Derivation of ionospheric activity indices for the European region from on-line ionosonde observations

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Abstract

From automatically scaled on-line data of several European ionosonde stations ionospheric activity indices can be derived. Such indices are used to distinguish between undisturbed ionospheric conditions and ionospheric disturbances caused by different solar events (flares, coronal mass ejections etc.). The most reliable indices have been derived from the critical frequency foF2 of the ionospheric F2-layer. Similar indices estimated from ionospheric M(3000)F2 values show a markedly lower variability indicating that the changes of the altitude of the F2-layer maximum are markedly smaller than those calculated from the maximum electron density in the F2-layer. With the ionospheric activity indices derived at different stations the ionospheric disturbance level over a substantial part of Europe (34°N-60°N; 5°W-40°E) can on-line be detected.

1. Introduction

In the frame of the EC *eContent* programme, the DIAS project (**Di**gital upper **A**tmosphere **S**erver) will create a computational infrastructure for a pan-European digital data collection to describe the state of the ionospheric part of the Earth's upper atmosphere over Europe (Belehaki et al., 2005). It bases on historical data series as well as real-time observations at different European digital ionospheric stations. For an interested user of ionospheric data it is very important to know if the current ionospheric state is normal due to the mean solar activity level or disturbed due to short-time solar activity changes or specific solar events (solar flares, coronal mass injections, etc.). This paper describes one way of making distinction between these ionospheric states by introducing ionospheric activity. Basis of such indices are automatically scaled ionosonde data which are derived at different places all over the world and especially also at several stations in Europe. In this paper there are described the definition of such indices, their general behaviour at different stations and during ionospheric disturbances as well as the limitations of their use.

2. Definition of ionospheric activity indices

For the description of the state of the ionospheric F2-layer, the critical frequency foF2 and the propagation factor M(3000)F2 are available from routine ionosonde observations. These two quantities can be used to derive ionospheric activity indices AI comparing the current data with undisturbed historical data according to the following two simple formulas:

$$AI(foF2) = 100^* (foF2-foF2^{med})/foF2^{med} \qquad (1)$$

$$AI(M(3000)F2) = 100^*(M(3000)F2 - M(3000)F2^{med})/M(3000)F2^{med} \qquad (2)$$

In these two equations $foF2^{med}$ and $M(3000)F2^{med}$ are the median values derived from the last 30 days before the current measuring values. Therefore, the AI values represent the deviations

of the current values from the corresponding median values in per cent. Here we assume that the median values describe the nearly undisturbed levels of both ionospheric measuring characteristics at the current moment. The use of median values instead of mean values is more appropriate as extreme values are more effectively eliminated.
Possible errors in the automatically scaled ionospheric parameters may be one error source for the estimated ionospheric indices. Some outliers in the individual values may be caused by such effects. Strong errors are however relatively seldom.

3. Data used in the investigations

For a description of the state of the ionospheric disturbance level in the European region it is necessary to use data from different stations to get an impression of possible dependencies of the derived activity indices on the latitude and longitude. In Table 1 the stations used in the presented analyses are listed together with their geographic coordinates.

Table 1: European ionosonde stations used to derive ionospheric activity indices.

Name of station	Geographic Latitude	Geographic Longitude
El Arenosillo	37.1°N	353.3°E
Athens	38.0°N	23.5°E
del Ebro	40.8°N	0.3°E
Rome	41.8°N	12.5°E
Pruhonice	50.0°N	14.6°E
Chilton	51.5°N	359.4°E
Juliusruh	54.6°N	13.4°E

For all 7 stations included in Table 1 the ionospheric indices AI(foF2) and AI(M(3000)F2) have been calculated according to equations (1) and (2) using data from October 2003 until March 2005. The data of the individual stations are in general hourly values, partly values obtained every 30 minutes or even every 10 minutes.
For some additional investigations hourly ionospheric activity indices have been derived from measurements at the station Juliusruh during the time interval between 1995 and 2004.

4. Investigations with ionospheric activity indices

In Fig. 1 the dependency between the hourly (including data with higher resolution if available) AI(M(3000)F2) and AI(foF2) values are separately shown for all 7 stations with the calculated linear regression lines and the corresponding correlation coefficients. First of all, the variability range of the AI(foF2) values is markedly larger than that of the AI(M(3000)F2) values. Secondly, there seems to be only a slightly positive correlation between both indices, at two stations the correlation is however negative. Therefore, in conclusion it must be stated that there is no significant correlation between these two activity indices.
In the correlation calculations between ionospheric activity indices of different stations only hourly indices have been included as for some stations only such values are available. The analyses are also restricted to data of the year 2004 only. In Fig. 2 the correlation results between the ionospheric indices of all seven stations are shown in dependence on the distance between these stations. Two tendencies can be detected. First of all, the correlations between the AI(foF2) values are systematically stronger than those between the AI(M(3000)F2) values. Secondly, the correlation becomes smaller if the distance between the investigated stations becomes larger.

During the period from October 2003 until March 2005 five geomagnetic storms occurred with maximum daily Ap values greater than 80. In Table 2 these storms are listed.

Table 2: Geomagnetic storms during the time interval between October 2003 and March 2005 The Apmax values are the Ap values at the first day of the disturbance, the values in brackets are the maximum Ap values during the storm if they are stronger than at the first day of the disturbance. The Dstmin values are the smallest hourly Dst value during the storm.

