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British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Observatory Data Products for Space Weather Applications

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Introduction

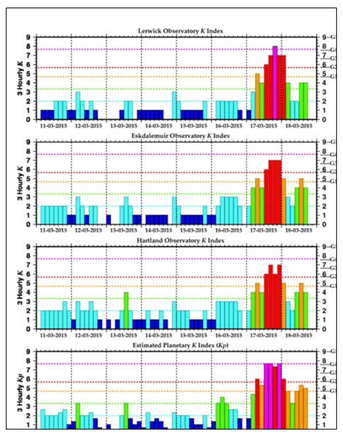
Space weather is on the UK government's national risk register. **Magnetic observatory measurements provide the underlying capability for real-time dissemination of information and advice on geomagnetic activity and space weather hazard.** Long-term operation of observatories enables continuous monitoring of activity levels and is therefore a key component. On-going operational outputs include:

- Real time estimates of local activity indicators (HSD, d**B**/dt, K, K_{BI}, A_{BI}, DRX) and global (Kp_{est}, ap/Ap_{est} and aa/Aa_{est}) indices which are updated at 5 minutes intervals.
- Forecasts of local and global 3-hourly and daily activity indices – from automated algorithms (ARIMA and Neural Net) and human-derived one, two and three day ahead categorical activity forecasts on a daily basis.

Geomagnetic Observatory Network: Data and Indices

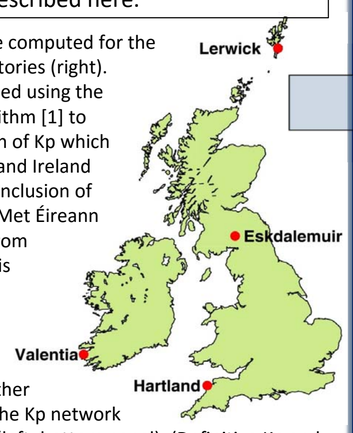
Accurate, timely and reliable space weather products rely on high quality, accurate and reliable observatory data. The real-time processing of data from the BGS observatory network and other INTERMAGNET-standard observatories provides the primary essential ingredients for the derivation of indices and forecasts described here.

Observatories operated by BGS (2 through commercial partnerships) are shown (left). Eight of the nine are INTERMAGNET observatories.

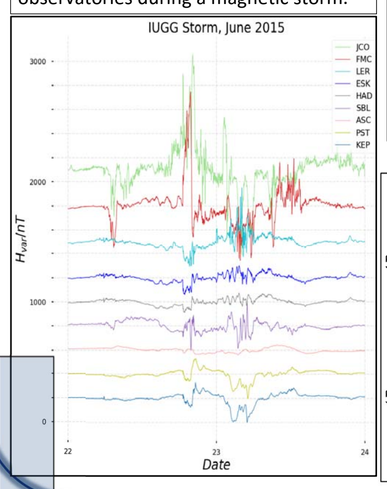


K indices (left) are computed for the three UK observatories (right). These are combined using the standard Ks algorithm [1] to calculate a version of Kp which is local to Britain and Ireland (BI) –named K_{BI}. Inclusion of VAL operated by Met Éireann along with data from Northern Ireland is Planned in 2017.

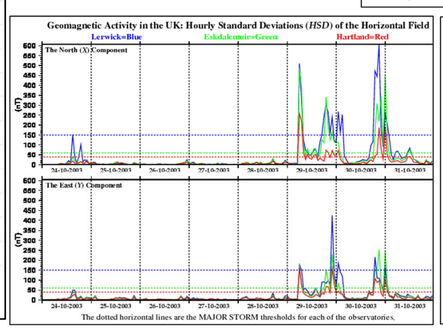
K indices are also computed for, or collected from, other observatories in the Kp network to calculate Kp_{est} (left, bottom panel). (Definitive Kp and Ap are provided by GFZ, Potsdam on behalf of ISGI [2]).

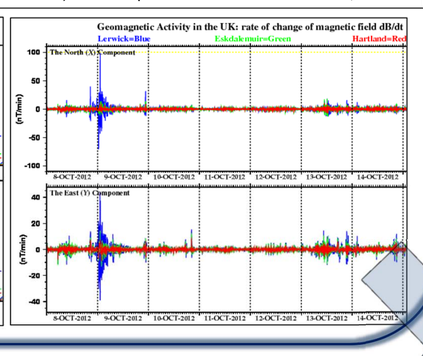


Horizontal field variations at all nine observatories during a magnetic storm.



