Comparison of Costello Geomagnetic Activity Index Model and JHU/APL Models for Kp Prediction

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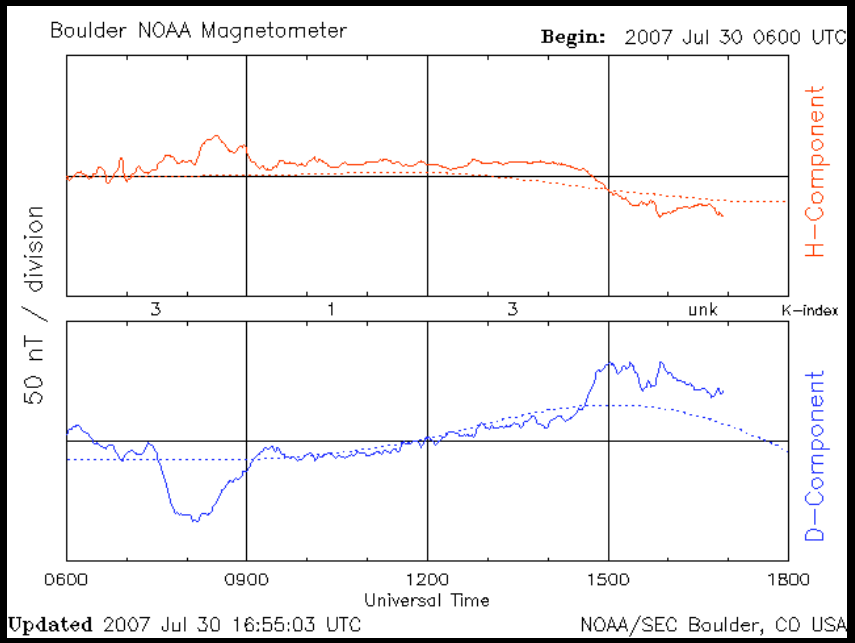
Outline

- Background
- Kp Prediction
- Costello Geomagnetic Activity Index Model
  - Validation Studies
- Research
- Results
- JHU/APL Models
- Conclusions

Kp Index

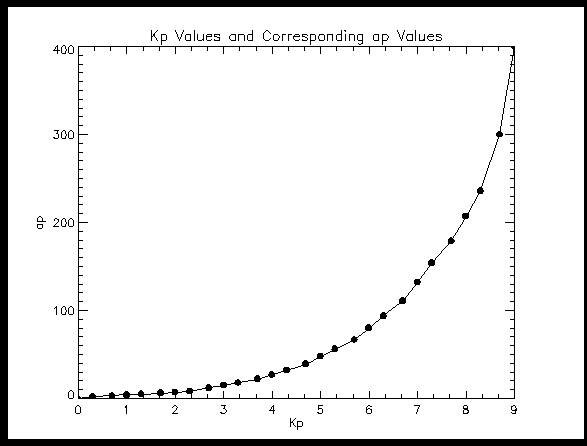
- Developed by Julius Bartels
- Measure of the maximum disturbances in the horizontal components of Earth's magnetic field caused by solar particle radiation
- Official index calculated every three hours using observations from 13 subauroral magnetometer stations

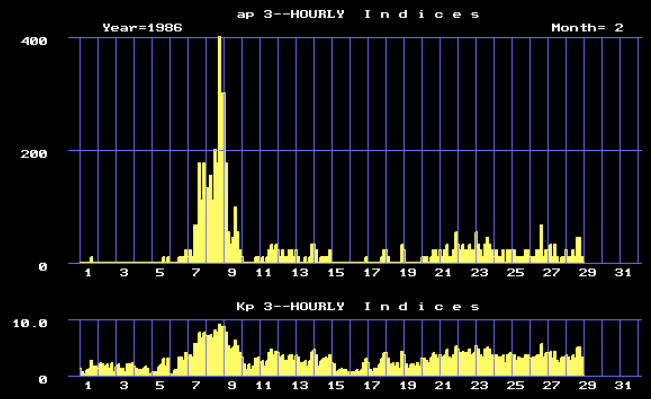


Kp Values

- Range from 0 to 9 in a scale of thirds
- Kp value of 0 corresponds to the quietest conditions
- Kp value of 9 corresponds to the most disturbed conditions
- Quasi-logarithmic scale
- ap index ranges from 0 to 400 and represents the Kp value converted to a linear scale in nT

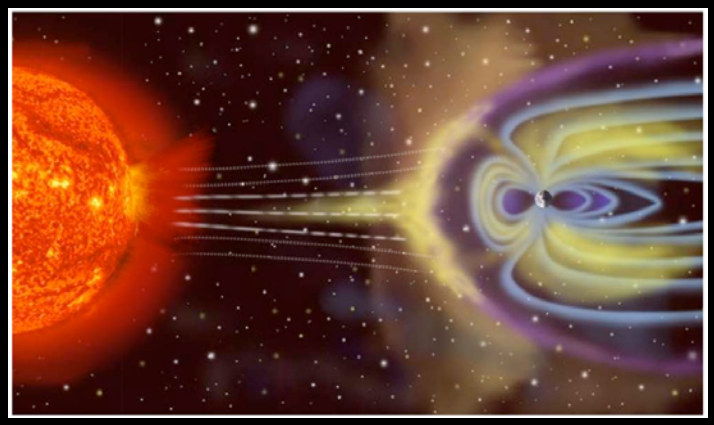
Kp	Numerical Value	ap (nT)
0	0.0	0
0+	0.3	2
1-	0.7	3
1	1.0	4
1+	1.3	5
2-	1.7	6
2	2.0	7
2+	2.3	9
3-	2.7	12
3	3.0	15
3+	3.3	18
4-	3.7	22
4	4.0	27
4+	4.3	32
5-	4.7	39
5	5.0	48
5+	5.3	56
6-	5.7	67
6	6.0	80
6+	6.3	94
7-	6.7	111
7	7.0	132
7+	7.3	154
8-	7.7	179
8	8.0	207
8+	8.3	236
9-	8.7	300
9	9.0	400