Date	Apmax	Dstmin
29 October 2003	204	-401 nT
20 November 2003	150	-472 nT
23 July 2004	52 (186)	-182 nT
8 November 2004	140 (161)	-383 nT
17 January 2005	58 (84)	-125 nT

All periods before, during and after these storms have been analysed by the estimated ionospheric activity indices. One storm interval is shown as a typical example in Figs. 3a and 3b connected with the ionospheric disturbances following the geomagnetic storm onset on 23 July 2004. In Fig. 3a the AI(foF2) values during this disturbance are strongly negative with AI(foF2) values partly below -60% over a period of up to 10 days, most pronounced at latitudes near and above 50°, but also clearly to be seen at lower latitudes. The negative phase of this storm starts at high latitudes together with the onset of the geomagnetic disturbance (sudden decrease of the Dst index, marked by the vertical dashed line). With decreasing latitudes the start of the negative disturbance is delayed by some hours. The corresponding AI(M(3000)F2) values in Fig. 3b are only very slightly negative just after the beginning of the disturbance, and the duration of this effect is essentially shorter than in the AI(foF2) values.
The more general behaviour of both indices during geomagnetic disturbances can be seen in Fig. 4 where the results of a superposed epoch analysis are presented, calculated only from the activity data AI(foF2) and AI(M(3000)F2) of the station Juliusruh. Here the data during all 5 geomagnetic storm shown in Table 2 are combined taking the beginning of the geomagnetic disturbances (e. g. marked by the vertical dashed lines in Figs. 3a and 3b) as time zero. In Fig. 4 the mean variations of Dst, AI(M(3000)F2) and AI(foF2) are shown in dependence on storm time. The general behaviour is characterized by marked negative AI(foF2) deviations starting with the beginning of the geomagnetic disturbance. This negative effect lasts up to more than 10 days. A similar effect has also been found in the corresponding AI(M(3000)F2) values. But here the effect is markedly smaller and shorter. The meaning of the small positive peak in AI(M(3000)F2) near the Dst-minimum is unclear until now, probably it is only an accidental effect.
The latitudinal variation of the ionospheric disturbance level deduced from the AI(foF2) values is shown in Fig. 5 by the occurrence probability in per cent of the absolute value of the AI(foF2) indices estimated for all 7 stations during the period from October 2003 until March 2005. The values |AI(foF2)| > X are presented for different disturbance levels X = 20%, …, 50% in dependence on latitude. Due to the results presented in Fig. 5 the disturbance level increases markedly from about 43° with increasing latitudes and with a smaller rate also towards lower latitudes below 40°.
The variability of the AI(M(3000)F2) index does not depend on latitude (not shown here) suggesting that the geomagnetic influence upon this index is markedly smaller than upon AI(foF2).
From daily AI(foF2) values estimated from observations at Juliusruh during 1995 until 2004 yearly ionospheric disturbance values have been derived. Here we use mean values of the occurrence probability of absolute AI(foF2) data |AI(foF2)| > 20%. These data are presented

in Fig. 6 in dependence on solar sunspot number (upper part) and on geomagnetic Ap index (lower part). In both cases a positive correlation has been detected. The best correlation has be found for the geomagnetic activity with a significance level better than 99% (Taubenheim, 1969), thus confirming the close connection between ionospheric activity indices AI(foF2) and geomagnetic disturbances as to be expected due to the results presented above.

5. Discussion

As to be seen from Fig. 1 the variability of the AI(foF2) values is markedly stronger than that of the AI(M(3000)F2) values.
Resulting from Fig. 5 the variability of the AI(foF2) values (described by the occurrence probability of |AI(foF2)| > X) increases with latitude above about 40-45°. This increase is mainly caused by negative storm effects. These storm effects increase with latitude as shown by an extensive statistical analysis of Matsushita (1959). The apparent increase of the occurrence probability of |AI(foF2)| > X below 40° latitude, however, is not fully clear. It cannot be excluded that it is an accidental effect as it bases mainly on the result at one station (El Arenosillo).
In contrast to the AI(foF2) values the variability of the AI(M(3000)F2) indices are nearly independent of the latitude and of the disturbance level. This finding is an indication that the impact of geomagnetic storms upon the AI(M(3000)F2) values is not so important as their impact upon the AI(foF2) values. The height of the F2-layer maximum, hmF2, can simply be estimated due to Shimazaki (1955) from the M(3000)F2 values by the following formula

$$hmF2 = \frac{1490}{M(3000)F2} - 176 \qquad (3)$$

Therefore, the AI(M(3000)F2) values can be interpreted by changes of the F2-layer peak height. Then it can be concluded that the variability of the peak height of the F2-layer is essentially smaller than that of the electron density at this height. This feature can also be seen from the investigations of the different geomagnetic storms, one example is presented in Fig. 3b.
The most marked ionospheric storm effects are observed in the AI(foF2) data with strong negative effects during the storms in summer and equinoxes; the storms during winter, however, have negative as well as positive phases (not shown her in detail). These seasonal differences are in general agreement with current storm theories (Prölss, 1993, 2005; Hargreaves, 1992). In summer the mean equatorward-directed thermospheric winds support the transport of atmospheric density changes (increasing ratio of molecular to atomic constituents caused by a magnetospheric energy input at polar latitudes) and create thus negative storm effects mainly at mid-latitudes. In winter the poleward-directed thermospheric wind system may at least partly prevent an effective propagation of such density disturbances towards the equator. In dependence on the strength of the auroral energy input and on the mean wind, positive and/or negative storm events may occur in winter.
The geomagnetic storm effects in AI(M(3000)F2) are relatively small, but mainly negative (that means increasing peak heights hmF2 during the main phase of the disturbances), and have an essentially shorter duration compared with the effects in AI(foF2).
The strong correlations between yearly mean values of the ionospheric disturbance level at Juliusruh (characterised by the values |AI(foF2)|>20% in Fig. 6) with the solar activity and especially the geomagnetic activity clearly demonstrates the expected behaviour that geomagnetically induced disturbances are the main reason of the observed ionospheric variability.

