Cyclic and secular variations of the inner structure of sunspot groups

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In this work, we will consider variations in the sunspot structure, i.e., the time variation of the relative area of the sunspot umbra q.

$$q = SU/S, \quad (1)$$

where SU and S are, respectively, the area of the umbra and the whole sunspot.

We used the data from

http://solarscience.msfc.nasa.gov/greenwch.shtml.

The dependence of the relative area of the umbra on other sunspot characteristics and on time was considered by various authors (e.g., see Waldmeier, 1941; Dezs¨o and Gerlei, 1964; Vitinsky, 1982; Antalov´a, 1971, 1991 and references therein)

Nicholson (1933) , and Waldmeier (1939) showed that, in isolated, circular spots q = 0.174. The cycle dependence of q was not considered in these papers.

Jensen, Nordø, and Ringnes (1955), Tandberg–Hanssen (1955) were the first to study the cycle variation of this ratio and found that for for regular spots and for bipolar and complex groups

1) q was lower in the epochs of 11-year maximum than in the epochs of minimum;

2) q is decreasing with the increase of the sunspot area S.

The results of Antalov´a, 1971, 1991 agree with the conclusions of Jensen, Nordø, and Ringnes (1955) and Tandberg–Hanssen (1955) with allowance for different definitions of the magnitude under examination.

Hathaway, Wilson, and Campbell (2007) showed that the mean value of q was 0.2 for the entire period under examination. The value was decreasing. with the increase of the mean sunspot area. The cycle dependence of q was weak, and the dependence on latitude was absent. An unexpected result was that q for small sunspot groups began to increase dramatically from 1910, attain the maximal value at 1930 and, then, restored to its “normal” value by 1950.

We started working on the problem in 2006 (see Bludova and Obridko, 2007).We studied the behavior of the ratio q of the umbral area to the total sunspot area over the entire period covered by the Greenwich Catalogue (1874–1976).

In Section 2, we demonstrate the time dependence of q and corroborate its dramatic increase in the 1930-ies. There is good reason to believe that the latter was partly due to the increased number of small spots.

Then, we analyze the dependence of the relative area of the umbra on the sunspot group total area (Section 3).

The linear approximation of this relation is considered in Section 4 where we analyze the dependence of the approximation coefficients on time and on the total group area.

Section 5 devoted to Cycle and time variations in the relative contribution of large and small sunspot groups

The Discussion is devoted to the relation of our results to the secular variation of sunspot characteristics and, probably, to the solar dynamo mechanisms.

