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Geomagnetic Activity Forecast Service (GAFS)

Final Project Report, Vol. 1

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Executive Summary

A. Project overview

The project “Geomagnetic Activity Forecast – a Service for Prospectors and Surveyors” was proposed to ESA as a Service Development Activity in response to ESA’s Announcement of Opportunity AO/1-4246/02/NL/LvH “Pilot Project for Space Weather Applications”, issued 29/07/2002. This activity is referred to as “GAFS – Geomagnetic Activity Forecast Service” in the context of SWENET, the ESA sponsored Space Weather European NETwork.

GAFS was motivated by the observation that the geomagnetic field tends to vary on a vast range of time scales. Magnetic field fluctuations ranging from minutes to days, often termed geomagnetic activity, are predominantly associated with magnetic storms and substorms caused by the highly variable interactions between the solar wind and the Earth’s magnetosphere. Variations on these time scales are a matter of concern for many scientific and commercial applications which utilize ground-based magnetic field observations as reference data (such as magnetometer-controlled directional drilling and airborne magnetic anomaly surveys). Accurate forecasts of the geomagnetic conditions are thus frequently desired to support such operations. GAFS is a computer-based, fully automatic system which delivers forecasts of geomagnetic activity hours to days ahead.

GAFS was developed by DMI in collaboration with the Geological Survey of Denmark and Greenland (GEUS) and Baker Hughes INTEQ Scandinavia. In this collaboration DMI assumed the role of the service provider, GEUS the role of a government user, and Baker Hughes INTEQ the role of an industrial user.

GAFS in its current state provides a graphical display of the level of geomagnetic field perturbation expected over the next three hours, the next 12 hours and the next two days. The observed and the predicted disturbance levels are binned into three classes which we refer to as alert levels: “quiet” (green), “active” (yellow), and “disturbed” (red). From the statistical distribution of many years of magnetic field disturbance records we defined these alert levels for different locations and different magnetic field elements and scaled them according to the geographic area – subauroral, auroral, and polar cap latitudes – and according to specific user requirements. A project summary including the forecast appears on the web site `http://www.esa-spaceweather.net/sda/gafs/`.

B. Methods for short- and medium-range forecasts

The fundamental principle underlying short-range forecasts (up to three hours ahead) is to take real-time data of solar wind plasma density, velocity and the interplanetar magnetic field (IMF) observed near the L1 libration point between Sun and Earth and transform them into a time series of ground-level geomagnetic variations using a data-based filter. The time series we work with consist of 5-min averages of observed solar wind parameters, and the predicted magnetic field variation is consequently also updated with 5-min averages. But we try to extend our forecast interval beyond the solar wind travel time from the L1 point to the magnetosphere. Hence our short-range forecast of alert levels is not merely based on a conversion of the predicted geomagnetic field into an alert level. Instead, we use the error distributions at different geomagnetic storm levels, different seasons and different local times to deduce the probabilities for certain alert levels. Hence, we combine deterministic and probabilistic approaches. From tabulated data of the conditional probabilities for a certain alert level we determine the forecast alert level given the deterministically predicted geomagnetic field, the predicted storm index, and season and time of day.

Our medium-range forecasts (up to two days ahead) rely on remote observations of the Sun and solar atmosphere made from ground and space based observatories, and on products derived from these data. Near-Earth solar wind data may also be used, but primarily as supplementary data supporting the conclusions drawn from solar wind models which are based on remote observations of the Sun. The accuracy of our forecast is severely affected by the limits posed on observing solar parameters and by the lack of understanding of how solar observations are physically connected to solar wind variability and geoeffective events. Therefore there is still much room for a human forecaster to interpret data, classify events based on incomplete data and judge the space weather situation based on his or her subjective experience. In GAFS, however, we have only considered methods which can be made fully automatic. We have further separated the medium-range forecasts into two sub-intervals with lead times of 3 to12 hours and 12 to 48 hours, respectively.

On the medium-range time scale, geomagnetic activity is governed by quasi-steady solar wind structures co-rotating with the Sun and by transient solar wind structures generated by eruptive events on the Sun. Hence, a distinction needs to be made between these two factors. The fundamental observations that are used in GAFS to indicate whether transient disturbances can be expected are the occurrence of a CME, as reported by the Naval Research Laboratory (NRL) based on white-light solar coronagraph images, in combination with certain SEP flux characteristics. If a CME is observed and if, from the CME characteristics and the observed SEP flux enhancements, we have reason to believe that the CME will be geoeffective, then this determines the medium-range forecast. The time of arrival of the expected CME ejecta is based on a simple empirical relationship between the observed CME expansion speed in the plane of the sky and the travel speed. In the absence of such observations, the forecast is governed by the quasi-steady solar wind structures as predicted by the Wang-Sheeley-Arge and Hakamada-Akasofu-Fry solar wind models. In practice, two forecasts are made simultaneously – one based on the WSA and HAF solar wind models, and one based on observations of CMEs and SEP fluxes – and the forecast indicating the largest geomagnetic disturbances determines the final forecast.

C. GAFS operation

Our service aims at predicting the level of geomagnetic activity at geographic regions of relevance to our users, namely the North Sea and Greenland. We provide forecasts of the level of geomagnetic activity expected to prevail at the sites of our four geomagnetic observatories, THL, GDH and NAQ in Greenland, and BFE in Denmark. Geomagnetic activity is divided into three levels, quiet, active and disturbed. For each level we specify thresholds individually for different geographic areas. The numbers were selected such that the probability to remain in the quiet range is 80%, and the probabilities to exceed the active and disturbed thresholds are 67%, respectively.

An analysis of many years of observatory data revealed a significant difference between the occurrence of positive and negative excursions during geomagnetically active times. This distinction is reflected in our web-based forecast scheme, but it is at present of no relevance to the users. However, for further developing our scientific understanding in physical modeling and making progress in forecasting a distinction between positive and negative perturbations may become important.

The service product is automatically updated once every hour. It displays on a dedicated public web site (`http://www.dmi.dk/projects/ESA_SWAPP/Public/magoutlook.shtml`) a forecast of the geomagnetic activity to be expected over the next three hours, the following nine hours, and the following 36 hours, that is, 48 hours in total. If an important piece of information is missing the concerned activity cell is left blank. This part of the service is publicly accessible. In addition to the public web site, we maintain restricted web sites only known to ESA technical officers, the SWENET operator and our project collaborators.

D. GAFS evaluation

The assessment of geomagnetic forecasts depends on a multitude of factors. We list here the general conclusions we drew from a statistical analysis of our forecast products.

- One hour ahead forecasts can be made with relatively high accuracy if plasma and IMF data from the L1 point are available. This is consistent with many studies published in the scientific literature.
- Meaningful 3-12 hours ahead forecasts can be made, although with low accuracy. With "meaningful" we mean forecasts that are significantly better than a random choice.
- Meaningful 12-48 hours ahead forecasts can be made, although with a low accuracy.
- The 12-48 hours ahead forecasts are better than the 3-12 hours ahead forecasts because the time of arrival allowed for a sucessful forecast spans a wider interval.
- The rare events with very strong disturbances are better predicted than the frequent intervals with moderate disturbances.
- Strong magnetic storms caused by full halo CMEs are predicted with high accuracy. Moderate storms caused by recurrent structures are predicted with low accuracy.

In addition to the statsistical analysis our project partner GEUS conducted a service performance assessment from a user's point of view. As no real aeromagnetic survey was scheduled in Greenland during the lifetime of GAFS we simulated a survey. The simulations were done for three survey areas corresponding to the regions covered by the DMI observatories at Qaanaaq, Qeqertarsuaq/Kangerlussuaq and Narsarsuaq. For all of the three survey areas, the simulated airborne surveys covered the time period from 10 October 2005 to 20 December 2005. In particular variations with periods up to one minute were considered since they are seen as a source of severe errors in airborne surveys which cannot be corrected with remote refererence magnetometer data. Geomagnetic activity was in general low during the simulation period. The predictions of the field variations and the resulting simulated flight decisions of the survey manager were confirmed to have been correct in general at all sites.

From a technical point of view the forecast has not always worked satisfactorily. We experienced black-outs of one or several of the real time data streams. The automatic restart of the server after a breakdown or power failure did not always work as intended, with the consequence that a manual restart became sometimes necessary. Various technical and logistic modifications (including a change of our Internet provider) and a server upgrade resulted in more stable real time data links.

E. Future service improvements

An improved utilization of solar and interplanetary data that can be combined with data extracted from white-light coronagraph images have the potential to improve the forecast accuracy of strong magnetic storms. In GAFS we have tried to take one step in this direction by utilizing SEP fluxes to infer the geoeffectiveness of an observed full halo CME. Other relevant data not yet implemented in GAFS include the solar magnetic field configuration at the site of the CME, the ambient solar wind into which the CME is released, and sweep-frequency radio bursts indicating the presence of propagating shocks.

The Solar-Terrestrial Relations Observatory (STEREO) twin space probes were launched successfully on October 26, 2006, see `http://stereo.gsfc.nasa.gov/`. The two spacecraft orbit the Sun on trajectories similar to that of the Earth but at some distance ahead and behind the Earth. They will map the structure of CMEs in 3-D as they leave the solar surface and expand into interplanetary space. This will allow observers to clearly idfentify earthward directed CMEs and quantify their velocity much more precisely than has hitherto been possible. The timing of the onset of geomagnetic storms is expected to become much more accurate. However, due to their particular orbit parameters the spacecraft slowly drift away from the Earth in opposite directions. The continuously changing constellation thus limits the mission time useful for mapping earthward directed CMEs. STEREO will be highly useful for space weather research but its usefulness for a continuous operational geomagnetic storm alert service will be limited.

Current solar wind models have a limited ability to describe the conditions in interplanetary space from observations of the Sun, partly for fundamental physical reasons. A simple way to improve the forecast ability would be to use current models as they are, but to try to adjust them based on actually observed data. This would primarily be observed solar wind data, but also observations of coronal hole boundaries from e.g. soft X-ray observations and, in the future, solar and solar wind observations with new types of radio telescopes and radars such as the LOFAR/LOIS facility currently under construction.

A major problem exists with the reconstruction of the magnetic field vector at the solar surface and within CMEs. Although better physical understanding of the processes will lead to better models, their accuracy will continue to be limited as long as no new instruments or methods become available which allow us to quantitatively specify the solar surface magnetic field.

The two users who are currently partners in the GAFS project represent operational commercial, semi-commercial and scientific activities in the North Sea (directional wellbore drilling) and in Greenland (airborne magnetostatic anomaly surveys). GAFS can in principle be extended to include other users in other geographic areas. Such an extension means basically redoing the analysis of historic time series from geomagnetic observatories representing the new areas under consideration, deriving statistical measures for the geomagnetic activity and finding the proper coefficients needed to build prediction filters for the geomagnetic activity at those newly added observatories. The procedure is thus straightforward, but a certain amount of work hours is needed in order to adapt the procedure to the new stations and to find and validate the statistical results and the inferred probabilities used to define quantitatively the corresponding activity levels. Since an extension requires extra resources it will only materialize if a paying customer can be identified.

F. Conclusion

DMI’s Geomagnetic Activity Forecast Service (GAFS) is an area specific service which is initially targeted towards two user categories who are represented as partners in the GAFS project

- oil companies which perform directional wellbore drilling in the North Sea
- service companies which conduct airborne magnetostatic anomaly surveys in Greenland

Starting from an initially manually driven and more qualitatively oriented predecessor, GAFS was developed to fulfill the requirement of a fully automated objective (i.e. operator independent) forecast service. This task has been accomplished within the project run time. GAFS is now operational, but interruptions or breakdowns due to technical or logistic problems still occur occasionally.

An objective statistical analysis of forecast versus observations has proven that the service gives under many conditions a better forecast than a random (uninformed) prediction. However, certain parameters, notably the time of the onset of geomagnetic storms and the activity levels of weak storms, are often poorly predicted.

The evaluation of a situation in which GAFS served as a decision aid for a simulated aeromagnetic survey in Greenland demonstrates that the decisions suggested by GAFS proved to have been correct in the vast majority of cases. This result lends credibility to GAFS. We must consider, though, that the simulation was performed during a geomagnetically relatively quiet period which made the prediction easier than would be under conditions with heavily mixed disturbance levels.

An extension of GAFS in order to cover additional geographic areas is possible. Using the same procedures as those used for Greenland and Denmark, such an extension could be implemented. However, a substantial amount of work hours is required to actually do the extension work.

GAFS is expected to continue running operationally over at least the next few years.

Content:

Abstract

The project “Geomagnetic Activity Forecast – a Service for Prospectors and Surveyors” was proposed to ESA as a Service Development Activity in response to ESA’s Announcement of Opportunity AO/1-4246/02/NL/LvH “Pilot Project for Space Weather Applications”, issued 29/07/2002. This activity is referred to as “GAFS – Geomagnetic Activity Forecast Service” in the context of the ESA sponsored Space Weather European Network SWENET.

The project was motivated by the observation that certain types of magnetic field fluctuations (often termed geomagnetic activity) are a matter of concern for many scientific and commercial applications. Accurate forecasts of the geomagnetic conditions are thus frequently desired. This led the Danish Meteorological Institute (DMI) to develop GAFS. The GAFS system now in operation at DMI is the result of an effort to convert current knowledge about solar activity and space weather into a computer-based, fully automatic system which delivers forecasts of geomagnetic activity hours to days ahead.

GAFS in its current state provides a short description of the present and expected geomagnetic activity which includes graphical displays of the perturbation level of the geomagnetic field expected over the next three hours, the next 12 hours and the next two days. The level of geomagnetic activity is divided into three classes, referred to as “quiet”, “active” and “disturbed”, which are scaled according to the geographic area – subauroral, auroral, and polar cap latitudes. The forecast is specifically geared toward regions where our project partners are active, namely the North Sea and Greenland. A project summary appears on the publicly accessible web page `http://www.esa-spaceweather.net/sda/gafs/` which also includes a link to our regularly updated forecast of geomagnetic activity levels.

Once GAFS had been in operation for about a year an objective statistical analysis of forecast versus observation was performed. It proved that the service gives under many conditions a quantitatively valuable forecast. However, certain parameters, notably the time of the onset of geomagnetic storms and the activity levels of weak storms, are often poorly predicted. This led to suggestions for improvements in a future version of GAFS.

The evaluation of a situation in which GAFS served as a decision aid for a simulated aeromagnetic survey in Greenland demonstrated that the decisions for *fly*, *wait* or *no fly* suggested by GAFS proved to have been correct in the vast majority of cases.

An extension of GAFS in order to cover additional geographic areas is possible. Using the same procedures as those used for Greenland and Denmark, such an extension could be implemented. However, a substantial amount of work hours is required to actually carry out the extension.

GAFS is expected to continue its operation over at least the next few years.

Acronyms and Abbreviations

ACE	Advanced Composition Explorer (*a space probe placed at the L1 point*)
AU	Astronomical Unit (*the mean distance between the centers of Sun and Earth*)
BFE	Brorfelde (Denmark) Geomagnetic Observatory
CGML	Corrected Geomagnetic Latitude
CME	Coronal Mass Ejection
DMI	Danmarks Meteorologiske Institut (the Danish Meteorological Institute)
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
GAFS	Geomagnetic Activity Forecast Service
GDH	Qeqertarsuaq (Greenland) Geomagnetic Observatory (*former name Godhavn*)
GETG	Ground Effects Topical Group (*a sub-group of the SWWT*)
GEUS	Danmarks og Grønlands Geologiske Undersøgelse (the Geological Survey of Denmark and Greenland)
GHB	Nuuk (Greenland) magnetometer station (*former name Godthab*)
GIC	Geomagnetically Induced Currents
HAF	Hakamada-Akasofu-Fry model (*a research model of the solar wind*)
IAGA	International Association of Geomagnetism and Aeronomy
ICME	Interplanetary Coronal Mass Ejection
IMF	Interplanetary Magnetic Field
ISGI	International Service of Geomagnetic Indices
MLT	Magnetic Local Time
NAQ	Narsarsuaq (Greenland) Geomagnetic Observatory
NOAA	National Oceanographic and Atmospheric Administration
NRL	Naval Research Laboratory
SDA	Service Development Activity
SEC	Space Environment Center (*located at NOAA*)
SEP	Solar Energetic Particle (*often used in connection with the terms "event" or "flux"*)
SOHO	Solar and Heliospheric Observatory (*a space probe placed at the L1 point*)
STEREO	Solar-Terrestrial Relations Observatory (*twin space probes for stereoscopic imaging*)
STF	Sondrestrom Research Facility (Kangerlussuaq, Greenland)
SWENET	Space Weather European Network
SWWT	Space Weather Working Team (*project advisory group initiated by ESA*)
THL	Qaanaaq (Greenland) Geomagnetic Observatory (*former name Thule*)
WSA	Wang-Sheeley-Arge model (*a research model of the solar wind*)

References

TN-010.2	Technical Note TN-010 Revision 2 (21 Oct 2005): Geomagnetic Activity Forecast Service (GAFS) – Service Product Development
TN-100.2	Technical Note TN-100 Revision 2 (18 Feb 2005): Geomagnetic Activity Forecast – a Service for Prospectors and Surveyors / User Requirements Document
TN-300/1.2	Technical Note TN-300/1 Revision 2 (09 Sep 2005): Geomagnetic Activity Forecast – a Service for Prospectors and Surveyors / Prediction Software Documentation
TN-300/2.1	Technical Note TN-300/2 Revision 1 (04 Jan 2006): Geomagnetic Activity Forecast Service (GAFS) – Forecast Analysis Report
Gleisner-2006a	Gleisner, H., and J. Watermann (2006), Concepts of medium-range (1-3 days) geomagnetic forecasting, Adv. Space Res., 37, p. 1116-1123
Gleisner-2006b	Gleisner, H., O. Rasmussen and J. Watermann (2006), Large-magnitude geomagnetic disturbances in the North Sea region: Statistics, causes, and forecasting, Adv. Space Res., 37, p. 1169-1174
Gleisner-2006c	Gleisner, H., and J. Watermann (2006), Solar energetic particle flux enhancement as an indicator of halo coronal mass ejections, Space Weather, 4, S06006, doi:10.1029/2006SW000220, 2006
Watermann-2006	Watermann, J., O. Rasmussen, P. Stauning and H. Gleisner (2006), Temporal versus spatial geomagnetic variations along the west coast of Greenland, Adv. Space Res., 37, p. 1163-1168

1. Introduction

The project "Geomagnetic Activity Forecast – a Service for Prospectors and Surveyors" was proposed to ESA as a Service Development Activity in response to ESA's Announcement of Opportunity AO/1-4246/02/NL/LvH "Pilot Project for Space Weather Applications", issued 29/07/2002. This activity is referred to as "GAFS – Geomagnetic Activity Forecast Service" in the context of the ESA sponsored Space Weather European Network SWENET.