The very small correlation between the AI(foF2) and AI(M(3000)F2) values (see Fig. 1) is mainly caused by the different behaviour of foF2 and hmF2 during geomagnetic disturbances (negative and positive effects in foF2 in dependence on season and small positive effects in hmF2, different duration of disturbance effects in both parameters) and partly by errors in the automatic derivation of the characteristic ionosonde standard parameters.
The decreasing correlations between the ionospheric indices with increasing distance (Fig. 2) demonstrate the regional differences of the ionospheric disturbance level and the necessity of derivation of such indices at different stations as prepared in the DIAS project for the European region (Belehaki et al., 2005). The main reason of the regional differences are caused by geomagnetic storm effects discussed above but may at least partly also be caused by ionospheric disturbances during quiet geomagnetic conditions probably connected with atmospheric wave phenomena having their origin presumably in the lower atmosphere (Mikhailov et al., 2004).
The presented activity indices due to equations (1) and (2) may be slightly effected by the problem that the undisturbed reference level deduced as median value from the 30 days before the current value. Here we have to consider that these median values are more appropriate to the middle of this 30 days interval that means about 15 days before the current time. Therefore, an bias can be introduced in the estimated AI values caused by the seasonal variation of the foF2 and M(3000)F2 values. Mainly during time periods with strong seasonal variations these reference values may be slightly over- or underestimated. The general features of the derived activity indices are however not essentially influenced. Nevertheless in future some additional investigations are planned to reduce this influence.

5. Conclusions

The following conclusions can be drawn:

- For the description of ionospheric disturbances the AI(foF2) index is more appropriate than the AI(M(3000)F2) index. The markedly stronger correlation between AI(foF2) values of different stations than the corresponding smaller correlation between AI(M(3000)F2) values suggest the impression that the AI(foF2) values give a more consistent picture of the ionospheric disturbance effects. Nevertheless the AI(M(3000)F2) values may be important for more scientific investigations of ionospheric storm effects as they contain important information about height changes during such disturbances.
- The general features of the AI(foF2) and AI(M(3000)F2) indices during geomagnetic storms (positive and negative storms in foF2, increases of hmF2, seasonal differences, latitudinal variation) are in general agreement with the current knowledge of ionospheric storms (Hargreaves, 1992; Prölss, 1993, 2005).
- For the quantitative modelling of the ionospheric disturbances in defining operational values for radio propagation purposes it is important to know that MUF(3000), Maximum Usable Frequency for ground distance 3000 km (=M(3000)F2*foF2), depends primarily on the variability of foF2.
- To get a representative picture of the disturbed ionosphere over Europe it is necessary to derive the corresponding disturbance index not only at one station but at different stations simultaneously in Europe. Otherwise regional differences (e. g. the different reactions of the ionosphere at the beginning of an ionospheric storm in dependence on latitude) cannot be considered.

Acknowledgements

This work was co-funded by *eContent* Programme of the European Commission, EDC-11150 DIAS/28655.