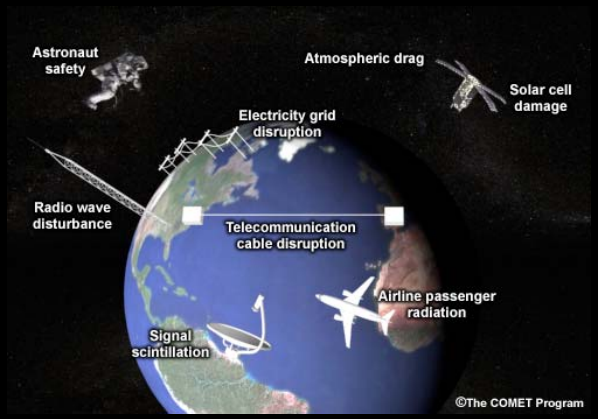


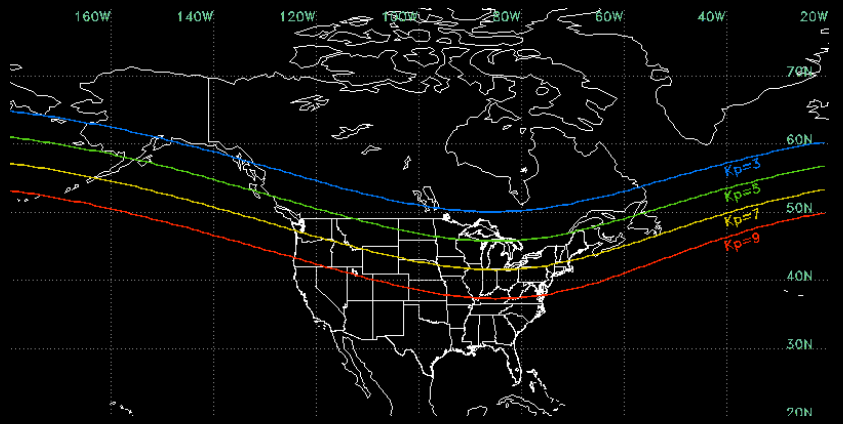


Effects of Geomagnetic Storms

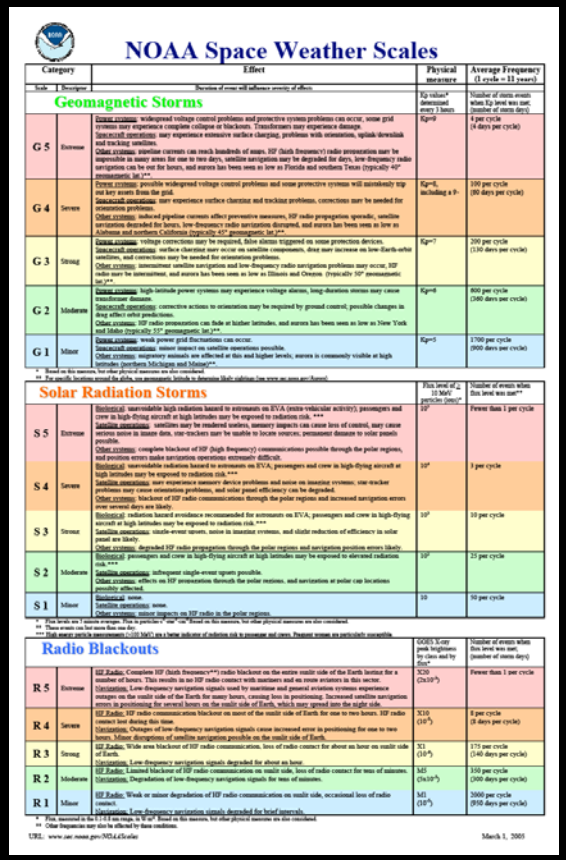
- Disrupt radio communications
- Disrupt GPS navigation
- Damage transformers and electric power grids
- Degrade satellite instrumentation
- Increase satellite drag
- Cause aurora
- Confuse racing pigeons







NOAA Space Weather Scales



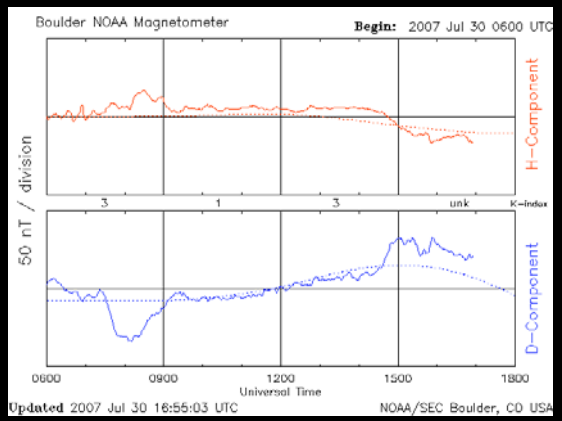
NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp value* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps. HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon. (typically 50° geomagnetic lat.)**	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**	Kp=5	1700 per cycle (900 days per cycle)
Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle
Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency***) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 1-8 Å x-ray range, in W/m^2. Based on this measure, but other physical measures are also considered.
** Other frequencies may also be affected by these conditions.

URL: www.swpc.noaa.gov/NOAAscales

March 1, 2005



- NOAA G-Scale based on Kp estimates from the Boulder-NOAA Magnetometer
- Warnings issued when Kp values of 4, 5, 6, and 7 or greater are expected
- Alerts issued for Kp values of 4, 5, 6, 7, 8, and 9

NOAA G-Scale

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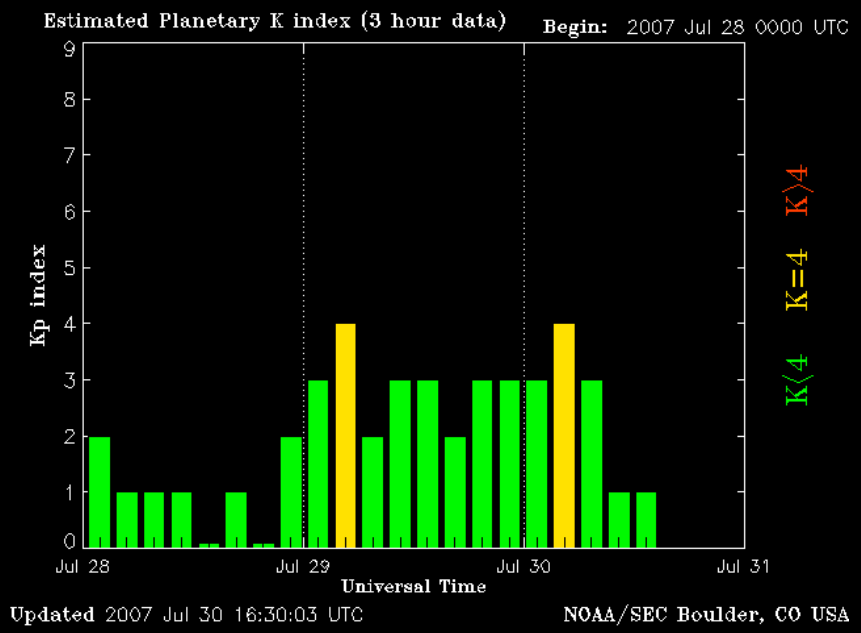
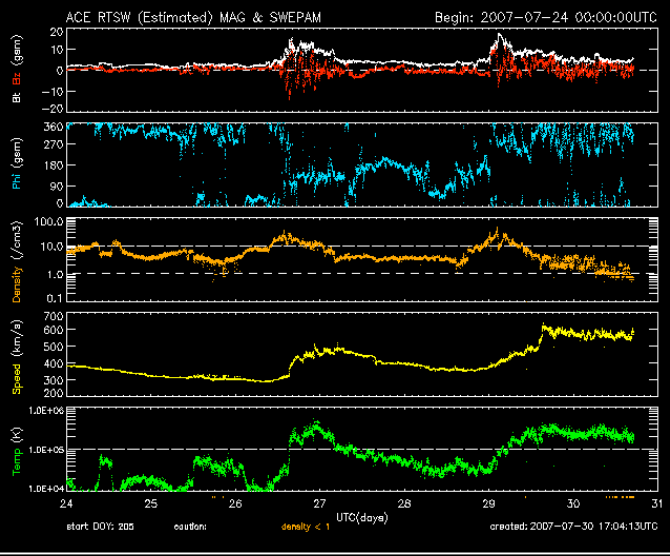
USAF Estimated Kp

