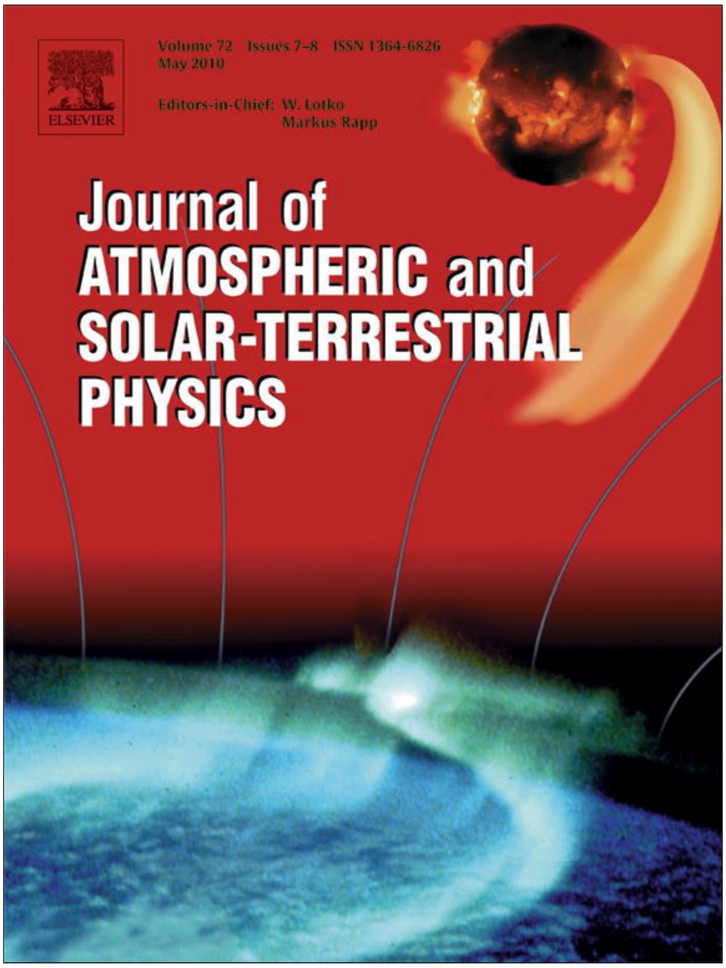
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Four decades of geomagnetic and solar activity: 1960–2001

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ABSTRACT

We analyze the relationship between some space weather indices (Dst, Ap, F10.7) and geomagnetic effects on the regional (European) scale, over the period 1960–2001. The remaining external field signal (RES) detected in the Northward magnetic component of the European observatory annual means are used as an indicator of the regional geomagnetic activity. Relationship RES-F10.7 suggests correction factors for getting the geomagnetic annual means of the Northern component less affected by the external sources. We have found some time lags among investigated parameters. These delays may suggest that the Ap responds to the solar activity in a differently than Dst and RES, Ap being more sensitive to the high-speed streams (HSS) and the Alfvenic waves present in HSS, while Dst and RES being more influenced by the coronal mass ejections activity (CME).

1. Introduction

1.1. Geomagnetic field and its temporal variations

The Earth'smagnetic field is a very complex phenomenon, to which magnetic contributions from different sources are involved. The dominant part of geomagnetic field is internal in origin. More than 90% of this field is due to the electric currents in the Earth's outer fluid core and is known as the *core* or *main* field (see e.g. Jacobs, 1987; Merill et al., 1998). The maximum intensity of the core field is around 60 000 nT near the magnetic poles and around 25 000 nT near the magnetic equator. Internal in origin is also the *lithospheric* or *crustal* field generated by magnetized rocks of the crust (e.g. Mandea and Thèbault, 2007). The magnitude of the crustal field varies from fractions to hundreds of nT, but can reach values as high as several thousands of nT.

The *external* fields are produced by ionospheric current systems (equatorial and polar electrojets (Campbell, 2003)) and magnetospheric currents (in magnetopause in the direction of the Sun, tail currents, ring current (Kivelson and Russel, 1995)). The values of these fields at the Earth's surface are of few tens of nT, even few hundred to thousand nT during magnetic storms. There are also external fields induced by currents flowing within the Earth's crust and upper mantle.

The geomagnetic field has been measured for more than 150 years in magnetic observatories and recently, since more than 9 years, also continuously from satellites (Mandea and Purucker, 2005; Olsen and Mandea, 2008). The magnetic observatory data provide a unique opportunity to study the temporal evolution of the geomagnetic field on different time scales, covering the period over which internal, as well as external field changes.

The core field varies over time scales of less than one year (Olsen and Mandea, 2008) to centuries and is referred to as *secular variation* (henceforth SV). The external fields change in space and time with periods from less than one second to the well-known solar cycle (~11 years) and its harmonics. Overlapping periods of external and occasionally rapid internal field variations makes it difficult to separate these two contributions. To study the long term variation of the Earth's magnetic field, it is necessary to remove the ~11 years fluctuations, thus the annual values have to be considered. In the following we are interested in the external geomagnetic field variations and their causes.

The problem of revealing the solar and interplanetary factors that cause magnetospheric disturbances has been addressed for a long time (e.g. Webb, 1995; Balasubramaniam et al., 1996; Crooker, 2000; Gonzales et al., 1996, 2001; Yermolaev and Yermolaev, 2002; Richardson et al. 2002a, b; Georgieva et al., 2006; Yermolaev and Yermolaev, 2006), however, this topic is still not completely understood (Zhang et al., 2007; McPherron et al., 2008; Dwivedi et al., 2009).

Beside daily regular geomagnetic field variation which arises from current systems due to the regular solar irradiation changes, there are irregular variations, mainly caused by two different solar drivers (e.g. Georgieva et al., 2006; Lavraud et al., 2006):

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coronal mass ejections (CMEs) and solar wind high-speed streams (HSSs). CMEs are eruptions of closed solar magnetic field structures and cause sporadic geomagnetic activity. There are two types of CMEs: magnetic clouds (MCs) and non-MCs. MCs are features which could be interpreted as magnetic flux ropes, their occurrence rate showing a strong solar cycle dependence. Geomagnetic activity related to interplanetary CMEs is either caused by the ejection itself, or by shock-sheath region ahead of it. The HSSs originate from long-lived regions of open magnetic field, coronal holes (CHs). They cause recurrent geomagnetic activity, persisting usually for several days. The importance of HSS in producing geomagnetic disturbances has been investigated by many authors (e.g. Tsurutani and Gonzales, 1987; Tsurutani et al., 1995; Gonzales et al., 1999; Georgieva et al., 2006). It seems that overall contribution of HSS to the geomagnetic activity is comparable, if not even more important than of CMEs. Further, it has been noticed (Echer et al., 2004) that the continuous, very intense geomagnetic activity at auroral region latitudes is caused by large-amplitude Alfvenic waves associated with HSS structures. At sunspot maximum the enhancement of the geomagnetic activity is primarily caused by CMEs. In the declining phase of the sunspot cycle the geomagnetic activity is mainly due to the large number of recurrent HSSs (see Vršnak et al., 2007 and reference therein). On average, the most geoeffective solar drivers are MCs, as they usually have a relatively strong and persistent southward magnetic field component.

