

Large-magnitude geomagnetic disturbances in the North Sea region: Statistics, causes, and forecasting

Hans Gleisner *, Ole Rasmussen, Jürgen Watermann

Danish Meteorological Institute, Atmosphere Space Research Division, Lyngbyvej 100, DK-2100 Copenhagen, Denmark

Received 30 September 2004; received in revised form 21 April 2005; accepted 26 April 2005

Abstract

Many scientific and commercial activities require an undisturbed geomagnetic field. The Danish Meteorological Institute currently offers real-time magnetometer data as a service to such activities in Denmark and the North Sea region. As a part of an ongoing project aiming at the development of geomagnetic forecast services, we have investigated the statistics of geomagnetic disturbances at the Brorfelde Geomagnetic Observatory in Denmark, with a focus on large-magnitude disturbances that might affect directional-drilling operations in the North Sea. We here report on the distribution of such disturbances as a function of season, time-of-day, and phase of the solar cycle. We demonstrate a close association with strong magnetic storms identified from significant depressions of the ring current index D_{st} , which have been shown to be caused primarily by coronal mass ejections (CMEs). Very few of the weaker storms, even though much more frequently occurring, generate disturbances exceeding the large-magnitude thresholds, here defined from an actual example of a directional-drilling campaign in the North Sea. Limiting the range of acceptable geomagnetic disturbances would, however, make the weaker storms play a more important role. The prospects of forecasting geomagnetic disturbances are briefly discussed.

© 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Geomagnetic disturbances; Geomagnetic forecasting; Space weather; Magnetic storm; Directional drilling

1. Introduction

Many scientific and commercial activities require an undisturbed geomagnetic field. In some applications, such as measurements of the Earth's crustal magnetic field for prospecting purposes, the disturbance field generated in the ionosphere and magnetosphere presents a source of error, potentially limiting the accuracy of the measurements (Campbell, 2003). In other applications, such as directional drilling in which the geomagnetic field is used to monitor the direction of a well-bore, the geomagnetic field is assumed to be known and is used as a reference (Russell et al., 1995; Clark and Clarke, 2001). Any deviations of the field from undis-

turbed levels may cause errors in referencing, in this case leading to departures from the intended drilling direction.

The Brorfelde Geomagnetic Observatory, operated by the Danish Meteorological Institute (DMI), is located in Denmark at geomagnetic latitude 52°N (Fig. 1). This location makes the observatory well suited for studies of geomagnetic disturbances in the North Sea region. The availability of real-time data allows us to provide customers both with information on the expected geomagnetic reference field in the absence of significant disturbances, and information on the currently observed deviations from this reference field.

Applications which currently use real-time data could benefit from the availability of geomagnetic forecasts. As a part of an ongoing project within the ESA *Space Weather Applications Pilot Project* (Daly and Hilger,

* Corresponding author. Tel.: +45 39 157 484.
E-mail address: hgl@dmu.dk (H. Gleisner).

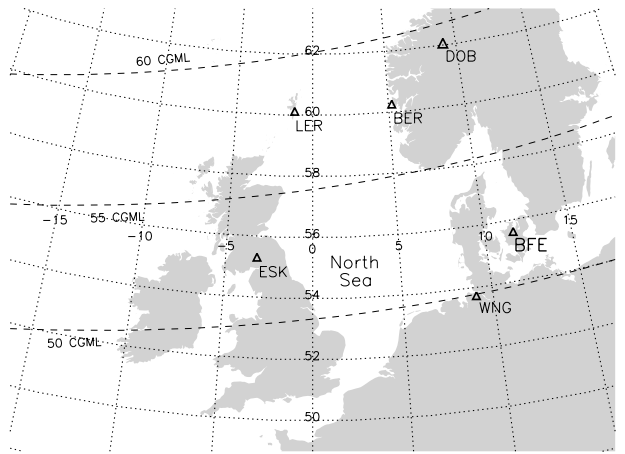


Fig. 1. Geomagnetic observatories in the North Sea region. The Brorfelde Observatory is located in Denmark just east of the North Sea at geomagnetic latitude 52°N .