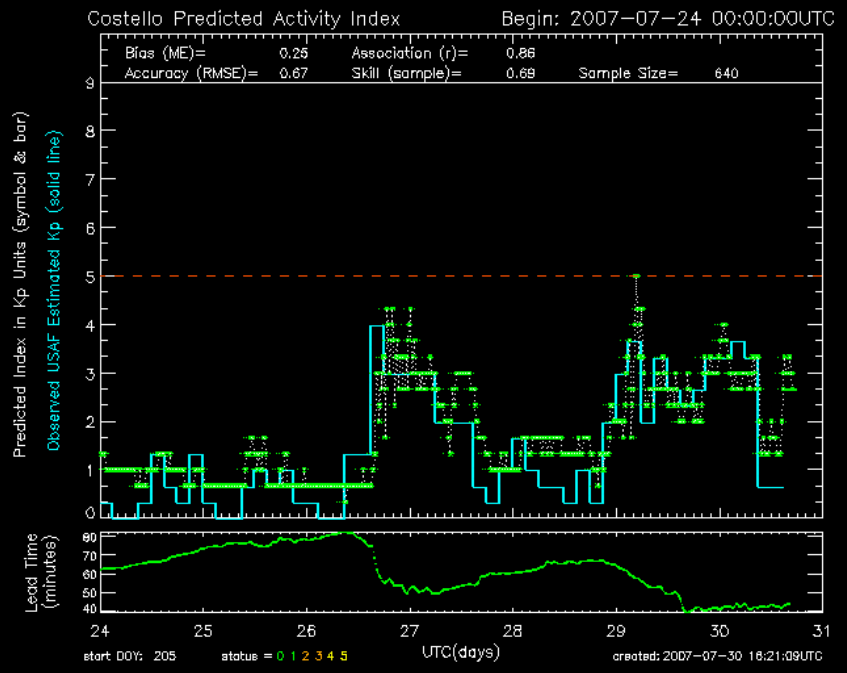
- Official Kp index published with significant time delay
- “Nowcast” Kp algorithm provides real-time estimates of Kp
- Derived using data from 9 ground-based magnetometers in North America
- Calculated by the United States Air Force 55th Space Weather Squadron



Costello Geomagnetic Activity Index

- Neural network algorithm trained on the response of Kp to solar wind data
- Input two hours of data for solar wind speed, IMF magnitude, and Bz
- Output running 3-hour Kp every 15 minutes

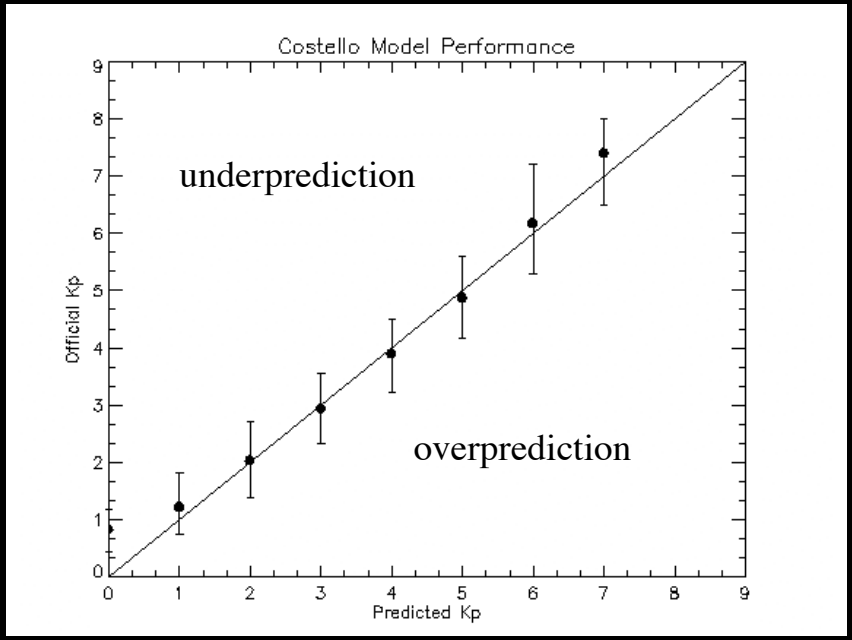




Motivation for Research

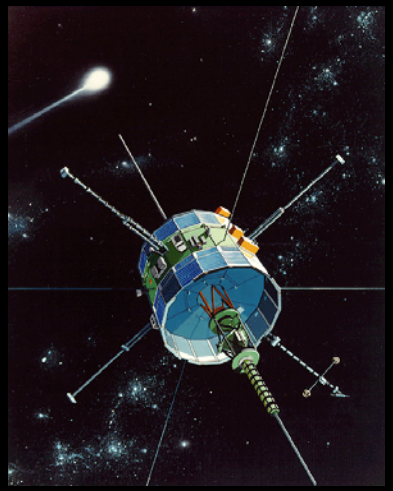
- Space weather forecasters need to know how reliable prediction models are
- Several validation studies have been done on the Costello model
  - Results are not complimentary
  - Important to determine the reasons for discrepancies

Costello Validation Study 1



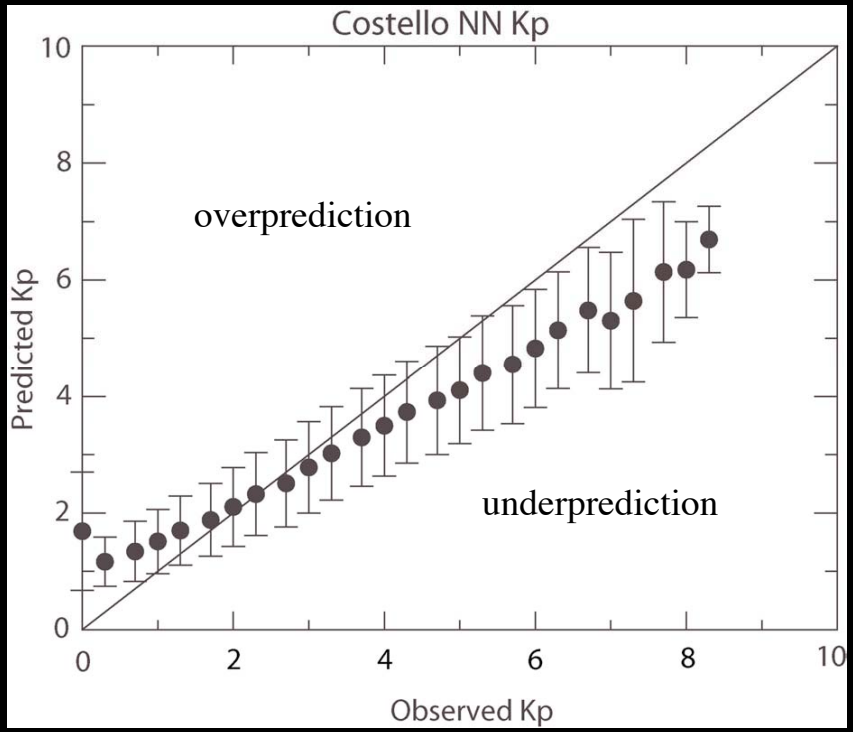
Study performed by members of the Space Environment Center.