1.2. Geomagnetic and solar indices

Various magnetic activity indices have been designed in order to describe the irregular geomagnetic field variations. They give a global picture of degree of disturbance level, providing information about the complex underlying phenomena. Space weather indices include geomagnetic indices (mostly used: Kp, Ap, AE, Dst, aa), solar wind parameters, sunspot number, flare index, solar radio flux (F10.7) and some more. In the following we detail only those indices used in this study.

Planetary geomagnetic activity index Ap is derived from a range of geomagnetic field variations over period of 3 h from measurements provided by 13 geomagnetic observatories between 44° and 60° northern or southern geomagnetic latitude. It is the measure of the solar particle radiation and of the daily level of the mid-latitude magnetic activity. In a similar way the aa index is computed, but using a pair of near-antipodal observatories (Hartland in England and Canberra in Australia). More details can be found at: http://www-app3.gfz-potsdam.de/obs/niemegk/en/.

The storm-time disturbance index Dst is derived from the horizontal component from four geomagnetic stations placed between −33° and 30° geomagnetic latitude. It represents the axially symmetric disturbance magnetic field at the dipole equator on the Earth's surface. Decrease of the Dst is mainly due to the ring current, while positive variations in Dst are caused by the compression of the magnetosphere due to the increase of the solar wind pressure. Details and data available at: http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/.

Ap and Dst indices are measured at different geomagnetic latitudes and are thereafter sensitive to different currents systems. Sometimes the geomagnetic activity is reflected in strong Dst signal, whereas the Ap signal remains low, and vice versa.

Geomagnetic index, *RES*, introduced in this study, is an indicator of the regional geomagnetic activity. It is derived from measurements provided by 36 European geomagnetic observatories between 36° and 70° northern geomagnetic latitude. RES represents average variation of the difference between measured magnetic field and modeled internal field and can be considered as external magnetic field variations persistent in the annual mean values of the Northward geomagnetic component. For studies of regional geomagnetic activity on shorter time scale we refer to Shugai et al. (2009).

The solar radio flux index, *F* 10.7 is a measure of solar radio-emission at the wavelength of 10.7 cm. The intensity of this radio noise is measured at the algonquin radio observatory in Ottawa daily at 17 UT and is used as an indicator of the overall solar activity. The solar radio flux is correlated with the number of sunspots and also with the solar extreme ultra-violet radiation, which controls the ionospheric conductivity. F10.7 data are available at: http://radbelts.gsfc.nasa.gov/RB_model_int/Psi_database.html.

Even if geomagnetic indices represent a good indicator of magnetic field variations, it is still difficult to get the observatory annual means (defined as being the average over all days of the year and all times of day) reflecting the core processes, only. For this reason, in the two recent studies presented by Verbanac et al. (2007a, 2007b), efforts have been done to obtain procedures for minimizing the external field contributions contained in the European observatory annual means. In the last study a new, physically-based method by which the external fields in the Northward, *X*, component are successfully suppressed, has been developed. However, this approach employs the Ap and Dst indices, both quantities derived from measurements on the Earth, meaning that they are influenced by the same external contributions as the measured *X* component.

1.3. Solar and geomagnetic activity

Not many dedicated studies on the relationship among geomagnetic indices have been published, especially not on longer time scales. On the other hand, there have been performed many studies on the inter-relationship among geomagnetic indices (mainly the aa and Dst indices), different solar wind parameters and events occurring on the Sun (Akasofu, 1981; Gorney, 1990; Gonzales et al., 1999; Richardson et al., 2006). Especially, the solar cycle related variability in the near Earth's environment has been widely studied, mainly focusing on the long-term correlation between sunspot and geomagnetic activity and its temporal variation (Cliver et al., 1996; Kishcha et al., 1999; Stamper et al., 1999; Richardson et al., 2002b; Wang et al., 2000; Echer et al., 2004). Echer et al. (2004) noticed that annual averages of both aa index and sunspot number change in phase within the period 1868–2000. They showed that the geomagnetic and solar activity correlation has decreased since the end of the 19th century, when the lag between them started to increase. Using more recent data (from 1964), a two-years time lag has been observed.

Here, we take the advantage of the high quality geomagnetic observatory annual means (Verbanac et al., 2007a), allowing us to perform the analysis of the relationship between geomagnetic and solar activity during four solar cycles (1960–2001), both on the global and regional scale. Worth noting is that the great advantage of the observatory annual means is that they are not contaminated by the seasonal variations, namely Russell and McPherron and Equinoctial/McIntosh effects (Russel and McPherron, 1973; McIntosh, 1959; Cliver et al., 2000). We have exploited the F10.7, Ap and Dst indices, investigated the correlations and further derived the relationship among them. The obtained expressions between F10.7 and RES allow us to provide correction factors for the *X* annual means. It is worth noting that the developed procedure is based on two observationally independent quantities (solar activity index, F10.7 and geomagnetic regional index, RES) and in such a way magnetospheric disturbances are directly linked to their source, namely processes on the Sun.

The main goals of our study are to:

- study the evolution of external geomagnetic field on the regional scale (as represented by RES) over different solar cycle phases for the period 1960–2001; in particular we focus on solar minima when the Earth's magnetic field is under quiet condition;
- analyze the relative evolution (phase shifts) of Dst, Ap, and RES, which can give an insight in behavior of the two major current systems: ring current and auroral electrojets, respectively;
- physically quantify the correlations between annual mean values of geomagnetic indices Ap, Dst, and RES and the solar activity index F10.7;
- quantify the correlations between annual mean values of regional geomagnetic index RES and global geomagnetic indices Ap and Dst;
- find the correction factors for the external field influence on the Northward component of the European geomagnetic observatory annual means, to be used for modeling the intrinsic, core field.

This paper is organized as follows. In the next section, we introduce the used data and method. Then, the cross-correlation analysis among different parameters are presented. Finally, we summarize and discuss the obtained results.

