Operational Space Weather Models & Supporting Data

The improvement and transitioning of research models to operations permit more reliable forecasts of the geomagnetic environment.

Wang-Sheeley-Arge Model:

The Wang-Sheeley-Arge (WSA) model is a combined empirical and physics-based representation of the quasi-steady global solar wind flow that is used to predict the background solar wind speed and the interplanetary magnetic field (IMF) polarity at Earth. It uses photospheric magnetic field data from three ONR-supported solar observatories (i.e., Wilcox, Mount Wilson, and Kitt Peak) as input to a magnetostatic model of the coronal expansion. Real-time solar wind predictions are routinely made available and current to NOAA/SEC forecasters and to the broader research community via an SEC web page. The model has been substantially improved recently (e.g., Figure 1) through the incorporation of an upper coronal model and the development of a significantly better empirical relationship used to assign solar wind speed near the Sun. The next upgrade planned for the WSA prediction scheme is the replacement of the simple 1-D modified kinematical model currently used to describe the solar wind flow out to Earth with the more advanced Zeus-3D magnetohydrodynamic (MHD) code.

Project Personnel: Charles N. Arge, Victor J. Pizzo, Dusan Odstrcil, and Leslie R. Mayer
Funding Sources: Office of Naval Research (ONR), National Science Foundation (NSF), and the Air Force Office of Scientific Research (AFOSR).

References:

Arge, C. N., D. Odstrcil, V. J. Pizzo, and L. R. Mayer. in press, 2003. Improved Method for Specifying Solar Wind Speed Near the Sun, Proc. of the Tenth Internat. Solar Wind Confer.

Arge, C. N., S. Wahl, J. Chen, S. Slinker, and V. J. Pizzo. 2002. Implementation and Verification of the Chen Prediction Technique for Forecasting Large Nonrecurrent Storms, Proceedings of the COSPAR Colloquia Series. 14:393-396.

Wang & Sheeley Model: http://www.sec.noaa.gov/ws/

Chen Model: http://www.sec.noaa.gov/chen/

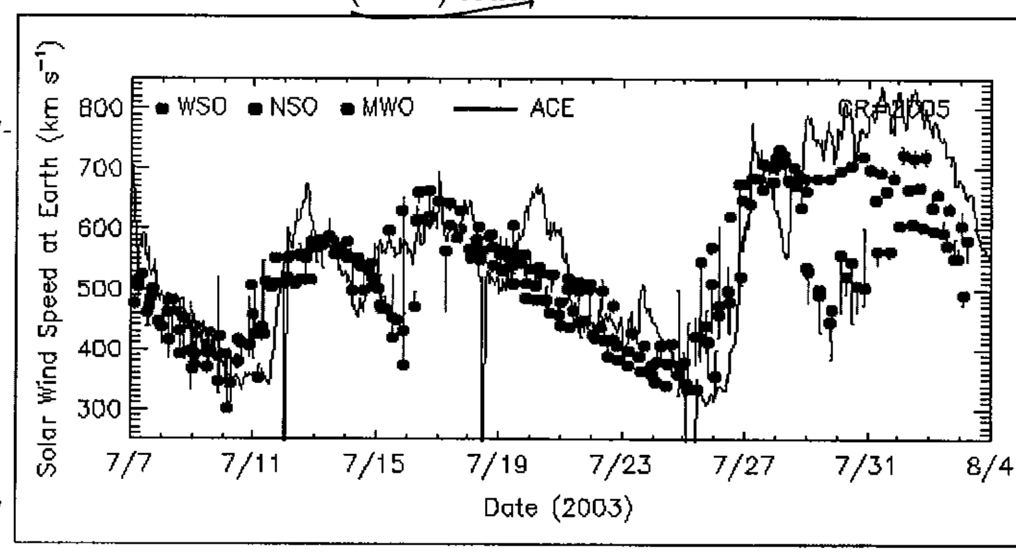


Fig. 1 Comparison of real-time ACE solar wind speed data (solid black line) with WSA model predictions (colored dots) for Carrington Rotation 2005. The three sets of predictions (i.e., red, green, and blue dots) are based on data from, respectively, Wilcox (WSO), Mount Wilson (MWO) and Kitt Peak (NSO) solar observatories. The vertical bars associated with the colored dots are uncertainty estimates of the solar wind speed predictions, which are determined by calculating the predicted solar wind speeds for the expansion factors located 2.5 degrees above and below the sub-earth point.