2001), aiming at the development of geomagnetic forecast services, we have investigated the statistics of geomagnetic disturbances at the Brorfelde Observatory. The study has a focus on large-magnitude disturbances that might affect directional-drilling operations in the North Sea region. In the following, we do not explicitly refer to other types of application, even though many of the results are of a more general interest. An improved understanding of the statistics of strong disturbances at the Brorfelde Observatory may give useful information on the likelihoods to encounter practical problems during activities in the North Sea region. Hence they may help direct our efforts to develop more accurate geomagnetic forecast schemes, but they may also help us disentangle the factors – e.g., the conditions in interplanetary space, type and phase of magnetic storms, state of ionospheric currents, and degree of upper-atmosphere ionization – that govern and modulate the locally observed geomagnetic disturbance field.

2. Statistics of major disturbances

2.1. The local disturbance field

The geomagnetic disturbance field ΔB at any location is here defined as the deviation from a quiet-time reference field

$$\Delta B(t) = B(t) - [B_0(t) + B_{S_q}(t)], \quad (1)$$

where $B(t)$ is the observed field, B_0 is the field at a certain epoch plus the secular variations since then, and B_{S_q} is the regular diurnal variations under geomagnetically quiet conditions. The quiet-time reference field $B_0 + B_{S_q}$, describing the geomagnetic field variations in the absence of any disturbances, is not an observable and has to be given by a model.

In this study, we have used 5-min averages of the field elements F (field magnitude), D (declination), and I (inclination). This choice of averaging interval reflects the need to describe disturbances related to magnetic storms and substorms. Geomagnetic pulsations and other high-frequency variations are filtered out, while disturbances on time scales related to magnetic storms and substorms are retained. Another consideration is the need to use quantities that realistically could be predicted. Experience shows that 5-min averages of the locally observed geomagnetic disturbance field could be predicted 1 h ahead (Gleisner and Lundstedt, 2001), whereas 1-min or shorter averages can not be reasonably well predicted.

2.2. Definition of large magnitudes

The level of geomagnetic disturbances that should be regarded as having a “large” magnitude is determined by the requirements of a particular application. The following limits have been used in actual directional-drilling campaigns in the North Sea (Simon McCulloch, private communication). We will here adopt them as the definitions of large-magnitude geomagnetic disturbances, even though the limits used in practice may deviate considerably from these values:

$$|\Delta F| > 145 \text{ nT}, \quad (2)$$

$$|\Delta D| > 22', \quad (3)$$

$$|\Delta I| > 10'. \quad (4)$$

These limits correspond to the 0.2% tail of the $|\Delta F|$ and the $|\Delta D|$ distributions, and to the 0.1% tail of the $|\Delta I|$ distribution. Hence, these limits are only rarely exceeded. The 0.2% tail correspond to approximately one 5-min sample every second day. However, the large-magnitude disturbances are not randomly distributed in time. Magnetic disturbances exceeding the thresholds given above are only observed during a relatively small number of events, each generating a prolonged sequence of disturbed conditions. As shown below, these events causing the majority of large-magnitude disturbances can be identified as strong magnetic storms.

2.3. Diurnal, seasonal, and solar-cycle distributions

The occurrence of geomagnetic disturbances at any geographic location is primarily governed by three factors:

- the state of the near-Earth space environment,
- the geomagnetic latitude and local time,
- the season.

