research*, 78, 617.
- Menvielle, M., T. Iyemori, A. Marchaudon, and M. Nosé, Geomagnetic indices, in *Geomagnetic Observations and Models*, IAGA Special Sopron Book Series, Vol. 5, edited by M. Manda and M. Korte, pp. 183-228, Springer, doi:10.1007/978-90-481-9858-0_8, 2011.

- Mugellesi, R., and D. J. Kerridge (1991), Prediction of Solar and Geomagnetic-Activity for Low-Flying Spacecraft, *Esa Journal-European Space Agency*, 15, 2, 123-134.
- Munsami, V. (2000), Determination of the effects of substorms on the storm-time ring current using neural networks, *Journal of Geophysical Research-Space Physics*, 105, A12, 27833-27840.
- Murphy, A. H. (1988), Skill scores based on the mean square error and their relationships to the correlation coefficient, *Monthly Weather Rev.*, 116, 2417-2424.
- O'Brien, T. P., and R. L. McPherron (2000), Forecasting the ring current index Dst in real time, *Journal of Atmospheric and Solar-Terrestrial Physics*, 62, 1295-1299.
- Price, C. P., and D. Prichard (1993), The Nonlinear Response of the Magnetosphere - 30 October 1978, *Geophysical Research Letters*, 20, 9, 771-774.
- Price, C. P., D. Prichard, and J. E. Bischoff (1994), Nonlinear Input-Output-Analysis of the Auroral Electrojet Index, *Journal of Geophysical Research-Space Physics*, 99, A7, 13227-13238.
- Prichard, D., and C. P. Price (1992), Spurious dimension estimates from time series of geomagnetic indices, *Geophysical Research Letters*, 19, 1623.
- Roberts, D. A., D. N. Baker, A. J. Klimas, and L. F. Bargatze (1991), Indications of Low Dimensionality in Magnetospheric Dynamics, *Geophysical Research Letters*, 18, 2, 151-154.
- Rostoker, G., and C. G. Falthammer (1967), Relationship between changes in the interplanetary magnetic field and variations in the magnetic field at the Earth's surface *Journal of Geophysical Research*, 72, 5853.
- Rucker, H. O., and K. J. Trattner (1991), Solar-Wind Terrestrial Magnetosphere Coupling - Application of Linear Prediction-Theory, *Journal of Atmospheric and Terrestrial Physics*, 53, 11-12, 1069-1072.
- Rusanov, A. A., and A. A. Petrukovich (2004), Influence of solar wind parameters on the level of geomagnetic field fluctuations, *Cosmic Research*, 42, 4, 354-361.
- Sharma, A. S. (1995), Assessing the nonlinear behavior of the magnetosphere: Its dimension is low, its predictability is high, *Reviews of Geophysics*, 33, 645.
- Siscoe, G., D. Baker, R. Weigel, J. Hughes, and H. Spence (2004), Roles of empirical modeling within CISM, *Journal of Atmospheric and Solar-Terrestrial Physics*, 66, 15-16, 1481-1489.
- Smith, J. P., and W. Horton (1998), Analysis of the bimodal nature of solar wind-magnetosphere coupling, *Journal of Geophysical Research-Space Physics*, 103, A7, 14917-14923.
- Snyder, C. W., and M. Neugebauer (1963), Solar Wind Velocity and Its Correlation with Cosmic-Ray Variations and with Solar and Geomagnetic Activity, *Journal of Geophysical Research*, 68, 24, 6361-&.
- Srivastava, N. (2005), Predicting the occurrence of super-storms, *Annales Geophysicae*, 23, 9, 2989-2995.
- Stepanova, M., E. Antonova, and O. Troshichev (2005), Prediction of D-st variations from Polar Cap indices using time-delay neural network, *Journal of Atmospheric and Solar-Terrestrial Physics*, 67, 17-18, 1658-1664.
- Sugiura, M. (1964) Hourly values of equatorial Dst for the IGY, *Annals of International Geophysics Year*, vol. 35, p. 9-45, Pergamon Press, Oxford.
- Sugiura, M, and T. Kamei (1991) Equatorial Dst index 1957–1986, IAGA Bulletin No. 40.
- Takalo, J., and J. Timonen (1997), Neural network prediction of AE data, *Geophysical Research Letters*, 24, 19, 2403-2406.

- Takalo, J., and J. Timonen (1998), On the relation of the AE and PC indices, *Journal of Geophysical Research-Space Physics*, 103, A12, 29393-29398.