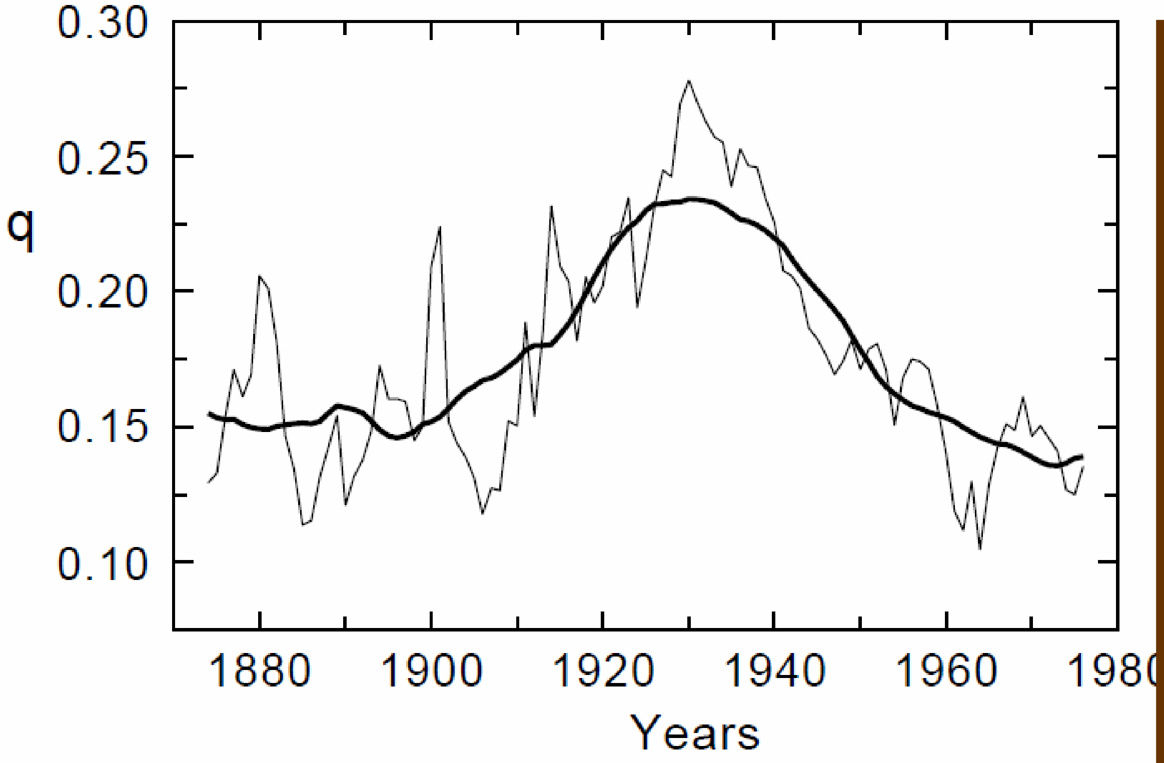
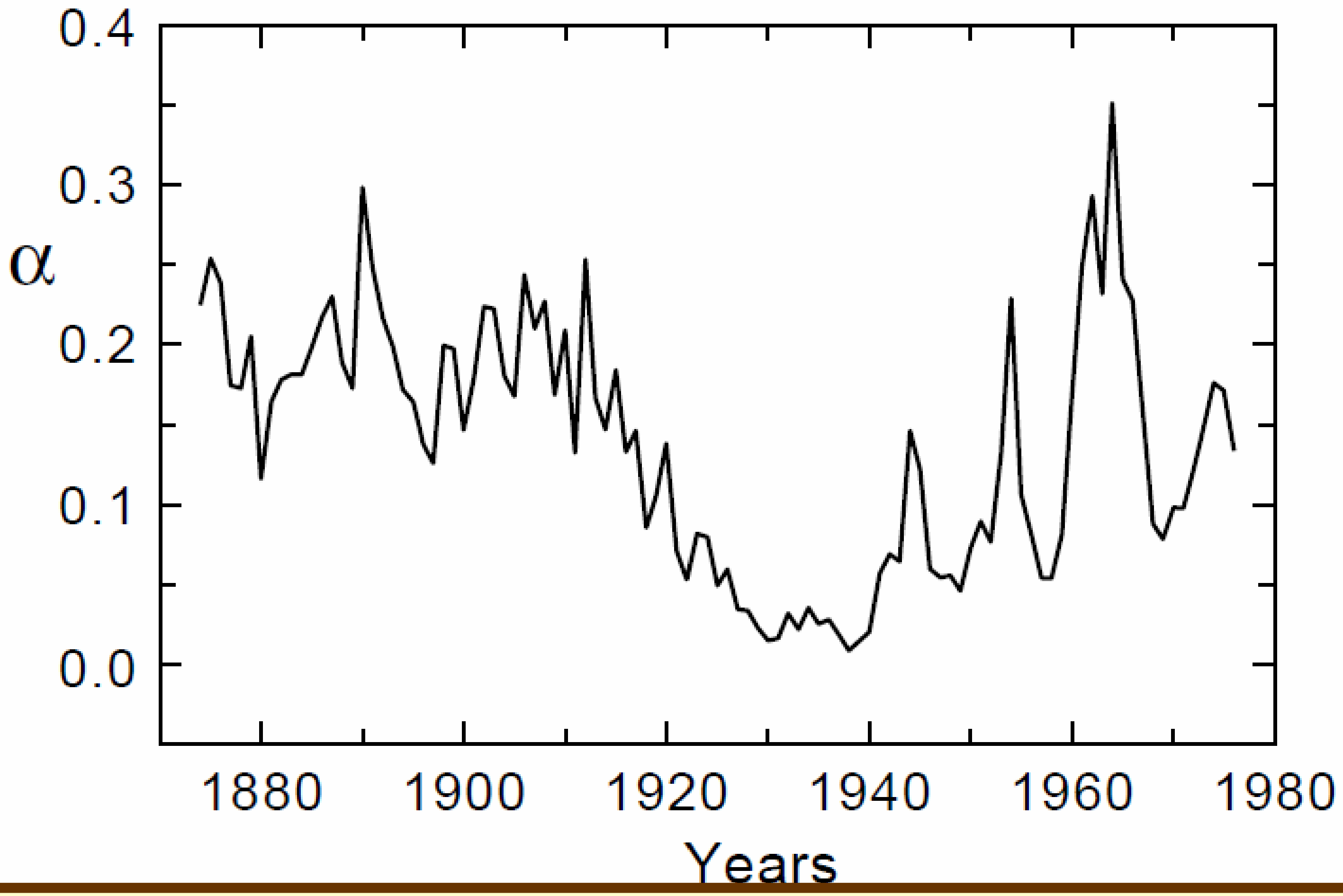


Fig.1. The ratio of the umbral area to the total area of the sunspot group (thin curve)
and its moving average obtained with a sampling window of 25 years (thick curve).

At the end of the 19th century, q was equal to 0.15.
At the beginning of the 20th century, q started to increase and reached its maximum of 0.28 in the early 1930-ies.
After that, it began to decrease and had dropped to 0.13 by the 1970-ies. This is, probably, the level that Hathaway, Wilson, and Campbell (2007) called “normal”.



Nonstandard objects – groups of sunspots without umbra.
Fig. 2 shows the relative number of sunspots without recorded umbra . This number changed significantly with time and was virtually zero during the 1930-ies and 1940-ies. The sunspots without umbra were scarce in the years when the annual mean relative area of the umbra q was maximum.