2. Data

Our study is based on the European geomagnetic observatory annual means, and the annual values of following space weather indices: F10.7, Ap, and Dst, all over the time span 1960–2001.

We focused on the Northward, *X*, component, which shows the most prominent magnetic field variations, external in origin Verbanac et al. (2007a). A detail description of these data is given in Verbanac et al. (2007a). The list of observatories with their corresponding IAGA codes and both geographical and geomagnetic coordinates is given in the Appendix (Table 1). The observatory time series, after subtracting the core field as predicted from the comprehensive model, CM4 (Sabaka et al., 2004), are shown in Fig. 1. The observatories (ordinate) are ordered by geomagnetic latitudes with the northern one at the top, and with the number assignment as given in Table 1. By vertical averaging these time series over all locations for each year, we obtained an average external magnetic field variation, RES, contained in the annual means of the considered

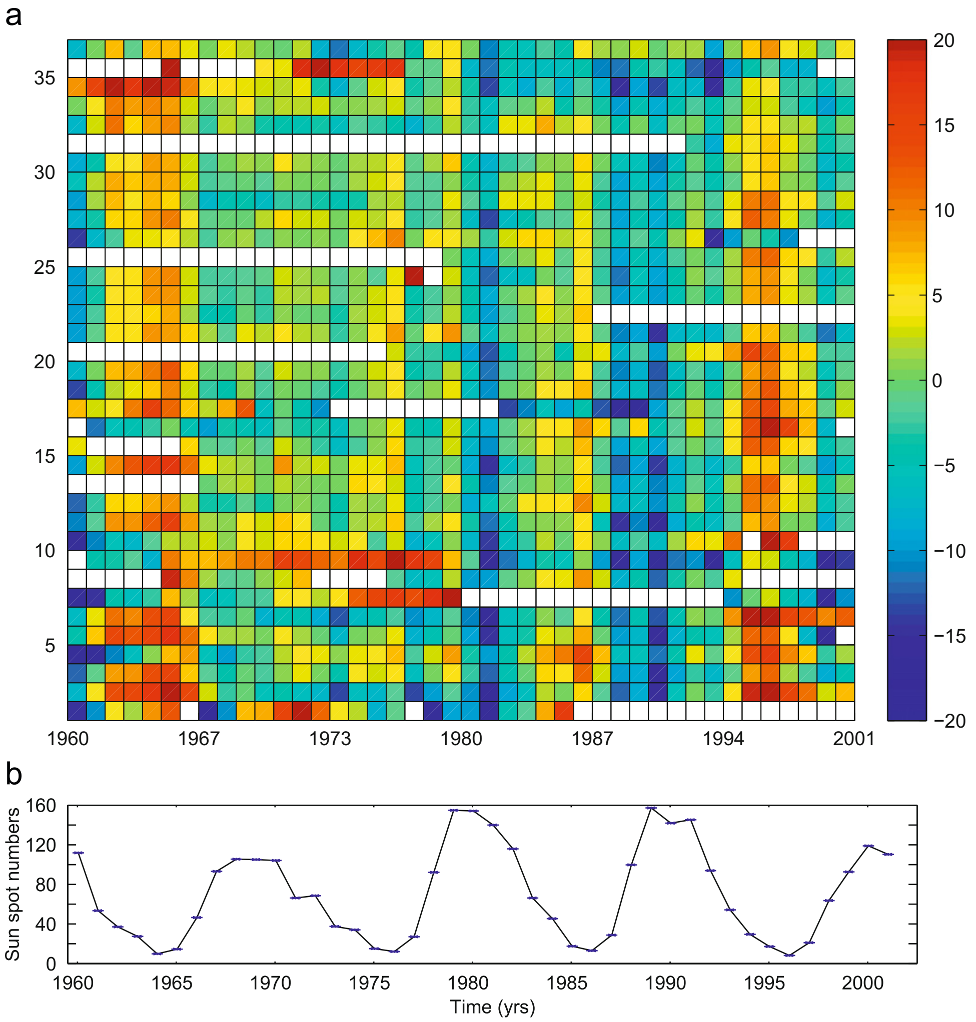

Fig. 1. Top: Pictogram of the *X* component residuals (differences between the observatory annual means and the core field as predicted from the CM4 model) at 36 European geomagnetic observatories (ordinate) which are ordered by geomagnetic latitudes (see Table 1 in the Appendix). Unit is nT. Bottom: Annually averaged Sun spot numbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

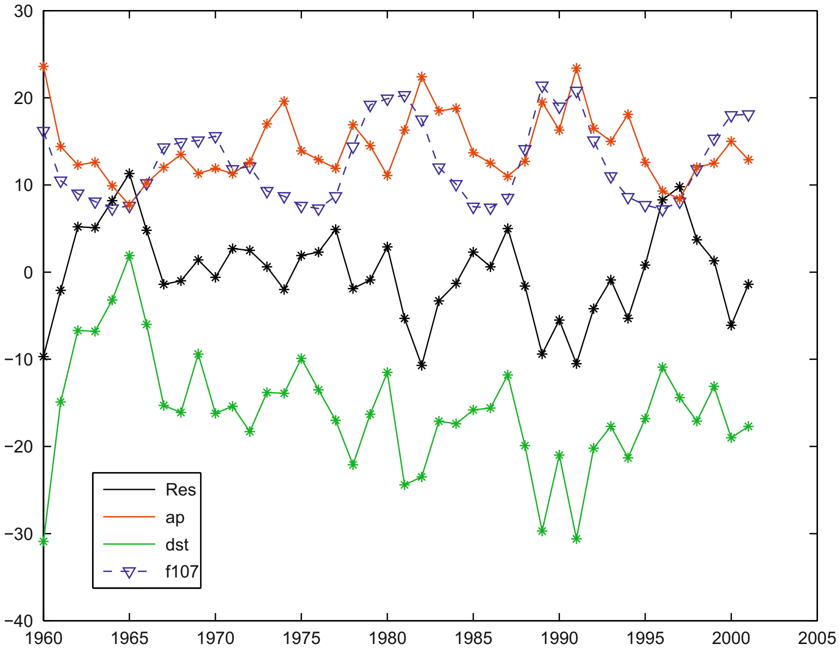

Fig. 2. RES (black): The *X* component residual signal, RES, obtained by a median averaging of the residuals shown in Fig. 1a, in each year; annual average values of the indices: Dst (green); Ap (red); F10.7 (blue). Units: nT for Dst and Ap, and Jy (Jy = 10^{-26} Wm^{-2} Hz) for F10.7. Note that F10.7 is scaled by factor 10. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

observatories. The RES as a function of time is shown in Fig. 2. When subtracting the obtained RES, the external field effects were successfully suppressed, what makes us confident that this RES, to large extent, represents external magnetic field signals typical for the studied region. Let us also note that the used observatories cover wide range of latitudes and longitudes (as seen in Table 1), namely the large enough region over which different magnetospheric response to the solar activity may be expected.