The project was motivated by the observation that the geomagnetic field tends to vary on a vast range of time scales. Magnetic field fluctuations ranging from minutes to days, often termed geomagnetic activity, are a matter of concern for many practical applications, both scientific and commercial. Accurate forecasts of the geomagnetic conditions are thus frequently desired. GAFS was developed at the Danish Meteorological Institute (DMI) in response to a need for a targeted geomagnetic activity forecast service. It was not our intention to develop new models or generate new data, rather to combine currently existing models and data into an operational system of practical use to specific user categories. The GAFS system now in operation at DMI is the result of an effort to convert current knowledge about solar activity and space weather into a computer-based, fully automatic system which delivers forecasts of geomagnetic activity hours to days ahead.

GAFS in its current state provides a short description of observed solar activity and the present and expected geomagnetic activity together with a graphical display of the level of perturbation of the geomagnetic field expected over the next three hours, the next 12 hours and the next two days. The level of geomagnetic activity is divided into three classes, referred to as "quiet", "active" and "disturbed", which are scaled according to the geographic area – subauroral, auroral, and polar cap latitudes – and according to specific user requirements. The service is provided automatically and without interruption other than occasional technical failures. Real-time magnetic field data and regularly updated, model-based forecasts of solar wind and interplanetary magnetic field conditions are presented in detail on a restricted web site. A project summary including expected activity levels appear on the web site `http://www.esa-spaceweather.net/sda/gafs/`.

GAFS is included in the subgroup of SDAs which deal with effects of geomagnetically induced currents (GIC) although GAFS, in a strict sense, is not concerned with or related to GIC effects. It is, however, relevant to GIC in a broader, qualitative sense: if geomagnetic activity is at a high level, the GIC effective magnetic field time derivatives also reach high values.

GAFS was developed by DMI in collaboration with the Geological Survey of Denmark and Greenland (GEUS) and Baker Hughes INTEQ Scandinavia. In this collaboration DMI assumed the role of the service provider, GEUS the role of a government user, and Baker Hughes INTEQ the role of an industrial user. The project grew out of informal discussions between DMI and its contact persons at Baker Hughes INTEQ and GEUS who expressed interest in an area-specific forecast of geomagnetic activity over a period of at least one day ahead but preferentially more.

Section 2 starts with a general overview of the nature of geomagnetic activity as far as it is relevant to this project, followed by a short description of DMI's predecessor to GAFS. Section 3 outlines the project management. In section 4 we review the methods including data acquisition and processing. Section 5 describes the routine operation of the automatic forecast service. Section 6 deals with the evaluation of the forecast service by presenting results from a statistical analysis of prediction vs. observation and from an assessment of the forecast quality in support of a survey campaign in Greenland. Plans for a campaign in 2005 or 2006 did not materialize so that a survey situation had to be simulated in order to test the forecast. In section 7 we discuss possible future improvements of the service in terms of science and data availability. Section 8 summarizes and concludes the report.

2. Project Background

2.1 The nature of geomagnetic activity – a brief review

The interaction between the solar wind (an omni-directional stream of tenuous hot plasma released by the Sun at all times) and the Earth's internally generated magnetic field creates a cavity called magnetosphere. The size, the plasma population and the dynamics of the magnetosphere depend largely on the conditions and state of the solar wind plasma and on the interplanetary magnetic field (IMF) which is carried along with the solar wind. The magnetosphere responds in a complex way to variations of the solar wind. Several types of interaction are known to exist which enable the transfer of mass, momentum, magnetic flux and energy from the solar wind into the magnetosphere. Interaction processes include field line merging, viscous interaction, impulsive plasma penetration and plasma instabilities at the interface between magnetosphere and interplanetary space.

The ionosphere (the ionised component of the upper atmosphere) constitutes the inner boundary of the magnetosphere and is thus strongly coupled to solar wind – magnetosphere interaction processes. As a result of this interaction ionospheric electric currents are launched which are occasionally very intense and may fluctuate wildly. The spectrum of ionospheric reaction to solar wind variations is wide, it ranges from an almost direct response (ionospheric reconfiguration of the polar regions at the sunward side of the Earth within a few minutes) to many hours delay (storage of solar wind energy in the magnetosphere and its subsequent release which occurs mainly in the nightside auroral zone). Magnetic field variations signaling fluctuations of the divergence-free part of the horizontal ionospheric current are routinely observed on the ground by sensitive magnetometers. Under extremely disturbed conditions the deviations of the geomagnetic field from its quiet time level can reach such magnitudes that the magnetic declination can change by several degrees and becomes clearly visible as a deflection of the needle of an ordinary compass.

The unsteady nature of the geomagnetic field with its many transient variations which are difficult to predict has an undesired negative effect on those scientific and industrial activities which utilize ground-based magnetic field observations as reference data, such as magnetometer-controlled directional drilling and airborne magnetic anomaly surveys.

Geomagnetic activity is typically highest at auroral and polar cap latitudes. However, when assessing the relevance of geomagnetic activity for specific users one has to go a step further and distinguish between the effects of large amplitudes of geomagnetic variations, $\mathbf{B}(t)$, and their time derivatives, $\partial\mathbf{B}(t)/\partial t$. Some users are interested in $\mathbf{B}(t)$ (like our partners Baker Hughes INTEQ and GEUS) while others are interested in $\partial\mathbf{B}(t)/\partial t$ (for instance, the operators of electric power networks, pipelines and communication lines).

2.2 DMI's geomagnetic observatories

DMI currently operates four permanent geomagnetic observatories, see Figure 1: one in Denmark (Brorfelde/BFE) and three along the west coast of Greenland (Qaanaaq/THL, Qeqertarsuaq/GDH and Narsarsuaq/NAQ). From these observatories we obtain absolute values of the northward (X), eastward (Y), and downward (Z) components of the geomagnetic field. Data from three of the observatories – BFE, NAQ, and THL – are transferred in real time to DMI while data from GDH are available within a day. DMI further operates 17 variometer stations in Greenland and one in Denmark which produce geomagnetic data with the same accuracy as the data from the observatories but which lack absolute reference values.

All stations are equipped with tri-axial fluxgate magnetometers designed and built at DMI. They are optimised for long-term stability (observatory-quality instruments) rather than high sensitivity. The rms-noise is approximately 0.1 nT in the ~DC–1-Hz band. The sensors are equipped with a gimbal suspension system which guarantees vertical alignment of the sensor body. The stations run fully automatically and require (under normal conditions) no manual intervention.

A statistical analysis of nine months of geomagnetic variations recorded at our four observatories in Denmark and Greenland revealed that the largest amplitudes tend to occur equally often deep in the polar cap and in the auroral zone while the largest time derivatives clearly peak in the auroral zone. Both amplitudes and time derivatives are almost always smaller at subauroral latitudes except under extremely disturbed conditions (superstorms) when the largest amplitudes (but not the largest time derivatives) were occasionally observed at subauroral observatories.

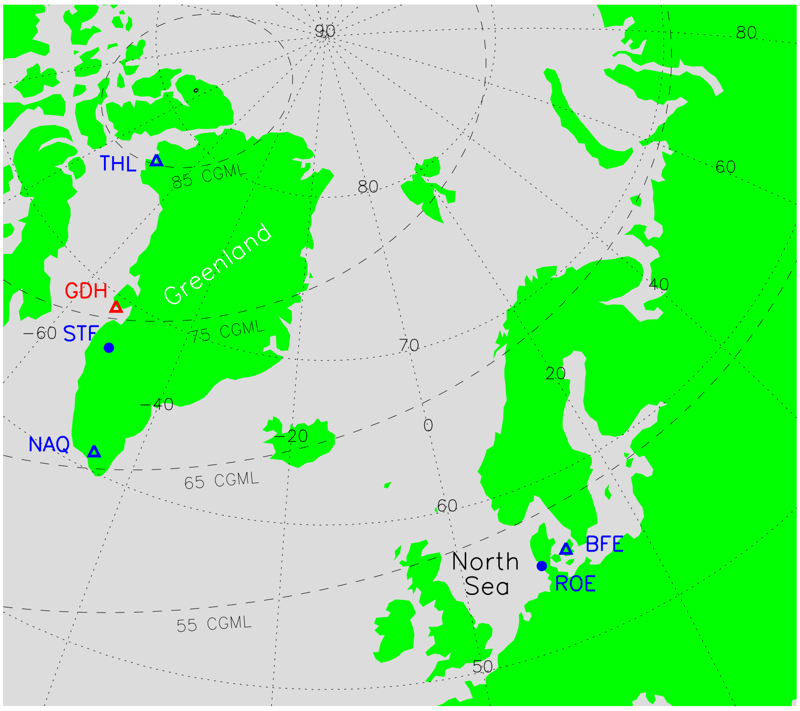


Fig. 1. *Regions of interest to the users collaborating in this SDA: Greenland – airborne magnetostatic anomaly surveys performed for and under supervision of GEUS; North Sea – directional well drilling activity guided by magnetic field reference techniques applied under the supervision of Baker Hughes INTEQ.*

Open triangles – geomagnetic observatories; full circles – variometer sites; blue – stations with real-time data transmission; red – stations without real-time data transmission. Dotted lines – geographic latitude-longitude grid; dashed lines – corrected geomagnetic latitude iso-contours.

This fact is evidenced in Figure 2 where the histograms represent the maximum amplitudes and maximum time derivatives within all available 1-min time intervals and in addition the maximum time derivatives during storm time intervals.

2.3 Geomagnetic time variations

The geomagnetic field exhibits variations on vastly different time scales, from the slow secular variations of the main field to sub-second pulsations of magnetospheric origin. In this project we are primarily concerned with field variations on the intermediate time scales – ranging from minutes to days. Variations on these time scales are predominantly associated with magnetic storms and substorms caused by the highly variable interactions between the solar wind and the Earth's magnetosphere. These irregular variations, ultimately governed by the conditions in interplanetary space, must be distinguished from the regular diurnal variations of the geomagnetic field caused by winds in the dynamo region of the upper atmosphere. More or less regular diurnal variations are always present, but are most easily noticed on days when the interaction between the solar wind and the Earth's magnetosphere is weak and steady. On time scales of a year and longer we also need to consider changes of the geomagnetic main field. Hence, for the purposes of this study we have to distinguish between three types of geomagnetic variations:

- slow secular variations
- regular quiet-time diurnal variations
- irregular variations

Only the latter are a direct manifestation of space weather while the other two together can be regarded as a quiet-time reference field against which to measure the irregular variations. Detailed information on the magnetic quiet time and disturbed time variations observed at the four Danish and Greenlandic observatories over a period of 20 years is found in the report TN-300/2.1.

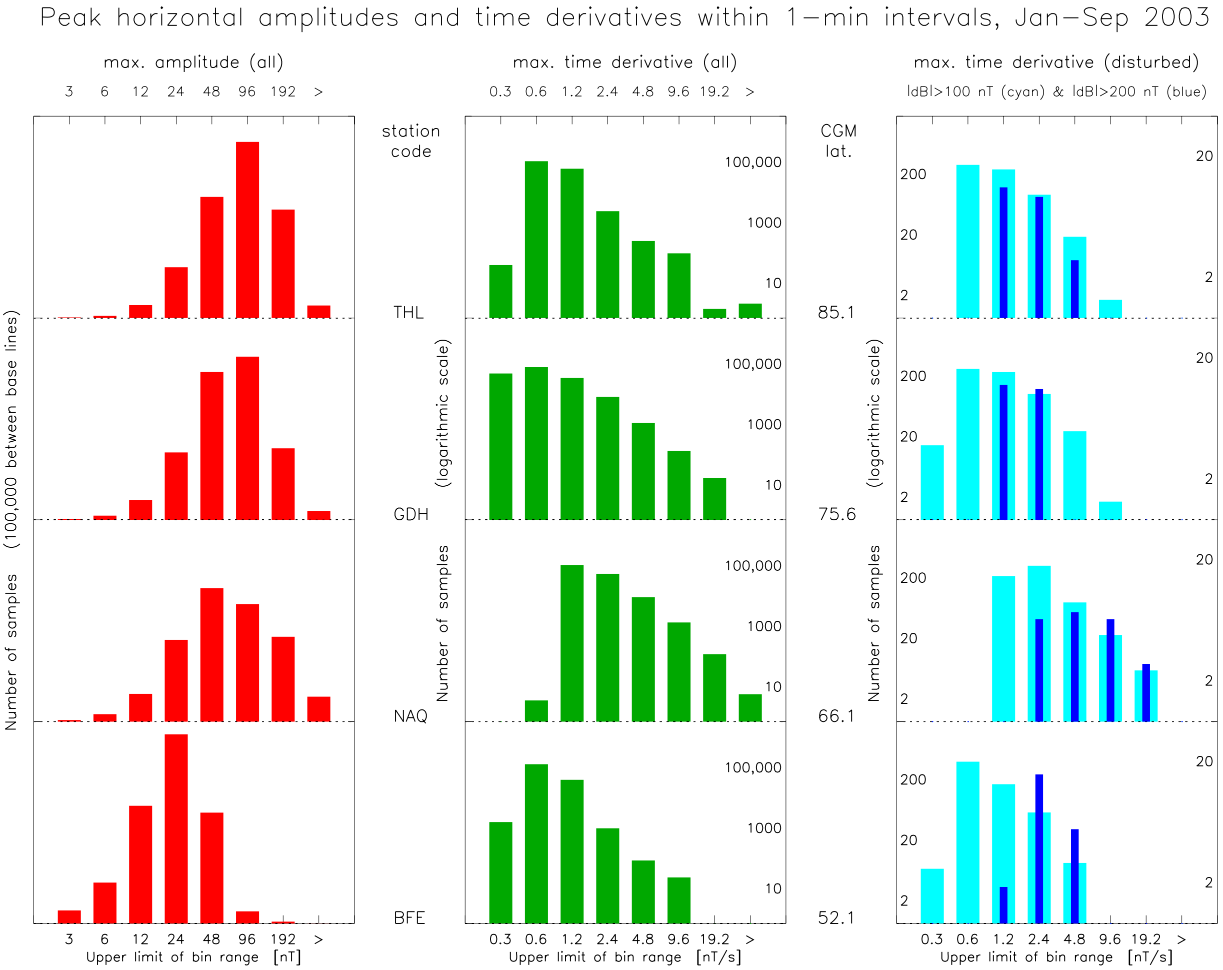


Fig. 2. *Histograms from nine months of geomagnetic variations recorded at the Danish and Greenlandic geomagnetic observatories. Data were sampled at 1-s rate. The maximum absolute amplitudes and time derivatives measured within each 1-min time interval were binned into ranges with widths doubling with increasing threshold. Left panel: absolute amplitudes (red); center panel: maximum time derivatives (green); right panel: maximum time derivatives during highly and extremely disturbed periods when the absolute amplitudes at Brorfelde exceeded 100 nT (cyan) and 200 nT (narrow blue), respectively. Note that the ordinate at the left panel is scaled linearly while the ordinates at the center and right panels are scaled logarithmically and different. This way of scaling was chosen because the number of time derivatives falls off quickly with increasing bin range. The three-letter codes between the panels indicate the observatories and the numbers their corrected geomagnetic latitudes.*

The secular variations can be described by a time varying baseline $\mathbf{B}_0(t)$ while the regular diurnal variations on geomagnetically quiet days are described by the *Sq* field $\mathbf{B}_{Sq}(t)$. The baseline and the *Sq* field together constitute a quiet-time reference field, and we define the geomagnetic disturbance field $\mathbf{B}(t)$ as the departures from this reference, such that

$$\mathbf{B}_{\mathrm{obs}}(t) = \mathbf{B}_0(t) + \mathbf{B}_{\mathrm{Sq}}(t) + \mathbf{B}(t) \qquad \text{(Eq. 1)}$$

where $\mathbf{B}_{\mathrm{obs}}(t)$ is the observed magnetic field. The baseline $\mathbf{B}_0$ is computed from quiet-time annual means, and the *Sq* field $\mathbf{B}_{\mathrm{Sq}}$ is here taken to be the climatology of seasonal and diurnal variations for geomagnetically quiet conditions. Both fields are computed from a list of UT days that are deemed as being geomagnetically quiet according to a classification of days adopted by IAGA. A list of quiet days starting with 1932 can be downloaded from the homepage of the International Service of Geomagnetic Indices (ISGI), http://isgi.cetp.ipsl.fr/lesdonne.htm.