Costello Geomagnetic Activity Index

Introduction

The Costello Geomagnetic Activity Index model was developed by Kirt Costello at Rice University under support from the US Air Force and Sterling Software, Inc. It is a neural network algorithm that was trained on the response of the Kp geomagnetic activity index to solar wind parameters. The model takes the most recent two hours of solar wind data and returns a 3-hour activity index prediction in units of Kp. The valid time of the prediction is indicated on the output graphics by horizontal bars. SEC's test product based on this model is an estimate of the geomagnetic activity level, in Kp units, generated every 15 minutes. The following is a brief description of the test product and supporting information:

Latest Output (1-day)

This graphic shows the latest output over the past 24 hours in two panels. The top panel plots the magnitude of the predicted index in Kp units and the 3-hour interval over which the prediction is valid. Error bars are plotted on the most recent prediction to show the 50% confidence interval. There is also an overplot of the most recent observed estimates of the Kp index as determined by the US Air Force. The predictions are color coded according to the amount of solar wind data that was available for each model run, ranging from green (most data) to yellow (little data). The bottom panel plots the lead time of the prediction which is the propagation time from L1 to the Earth. The plot will automatically update after each model run (every 15 minutes).

Latest Output (7-day)

This graphic is similar to the 1-day plot but shows the most recent 7 days of model output. In addition, simple statistics are calculated to characterize the model's performance in terms of accuracy (rms error), bias (mean error), association (correlation), and skill or prediction efficiency (relative error). This plot, as well as the statistics, are updated after each model run (every 15 minutes).

Output List

This is a tabulated listing of model output that includes the model run time, valid time of the prediction, magnitude of the prediction in Kp units, the prediction lead time (L1 propagation time), and the observed estimate of the Kp index.

Historical Validation

These pages summarize an SEC in-house study of the model performance using ISEE-3 solar wind observations as input. The error bars on the real-time plots are derived from this study.

References

This is a short list of relevant references, including an on-line poster paper by Kirt Costello that gives a brief overview of the model.

Space Weather Highlights
09 - 15 May 2005

SWO PRF 1550
17 May 2005

Solar activity ranged from low to high. The majority of the period's activity was split between two very active regions, Region 758 (S10, L=141, class/area, Ekc/630 on 11 May) and new Region 759 (N14, L=052, class/area, Ehi/540 on 09 May). During the summary period, Region 758 was responsible for 24 C-class and 3 M-class flares, while Region 759 had 14 C-class and 3 M-class flares observed. Of these flares, two M-class flares were significant. On 11 May at 1939 UTC, Region 758 produced an M1.1/Sf long duration event (LDE) with an accompanying full halo CME. LASCO/EIT imagery detected the mean plane-of-sky speed of the CME at about 470 km/s. Later in the summary period, Region 759 produced an M8.0/2b LDE at 13/1657 UTC with Type II (1349 km/s) and Type IV sweeps and a 2900 sfu Tenflare. LASCO/EIT imagery observed a bright, full halo CME. Because of limited imagery, the mean plane-of-sky speed could only be estimated at between 794 - 1020 km/s. Other activity included an impulsive M3.5/1n flare at 15/2236 UTC from new Region 763 (S15, L=015, class/area, Dao/200 on 13 May). The remainder of the disk and limb were quiet and stable.

Solar wind data were available from the NASA Advanced Composition Explorer (ACE) spacecraft during most of the summary period. Solar wind speed ranged from a low of 455 km/s early on 11 May to a high of 1000 km/s near 15/0900 UTC. The period began with solar wind speed elevated near 670 km/s and the IMF Bz ranging between – 8 to + 5 nT as effects from a coronal hole high speed wind stream waned. By the end-of-day on 09 May, wind speed had decayed to 515 km/s and the IMF Bz had relaxed to +/- 5 nT. These trends persisted through late on 12 May. By 12/2100 UTC, ACE data indicated an increase in density and a slight increase in wind speed from about 490 km/s to 525 km/s as effects from the 11 May CME became geoeffective. The IMF Bz stayed mostly south at -7 nT. By 13/1600 UTC, wind speed increased to 615 km/s. Thereafter, through early on 15 May, wind speed slowly decayed and the IMF Bz did not vary much beyond +/- 4 nT.
Early on 15 May, effects from the large, full halo CME from the 13 May M8.0 flare arrived at Earth. At 15/0238 UTC, the Boulder magnetometer recorded a 67 nT sudden impulse. Solar wind jumped from 460 km/s to near 900 km/s and the IMF Bz turned sharply southward and by 0600 UTC, it read -43 nT. By about 0800 UTC, the Bz turned northward and the total field remained strong near 56 nT. The IMF Bz remained northward through about 1700 UTC when it turned south to about -9 nT and remained so for the remainder of the summary period. By 0900 UTC, wind speed reached its maximum of 1000 km/s, but for the remainder of the 15th, velocity rapidly decayed and ended the summary period near 740 km/s.

A greater than 10 MeV proton event began at 14/0525 UTC. The peak of 3140 pfu occurred at 15/0240 UTC, following the CME shock arrival, and ended at 15/1120 UTC. The suspected source of this event was believed to be the 13 May M8.0 flare.

The greater than 2 MeV electron flux at geosynchronous orbit reached high levels on 11 – 15 May.