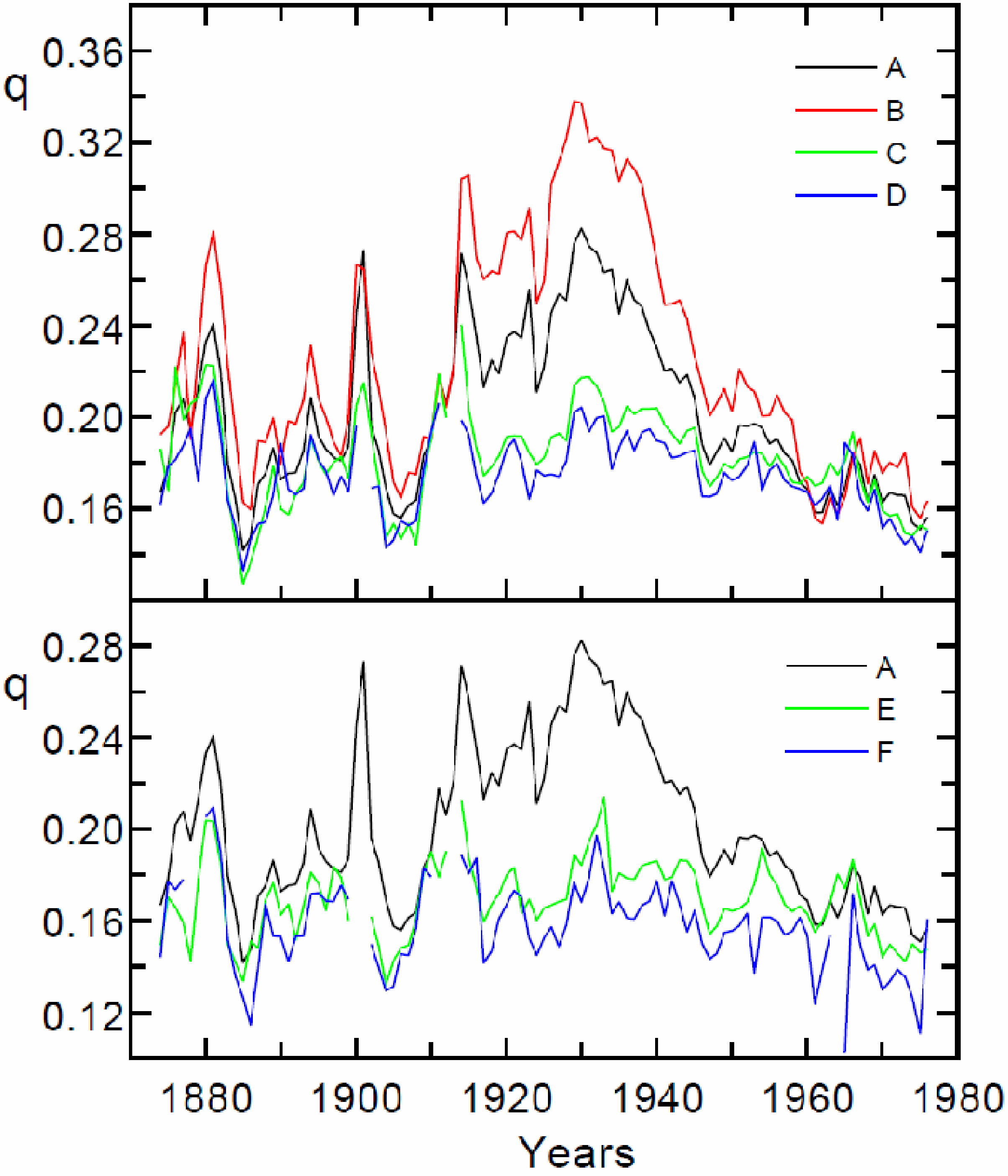


Figure 3. Upper panel, from top down: q for the spots of area no more than 100 m.v.h. (red curve), for all spots (black curve), for the spots of area 100-200 m.v.h. (green curve), and for the spots of area 200-300 m.v.h. (blue curve). Lower panel, from top down: q for all spots (black curve), for the spots of area 300-600 m.v.h. (green curve), and for the curves more than 600 m.v.h. (blue curve).