Fig. 2 shows the statistical distributions of large-magnitude disturbances at Brorfelde as a function of time-of-day, season, and phase of the solar cycle, deduced

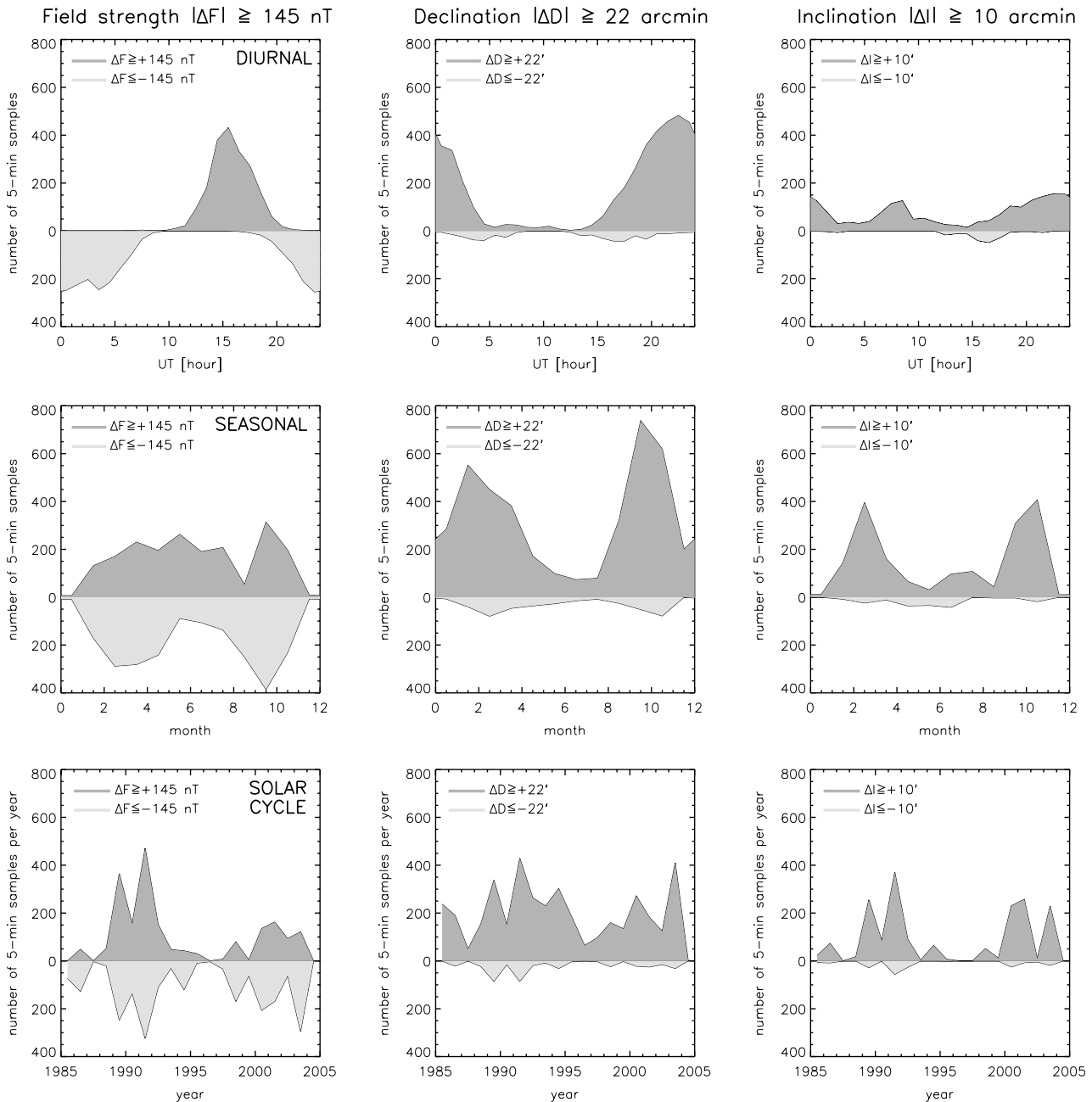


Fig. 2. Diurnal (upper panels), seasonal (middle panels), and solar-cycle (lower panels) distributions of large-magnitude geomagnetic disturbances at the Brorfelde Observatory. The distributions for positive and negative disturbances have been separated, and the distributions for negative disturbances (light grey) are shown upside down. The thresholds have been chosen as the 0.2% tail of the $|\Delta F|$ and the $|\Delta D|$ distributions, and as the 0.1% tail of the $|\Delta I|$ distribution. This corresponds roughly to the requirements set by directional-drilling operations in the North Sea.

from the 19-year period 1985–2003. The distributions for positive and negative disturbances have been separated, as they show distinctly different patterns.