3. Analysis

An examination of Fig. 1 reveals noticeable variations seen as vertical stripes which occur simultaneously at all observatories, indicating that they are real phenomena. Moreover, these vertical stripes coincide with the solar cycle (the yearly mean sunspot number for this period is displayed below the pictogram), suggesting their link to the solar wind variability.

Generally, it can be noticed that the years close after the solar maximum are characterised by a decreasing of geomagnetic field, and the years after the solar minimum are characterised by an increasing of geomagnetic field. The significant magnetic field depletion is observed (bluish colors) in 1960, 1981 and between 1988 and 1990. The behavior observed for the first year of the investigated period has to be considered with caution, as being at one end of the time-interval. The next ones are related to solar maximum in 1980 and 1990, respectively. In comparison to above mentioned solar maxima, those occurred in 1969 and 2000 are weaker and consequently caused the smaller effects on the magnetic field. On the other hand, during the minimum of solar activity, the field recovers to its true value, seen as an reddish colors in the pictogram. Interestingly to note is that the significantly higher field values are reached in years 1962–1965 and 1995–1996 (solar minimum in 1965 and 1996) then for years of solar minimum in 1976 and 1987.

To study in detail the external field pattern observed in the color-coded matrix, we plot the RES as black curve in Fig. 2 together with the annual averages of the Ap, Dst and F10.7 indices. For convenience, the F10.7 values are scaled by factor 10. All investigated parameters reveal changes similar to the solar cycle variability. There is a close similarity between the RES and Dst variations all over the considered period. However, the most prominent similarity seems to be between RES and Ap, though with the opposite sign, which is also confirmed by the cross-correlation analysis (see next section). The Ap and F10.7 tracks each other well, however with some time lag and are both anti-correlated with Dst and RES. To investigate in details the relationships among these quantities, we performed a cross-correlation analysis. We first discuss the interrelationship among various indices. Then, we analyze the relationship between RES and F10.7, Ap, and Dst, respectively.

3.1. Cross-correlations

In the following we investigate on yearly basis how the level of geomagnetic activity caused by interplanetary phenomena varies with the level of solar activity, and how the geomagnetic indices are related to each other.

For this, a cross-correlation analysis is done comparing the different solar and geomagnetic indices. The cross-correlation function is derived up to a time lag of ± 20 years, with a step of one year (data resolution) in all investigated cases. The time lag was chosen to cover the length of the data series of 42 years.

The F10.7-Ap, F10.7-Dst as well as Dst-Ap cross-correlations are shown in Fig. 3. The F10.7-Ap cross-correlation function peaks at $\Delta t = +2$ years, meaning that variations in Ap appear, on average, two years after the F10.7 variations. However, the detailed look into Fig. 2 reveals that there are significant differences from cycle to cycle, e.g. Ap peaked four years after F10.7 in cycle 21, one year after F10.7 in cycle 22, and concurrently with F10.7 in cycle 23. The F10.7-Dst cross-correlation function has minimum for the zero time lag. However, it shows an asymmetry (i.e. the dip is broader at

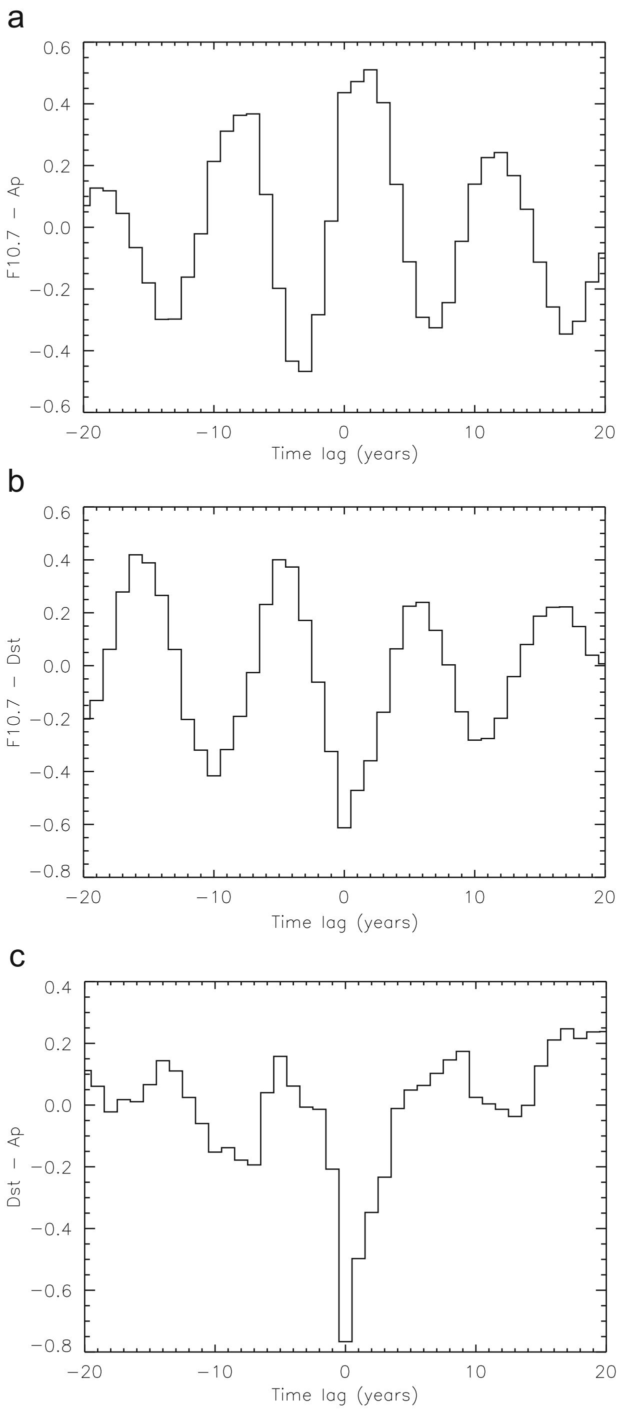

Fig. 3. Cross-correlation between: Ap and F10.7 (top); Dst and F10.7 (middle); Dst and Ap (bottom). The smaller side lobes are a consequence of the 11 year periodicity of the solar cycle.

the right side of the dip), giving two possibilities: (i) Dst is somewhat (between 0.5 year and 1 year) delayed after F10.7 and (ii) Dst-related activity peaks in F10.7 maximum and persists for some time after F10.7 maximum though at a lower level (the correlation coefficient at lag +1 is lower than correlation coefficient at lag 0). The Dst-Ap cross-correlation function has a minimum at $\Delta t = 0$, and also shows an asymmetry which indicates that Ap might be delayed (say, for one year) with respect to Dst. We would like to recall that the analyses is performed on yearly values, hence, a time lag of one year is the resolution limit. It should be emphasize that data scatter is quite large and time series are limited, so it is difficult to distinguish between zero and one year lags.

