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A new reconstruction of the D_{st} index for 1932–2002

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Abstract. We have reconstructed a new, homogeneous geomagnetic D_{st} index for 1932–2002, thus extending the original D_{st} index by 25 years, i.e. by more than one full solar magnetic cycle. The extension was done by using data from the original set of four low-latitude stations for 1941–1956, and by using the nearby CTO station as a predecessor of the HER station for 1932–1940. Despite some open questions related to the composition of the original D_{st} index, the reconstructed index is quite similar to the original one during the overlapping time interval (1957–2002). However, the reconstructed D_{st} index corrects for some known errors in the original D_{st} index, such as the erroneously large daily UT variation in 1971. Also, despite the overall agreement, the reconstructed index deviates from the original index even on the level of annual averages for several years. For instance, all annual averages of the reconstructed index are negative, and for 1962–1966 they are systematically lower (more stormy) than those of the original index. Accordingly, we disagree with the uniquely positive annual average of the original index in 1965, which most likely is erroneous. We also find somewhat higher (less stormy) values than in the original D_{st} index for the three lowest annual averages in 1960, 1989 and 1991, out of which the lowest annual average is found in 1989 rather than in 1991. The annual averages of the geomagnetic A_p index and the reconstructed D_{st} index correlate very well over this time interval, except in the beginning of the series in 1932–1940 and in the declining phase of solar cycles 18, 20 and 21, where high speed solar wind streams cause enhanced geomagnetic activity. Using the superposed epoch method we also find that, on average, the storms in the early extended period (1932–1956) are less intense but tend to have a longer recovery phase, suggesting that there are more HILDCAA-type medium activity intervals during the early period than more recently. We also study the annually averaged storm structure over the 71-year time interval and find that the most stormy years occur during the declining phase of solar cycles 17 and 21 and around the solar maxima of cycles 19 and 22.

Key words. Magnetospheric physics (Magnetospheric configuration and dynamics; Current systems; Storms and substorms)

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1 Introduction

The D_{st} index is traditionally calculated from the observations at the four low-latitude magnetic field stations of Hermanus (HER), Honolulu (HON), Kakioka (KAK) and San Juan (SJG). (For the coordinates and data coverages of the magnetic stations used here, see Table 1). Although the magnetic observations already started earlier at these stations the D_{st} index has been calculated only since the International Geophysical Year in 1957.

At low latitudes the horizontal H component of magnetic perturbation is mostly affected by the intensity of the equatorial ring current. Accordingly, the D_{st} index is calculated from the (normalized) values of this component. Major disturbances in the D_{st} index during geomagnetic storms are negative due to an increasing number of energetic particles carrying the ring current. Large amounts of energy are fed into the inner magnetosphere, for example, in the form of energetic particles, during long periods of southward directed interplanetary magnetic field (IMF). Once the IMF turns northward the ring current begins to decrease and the D_{st} index soon begins a slow rise back to its quiet time level. Positive variations in the D_{st} index are mostly caused by magnetospheric compressions due to interplanetary shocks often occurring in the initial phase of magnetic storms. In this phase, an abrupt increase in solar wind dynamic pressure is often measured on the Earth's surface as a sudden increase in magnetic intensity called the sudden storm commencement (SSC).

Note that rather than a homogeneous ring, the ring current is quite asymmetric and often consists of a number of longitudinally limited sections (Lui et al., 1987). Also, it has been known already for quite a long time that other current systems contribute to the magnetic variations even at low latitudes and thereby also to the D_{st} index. This is simply demonstrated by a recent result (Campbell, 2004) that the storm time disturbance at one longitude usually decreases rather than increases with latitude. In particular, the dayside magnetopause current, which depends on solar wind pressure, causes a contribution that is often subtracted from the D_{st} index when estimating the intensity of the ring current (see, e.g. Burton et al., 1975; O'Brien and McPherron, 2000). Also, contributions to the D_{st} index by the tail current and the field-aligned currents (Burton et al., 1975; Alexeev et al., 1996; Campbell, 1996; Turner et al., 2000) and

Table 1. Geographical and geomagnetic coordinates, according to IGRF 2000 model (IGRF, 2000) and data coverages of the D_{st} magnetic stations.

Station, IAGA Code	Geographic Lat.	Geographic Long.	Geomagnetic Lat.	Geomagnetic Long.	Data Availability
Cape Town, CTO	−34.57°	18.28°	−33.89°	82.73°	1932–1940
Hermanus, HER	−34.42°	19.23°	−33.91°	83.69°	1941–2002
Honolulu, HON	21.32°	202.00°	21.60°	269.45°	1902–2002
Kakioka, KAK	36.23°	140.18°	27.17°	208.50°	1913–2002
San Juan, SJG	18.12°	293.15°	28.53°	5.87°	1926–2002

currents induced in the ground (Häkkinen et al., 2002) have been identified. Note also that the zero level of the D_{st} index is not the physical zero level of the intensity of the ring current (Mayaud, 1978). Therefore, although the ring current is among the dominant contributions to the D_{st} index, the exact dependence between the D_{st} index and the various magnetospheric current systems is quite complicated and will not be studied in this paper. However, this complicated interpretation does not decrease the value of the D_{st} index as an important measure of the global state of the magnetosphere and, in particular, of the development of magnetic storms. Moreover, the role of the D_{st} index as a long-term (solar cycle and inter-decennial) monitor of the magnetosphere is receiving increasing interest.

In this paper we will reconstruct the D_{st} index following the original formula (see, e.g. Sugiura, 1964, 1969; Sugiura and Kamei, 1991; WDC-C2, 2004) as closely as possible (see also Häkkinen et al., 2003). Using the reconstructed D_{st} index we find and correct some obvious errors and suspectable features in the original D_{st} index. Moreover, using the early data of the original D_{st} stations, supplemented by the near-by Cape Town station, we will extend the D_{st} index by 25 years, i.e. by more than one full solar magnetic cycle, to start already in 1932. Thereby, a fully reproducible and more homogeneous D_{st} index is obtained for a considerably longer time interval than presently available. This prolonged D_{st} index will, for example, contribute to studies related to the suggested centennial increase in solar magnetic activity (Clilverd et al., 1998; Lockwood et al., 1999).

This paper is organized as follows. The next section discusses the availability of related magnetic observations, changes in the magnetic baseline, outliers and data gaps. Section 3 reviews the procedure of calculating the D_{st} index. In Sect. 4 we compare the original and the newly-reconstructed D_{st} indices in 1957–2002 and note some problems in the original D_{st} index. In Sect. 5 we present and discuss the results obtained by extending the D_{st} index with the early part (1932–1956). There we first study the statistical properties of the D_{st} index in the early part and compare them with those in the later part. Then we discuss the properties of the new, longer D_{st} index and compare them with those of the long-term magnetic activity index A_p. Also, we make a superposed epoch analysis of magnetic storms. Section 6 presents our final conclusions.