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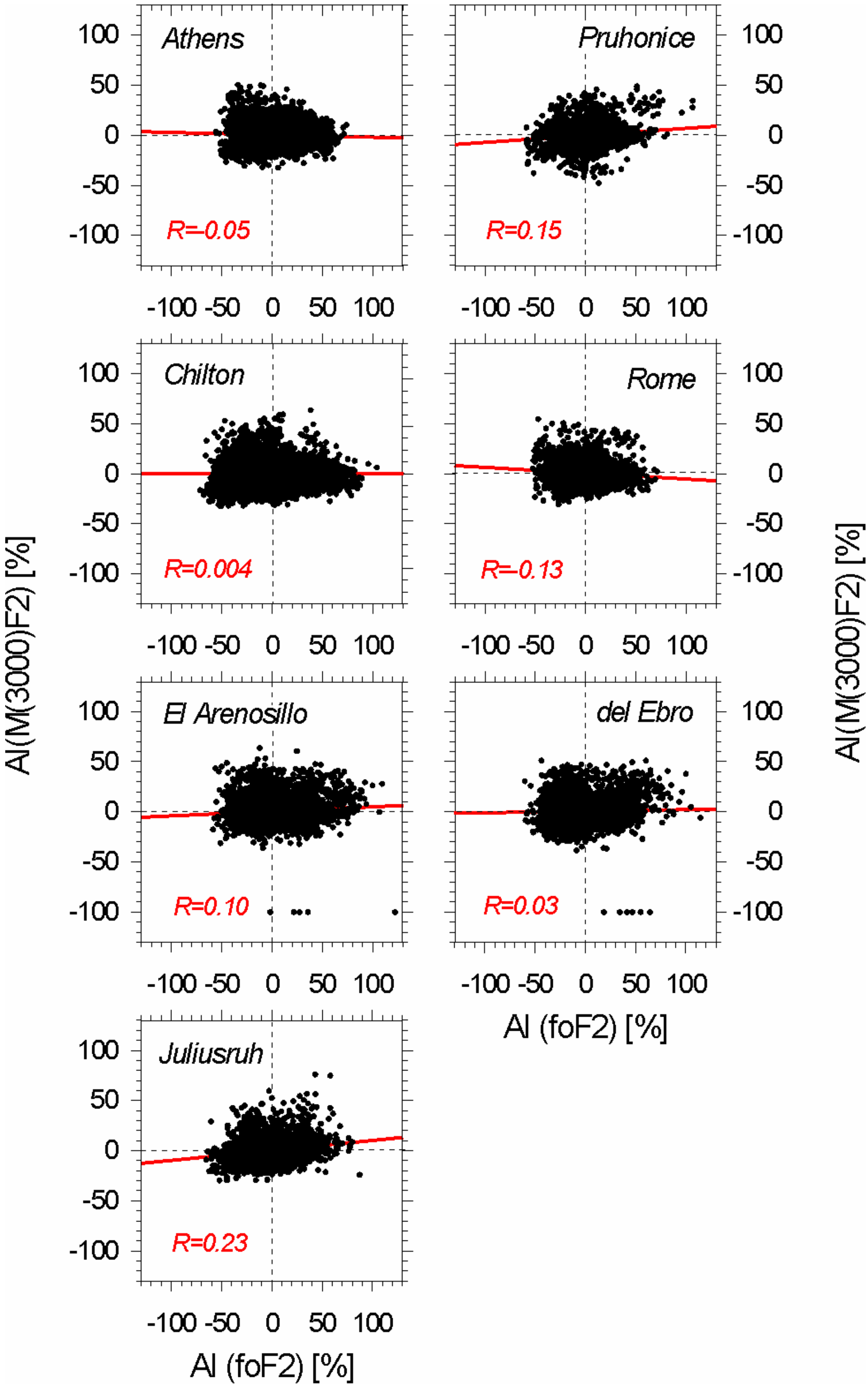

Fig. 1: Correlation between AI(foF2) and AI(M(3000)F2) indices estimated at 7 European ionosonde stations using data from October 2003 until March 2005. The regression lines and correlation coefficients are included.

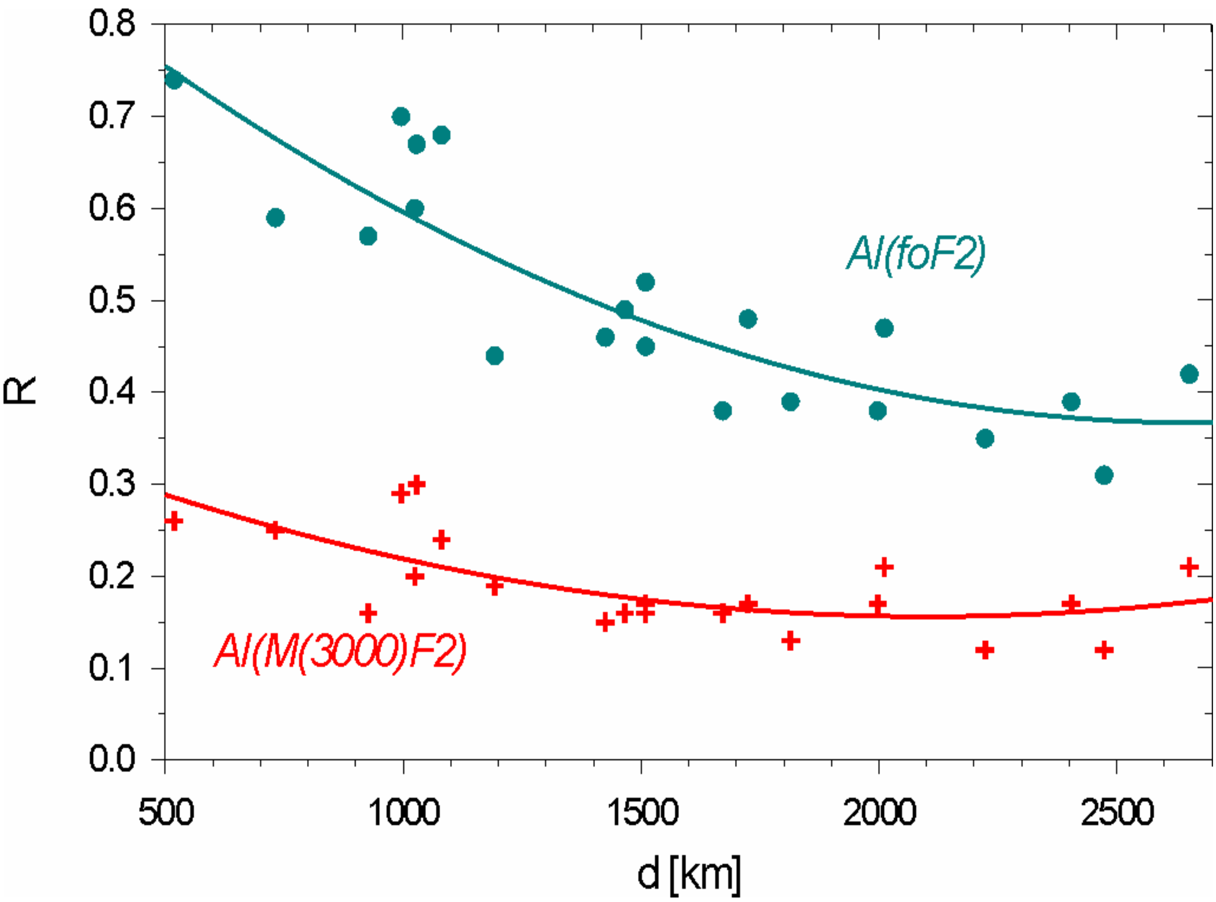

Fig. 2: Correlation coefficients R between hourly AI(foF2) or AI(M(3000)F2) indices estimated at different ionosonde stations in dependence on the distance between these stations. The data used are from the year 2004.

