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# SEMIANNUAL FLUCTUATION AND EFFICIENCY FACTORS IN SUN-WEATHER RELATIONS

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Abstract. The changing nature of the Sun-weather relations over a 119-year period has been studied by using the geomagnetic aa index. The analysis yields consistent results on several time scales. The most important fluctuation found is a semiannual variation which can be related to the well-known variation of the geomagnetic activity. A threshold value of about aa≅19-20 nT is necessary to detect any solar influence on the weather. The role of the aa index (i.e., corpuscular influences) seems to be determinant in certain cases.

## Introduction

There is a widespread scepticism concerning the reality of the solar-meteorological relations. Although they are physically expectable, the obtained correlations are low in general, and the regularities are often ambiguous and short lived. Pittock [1978] gave a comprehensive review of the available literature and analyzed the different attempts, methods, and results. Only a few reported relationships can be regarded as convincing, mainly for methodological reasons and because of the complexity of the subject. However, the success of the quasi-biennial oscillation study [Labitzke and Van Loon, 1988] indicates that unambiguous regularities can be recognized even among seemingly stochastic events by chance and by a suitable separation of the data. Therefore we think the success of these studies will depend primarily on the consideration of the relevant factors and peculiarities (perhaps hidden as yet).

One of the most important methodological points is the use of suitable parameters. The Wolf number characterizes solar activity statistically fairly well in many aspects, but from the point of view of the terrestrial influences it is not always satisfactory. We compare its applicability with that of the geomagnetic disturbances, which indicates not only the occurrence of solar phenomena but also whether they affected the terrestrial environment. On the other hand, significant geomagnetic effects can happen also during the solar activity minimum because of the coronal holes.

The choice of the Wolf number or geomagnetism depends in part on the source of the solar energy input. The Wolf number is mainly related to the variations of the electromagnetic radiation but it is also related to the sporadic corpuscular events arising from the flares. On the other hand, the geomagnetic activity gives information primarily about the corpuscular impacts, i.e., about the various types of solar wind - magnetosphere interactions including the mentioned flare activity, but it is also slightly affected by the electromagnetic (EUV and X) radiation by means of the ionospheric currents. So the two sources are mixed to some extent in these two kinds of information; nonetheless, the geomagnetic activity characterizes overwhelmingly the solar corpuscular influence. The complex scenario is analyzed in detail by Simon and Legrand [1989]

The most suitable geomagnetic parameter for the investigation of long-term variability is the aa index introduced by Mayaud [1972]. It correlates highly with the geomagnetic am index, being the most sensitive indicator of the solar influence on the terrestrial magnetosphere. Its time span ranges from 1868 until 1986 in the present work, so it amounts to 119 years. This is the longest geomagnetic data series.

A thorough analysis has been published by Legrand and Simon [1989] and Simon and Legrand [1989] describing the details of the solar-geomagnetic phenomena on the basis of the aa index. The aa index has been used also by Gerety et al. [1977] who found no trace of solar influence on weather for four frequencies at a number of stations. They admit their method can be insensitive to some less common factors.

We examined some possible reasons for the mentioned ambiguities and the changing nature of the solar influences using temperature (T) and precipitation (r) data measured in Budapest.

## Semiannual Variations

The most surprising result of the present work is how effectively solar variations influence weather over the course of a year. Figure 1b shows the annual distribution of the K(T,aa) correlations of the monthly mean temperature and aa values for the whole 119-year period (the January value is the correlation between the monthly averages of T and aa for January of all 119 years and so on, these are 12 correlation values for the 12 months). The curve has two appreciable maxima, in spring and autumn, and a third one in winter. This latter maximum can be understood, by taking into account the so-called winter effect reported several times [e.g., Bucha, 1984], i.e., the highest efficiency of Sun-weather effects during wintertime. The other two maxima are rather similar to another distribution. As is well known, the geomagnetic indices have a semiannual run having peaks near the equinoxes. The 119-year averages of aa index for every month are plotted in Figure 1a; this semiannual variation is analyzed by Russell and McPherron [1973]. The enhancements of the correlation coefficients in spring and autumn seem to support the idea that the efficiency of Sun-weather effects is connected with the same factor as the above modulation of the geomagnetic activity level.