A fundamental observation is the significant variation of occurrence frequencies – some combinations of season and time-of-day virtually exclude the presence of certain type of disturbances. Disturbances of the declination ΔD , most of them positive, are rarely observed from early morning to late afternoon. Negative disturbances of the field magnitude ΔF are totally absent dur-

ing daytime, whereas positive disturbances are absent during night. Negative disturbances of the inclination ΔI are never observed in the morning hours.

The diurnal distribution of large-magnitude ΔF disturbances (Fig. 2; upper left panel) exhibit a behaviour we would expect from the *convection electrojets*; positive disturbances in the afternoon-to-premidnight sector and negative disturbances in the midnight-to-morning hours. This pattern is related to the so called DP-2 equivalent ionospheric current system (e.g., Clauer and Kamide,

1985), i.e., Hall currents flowing along the auroral oval in response to enhanced magnetospheric convection. Closer inspection of the data show that this temporal behaviour is typical also for the individual events – it is not merely statistical.

The diurnal distribution of large-magnitude ΔD disturbances (Fig. 2; upper middle panel) is dominated by positive disturbances in the midnight sector. Few observations of negative ΔD disturbances of large magnitudes have been made during the 19-year period. The diurnal distribution of large-magnitude ΔI (Fig. 2; upper right panel) exhibit a similar dominance of positive disturbances, although the concentration around midnight is less pronounced than for ΔD .

The seasonal distribution of large-magnitude disturbances exhibits a strong influence from the Russell–McPherron effect – the regular semi-annual variation of the coupling efficiency between the Earth’s magnetic field and the interplanetary magnetic field – with peaks around the equinoxia and minima near the solstices. However, the positive ΔF and ΔI disturbances also show signs of an annual modulation with a single summertime maximum, most likely caused by the annually varying degree of ionization in the northern hemisphere ionosphere. The combination of these two effects gives rise to a three-peaked seasonal distribution of the positive ΔF and ΔI disturbances, while the other disturbance field components are dominated by the Russell–McPherron effect and, hence, exhibit a two-peaked seasonal distribution.

The distributions of annual frequencies of large-magnitude disturbances (Fig. 2; lower panels) are dominated by the solar cycle. This variation is most evident for ΔF and positive ΔI disturbances which show a typical two-peaked distribution with one peak near solar maximum and a second peak during the declining phase of the solar cycle.

3. Causes of major disturbances

3.1. Solar-wind conditions and magnetic storms

Magnetic storms are caused by solar-wind disturbances interacting with the Earth’s magnetic field. A combination of high solar-wind speed V and a large southward component B_Z of the interplanetary magnetic field (IMF) is most efficient in producing geomagnetic disturbances. Most of the time, the out-of-ecliptic IMF component B_Z is small and highly irregular. Occasionally this component can be large and relatively sustained. The two predominant drivers of such conditions are *solar-wind stream interactions* and *coronal mass ejections* (CMEs).

These two sources of geoeffective solar-wind conditions are not equally efficient in producing magnetic storms. Several studies have shown that strong magnetic storms, i.e., storms during which the ring current index D_{st} reach levels below -100 nT, are almost exclusively caused by CMEs (Gosling et al., 1991; Tsurutani and Gonzalez, 2000). During the passage of an interplanetary CME, a strong and relatively steady IMF with a significant out-of-ecliptic component can be sustained for many hours. If the B_Z component is directed southward a strong magnetic storm is almost certain to occur. The conditions during the passage of stream interactions tend to be more variable and these solar-wind structures are an important source of the more frequent, but less severe, recurrent magnetic storms.