The geomagnetic field ranged from quiet to severe storm levels. The period began with quiet to active conditions through 12 May. Isolated minor storming was observed at high latitudes midday on 11 May and late on 12 May, while an isolated major storm period occurred midday on the 12th. By early on 13 May, active to minor storming, with periods of high latitude major storming, were observed as effects from the 11 May CME became geoeffective. These conditions persisted through most of the 13th. For the remainder of the 13th, and through 14 May, conditions relaxed to quiet to unsettled. Early on 15 May, geomagnetic conditions increased significantly as the CME shock from the 13 May M8.0 flare arrived. Through the first 12 hours of the 15th, the field was at minor to severe storming, but by 1500 UTC, and through the end of the summary period, conditions relaxed to mostly active to minor storming.

Space Weather Outlook
18 May - 13 June 2005

Solar activity is expected be at low to moderate levels. Further M-class activity is possible from Regions 759 through 20 May and 763 through 23 May when they are due to depart the visible disk. Old Region 758 (S10, L=136) is due to return by 28 May and was an M-class flare producer on its last rotation. Otherwise expect very low to low conditions.

There is a chance for a greater than 10 MeV proton event from Regions 759 and 763 through 23 May.

The greater than 2 MeV electron flux at geosynchronous orbit is expected to be at high levels on 19 – 20 May, 28 May – 02 June, and 07 – 13 June.

The geomagnetic field is expected to range from quiet to minor storm levels. Effects from two weak CME's on 16 and 17 May are expected to produce active to minor storm levels on 18 - 19 May. Recurrent coronal hole high speed wind streams are expected to produce active to minor storm levels on 27 – 28 May and 11 – 12 June. Otherwise, expect quiet to unsettled conditions.

Daily Solar Data

Date	Radio Flux 10.7 cm	Sun spot No.	Sunspot Area (10^{-6} hemi.)	X-ray Background	Flares X-ray Flux C	M	X	Optical S	1	2	3	4
09 May	110	106	910	B4.1	8	0	0	3	0	0	0	0
10 May	119	106	870	B4.1	7	1	0	4	1	0	0	0
11 May	125	117	1330	B4.4	9	2	0	3	2	1	0	0
12 May	117	110	1140	B3.4	14	2	0	11	1	2	0	0
13 May	126	100	1280	B2.7	2	1	0	3	0	1	0	0
14 May	100	91	720	B6.8	4	0	0	2	0	0	0	0
15 May	103	69	490	B2.9	9	1	0	1	1	0	0	0

Daily Particle Data

Date	Proton Fluence (protons/cm^2-day-sr) >1MeV	>10MeV	>100MeV	Electron Fluence (electrons/cm^2-day-sr) >.6MeV	>2MeV	>4MeV
09 May	2.7E+6	1.3E+4	2.2E+3		7.7E+6	
10 May	7.5E+5	1.2E+4	2.3E+3		1.6E+7	
11 May	7.8E+5	1.5E+4	2.4E+3		7.3E+7	
12 May	9.7E+5	2.1E+4	2.6E+3		5.3E+7	
13 May	1.4E+6	2.7E+4	3.0E+3		1.4E+8	
14 May	6.6E+7	7.7E+6	8.0E+3		1.4E+8	
15 May	6.7E+8	2.2E+7	3.1E+3		1.1E+8	

Daily Geomagnetic Data

Date	Middle Latitude Fredericksburg A	K-indices	High Latitude College A	K-indices	Estimated Planetary A	K-indices
09 May	10	3-3-1-1-1-2-3-3	10	3-3-2-0-0-2-2-4	11	3-3-1-1-1-2-3-4
10 May	6	3-1-2-1-1-0-2-2	11	2-3-4-3-2-1-2-1	10	3-3-3-2-2-2-2-2
11 May	7	1-0-2-2-1-2-3-3	16	1-1-2-5-3-4-2-3	11	1-0-2-3-2-3-3-4
12 May	13	2-4-2-3-2-2-3-3	25	3-3-3-6-2-5-2-3	17	3-4-3-4-2-3-3-3
13 May	21	5-4-4-2-3-3-3-3	43	5-5-6-4-5-6-2-1	27	5-5-5-3-3-4-3-2
14 May	4	1-1-2-1-1-1-1-1	8	1-1-3-2-3-2-2-1	8	2-1-3-2-2-2-2-2
15 May	44	5-5-7-5-2-3-3-4	77	6-5-8-7-4-4-4-4	105	5-5-9-8-4-4-4-5