- Covers the time period from August 17, 1978 to February 16, 1980 (ISEE-3)
- Predictions binned to integer values between 0 and 7
- Tends to underpredict high and low Kp values



Costello Validation Study 2

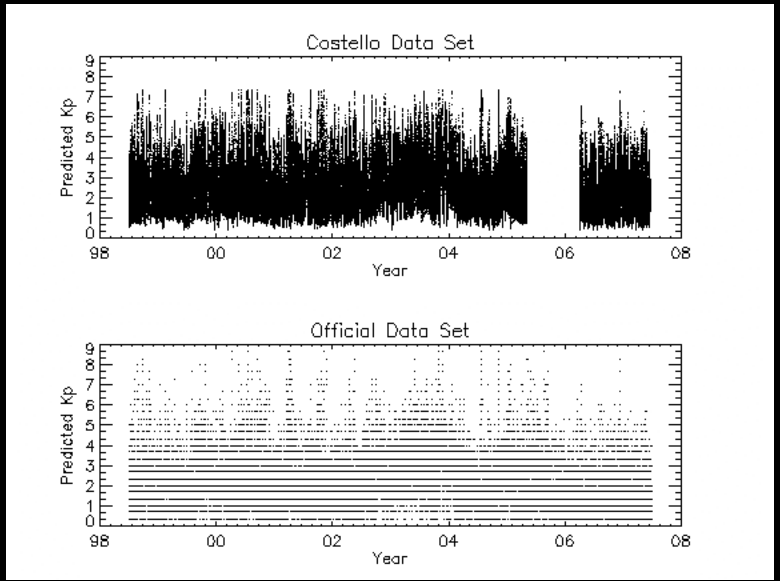
- Covers the time period from 1975-2001 (IMP-8, Wind, ACE)
- Official Kp values obtained by interpolating between points to match 15 minute time granularity
- Tends to overpredict low Kp values and underpredict high Kp values
- Correlation coefficient = 0.75



Study performed by Wing et al.

Research

- Find the distribution of official Kp values for a given prediction
- Determine if the models perform differently during solar maximum years than during solar minimum years
- Compare the performance of the Costello model to the JHU/APL models

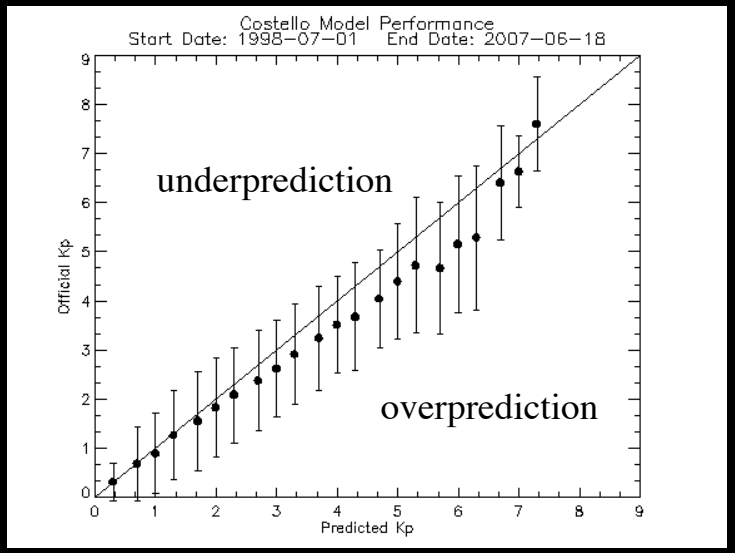


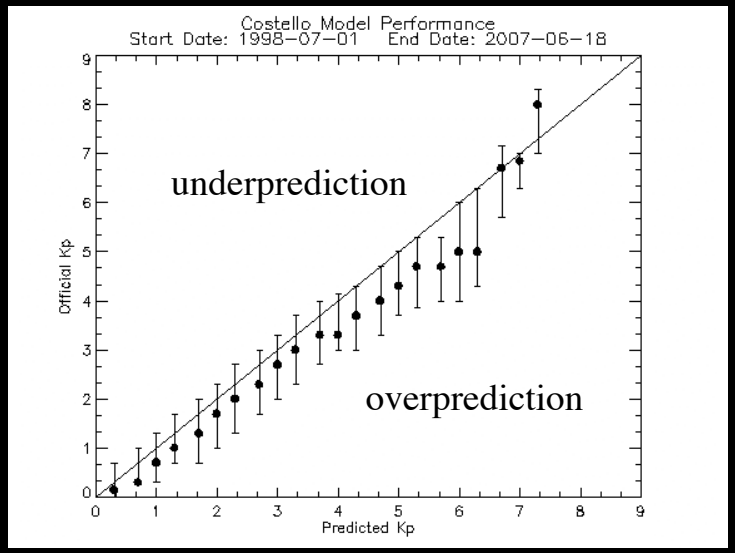
- Data Set
  - Supplied Costello prediction data spans from July 1, 1998 until June 18, 2007
  - Data gap from May 7, 2005 until April 1, 2006
    - Time granularity of 15 minutes
  - Official Kp database is essentially uninterrupted since 1932
    - Time granularity of 3 hours

Problem

- Time granularity
  - Model predictions are made approximately every 15 minutes
  - Official Kp values are calculated once every 3 hours
- Solution
  - Time-tag each of the official Kp values at the beginning of the 3 hour interval and find model predictions that are made between 0 and 10 minutes after this time