- Takalo, J., and J. Timonen (1999), Neural network prediction of the AE index from the PC index, *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science*, 24, 1-3, 89-92.
- Temerin, M., and X. L. Li (2002), A new model for the prediction of Dst on the basis of the solar wind, *Journal of Geophysical Research-Space Physics*, 107, A12, -.
- Thomson, A. W. P. (1992), Neural Networks and Non-linear Prediction Filters for the Ap Geomagnetic Index, in *Brit. Geol. Surv. Tech. Rept.*, edited, p. WM/92/33.
- Thomson, A. W. P. (1993), The use of solar activity data in the short-term prediction of the Ap geomagnetic index, in *Brit. Geol. Surv. Tech. Rept.*, edited, p. WM/93/19R.
- Thomson, A. W. P. (1996), Non-linear predictions of Ap by activity class and numerical value, *Pure and Applied Geophysics*, 146, 1, 163-193.
- Trattner, K. J., and H. O. Rucker (1990), Linear prediction theory in studies of solar wind-magnetosphere coupling, *Annales Geophysicae*, 8, 733-738.
- Tsurutani, B. T., and W. D. Gonzalez (1995), The Future of Geomagnetic Storm Predictions - Implications from Recent Solar and Interplanetary Observations, *Journal of Atmospheric and Terrestrial Physics*, 57, 12, 1369-1384.
- Tsurutani, B. T., W. D. Gonzalez, A. L. C. Gonzalez, F. Tang, J. K. Arballo, and M. Okada (1995), Interplanetary Origin of Geomagnetic-Activity in the Declining Phase of the Solar-Cycle, *Journal of Geophysical Research-Space Physics*, 100, A11, 21717-21733.
- Ukhorskiy, A. Y., M. I. Sitnov, A. S. Sharma, and K. Papadopoulos (2002), Global and multiscale aspects of magnetospheric dynamics in local-linear filters, *Journal of Geophysical Research-Space Physics*, 107, A11, -.
- Ukhorskiy, A. Y., M. I. Sitnov, A. S. Sharma, and K. Papadopoulos (2003), Combining global and multi-scale features in a description of the solar wind-magnetosphere coupling, *Annales Geophysicae*, 21, 9, 1913-1929.
- Ukhorskiy, A. Y., M. I. Sitnov, A. S. Sharma, and K. Papadopoulos (2004), Global and multi-scale features of solar wind-magnetosphere coupling: From modeling to forecasting, *Geophysical Research Letters*, 31, 8.
- Valdivia, J. A., A. S. Sharma, and K. Papadopoulos (1996), Prediction of magnetospheric storms by nonlinear dynamical models, *Geophysical Research Letters*.
- Valdivia, J. A., D. Vassiliadis, A. Klimas, A. S. Sharma, and K. Papadopoulos (1999), Spatiotemporal activity of magnetic storms, *Journal of Geophysical Research-Space Physics*, 104, A6, 12239-12250.
- Vallee, M. A., L. Newitt, R. Dumont, and P. Keating (2005), Correlation between aeromagnetic data rejection and geomagnetic indices, *Geophysics*, 70, 5, J33-J38.
- Vassiliadis, D. (1994), The input-state space approach to the prediction of auroral geomagnetic activity from solar wind variables, in *Proceedings of the International Workshop on Artificial Intelligence Applications in Solar Terrestrial Physics*, edited by J. A. Joselyn, H. Lundstedt and J. Trolinger, pp. 141-151, NOAA, Boulder.
- Vassiliadis, D., V. Angelopoulos, D. N. Baker, and A. J. Klimas (1996), The relation between the northern polar cap and auroral electrojet geomagnetic indices in the wintertime, *Geophysical Research Letters*, 23, 20, 2781-2784.

- Vassiliadis, D., and A. J. Klimas (1995), On the Uniqueness of Linear Moving-Average Filters for the Solar Wind-Auroral Geomagnetic-Activity Coupling, *Journal of Geophysical Research-Space Physics*, 100, A4, 5637-5641.
- Vassiliadis, D., A. J. Klimas, and D. N. Baker (1996), Nonlinear ARMA models for the Dst index and their physical interpretation, in *Proceedings of the Third International Conference on Substorms (ICS-3)*, edited, Versailles, France.