The geomagnetic disturbance field $\mathbf{B}(t)$ can be defined according to Equation 1 as the departure from the quiet-time reference field. Our data analysis has shown that large-magnitude disturbances occur most frequently at NAQ which is located within the auroral zone. The occurrence frequencies of large-magnitude disturbances drop rapidly equatorward, but only slowly poleward, with increasing distance from the auroral zone. Some of the distributions are markedly asymmetric which is presumably due to the influence of the westward electrojet flowing during substorms.

The geomagnetic activity varies in a seemingly irregular way in response to the irregularly varying conditions in interplanetary space. However, geomagnetic activity is also governed by seasonal and diurnal variations in the ionosphere, and the geomagnetic disturbances observed at a single location are strongly modulated throughout the day and throughout the year. An important observation from a forecasting perspective is that the large-magnitude disturbances occur predominantly during certain times of the day and during certain seasons, whereas for other hours and seasons we can practically exclude the possibility of strong geomagnetic activity. It is also important to note that the diurnal and seasonal modulations are very different for positive and negative disturbances.

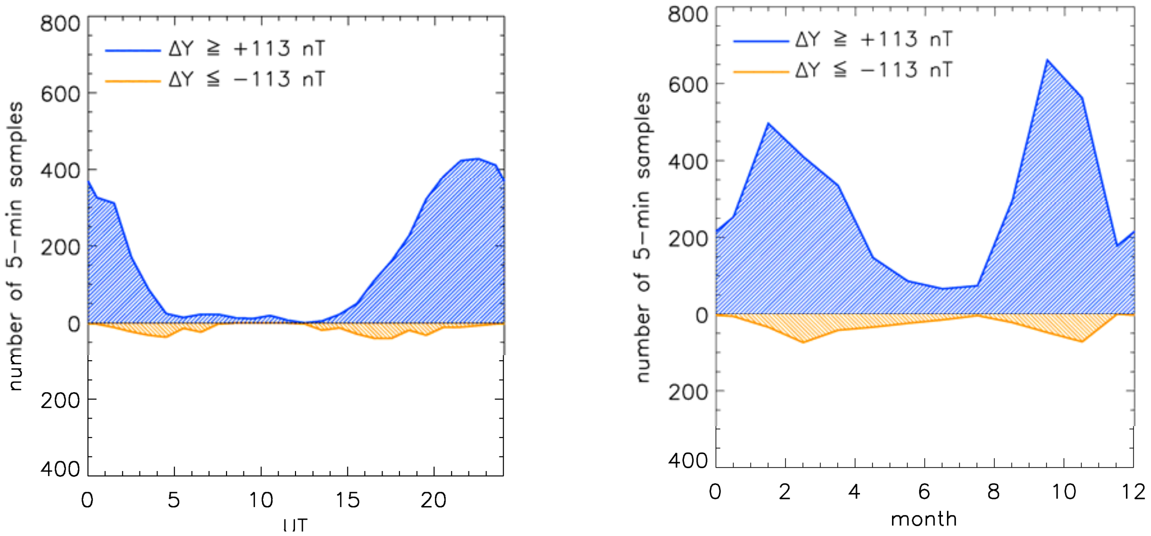


Fig. 3. *Diurnal (left) and seasonal (right) distributions of the largest 0.2% of magnetic perturbations observed at BFE (Denmark) over the period 1985 through 2003. Shown is the east-west component (practically the magnetic declination), separateed into positive (blue) and negative (orange) excursions.*

In order to demonstrate this with an example we show in Figure 3 results for the eastward magnetic field component from BFE which is practically identical to the declination, except for the physical unit used (nT rather than degree). Figure 3 represents the diurnal resp. seasonal distributions of the 0.2% of days between 1985 and 2003 for which the largest amplitudes were observed at BFE. We note that we rarely observe any negative excursion exceeding –113 nT, and between 06 and 14 UT (equivalent to 08-16 MLT) we see hardly any large positive excursions. We note further that we observe very few large negative and only a modest number of large positive excursions during the month of July. This suggests that industrial operations in the North Sea which rely on a quiet geomagnetic background have the highest probability of not being harmed if carried out in the month of July between 06 and 14 UT. However, there are two caveats. Firstly, these results are statistical, i.e. on any individual day the conditions may differ substantially from the statistical average, secondly, many operations, specifically wellbore drilling, are economically most reasonable if carried through from start to end without interruption. More details on the diurnal and seasonal behaviour of large-amplitude geomagnetic variations are found in Gleisner-2006b.

2.4 The GAFS predecessor

2.4.1 Supply of real-time and recent geomagnetic observations

Since several years DMI has been supplying measurements of variations of the geomagnetic field at 1-min resolution to Baker Hughes INTEQ. The service is implemented as a password-protected web site where the magnetic field disturbance recorded at BFE (55.63°N geographic latitude, 11.67°E geographic longitude) is retrieved and presented in graphical form. Measured intensity, declination (the angle between geographic north and geomagnetic north) and inclination (the angle between the magnetic field vector and the horizontal plane) are shown as time series which fluctuate around their quiet time values. Such a display allows a quick grasp of whether the magnetic field perturbations are acceptable or have exceeded predefined thresholds.

This scheme only delivers past data, uninterrupted and up to the present minute in the ideal case. It is provided as a decision aid for our customer, Baker Hughes INTEQ. The scheme tells the user whether the magnetic field data he has acquired so far with his own system are suitable for the intended purpose, namely control of directional wellbore drilling, or if the data are contaminated by excessively large magnetic disturbances and therefore useless. While this information meets the user’s most essential requirements it may not always be fully satisfactory.

It is valuable to the user to know that his own hardware and software is not to be blamed for unexpected measurement results. It is also valuable to the user to become aware that certain past measurements which were taken during magnetically disturbed times should not be used and may have to be repeated if deemed necessary. However, it would be more valuable if the user could know in advance whether it makes sense to conduct measurements or if one should rather wait until less disturbed conditions prevail. As an example, an airborne magnetic survey program would benefit from such knowledge since it means that flight operations can be scheduled according to the predicted level of geomagnetic activity.

2.4.2 Forecasting geomagnetic activity in the immediate future

In order to overcome the deficiency identified above we devised a scheme to generate semi-quantitative geomagnetic field disturbance predictions based on a variety of publicly accessible information and data from DMI's own sources. We had selected three reference magnetometer stations, BFE representing a subauroral site, GHB representing a high-latitude site just poleward of the nominal auroral peak latitude and THL representing a central polar cap site. Our preliminary prediction was generated every morning shortly before 09 UT and displayed on a web page available to authorised users only. We used activity classes scaled with the local *K* index as shown in Table 1. Figure 4 shows a screen dump of the forecast generated on Oct 28, 2002, at 09 UT.

Our prediction method was almost entirely manual. We examined data from various sources including SOHO observations of the sun and solar corona, ACE real-time solar wind data, and a number of real-time ground-based magnetometer measurements. We further examined reports on past solar and geomagnetic activity, including those issued by the Space Environment Center (SEC) of the US National Oceanographic and Atmospheric Administration (NOAA). These data and reports were then evaluated with respect to information on the geoeffectiveness of events, where geoeffectiveness refers to such solar events and solar wind conditions which have a detectable impact on geospace.

activity	K value	BFE range (nT)	GHB range (nT)	THL range (nT)
weak	0 – 3	≤ 48	≤ 192	≤ 144
moderate	4 – 5	49 – 144	193 – 576	145 – 432
strong	6 – 7	145 – 396	577 – 1584	433 – 1188
storm	8 – 9	> 396	> 1584	> 1188

Table 1. *Geomagnetic activity classes at selected Danish and Greenlandic magnetometer stations.*

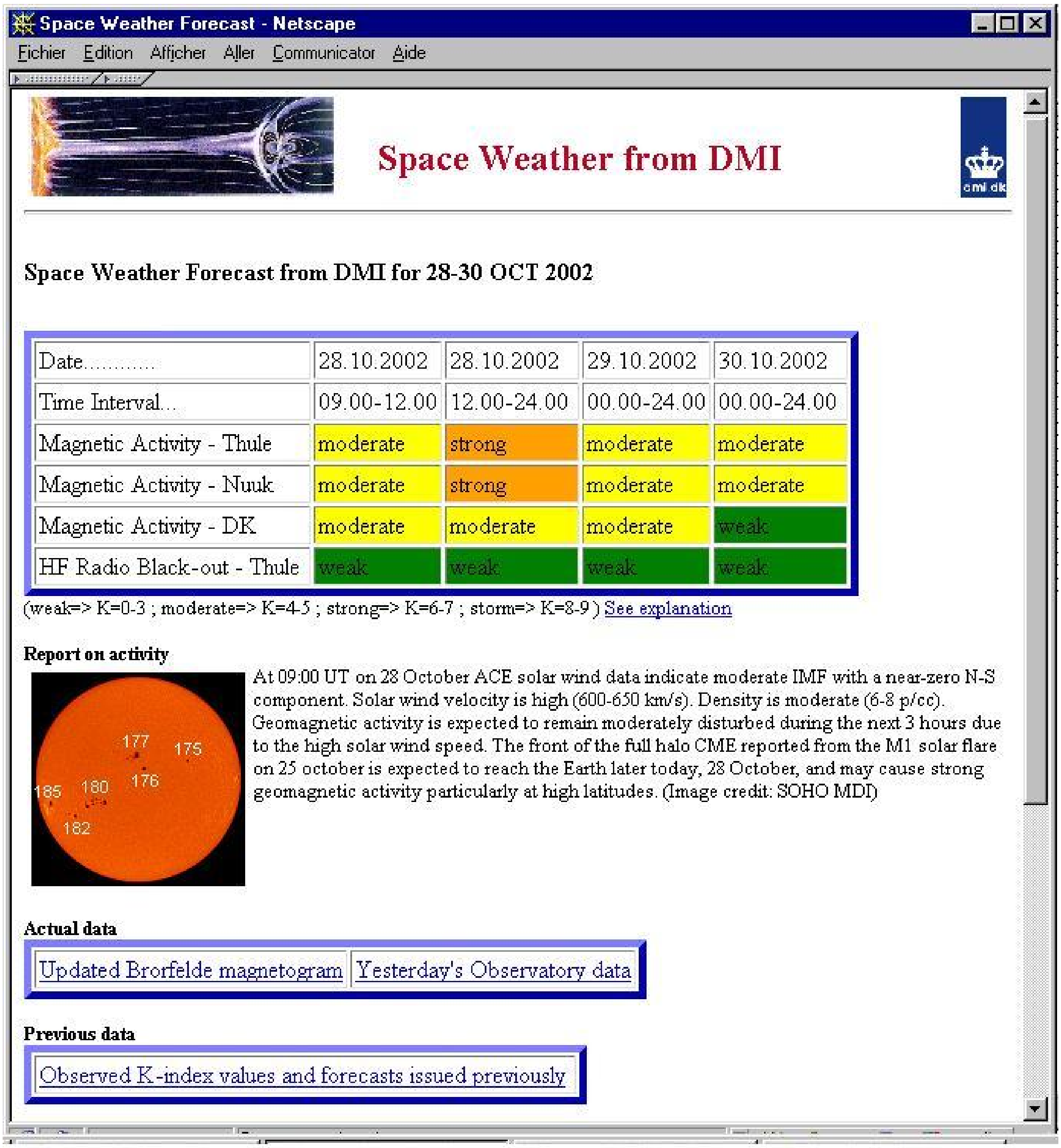
Bursty solar events as well as corrotational solar wind perturbations are geoeffective only under certain conditions. The solar source or the solar wind interaction regions need to be suitably positioned with respect to the Earth in order to have an impact on geospace. We considered therefore the location from where coronal hole streams or CME were reported to originate, and the speed with which CME were reported to propagate. Very often different velocity estimates are published, and the exact time of arrival at the magnetospheric bow shock is poorly determined. The CME travel time from the Sun to the Earth lies usually between 1 and 4 days. We therefore restricted our prediction of the level of geomagnetic activity resulting from recently observed solar and solar wind events to the announcement of the expected day of arrival and the expected magnitude of geomagnetic disturbances.

Once the development of a solar event has been followed for a certain time by observers the uncertainty is gradually reduced and the prediction of the time of arrival becomes more accurate. That means in practice that predictions for today bear a higher grade of certainty than those for tomorrow, and these again bear a higher grade of certainty than those for the day after tomorrow. The situation changes dramatically once the ICME or a high-speed stream or sector boundary passes the ACE spacecraft (or any other spacecraft positioned at the Lagrangian libration point between Sun and Earth). Once ACE records the shock front associated with the ejecta we can expect to notice the start of geomagnetic disturbances within the next 1-2 hours. The situation with coronal hole streams is similar: Once recorded at the Lagrange point the stream will take one hour at maximum to start buffeting the magnetosphere.

Altogether these considerations suggest that we divide the prediction for the present day into two intervals, the next three hours (i.e., 09-12 UT) and the rest of the UT day, and then give a prediction for the full next day and the full day after.

2.4.3 Performance assessment

In order to assess the quality of this largely operator controlled scheme we evaluated our forecast performance against actually observed magnetic field perturbations.



Space Weather from DMI

Space Weather Forecast from DMI for 28-30 OCT 2002

Date...........	28.10.2002	28.10.2002	29.10.2002	30.10.2002
Time Interval...	09.00-12.00	12.00-24.00	00.00-24.00	00.00-24.00
Magnetic Activity - Thule	moderate	strong	moderate	moderate
Magnetic Activity - Nuuk	moderate	strong	moderate	moderate
Magnetic Activity - DK	moderate	moderate	moderate	weak
HF Radio Black-out - Thule	weak	weak	weak	weak

(weak=> K=0-3 ; moderate=> K=4-5 ; strong=> K=6-7 ; storm=> K=8-9) See explanation

Report on activity

At 09:00 UT on 28 October ACE solar wind data indicate moderate IMF with a near-zero N-S component. Solar wind velocity is high (600-650 km/s). Density is moderate (6-8 p/cc). Geomagnetic activity is expected to remain moderately disturbed during the next 3 hours due to the high solar wind speed. The front of the full halo CME reported from the M1 solar flare on 25 october is expected to reach the Earth later today, 28 October, and may cause strong geomagnetic activity particularly at high latitudes. (Image credit: SOHO MDI)

Actual data

Updated Brorfelde magnetogram | Yesterday's Observatory data

Previous data

Observed K-index values and forecasts issued previously

Fig. 4. *DMI's Space Weather Forecast web page, the predecessor to GAFS (designed for internal use only). This page was manually updated every workday shortly before 09 UT. It became obsolete with the advent of GAFS.*

Each time we issue a forecast we generate a forecast matrix with 12 elements (four different time intervals and three different locations, i.e., the equivalent to the upper three rows in the forecast table of Figure 4). Each element can be tagged with one out of four possible activity categories according to Table 1. After the forecast period has passed we examine the actually recorded magnetic disturbances at the three selected sites and construct an associated observation matrix covering the same time intervals. We issued some 300 forecasts in the pre-GAFS phase and used them to create an equal number of forecast and observation matrices. We then compared forecast and observation in the following way.

For each of the three stations and each of the four time intervals we examined the observations and determined whether our prediction was a correct estimate, an underestimate, or an overestimate of the activity. The results are binned according to the disturbance category. The "weak" category ($K \leq 3$) for the "09-12 UT today" interval contains two numbers, the number of correctly predicted weak activity intervals and the number of activity overestimates (obviously, underestimates can not occur in this category). Similarly, the "moderate" category ($4 \leq K \leq 5$) for the "09-12 UT today" interval contains three numbers, the number of correctly predicted intervals, the number of underestimates and the number of overestimates. The situation is somewhat different for the other time intervals as they cover 12 and 24 hours (four and eight K values), respectively. In these cases we select the second highest K as the representative activity parameter for the entire interval. The choice for the second highest rather than the highest value was made in order to avoid being trapped into assuming a high activity day solely because of a single and short-lived large excursion (impuls) of the magnetic field which would have raised one single K number to a large value.