Alerts and Warnings Issued

Date & Time of Issue	Type of Alert or Warning	Date & Time of Event UTC
09 May 0016	1 – 245 MHz Radio Burst	08 May
09 May 0110	EXT WARNING: Geomagnetic K= 4	07 May 2230 - 09 May 1500
10 May 0007	3 – 245 MHz Radio Bursts	09 May
11 May 0006	2 – 245 MHz Radio Bursts	10 May
11 May 0033	ALERT: Type IV Radio Emission	10 May 0519
11 May 1156	ALERT: Electron 2MeV Integral Flux > 1000pfu	11 May 1135
11 May 1954	ALERT: Type II Radio Emission	11 May 1938
11 May 2038	ALERT: Type IV Radio Emission	11 May 1951
12 May 0010	1 – 245 MHz Radio Burst	11 May
12 May 0010	1 – 245 MHz Radio Noise Storm	11 May
12 May 0427	ALERT: Geomagnetic K= 4	12 May 0425
12 May 1018	WARNING: Geomagnetic K= 4	12 May 1019 - 1330
12 May 1024	ALERT: Geomagnetic K= 4	12 May 1024
12 May 1407	ALERT: Electron 2MeV Integral Flux > 1000pfu	12 May 1345
13 May 0035	1 – 245 MHz Radio Burst	12 May
13 May 0138	ALERT: Geomagnetic K= 4	13 May 0135
13 May 0142	ALERT: Geomagnetic K= 5	13 May 0141
13 May 0311	ALERT: Geomagnetic K= 4	13 May 0309
13 May 0327	WARNING: Geomagnetic K= 5	13 May 0328 - 1500
13 May 0337	ALERT: Geomagnetic K= 5	13 May 0336
13 May 0434	ALERT: Geomagnetic K= 5	13 May 0336
13 May 0956	ALERT: Electron 2MeV Integral Flux > 1000pfu	13 May 0935
13 May 1548	WARNING: Geomagnetic K= 4	13 May 1549 -May 14 1500
13 May 1614	ALERT: Geomagnetic K= 4	13 May 1612
13 May 1647	ALERT: X-Ray Flux exceeded M5	13 May 1647
13 May 1710	ALERT: Type II Radio Emission	13 May 1643
13 May 1757	SUMMARY: X-ray Event > M5	13 May 1657
13 May 1819	SUMMARY: 10cm Radio Burst	13 May 1633
13 May 2012	WATCH: Geomagnetic A ≥ 50	15 May
13 May 2015	WATCH: Geomagnetic A ≥ 30	16 May
13 May 2127	ALERT: Type IV Radio Emission	13 May 1645
14 May 329	WARNING: Proton 10MeV Integral Flux > 10pfu	14 May 0350 -May 15 0350
14 May 544	ALERT: Proton Event 10MeV Integral Flux > 10pfu	14 May 0525
14 May 1121	ALERT: Electron 2MeV Integral Flux > 1000pfu	14 May 1100
14 May 1333	EXT WARNING: Proton 10MeV Integral Flux > 10pfu	14 May 0350 - 15 May 0350
14 May 1413	ALERT: Proton Event 10MeV Integral Flux > 100pfu	14 May 1355
14 May 2112	ALERT: Type II Radio Emission	14 May 2046
14 May 2119	ALERT: Type IV Radio Emission	14 May 2058
15 May 0148	3 – 245 MHz Radio Bursts	14 May
15 May 0148	1 – 245 MHz Radio Noise Storm	14 May
15 May 0003	EXT WARNING: Proton 10MeV Integral Flux > 10pfu	14 May 0350 - 15 May 2359
15 May 0022	CONT ALERT: Proton Event 10MeV Integral Flux > 100pfu	14 May 1355
15 May 0136	WARNING: Geomagnetic K= 5	15 May 0140 -16 May 1500
15 May 0227	WARNING: Proton 10MeV Integral Flux > 10pfu	15 May 0230 - 16 May 0300
15 May 0237	ALERT: Proton Event 10MeV Integral Flux > 1000pfu	15 May 0215
15 May 0253	SUMMARY: Geomagnetic Sudden Impulse	15 May 0238
15 May 0256	ALERT: Geomagnetic K = 5	15 May 0255
15 May 0322	WARNING: Proton 10MeV Integral Flux > 10pfu	15 May 0230 -16 May 0300
15 May 0516	ALERT: Electron 2MeV Integral Flux > 1000pfu	15 May 0500
15 May 0609	WARNING: Geomagnetic K = 6	15 May 0610 - 1500
15 May 0629	ALERT: Geomagnetic K = 6	15 May 0629
15 May 0640	WARNING: Geomagnetic K ≥ 7	15 May 0640 - 1500
15 May 0646	ALERT: Geomagnetic K = 7	15 May 0645
15 May 0737	ALERT: Geomagnetic K ≥ 8	15 May 0736

Alerts and Warnings Issued – continued.

Date & Time of Issue	Type of Alert or Warning	Date & Time of Event UTC
15 May 0849	ALERT: Geomagnetic K = 9	15 May 0849
15 May 0917	ALERT: Geomagnetic K = 6	15 May 0915
15 May 0929	SUMMARY: Proton Event 10MeV Integral Flux > 1000pfu	15 May 0215
15 May 0939	SUMMARY: Proton Event 10MeV Integral Flux > 100pfu	14 May 1355
15 May 1009	ALERT: Geomagnetic K = 7	15 May 1009
15 May 2141	CANCEL WATCH: Geomagnetic A ≥ 30	16 May
15 May 2143	WATCH: Geomagnetic A ≥ 20	16 May

A Neural Network for Kp Using Solar Wind Data Only

Kirt Costello

Costello has a model that predicts

INVERSION KP

GUSSENHOVEN ET. AL., 1983 SHOWED A STRONG CORRELATION BETWEEN THE LOCATION OF THE BOUNDARY OF THE DIFFUSE AURORA AND THE CURRENT KP VALUE.