Magnetic storms often generate prolonged periods of globally disturbed geomagnetic conditions lasting for several days. However, even during a storm the locally observed magnetic disturbance field is not continuously upset. Rather, the local field exhibits a diurnal modulation in accordance with the statistical results in Fig. 2.

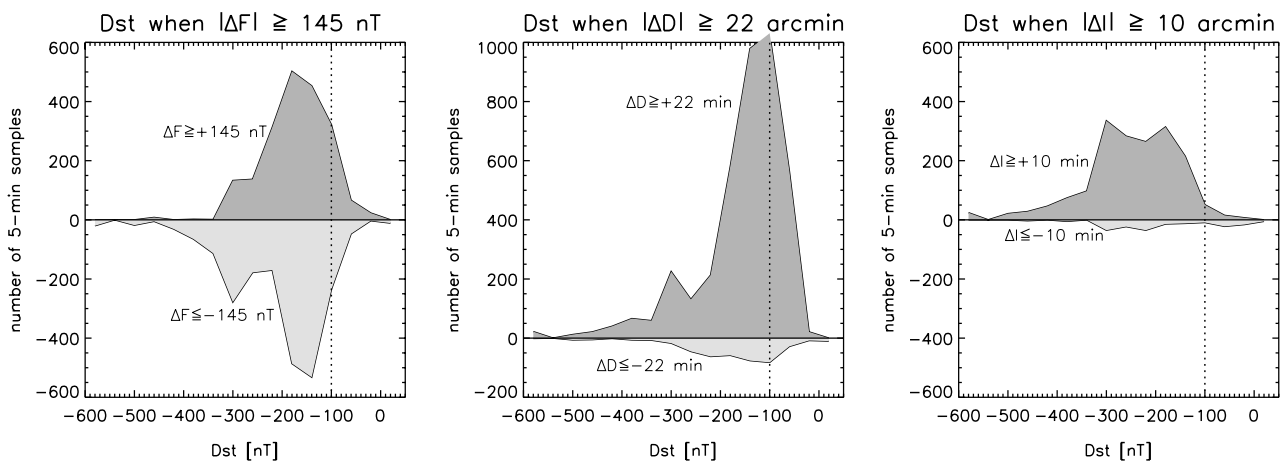


Fig. 3. Distribution of D_{st} values for large-magnitude geomagnetic disturbances at the Brorfelde Observatory. Highly disturbed conditions at Brorfelde are predominantly associated with strong magnetic storms (threshold indicated by the dashed line in the panels).

3.2. Association with strong magnetic storms

We expect large-magnitude magnetic disturbances at the sub-auroral latitudes of Brorfelde to predominantly occur during magnetic storms when the auroral oval expands to lower latitudes. This would be indicated by depressed levels of the geomagnetic index D_{st} . In Fig. 3 we show the distribution of D_{st} values for all times when the disturbance field at Brorfelde exceeds the large-magnitude thresholds. A vast majority of the locally observed large-magnitude disturbances are found during strong magnetic storms when D_{st} is depressed to levels below -100 nT, and a significant fraction is in fact associated with the rare storms reaching D_{st} levels below several hundred nano-Teslas. A substantial part of the relatively few large-magnitude disturbances that occur when D_{st} is larger than, but still close to, -100 nT are also found during strong storms. Apparently, there is a close association, not with magnetic storms in general, but predominantly with strong magnetic storms. Very few of the weaker storms, even though much more frequently occurring, generate disturbances of a magnitude exceeding the acceptance thresholds for directional-drilling operations in the North Sea region. However, it should be noted that this conclusion depends on the use of our particular definition of what constitute a “large magnitude”. Applications using more narrow limits, substantially smaller than those defined by the relations 2–4 in Section 2.2, would also be affected by the more frequently occurring weaker storms.