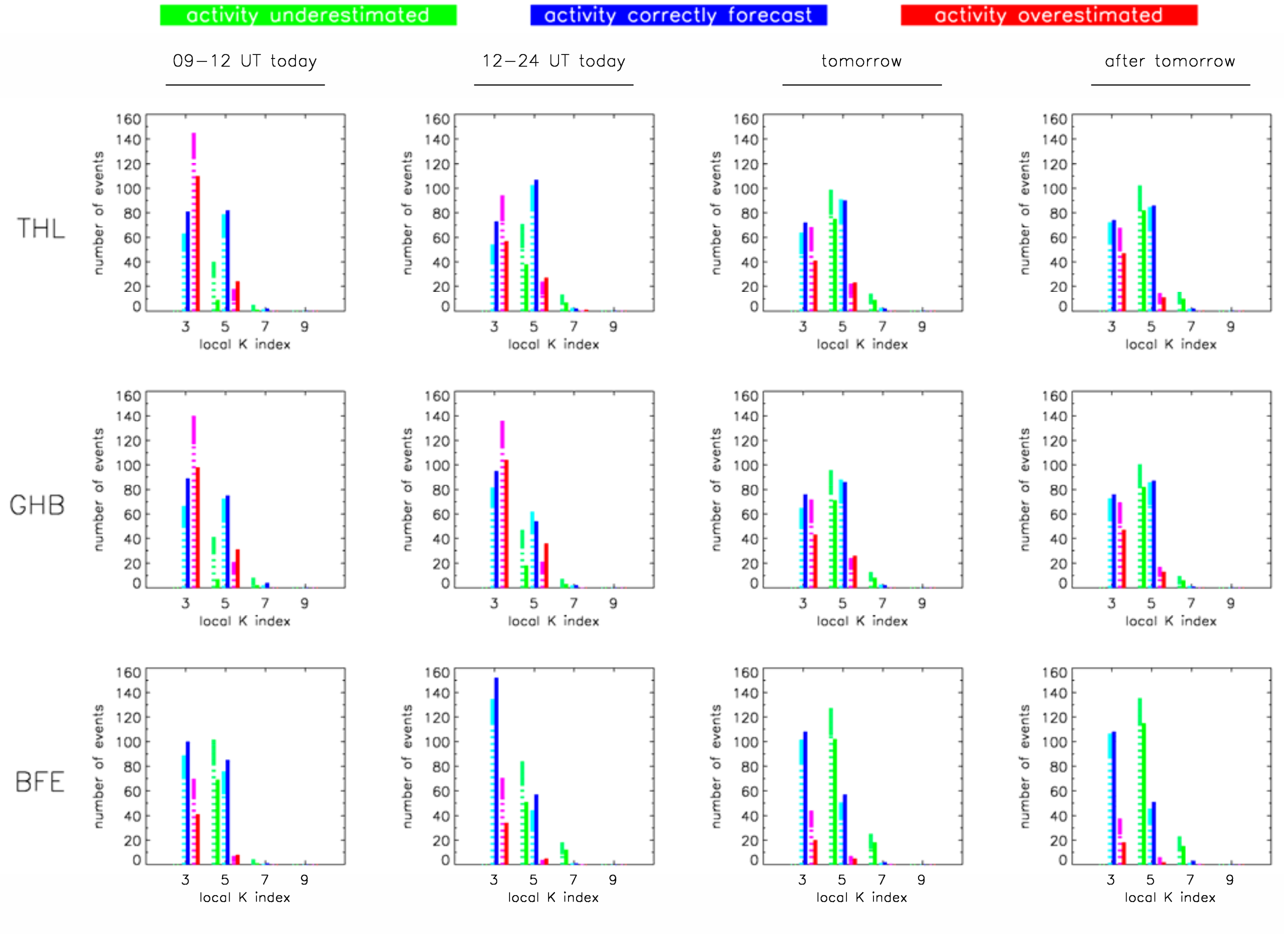


Fig. 5. *Predicted versus observed geomagnetic activity classes. Each panel refers to a specific magnetometer station and forecast interval. Blue solid bars denote correctly predicted activity, green solid bars underestimates and red solid bars overestimates, respectively. The dotted bars (light green, cyan and magenta to correspond to green, blue and red) show the results obtained from 200 randomly reordered observation sequences, with the solid segments at the top end covering the* $\pm\sigma$ *range of the prediction from random observations.*

Figure 5 shows the results from the comparison. Each panel represents one of the above noted matrix elements. The number of occurrences are marked by solid bars, blue denotes correctly predicted, green (left of blue) underestimated and red (right of blue) overestimated, respectively. We note that the number of correctly predicted activity exceeds the numbers of underestimates and overestimates in most panels, and quite substantially in some of them. Striking exceptions are the BFE predictions for tomorrow and the day after where we tended to underestimate the activity level most of the time.

In order to determine whether our result is statistically significant we have randomly reordered the observation days and made the same type of comparison. This procedure was repeated 200 times, each time with a different random sequence of observation days. The results from the comparison between predicted activity and randomly reordered observations are shown by dotted bars adjacent to the solid bars. The solid segments at the top end of the dotted bars indicate the ±σ ranges of the distribution of the comparison between prediction and 200 random order observation sequences. Let us take the "12-24 UT today" interval of BFE as an example. In the "moderate" activity ($4 \leq K \leq 5$) we have 57 intervals correctly predicted, 51 intervals underestimated and 5 intervals overestimated. This is better than the result from the random sequence of observations where we would have been correct in only 36±10 cases, underestimated in 74±8 cases and overestimated in 2±2 cases.

We have repeated the comparison using the highest (rather than the second highest) K index observed in each time interval. The bin sizes change, but the relative results (the relative occurrence of correctly predicted activity levels) were insignificantly different from what is seen in Figure 5.

The overall conclusion from the comparison is: we perform generally better than random statistics for the very near future, i.e., today's 9-12 UT and 12-24 UT intervals. In contrast, we perform only slightly or not at all better than random statistics for the next day and the day after. In other words, for the rest of today we do better than an operator who has no access to observations to aid his decision, but for tomorrow and the day after we see little difference between our prediction and that of an operator who has no up-to-date observations at hand. We considered this an area which needed improvement and which was consequentyly addressed in the development of GAFS.

3. Project Management

The GAFS Work Package structure is shown in Figure 6. The overall management is exercised by DMI. GAFS comprises six top level work packages two of which are resolved into two second level work packages. The six top level packages (WP000 to WP500) match the six major areas of work performed in the execution of the project. The resolution of top level work packages into second level work packages was driven by the natural division between work package contents and the associated experts.

The aim of WP000 is the detailed management of the project which is led by J. Watermann. It has an internal and an external element. The internal element (WP010, led by H. Gleisner) concerns managing the development and operation of the service which was performed at DMI and solely by DMI staff. An interim reprort (TN-010.2) describes the development of the service product. The external element (WP020, led by J. Watermann) concerns the interaction of GAFS with other SDA and with SWENET which so far has happened mainly during SWENET meetings and via SWENET questionnaires and at meetings of the SWWT/GETG.

WP100 addresses the user requirements and satisfaction criteria. User requirements were quantified and documented in TN-100.2.

The input data flow (WP200) comprises two elements. WP210 deals with data from external sources such as the ACE and SOHO spacecraft, the GOES satellites, NRL e-mail alerts etc. This is managed by H. Gleisner (DMI). WP220 concerns DMI's own holding of ground-based magnetometer data which was established and maintained under the supervision of the project engineer O. Rasmussen (DMI). A substantial part of WP 220 dealt with the establishment of real-time links to several of our geomagnetic observatories and magnetometer stations.

The development of the algorithm (WP300, led by H. Gleisner) consumed the first year of the project and continued on a reduced level through the second year when small improvements, error handling and fine-tuning were applied. The software developed and used for GAFS is described in detail in TN-300/1.2. After the second year, when a sufficiently large amount of data had been acquired, a statistical analysis of the prediction errors was conducted. This is described in detail in TN-300/2.1. Because we consider the results of the statistical analysis important for an assessment of GAFS they appear in condensed form in section 6.1.

WP400 (led by H. Gleisner) deals with the establishment and maintenance of a multi-section project web site. A hidden web page contains some proprietary data and specific non-public information from various sources. Its URL is known only to the project collaborators, ESA officers, SWENET and the "Service Benefits Evaluation" project. A second web page which also known only to this selected group houses documents, meeting minutes, progress reports, technical notes, software documentation and other documents which are relevant to the project but not meant for public distribution. Another, open web page is used to present the project to the outside world. It contains information of general interest such as a brief project description and a selection of forecast products which is at present the overview of predicted activity levels as shown in Figure 7 (section 5.1).

The performance evaluation (WP500, led by T.M. Rasmussen) must be distinguished from the statistical forecast analysis. The performance evaluation attempts to generate a true operation environment where the service product is accessed by the project collaborators and used in their operation. The performance evaluation is then an assessment of the problem whether and to which extent the service helped to improve the field operation of the user. The performance evaluation suffered to some extent from the fact that the staff at Baker Hughes INTEQ who was associated with the project changed frequently which left an element of discontinuity. In the end, the only real-world performance evaluation was carried out by GEUS. It is documented in section 6.2.

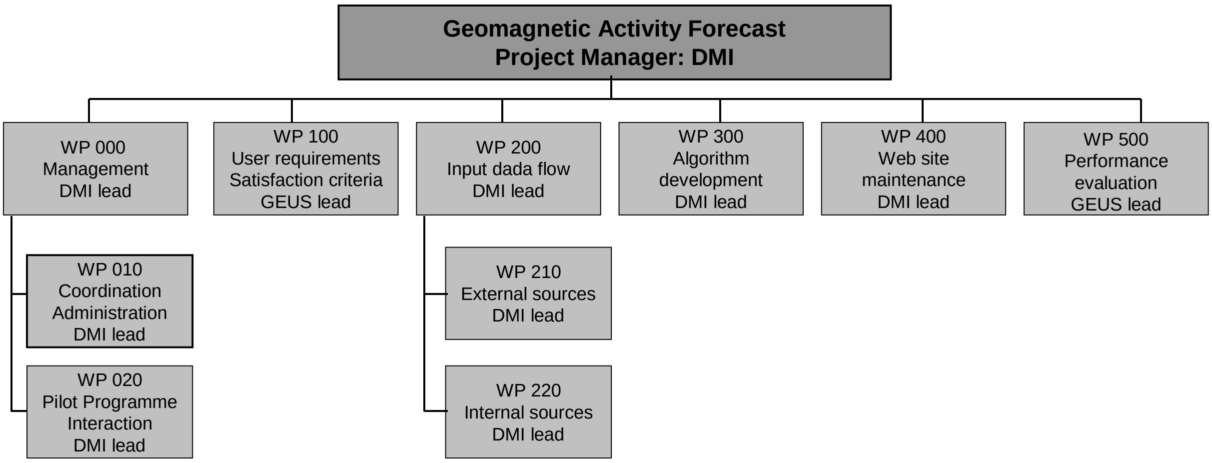


Fig. 6. *Formal Work Package diagram of GAFS.*

4. Methods in Geomagnetic Forecasting

4.1 Man or machine

Short-range forecasts (forecasts about one hour ahead) of geomagnetic activity are normally based on observations of the physical conditions in interplanetary space. From a stream of real time data of solar wind plasma density, velocity and the interplanetar magnetic field (IMF) observed between Sun and Earth physical models or data-based filters are used to compute how the geomagnetic field and physical properties of the Earth's magnetosphere will respond to external forcing. The models that are used or have been used range from purely statistical to almost fully deterministic and from partly physics based to purely data based models. A common feature of these models, which has to do with the fact that the problem at hand is relatively well defined, is that they can be prepared to run almost fully automatically. Once developed the need for subjective judgements by a human forecaster is minimal.

The situation is quite different for medium-range forecasts (up to four days ahead). The range is determined by the time it takes a solar wind disturbance to propagate from the Sun to the Earth, which is between one and four days under almost all conditions. At this lead time the solar wind conditions and the geomagnetic response to disturbances can only be obtained from remote observations of the Sun and the solar atmosphere. However, currently available observations of solar parameters are not sufficiently comprehensive to unambiguously determine future conditions in interplanetary space. There is also a lack of understanding of how the data we retrieve from solar observations are physically connected to solar wind variability and the geoeffective events we find in the solar wind. Much of the data derived from solar observations can be regarded as proxy data rather than well-defined physical quantities.

A result of all these uncertainties is that there is still much room for a human forecaster to interpret data, classify events based on incomplete data and judge the space weather situation based on his or her subjective experience. To make medium-range forecasts fully automatic somewhat limits the selection of usable data and methods. At the same time, a fully automatic procedure is more likely to gain from stepwise improvements than the subjective judgements of a human forecaster. In this project, we have only considered methods that can be made fully automatic, and we have separated the medium-range forecasts into two sub-intervals with lead times of 3 to12 hours and 12 to 48 hours, respectively.

4.2 Geomagnetic alert levels

For forecasting purposes we prefer to quantify the geomagnetic disturbance field not by complete time series but by simpler measures (or parameters) which can be defined within certain time intervals. The *K* index (a local range index) is an example of such a measure.

In this project, we have chosen to use the maximum and minimum values obtained or expected within a certain time interval. The observed and the forecast values are binned into three classes which we refer to as alert levels: quiet (green), active (yellow), and disturbed (red). From the statistical distribution of many years of magnetic field disturbance records we defined alert levels at different locations and for different magnetic field elements as listed in Table 2 (for details of the statistics see TN-300/2.1).

THL	$\lvert X\rvert < 130$ nT $\lvert Y\rvert < 140$ nT $\lvert Z\rvert < 140$ nT	$\lvert X\rvert > 130$ nT $\lvert Y\rvert > 140$ nT $\lvert Z\rvert > 140$ nT	$\lvert X\rvert > 200$ nT $\lvert Y\rvert > 220$ nT $\lvert Z\rvert > 230$ nT
GDH	$\lvert X\rvert < 150$ nT $\lvert Y\rvert < 120$ nT $\lvert Z\rvert < 170$ nT	$\lvert X\rvert > 150$ nT $\lvert Y\rvert > 120$ nT $\lvert Z\rvert > 170$ nT	$\lvert X\rvert > 250$ nT $\lvert Y\rvert > 200$ nT $\lvert Z\rvert > 270$ nT
NAQ	$\lvert X\rvert < 220$ nT $\lvert Y\rvert < 120$ nT $\lvert Z\rvert < 150$ nT	$\lvert X\rvert > 220$ nT $\lvert Y\rvert > 120$ nT $\lvert Z\rvert > 150$ nT	$\lvert X\rvert > 370$ nT $\lvert Y\rvert > 210$ nT $\lvert Z\rvert > 270$ nT
BFE	$\lvert F\rvert < 100$ nT $\lvert D\rvert < 17'$ $\lvert I\rvert < 7'$	$\lvert F\rvert > 100$ nT $\lvert D\rvert > 17'$ $\lvert I\rvert > 7'$	$\lvert F\rvert > 150$ nT $\lvert D\rvert > 23'$ $\lvert I\rvert > 9'$

Table 2. *Geomagnetic alert levels used in GAFS. Green – quiet: predicted field element with 80% certainty smaller than the quiet field threshold; yellow – active: predicted field element with 67% certainty larger than the quiet field; red – disturbed: predicted field element with 67% certainty larger than the disturbed field threshold.*

4.3 Short-range forecasts

4.3.1 Data

Two interplanetary space probes currently provide solar wind data in real time – the ACE and the SOHO spacecraft. Both are located near the Sun-Earth libration point usually referred to as the L1 point. ACE data relevant to GAFS include plasma density and bulk velocity and the interplanetary magnetic field (IMF) while SOHO data used in our forecast only include the plasma parameters. ACE data are continuously transmitted to the Earth and processed in near-real time, i.e. within a few minutes, while SOHO data have a delay ranging from a few minutes to a few hours. The real-time solar wind data from ACE and SOHO are freely available through open FTP and HTTP servers (for a more elaborate description of data availability and access, see TN-300/1.2).

Ground-based magnetometer data from three out of DMI's four observatories, BFE (52.1º), NAQ (65.8º) and THL (85.0º), and one variometer station, STF (72.8º), are currently available in real or near-real time (the numbers denote the corrected geomagnetic latitude at epoch 2005.0). These four sites roughly represent Denmark and the southern, middle, and northern parts of Greenland. Data from the fourth observatory, GDH (75.4º) and the majority of DMI's other magnetometer stations in Greenland become available within a day. Through the World Data Center system we are able to access a preliminary, or quick-look, geomagnetic *Dst* index in near real time.

4.3.2 Methods

The fundamental principle underlying short-range forecasts is to take real-time solar wind data observed near L1 and transform them into a time series of ground-level geomagnetic variations. The propagation of the solar wind plasma from L1 to the Earth (determined by the solar wind speed and the distance between L1 and the Earth's bow shock) plus the time it takes the magnetosphere to respond to the impact of solar wind variations, gives the required lead time, τ_w, which is typically around one hour and rarely more than 1.5 hours.

The transformation of a time series of observed solar wind data to a time series of ground-level geomagnetic variations can be done by a linear integrating filter or, alternatively, by a non-linear neural network. Relatively simple linear filters can give nearly as accurate results as more complicated non-linear filters, provided that the solar wind data are given in an appropriate form.