THEIR DATA FOR THIS AURORAL BOUNDARY LOCATION WAS TAKEN FROM THE DMSP SATELLITE PASSES OVER THE POLAR REGIONS AND BINNED INTO 1 HOUR MAGNETIC LOCAL TIME BINS.

FOR EACH BIN STATISTICAL LINEAR REGRESSION SHOWED A FIT TO THE KP VALUES WITH CORRELATION COEFFICIENTS RANGING FROM -0.50 TO -0.81.

THE EQUATION TO DESCRIBE THIS RELATIONSHIP WAS GIVEN AS:

$$\Lambda = \Lambda_0 + \alpha Kp$$

WHERE Λ IS THE EQUATORWARD EDGE OF THE AURORA, KP IS THE GOTTINGEN KP AT A GIVEN TIME, AND Λ_0 AND α ARE THE LEAST SQUARES FIT INTERCEPT AND SLOPE FROM THEIR STUDY.

IF WE KNOW THE MEB THEN IT IS POSSIBLE TO INVERT THIS RELATIONSHIP TO OBTAIN KP.

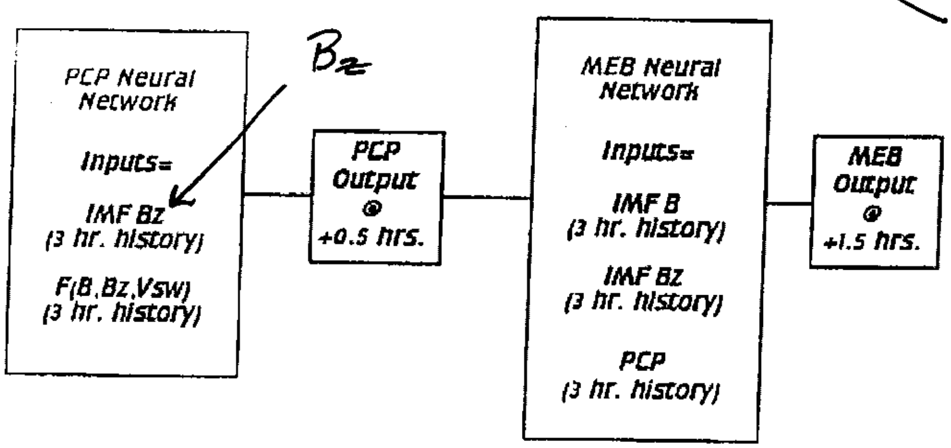
$$Kp = \frac{\Lambda - \Lambda_0}{\alpha}$$

2

USING THE STATISTICS FOR THE 2300-2400 BIN AND THE 0000-0100 BIN FROM THE GUSSENHOVEN STUDY WE HAVE:

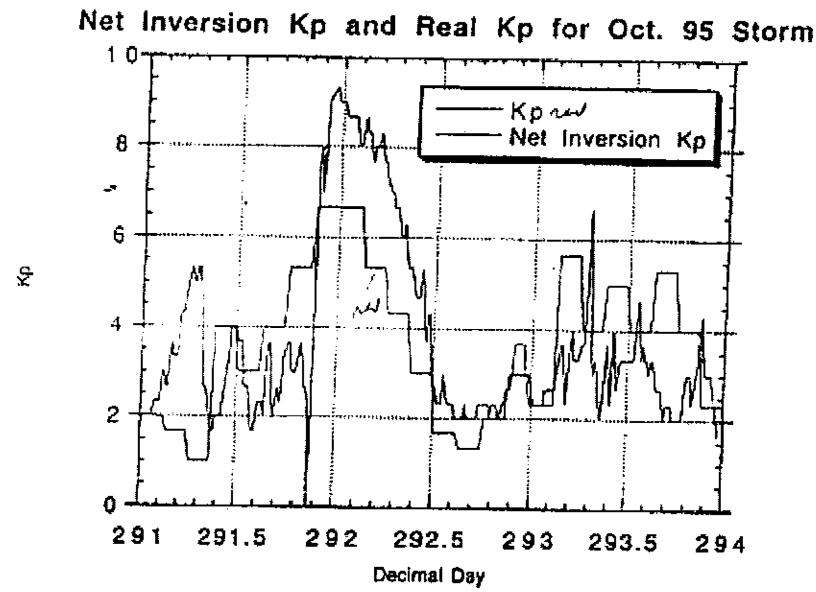
$$Kp = -\frac{MEB - 66.95^{\circ}}{2.03}$$

NOW TO GET THE MEB WE MUST EMPLOY TWO ARTIFICIAL NEURAL NETWORKS FIRST DEVELOPED BY AKIRA NAGAI IN 1992:



3

INVERSION KP RESULTS:



PROBLEMS:

- THE GUSSENHOVEN CORRELATION STUDY HAD STATISTICAL AMOUNTS OF DATA ONLY FOR KP'S 0-5+. RESPONSES TO MEB INVERSION WITH KP>5+ ARE LINEAR PROJECTIONS.
- ALGORITHM REQUIRES AN UPSTREAM SOLAR WIND MONITOR BE IN PLACE TO PROVIDE DATA FOR THE MEB NEURAL NETWORK SINCE THE CURRENT PCP NETWORK PRODUCES A FORECAST.
- REQUIRES A 3 HOUR HISTORY OF SOLAR WIND DATA.