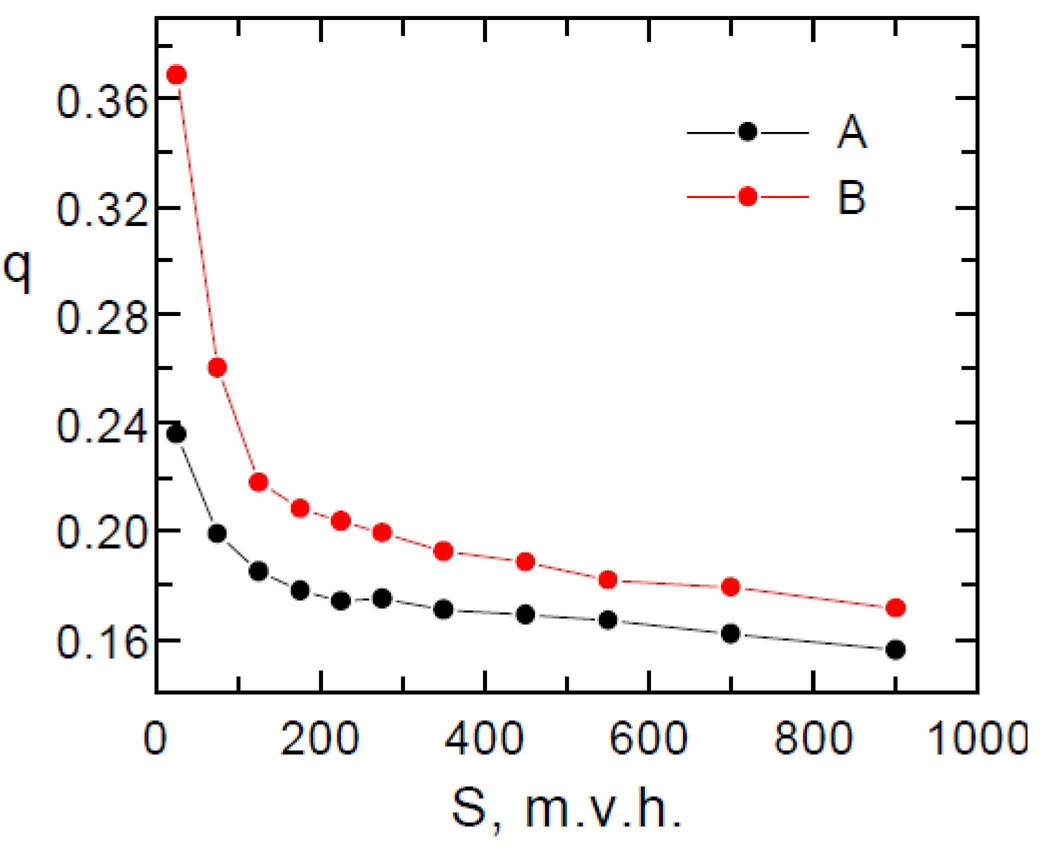


Figure 4 shows the mean value of q for the entire period under consideration (curve A) and, as an example, for 1929 (curve B). One can see that q decreases with the increasing mean area of the sunspot group. The same is true for any other year.

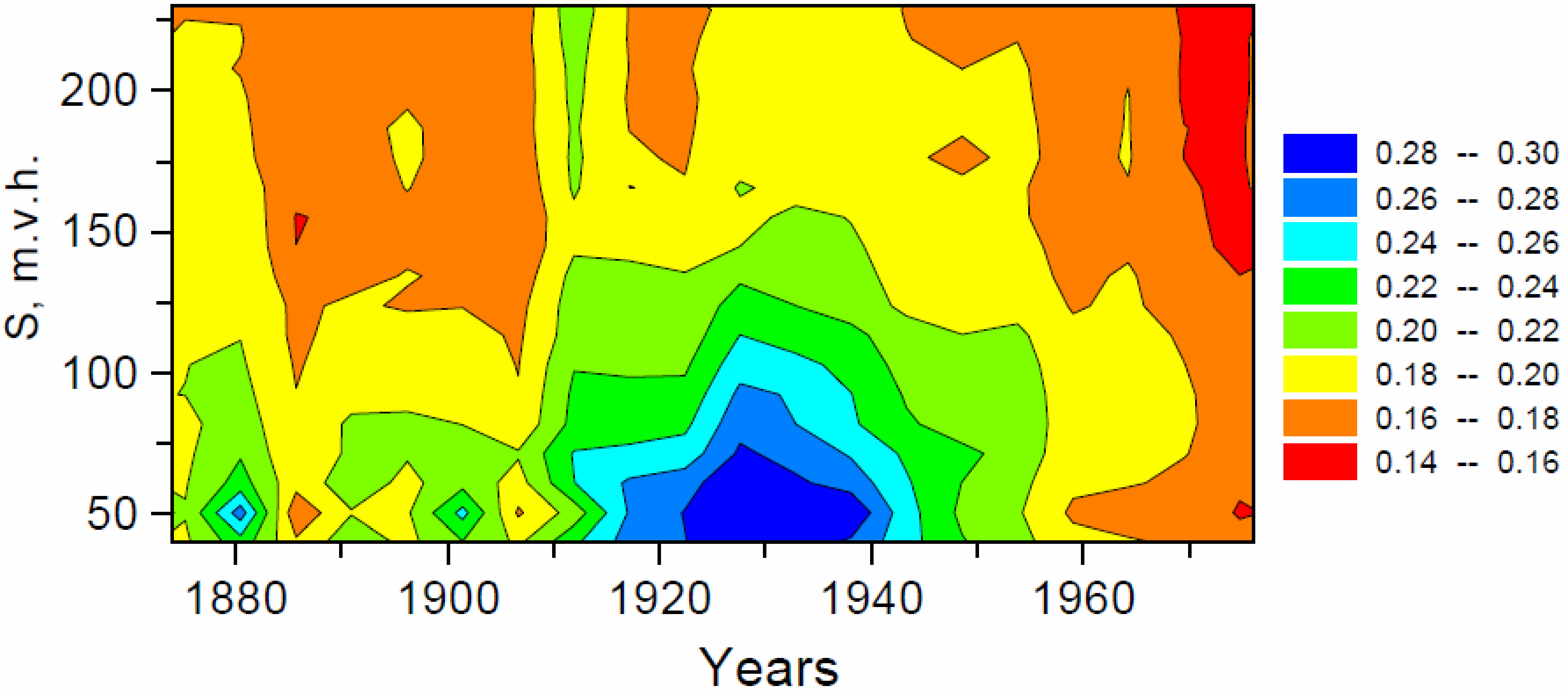


Figure 5 illustrates the conclusions drawn above. It represents the general distribution of q in the time–area reference frame. Different colors denote eight ranges of q. Red corresponds to the smallest values and blue, to the largest ones. It is readily seen that the parameter q increased in the 1930-ies. The increase can be revealed for the spot of areas up to 200 m.v.h., but it is best pronounced for the smallest spots. The figure shows also that the mean value of q was decreasing with the increase of the group area throughout the time interval under consideration