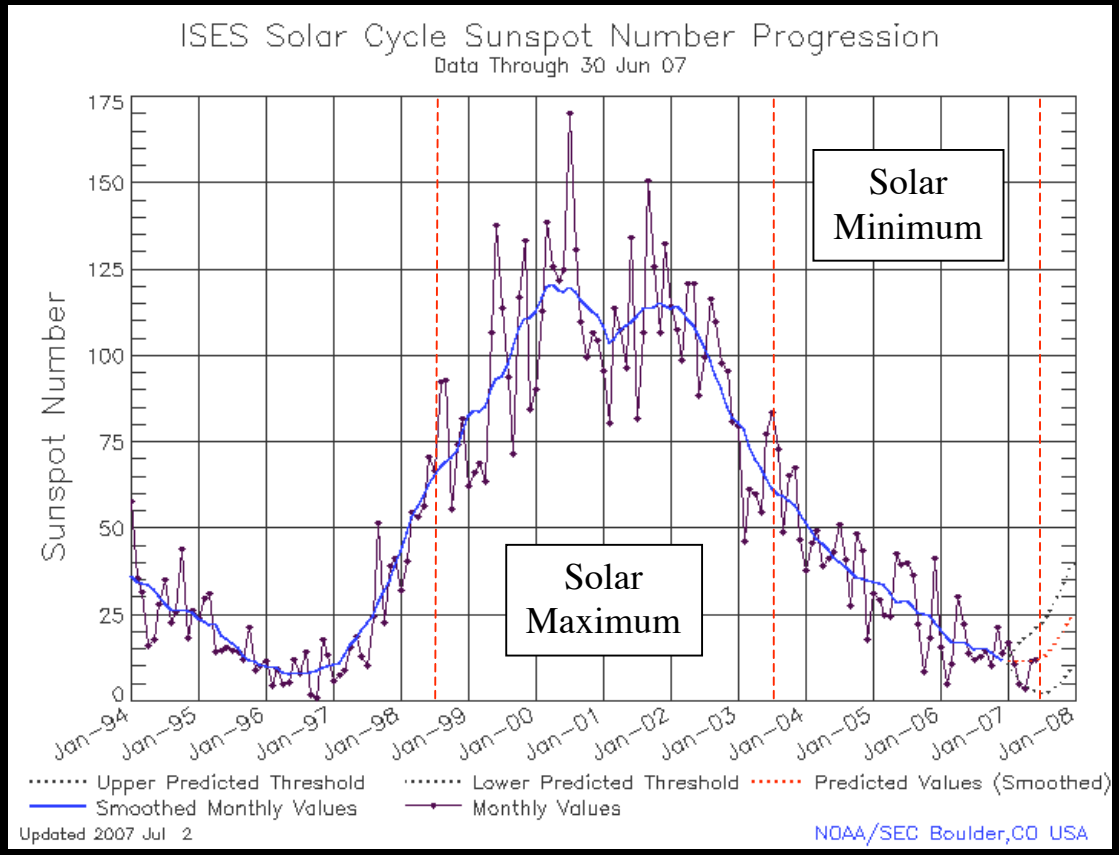
Costello Validation





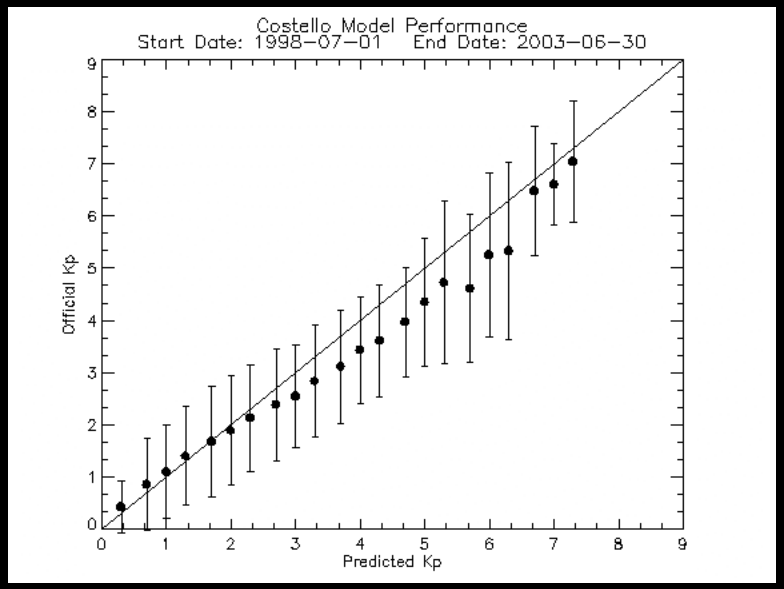
- Kp bins range from 0+ to 7+
- Figure 1: official Kp averages for each bin are plotted with error bars one standard deviation in length
- Figure 2: the median official Kp values for each bin are plotted with error bars showing the upper and lower quartiles

Solar Cycle Dependence

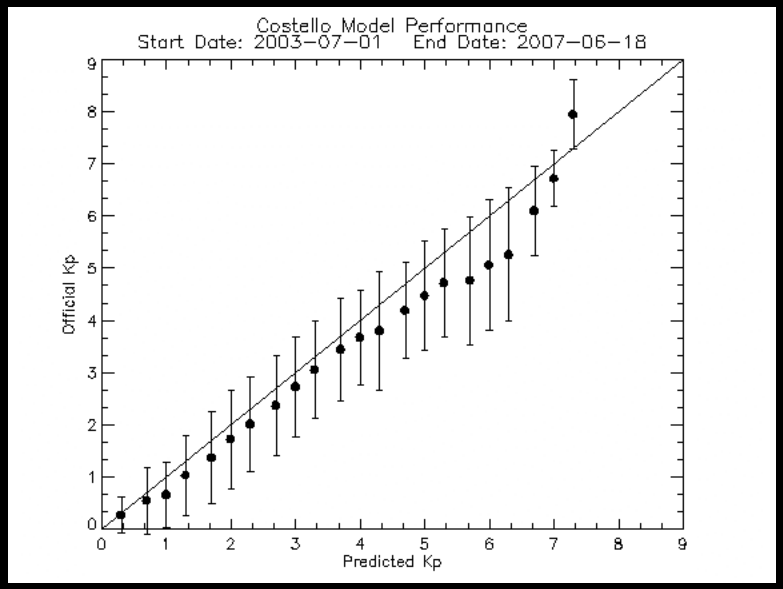


- During solar maximum external influences dominate activity in the magnetosphere
- During solar minimum internal dynamics are responsible for fluctuations in magnetic field strength

Solar Cycle Dependence (Cont.)



