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Response of the polar magnetic field intensity to the exceptionally high solar wind streams in 2003

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[1] The exceptionally high solar wind stream activity in 2003 caused a record intensity in the auroral electrojet currents, leading to a major reduction of the horizontal field at auroral latitudes and to a notable strengthening of the vertical geomagnetic field in the polar cap. This strengthening is clearly visible in the observatory annual values as a significant deflection in the corresponding secular variation. A similar but weaker deflection also occurs during the strongest high speed stream years of the earlier solar cycles, e.g., in 1983 and 1994. We also found that, in addition to the disturbed times, the westward electrojet was often enhanced even during the most quiet times of the strongest high speed stream years. The quiet time level was more disturbed in 2003 than in other high speed stream years, when an exceptionally clear signal was seen in the polar cap Z intensity even in the annual mean curve in this year. We exclude other current systems like the ring current or the DPY current as possible explanations. **Citation:** Lukianova, R., K. Mursula, and A. Kozlovsky (2012), Response of the polar magnetic field intensity to the exceptionally high solar wind streams in 2003, *Geophys. Res. Lett.*, *39*, L04101, doi:10.1029/2011GL050420.

1. Introduction

[2] Observatory annual means (OAM), defined as the average of all days of a year and all times of a day, are routinely calculated by the geomagnetic observatories all around the world. The OAM mostly reflects the Earth's internal (core and lithospheric) magnetic field. The long term time series of OAM are usually smooth because the main field varies typically on time scales of more than a year, as the response of the so called secular variation of the geomagnetic field. The OAM also contains the external field produced by the electric currents flowing in the magnetosphere-ionosphere (MI) system. On an average more than 95% of the field measured on the ground is of internal origin. However, MI currents can create magnetic disturbances of up to a few percent of the ground magnetic field during magnetic storms [see, e.g., *Yukutake and Cain*, 1987].

[3] In polar regions, the intensity of the vertically oriented internal field (downward at the northern pole and upward at the southern pole) has the largest intensity, of about 60000 nT. The effect upon the Z component due to the space currents is at largest about one permille of the total magnitude. Only electric currents flowing along a circular path around the geomagnetic pole are able to significantly affect the vertically directed magnetic field within the polar cap.

[4] In this paper we discuss a so far ignored effect of space currents upon the OAM at polar latitudes in 2003, when the solar wind (SW) included very intense high speed streams (HSS). We present the observations at polar latitudes in Section 2. Section 3 discusses the corresponding effects at auroral latitudes, and Section 4 relates the observations to the HSS. In Section 5 we discuss the observations and give our final conclusions in Section 6.

2. Observations in the Northern and Southern Polar Caps

[5] Within the polar cap, the Thule (THL) and Resolute Bay (RES) observatories (see Table 1 for station coordinates) have the longest-running geomagnetic field registrations available. Figure 1 shows the OAM for the Z component (OAM-Z) of these observatories since 1958. The long term evolution of OAM is, as general, fairly smooth, depicting a slow increase by roughly one percent from late 1950s to late 1970s and a decline thereafter. However, in 2003 both observatories detect an abrupt strengthening of the vertical geomagnetic field. The change in 2003 is almost 10% of the total secular variation during the time included in Figure 1.

[6] We have also studied the magnetic observations in the southern polar cap. The time span of geomagnetic observations in the Antarctic is generally shorter than in the Arctic. Unfortunately, due to a fire, there is no data from the longest running Antarctic station of Vostok in 2003. However, there is data available from two other Antarctic observatories, Dumont D'Urville (DRV) and Casey (CSY) since 1990s, thus covering the year 2003. Figure 2 depicts the OAMs of the Z component at these two southern stations (located at somewhat lower latitudes than THL and RES at the polar cap boundary), showing a very similar secular decline of the geomagnetic field intensity, by roughly the same rate as observed in the northern stations (see Figure 1) over the same time interval. The steady decline is, however, interrupted in 2003 when both stations depict a clear enhancement of about 20–30 nT, i.e., by an amount which is a significant factor of the secular variation experienced by the two stations during the depicted time interval.