- Vassiliadis, D., A. J. Klimas, and D. N. Baker (1999), Models of D-st geomagnetic activity and of its coupling to solar wind parameters, *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science*, 24, 1-3, 107-112.
- Vassiliadis, D., A. J. Klimas, D. N. Baker, and D. A. Roberts (1995), A description of solar wind magnetosphere coupling based on nonlinear filters, *Journal of Geophysical Research*.
- Vassiliadis, D., A. J. Klimas, D. N. Baker, and D. A. Roberts (1996), Nonlinear predictor error for the vBz-AL coupling, *Journal of Geophysical Research*.
- Vassiliadis, D., A. J. Klimas, J. A. Valdivia, and D. N. Baker (1999), The D-st geomagnetic response as a function of storm phase and amplitude and the solar wind electric field, *Journal of Geophysical Research-Space Physics*, 104, A11, 24957-24976.
- Vassiliadis, D., A. J. Klimas, J. A. Valdivia, and D. N. Baker (2000), The nonlinear dynamics of space weather, *Space Weather: Physics and Applications*, 26, 1, 197-207.
- Vassiliadis, D., A. S. Sharma, and K. Papadopoulos (1993), An Empirical-Model Relating the Auroral Geomagnetic-Activity to the Interplanetary Magnetic-Field, *Geophysical Research Letters*, 20, 16, 1731-1734.
- Voros, Z., and D. Jankovicova (2002), Neural network prediction of geomagnetic activity: a method using local Holder exponents, *Nonlinear Processes in Geophysics*, 9, 5-6, 425-433.
- Watanabe, S., E. Sagawa, K. Ohtaka, and H. Shimazu (2003), Operational models for forecasting Dst, *Space Weather* 2000, 31, 4, 829-834.
- Wei, F. S., and S. Q. Liu (1996), Prediction of geomagnetic disturbance profile from interplanetary shock wave energy transfer index, F-s, in interplanetary space, *Journal of Geomagnetism and Geoelectricity*, 48, 3, 291-297.
- Wei, H. L., S. A. Billings, and M. Balikhin (2004), Analysis of the geomagnetic activity of the D-st index and self-affine fractals using wavelet transforms, *Nonlinear Processes in Geophysics*, 11, 3, 303-312.
- Wei, H. L., S. A. Billings, and M. Balikhin (2004), Prediction of the Dst index using multiresolution wavelet models, *Journal of Geophysical Research-Space Physics*, 109, A7, -.
- Weigel, R. S., W. Horton, T. Tajima, and T. Detman (1999), Forecasting auroral electrojet activity from solar wind input with neural networks, *Geophysical Research Letters*, 26, 10, 1353-1356.
- Weigel, R. S., A. J. Klimas, and D. Vassiliadis (2003), Solar wind coupling to and predictability of ground magnetic fields and their time derivatives, *Journal of Geophysical Research*, 108, A7, doi:10.1029JA009627.
- Wing, S., J. R. Johnson, J. Jen, C. I. Meng, D. G. Sibeck, K. Bechtold, J. Freeman, K. Costello, M. Balikhin, and K. Takahashi (2005), Kp forecast models, *Journal of Geophysical Research-Space Physics*, 110, A4, -.
- Wu, C. C., and R. P. Lepping (2005), Relationships for predicting magnetic cloud-related geomagnetic storm intensity, *Journal of Atmospheric and Solar-Terrestrial Physics*, 67, 3, 283-291.

- Wu, J. G., and H. Lundstedt (1996), Prediction of geomagnetic storms from solar wind data using Elman recurrent neural networks, *Geophysical Research Letters*, 23, 4, 319-322.
- Wu, J. G., and H. Lundstedt (1997), Neural network modeling of solar wind magnetosphere interaction, *Journal of Geophysical Research-Space Physics*, 102, A7, 14457-14466.
- Wu, J. G., and H. Lundstedt (1997), Geomagnetic storm predictions from solar wind data with the use of dynamic neural networks, *Journal of Geophysical Research-Space Physics*, 102, A7, 14255-14268.
- Yermolaev, Y. I., and M. Y. Yermolaev (2002), Statistical relationships between solar, interplanetary, and geomagnetospheric disturbances, 1976-2000, *Cosmic Research*, 40, 1, 1-14.
- Zhou, X. Y., and F. S. Wei (1998), Prediction of recurrent geomagnetic disturbances by using adaptive filtering, *Earth Planets and Space*, 50, 10, 839-845.