The correlations among F10.7, Ap, and Dst are shown in Fig. 4. Note that the two-year time lag is applied to correlate F10.7 and Ap, and zero time lag in other cases. As can be seen in Fig. 4, a linear relation between different parameters is derived. Applying these relations we obtain the following functions: RES(F), Ap(F), and Dst(F). In the following we denote the correlation coefficients as: R_0, R_1 and R_2 when zero, one-year and two-year time lags are applied, respectively.

The correlation coefficient between the solar activity index F10.7 and non-shifted Ap data equals only to $R_0 = 0.44$ (statistical significance $P_0 > 99.60\%$). However, if we apply the one and two years Ap delay after F10.7, the corresponding correlation coefficients increase to $R_1 = 0.52$ (statistical significance $P_1 > 99.95\%$) and $R_2 = 0.57$ (statistical significance $P_2 > 99.98\%$), respectively. This confirms the two-year lag of Ap after F10.7 that was revealed by the cross-correlation analysis. Consequently, the relationship between the Ap and F10.7 is given by the following expression:

$$\mathrm{Ap}(t) = 0.05\,\mathrm{F10.7}(t-2) + 8.3.$$

The correlations between F10.7 and Dst reads

$$\mathrm{Dst}(t) = -0.09\,\mathrm{F10.7}(t) - 4.6,$$

with the correlation coefficient $R_0 = 0.61$ ($P_0 > 99.99\%$). If the Dst data are shifted by one year, we find $R_1 = 0.51$ (statistical significance $P_1 > 95\%$), consistent with the asymmetry of the cross-correlation function. Such a behavior indicates that the average time lag of Dst after F10.7 is less than one year.

The correlation between Ap and Dst is characterized by a high correlation coefficient $R_0 = 0.77$ ($P_0 > 99.99\%$). When the Dst data are shifted by one year, correlation is still statistically significant ($R_1 = 0.54$, $P_1 > 95\%$), confirming the delay of Dst with respect to Ap that was indicated by the cross-correlation analysis. The found relationship between these two quantities reads

$$\mathrm{Ap}(t) = -0.44\,\mathrm{Dst}(t) + 7.3.$$

The cross-correlation functions for the RES versus F10.7, Ap, and Dst indices are shown in Fig. 5. The best correlation/anti-correlation is obtained for the zero time lag. Distinct asymmetries are seen in the RES-F10.7 cross-correlation function. The main dip in the curve is broader for negative time lags, and the secondary cross-correlation peaks are located at $\Delta t = -6$ and $\Delta t = +4$ years. Note that the negative time lag means that variations in the RES occur, on average, after the F10.7 variations. A slight asymmetry could be also noticed in the RES-Ap cross-correlation function, being somewhat broader at the positive side of the dip (Ap delayed after RES).

In Fig. 6, we present the regression analysis between various parameters. The correlation between the RES and Dst, and anti-correlation between the RES and Ap, are both prominent being characterized by a high correlation coefficient of $R_0 = 0.86$ and 0.88, respectively. The correlations read

$$\mathrm{RES}(t) = -1.2\,\mathrm{Ap}(t) + 17$$

and

$$\mathrm{RES}(t) = 0.67\,\mathrm{Dst}(t) + 11.$$

The relationship between the RES and F10.7 is given by the following expression:

$$\mathrm{RES}(t) = -0.08\,\mathrm{F10.7}(t) + 9.9,$$

with somewhat weaker correlation coefficient of $R_0 = 0.68$. However, it is worth noting that this is still a very distinct correlation, since measurements of these two quantities are entirely independent. The same correlation coefficient is obtained