The fact that all locally observed disturbances exceeding the large-magnitude thresholds occur in conjunction with strong magnetic storms, does not imply that all strong storms necessarily generate large-magnitude local disturbances in the North Sea region. A full understanding of the association would also require a description of the fraction of strong magnetic storms that actually lead to large-magnitude local disturbances. We can expect this fraction to vary over time, e.g., with season.

4. Prospects of geomagnetic forecasts

4.1. Probabilistic and deterministic forecasting

With a solar-wind monitor located upstream in the solar wind, *short-range* geomagnetic forecasts (an hour ahead) have become a reality. However, *medium-range* geomagnetic forecasts (up to 3 days ahead) is still at a level of development where we often have to fall back on *probabilistic* methods, i.e., the use of solar-cycle, seasonal, or diurnal climatologies, in combination with persistence, recurrency, or other type of statistics. The alternative use of purely *deterministic* methods would require us to forecast the detailed near-Earth solar-wind conditions several days ahead from observations of the

Sun and of processes taking place close to the Sun. With a few exceptions, such as certain type of coronal mass ejections generating some of the most intense magnetic storms (Zhao and Hoeksema, 1997), this is not possible and will not be in the foreseeable future due to the small spatial and temporal scales of typical out-of-ecliptic interplanetary magnetic field variations.

We can, however, improve on statistics-based forecasting by the use of a combination of deterministic and probabilistic methods (McPherron and Siscoe, 2003). Observations of the Sun and of processes taking place close to the Sun actually tell us – through the use of physics-based or data-based solar-wind models, or through established links between solar eruptive events and solar-wind disturbances – what type of solar-wind structures that are likely to encounter the Earth within the next few days. Depending on how well-defined the predicted class of solar-wind structure is, and the expected accuracy of the prediction, we can then assign likelihoods for the resulting geomagnetic disturbances.

This simplistic scheme can be difficult to implement in practice, largely due to the lack of understanding of the relations between the solar observations and the near-Earth solar-wind conditions. However, we have seen above that all major disturbances in the North Sea region are found during very strong magnetic storms. These are nearly exclusively caused by CMEs which can be identified from white-light coronagraph images. After an appropriate classification and together with additional information, the likelihood for upcoming disturbances can be estimated.

4.2. An example: September 7, 2002

In the late afternoon of September 5, 2002, a full halo CME was observed by the coronagraph onboard the *SOHO* spacecraft, a space based solar observatory from which the Sun can be continuously observed (e.g., Bonnet and Felici, 1997). Through an effort by researcher at the Naval Research Laboratory (NRL), data on CMEs are rapidly dispersed to the user community to give an early warning of possible space weather disturbances (St. Cyr et al., 2000), and in this case the speed of the CME was estimated to be more than 1600 km/s. Within minutes, a relatively strong type II radio burst was reported by NOAA’s Space Environment Center (SEC) in Boulder, indicating the presence of a shock wave propagating in the solar corona with a velocity of around 700 km/s. On the following morning, NOAA/SEC also reported an increase of the energetic-proton fluxes observed from satellites in geostationary orbit, and by noon the fluxes had reached levels indicating enhanced particle acceleration by strong shocks travelling in interplanetary space. Apparently, a substantial solar-wind disturbance could be expected to arrive during the

next day, September 7, the exact time depending on which velocity we regard as most reliable. After consulting the diurnal and seasonal modulations shown in Fig. 2, the appropriate warnings could be issued for the geomagnetic field at Brorfelde.