There is another argument in favor of the above idea. The annual distribution of the 119-year correlation between aa index and monthly

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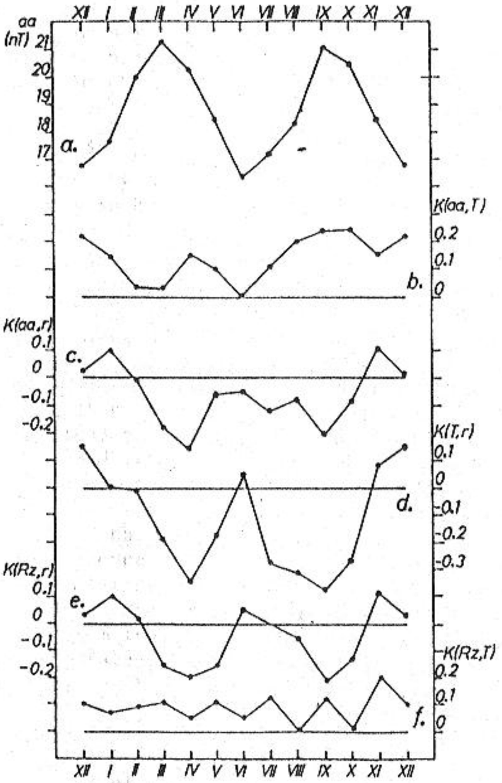

Fig. 1. (a) The 119-year averages of aa index for each month. (b-f) Annual distribution of correlation over the 119-year period for different parameters.

total precipitation (K(aa,r)) shows a similar course with opposite sign, having two minima, at the equinoxes (see Figure 1c). The behavior of the third (winter) extreme is different, suggesting that the winter effect operates differently from the semiannual variability. Since the precipitation and temperature are obviously not independent, it is worth examining their relation in the course of the year. The annual distribution of the 119-year precipitation-temperature correlation (K(r,T) (Figure 1d) is similar to that of K(aa,r); i.e., it is not constantly negative. This can also be of solar origin considering the foregoing discussion.

Thus the monthly values of the temperature and precipitation are not always correlated (at a given location), but if they are, then the correlation is solar-induced and follows the scheme plotted in Figure 2.

The question of the correlation significance is rather complex. If the data were statistically independent, then the peak values of, for example, K(aa,r) would exceed the correlation of two uncorrelated random series with probabilities of 99% and 95%, respectively. However, the data are not independent, because of the trends in the geomagnetic activity (solar cycle) and in the weather patterns (e.g., El Nino Southern Oscillation), so the mentioned probabilities might be overestimated. On the other hand, the solar-induced effects can lag with respect to the solar effect itself, so if we deal with the solar and terrestrial data measured in the same (unshifted) periods, i.e., in the calendar months (as in the present case), then it is very likely that we can get correlation values even lower than they are in fact. So this complicated matter can be treated only with a more detailed data base and more sophisticated time series analysis in the future, and now we just focus on the qualitative features of these distributions.

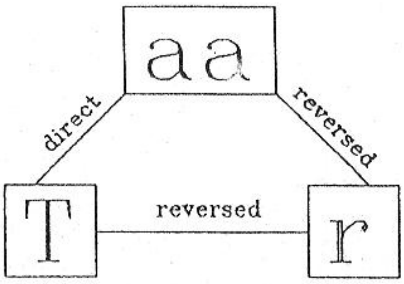

Fig. 2. Relations of geomagnetic activity (aa), temperature (T) and rainfall (r) in Budapest in the case of sufficient level of geomagnetic activity.

The shapes of the mentioned correlation curves are not identical with the shape of the aa curve. For instance, the vernal extremes fall in April instead of March, which may be a lag effect as mentioned above, but the semiannual character is perceivable nonetheless.

It is interesting to compare these curves with the annual variation of correlation between the Wolf number (Rz) and precipitation or temperature, i.e., K(Rz,r) or K(Rz,T) (see Figures 1e and 1f). Surprisingly, K(Rz,r) has a similar shape to K(aa,r), although we do not expect a higher efficiency rate of any effect of the Wolf number around the equinoxes, which is expected mainly for magnetic features. The semiannual character of the K(Rz,r) curve is probably caused merely by the Rz-aa connection. This is an interesting example in that there is an apparent relationship with the Wolf number, but it can be interpreted only through geomagnetism. On the other hand, the K(Rz,T) curve (Figure 1f) does not have any semiannual character, so this fluctuation is certainly of magnetic (corpuscular) origin.