2 Data quality and availability

As seen in Table 1 all four original D_{st} index stations (HER, HON, KAK, SJG) started operating already long before the international geophysical year (IGY) 1957 when the calculation of the original D_{st} index began (Sugiura and Kamei, 1991; WDC-C2, 2004). Accordingly, we have reconstructed the new D_{st} index using data from these four stations since the start of the HER station in 1941 until the end of 2002. Moreover, since HER was preceded by the nearby Cape Town (CTO) station we have calculated the new D_{st} index from 1932 onwards, using the observations at CTO for 1932–1940 as a substitute for HER. (The exact starting time is 3 August 1932, at 00:00 UT). Taken into account the close proximity of HER and CTO the reconstructed D_{st} series will be quite homogeneous over the whole 71-year time interval. Also, the effects related to the imperfect hemispherical and longitudinal coverage of the D_{st} stations (like the UT variation, see Takalo and Mursula, 2001a,b) will remain closely similar. Unfortunately, no intercalibration between HER and CTO could be made because no simultaneous observations were available.

2.1 Baseline steps

As to data quality, we would like to note that there are some shifts in the baseline level of the H component at HON and SJG. These shifts may be, for example due to an erroneous documentation of the baseline in the original annals of the station. Figure 1 depicts the raw data of the HON station which includes two steps in the baseline, the first on 1 April 1947 at 21:00 UT and the latter on 1 May 1960 at 11:00 UT (see Fig. 1). At SJG, there was one such step on 1 January 1966 at 00:00 UT. Also, a small step was induced and corrected when joining CTO and HER data. We have treated the data around these steps as follows. The data after the step were raised or lowered so as to smoothly join the level before the step. We would like to note that the steps cannot be removed by eliminating the secular variation (see later). However, once the steps are removed and the data are smooth, the absolute level (baseline) of data is not important and will be removed when removing the secular variation.

2.2 Outliers

There are also some clearly erroneous data points at some stations which are seen as outliers and which have been removed from data. The outliers were found as follows. We have first constructed a new data set by filtering the original data by a three-point median filter which replaces each point by the median of the point itself and the two surrounding data points, thus removing all single outliers. Then the filtered data set was subtracted from the original data set. The standard deviation of this difference data set is on the order of magnitude of the average absolute difference between two successive (normal) data points. Finally, we have examined as possible outliers all those data points where the difference

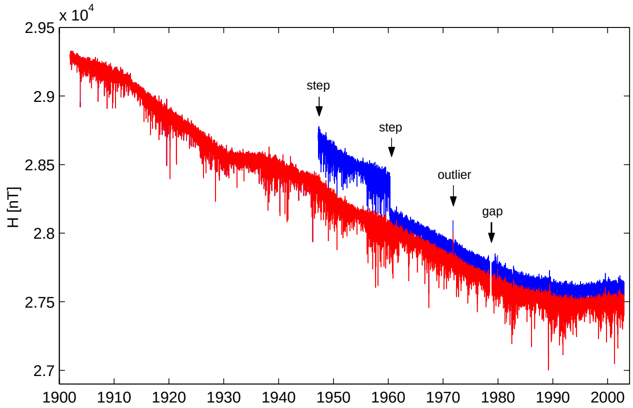

Fig. 1. The H component at HON before (blue) and after (red) removing the two steps at 1 April 1947 and 1 May 1960. One outlying data point during 1971 was removed from the data. The gap during 1978 was filled.

is more than 20–40 times the standard deviation (about to 100–200 nT). Based on this analysis we found seven outlying data points in SJG data (27 October 1932 at 15:00, 12 March 1933 at 16:00, 3 April 1933 at 08:00, 7 April 1933 at 14:00, 20 January 1947 at 11:00, 4 June 1952 at 18:00, and 21 March 1979 at 11:00), and only one outlier in HON data (18 October 1971 at 17:00; see Fig. 1). The CTO, HER and KAK stations had no outliers in their data.

2.3 Data gaps

There are some data gaps at all five stations. The overall data coverages at the five stations during the respective observation times during 1932–2002 were the following: CTO 99.743%, HER 99.988%, HON 97.497%, KAK 99.755%, and SJG 97.850%. Fortunately, most data gaps are relatively short, only a few hours long. In fact, the number of data gaps rapidly decreases with length, and only relatively few data gaps were longer than three days. We have listed the dates of these "long" data gaps in Table 2. Note that there were no such long data gaps in HER or CTO, only one in KAK (corresponding only to 0.028% of observation time), 23 in SJG (1.469% of observation time) and 26 in HON (1.697% of observation time). There were only 3 data gaps longer than one month in SJG and HON, the longest of about 5 months in HON in 1978 (see Fig. 1).

We have treated the data gaps in the following way. Firstly, data gaps that were at most 6 h long were simply filled by interpolating the original H component linearly. After this treatment of the raw data we computed $D(t)$, the disturbance variation, for each station (see Sect. 3 for more details) and interpolated the data gaps that were at most 3 days long in $D(t)$ data for each station. This two-step procedure was found appropriate and necessary because of the following reasons. Short data gaps of at most six hours can be interpolated without distorting the diurnal variation too severely. However, longer data gaps cannot be treated similarly since they would induce a large error in the diurnal curve (see Sect. 3). Accordingly, the longer data gap can be filled only after the diurnal variation has been removed and the $D(t)$ series has been calculated for the station in question. Three days is an appropriate length to interpolate since the D_{st} index depicts strong autocorrelation up to a lag of about a week, corresponding to the typical development of a storm. The net effect of these short data gaps (at most 3 days) is that some 1.367% out of the hourly D_{st} indices in the early period (1932–1956) and 1.789% in the later period (1957–2002) were reconstructed based on such partly missing, linearly interpolated data.

Table 2. Data gaps longer than 3 days for HON, SJG and KAK. All gaps in HER and CTO were shorter than 3 days. Dates are in universal time (UT).