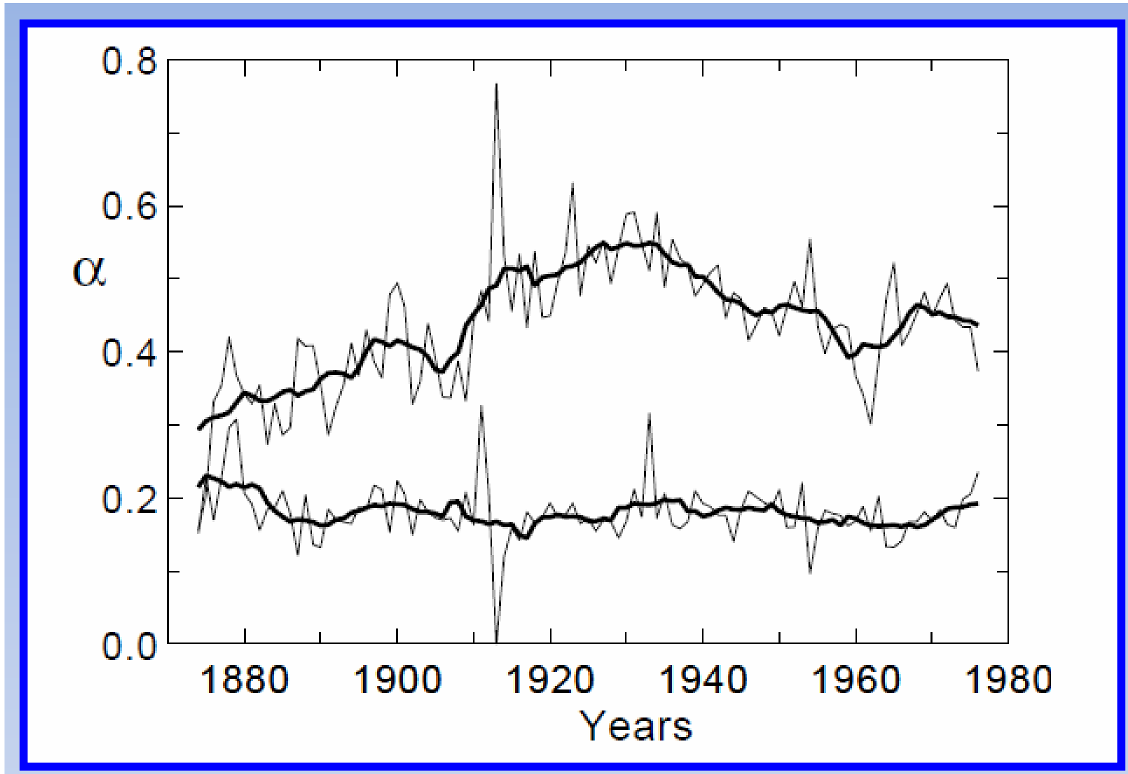


Figure 6 represents the time dependence of the fraction of small sunspot groups of areas less than 100 m.v.h. (upper curves) and 100–200 m.v.h. (lower curves) in the total number of groups in each year including the spots without umbra. The thin curves show the annual mean values and the thick ones, the values smoothed by a 9-year window.

As seen in Figure 6, the relative number of small groups was quite essential throughout the period under examination. It reached its maximum in the early 1930-ies, i.e., at the minimum and rise of a relatively low Cycle 17 (the Wolf number at the maximum equaled 119.2). Then, decreased gradually by the early 1950-ies reaching its minimum at the maximum of the record–high Cycle 19. At the same time, the fraction of the groups of area 100 < S < 200 m.v.h. did not, in fact, depend on time. On the whole, the fraction of sunspot groups of area less than 200 m.v.h. ranged from 50% to 80% of their total number. Correspondingly, the fraction of the groups of area S > 200 m.v.h. dropped to the minimum in the period 1920 – 1940. Somewhat unexpected is the absence of 11-year periodicity for these ranges, though a clear secular dependence does exist.

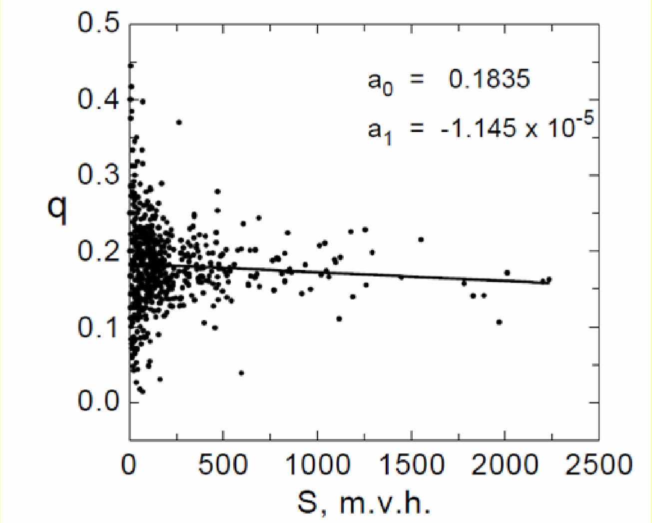
The fact that the mean value of q varies in time might be explained by the change in the relative number of small sunspot groups. This conclusion is induced by Figures 3 and 6. It should be noted, however, that a simple increase of the number of small spots can not account for all effects observed in the 1930-ies. E.g., one can see from Figures 4 and 5 that in 1929, q was higher than the mean value for the sunspots of all sizes. This suggests that the maximum in Figure 1 is determined not only by the increased number of small sunspot groups, but also by a certain additional, yet unknown factor.

Linear approximation of the dependence of q on the sunspot group area

The dependence of the relative area of the umbra q on the total sunspot area can be expressed by the following linear equation,

$$SU/S = a0 + a1xS,$$

where SU and S are the total areas of the umbra and the entire group, respectively. Such a relation for the sunspot groups recorded in 1898 is shown by way of example in Figure 7. The fraction of the umbra decreases with the increase of the area of sunspot groups as was pointed out above.