It is very important to emphasize that the above statements refer to a 119-year time interval. When checking the phenomenon over decreasing periods, the semiannual character gradually decreases. But the shorter the period is, the less significant are the correlation values. In any case, this is a somewhat paradoxical situation: a short-term variation manifests itself only over a long period.

Work is in progress to investigate the site dependence of this phenomenon. We have some preliminary results indicating similar behavior at several remote European sites under certain conditions. But this is beyond the scope of the present paper, and it will require the gathering and analysis of a large number of data in the future.

## Variations During Solar Cycles

We followed the method of Clayton [1923] (see also Herman and Goldberg [1978]) to make our results comparable. This is a superposed epoch analysis with two fitting markers: the maximum years (M) and minimum years (m). Eleven cycles were used (in Clayton's work, five cycles) from 1866 until 1986. Intervals of 8 years were chosen around M and m (the (M-4)-(M+3) and the (m-3)-(m+4) intervals), and they were matched to each other, resulting in eleven 16-year periods. In order to eliminate any secular change the periods were normalized in such a way that the 16-year averages were computed for all 11 periods and they were subtracted from the yearly data in each period (this normalization is lacking in Clayton's work because he considered only five periods). After that the corresponding years of these intervals were averaged, and the obtained 16-year interval was smoothed by a 5-year running mean truncating the period to 12 years. The above procedure eliminates all the disturbing factors, so that the obtained trends reflect the properties due to the solar cycle; the curve is plotted in Figure 3.

At first glance, these curves are not characteristic, but in comparing the rainfall curve with Clayton's plots, we see that it is similar to Clayton's plots for middle latitudes; furthermore, our plots seem to show the opposite behavior of the temperature and rainfall shown in Figure 2, so they cannot be considered incidental.

As a matter of fact, such curves alone cannot be regarded as decisive; one can treat them only by comparing with others. For instance, the standard deviations of the single values are so high (their mean values are 0.7°C and 110 mm, respectively) that the obtained curves could even be replaced by a horizontal straight line, from a purely statistical point of view. However, the two considerations in the previous paragraph confirm the reality of these curves, and so they enable us to estimate the rate of solar and non-solar effects, that is, the ratio of the variability of smoothed curves and the greatest error bar. This ratio amounts to less than 20% in Budapest (temperature: 0.25°C/1.6°C=0.156; rainfall: 50 mm/317 mm=0.158) for the above 11 solar cycles, so the role of the solar cycle is rather weak, and the forecast can hardly be improved by taking it into account.

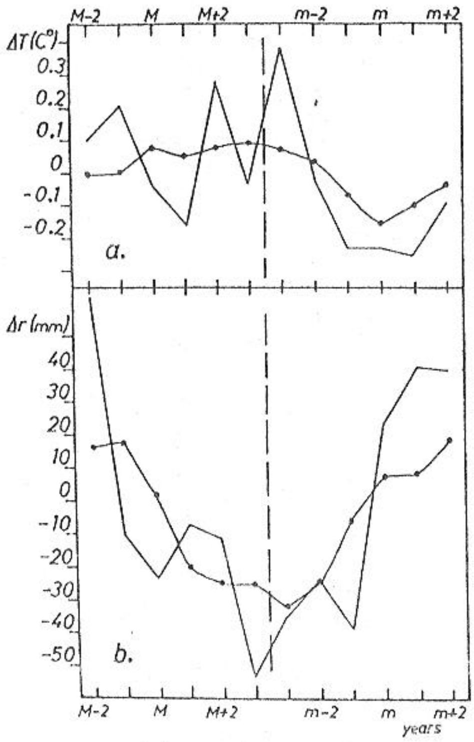

Fig. 3. Runs of (a) annual mean temperature (T) and (b) total annual rainfall (r) in Budapest, averaged over 11 solar cycles by superposed epoch analysis. Solid lines: annual averages; dotted curves: 5-year running means.