Denoting the time of the most recent solar wind observation by *t* and the lead time by τ_w, the disturbance field $\vec{B}$ at a geomagnetic station can be described as

$$\vec{B}(t+\tau_w) = \vec{c}_0 + \vec{c}_1\sqrt{\rho V^2} + \vec{c}_2 V^2 B_s + \vec{c}_3 \int_{-80\,\mathrm{min}}^{0\,\mathrm{min}} V^2 B_s + \vec{c}_4 \int_{-20\,\mathrm{min}}^{0\,\mathrm{min}} V^2 B_s \qquad \text{(Eq. 2)}$$

where ρ is the solar wind density, V is the velocity and B_s is the southward IMF component, all observed at time *t*. The regression coefficients c_k are determined individually for each station, each geomagnetic field element, and each bi-hourly local time bin. Having stored these coefficients in look-up tables enables us to quickly find the expected disturbance field within the nearest hour once solar wind observations are available.

Applying the above filter to the time series of real-time solar wind data gives us a time series of predicted geomagnetic field elements. The time series we work with consist of 5-min averages of observed physical parameters, and the predicted magnetic field variation is consequently also updated with 5-min averages.

We are, however, also interested in forecasts of geomagnetic activity for an extended interval of up to three hours ahead. Therefore we modified the method described above using a probability argument. The short-range forecasts of alert levels are not merely based on a conversion of the predicted geomagnetic field into an alert level, which might seem natural. Instead, we have found it more useful to take the deterministic forecast given by Eq. 2 and use the error distributions at different *Dst* levels, different seasons and different local times to deduce the probabilities for certain alert levels. Hence, we combine deterministic and probabilistic approaches. From tabulated data of the conditional probabilities for a certain alert level we determine the forecast alert level given the deterministically predicted geomagnetic field, the predicted *Dst* index, and season and time of day.

4.4 Medium-range forecasts

The concept underlying our medium-range forecast is concisely described in Gleisner-2006a. The main elements are presented below.

4.4.1 Data

Medium-range forecasts necessarily rely on remote observations of the Sun made from ground and space based observatories, and on products derived from these data. Near-Earth solar wind data may also be used, but primarily as supplementary data supporting the conclusions drawn from solar wind models which are based on remote observations of the Sun.

Solar wind models extrapolate the observed conditions in the solar photosphere and corona using more or less sophisticated assumptions. They require that the quasi-steady conditions at an inner boundary in the solar corona are defined, and these conditions are almost exclusively based on a synoptic view of observed photospheric magnetic fields and computed coronal magnetic fields. Modeled solar wind data from the Wang-Sheeley-Arge (WSA) and Hakamada-Akasofu-Fry (HAF) models are currently available in real time. The corresponding solar wind measurements are also available in real time as described in Section 4.3.1.

Another set of data signifies eruptive events on the Sun. The data include observed characteristics of Coronal Mass Ejections (CME) deduced from white-light coronagraph images, radio emissions from coronal shock waves (type II radio bursts), X-ray flares, disappearing filaments, and Solar Energetic Particle (SEP) fluxes observed in near-Earth space.

A third set of data describes the effects of the solar wind interaction with the Earth's magnetosphere. The data are primarily geomagnetic records from ground based observatories. As stated in Section 4.3.1, most of them are obtained from DMI's own data holdings.

4.4.2 Methods

On the medium-range time scale, geomagnetic activity is governed by quasi-steady solar wind structures co-rotating with the Sun or by transient solar wind structures generated by eruptive events on the Sun. Hence, a distinction needs to be made between these two factors. The fundamental observations that are used in GAFS to indicate whether transient disturbances can be expected are the occurrence of a CME, as reported by the Naval Research Laboratory (NRL) based on white-light solar coronagraph images, in combination with certain SEP flux characteristics. If a CME is observed and if, from the CME characteristics and the observed SEP flux, we have reasons to believe that the CME will be geoeffective, then this determines the medium-range forecast. In the absence of such observations, the forecast is governed by the quasi-steady solar wind structures as predicted by solar wind models. In practice, two forecasts are made simultaneously – one based on the solar wind models, and one based on observations of CMEs and SEP fluxes – and the forecast indicating the largest geomagnetic disturbances determines the final forecast.

No solar eruptive event. In the absence of eruptive events, the forecasts rely on the output from a solar wind model. Moderate magnetic storms have a tendency to be associated with the interface between low and high speed solar wind streams which often cause substantial geomagnetic activity, particularly at higher latitudes. The stream interfaces are detected in the solar wind models by a fully automatic procedure based on a cross-correlation technique using the covariance between the solar wind model velocity, appropriately normalized, and a reference solar wind speed profile. After normalization to zero mean and the same standard deviation as the reference velocity profile, the model solar wind data are scanned for local maxima of the covariance between the model time series and the reference time series. Covariances exceeding 0.5 are interpreted as geoeffective stream interfaces generating yellow (active) alerts (for details of the method see TN-300/2.1).

Solar eruptive event. Nearly all strong magnetic storms are generated by halo CMEs, but most earthward directed halo CMEs are not followed by strong storms. Additional information is required to discriminate strongly geoeffective CMEs from those less geoeffective. We found that characteristic enhancements of the SEP flux close to CME onset can be used as an indicator of the geoeffectiveness of full halo CMEs. The observation of a full halo CME together with a SEP flux enhancement above a predefined level results in a red (disturbed) alert. The observation of a full halo CME with a SEP flux enhancement below that level gives a yellow (active) alert. Other CME observations – partial halos or other CMEs – may be followed by forecast geomagnetic activity, but only if this is indicated by the solar wind models using the method described above. The time of arrival of the expected CME ejecta is based on a simple empirical relationship between the observed CME expansion speed in the plane of the sky and the travel speed as described in the scientific literature (for details see TN-300/2.1).

An investigation of the relation between full halo CMEs reported by NRL and strong magnetic storms (defined as periods with *Dst* exceeding –100 nT) showed that the optimal choice of an SEP enhancement threshold resulted in false alarm rates and miss rates of both ~30% (see also Gleisner-2006c).

5. GAFS Operation

5.1 Service products

Our service aims at predicting the level of geomagnetic activity at geographic regions of relevance to our users (the North Sea and Greenland). We provide a forecast of the level of geomagnetic activity expected to prevail at the sites of our four geomagnetic observatories, THL, GDH and NAQ in Greenland, and BFE in Denmark (see the map in Fig. 1).

Geomagnetic activity is divided into three levels, quiet (green), active (yellow), and disturbed (red). For each level we specify thresholds individually for different geographic areas (sites) but also for positive and negative disturbances. The numbers were selected such that the probability to remain in the quiet range is 80%, and the probabilities to exceed the active and disturbed thresholds are 67%, respectively.

An analysis of many years of observatory data has revealed a significant difference between the occurrence of positive and negative excursions during geomagnetically active times as described in section 2.3 and demonstrated in Figure 3. At present this distinction is of no relevance to the users since the users are only interested to know whether or not the deviations stay within the specified ±range of validity (which is symmetric with respect to the quiet level). However, for further developing our scientific understanding in physical modeling and thus making progress in forecasting it will likely be of importance to distinguish between positive and negative perturbations.

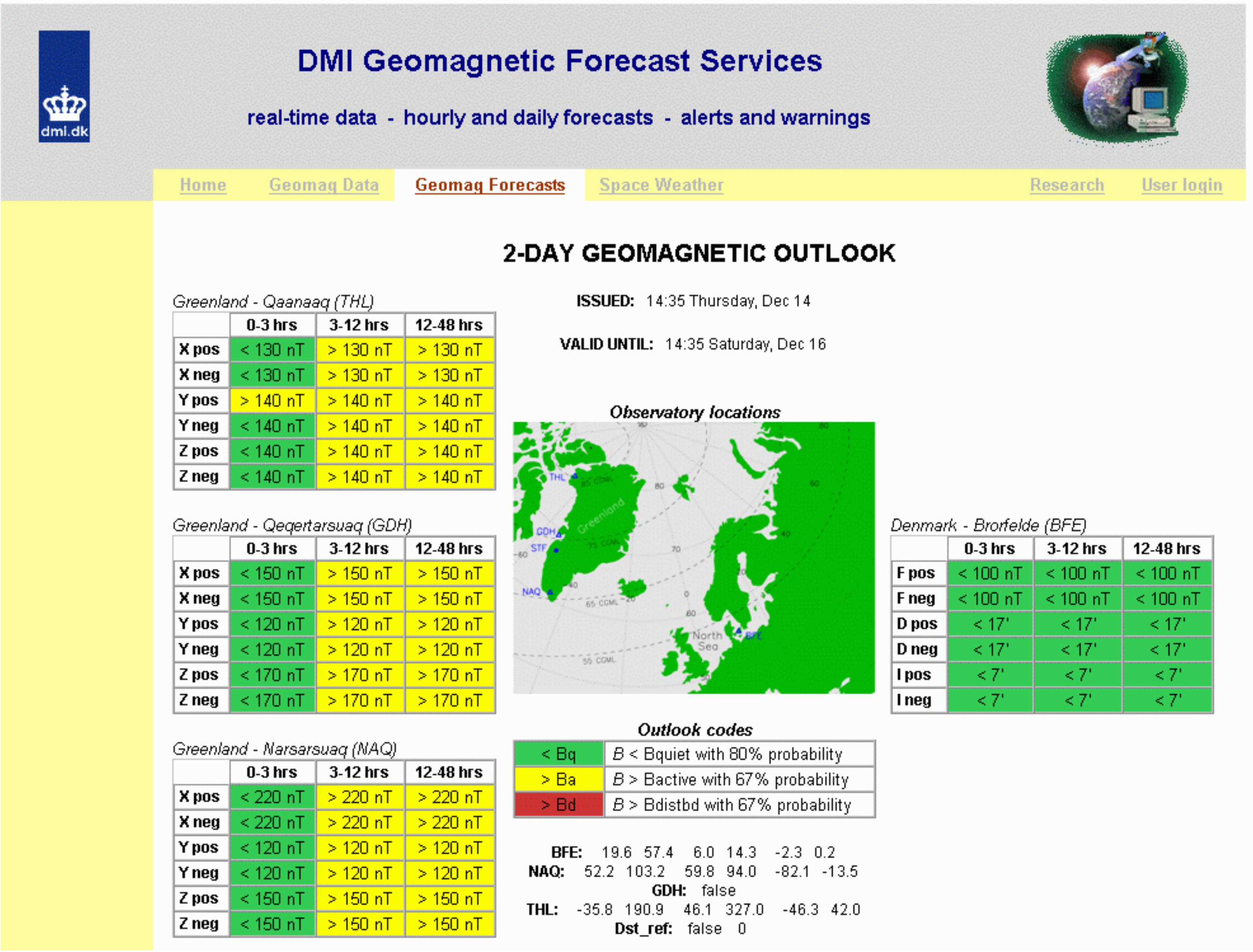
The service product is automatically updated once every hour. It displays on a dedicated web site (`http://www.dmi.dk/projects/ESA_SWAPP/Public/magoutlook.shtml`) a forecast of the geomagnetic activity expected over the next three hours, the following nine hours, and the following 36 hours, that is, 48 hours in total. If an important piece of information is missing the concerned activity cell is left blank. This part of the service is publicly accessible. A screen dump of the public web page is displayed as Fig. 6. In addition to the public web site we maintain restricted web sites only known to ESA technical officers, the SWENET operator and our project collaborators.

The restricted web site starts with the same 2-day geomagnetic outlook page display, and most of the links shown on the top row are here enabled. One of the restricted pages shows information extracted from reports and selected observations of solar eruptive events. They include the density of the high-energy ion flux observed by the GOES satellite which are in geostationary orbit, the reports on halo Coronal Mass Ejections (CME) sent out by the Naval Research Laboratory (NRL) and observations of type II radio bursts published by the National Oceanographic and Atmospheric Administration (NOAA). When enhanced solar energetic particle (SEP) fluxes are observed in combination with halo CME and type II radio bursts we consider this an indication that ejecta from solar eruptions are likely to be earthward directed and may hit the Earth's magnetosphere within the next few days, with the consequence that elevated levels of magnetic activity are likely to occur.

The second part of the web page on solar activity deals with solar co-rotating structures, namely IMF sector boundaries and solar wind stream boundaries. The undulation of the current sheet which does not normally coincide with the ecliptic plane has the effect that a point in the ecliptic plane, e.g., at the location of the Earth, experiences IMF directions alternating between toward and away from the Sun. Most often four sectors are observed over one full solar rotation which is completed after ca. 27 days. The main effect of the Earth's crossing a sector boundary is a change of the vertical magnetic field component which either facilitates or prevents merging between interplanetary and magnetospheric magnetic field lines which in turn either facilitates or prevents the magnetosphere from being loaded with solar wind energy.

During the quiet years of the solar cycle the solar polar regions tend to emit a stream of tenuous hot plasma at high speed (approximate reference numbers are 1 H^+/cm^3, 700 km/s and 10^6 K) while the middle and low solar latitudes tend to emit a stream of dense but colder plasma at low speed (approximate reference numbers are 5 H^+/cm^3, 350 km/s and 10^5 K). The solar polar areas are - similar to the terrestrial polar areas - regions of open magnetic field lines. They are often referred to as coronal holes. During the quiet years of the solar cycle coronal hole streams reach less often the ecliptic plane at 1 AU and are therefore rarely geoeffective. During the more disturbed years the coronal holes (more precisely low-density high-temperature high-speed regions) can move to much lower solar latitudes and even down to the solar equator. They are thus more often geoeffective. Their main effect on geospace lies in a change of the solar wind dynamic pressure on the Earth's magnetosphere, the subsequent reconfiguration of the magnetosphere and the associated waves, currents and particle fluxes which propagate the disturbances to various parts of the magnetosphere.

The trade-off between the frequence of false alarms and missed events cannot be set once for all users. They have about equal weight (i.e., are equally annoying) for aeromagnetic surveys while wellbore surveying is very sebsitive against false alarms. An unjustified rescheduling of operations is considered more economically damaging than a continuation of operations during a magnetic storm. In the former case precious time is simply lost while in the latter case a possibility for post-drilling correction may be possible and successful.



2-DAY GEOMAGNETIC OUTLOOK

ISSUED: 14:35 Thursday, Dec 14

VALID UNTIL: 14:35 Saturday, Dec 16

Greenland - Qaanaaq (THL)

	0-3 hrs	3-12 hrs	12-48 hrs
X pos	< 130 nT	> 130 nT	> 130 nT
X neg	< 130 nT	> 130 nT	> 130 nT
Y pos	> 140 nT	> 140 nT	> 140 nT
Y neg	< 140 nT	> 140 nT	> 140 nT
Z pos	< 140 nT	> 140 nT	> 140 nT
Z neg	< 140 nT	> 140 nT	> 140 nT

Greenland - Qeqertarsuaq (GDH)

	0-3 hrs	3-12 hrs	12-48 hrs
X pos	< 150 nT	> 150 nT	> 150 nT
X neg	< 150 nT	> 150 nT	> 150 nT
Y pos	< 120 nT	> 120 nT	> 120 nT
Y neg	< 120 nT	> 120 nT	> 120 nT
Z pos	< 170 nT	> 170 nT	> 170 nT
Z neg	< 170 nT	> 170 nT	> 170 nT

Greenland - Narsarsuaq (NAQ)

	0-3 hrs	3-12 hrs	12-48 hrs
X pos	< 220 nT	> 220 nT	> 220 nT
X neg	< 220 nT	> 220 nT	> 220 nT
Y pos	< 120 nT	> 120 nT	> 120 nT
Y neg	< 120 nT	> 120 nT	> 120 nT
Z pos	< 150 nT	> 150 nT	> 150 nT
Z neg	< 150 nT	> 150 nT	> 150 nT

Denmark - Brorfelde (BFE)

	0-3 hrs	3-12 hrs	12-48 hrs
F pos	< 100 nT	< 100 nT	< 100 nT
F neg	< 100 nT	< 100 nT	< 100 nT
D pos	< 17'	< 17'	< 17'
D neg	< 17'	< 17'	< 17'
I pos	< 7'	< 7'	< 7'
I neg	< 7'	< 7'	< 7'

Outlook codes

< Bq	*B* < Bquiet with 80% probability
> Ba	*B* > Bactive with 67% probability
> Bd	*B* > Bdistbd with 67% probability

BFE: 19.6 57.4 6.0 14.3 -2.3 0.2
NAQ: 52.2 103.2 59.8 94.0 -82.1 -13.5
GDH: false
THL: -35.8 190.9 46.1 327.0 -46.3 42.0
Dst_ref: false 0

Fig. 7. *Public web page for DMI's GAFS (Geomagnetic Activity Forecast Service). Activity levels are color-coded for a quick qualitative grasp of the expected geomagnetic conditions (green – quiet; yellow – active; red – disturbed). In addition, site-specific quantitative thresholds for the associated activity levels are printed. In general, forecasts for geomagnetic perturbations differ between positive and negative magnetic field excursions.*

Another page of the restricted web sites displays the geomagnetic variations at our four real-time magnetometer stations, namely the observatories BFE, NAQ and THL and the Greenland variometer site STF, see site map in Fig. 1. The data are received at regular intervals at DMI. Each time a user accesses or refreshes the web page the most recent data are grabbed and converted into a graphical presentation.