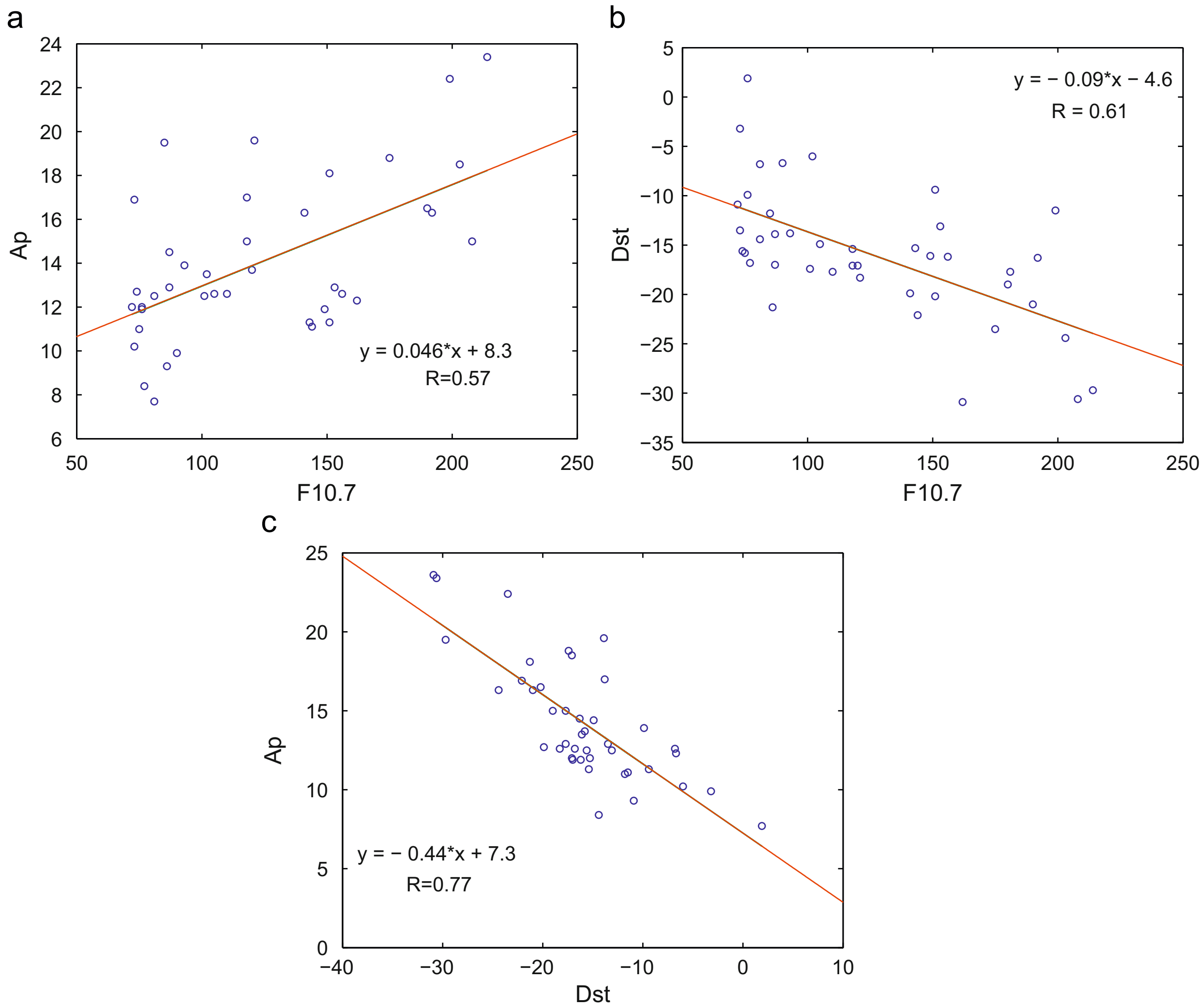

Fig. 4. Correlation of F10.7 and Ap (top); F10.7 and Dst (middle); Dst and Ap (bottom). Two year time lag is applied to correlate F10.7 and Ap; Zero time lag in last two cases. The linear least squares fit and correlation coefficient, *R*, are presented in the inset.

if the RES data are shifted for one year with respect to the F10.7 data, confirming the possible time delay of RES after F10.7. The intrinsic property of the procedure applied in calculating the RES variations is that its mean value is zero (see Fig. 2). As a consequence, at the minimum of the solar activity the RES is larger then zero, namely it amounts for 9.9 nT. This value represents the base value for eliminating the solar activity effects.

All above mentioned correlation coefficients, namely R_0, R_1 and R_2, are of high statistical significance ($P>99.99\%$). We would like to stress that the statistical significance always decreases below 95% when other time lags were applied.

4. Discussion and conclusion

In this study the solar-terrestrial relationship over three full solar cycles (1960–2001) is investigated on both global and regional scale. Special attempt is given to physically quantify the geomagnetic field disturbances at restricted region of the Earth. The variations regarded as the external field signal (RES) and present in the European observatory annual means of the Northward magnetic component is used as the indicator of the regional geomagnetic activity and is pointed to different processes occurring on the Sun. Since in annual means the seasonal variations caused by Russell–McPherron and Equinoctial/McIntosh effects are smeared out, we suppose that RES results mostly from the change in the amplitude of the westward flowing ring current (Verbanac et al., 2006). The magnetic field of this current has a sign opposite of the Earth's magnetic field and in such a way depresses it. During the period of enhanced solar activity, the ring current becomes stronger and consequently largely suppresses the intrinsic geomagnetic field.

Our analysis reveals a significant magnetic field depletion of the order of 20 nT in 1981 and between 1988 and 1990, the years related to the solar maximum in 1980 and 1990, respectively. The field is less suppressed during the other two solar maxima within investigated time span (in 1969 and 2000) because the maximum solar activity was less intense in these years. The Earth magnetic field approaches its true value when the Sun is very low in activity. Interestingly, we found the unequal recovering of the field for the years of the solar minimum that occurred in last 42 years. Namely, the field is significantly higher for the solar minimum in 1965 and 1996 then for solar minimum in 1976 and 1987. This obviously cannot be related to even or odd solar cycles. It may be understood in terms of unequal activity of the Sun during different minima.

RES has smaller positive values, corresponding to higher geomagnetic activity, in sunspot minima preceding higher

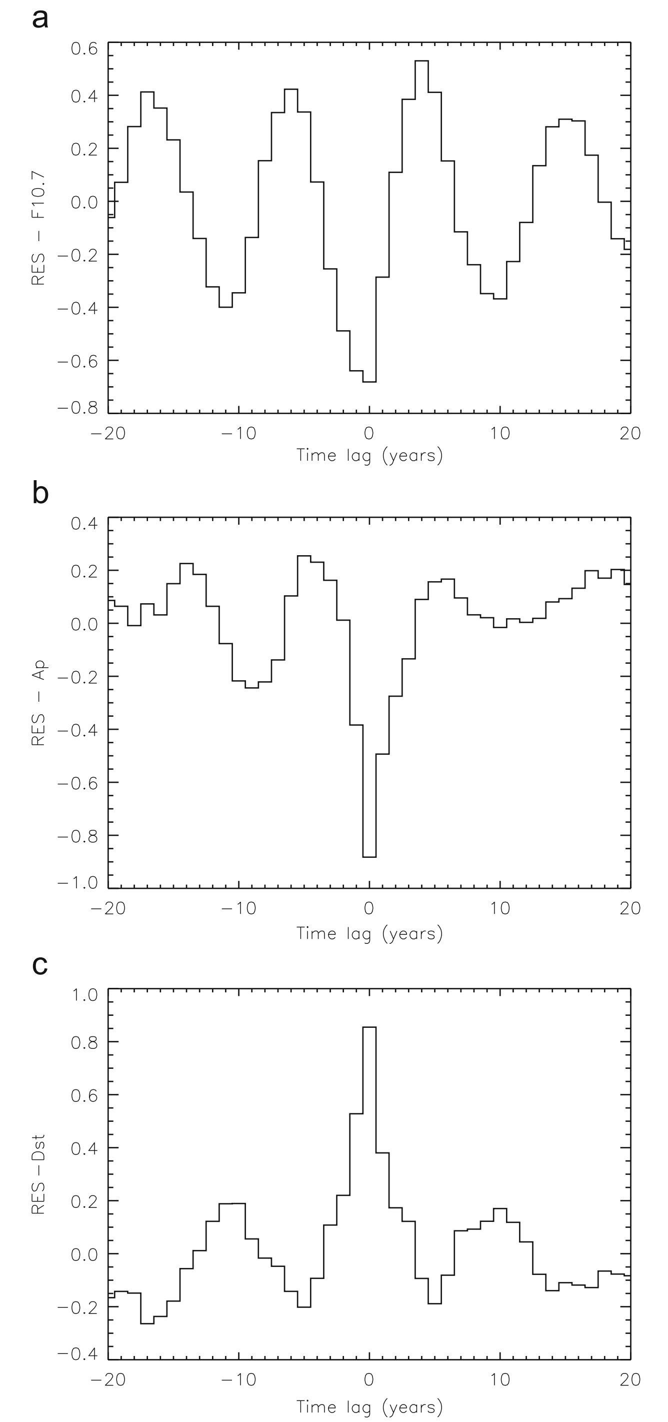

Fig. 5. Cross-correlation between RES and: F10.7 (top); Ap (middle); Dst (bottom). The cross-correlation functions were calculated up to a time lag of ± 20 years.