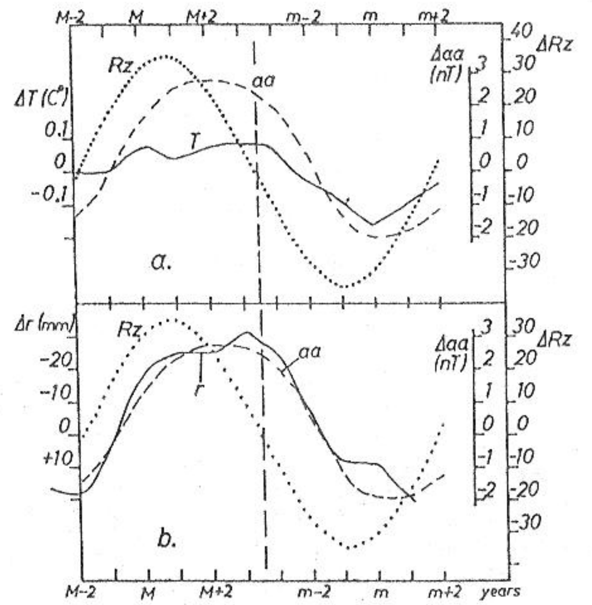

Fig. 4. Comparison of superposed epoch curves (as in Figure 3) of the Wolf number (Rz, dotted lines) and aa index (aa, dashed lines) with (a) temperature (T) and (b) rainfall (r); r is inverted and shifted by 1 year to the left.

Let us compare these superposed epoch curves with those of the Wolf number and aa index processed by the same method (Figures 4a and 4b). If we invert the precipitation curve through the x axis and shift it by 1 year to the left, it becomes quite comparable with the aa curve, but not with that of the Wolf number (whose maximum here does not coincide with the marker M on account of the strong asymmetry of the original unsmoothed Rz curve). The shapes of curves suggest the connection with aa rather than with Rz. The T, aa, and Rz curves are plotted without any shift, confirming the foregoing. This also indicates the role of the corpuscular processes.

The 1-year shift of the precipitation may be real. If we compute the aa-r and aa-T correlations by shifting the r and T series (annual means) with respect to the aa series, then the K(aa,T) values are decreasing (0.411, 0.338, 0.233, 0.124,...), whereas the absolute value of K(aa,r) is higher at 1- to 2-year shifts and only after that decreases (-0.270, -0.316, -0.316, -0.244, -0.235,...) so there may in fact be inertia of the precipitation response, presumably because the ocean is a large heat reservoir.

On the other hand, the maximum of the aa curve is also shifted with respect to that of the Rz curve to the declining phase of the activity cycle. The similarity of the T and r curves to the aa curve indicates that the meteorological parameters may be related to the corpuscular phenomena of the declining phase, namely to the solar wind streams from the polar coronal holes extending to low heliographic latitudes in the before-minimum periods and causing recurrent geomagnetic disturbances [Livshits et al., 1979; Legrand and Simon, 1981].

We note that the relations in Figure 2 remain valid.

## Long-Term Solar-Climatic Relationships

Figure 5a shows the permanent increase of the annual mean of aa and temperature and the decrease of the total annual precipitation over the truncated 119-year interval smoothed by a 11-year running mean. The secular increase of the temperature may also have nonsolar causes (greenhouse effect), but the similar trends of aa and T and the opposite trend of r are in accordance with Figure 2, so the solar activity probably also contributes to these trends.

The shorter-term behavior has been studied by a low-pass filter technique. The Fourier series of the T and aa series have been computed, and approximations of both series have been produced using components of periods longer than 6 years (Figure 5b). The relation of the two curves has a random character until about 1950, and following that they become somewhat "coherent", suggesting that the efficiency of Sun-weather relations may increase with the disturbance level, as suggested above in connection with the semiannual wave. The case is rather similar to the precipitation curve processed in the same way and inverted (Figure 5c). The fluctuations of the curves are obviously not real; they just reveal that any Sun-weather connections may manifest themselves on a time scale of more than a few years. On shorter time scales some nonsolar phenomena could be predominant over the solar effects or at least alter them by influencing the ability of the atmosphere to respond, such as the stratospheric QBO phenomenon [Labitzke and Van Loon, 1988], which may also play a role in the big statistical scatter mentioned for the cycle dependence. This improvement in relationship is not an artifact of the Fourier procedure; it can be seen also by comparing the original curves through the noises. The low-pass filter technique can be performed also by 5-year smoothing, which leads to the same conclusion. In any case, the relations in Figure 2 are also confirmed on a time scale of a half decade.