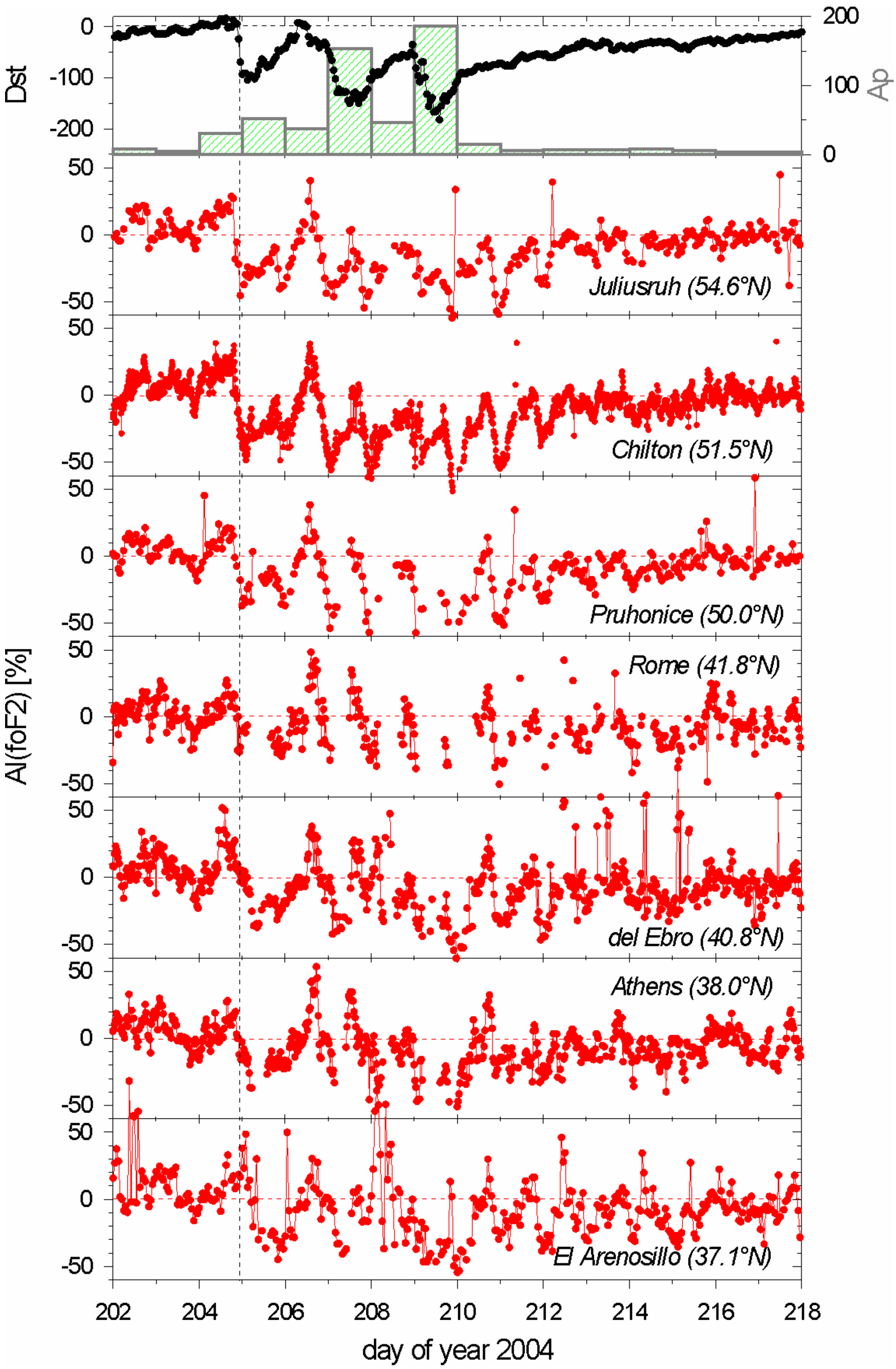

Fig. 3a: Variation of the AI(foF2) index at different stations as well as of the geomagnetic Ap and Dst indices during the geomagnetic storm starting on 23 July 2004. The latitude of the stations is given in brackets.