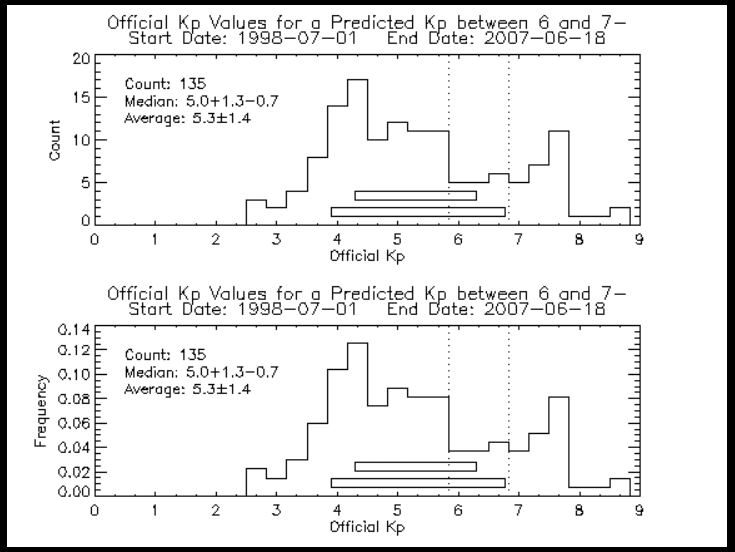
Solar Maximum



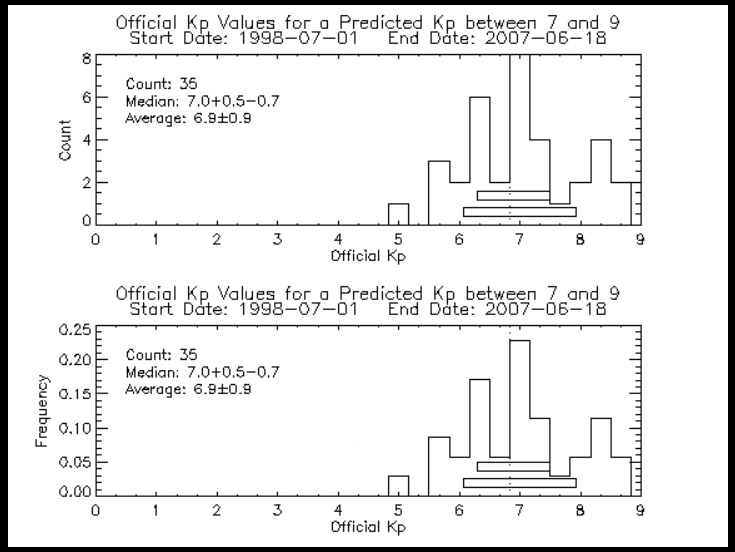
Solar Minimum

- Costello model appears to predict low Kp values slightly better during solar maximum years

Forecast Specific Validation



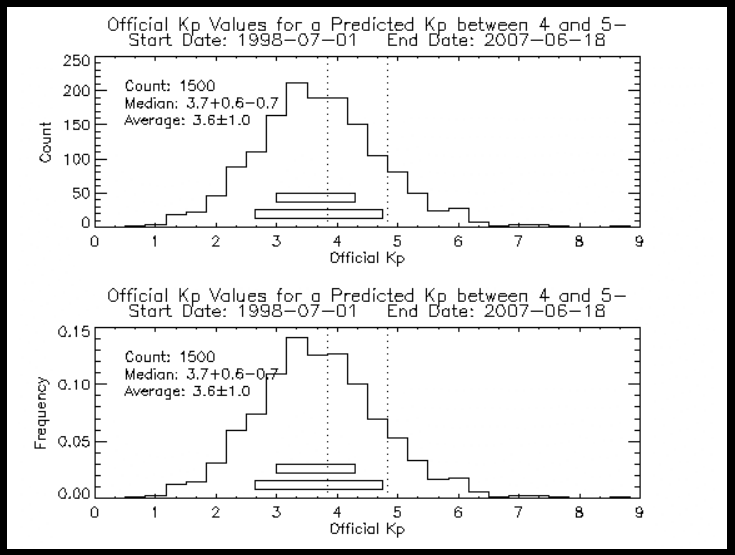
Expected Kp of 6
(G2 storm)



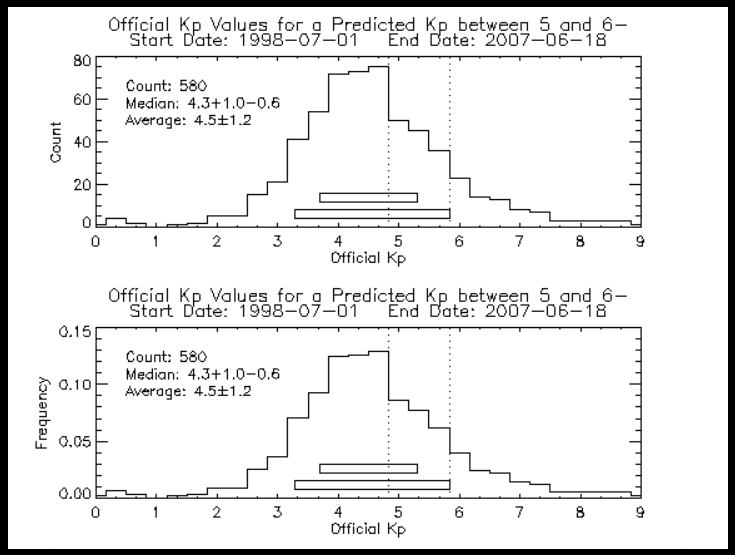
Expected Kp of 7 or greater
(G3 or higher storm)

- Figures show the distribution of official Kp values for Costello predictions corresponding to NOAA warnings

Forecast Specific Validation (Cont.)



Expected Kp of 4

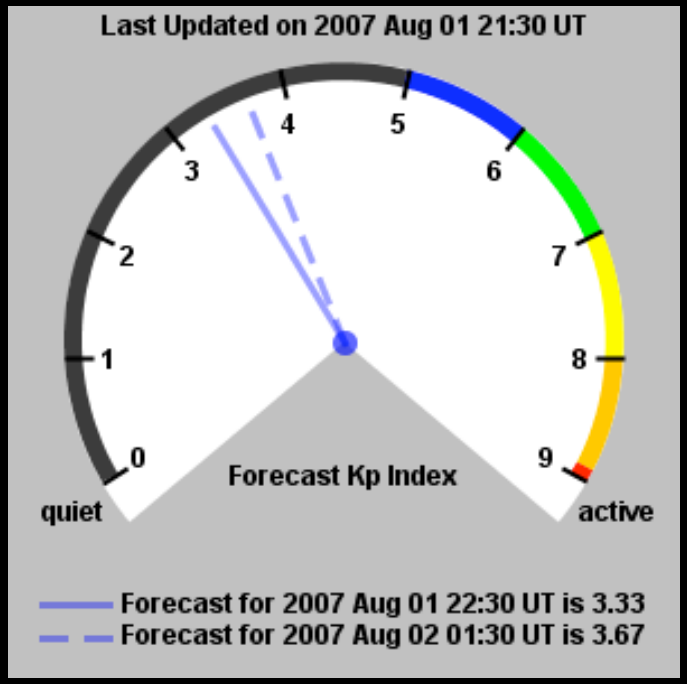


Expected Kp of 5
(G1 storm)