5. Discussion and conclusions

In this paper, we have taken certain limits on geomagnetic activity required by directional-drilling operators as a starting point for an investigation of large-magnitude geomagnetic disturbances in the North Sea region. We have seen that geomagnetic disturbances of a magnitude large enough to adversely affect the precise monitoring of the drilling direction exhibit a pronounced modulation by time-of-day, season, and solar cycle. The diurnal variation is caused by the local-time dependence of the electrojet current system during magnetic storms. The summertime and wintertime minima are typical for the semi-annual variation of the solar wind-magnetosphere coupling, while on the solar-cycle time scale the geomagnetic disturbance field is modulated by the varying solar activity.

We have also found that geomagnetic disturbances with a magnitude exceeding the limits defined by relations 2–4 in Section 2.2 are almost exclusively associated with strong magnetic storms, which are caused by the passage of interplanetary CMEs. Using more narrow limits on the acceptable geomagnetic disturbances, would mean that also the weaker, but more frequently occurring storms, play a role. The solar eruptive events generating the geoeffective solar-wind disturbances are nowadays routinely observed, and the relevant information is distributed in real time or near-real time. This has opened up the possibility to actually forecast these disturbances – or to rule out substantial geomagnetic disturbances in the absence of eruptive events on the Sun.

Within the frame of the *ESA Space Weather Applications Pilot Project*, we are currently developing and testing methods for medium-range geomagnetic forecasts at the Danish Meteorological Institute. This, and other, initiatives will hopefully lead to an improved accuracy

of the geomagnetic forecasts and a more widespread use of geomagnetic forecast services.

Acknowledgement

This work was done as a part of the *ESA Space Weather Applications Pilot Project*, under ESTEC contract 16983/03/NL/LvH.

References

- Bonnet, R.M., Felici, F. Overview of the SOHO mission. *Adv. Space Res.* 20, 2207–2218, 1997.
- Campbell, W.H. *Introduction to Geomagnetic Fields*, second ed. Cambridge University Press, Cambridge, UK, 2003.
- Clark, T.D.G., Clarke, E. Space weather services for the offshore drilling industry, in: *Proceedings of the ESA Space Weather Workshop*, ESTEC, the Netherlands, 17–19 Dec, 2001, ESA WPP-194, 2001.
- Clauer, C.R., Kamide, Y. DP1 and DP2 current systems for the March 22, 1979 substorms. *J. Geophys. Res.* 90, 1343–1354, 1985.
- Daly, E.J., Hilger, A. Space weather: European Space Agency perspective, *Space weather*, AGU Geophysical Monograph 125, AGU, Washington, MD, p. 53–57, 2001.
- Gleisner, H., Lundstedt, H. A neural network-based local model for prediction of geomagnetic disturbances. *J. Geophys. Res.* 106, 8425–8434, 2001.
- Gosling, J.T., McComas, D.J., Phillips, J.L., Bame, S.J. Geomagnetic activity associated with earth passage of interplanetary shock disturbances. *J. Geophys. Res.* 96, 7831, 1991.
- McPherron, R.L., Siscoe, G. Probabilistic forecasting of geomagnetic indices using solar wind “air mass” analysis. *Space Weather* 1, 3–14, 2003.
- Russell, J.P., Shiells, G., Kerridge, D.J. Reduction of well-bore positional uncertainty through application of a new geomagnetic in-field referencing technique, in: *Proceedings of the 1995 SPE Annual Technical Conference and Exhibition*, paper SPE 30452, Dallas, Texas, October 22–25, 1995.
- St. Cyr, O.C., Howard, R.A., Sheeley, N.R., et al. Properties of coronal mass ejections: SOHO LASCO observations from January 1996 to June 1998. *J. Geophys. Res.* 105, 18169–18185, 2000.
- Tsurutani, B.T., Gonzalez, W.D. Interplanetary causes of magnetic storms: a review, in: *Magnetic storms*, AGU Geophysical Monograph 98, AGU, Washington, MD, pp. 77–90, 2000.
- Zhao, X.-P., Hoeksema, J.T. Is the geoeffectiveness of the January 6, 1997, CME predictable from solar observations?. *Geophys. Res. Lett.* 24, 2965–2968, 1997.