[7] The observations shown in Figures 1 and 2 yield convincing evidence for the global nature of the phenomenon in 2003, and exclude the possibility that the observations in 2003 were due to an erroneous treatment of the baseline or other problems in the data. The latter is a viable concern, e.g., because of the fact that a new magnetometer was installed at THL exactly in 2003. The similarity of observations in the four polar stations also shows that the effect of the phenomenon in 2003 was to strengthen the field at both poles, which

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Table 1. Observatory Coordinates

Name	IAGA Code	Geographic Latitude/Longitude	Geomagnetic Latitude/Longitude
Thule/Qaanaaq	THL	77.48 290.83	88.46 14.10
Resolute Bay	RES	74.70 265.10	83.14 295.98
Dumont D'Urville	DRV	−66.66 140.01	−75.06 232.15
Casey	CSY	−66.28 110.53	−76.28 184.12

is important for the interpretation of the phenomenon to be discussed later.

[8] In order to study if the observed temporal global strengthening of the field in 2003 is due to space currents, we have calculated the OAM-Z for geomagnetically quiet times (using the five international quiet days in each month), thus forming the quiet-day OAM-Z to be called OAM-Zq, and for geomagnetically disturbed times (using the five most disturbed days in each month), forming the OAM-Zd. The annual values of OAM-Zq and OAM-Zd for one northern observatory (THL) and one southern observatory (DRV) are shown in Figure 3 for solar cycle 23. The OAM-Zq and OAM-Zd curves run almost in parallel with an average separation of about 10 nT. At THL the OAM-Zd curve lies above the OAM-Zq curve indicating that during disturbed days the polar field is systematically more intense than in quiet days. The same conclusion is valid for DRV, where the OAM-Zd curve lies below the OAM-Zq curve because the sign of the Z component is reversed.

[9] The most unexpected feature in Figure 3 is that not only the disturbed time field increased in 2003 by about 40 nT, but also the quiet time field was by about 20 nT above the level expected from the smooth secular variation. It is commonly assumed that the quiet time field forms a smoothly evolving background upon which the geomagnetic disturbances are imposed. Moreover, the quiet time field is used to more accurately determine the secular variation due to the evolution of the main field. However, Figure 3 shows that the OAM-Z curves have a fairly similar evolution during the time interval included, and that the field enhancement in 2003 affected both the disturbed time field and the quiet time field, at least when quietness is defined as an average during the internationally quiet days.

3. Observations at Auroral Latitudes

[10] Strong electric currents called auroral electrojets flow in the high-latitude ionosphere, somewhat equatorward of the polar cap. The westward directed electrojet (WEJ) is concentrated in the midnight and morning sectors, while the eastward electrojet maximizes in the afternoon sector. The westward directed electrojet is, on an average, stronger and dominates the daily average disturbance. The effect of the WEJ is to decrease the horizontal component of the magnetic field in the auroral zone. The effect of WEJ upon the Z component depends on the location of the station with respect to the current, being negative equatorward and positive poleward of the WEJ region [*Lyatsky et al.*, 2006]. Accordingly, the WEJ strengthens the Z-directed polar cap field in both hemispheres.

[11] The WEJ is routinely monitored by the auroral AL index [*Davis and Sugiura*, 1966]. In order to study the interannual variability of the WEJ during both quiet and disturbed times, we have calculated the yearly means of the AL index during the five quietest days (thus forming an ALq index) and the five most disturbed days (the ALd index). Figure 4 shows the annual means of the ALq and

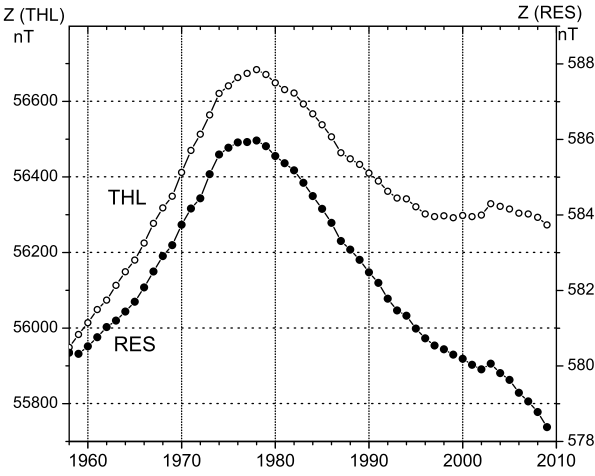

Figure 1. Observatory annual means of the geomagnetic Z component for THL (open circles, left y-axis) and RES (closed circles; right y-axis).