Long data gaps	
Honolulu	San Juan
26 May 1934 00:00–01 Jun 1934 10:00	01 Nov 1934 04:00–30 Nov 1934 23:00
08 Feb 1939 22:00–03 Mar 1939 02:00	17 Jul 1941 13:00–13 Aug 1941 20:00
11 Mar 1944 23:00–06 Apr 1944 02:00	01 Aug 1949 00:00–01 Sep 1998 03:00
12 Mar 1947 18:00–01 Apr 1947 20:00	01 Jan 1977 00:00–09 Jan 1977 23:00
01 Oct 1954 11:00–09 Nov 1954 19:00	01 Jan 1983 00:00–21 Jan 1983 19:00
02 Apr 1968 18:00–05 Apr 1968 18:00	02 Mar 1983 11:00–25 May 1983 14:00
01 Jul 1978 00:00–01 Dec 1978 01:00	08 Nov 1983 18:00–27 Dec 1983 15:00
23 Jun 1979 00:00–30 Jun 1979 23:00	13 Oct 1984 00:00–16 Oct 1984 03:00
03 Aug 1984 03:00–06 Aug 1984 17:00	08 Jan 1985 19:00–16 Jan 1985 13:00
12 Oct 1984 23:00–17 Oct 1984 19:00	13 Sep 1985 18:00–17 Sep 1985 07:00
31 Dec 1984 00:00–15 Feb 1985 17:00	23 Sep 1985 15:00–03 Oct 1985 15:00
06 May 1985 19:00–16 May 1985 18:00	20 Dec 1985 20:00–18 Jan 1986 22:00
22 Aug 1985 12:00–02 Sep 1985 06:00	01 Jun 1987 06:00–06 Jun 1987 00:00
28 Mar 1986 09:00–31 Mar 1986 17:00	28 Aug 1987 13:00–01 Sep 1987 18:00
08 Jun 1986 19:00–12 Jun 1986 22:00	05 Feb 1988 15:00–16 Feb 1988 14:00
20 Jun 1986 14:00–26 Jun 1986 20:00	01 Jul 1988 00:00–12 Jul 1988 19:00
14 Jul 1986 18:00–30 Jul 1986 23:00	16 Sep 1989 00:00–20 Sep 1989 21:00
31 Jul 1986 18:00–05 Aug 1986 20:00	08 Nov 1989 17:00–13 Nov 1989 17:00
04 Sep 1987 03:00–08 Sep 1987 18:00	18 May 1990 12:00–22 May 1990 18:00
11 Sep 1988 02:00–21 Sep 1988 23:00	06 Jul 1990 13:00–13 Jul 1990 12:00
26 Sep 1988 18:00–01 Oct 1988 09:00	01 Nov 1990 11:00–06 Nov 1990 14:00
10 Feb 1989 20:00–14 Feb 1989 23:00	01 Jan 1992 13:00–11 Jan 1992 12:00
16 Dec 1990 19:00–24 Dec 1990 15:00	11 Dec 2000 11:00–15 Dec 2000 20:00
01 Mar 1992 00:00–04 Mar 1992 21:00	Kakioka
19 Nov 1997 22:00–24 Nov 1997 17:00	
11 Dec 1998 01:00–17 Dec 1998 19:00	27 May 1948 00:00– 3 Jun 1948 02:00

For the long data gaps (Table 2) we have not used interpolation nor filled the gaps with data from other stations. Rather, during the long gaps we have calculated the D_{st} index using only data from those original D_{st} stations which were in operation. Note that this differs from the policy of the original D_{st} index where data from stations other than the original D_{st} stations have been used. As mentioned by Mayaud (1980), gaps did exist in the data that were used to construct the original D_{st} index. Thus, the original D_{st} index includes data from one or more stations beyond the four original D_{st} stations. However, there is no explicit mention of data gaps in the original D_{st} formula, nor how such data gaps were filled, nor which stations were used. Therefore, the original D_{st} index is not fully reproducible and, in this sense, not a truly scientific quantity.

Naturally, our different data gap policy leads to a larger difference between the original D_{st} index and the reconstructed D_{st} index during the long data gaps than on average. Also, the smaller set of stations leads, for example to a slightly different UT variation in the D_{st} index during the long gaps. However, similar changes also occur in the original D_{st} index where the data gaps have been filled with other stations. Our data gap procedure is only more straightforward and fully reproducible. Moreover, if needed for a detailed analysis of some gap interval, a more detailed D_{st} index can be reconstructed using data from a larger number of stations, yielding a more reliable longitudinal and hemispheric coverage. (For example, Häkkinen et al. (2003) have suggested using 6 stations to calculate a more symmetric D_{st} index called D_{st6}).

Fortunately, there were very few simultaneous long data gaps. In fact, there were only two data gaps that occurred simultaneously in HON and SJG and were 3–4 days (13 October 1984 00:00–16 October 1984 03:00) and 7–8 days (8 January 1985 19:00–16 January 1985 13:00) long. At these times the D_{st} index was reconstructed based only on HER and KAK data. Otherwise, for a very large fraction of long data daps, data from three stations were available.

3 D_{st} derivation

In the derivation of the D_{st} index we have followed, as far as possible, the original formula (Sugiura, 1964; Sugiura and Hendrics, 1967; Sugiura, 1969; Sugiura and Kamei, 1991) (see also the D_{st} index homepage of WDC-C2, 2004). Hourly values of the H component of the magnetic stations were obtained from WDC-C1 (2004) at Copenhagen, WDC-C2 (2004) at Kyoto and SPIDR (2004) at Boulder. The formula can be divided into three parts as follows.

3.1 Removing the secular variation

For each observatory, annual mean values of H were calculated for the five internationally selected quietest days of each month (for a list of these days, see, e.g. WDC-C1 (2004) web page). For the first five years, 1932–1936, a second order polynomial was fitted to these annual averages in order to find a baseline or the secular variation for these years. This polynomial was then extended until the end of 1936 in order to find the baseline at the end of that year. When calculating the baseline for 1937, the point at the end of 1936 was used as an additional data point in the polynomial fitting, together with the annual averages in 1933–1937. This procedure for calculating the polynomial baseline was then repeated analogously for all later years using the corresponding six data points (the annual averages of the year in question and the four previous years, and the additional data point at the end of the previous year from the previous fit).

Finally, in order to remove the secular variation, the baseline value calculated for each hour using the polynome of the respective year was subtracted from all hourly H values. These differences then form the deviations ΔH. We would like to note that the formula to calculate the D_{st} index (see, e.g. the D_{st} web page of WDC-C2 (2004)) is unambiguous on this point of removing the secular variation.

3.2 Treatment of the S_q variation

The daily solar quiet (S_q) variation was treated in the following way. First, the average 24-hour local time (LT) variation (superposed daily variation) was calculated from the ΔH values of the five quietest days of each month. A linear change from one superposed day (or rather night) to another was calculated using the nightside activity levels, and then subtracted from the 24 hourly values. Accordingly, 24 rescaled hourly values were obtained for each month. These 288 (12×24) values for each year form a 2-dimensional matrix which is called here S_q^o. The midnight activity levels were calculated here using the last and first hourly values around the local midnights, in order to have a symmetric treatment for the two nights. This choice also yielded a slightly better correlation with the original D_{st} index, although the original formula, as we understand it, uses only one hour from each midnight (one hour before the first midnight, and one hour after the second midnight). This is one point where the formula is slightly ambiguous.

Second, the S_q^o matrix for each year was replaced by the following 2-dimensional inverse Fourier series approximation:

$$S_q^L(s,t) = \sum_{m=0}^{N_1-6} \sum_{n=0}^{N_2-18} A(m,n) e^{i2\pi \frac{sm}{N_1}} e^{i2\pi \frac{tn}{N_2}}, \tag{1}$$

where s (actually $s+1$) and t describe the month and hour, respectively, and N_1=12 and N_2=24. Only the DC component and the first six Fourier components were included in Eq. (1), in agreement with the original formula. The Fourier amplitudes $A(m,n)$ were calculated from the S_q^o values as follows:

$$A(m,n) = \sum_{s=0}^{N_1-1} \sum_{t=0}^{N_2-1} S_q^o(s,t) e^{-i2\pi \frac{sm}{N_1}} e^{-i2\pi \frac{tn}{N_2}}. \tag{2}$$

This expression involves the same number (48) of Fourier coefficients as the original formula, although a slightly different form of the inverse Fourier transformation 1 is given there. We calculate the Fourier transform and its inverse using the FFT code adopted within the MATLAB program package (MATLAB, 2001). We are not aware of how this numerical exercise was conducted for the original D_{st} index.