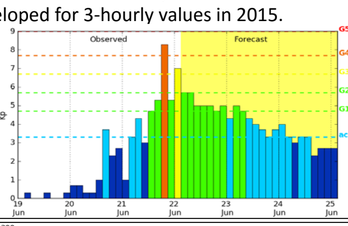
Hourly standard deviation (HSD) and d**B**/dt at the UK observatories for 2 different storms are shown below. These data form part of the MAGIC (Monitoring and Analysis of GIC) service provided to National Grid, UK.



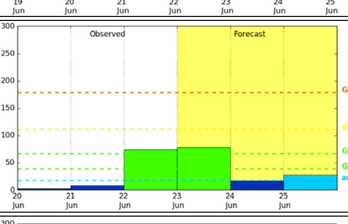


Geomagnetic Activity Forecasts: Hand Built by Humans

Real-time prediction of Kp_{est} using ARIMA method [3]. Used operationally for daily index prediction at the European Space Operations Centre since 1992, the ARIMA method was further developed for 3-hourly values in 2015.

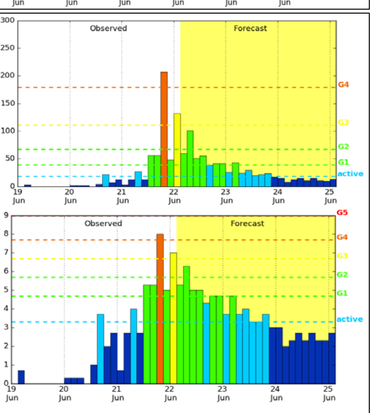


Real-time observed and prediction of daily Ap_{est} using a Neural Network method [4].

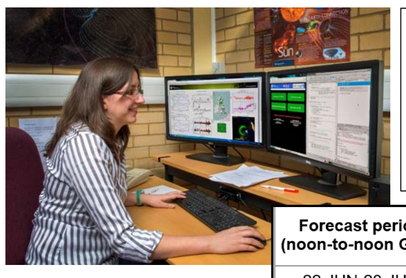


Real-time observed and automated prediction of local 3-hourly a_{BI} and K_{BI} using the ARIMA method.

Local indices are more appropriate than planetary for most ground-based applications.



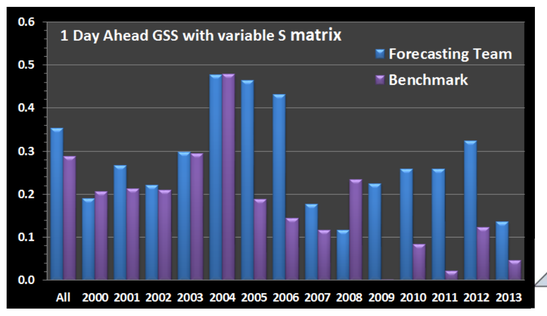
Although spanning 3-hourly time windows, the real-time operational cadence of all these indices is 5 minutes.



A forecaster (left) making 1, 2 and 3-day ahead forecasts. Various solar and solar wind observations, data and models available in the public domain, as well as in-house products are analysed and interpreted.

Forecast period (noon-to-noon GMT)	Forecast Global Activity level	
	Average	Max
22 JUN-23 JUN	STORM G1	STORM G3
23 JUN-24 JUN	ACTIVE	STORM G2
24 JUN-25 JUN	ACTIVE	STORM G1

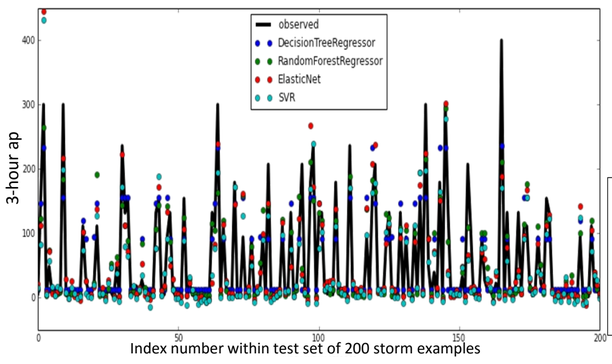
Above is the forecast made by the duty forecaster at 09.47UT on 22nd June 2015. The maximum predicted level of G3 storm was later (at 19.36UT) increased to G4. This 'Summer-Solstice' or 'IUGG' Storm, peaked at G4 in the end with the noon-to-noon period averaging to G2 (plotted in top left box). The human forecast on this occasion, although not perfect, out-performed any automated algorithms (ARIMA, Neural Net) running at BGS at the time.