5.2 Routine operation

5.2.1 Service availability

For aeromagnetic surveys in Greenland it will be sufficient to provide the service during the actual survey period (typically up to four summer months), and then only from 06 UT until 24 UT. But it does not require extra work to run the service continuously, therefore we are running it on a 24/7 schedule. In addition, a continuous operation will alert us of potential errors and service malfunctioning at the earliest occasion and will permit us to interfere as soon as we have become aware of a problem.

For drilling operations in the North Sea the service has to be available 24 hours a day during a drilling activity and not at all if no drilling operation is ongoing. However, it will only complicate the scheme if the service would be switched on and off, and it is a potential source of error if accurate communication about drilling activities would fail to reach us. In addition, drilling activities are not always published in detail, and the survey management company wants to reserve the right to start and stop operation without informing us.

5.2.2 Service constraints

In principle the service runs automatically and without interruption and does not require scheduled manual interference. However, an interruption of the stream of data coming from original sources will result in a failure to update the forecast, i.e. the forecast remains in the state which was issued after the last valid data sample had arrived. The system is designed in such a way that resumption of the data stream will automatically result in resumption of the forecast. The real-time magnetogram display works in the same way, it will resume automatically once the original magnetometer data stream resumes its flow. That means, in theory the system does not require a manual restart. In practice, however, it happened occasionally that the forecast web page did not restart automatically even though all necessary input data were available. Hence a minimal operator support is still necessary.

Real-time measurements of solar wind plasma and IMF parameters are essential to the service. The ACE spacecraft is the primary source. In case ACE plasma data fail to be available SOHO solar wind density and velocity data will be used instead. However, ACE is presently the only space probe which can deliver a continuous IMF time series. If this is interrupted the geomagnetic activity forecast will be interrupted as well.

If the data stream from GOES satellites is interrupted the panel showing solar energetic particle fluxes will remain empty. A mid-range forecast of geomagnetic activity will still be issued, but the lack of GOES data renders it less reliable since enhanced energetic ion fluxes are an indicator for a geoeffective CME within the next few days, see Gleisner-2006c. If the output parameter stream from the WSA or HAF models is interrupted it will prevent us from forecasting solar wind discontinuities and associated geomagnetic perturbations. Their failure thus constitutes a major problem for mid-range forecasting although our service process will continue to run.

6. Forecast Evaluation

6.1 Statistical analysis: forecast *vs* observation

6.1.1 One hour ahead forecast

Some details on statistical results and their physical explanation are found in Gleisner-2006b.

For the one-hour forecast we start with 5-min averages of solar wind data acquired by the ACE and/or SOHO space probes. The 5-min averaged geomagnetic field is predicted by the methods described in Section 4.3.2. In this section we analyze the forecast accuracy by evaluating the linear correlation between the forecast and observed disturbance field elements. It should be emphasized that we use the disturbance field to compute the correlation – had we used the total field instead, i.e. including the regular diurnal variations, we would get higher correlation since a large fraction of all data are dominated by the regular variations which are easily and accurately predicted. As the forecast accuracy varies strongly over the day, we bin the data according to UT, compute correlations for each bin, and then plot the correlation as a function of UT. At each observatory, this is done separately for the field elements X, Y, and Z. The results are shown in Figure 8.

The correlations vary from around 0.2 to 0.7, exhibiting a very characteristic modulation over the day. A more detailed examination has shown that most correlation minima coincide either with a very low probability for large-magnitude disturbances during that part of the day or with an equal probability for positive and negative disturbances. Apparently, these cases are difficult to handle by the method used in GAFS. In the first case, noise in the data is the likely cause of this effect. However, the second type of correlation minima probably points to a real inability of our forecast method to correctly predict the disturbance field. It is likely that an additional division of the correlation data into seasonal bins would improve the results, but the major features would nevertheless remain.

6.1.2 3–12 hours ahead forecast

In this report, the *false alarm rate* is defined as the fraction of issued alerts that were never followed by geomagnetic activity above the threshold for the predicted alert level. The *miss rate* is correspondingly defined as the fraction of time intervals with observed geomagnetic activity exceeding the predicted alert level.

The 3-12 hours forecast provided by GAFS has been analyzed in the following way: each day at 6:00 UT we note the alert levels forecast for the time interval 3 to 12 hours ahead. The forecast alert levels are later compared to the observed alert levels based on the peak disturbances that actually occurred within the forecast time interval. From these data we compute the false alarm rates and the miss rates – one for each observatory, field element, and alert level exceeding the quiet level. We also compute reference false-alarm and missed-prediction rates using a random method with zero forecast skill. The results are shown in Figure 9 where the rates of the no-skill reference method are indicated by the hatched bar tops, with yellow representing the active and red the disturbed geomagnetic activity level.

The results are not very impressive. This is predominantly a consequence of the shortcomings of the solar wind models. It is further discussed in the next section. The low miss rates for some of the field elements at some of the observatories are due to the fact that we here only look at forecasts issued at 6:00 UT.

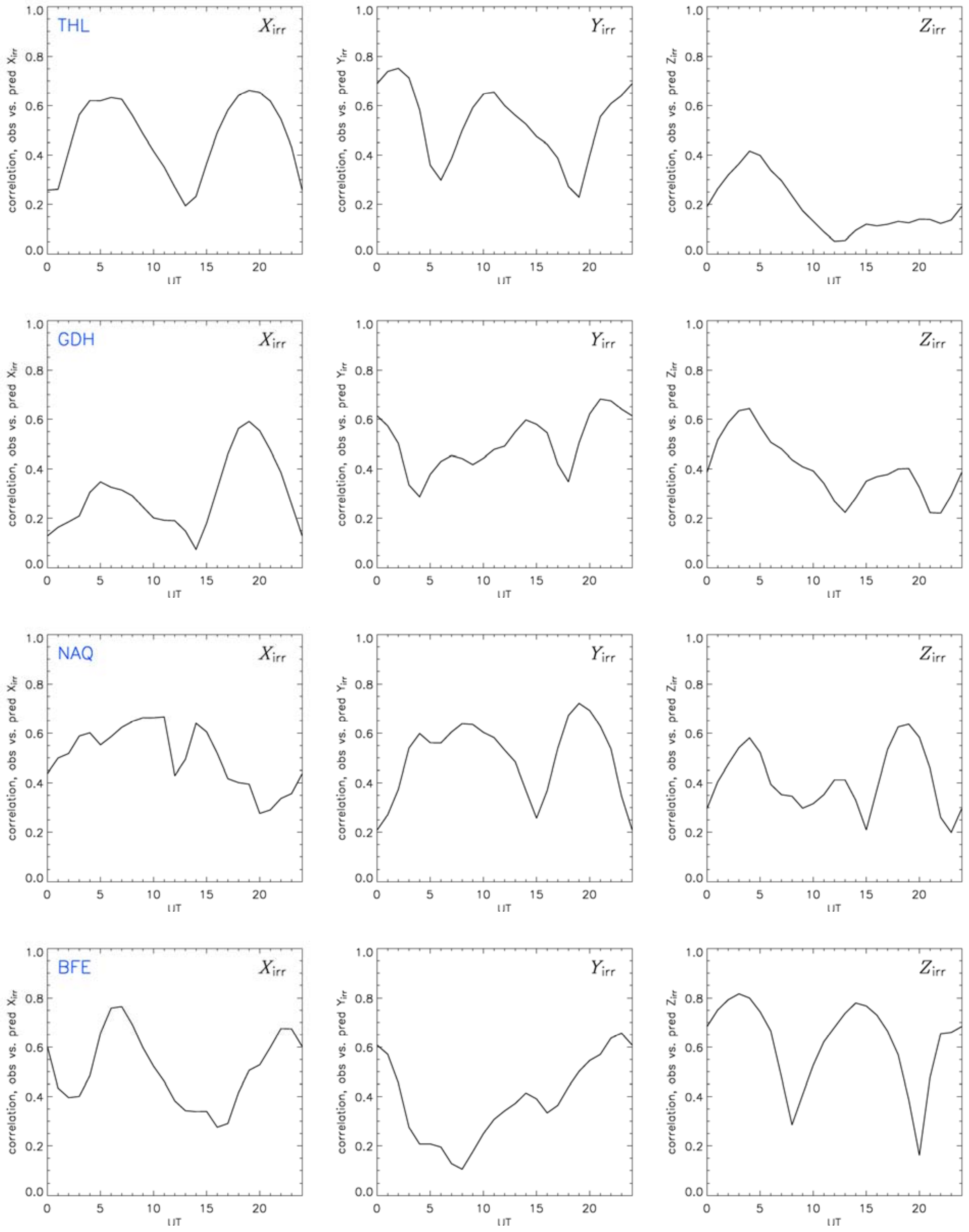


Fig. 8. *Linear correlations between observed and predicted 5-min averaged geomagnetic field elements X, Y, and Z at the four DMI observatories. The linear correlations are plotted as a function of UT. Note that these are correlations between predicted and observed disturbances. The same type of plot based on the total field, i.e. including the regular diurnal variations, would give higher correlations.*

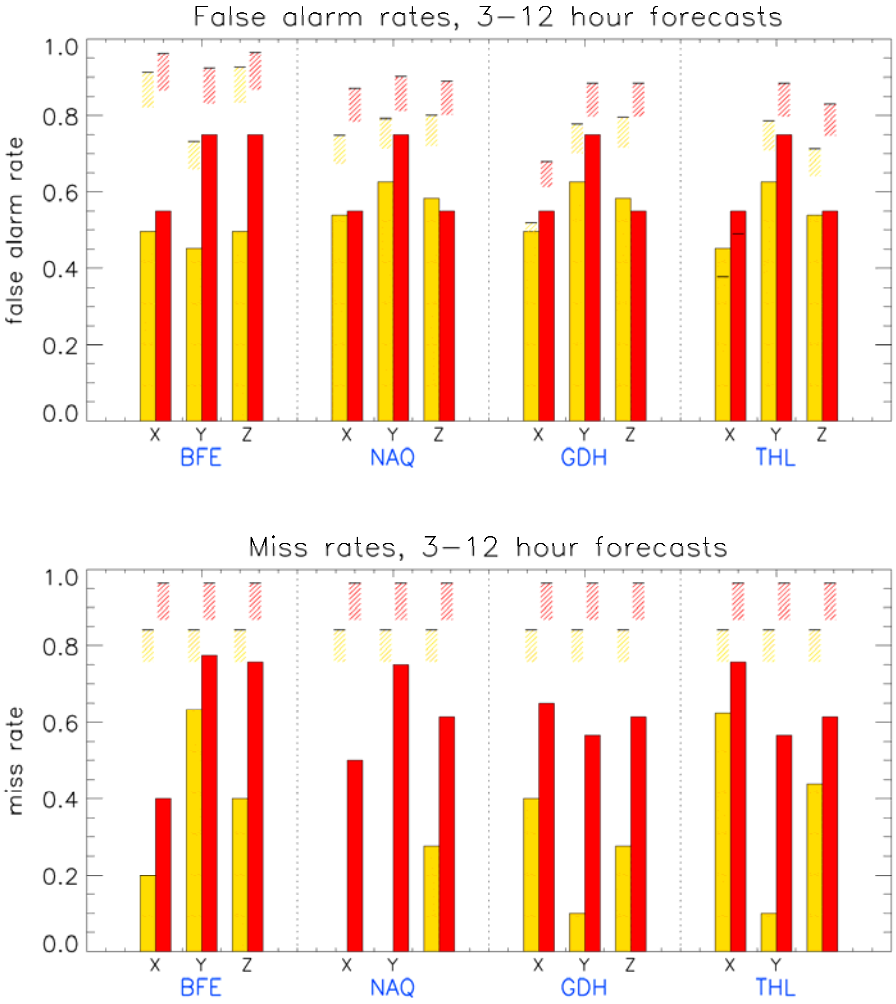


Fig. 9. *False alarm rates (upper panel) and miss rates (lower panel) for the 3-12 hour forecast provided by GAFS (solid bars). The corresponding rates for a random method with zero forecast skill are given for reference (hatched segments). Yellow refers to the activity level labeled "active" and red to the level labeled "disturbed".*

6.1.3 12–48 hours ahead forecast

The 12-48 hours forecast provided by GAFS is analyzed in the same way as the 3-12 hours forecast. On each day, at 6:00 UT, we note the alert levels forecast for the time interval 12-48 hours ahead. The forecast alert levels are later compared to the observed alert levels based on the peak disturbances that actually occurred within the forecast time interval. From these data we compute the false alarm rates and the miss rates – one for each observatory, field element, and alert level. As in Section 6.1.2, we also compute reference false-alarm and missed-prediction rates using a random method with zero forecast skill. The results are shown in Figure 10.

We first note that – not surprisingly – there appears to be a fundamental difference in the 12-48 hours forecast accuracy between the sub-auroral station BFE and the higher-latitude stations NAQ, GDH, and THL. The most striking difference lies in their miss rates, where the high-latitude stations mostly perform very poor whereas the sub-auroral station shows an ability to produce meaningful predictions. The false alarm rates for all four stations are significantly better than random forecasts, also indicating an ability to actually produce meaningful forecasts.

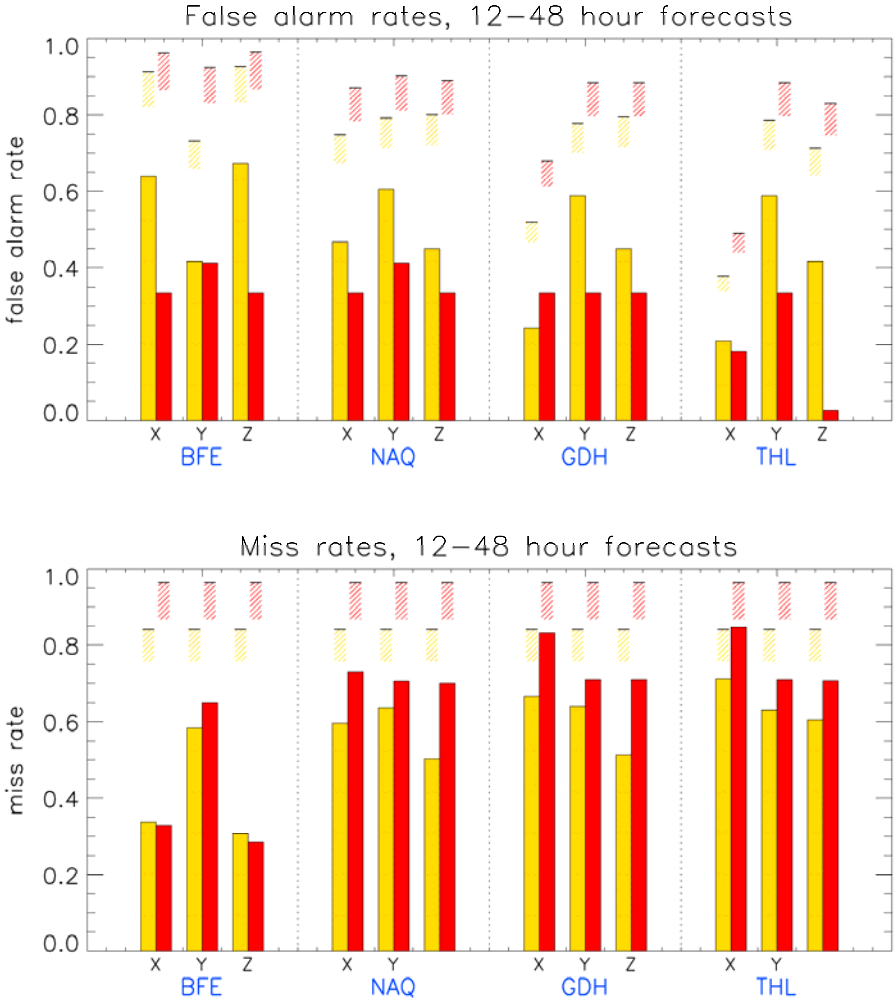


Fig. 10. *As Fig.9 but for the 12-48 hours forecast interval.*

The combination of acceptable false alarm rates and excessively high miss rates at the high-latitude stations can partially be attributed to the difference of the processes associated with the two principally different sources of geomagnetic disturbances. The strong disturbances caused by CMEs are reasonably well predicted both in terms of their false-alarm and missed-prediction rates whereas the disturbances that are not caused by CMEs are to a very large extent not predicted at all. This type of geomagnetic activity is more important at higher latitudes, and as a result we get high miss rates, predominantly at the higher latitude stations.

An important factor which strongly contributes to our results lies in the limitation of current solar wind models. They have a limited ability to actually predict the arrival at the Earth of geoeffective structures and discontinuities that appear in the solar wind. Although they predict correctly the near future occurrence of those events as such, they have a limited ability to predict the correct timing of those events. It was shown in TN-300/2.1 that in many cases the occurrence of a stream boundary is correctly predicted, but the prediction of strength and timing of the boundary is not very accurate. Interesting in this context is the observation that the 12-48 hours forecasts obtained from the solar wind models are actually slightly better than the 3-12 hours forecasts. The reason for this is simply that errors in the timing of events have a more serious effect for short time intervals than for long time intervals.