3.3 Hourly D_{st} index

The above derived S_q^L values give the final quiet-time S_q variation for each year, which is then subtracted from the hourly ΔH values to yield the disturbance variations $D(t)$ for each observatory. Finally, the disturbance variations in universal time (UT) from the four stations were normalized by their respective cosines of geomagnetic (dipole) latitudes and then averaged. Note that the dipole latitude is not a constant but rather changes in time. Therefore, we have calculated the dipole latitudes for each hour using the IGRF models (IGRF, 2000) determined for every fifth year. For the intermediate time, the Gaussian coefficients (for more details, see IGRF,

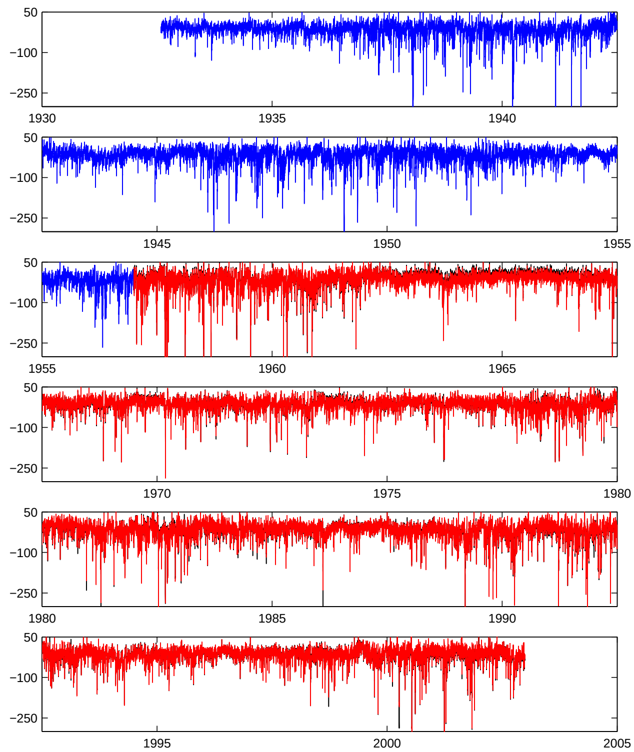

Fig. 2. The reconstructed D_{st} in 1932–1956 (blue) and in 1957–2002 (red). The original D_{st} in 1957–2002 (black) is depicted under the reconstructed D_{st}.

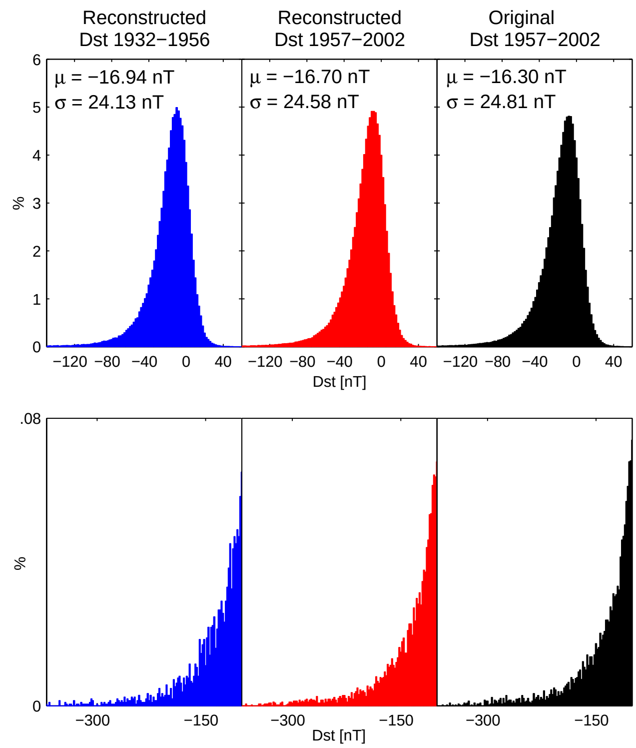

Fig. 3. Histograms of the reconstructed D_{st} in 1932–1956 (blue), in 1957–2002 (red) and of the original D_{st} 1957–2002 (black). Top panel depicts the values for D_{st} >–150 nT, bottom panel for D_{st} <–100 nT. Only gapless data were included.

2000) were interpolated (after 2000 extrapolated) and the dipole latitude was calculated for each station. Note also that, according to the original formula (e.g. Sugiura and Kamei, 1991), the disturbance variations should first be averaged and then normalized by the average cosine of the dipole latitudes. However, similarly to some other authors reconstructing the D_{st} index (e.g. Häkkinen et al., 2003) we find little motivation for the original formula on this point. Moreover, we also obtain a slightly better correlation with the original D_{st} using the chosen method rather than the formula, suggesting that there may be a lapse in the formula on this point. However, as already noted by Häkkinen et al. (2003), the difference between the two methods is rather small.

4 Original and reconstructed D_{st} indices in 1957–2002

Figure 2 depicts the original D_{st} index for 1957–2002 and the reconstructed index for 1932–2002, with the early part (1932–1956) and the later part (1957–2002) denoted in different colors. The mean and the standard deviation of the original D_{st} are μ=−16.48 nT and σ=25.06 nT while those for the full reconstructed D_{st} index in 1957–2002 are closely similar: μ=−16.79 nT and σ=24.81 nT. The correlation between the original and the reconstructed D_{st} indices over the whole time interval of 1957–2002 is 98.68%. Moreover, the average absolute difference between the two series during this time is only 3.09 nT. Comparing this with the average absolute value of the original D_{st} index of 19.99 nT, one can say that we have reconstructed the hourly D_{st} index with an overall accuracy of about 15.48%. The agreement is so good that the original D_{st} index is only seldom distinguishable in Fig. 2 from the reconstructed D_{st} index. The largest difference comes most likely from the subtraction of the secular variation from the data of the individual D_{st} stations (Häkkinen et al., 2003).

In fact, the reconstruction is even better than suggested by the above numbers. Since, as described above, the treatment of data gaps in the original formula is unknown, the original and reconstructed D_{st} indices will be different for these times. Accordingly, if we neglect all hours with no data in any of the stations (including short and long data gaps), the correlation between the two D_{st} indices increases to 98.75% and the average absolute difference between the two series decreases to 3.03 nT. This set of common measurements covers 94.326% of the time interval 1957–2002. The corresponding D_{st} indices are called here the gapless D_{st} values. However, we would like to note that the data gap policy even affects these values since there are gaps also during the five quietest days of some months, and the S_q variation and, thus, the disturbances $D(t)$ depend on how the data gaps are treated. Therefore, without knowing the data gap policy, one cannot completely reconstruct the D_{st} index. This problem is one of the main features contributing to the

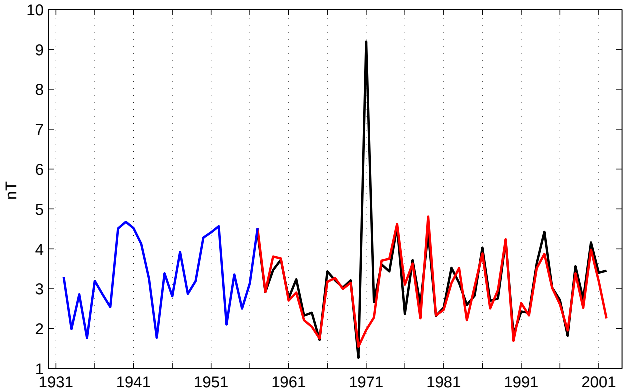

Fig. 4. Annual average range of the diurnal UT variation in the reconstructed D_{st} in 1932–1956 (blue), in 1957–2002 (red) and in the original D_{st} in 1957–2002 (black). All hourly values were included.