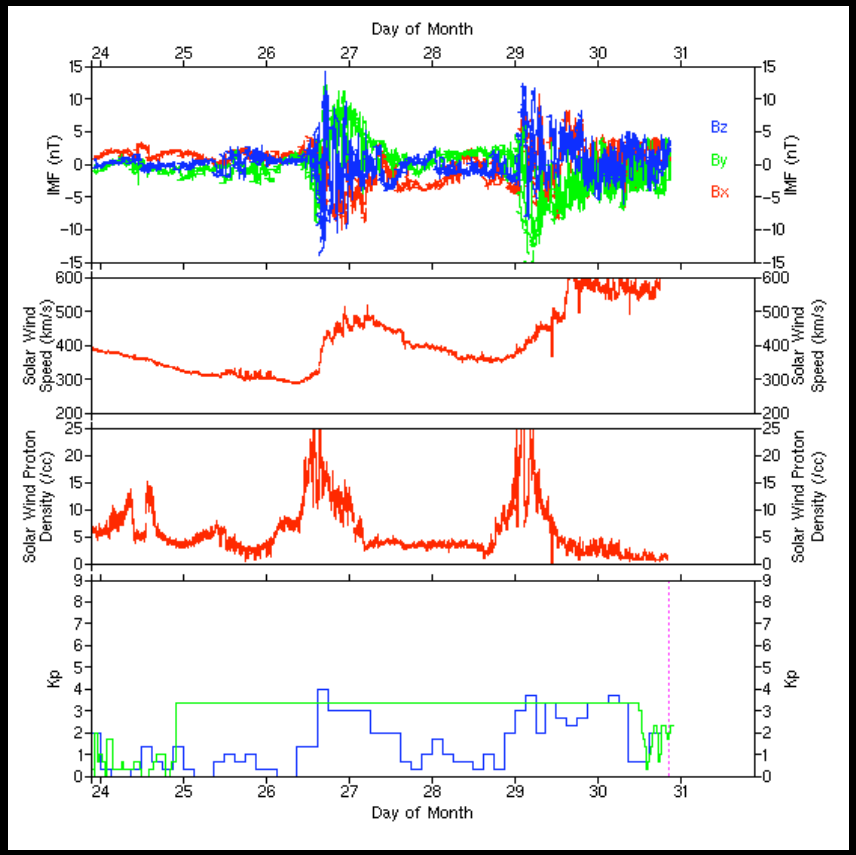
- Figures show the distribution of official Kp values for Costello predictions corresponding to NOAA warnings

JHU/APL Models

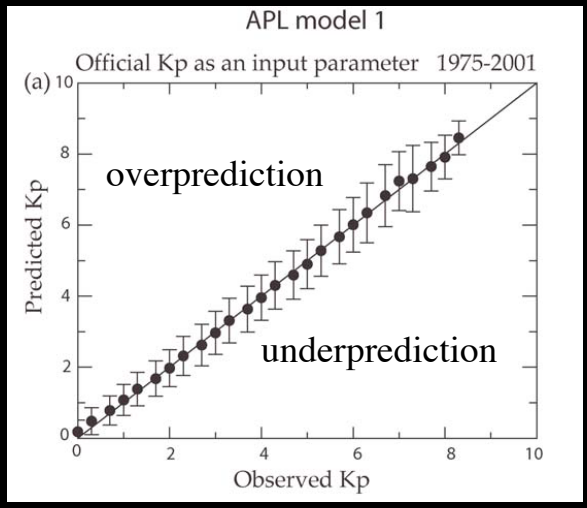
- APL Model 1
  - Inputs nowcast Kp and solar wind parameters
  - Predicts Kp 1 hour ahead
- APL Model 2
  - Same inputs as APL Model 1
  - Predicts Kp 4 hours ahead
- APL Model 3
  - Inputs solar wind parameters
  - Predicts Kp 1 hour ahead



APL Model 1

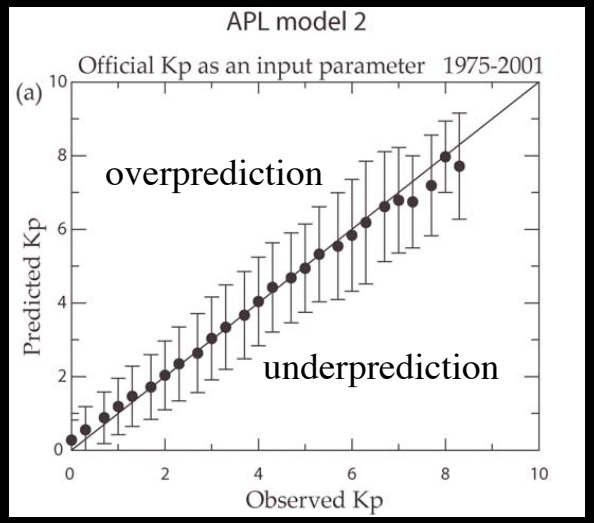


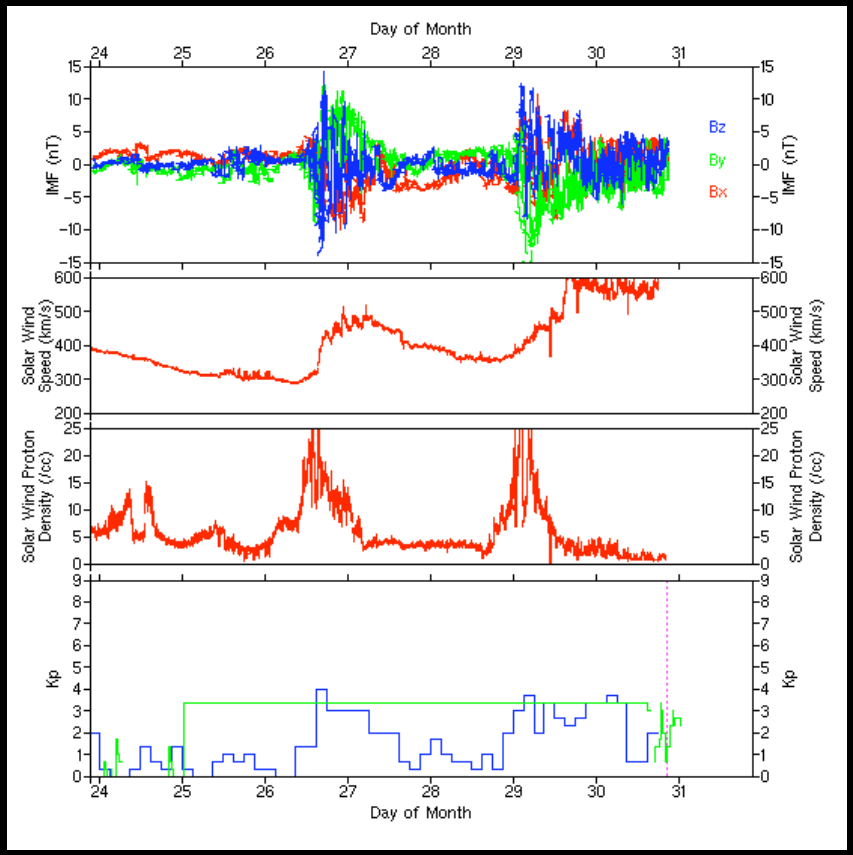
- Inputs nowcast Kp and solar wind parameters
- Predicts Kp 1 hour ahead
- Correlation coefficient = 0.92