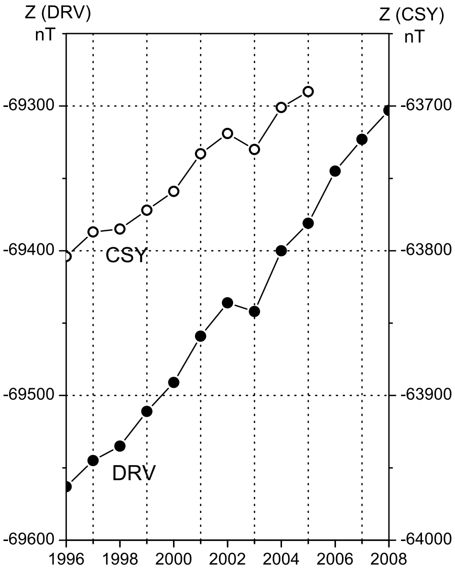

Figure 2. Observatory annual means of the geomagnetic Z component for DRV (open circles, left y-axis) and CSY (closed circles; right y-axis). Note the negative values.

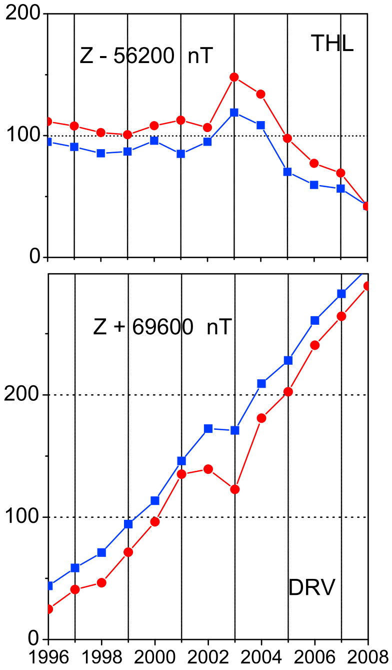

Figure 3. Observatory annual means of the geomagnetic Z component for the five quietest days in each month (blue circles) and for the five most disturbed days (red circles) for (top) THL and (bottom) DRV. We have scaled the y-axis by subtracting 56200 nT from THL values and by adding 69600 nT to DRV values.

ALd indices since the beginning of the AL index in 1966. (There are a few data gaps in Figure 4, since no AL indices are available for some years.) Note that the average level of the ALq (about −40 nT) is significantly above the mean level of ALd (about −300 nT) during this time interval. ALd varies quasi-periodically and depicts the deepest minima during the declining phase of each of the four solar cycles included in Figure 4, in particular in years 1974, 1982/1984, 1991/1994 and 2003. The deepest (most negative) peak in ALd is found in 2003. Note also that the level of ALd is considerably higher since 2007 than in any of the previous years, reflecting the exceptional solar quietness in the last years of SC 23 [*McComas et al.*, 2008; *Smith and Balogh*, 2008].

[12] The solar cycle variation is less clear in ALq which depicts a rather flat overall evolution. However, interestingly, ALq shows minima in the same years as ALd. Even the size of the minima in ALq roughly follows the depth of ALd minima. Both indices depict by far the deepest minimum in 2003, while the minimum in 1982 was the second deepest cycle minimum. ALq in 2003 was about −75 nT, almost twice deeper than its overall average level. ALq also depicts a similar increase during the most recent years as ALd, as a reflection of exceptional solar quietness.

4. Relation to the SW High Speed Streams

[13] In order to discuss the causes and the long-term occurrence of the phenomenon at hand, we have depicted in Figure 5 the differences between the most disturbed ("d") and the quietest ("q") times for AL index (Figure 5a) and for OAM-Z from THL (Figure 5b), RES (Figure 5c), DRV (Figure 5d), and CSY (Figure 5e), together with the yearly averaged solar wind speed (Figure 5f).

[14] For each observatory the "d-q" differences, i.e., OAM-Zd minus OAM-Zq, mostly follow the same solar cycle variation with cycle maxima in the declining phase in the years of high SW speed. This is particularly true for RES, where the cycle maxima are in the years of SW speed maxima for cycles 21–23 (in 1983, 1994, 2003) and in the previous year 1973 for cycle 20. In THL, the cycle maxima are seen in the same years as in RES except for the last cycle where THL sees the maximum in 2001. Only a secondary maximum is seen in THL in 2003 because OAM-Zq was particularly disturbed in 2003 there, as demonstrated by the close proximity of the two THL curves in Figure 3. Similarly, the two Antarctic stations see their minima in 1994 and 2003, in a good agreement with SW speed maxima. This clearly demonstrates the general connection of the "d-q" differences with the occurrence of high solar wind speed intervals.