sunspot maxima, and higher positive values, corresponding to lower geomagnetic activity, in sunspot minima preceding lower sunspot maxima. In this respect, it is worth noting that the relation between geomagnetic activity in sunspot minimum and the magnitude of the following sunspot maximum might be interesting for the solar dynamo theory. Namely, the geomagnetic activity in sunspot minimum is believed to be mainly due to HSSs which are manifestations of the solar poloidal field, and the solar poloidal field is the seed of the solar toroidal field of the following sunspot cycle, governing the number of sunspots in the maximum.

In this study, we quantified the correlation between the solar and terrestrial parameters and presented the cross-correlation between the solar activity index F10.7 and geomagnetic indices Dst, Ap (representing low and high latitude geomagnetic indices), as well as between F10.7 and RES. Worth noting is that the regional field variations is better correlated with F10.7 then the Ap. The analysis shows that both RES and Dst are roughly synchronized with the solar activity cycle, and reveals a delay in the order of one year. On the other hand, the variation of Ap is delayed for two years with respect to F10.7, and about one year with respect to both Dst and RES. Note that lags represent average values over three solar cycles. The differences from cycle to cycle are obvious, as seen in Fig. 2 (e.g. Ap peaked four years after F10.7 in cycle 21, one year after F10.7 in cycle 22, and concurrently with F10.7 in cycle 23.). These are consistent with what was shown by Echer et al. (2004) and Georgieva et al. (2006) among others, that this lag has been changing between zero and three years in the last century. Our results indicate that Ap responds to the solar activity in a different manner than Dst and RES. In this respect, we should bear in mind that there are two main sources of the geomagnetic activity. The CMEs are the principal driver of geomagnetic storms in the interval around solar activity maximum, whereas the HSS wind streams, originating from the low latitude coronal holes, dominate in the declining phase of the solar cycle.

Furthermore, yearly percentages of storms generated by magnetic clouds and CIRs have two maxima per solar cycle, because the magnetic cloud and CIR activities are shifted in time. This could explain time delay between F10.7 and indices.

The obtained results suggest that Dst is dominated by CME activity and that the Ap index might be more sensitive to the HSS than Dst. This would explain why Dst is better synchronized with F10.7, since the CME activity is closely linked to solar activity indices (e.g., sunspot number and F10.7), whereas HSSs become more prominent a few years after the peak of F10.7. Moreover, these suggest that Ap may be more sensible on the high-latitude activities as auroral electrojects than on the lower-latitude activity described by ring current. Thus, it seems that it is significantly influenced by Alfvenic waves present in HSS (Tsurutani et al., 1990, 1995). These waves have enhanced fluctuating southward component of interplanetary magnetic filed, favorable for magnetic reconnection with the Earth magnetic field. By this mechanism, the energy from the solar wind is transmitted into the magnetosphere causing weak but long duration activity as seen in Ap. Further, the existence of the time lag between F10.7 and the Ap is consistent with two-year time lag between aa index and sunspot numbers notice by Echer et al. (2004), and is understood in terms of stronger average geomagnetic activity during declining phase than during solar maximum. This is likely related to the HSS effects. The observed Dst delay in regard to F10.7 can be related to the temporary decrease of both solar wind speed and interplanetary magnetic field strength for periods of approximately one year at solar maximum, i.e. "Gnevyshev Gap" (Gnevyshev, 1977; Richardson et al., 2002a).

The situation regarding RES seems to be more complex. As already stated the level of correlation is similar for RES-Ap and RES-Dst (coefficient correlations 0.88, 0.86, respectively). Furthermore, asymmetries in the cross-correlation functions show that RES is somewhat delayed with respect of Dst, thereas Ap is somewhat delayed with respect to RES. This may indicate that RES is influenced by both CMEs and HSSs, which is consistent with mid-latitude location of the most geomagnetic observatories used in this study.

To summarize, in this study, the regional (European) geomagnetic activity and the low- and high-latitude geomagnetic indices are related to the solar activity.

The empirical relationship between RES and F10.7 offers a procedure to get the geomagnetic annual means of the Northward