Even though the simplicity of currently available models is a serious limitation which renders the forecasts from current solar-wind models unacceptably inaccurate, the results nevertheless suggest that future improved solar wind models can solve some of the problems.

We may also note that other definitions of alert levels – obtained by simply changing the thresholds, or by using completely different measures to quantify the degree of geomagnetic activity – would have implications for the false-alarm and missed-prediction rates.

6.1.4 Statistical analysis summary

The assessment of geomagnetic forecasts depends on a multitude of factors. We draw here some general conclusions.

- One hour ahead forecasts can be made with relatively high accuracy if plasma and IMF data from the L1 point are available. This is consistent with many studies published in the scientific literature.
- Meaningful 3-12 hours ahead forecasts can be made, although with low accuracy. With "meaningful" we mean forecasts that are significantly better than a random choice.
- Meaningful 12-48 hours ahead forecasts can be made, although with a low accuracy.
- The 12-48 hours ahead forecasts are better than the 3-12 hours ahead forecasts because the time of arrival allowed for a sucessful forecast spans a wider interval.
- The rare events with very strong disturbances are better predicted than the frequent intervals with moderate disturbances.
- Strong magnetic storms caused by full halo CMEs are predicted with high accuracy. Moderate storms caused by recurrent structures are predicted with low accuracy.

6.2 Lessons learned from past aeromagnetic surveys

6.2.1 Flight scheduling details

Aeromagnetic surveys in Greenland are conducted during the summer over a time span of up to four months. A typical single day survey flight lasts around six hours and covers a survey size of around 1500 production kilometers. The flights are conducted 60-300 m above a virtual ground surface which is a smooth approximation to the real topographical surface. The main survey lines are parallel lines at 100-500 m spacing; they are supplemented by orthogonal tie lines at 1000-5000 m spacing. Aircraft horizontal position is deduced from differential GPS reception and aircraft altitude from barometric and radar measurements. The airborne measurements are corrected for temporal geomagnetic variations (of external origin) with the help of a fixed reference magnetometer established at a base station located within or close to the survey area.

Each morning prior to take-off the operation manager examines weather reports and weather forecast and inspects recordings from the base station magnetometer. While weather report and forecast provide information on the actual and on the expected tropospheric weather the magnetometer gives only information about the actual geomagnetic activity. Information of the expected geomagnetic activity is still missing. Based on weather and actual geomagnetic activity information the operation manager decides whether a flight will commence according to plan, will be postponed or will be entirely cancelled. If a flight is postponed there is still a chance to perform it later on the same day since solar illumination extends deep into the night hours at this high geographic latitude. A production day is possibly not fully lost, but the pilots have to stay on alert. If the flight is entirely cancelled a production day is lost but the pilots can divert to other activities or take a rest day and thus gain back the day which was lost for production.

6.2.2 Post survey schedule analysis

We conducted an analysis of the three most recent surveys in Greenland which were conducted in 1998, 1999 and 2001 by Sander Geophysics Ltd. The surveys lasted 16 weeks each, i.e. about 110 days each summer. These days include aircraft ferry and maintenance time as well as pilot rest days, i.e. not all days were available for production. We combined the three surveys into one set of 331 days for performance evaluation. The following results were obtained.

	number of days
flight survey production affected by technical problems	14
flight delayed because of adverse weather conditions	11
flight delayed because of excessive geomagnetic activity	35
flight delayed because of both bad weather and geomagnetic activity	8
flight canceled because of adverse weather conditions	94
flight canceled because of excessive geomagnetic activity	7
flight canceled because of a both bad weather and geomagnetic activity	19
flight cut short because of adverse weather conditions	35
flight cut short because of excessive geomagnetic activity	6
flight cut short because of both bad weather and geomagnetic activity	5
reflight of previously flown survey lines	14

Among the days listed we find 14 days which were basically lost because they were reflights of already flown segments, probably necessitated by excessive geomagnetic activity during the original flights. Another 13 days were at least partially lost solely because of excessive geomagnetic activity because flights were canceled prior to take-off or called off at some time after take-off but before the planned production was complete. In some cases the aircraft turned back right upon arrival at the survey line and prior to starting production. These 27 days constitute not only lost time but also extra expenses because of actually incurred but eventually useless aircraft flight hours on some of these days.

We must stress, though, that the vast majority of decisions to cancel or shorten a flight was related to adverse troposheric weather and not to excessive geomagnetic activity or technial problems with the equipment. Tropospheric weather remains to be the biggest threat to a successful survey day.

6.3 GAFS under simulated survey conditions

6.3.1 Survey setting

Since the start of GAFS no airborne surveys have been scheduled for Greenland. In order to evaluate the forecast service, simulations of airborne magnetic surveys were performed by our project partner (service user) GEUS. The simulations were done for three survey areas corresponding to the regions covered by the DMI observatories at Qaanaaq, Qeqertarsuaq/Kangerlussuaq and Narsarsuaq. For all of the three survey areas, the simulated airborne surveys covered the time period from 10 October 2005 to 20 December 2005 which corresponds to Julian days 283 to 354.

6.3.2 Evaluation procedure

In Greenland, the normal airport opening hours are 08:00 to 16:00 local time from Monday to Saturday, and the airports are closed on Sunday. A request for opening an airport outside the normal hours can be fulfilled but incurs an additional fee. Therefore, when no specific reasons exist to delay the measurements, the optimum survey time falls into the normal airport opening hours. Reasons for delaying a survey flight usually are bad weather conditions, the occurrence of magnetic disturbances and technical problems with the equipment.

In the simulation of the airborne surveys we did not attempt to include the interference of problems other than those caused by magnetic disturbances. The exclusion of the other types of problems that can delay a survey flight in the simulation simplifies the evaluation of the forecast service, but the simulation obviously differs from a real survey situation.

During the evaluation period, Thorkild M. Rasmussen, GEUS, used the information on the GAFS restricted Internet site to decide if and when a survey flight should start. Whenever possible, the decisions about flying were made around 06:00 local Greenland time. In a real survey situation, a decision by the survey manager at 06:00 will give the technicians sufficient time to make the final preparation for the flight and the pilots time to get ready for take-off around 08:00. The maximum flight duration is between five and seven hours depending on the type of aircraft employed. In the simulation each flight had a duration of six hours. Thus, an early take-off will allow the pilots to complete a full survey flight and return within the normal airport opening hours.

During the evaluation period, T.M. Rasmussen issued a flight decision every day on which he had access to the Internet. This included most normal office days, Monday to Friday, and in some cases also Saturdays and Sundays. The additional airport fee charged on Sundays was not considered when decisions were made on Sundays. Lack of daylight was not taken into account for the simulations. October through November are unusual months for survey flights in Greenland, the standard is May through August when daylight extends over many more hours.

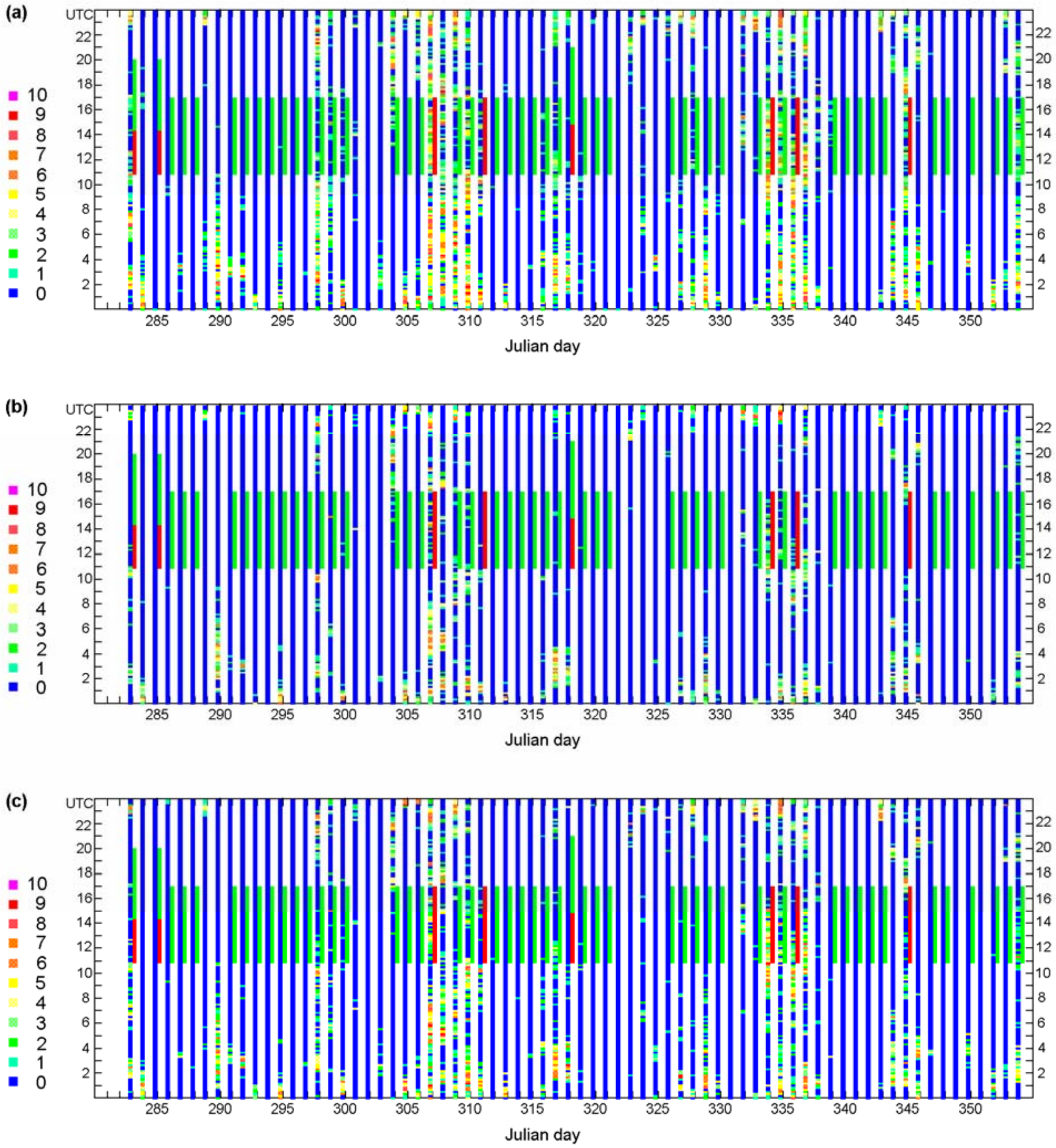


Fig. 11. *Statistics of the magnetic field variations at NAQ for (a) the east component, (b) the north component and (c) the vertical component for Julian days 283–354, together with decisions on survey flights. The number of occurrences per 10-minute interval where the difference between two consecutive samples of 1-min magnetic field averages exceeds 10 nT are shown in the left column for each day (24-hour bars). The decision of doing a survey flight is indicated by green colour (duration 6 hours) in the right column whereas a decision for delaying or canceling a flight is indicated by red colour.*

Before taking a decision about the start of a survey flight, both the forecasts on the Internet site and the actual near real-time magnetic field recordings were considered. In particular the high frequency variations were evaluated when analysing the real-time recordings since this type of variation is considered a source of severe errors in airborne surveys. It is generally assumed that low frequency variations are spatially in-phase over a large area whereas high frequency variations are more localised. Low frequency variations can thus be easier compensated for with the help of a remote reference station. In order to examine and quantify this assumption a study has been initiated at DMI (Watermann-2006) which has rendered first encouraging results. Note that the terms *low frequency* and *high frequency* have a different meaning in this context than they have in a radio science context. In our case *low frequency* denotes quasi-static variations and *high frequency* denotes variations in the ULF band.

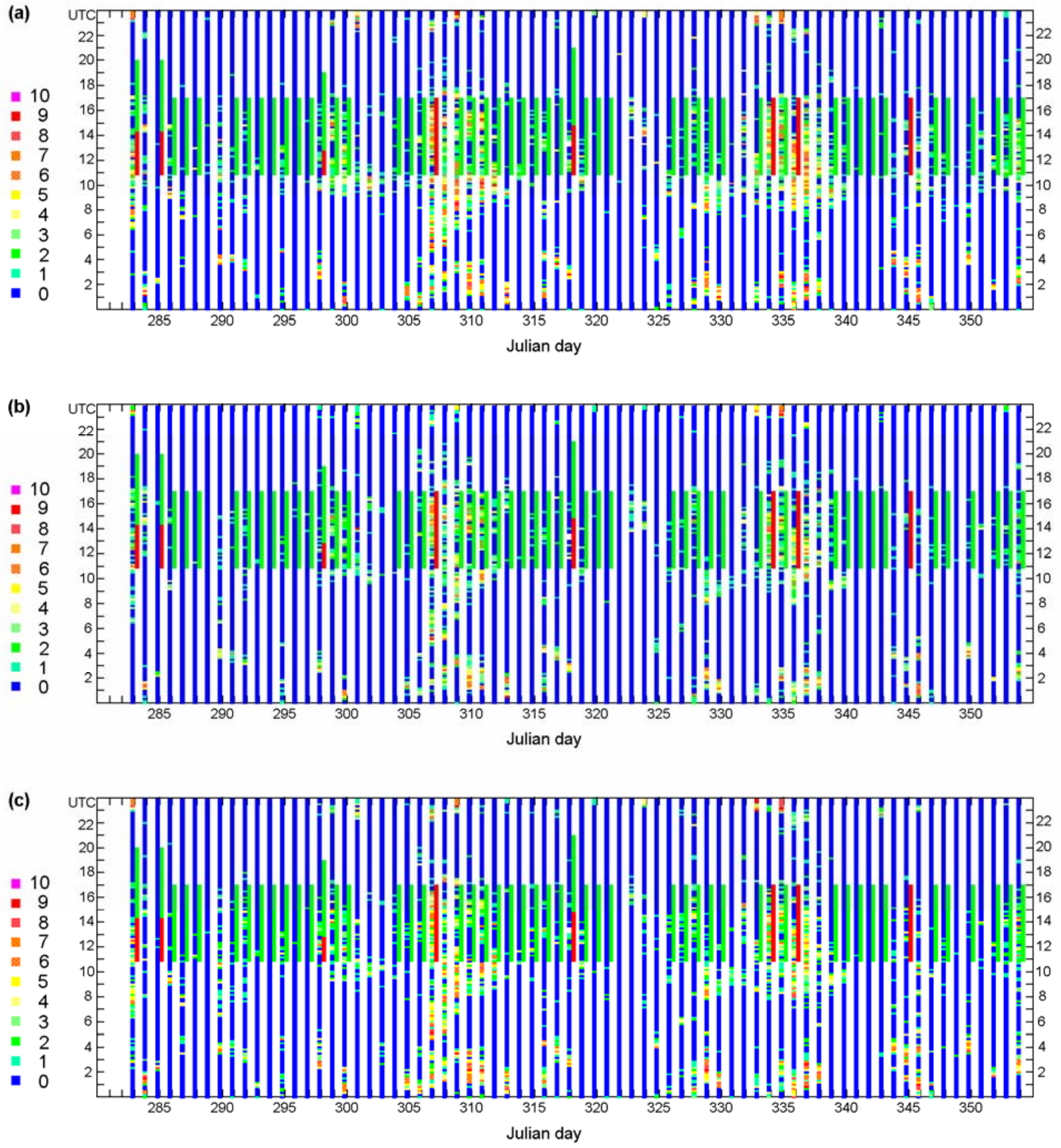


Fig. 12. *As Figure 11 but for the station STF.*

Geomagnetic activity was in general low during the period when the surveys were simulated. Qualitatively, the predictions of the field variations were in general confirmed both for the short- and long-term predictions. A detailed quantitative evaluation follows in the next section.

6.3.3 Detailed results of the evaluation

For a quantitative evaluation the actual field variations from 1-min averages of the field vector components were used. The number of occurrences per 10-minute interval where the field difference exceeded 10 nT between two consecutive 1-min averages was used as a measure for geomagnetic high frequency activity. This reflects the assumption that the high frequency part of the variation spectrum is the most difficult to compensate for.