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Solar Wind Driven ANN for Kp Specification

Idea:

"Since we can get a solar wind driven Kp through the inversion of the outputs of several neural networks we should be able to create an ANN to directly predict Kp."

Table of Training Set Statistics:

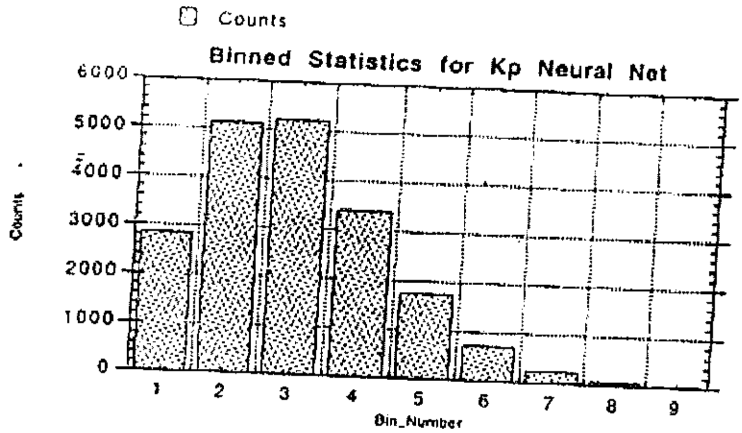
Years Data Taken From	1970, 1976, 1978, 1980, 1981, 1982, 1989
Number of Training Vectors	19,378
Range of Kp	0_0-9_0
Range of IMF B	0 - 37 nT
Range of IMF Bz	-32 - 37 nT
Range of Velocity	156 - 961 km/s

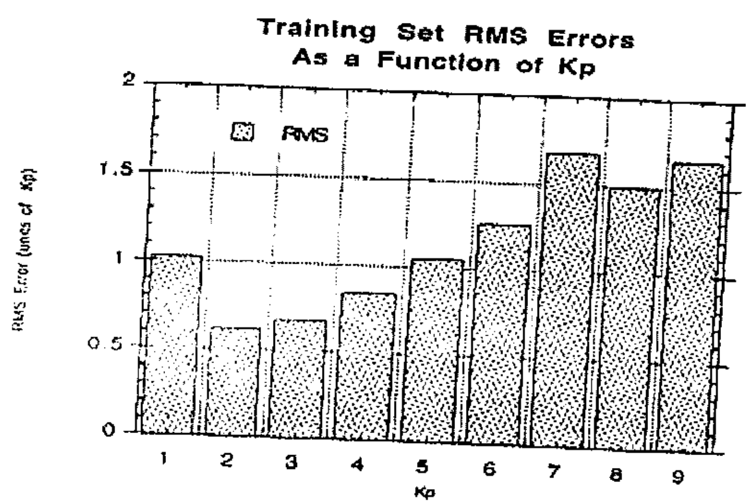
Table of Testing Set Statistics

Years Data Taken From	1969, 1979, 1986, 1990
Number of Training Vectors	18,007
Range of Kp	0_0-8_+
Range of IMF B	0 - 54.4 nT
Range of IMF Bz	-40 - 31.4 nT
Range of Velocity	139.3 - 892 km/s

RESULTS OF TRAINING:
(TRAINING SET RESULTS)

CORRELATION COEFFICIENT FOR TRAINED NETWORK = 0.814
(OVER TRAINNG SET)