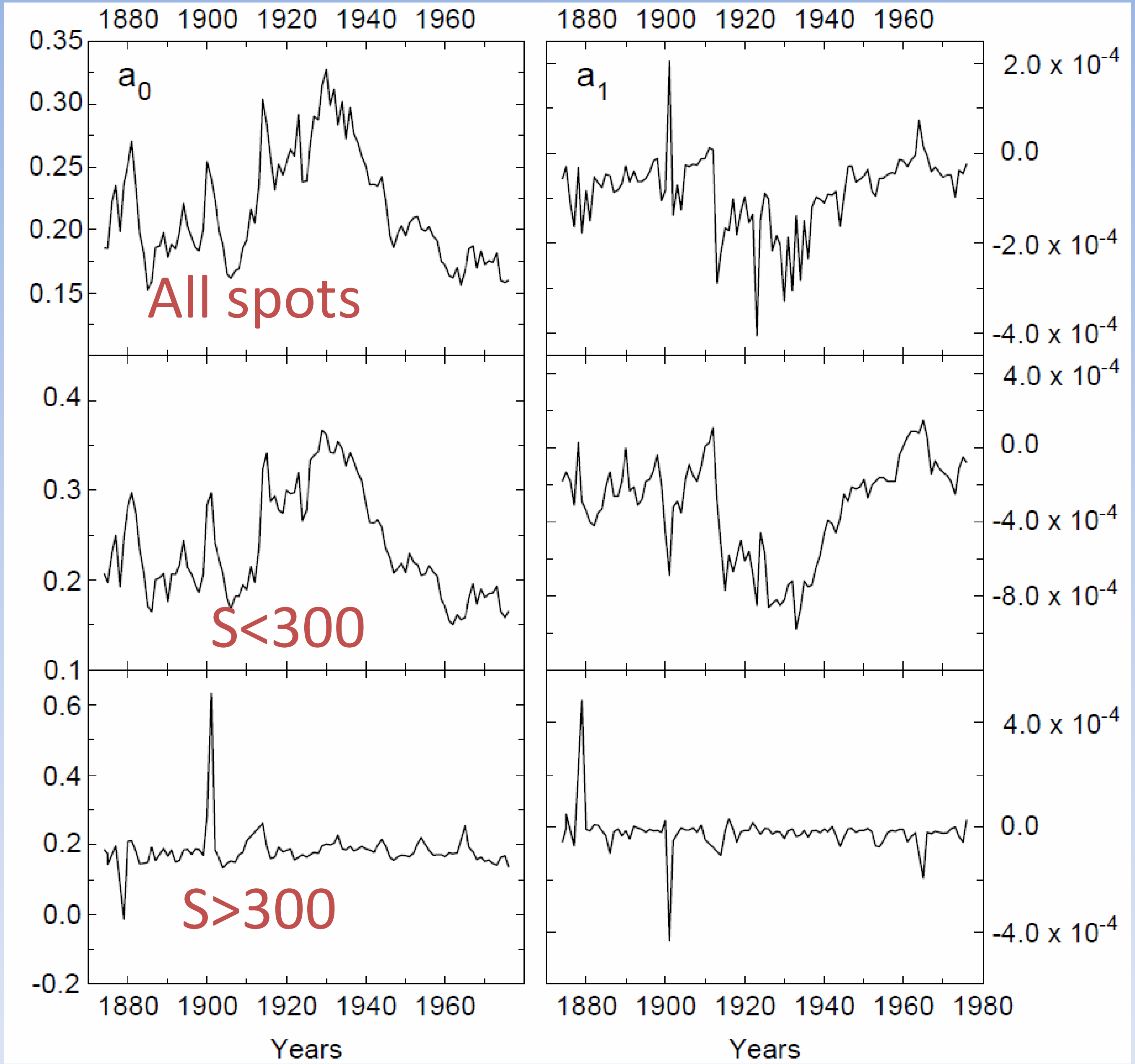


Figure 8. Coefficients a0 (left) and a1 (right)).

Behavior of a0 is very similar to that of q in Figure 1.