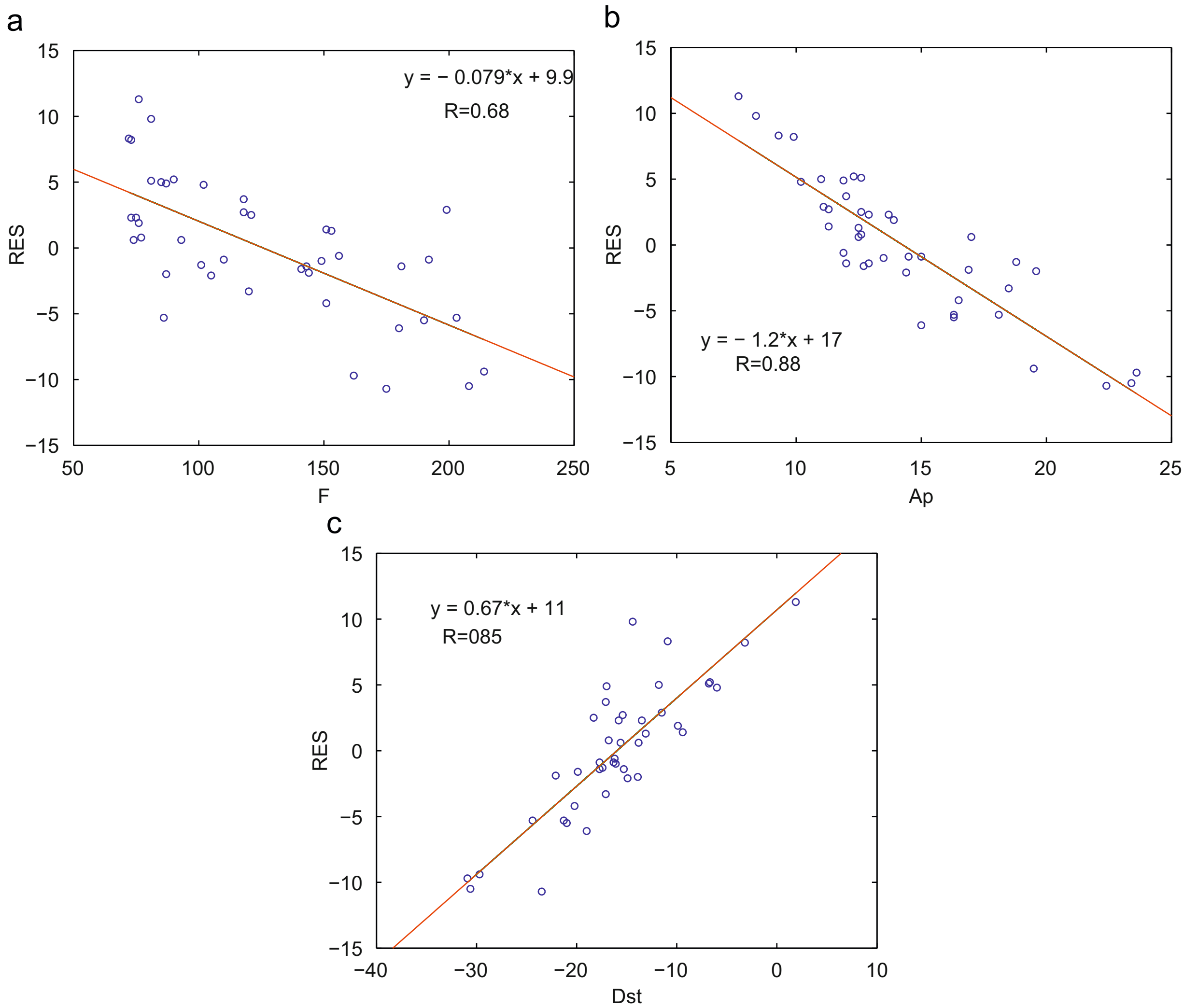

Fig. 6. Correlation of RES and: F10.7 (top); Ap (middle); Dst (bottom). Zero time lag is applied. In the inset the linear least squares fit and correlation coefficient *R* are presented.

component less affected by the external sources, what is very important for modeling and understanding the internal, core, geomagnetic field. Worth noting is that these correction factors are linked directly to their prime source, i.e., solar activity. It was possible to obtain these connections, because we have shown that the relationship between solar activity and geomagnetic activity, beside being obvious on shorter time scales (10 min to 10 days), appears also on the annual scale, which we quantified. The physical background is not entirely clear, but it is pretty much obvious that larger frequency of solar geoeffective events will leave trace in yearly values too.

In conclusion, our main results we summarize as follows:

- unequal recovery of the geomagnetic field (over the European region) at different solar cycle minima is revealed, which is not related to even/odd cycles;
- we have quantified time lags and found explicit relationships between annual mean values of geomagnetic indices Ap, Dst and RES and the solar activity index F10.7;
- it is shown that RES is better correlated with F10.7 then Dst and Ap are;
- we have quantified time lags and found explicit relationships between annual mean values of regional geomagnetic index RES and global geomagnetic indices Ap and Dst;
- with the empirical relationship between RES and F10.7, we offer a procedure to get the European geomagnetic annual means of the Northward component less affected by the external sources i.e., solar activity.

Finally let us note that we have considered so far only the Northward geomagnetic component, because it is the one most severely affected by external sources (Verbanac et al., 2007a). We regard this study as a test of concept and will analyze the other geomagnetic field components as well. Furthermore, we aim to extend this research by using a larger number of solar activity parameters in order to get a better understanding of the observed time lags and their causes (Verbanac et al., in preparation).

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Table 1
Geomagnetic observatories considered present study.

Nr.	IAGA code	Station	Geographic long	Coordinates lat	Geomagnetic long	Coordinates lat
1	PEG	Penteli	23.87	38.05	103.05	36.32
2	PAG	Panagjuriste	24.18	42.52	104.76	40.59
3	AQU	L'Aquila	13.32	42.38	94.37	42.53
4	SPT	San Pablo	355.65	39.55	104.22	43.20
5	GCK	Grocka	20.77	44.63	102.29	43.27
6	ODE	Odessa - Stepanovka	30.88	46.78	112.44	43.48
7	EBR	Ebro	0.50	40.82	98.85	43.51
8	CTS	Castello Tesino	11.65	46.05	94.14	46.39
9	NCK	Nagycenk	16.72	47.63	99.64	46.93
10	KIV	Kiev - Dymer	30.30	50.72	113.44	47.37
11	WIK	Wien - Cobenzl	16.32	48.27	99.53	47.62
12	FUR	Fuerstenfeldbruck	11.28	48.17	94.68	48.49
13	BDV	Budkov	14.02	49.07	97.70	48.83
14	CLF	Chambon-la-Foret	2.27	48.02	94.22	50.10
15	BEL	Belsk	20.80	51.83	105.31	50.17
16	MNK	Minsk - Pleshchenitzi	27.88	54.50	112.99	51.42
17	MAB	Manhay	5.68	50.30	90.22	51.61
18	DOU	Dourbes	4.60	50.10	90.93	51.63
19	NGK	Niemegk	12.68	52.07	97.85	51.94
20	BOX	Borok	38.97	58.03	124.30	52.89
21	HLP	Hel	18.82	54.60	104.89	53.17
22	WIT	Witteveen	6.67	52.82	92.49	53.82
23	WNG	Wingst	9.07	53.75	95.31	54.23
24	HAD	Hartland	355.52	51.0	99.60	54.24
25	BFE	Brorfelde	11.67	55.63	98.86	55.50
26	LNN	Leningrad - Voiekovo	30.70	59.95	118.42	56.08
27	VAL	Valentia	349.75	51.93	105.11	56.22
28	NUR	Nurmijarvi	24.65	60.52	113.65	57.67
29	LOV	Lovo	17.83	59.35	106.89	57.82
30	ESK	Eskdalemuir	356.80	55.32	95.80	58.09
31	OUL	Oulujarvi	27.23	64.52	118.77	60.92
32	DOB	Dombas	9.12	62.07	101.14	61.97
33	LER	Lerwick	358.82	60.13	90.26	62.18
34	SOD	Sodankyla	26.63	67.37	120.83	63.62
35	KIR	Kiruna	20.40	67.80	116.37	65.06
36	LRV	Leirvogur	338.30	64.16	107.76	69.77

Appendix

Table 1 shows the geomagnetic observatories considered in present study.

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