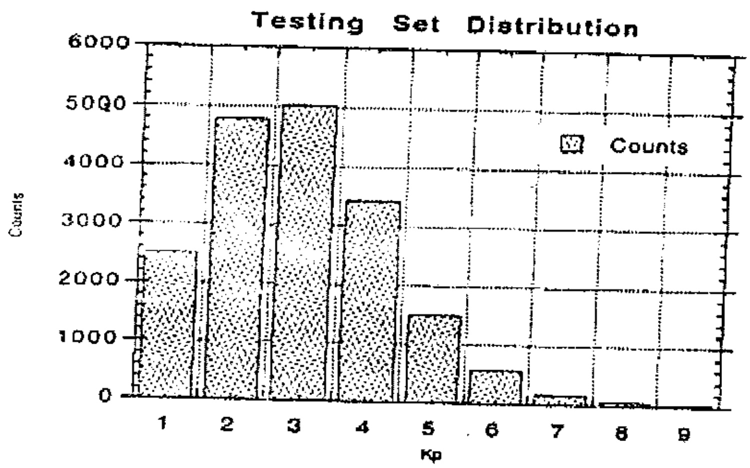


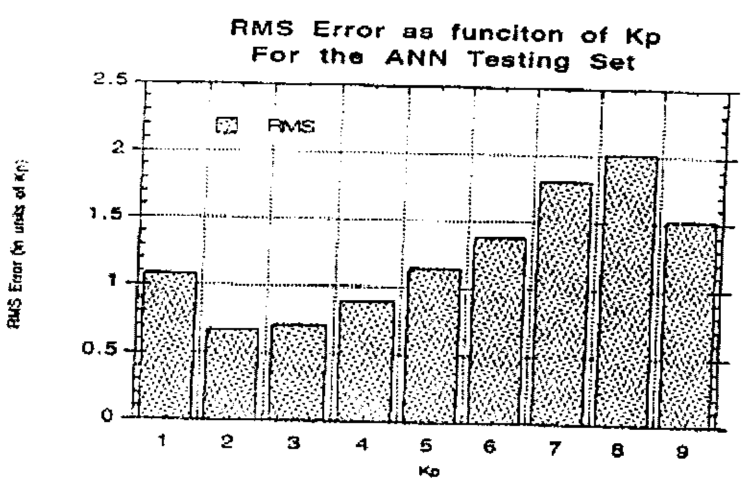


6

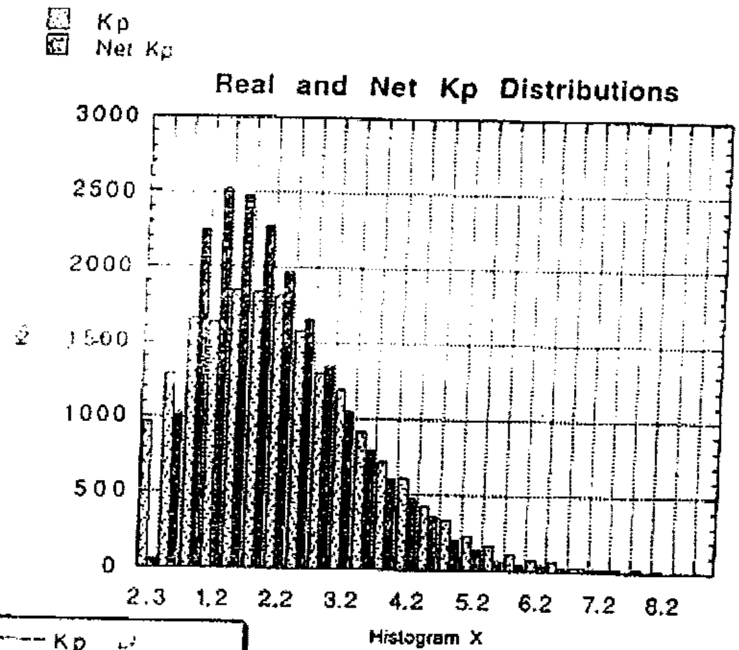
RESULTS OF TRAINING:
(TESTING SET RESULTS)

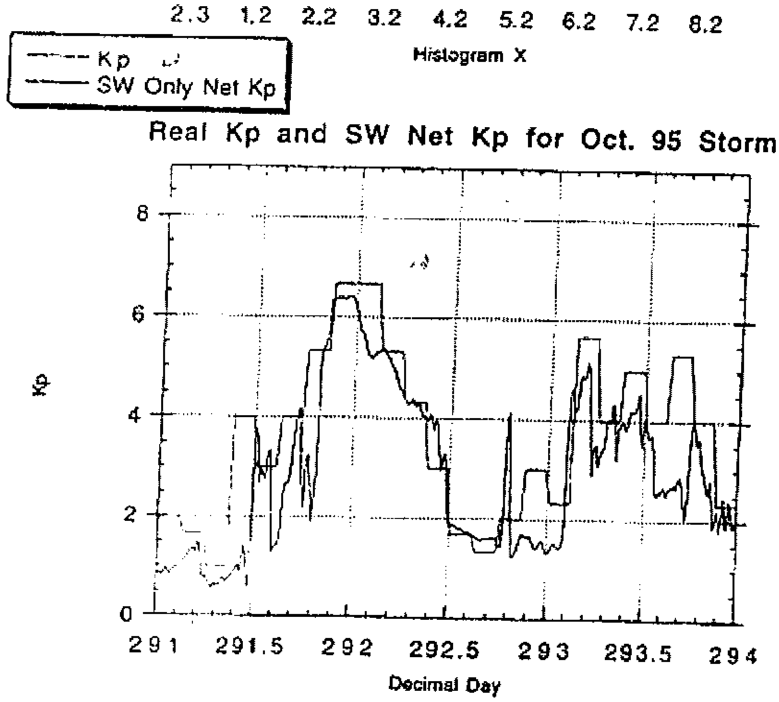
CORRELATION COEFFICIENT FOR TRAINED NETWORK = 0.757
(OVER TESTING SET)