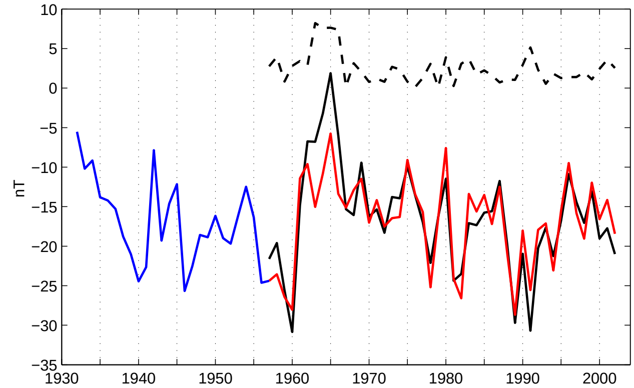

Fig. 5. Annual average value of the reconstructed D_{st} in 1932–1956 (blue), in 1957–2002 (red) and of the original D_{st} in 1957–2002 (black). The absolute difference between the original and reconstructed D_{st} in 1957–2002 is depicted as a dashed line. All hourly values were included.

remaining difference between the original and reconstructed D_{st} indices, especially during the "gapless" time intervals.

Nevertheless, the agreement between the original and reconstructed D_{st} indices is better during the gapless intervals than during gaps. The correlation between the two indices during the short data gaps is 98.22% and 97.89% during the long data gaps. The average absolute differences for the two cases are about 4.52 nT and 4.07 nT. (The fact that the latter is slightly smaller may result from the fact that there are relatively more simultaneous short data gaps in two or more D_{st} stations than simultaneous "long" data gaps mentioned above.) Taking into account the total amounts of the short and long data gaps in 1957–2002, their contributions to the average absolute difference between the original and reconstructed D_{st} indices are about 2.62% and 4.71%, respectively.

We have further compared the original and the reconstructed D_{st} indices during the gapless intervals. The mean and the standard deviation of the original D_{st} for these times are $\mu=-16.30$ nT and $\sigma=24.81$ nT while those for the reconstructed D_{st} are closely similar: $\mu=-16.70$ nT and $\sigma=24.58$ nT. Figure 3 depicts the histogram distributions of these indices separately for two ranges: the bulk of the values for $D_{st}>-150$ nT and the long tail of $D_{st}<-100$ nT. The close similarity of these figures further verifies that the agreement between the original and reconstructed D_{st} indices is very good during gapless time intervals.

4.1 Problems in the original D_{st} index

The D_{st} index is known to depict a small but persistent diurnal UT variation (Mayaud, 1978; Saroso et al., 1993; Siscoe and Crooker, 1996; Cliver et al., 2000) which mainly results from the asymmetric distribution of the D_{st} stations (Takalo and Mursula, 2001a). Figure 4 shows the annual averages of the diurnal UT variation in the original and reconstructed indices using all hourly values. Note first how similar the overall level and the temporal fluctuations in the two indices are for most years. However, the original D_{st} index exhibits an exceptionally large UT variation in 1971 (Takalo and Mursula, 2001a,b). It was noted earlier (Karinen et al., 2001) that an UT variation closely similar to that in 1971 can be reproduced if the S_q variation was erroneously treated in SJG when deriving the original D_{st} index. Since the reconstructed D_{st} index depicts a roughly similar average in 1971 as in all other years, it is highly probable that the derivation of the original D_{st} index for 1971 was indeed erroneous. This is also reflected in the fact that the correlation between the original and reconstructed indices is only 97.97% in 1971, i.e. weaker than on average. Note also that the data gaps in 1971 were not abnormally large and that the annual average of the UT variation in the original index remains the same, exceptionally high level, even if one uses only gapless days. Thus, the problem is not related to the treatment of data gaps. Concluding, the original D_{st} index in 1971 is erroneous and can be corrected by the newly reconstructed D_{st} index.

Figure 5 shows the annual averages of the original and the reconstructed D_{st} indices using all hourly values. Also, the absolute difference between the original and reconstructed D_{st} in 1957–2002 is depicted. For most years, this difference is typically about 2–3 nT, i.e. on the same order of magnitude as the average absolute difference between hourly values that was discussed earlier. However, there are a few years where the difference is enhanced. In particular, in 1963–1966, this difference is nearly three times larger than the average difference, with the original D_{st} index being larger (less negative) than the reconstructed index. Among these years the year 1965 is very special since it is the only year for which the annual average of the original D_{st} index is positive, far above the annual average of any other year. Not questioning this result, the traditional view has been to accept the year 1965 as having been exceptionally quiet in the D_{st} index. According to the reconstructed D_{st} index, the annual average in 1965, although still attaining the highest value, is negative as in all other years and reaches roughly the same level as some other quiet years. Thus, the extremely special nature of the year 1965 in the original D_{st} index is most likely an artefact. Note also that the two years (1960, 1991) with the lowest annual values in the original D_{st} index tend to be raised slightly higher, thus, to a more regular level in the reconstructed index.

We have also calculated the annual averages for both the original and the reconstructed D_{st} index using only gapless data. For most years the values are roughly the same as in Fig. 5 and the difference remains enhanced for the same years. Thus the problem in the original D_{st} index with the year 1965 is not related to data gaps.

5 The early D_{st} index in 1932–1956

5.1 Statistical properties and comparison with later period

The full reconstruction of the D_{st} index for the early period 1932–1956 is depicted in Fig. 2. The mean and the standard deviation of the reconstructed D_{st} index for this period are $\mu=-17.03$ nT and $\sigma=24.41$ nT, using all data. These are quite similar to the corresponding values ($\mu=-16.79$ nT and $\sigma=24.81$ nT) for the later time interval 1957–2002. Using only gapless data in 1932–1956 (which form about 96.158% of time) the values are $\mu=-16.94$ nT and $\sigma=24.13$ nT, i.e. almost exactly the same as those for the reconstructed D_{st} in 1957–2002 ($\mu=-16.70$ nT and $\sigma=25.58$ nT; see Fig. 3). On the other hand, if only the values during the gaps are taken into account, we find $\mu=-19.48$ nT and $\sigma=30.84$ nT for the early period and $\mu=-18.36$ nT and $\sigma=28.41$ nT for the later period.