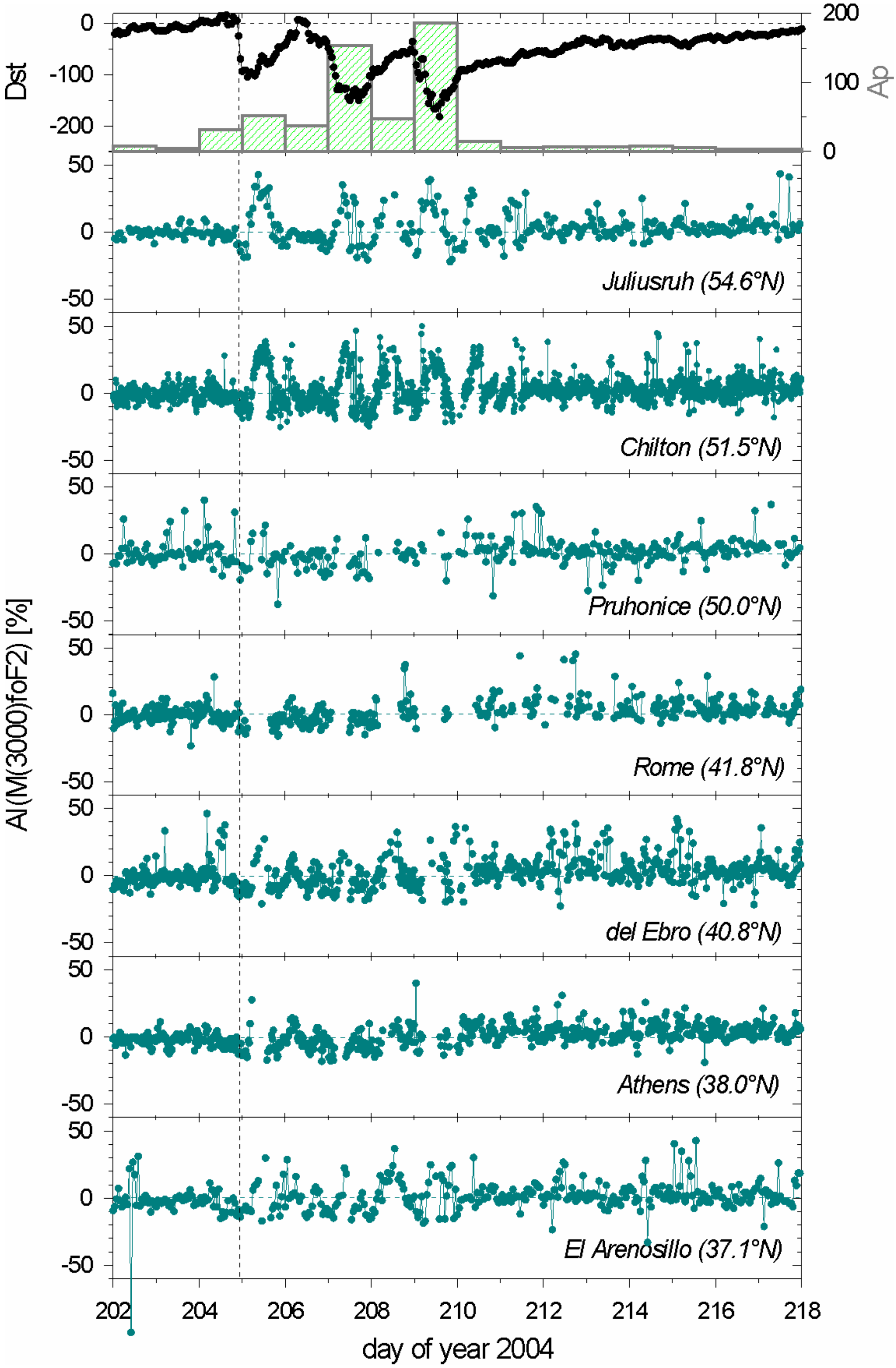

Fig. 3b: Variation of the AI(M(3000)F2) index at different stations as well as of the geomagnetic Ap and Dst indices during the geomagnetic storm starting on 23 July 2004. The latitude of the stations is given in brackets.