[15] Note also that peaks of the D-Q differences of station OAM-Z's in Figure 5 depict a considerably more systematic and clear connection to the high speed stream years than the ALd-ALq difference (or the ALd separately, see Figure 4). This is because of the other solar wind drivers like coronal mass ejections (CME) causing strong activity in the AL index (geomagnetic activity in general) especially around solar maxima like in 1991. This difference emphasizes that only the more persistent and repeating activity due to the high speed streams can cause sufficiently systematic semi-circular currents that can eventually lead to observed enhancements in the Z-component at polar latitudes. It is well known that the number of substorms (typically driven by HSS streams) maximized in 2003 [*Tanskanen et al.*, 2011].

[16] One can also see that the cycle maxima of the "d-q" difference in the northern hemisphere are roughly similar in each cycle. This is particularly true for THL while RES depicts a weakly decreasing trend since 1983. In the Antarctic stations the difference is considerably larger in 2003 than in 1994 in both stations. This is also seen in Figure 4 where the OAM-Zq and OAM-Zd curves line up more closely at THL than at DRV where the difference is clearly increased in 2003. This hemispheric difference may be related to the somewhat different latitudinal location of the

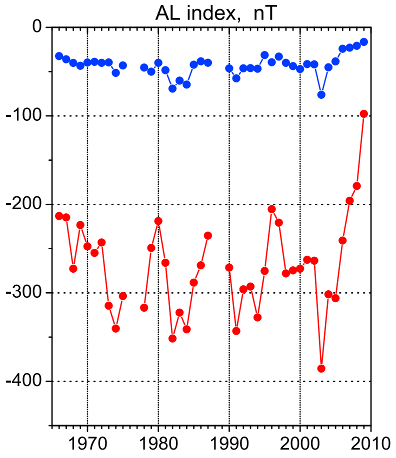

Figure 4. Annual means of the AL index during the five quietest days in each month (blue circles) and during the five most disturbed days (red circles).

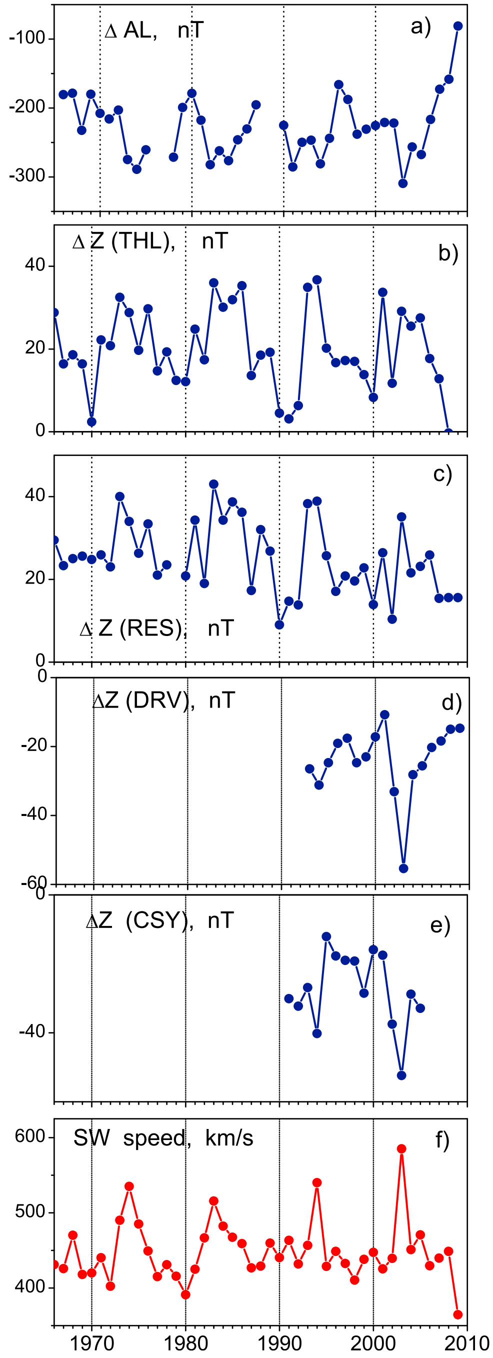

Figure 5. Difference between the most disturbed days and the quietest days for (a) AL index, (b) THL Z component, (c) RES Z component, (d) DRV Z component, (e) CSY Z component, and (f) the solar wind speed. All values are yearly averages.

observatories in the northern and southern hemisphere. As noted above, while THU and RES are clearly within the polar cap, CSY and DRV are at somewhat lower latitudes near the polar cap boundary.