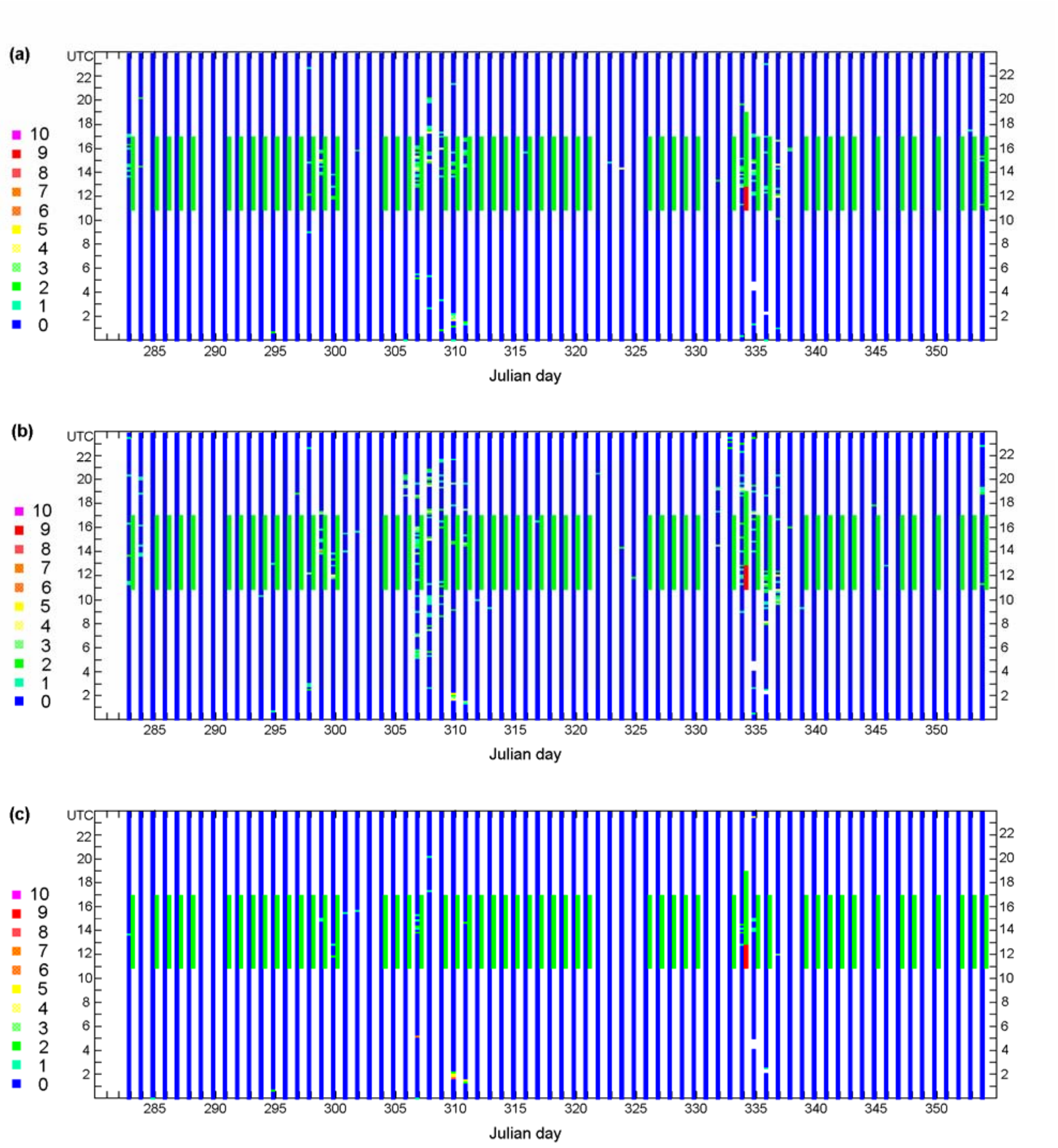


Fig. 13. *As Figure 11 but for the station THL.*

Geomagnetic activity is displayed in Figures 11-13 for Narsarsuaq, Qeqertarsuaq/Kangerlussuaq and Qaanaaq respectively, together with the survey decisions. Data and decisions for each day are shown in two adjacent columns with the field statistics shown in the left and the decision in the right column. UTC is used for the ordinate. A decision to perform a survey flight with a 6-hour duration is marked green and a decision to delay or cancel a survey flight is marked red.

Although some of the decisions turned out to be wrong, the results shown in Figures 11-13 indicate an overall success in predicting the geomagnetic activity. The experience gained from these simulations is that the predictions are valuable as a guide when making decisions, and it is found that decisions can be made with higher confidence compared to the situation where only reference data from a remote base station are available.

6.2.4 Statistical assessment of the forecast usefulness

Figures 11-13 show all details about magnetic variation in excess of 10 nT between consecutive 1-min samples, binned into 10-min intervals at each station and for each magnetic field component, along with the flight decisions on all survey days. However, this comprehensive information is difficult to digest. In order to give a more condensed picture of the occurrence of magnetic activity and the quality of the resulting flight decision we have binned geomagnetic activity into ten classes of occurrence frequency separately for the three sites, NAQ, GDH/STF and THL, and the three possible flight decisions, *fly*, *wait* and *no fly*.

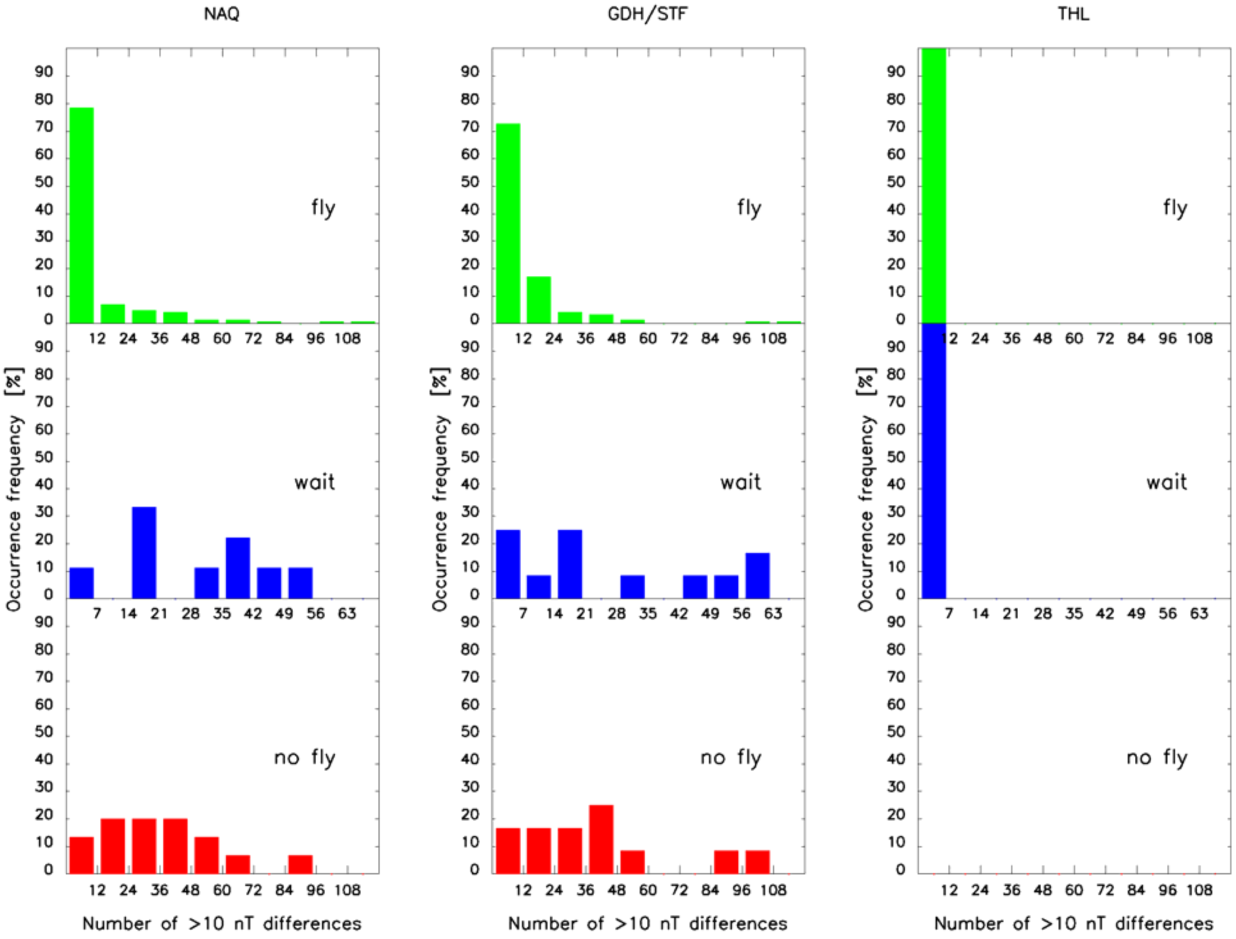


Fig. 14. *Relative distribution of days with a certain maximum number of excess samples (1-min samples which differ more than 10 nT from their preceding 1-min samples), cumulative for the three magnetic field vector components, X (north), Y (east) and Z (down). Each panel represents either the "fly", the "wait" or the "no fly" category for a specific observatory. The ordinates show the percentage of days where the number of excess samples stayed within the bins marked on the abscissae.*

A label *fly* indicates that a flight is performed as nominal which means start at 08:00 LT (equivalent to 11:00 UT) and return after 6 hours standard survey time at 14:00 LT (17:00 UT). The label *no fly* means that flight preparation is called off and all flights are cancelled for the rest of the day. The label *wait* means that flight preparation is put on hold, awaiting the survey manager's final decision about a schedule delay which comes typically 3-4 hours later. In the majority of cases the second decision came 3.5 hours later, and we have for the sake of statistical homogenity fixed all *wait* intervals to 3.5 hours. If the survey manager allows *fly* after the *wait* period a full 6-hour survey is conducted. The combined results are displayed in Figure 14. Each column represents a Greenland magnetometer station. The upper panel shows the relative occurrence of 1-min intervals during *fly* hours which exceeded 10 nT difference, the middle panel shows the corresponding information for the *wait* hours and the bottom panel for *no fly* hours.

In order to compile Figure 14 we computed histogram numbers in the following way. 53 campaign days were simulated and evaluated. During each campaign day we had either six hours *fly* or else six hours *no fly*, equivalent to 360 *fly* or 360 *no fly* data samples. On some days we had an additional 3.5 hours *wait* time (210 wait data samples) before the final *fly* or *no fly* decision was taken. We summed up the results from the three magnetic field vector components which gives a total of 1080 (*fly* or *no fly*) respectively 630 (*wait*) samples per day and station for which the difference to the preceding sample could exceed 10 nT. In the following we term the samples which exceed a 10-nT difference to the preceding sample shortly "excess samples". The campaign period was magnetically relatively quiet so that the number of actually observed excess samples was much below the maximally possible number. At no station we recorded more than 120 excess samples per day. We therefore chose ten bin classes with each class 12 counts wide. The counts are printed along the abscissa.

Let us look at the upper left panel. On nearly 80% of all *fly* days we counted less than 12 excess samples. On nearly 7% of all days we found more than 11 but less than 24 excess samples, on nearly 5% of all days more than 23 but less than 36 excess samples, and so forth. On one single day (0.7% of all days) we counted 120 excess samples which was the overall maximum of the campaign. The other panels of Figure 12 were constructed in a similar way. Since we have a possible maximum of 1080 samples for the *fly* and *no fly* categories but only 630 for the *wait* category we divided the latter in bins of width 7 rather than 12, in order to set equal distribution conditions.

The most impressive station is THL at the poleward end of Greenland. All days were tagged *fly* or *wait* (followed by a later *fly* command), and not a single *no fly* day occurred. The *fly* command has proven correct since the number of excess samples stayed below 12 on every single day. The *wait* command caused unnecessary delays since the number of excess samples remained below 7 during all *wait* intervals. The situation is different for NAQ and GDH/STF where we have a certain number of *no fly* days.

The analysis of the survey simulation demonstrates that the decision of the survey manager was in general correct for all three sites. The number of excess samples was below 12 on the vast majority of *fly* days while the *wait* and *no fly* intervals were indeed characterized by a more even percentage distribution between days with smaller and larger numbers of excess samples. The *fly*, *wait* and *no fly* alerts issued for NAQ and GDH/STF were thus justified on a large number of days, and the *fly* commands given for THL were fully justified.

7. Opportunities for Improvement

7.1 Use of supplementary data

Several areas can be identified where more research is required. Here we point out some critical areas in geomagnetic forecasting where more development is warranted. In some of them we can expect to make progress by using currently available solar and solar wind observations.

The geoeffectiveness of CMEs. An improved utilization of solar and interplanetary data that can be combined with data extracted from white-light coronagraph images have the potential to improve the forecast accuracy of strong magnetic storms. In GAFS we have tried to take one step in this direction by utilizing SEP fluxes to infer the geoeffectiveness of an observed full halo CME, see Gleisner-2006c. Other relevant data not yet implemented in GAFS include the solar magnetic field configuration at the site of the CME, the ambient solar wind into which the CME is released, and sweep-frequency radio bursts indicating the presence of propagating shocks.

STEREO observations of CMEs. The Solar-Terrestrial Relations Observatory (STEREO) twin space probes (`http://stereo.gsfc.nasa.gov/`) were launched successfully on October 26, 2006. The two spacecraft orbit the Sun on trajectories similar to that of the Earth but at some distance ahead and behind the Earth. They will map the structure of CMEs in 3-D as they leave the solar surface and expand into interplanetary space. This will allow observers to clearly idfentify earthward directed CMEs and quantify their velocity much more precisely than has hitherto been possible. The timing of the onset of geomagnetic storms is expected to become much more accurate. However, due to their particular orbit parameters the spacecraft slowly drift away from the Earth in opposite directions. The continuously changing constellation thus limits the mission time useful for mapping earthward directed CMEs. STEREO will be highly useful for space weather research but its usefulness for a continuously operational geomagnetic storm alert service will be limited.

Improved solar wind models. Current solar wind models have a limited ability to describe the conditions in interplanetary space from observations of the Sun, partly for fundamental physical reasons. A simple way to improve the forecast ability would be to use current models as they are, but to try to adjust them based on actually observed data. This would primarily be observed solar wind data, but also observations of coronal hole boundaries from e.g. soft X-ray observations and, in the future, solar and solar wind observations with new types of radio telescopes and radars such as the LOFAR/LOIS facility currently under construction.

7.2 Data possibly available in the future

In other areas the need for more information and better physical understanding has been identified, but there is still a long way to go to meet the need.

Solar surface magnetic field reconstruction. A major problem exists with the reconstruction of the magnetic field vector at the solar surface and within CMEs. Although better physical understanding of the processes will lead to better models, their accuracy will continue to be limited as long as no new instruments or methods become available which allow us to quantitatively specify the solar surface magnetic field.

7.3 Operational stability and reliability

From a technical point of view the forecast scheme has not always worked satisfactorily. We have experienced black-outs of one or several of the real time data streams, more frequently in the beginning and less frequently towards the end of the development period. Further, the automatic server restart after a server breakdown or power failure did not always work as intended, with the consequence that a manual restart sometimes became necessary. Various technical and logistic modifications (including a change of our Internet provider) have by now resulted in more stable real time data links. An upgrade of the DMI server is currently underway.

Taking all glitches together, the reliability is not yet high enough to make the service fully acceptable for a well-paying customer. At present it would be necessary to have a designated person (watchdog) who keeps an eye on the service in case problems arise. It is not required that the watchdog is a trained software or hardware engineer since the vast majority of problems are resolved by a reboot or restart of the system as a whole or of individual components.

An alternative might be to implement GAFS on at least two fully independent systems. DMI's observatories employ already two separate but identical sensor and data acquisition systems. For full independency two separate Internet links and two individual servers at DMI would be required.

7.4 Geographical extension of the service

The two users who are currently partners in the GAFS project represent operational commercial, semi-commercial and scientific activities in the North Sea (directional wellbore drilling) and in Greenland (airborne magnetostatic anomaly surveys). GAFS can in principle be extended to include other users in other geographic areas. Such an extension means basically redoing the analysis of historic time series from geomagnetic observatories representing the new areas under consideration, deriving statistical measures for the geomagnetic activity and finding the proper coefficients needed to build prediction filters for the geomagnetic activity at those newly added observatories. The procedure is thus straightforward, but a certain amount of work hours is needed in order to adapt the procedure to the new stations and to find and validate the statistical results and the inferred probabilities used to define quantitatively the corresponding activity levels. Since an extension requires extra resources it will only materialize if a paying customer can be identified.

8. Conclusion

DMI's Geomagnetic Activity Forecast Service (GAFS) is an area specific service which is initially targeted towards two user categories who are represented as partners in the GAFS project

- oil companies which perform directional wellbore drilling in the North Sea
- service companies which conduct airborne magnetostatic anomaly surveys in Greenland

Starting from an initially manually driven and more qualitatively oriented predecessor, GAFS was developed to fulfill the requirement of a fully automated objective (i.e. operator independent) forecast service. This task has been accomplished within the project run time. GAFS is now operational, but interruptions or breakdowns due to technical or logistic problems still occur occasionally.

An objective statistical analysis of forecast versus observations has proven that the service gives under many conditions a better forecast than a random (uninformed) prediction. However, certain parameters, notably the time of the onset of geomagnetic storms and the activity levels of weak storms, are often poorly predicted. These problems have been identified and suggestions for future improvements are made.

The evaluation of a situation in which GAFS served as a decision aid for a simulated aeromagnetic survey in Greenland demonstrates that the decisions for *fly*, *wait* or *no fly* suggested by GAFS proved to have been correct in the vast majority of cases. This result lends credibility to GAFS. We must admit, though, that the simulation was performed during a geomagnetically relatively quiet period which made the prediction easier than it would be under conditions with heavily mixed disturbance levels.

An extension of GAFS in order to cover additional geographic areas is possible. Using the same procedures as those used for Greenland and Denmark, such an extension could be implemented. However, a substantial amount of work hours is required to actually do the extension work.

GAFS is expected to continue running operationally over at least the next few years.

Previous reports

Previous reports from the Danish Meteorological Institute can be found on:
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