7


Kp
Net Kp
Real and Net Kp Distributions
3000
2500
2000
1500
1000
500
0
2.3
1.2
2.2
3.2
4.2
5.2
6.2
7.2
8.2
Histogram X


Kp
SW Only Net Kp
Real Kp and SW Net Kp for Oct. 95 Storm
8
6
4
2
0
Kp
291
291.5
292
292.5
293
293.5
294
Decimal Day

COMPARISONS:

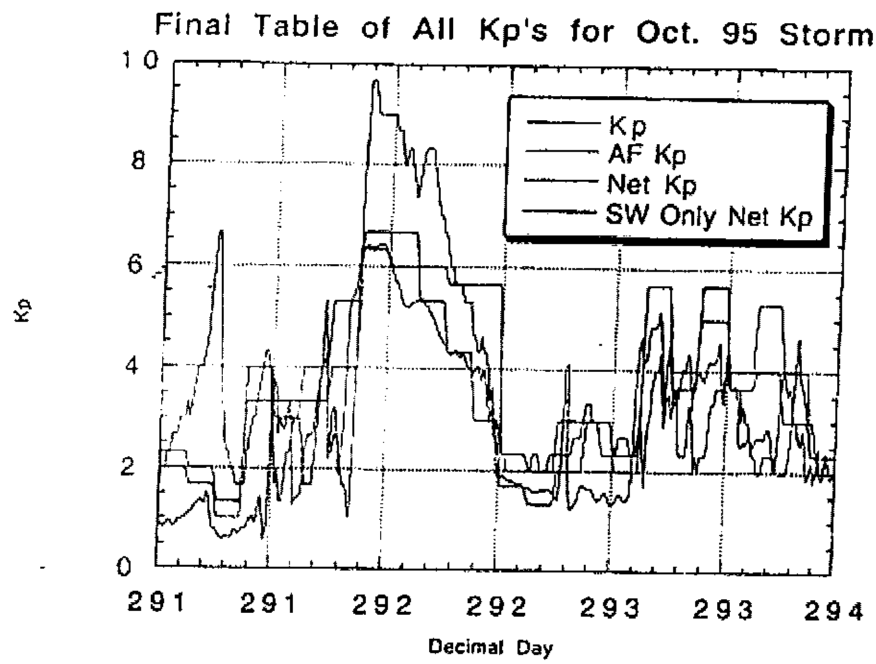
RMS ERRORS FOR THE OCTOBER 1995 EVENT:

KP TYPE	RMS ERROR FOR OCT. 95 STORM
AIR FORCE KP	1.26512
NET INVERSION KP[1]	1.85672
SOLAR WIND ANN KP[2]	1.23169
PERSISTENCE	1.48420

MSFM 10 KEV ELECTRONS EQUATORIAL FLUXES LOG RMS ERRORS:

KP TYPE	BIAS	VARIANCE	LOG RMS ERROR
GOTTINGEN KP	-1.0888	0.2951	1.2161
AIR FORCE KP	-1.2117	0.3175	1.3363
INVERSION KP[1]	-1.2109	0.3945	1.3641
SW ANN KP[2]	-1.0459	0.3867	1.2168

[1]OUTPUT IS A 1.5 HOUR FORECAST OF KP
[2]OUTPUT FORECAST TIME IS SPECIFIED BY UPSTREAM SOLAR WIND TRANSIT TIME.



BENEFITS AND PROBLEMS WITH SW ANN FOR KP:

① ANN ONLY REQUIRES B, BZ AND VELOCITY INPUTS.

② OUTPUT IS THE SPECIFIED KP (NOT A FORECAST).

③ USE OF UPSTREAM SOLAR WIND MONITORS AND A GOOD SOLAR WIND TRANSPORT MECHANISM GIVES YOU THE TRANSIT TIME AS YOUR FORECAST LEAD TIME. [G. LINDSAY, 1995]

④ MOVING AVERAGE WINDOWS CAN PROVIDE A HIGH TIME RESOLUTION KP.

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THE BIG PICTURE:

① KP WAS THE LAST HURDLE KEEPING THE MSFM AND OTHER MODELS TIED TO THE GROUND. WITH A REAL TIME SOLAR WIND MONITOR IT WILL FINALLY BE POSSIBLE TO EXERCISE A TRUE FORECAST MODE.

② THE TWO SOLAR WIND DRIVEN INDICES OVERPREDICT [INVERSION] AND UNDERPREDICT [ANN] THE TRUE GOTTINGEN KP, BUT OFFER A MUCH HIGER TIME RESOLUTION INDEX WHILE BEING ABLE TO REPRODUCE THE GLOBAL BEHAVIOR OF THE GOTTINGEN INDEX.

③ THE FACT THAT THESE APPROXIMATIONS ARE SOLAR WIND DRIVEN ALLOWS US TO GAIN THE SOLAR WIND TRANSPORT TIME FOR FORECASTING CONDITIONS AT 1 AU.

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