5. Discussion

[17] The declining phase of solar cycle 23 exhibited an all-time record in solar wind speed in 2003, which was significantly larger than the cycle maxima in all previous solar cycles for which direct solar wind observations exist. This extreme HSS event affected the Earth's magnetosphere very strongly, leading to a long-term maximum in geomagnetic activity, auroral electrojet activity, and to a global strengthening of the vertical geomagnetic field in the polar cap. The latter is clearly shown in the annual magnetic field values at a number of polar geomagnetic observatories both in the northern and southern hemisphere.

[18] The difference in the auroral AL index between the most disturbed and quietest times exhibits a solar cycle variation of about 150 nT with minima (most disturbed values) mainly in the declining phase of the solar cycle. Although other drivers like CMEs affect the AL index, the cycle minima of the ALd-ALq difference mostly (but not always) coincide fairly well with the HSS years (and with maximum years of geomagnetic activity [e.g., *Mursula and Martini*, 2007]). The difference between disturbed and quiet times in the polar cap vertical component is typically about 10 nT. However, during the HSS years, the difference is increased to about 35–45 nT in the Arctic, and even up to about 55 nT in the Antarctic.

[19] The quiet time level of annual disturbance in the AL index (ALq, see Figure 4) depicts a minimum in 2003, which is deeper than in any other year since 1966. This shows that the quiet days were indeed more disturbed at auroral latitudes in this year than in all other years. Consequently, the quiet time level of the polar cap Z component was higher than in all other years, contributing significantly to the observed exceptionally high level of the annual mean of this component in the polar cap observatories. This made the Z component in 2003 to deviate so dramatically from the otherwise quite smooth evolution of the OAM secular variation curve.

[20] As noted above, high speed streams cause the most significant variations in the high-latitude magnetosphere and ionosphere (for reviews see, e.g., *Tsurutani et al.* [1995, 2006], *Denton et al.* [2008], and *Lyons et al.* [2009]). The present observations connect the field intensity (actually H component) depletions at auroral latitudes to simultaneous Z field intensity increases at polar cap latitudes. The westward electrojets dominate the auroral currents, forming a semi-circular pattern of westward currents around the polar cap, leading to the observed signal at the different latitudes. Note that not all HSS years, in particular 1994, depict a clear minimum in ALq. The deepest minima are found in cycle 21 and 23, and weaker (or none) in cycle 20 and 22. This suggests that there may also be some dependence on the overall solar polarity, not only on solar wind speed. (This will be studied in detail later.) Also, as already mentioned above, ALd is enhanced in some non-HSS years when the OAM-Z differences are not raised.

[21] During magnetically disturbed times also other current systems are enhanced that, in principle, might contribute to the increase of field intensity at polar latitudes, e.g., the ring current, a westward flowing current system in the equatorial magnetosphere has the correct orientation to enhance the polar cap field. However, we note that the polar cap enhances were always found to occur in HSS years, which cause substorms and weak storms, not in sunspot maximum years when coronal mass ejections cause the most dramatic geomagnetic storms and the largest ring currents, e.g., in 2003 the yearly averaged Dst index describing

the ring current intensity was moderate and not too low to cause the observed enhancement.

[22] Another current system that affects the magnetic field in the polar cap is the dayside high-latitude DPY currents that are dependent on the Y component of the interplanetary magnetic field. However, the ionospheric currents produced by this system flow in opposite directions in the two hemispheres [*Lukianova et al.*, 2010], thus leading to a field depletion in one hemisphere and to a field increase in the other hemisphere, which is against the present observations.

6. Conclusions

[23] The exceptionally high solar wind stream activity in 2003 caused a record intensity in the auroral electrojet currents, leading to a major reduction of the horizontal field at auroral latitudes and to a notable strengthening of the vertical geomagnetic field in the polar caps. This strengthening was so strong that it was clearly visible in the observatory annual values as a significant deflection in the corresponding secular variation. We showed that similar but weaker deflections also occurred during the strongest HSS years of the earlier solar cycles.

[24] We found that the westward electrojet was enhanced even during the quietest times of most of the strongest high speed stream years, not only during the disturbed times. The quiet time level of the westward electrojet was found to be more disturbed in 2003 than in other high speed stream years, thereby leading to the exceptionally clear signal in the polar cap Z intensity even in the annual mean curve. This is important also because the quiet time observatory annual means are used to study the evolution of the internal field. We also noted that other current systems like the ring current or the DPY current cannot explain the observations.

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