Figure 3 depicts the histogram distribution also for the reconstructed D_{st} in 1932–1956, using gapless data. The histograms for the early D_{st} index and the two other D_{st} indices are very similar, although the former depicts a slightly less regular pattern, especially around -150 nT, probably due to smaller statistics. The close similarity of these figures further verifies that the agreement between the original and reconstructed D_{st} indices is very good, especially during gapless time intervals.

The annually averaged range of the diurnal UT variation (see Fig. 4) remains roughly at the same level in the early period as later. This is true although Fig. 4 includes all hourly values, and despite the fact that a new station (CTO) with a slightly different longitude was used in 1932–1940. Note also that no year in the early period depicts a similar, exceptionally large UT variation as in 1971. This further underlines the above discussed erroneous nature of the D_{st} index in 1971.

5.2 Long-term evolution of the D_{st} index

The long-term evolution of the D_{st} index depicted in Fig. 5 includes interesting details that greatly motivate the extension of the series to earlier times. Note first that the original D_{st} index depicts dramatic fluctuations during its first years from very low values in late 1950s and early 1960s to exceptionally high values in mid-1960s. Also, because of the particular construction method of the D_{st} index (viz., the way in which secular variation is removed) the low values of the D_{st} index during the first 4–5 years of the time series, in particular the minimum of the original D_{st} index in 1960 (the fourth year of the original D_{st} index) and the implied extremely disturbed time period, may be doubted.

However, our continuation of the D_{st} index to earlier years removes this doubt and, as depicted in Fig. 5, verifies that 1960 was among the most disturbed years in the D_{st} index during the whole 71-year period. Note also that according to the newly reconstructed D_{st} index the most disturbed year during the last 20 years was not 1991, as in the original D_{st} index, but rather 1989. Furthermore, although the high annual averages in the original D_{st} index in the mid-1960s are, as discussed above, erroneous and overestimated, they still remain above the long-term D_{st} average.

When moving further back in time with the new D_{st} index, we find (see Fig. 5) that the annually averaged D_{st} indices in the early period 1932–1956 are roughly in the same level as in the later period. For instance, there are no years in the early period where the annual D_{st} index is positive or even very close to zero. (This also suggests that the positive value in 1965 in the original D_{st} index was erroneous.) Curiously, the highest values in the early part and the later part are roughly equal (about -6 nT) in the reconstructed index.

The following long-term evolution in the D_{st} index can be noted over the 71-year time interval (Fig. 5; see also Fig. 7). First, the D_{st} index decreases with the increase of solar activity related to the start of the solar cycle 17. With the increasing height of the subsequent solar cycles the D_{st} values decrease fairly systematically during the two next solar maxima and the D_{st} index reaches a local minimum of -28.1 nT in 1960. Soon thereafter the D_{st} index raises rapidly to its absolute maximum -6 nT during the subsequent solar minimum in 1965. Thereafter, during solar cycles 20–22, the D_{st} indices at solar maxima decrease again slowly but systematically, reaching the overall minimum of -28.6 nT in 1989, close to the maximum of solar cycle 22. However, the D_{st} indices at solar minima show no clear trend but remain roughly at the same level during the last three minima.

5.3 Comparison with A_p index

The so-called K-related indices (Mayaud, 1980) form a uniform series of geomagnetic activity. The K-related indices have been calculated since 1932 and thus can be used to study the long-term evolution of geomagnetic activity over the same time interval as covered by the new reconstructed D_{st} index. Figure 6 correlates the annual averages of the quasi-linear A_p index with the absolute values of the simultaneous reconstructed D_{st} indices, separately for the early and later periods. (Only gapless data were used to calculate the annual averages of the D_{st} index. A similar procedure could not be followed for A_p because it is a daily index.) As seen in Fig. 6 the correlation between the two indices is

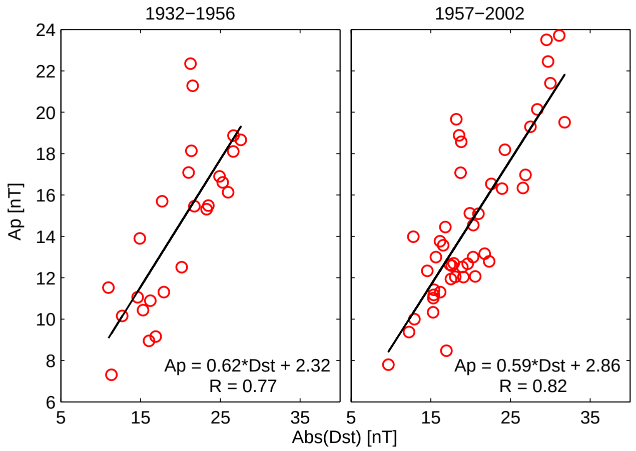

Fig. 6. Scatterplot of annually averaged A_p indices vs. annually averaged absolute values of the reconstructed D_{st}. Left: 1932–1956, right: 1957–2002. Best fitting lines are also given in the figure.

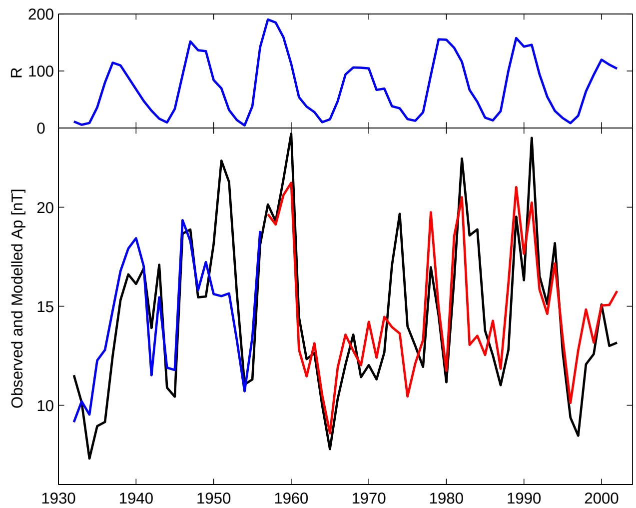

Fig. 7. Top: annual sunspot numbers. Bottom: annually averaged A_p indices (black) and A_p calculated from the best fitting correlation with the reconstructed D_{st} index in 1932–1956 (blue) and in 1957–2002 (red).

strong and fairly similar for both time intervals. The correlation coefficients are R=0.77 in 1932–1956 and R=0.82 in 1957–2002. (The corresponding correlation coefficients using daily averages are R=0.78 for both periods.)

The similarity of correlations in the two periods gives further evidence for the correctness of our construction of the D_{st} index and especially its extension into the early period. Note also that the correlation coefficient between the annually averaged A_p and the original D_{st} indices is smaller (R=0.80) than for the reconstructed index in 1957–2002 using gapless data.