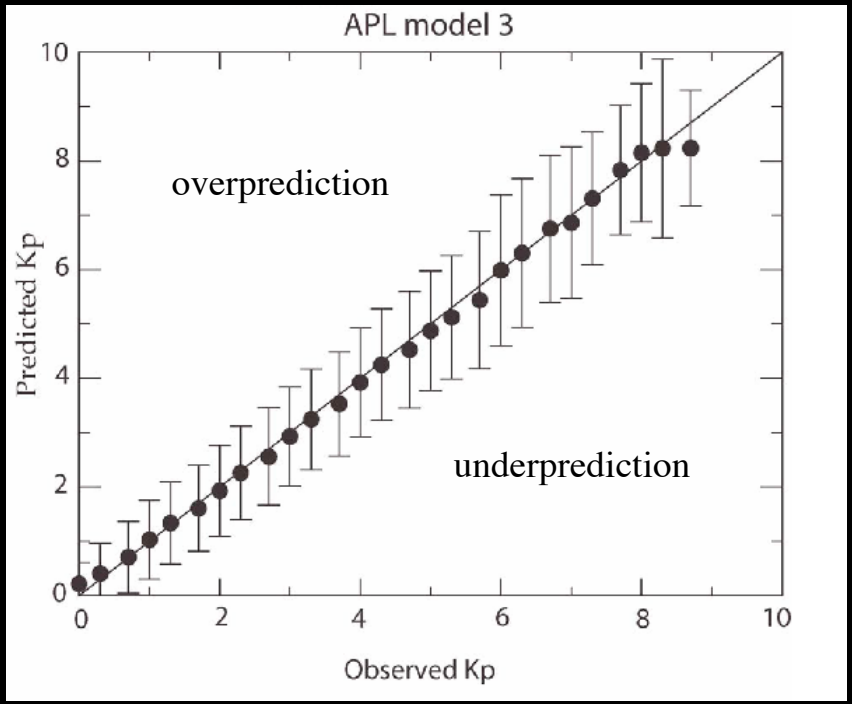
APL Model 2

- Inputs nowcast Kp and solar wind parameters
- Predicts Kp 4 hours ahead
- Correlation coefficient = 0.79



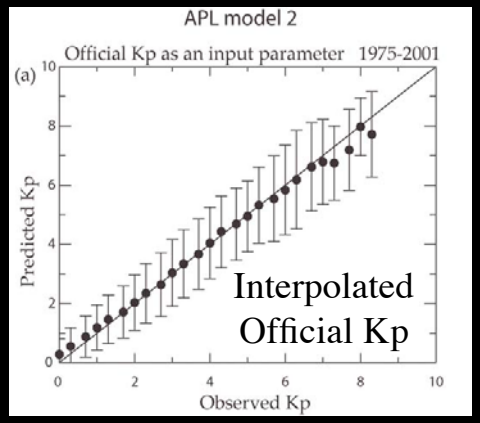


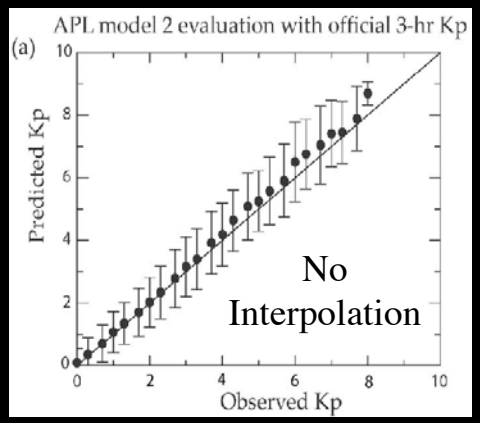
APL Model 3



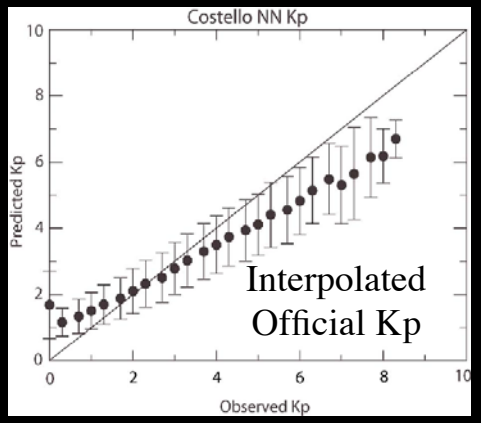
- Inputs solar wind parameters
- Predicts Kp 1 hour ahead
- Correlation coefficient = 0.84

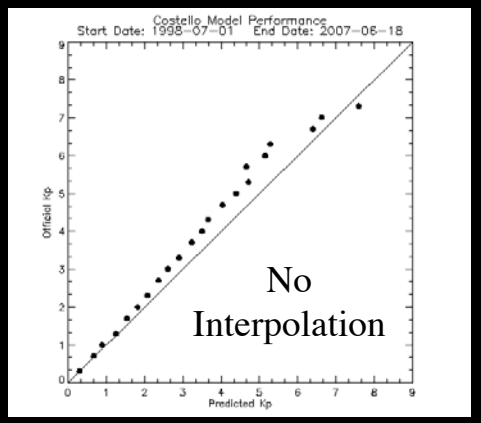
Resolution to Discrepancy?





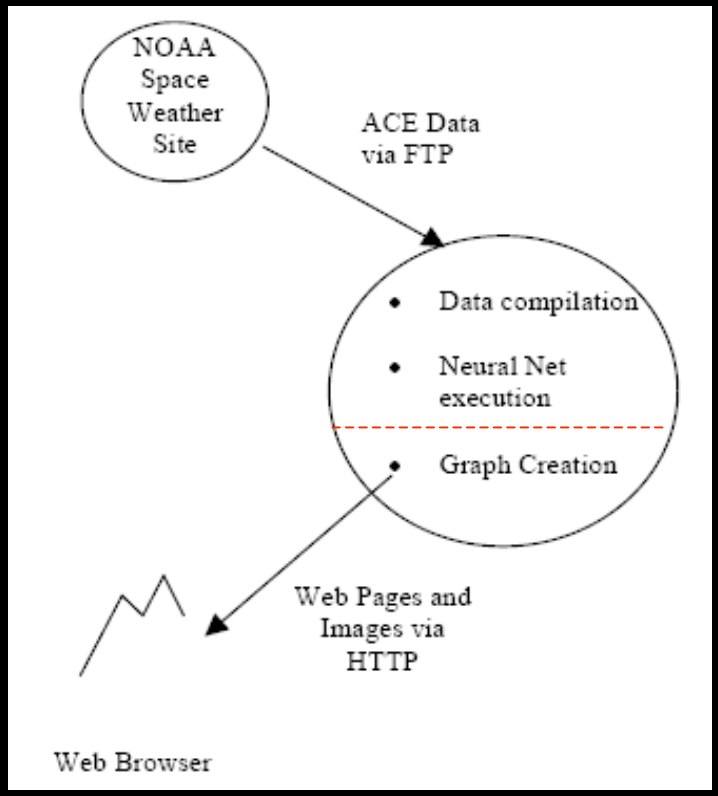
- Interpolation of official Kp values may lead to skew in Wing's validations
- When no interpolation is used, APL model tends to overpredict Kp instead of underpredicting
- Similar skew may be responsible for discrepancy in Costello validations





APL Model Validations

- APL models installed
- Code edited to run on a NOAA/SEC computer
- Models successfully produce real-time Kp estimates
- Real-time data plots were not produced
- Modifications to run models off of historical data were not completed



Summary

- We found that the Costello model tends to overpredict Kp consistently
- Model performance may exhibit some solar cycle dependency
  - Statistical evaluations will have to be performed in order to determine the extent of this dependency
  - Differences in performance are likely irrelevent for forecasting purposes
- Directly comparable validation studies should be carried out to determine if the JHU/APL models perform significantly better than the Costello model
  - Time interval, time granularity, and data set used should be identical

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