Skill of human forecasters over 13 years against a benchmark of persistence and recurrence. A higher score indicates more skill. The S matrix of the Equitable (Gerrity) Skill Score (GSS) [5,6] was adapted to account for geomagnetic activity levels for each year[7]. Both the individual example above and the long term skill scores are clear evidence of the need for human interpretation in geomagnetic activity forecasting.

Improving activity predictions with Machine Learning (ML)

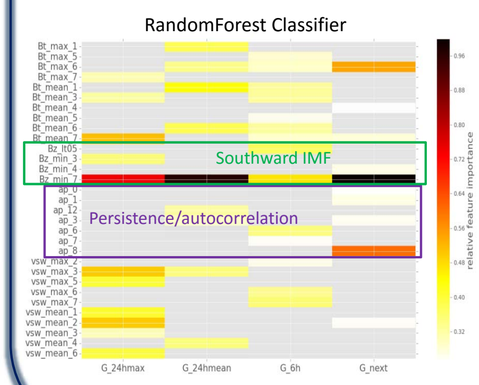
The algorithm for predicting 3-hour ap using the ARIMA method relies entirely on patterns within the time-series itself. It is now well established that making use of precursor data - solar and solar wind - can improve geomagnetic predictions. Exactly the best way of making use of the available data in an operational sense, is not yet established. In 2014 [8] work was carried out to evaluate Machine Learning (ML) algorithms [9] in predicting ap at one 3-hour period ahead, using the ap time series and ACE solar wind measurements as input. Further work in 2016 [10] found that the method was more useful for activity categories, such as NOAA's G storm scale. Selected results are highlighted here.



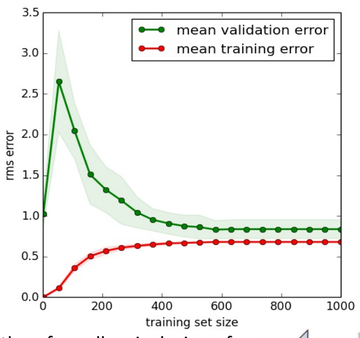
Evaluation of various methods against observed ap [8]

(with 1000 samples)	rms	% within ± 5	% within ± 10	HitRate	HSS	FAR
DecisionTreeRegressor	41.40	16.42	52.24	0.89	0.84	0.11
RandomForestRegressor	34.26	56.22	69.65	0.97	0.89	0.12
ElasticNet	36.48	34.33	56.72	0.95	0.91	0.08
SVR	38.18	35.82	63.68	0.90	0.88	0.07
LinearRegression	37.26	34.83	54.73	0.95	0.91	0.08
ARIMA	49.04	59.79	70.10	0.82	0.84	0.04

Performance (left and above) for the best of the ML algorithms showed:
- all ML methods out-perform ARIMA in Skill (HSS), Hit Rate and rms
- ARIMA more accurate (within ±5/±10 ap units) most of the time and best False Alarm Rate (FAR)
- best scoring all rounder is `Random Forest Regressor' although it has the poorest FAR



This work (2016) [4] showed:
→ advantages to using classifications of activity rather than numerical values
→ ML methods allow the discovery of the most important features - less 'black box' than Neural Networks
→ The most informative features (shown left) for the best method found so far - the 'RandomForest Classifier'.



Training converges quickly (above right) – this will therefore allow inclusion of more features in the future e.g. solar data, radio bursts, solar wind coupling functions

Work is now required to advance the ML code to an operational level. Further performance tests compared to other operational forecasts would then be possible.