We have used the best fitting linear correlation equations included in Fig. 6 in order to model the A_p index using the the reconstructed D_{st} index. This "model" A_p index and the observed A_p index are shown in Fig. 7. The annual sunspot numbers are included in Fig. 7 for comparison. Figure 7 shows that there is a good overall agreement between the observed A_p index and the modelled A_p index, i.e. the reconstructed D_{st} index. Large differences are found during the declining phase of solar cycles (in particular in 1951–1952, 1973–1974, 1983) when recurrent high-speed streams occur in the solar wind. Such streams typically cause rather weak magnetic storms and other types of geomagnetic activity (e.g. substorms) that are more restricted to higher latitudes and do not affect very strongly at the low-latitude D_{st} index stations. On the other hand, large storms mainly occur around solar maxima. Since a similar difference between the the observed and modelled A_p index is found both in the early period (1951–1952), as well as in the later period (1973–1974, 1983), we find that the conditions of the solar wind causing geomagnetic activity, on the one hand, and large magnetic storms, on the other have, remained quite similar over the studied 71-year time interval. We would also like to note that, in agreement with the modern view of the solar cycle, the difference between the observed and modelled A_p index (a proxy of the strength of high speed streams) seems to be a good predictor of the height of the coming solar cycle.

Note that the two A_p curves in Fig. 7 depict a fairly similar long-term evolution during the 71-year interval. The observed A_p index includes all of the above-mentioned properties of the long-term D_{st} activity: systematic increase from 1930s to a maximum in 1960; rapid decrease to a minimum in 1965; increase of activity during subsequent cycle maxima and rough levelling off during minima. However, the overall range of observed A_p values is somewhat larger than the range of modelled A_p values. The largest A_p values are above the corresponding model values and the smallest A_p values are below the model values. This is also seen in Fig. 6 where the points with the largest (smallest) A_p values are well above (below) the best fitting line. Accordingly, the long-term fluctuations are slightly (relatively) larger in the A_p index than in the D_{st} index.

Note also that the observed A_p index is systematically lower (see Fig. 7) than the modelled A_p index in the beginning of the early period (1933–1940; ascending phase and maximum of SC 17). Also, the absolute minimum in the observed A_p index is already reached in 1933. We are confident that this difference lasting 8 years is not technical, i.e. due to the method of reconstructing the D_{st} index or due to the above-mentioned question related to the first four years, and hardly due to statistical fluctuation. Rather, it may indicate a problem in the A_p index (K-indices more generally) or an interesting deviation in the physical relations between the two indices at this time. Taking into account that the increase of geomagnetic activity in 1930s is part of a longer increase present in the *aa* index since the beginning of the century (see, e.g. Clilverd et al., 1998; Lockwood et al., 1999), the observed difference would motivate an extension of the D_{st} index (or a related proxy) even to earlier years.

5.4 Superposed epoch analysis of geomagnetic storms

We have studied the D_{st} index and the magnetic storms also by using the superposed epoch (SPE) analysis method. We have included in the analysis all the SSC (sudden storm commencement) storms mentioned in the SSC list by NGDC (2004), and used the SSC times as the superposed epoch zero times. (There are 729 SSC storms in the list in the early period and 1497 in the later period.) For each storm, the D_{st} indices from one day before the SSC time until 6 days after it were included in the SPE analysis. Figure 8 depicts the resulting SPE storm curves for the reconstructed D_{st} index in the early and the later period separately, as well as for the original D_{st}. (This analysis includes full D_{st} data, not only gapless data.) Note how closely the SPE storm curves for the original and reconstructed D_{st} indices in 1957–2002 follow each other over the whole 7-day storm time. In fact, the average difference between the two curves is only 0.08 nT, i.e. much smaller than the average difference between the two D_{st} time series. This is due to the fact that the SPE method randomizes the statistical differences between the two indices for each SPE hour. In fact, this agreement also verifies that there are no large systematic differences between the two D_{st} indices.

On the other hand, the SPE storm curve for the early period deviates from the later period in several ways. Statistically, the average difference between the two curves is 1.07 nT. Compared to the above-mentioned result that a difference due to statistical fluctuations is at most 0.08 nT, the difference between the two SPE curves for the two periods is significant. In the compression phase before the SSC and, in particular, at the D_{st} minimum the SPE curve for the early period is a few nT above the curve for the later period. Accordingly, on average, the storms in the early period seem to be slightly less intense than in the later period. This is consistent with the fact that the D_{st} indices (e.g. the annual values, see Fig. 5) include considerably larger values in the later period than in the early period. However, in the late recovery of the storm, since SPE day 4 onwards, the D_{st} index in the early period remains lower than in the later period. This feature recovers the above-mentioned similar overall averages of the D_{st} indices in the two periods, and suggests that, on average, storms may recover slower in the early period. These differences, although rather small for conclusive evidence, may still be indicative of a systematic long-term change in the interplanetary conditions. The weaker main phase and the longer recovery phase in the early period suggests that the storms at that time were more typically driven by recurrent streams (often producing HILDCAA, high intensity long duration continuous AE activity, type storm recovery phases (Tsurutani and Gonzales, 1987; Søraas et al., 2004)), rather than by strong CMEs, as typical in more recent times.

As a final study, we have depicted in Fig. 9 the annually calculated superposed storm curves, with the SPE day running vertically and years horizontally. The D_{st} values are given in colour code with strongly negative values in blue,

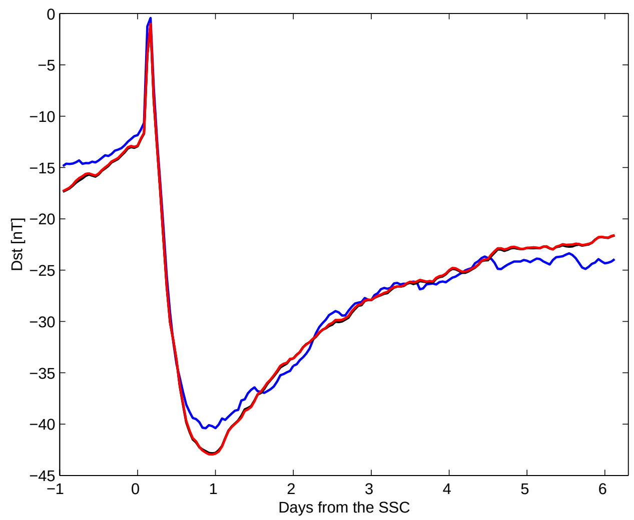

Fig. 8. Superposed epoch storm curves using the reconstructed D_{st} in 1932–1956 (blue) and 1957–2002 (red). The curve using the original D_{st} (black) in 1957–2002 is depicted under the red curve.

weakly negative values in yellow and positive values in red. (Here, as in Fig. 8, we have used all D_{st} data, not only gapless data.) Figure 9 shows clearly the strong solar cycle variation in the storm development, with blue colour dominating after the SPE zero time in solar cycle maximum years and yellow colour in minimum years. The strongest and most persistent blue colours are found during the maximum of SC 19, in agreement with the annual D_{st} maximum in 1960 (see Fig. 7). Strongly stormy years are also found around the maxima of solar cycles 17, 21 and 22. However, strong storm activity in SC 17 is quite surprising, taking into account the rather low annual averages during this cycle. Note also that the most stormy years during this cycle occur rather late in the declining phase of the cycle and that there are only rather a few stormy years in this cycle. In fact, these properties are most closely reproduced during cycle 21 while the storm activity in cycles 19 and 22 lasts longer and extends over the whole sunspot maximum.