The above mentioned improvement can be checked

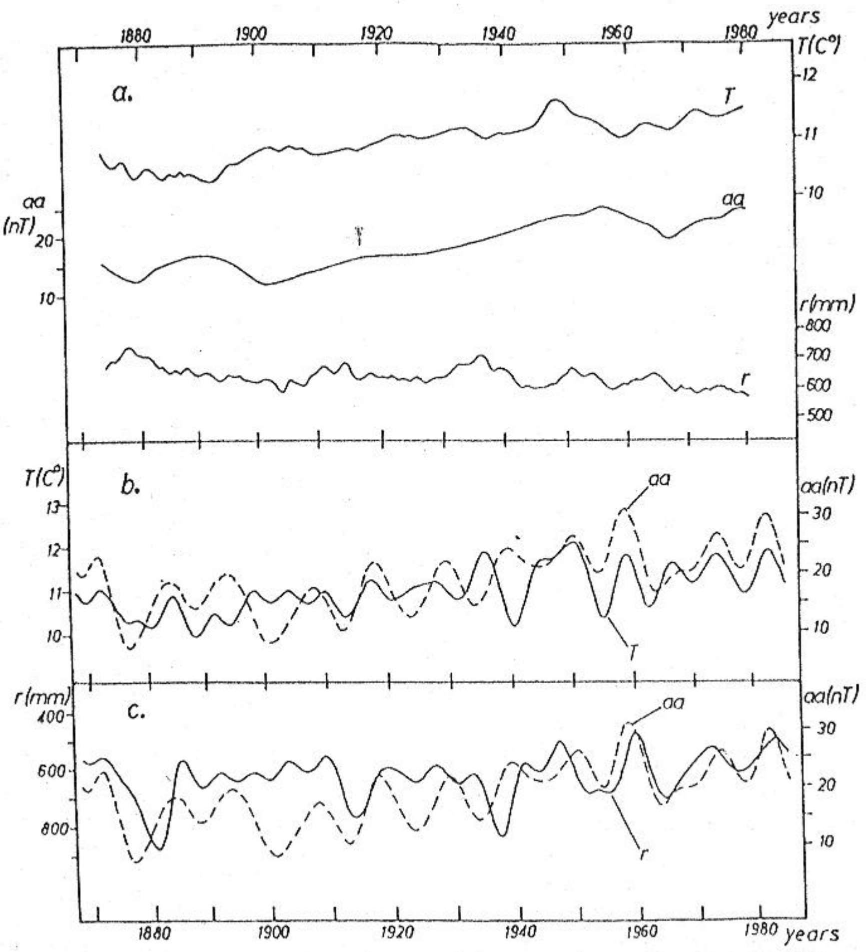

Fig. 5. (a) Secular changes of T and r (in Budapest) and aa index; (b and c) data series processed by low-pass filter for periods longer than 6 years; annual mean temperature (Figure 5b), annual total rainfall (Figure 5c), and aa index (dashed lines in both panels). The scale of the rainfall is inverted.

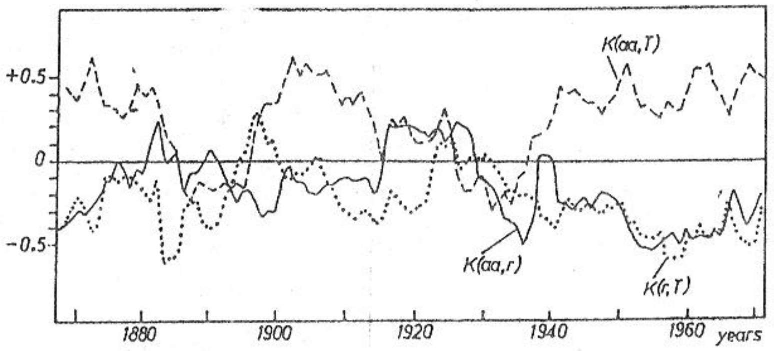

Fig. 6. The 15-year sliding correlations for various parameters. The correlation values indicated for a given date refer to the following 15 years.

with the procedure of Bell [1977]. Correlation coefficients have been computed between precipitation, temperature, and aa index over 15-year periods (called "windows" by Bell) by shifting these periods by 1-year steps. The resulting curves are plotted in Figure 6. The correlation coefficients for a given year refer to the following 15-year interval. The reliability of the curves is supported by the fact that their trends correspond to the relations in Figure 2, and this becomes particularly remarkable after 1940, as in Figures 5b and 5c, considering the definition of the sliding correlation.