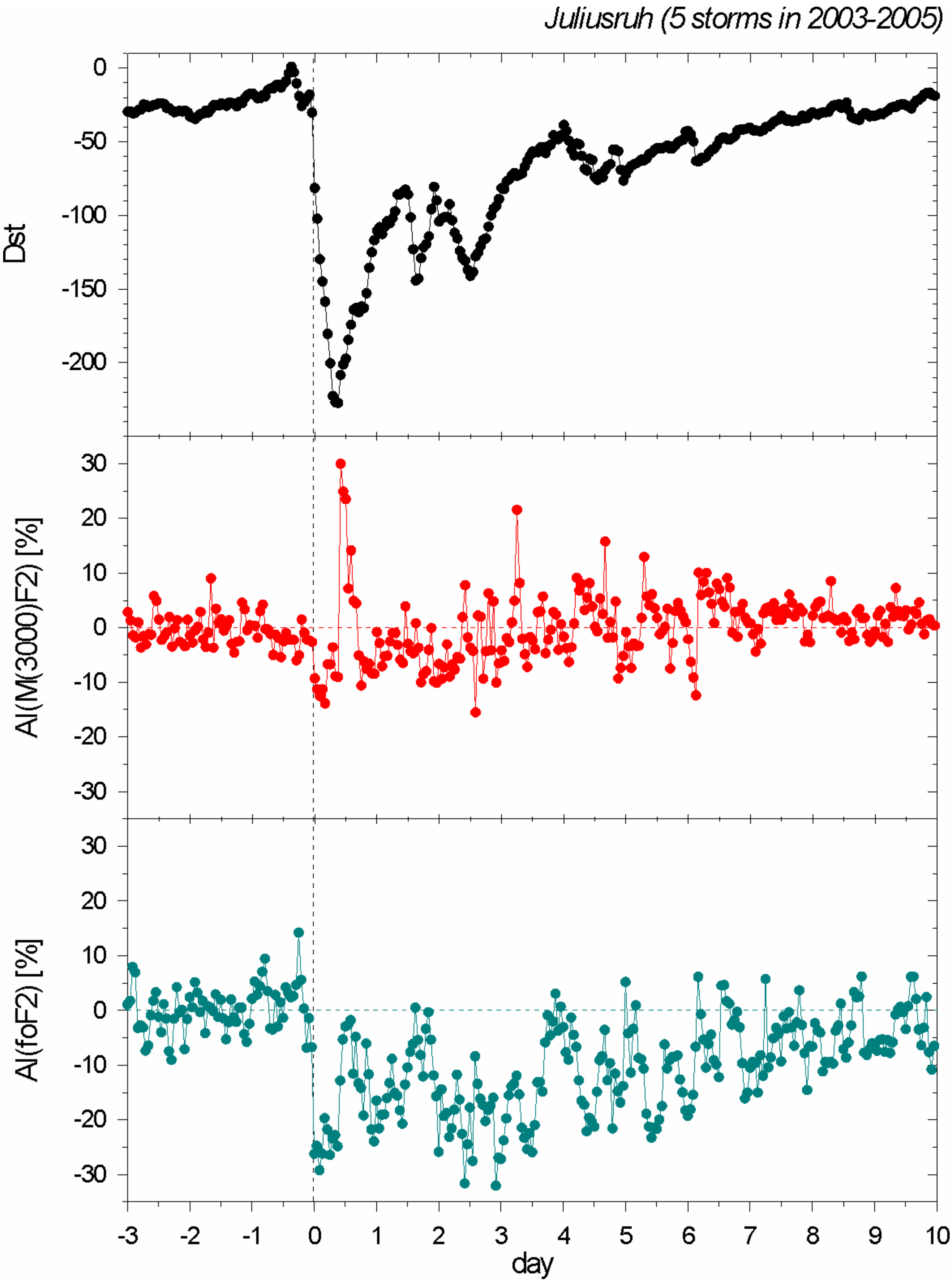

Fig. 4: Mean variation of the AI(foF2) and AI(M(3000(F2) indices at the station Juliusruh and of the geomagnetic Dst index derived from 5 geomagnetic disturbances (Table 2) with a superimposed epoch analysis using the start of the geomagnetic Dst disturbances a key time zero.