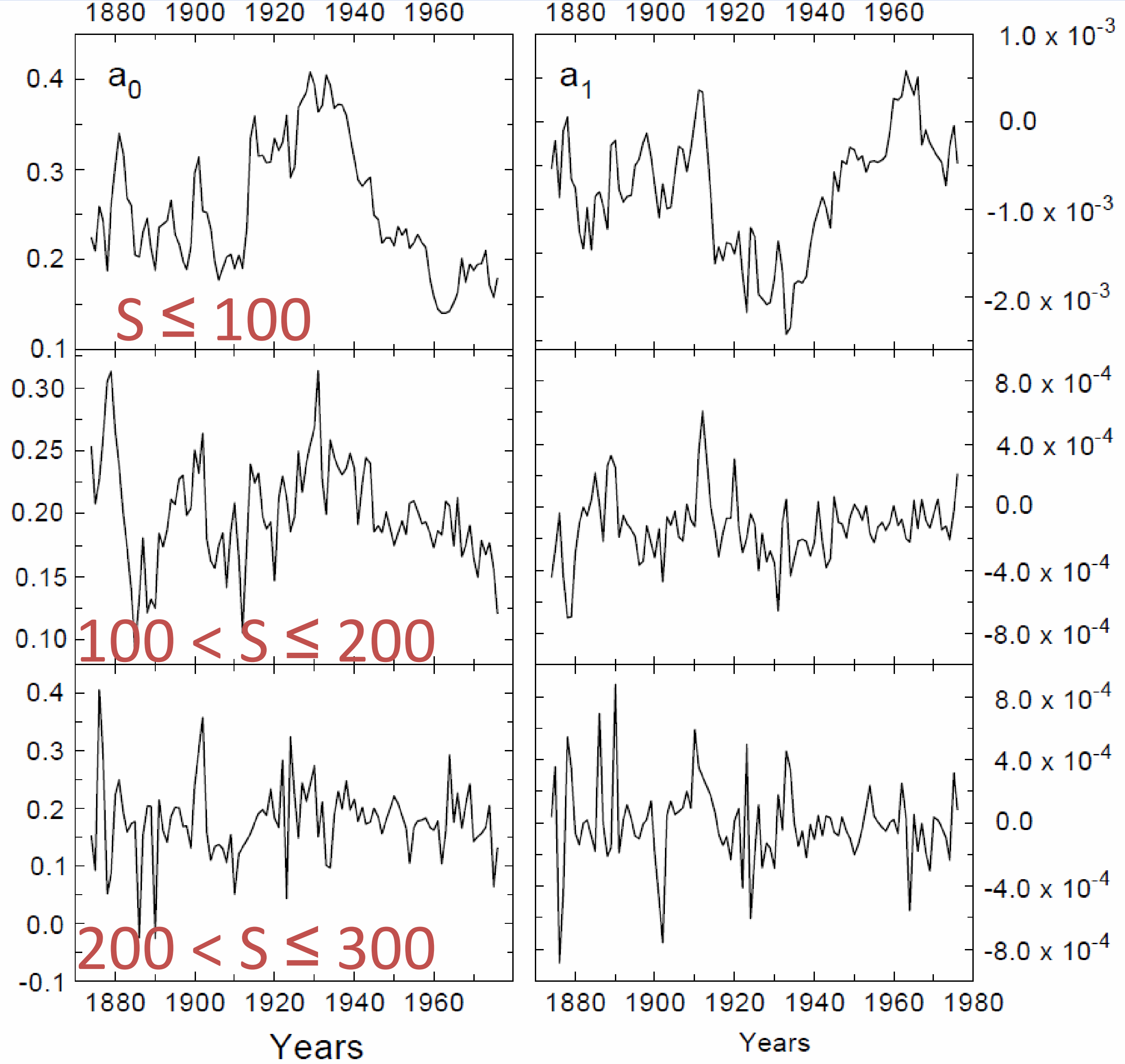


Figure 9. Coefficiennts a0 (left) and a1 (right) for the spots of area $S \leq 100$ m.v.h. (top), $100 < S \leq 200$ m.v.h. (middle), and $200 < S \leq 300$ m.v.h. (bottom).

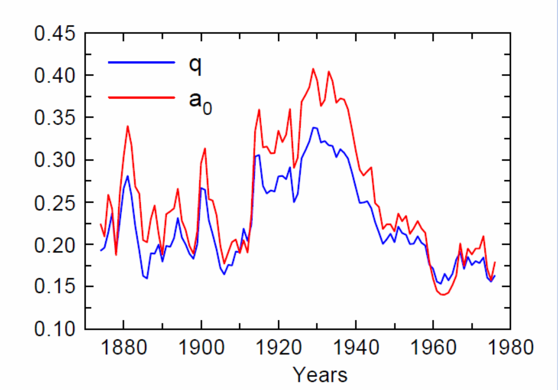


Figure 10. Comparison of the a0 and q curves for the smallest sunspot groups.

Figures 8 and 9 show that:

1.The curves a0 and a1 for the smallest spots (upper panels in Figure 9) and for all spots with umbra (upper panels in Figure 8) are very similar. The maxima of the a0 curves occur in the 1930- ies when the a1 curves display minimum values.

2. In Figure 9, the middle panels illustrate the transition from small to large spots, while the curves on the lower panels have little in common with the upper ones and resemble more the curves for the 300 m.v.h. spots represented on the lower panels in Figure 8.

3. As the area of sunspot groups increases, the parameter a0 approaches gradually a constant value of about 0.18. Simultaneously, the parameter a1 approaches zero.

Cycle and time variations in the relative contribution of large and small sunspot groups

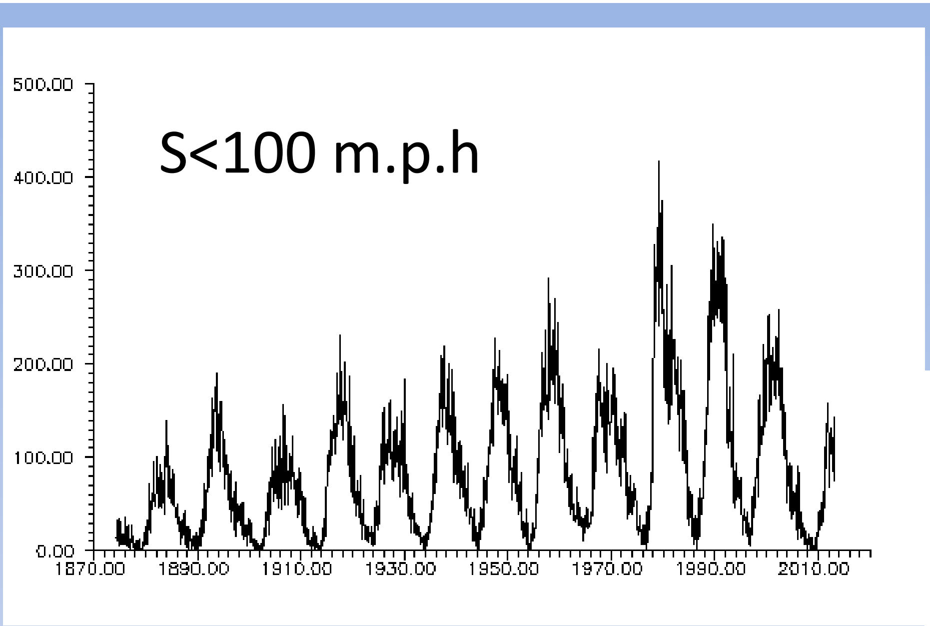
Tang et al. (1983) showed that the share of well-developed groups with large areas was higher at the maximum of the cycle. This result has been recently corroborated by Javaraiah and Javaraiah, (2012).