There are also some differences in the storm activity level during solar minimum times. We find three periods of exceptionally high D_{st} values (weak activity) after the SPE zero time. These appear in Fig. 9 as large yellow regions in early 1930s, in mid-1960s and in mid-1990s. Note that these seem to appear every third solar minimum, when the lowest values of the A_p index are also found (see Fig. 7). This gives additional support for the suggested 3-cycle periodicity in solar activity and, for example, cosmic rays (Ahluwalia, 1998). Moreover, the higher D_{st} level during these times is also found before the SPE zero time and, especially, at the SPE zero time when the D_{st} attains typically positive values. On the other hand, during solar maximum years, in particular during the strongest maxima discussed above, the SPE zero time D_{st} level is clearly lower, weakly negative.

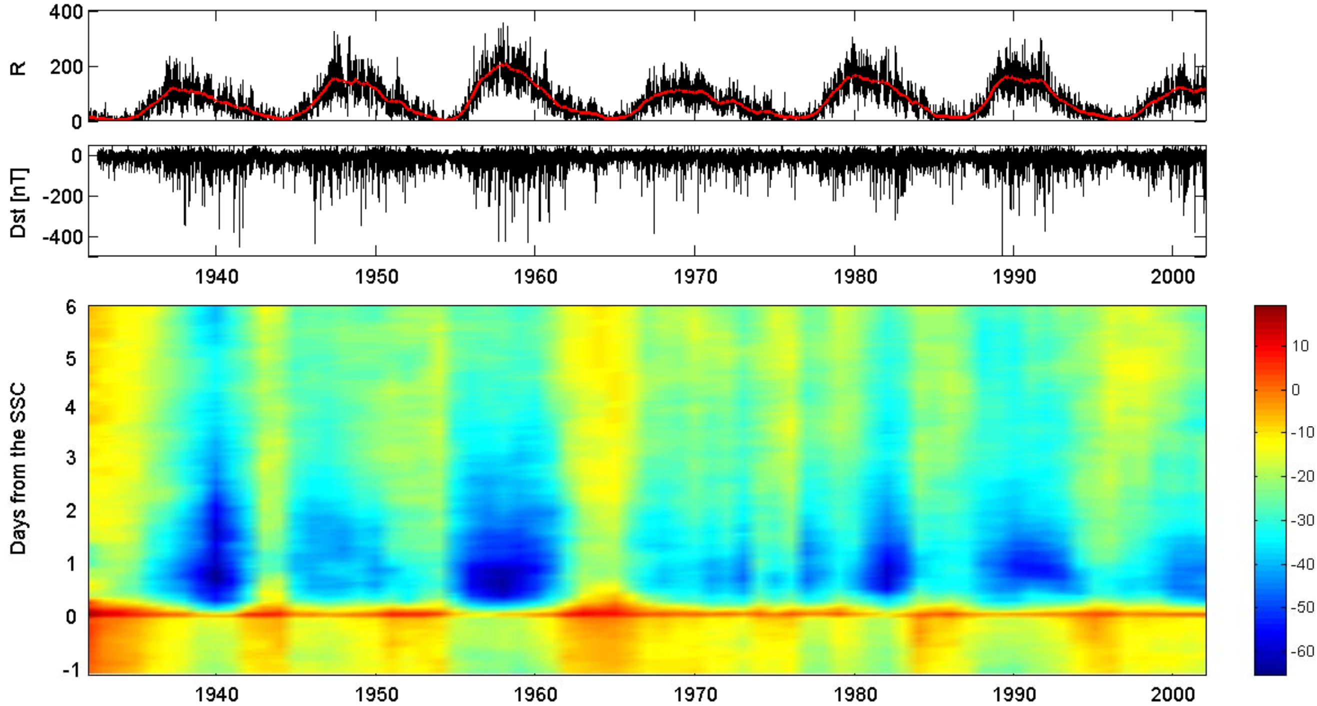

Fig. 9. Top: daily sunspot number in 1932–2002. One-year running mean of the sunspot counts is depicted in red. Center: reconstructed D_{st} index in 1932–2002. Bottom: annually calculated superposed storm curves using the reconstructed D_{st} in 1932–2002.

6 Conclusions

We have reconstructed the geomagnetic D_{st} index for 1932–2002, thus extending it by 25 years, i.e. by more than one full solar magnetic cycle. The extension was done by using data from the original set of four low-latitude stations for 1941–1956, and by using the nearby CTO station as a predecessor of the HER station for 1932–1940. Although we have followed the original D_{st} formula as closely as possible, the D_{st} index cannot, because of inadequate information, be fully reproduced and therefore remains partly unscientific. As a comparison, we give here a complete formula for our reconstruction of the D_{st} index. Despite the open questions related to the formula of the original D_{st} index, the reconstructed index is quite similar to the original one during the overlapping time interval (1957–2002). The average difference between the two indices is only about 3 nT and their correlation coefficient is about 98.7%.

We note that the reconstructed D_{st} index corrects for some known errors in the original D_{st} index, such as the erroneously large daily UT variation in 1971. Despite the fair overall agreement, the reconstructed index deviates from the original index even on the level of annual averages for some years. All annual averages of the reconstructed index are negative and for 1962–1966 they are systematically lower (more stormy) than those of the original index. Accordingly, we disagree with the uniquely positive annual average of the original index in 1965, which most likely is erroneous. We also find somewhat higher (less negative) values than in the original D_{st} index for the three lowest annual averages in 1960, 1989 and 1991. Out of these the lowest annual average is found in 1989 rather than in 1991.

The reconstructed D_{st} index presents a homogeneous, 71-year series which can be used, for example, to study the long-term development in the ring current and in the evolution and structure of storms. The annual averages of the geomagnetic A_p index and the reconstructed D_{st} index correlate very well over this time interval, except at the beginning of the series in 1933–1940 and in the declining phase of solar cycles 18, 20 and 21, where high speed solar wind streams cause enhanced geomagnetic activity. While the reconstructed D_{st} indices in 1932–1956 and 1957–2002 are statistically quite similar, we find differences in the average storm development during the two periods using the superposed epoch method. During the early period in 1932–1956 the storms are less intense but tend to have a longer recovery phase, suggesting that there are more HILDCAA-type medium activity intervals during the early period than more recently. We also study the annually averaged storm structure using the superposed epoch method and find that the most stormy years occur during the declining phase of solar cycles 17 and 21 and around the solar maxima of cycles 19 and 22. On the other hand, the least stormy years are found in early 1930s, mid-1960s and mid-1990s, in agreement with the lowest cycle minima of the A_p index.

Note: The extended and reconstructed D_{st} index described and studied in this paper will be released to the geophysical community via the World Data Center system as soon as possible. At the same time we will introduce a new symbol for our index in order to avoid confusion with the original D_{st} index. At present, our best candidate for the coming name is the D_{xt} index, emphasizing the fact that the time range of the D_{st} index was greatly extended.

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