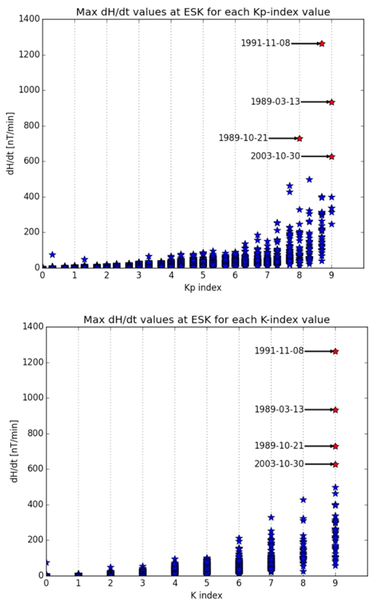
Finding the 'Right' Geomagnetic Parameter for the Job

Kp (and the related Ap) are used extensively in space weather applications and models. Kp has become an (informal) standard for geomagnetic activity, despite its well documented limitations in both space and time. There are many applications where these drawbacks are not significant and its use is reasonable. However, there are some applications where it could be misleading to consider only Kp, in particular where localised geomagnetic activity levels are required and over a shorter time span than 3 hours. One such example is the monitoring of geomagnetically induced currents (GIC) in power systems.

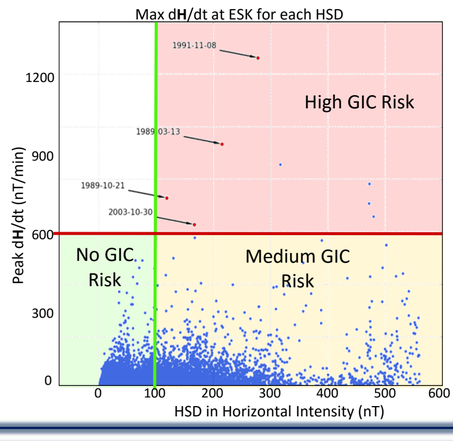
Kp	BGS categories since 2014		NOAA G-scales	
	Category	Description	Category	Description
<3+	QUIET	Kp < 3+		
3+	ACTIVE	3+ < Kp < 5-		
4-				
4o				
4+				
5-	STORM G1	5- < Kp < 5+	G1	Kp = 5
5o				
5+				
6-	STORM G2	6- < Kp < 6+	G2	Kp = 6
6o				
6+				
7-	STORM G3	7- < Kp < 7+	G3	Kp = 7
7o				
7+				
8-	STORM G4	8- < Kp < 9-	G4	Kp = 8
8o				
8+				
9-				
9o	STORM G5	Kp = 9o	G5	Kp = 9

Kp categories of geomagnetic activity and NOAA G scales.

Power companies in the UK are only likely to take action at G5.



Power companies require a parameter that will represent likely GIC flowing in the system and one that can be forecast to provide warnings. GIC is known to relate to rate of change of the magnetic field (d**B**/dt). How peak d**H**/dt at ESK relates to Kp is shown (left). The red starred events indicate storms with known GIC impacts. d**H**/dt is spread at high levels of Kp and Kp>8 doesn't necessarily result in problems. Replacing Kp with local K shows the known impact events were for the highest K and highest d**H**/dt. However, many K=9 periods do not correspond to high d**H**/dt. Conclusions from this are that a monitor for GIC needs to be at a higher time resolution and local to the power grid location. Planetary indices are therefore of limited use and could be misleading. HSD (below), a parameter that is physically related to GIC [11], is more appropriate. Computed with a 5-min cadence, HSD has been used operationally to monitor GIC in the UK since 2000 [12].



A better threshold for warnings/alarms could be a combined approach as shown diagrammatically on the right. Work is in progress at BGS in collaboration with UK Met office and National Grid to determine the most suitable local parameter for GIC monitoring. For example, by exploiting the correlation between measured historical GIC and parameters such as log[d**B**/dt] at various time windows, such as 15 or 30 minutes.

Summary and Future Work

The use of geomagnetic data and indices for BGS space weather applications has been reviewed and a summary has been given on the research carried out to enable and to improve on present-day operational capabilities.

Forecasting activities have been examined, and we argue that the inclusion of a human forecaster or "scientist in the loop" is still more likely to provide better forecasts than entirely automated computer-based methods. Despite this, attempts will continue to be made to improve the accuracy of automated predictions.

Collaborative work to establish the best monitoring parameter for GIC is on-going and this feeds directly into a new project recently started in the UK to cover *Space Weather Impact on Ground-based Systems* (SWIGS). A network of new magnetometer station pairs across the UK is planned to measure and assess GIC in power, pipeline and railway networks. These new data sets will complement those from the existing long-running magnetic observatories in Britain and Ireland and collectively provide an invaluable resource towards the on-going space weather research activities that have been described.

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