It appears that the improvement of correlation can be detected above an average geomagnetic activity level of about 19-20 nT on the basis of Figures 1, 5, and 6, which means on both annual and decennial time scales. The important difference is that the secular change is an intrinsic solar phenomenon but the semiannual variation is just a modulation of that, indicating that we cannot rely only upon the solar phenomena but we should know what hits the Earth in fact. So this threshold is important for the functioning of solar influences on weather. If the aa index reaches this level, it indicates solar effects capable of affecting the weather processes; below this level, nonsolar effects prevail.

This is the activity level below which the days are classified by Legrand and Simon [1989] as quiet days. The recurrence activity is caused above this level (disturbed days) by the solar wind of velocity v ≥ 450 km/s, emitted by the polar coronal holes [Simon and Legrand, 1989].

Work is under way to clarify the impact of the different geomagnetic activity classes described by Simon and Legrand [1989]. This will require the proper grouping and selection of data, unlike the present studies where the complete data sets are used in each case.

Furthermore, the curves of Figure 6 offer a new kind of information: a longer-term fluctuation appears to be present in the Sun-weather connection, influencing the ability of the atmosphere to respond to solar effects also on a time scale of a few decades. This may be the reason for many correlation reversals and failures around 1940-1950, summarized by Herman and Goldberg [1978].

TABLE 1. Correlation Coefficients for 119 Years

| | aa | Rz | RzH |
|---|---|---|---|
| T | 0.423 | 0.230 | −0.097 |
| r | −0.289 | −0.160 | 0.011 |
| Rz | 0.579 | | |

Now that we have discussed the time scales, let us consider the 119-year period as a whole and compare the correlation coefficients (K) of the annual means of the parameters during the period (Table 1); RzH is the Wolf number of the Hale (22-year) cycles when the consecutive cycles have alternating signs. The meteorological parameters have much higher correlations with the aa index than with the Wolf number, and the table also confirms the relations of Figure 2.

## Summary and Conclusions

We can summarize some reasons for the low correlations in the Sun-weather relations and some conditions for the efficient solar influences.

1. The use of the geomagnetic aa index is proven to be more relevant than that of the Wolf number in some cases studied. This does not concern the general applicability of the Wolf number

2. A semiannual wave has been found in the correlation coefficients of Sun-weather connections over a 119-year interval, having peaks near the equinoxes. This can be related to the semiannual modulation of the geomagnetic disturbance level. Thus the solar influences are not uniformly efficient in the course of a year (Figure 1).

3. The solar activity is not determinant among the influencing factors; its weight can be estimated to about 15-20% during the solar cycle.

4. The meteorological parameters have a closer relationship with the geomagnetic activity cycle than with the temporal distribution of the Wolf numbers. The influence of the before-minimum high-velocity wind streams is probable.

5. Correlations can be detected only above the geomagnetic activity level of about 19-20 nT (Figures 1, 5, and 6).

6. A long period is necessary to point out any correlation, but both the state of the atmosphere and the solar activity can change during such a period (Figures 5 and 6).

In spite of the above mentioned fluctuations all the time scales studied have a common feature at the location studied (Figure 2): if the solar influence works at all, then the aa index* is positively correlated with the temperature and negatively with the precipitation, and consequently the precipitation and temperature are negatively correlated (which is certainly not trivial; see Figure 1) in Hungary. These time scales are (1) a half year (Figure 1), (2) about a half decade (Figure 5b), (3) the solar cycle (Figure 4), (4) several decades (Figures 5 and 6), (5) centennial trends (Figure 5), and (6) the entire period as a whole (Table 1). This complexity, along with such phenomena as, for example, the QBO, can perhaps partly explain the difficulties of detecting Sun-weather effects, as well as the weak, ambiguous, or absent cycle dependence [Gerety et al., 1977]. Many conditions can be superposed, and they can alter or reverse the overall trends.

As for the connection of the precipitation and temperature, it is more or less incidental at low-level solar influence, but we may suppose that if this influence becomes greater (growing K(aa,T)) it can generate occasionally circulation mechanisms which result in a more obviously opposite behavior of precipitation and temperature at a given site. The possible link between the polar heating and atmospheric circulation is studied by Bucha [1976, 1984]. The validity of the relations in Figure 2 is restricted to the given station; the above mentioned circulation mechanisms can result in different relations at different places. The dependence of the above processes on the geographic position will be the subject of a following study. The subject of the present paper is primarily the time factor, which can be studied only with the longest available data series, which makes the aa index a very important parameter in Sun-weather studies. We can fully take advantage of it by using the total number of data without any arbitrary selection in all cases studied.

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