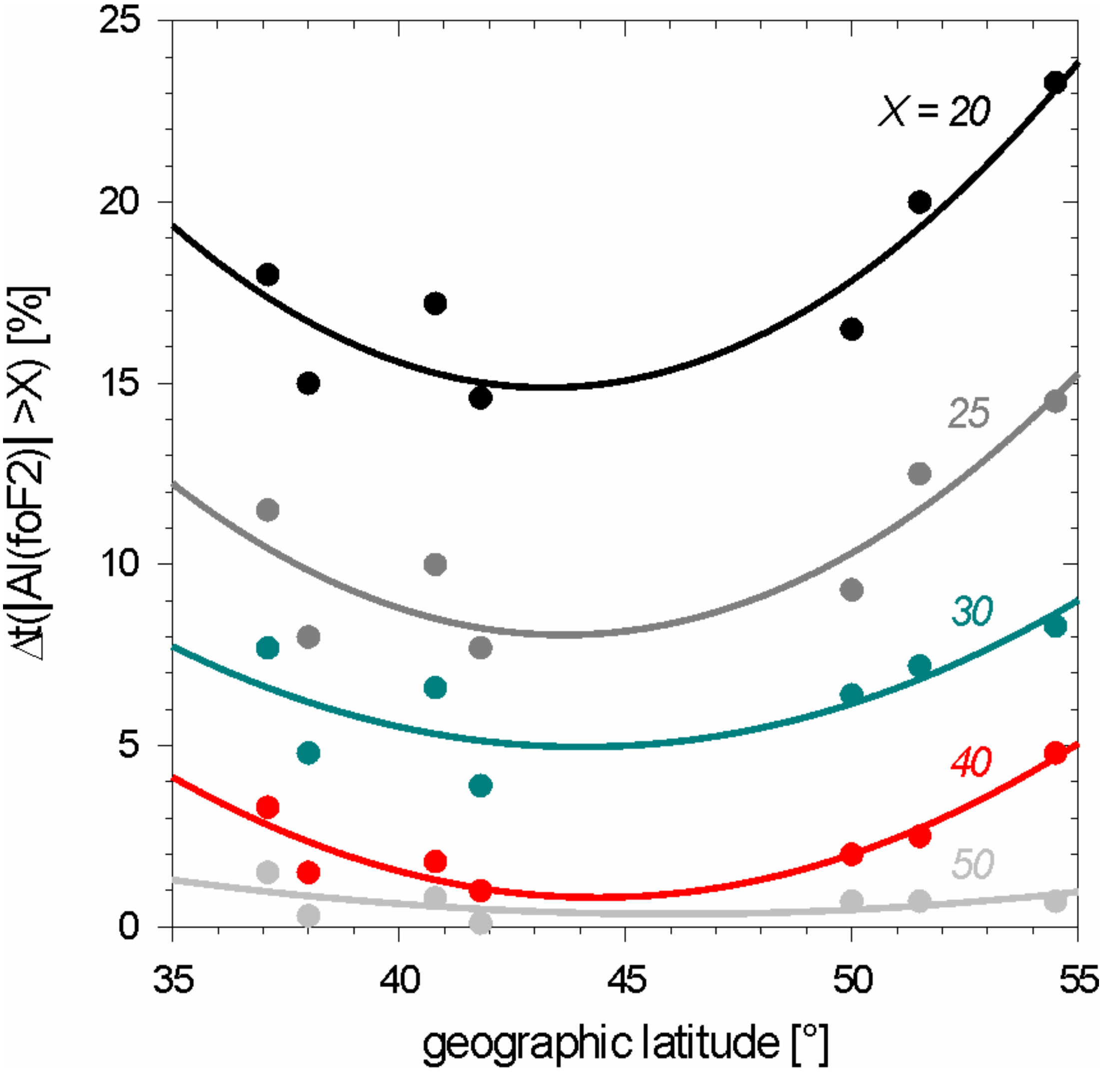

Fig. 5: Occurrence probability of |AI(foF2)|>X in per cent for different threshold values X in dependence on latitude derived from observations at different stations during the time interval from October 2003 until March 2005.

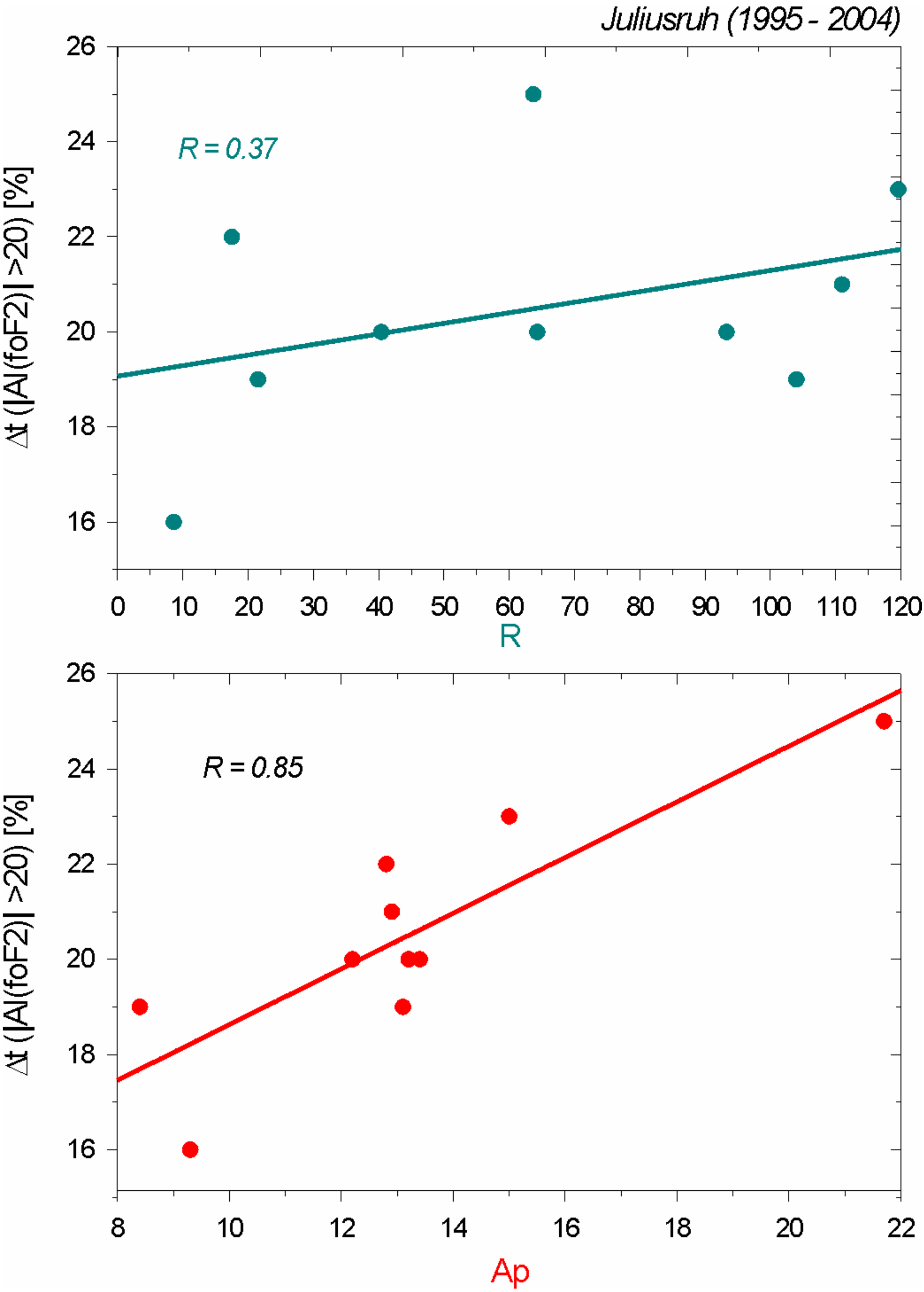

Fig. 6: Dependence of yearly mean values of the occurrence probability of |AI(foF2)| > 20% on solar sunspot number (upper panel) and on geomagnetic activity (lower panel) using AI(foF2) values from ionosonde observations at Juliusruh during the time interval from 1995 until 2004.