Lefèvre, L.; Clette, F. (2011) revealed a deficit of small spots in the declining phase of cycle 23.

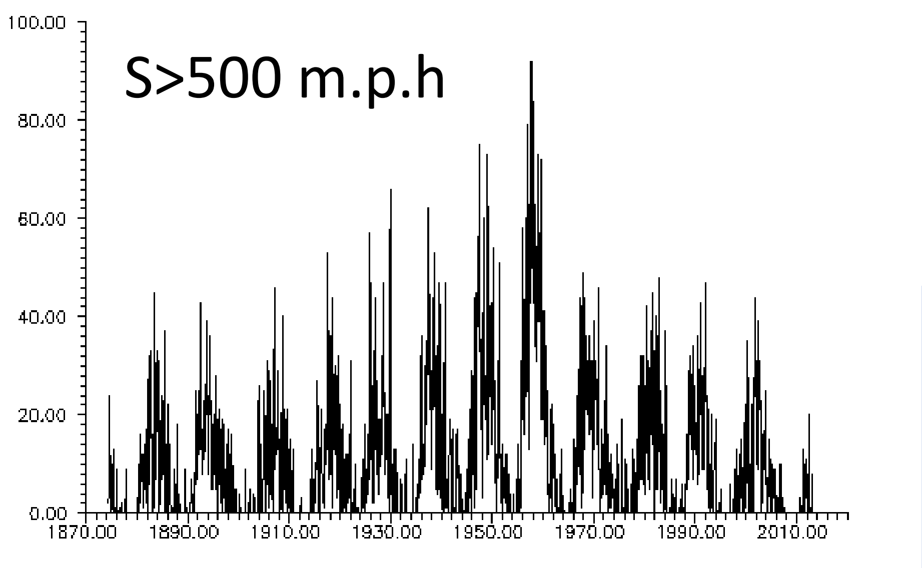
On the other hand, *Nagovitsyn; Pevtsov, and Livingston (2012)* associate the decrease observed in the maximum intensity of sunspot magnetic fields (Penn and Livingston, 2011) with the increased number of small spots.

A similar conclusion was drawn by Bludova et al. (2013) from the analysis of variations of the relative area of the umbra in sunspots.

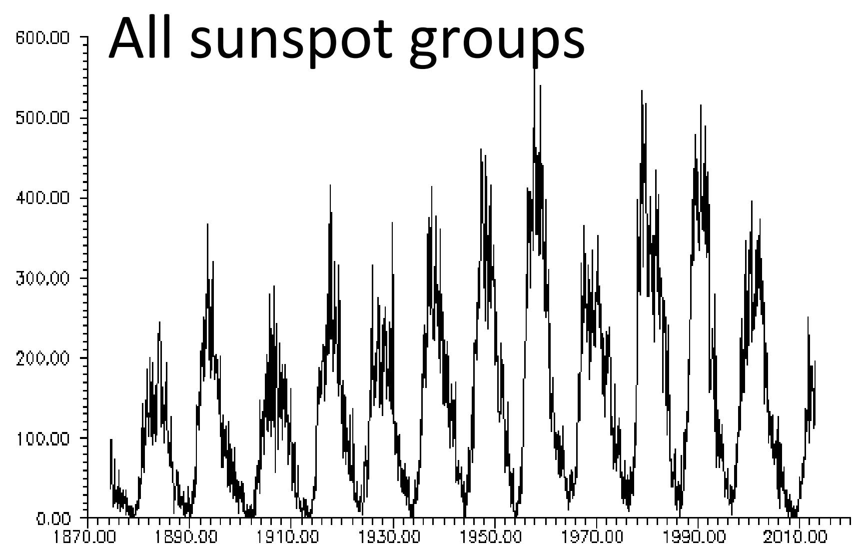
Ringnes (1981) noted that the occurrence rate of short-lived groups depends strongly on the phase of the secular cycle.



S<100 m.p.h



S>500 m.p.h



All sunspot groups

One can see that the time dependence of the number of sunspot groups both for small and for large groups differs from such dependence for all groups. For large sunspot groups, the highest cycle was 19, as well as for all groups. However, the heights of cycles 20, 21, 22, and 23 were equal for the former and differed substantially for the latter. As far as the small spots are concerned, the difference is even more significant. Here, cycle 19 is not distinguished by any features, while cycles 21 and 22 are, definitely, the highest. In contrast to Leifèvery L. and Colette F. (2011), one can hardly see any particular deficit of small groups in the declining phase of cycle 23.

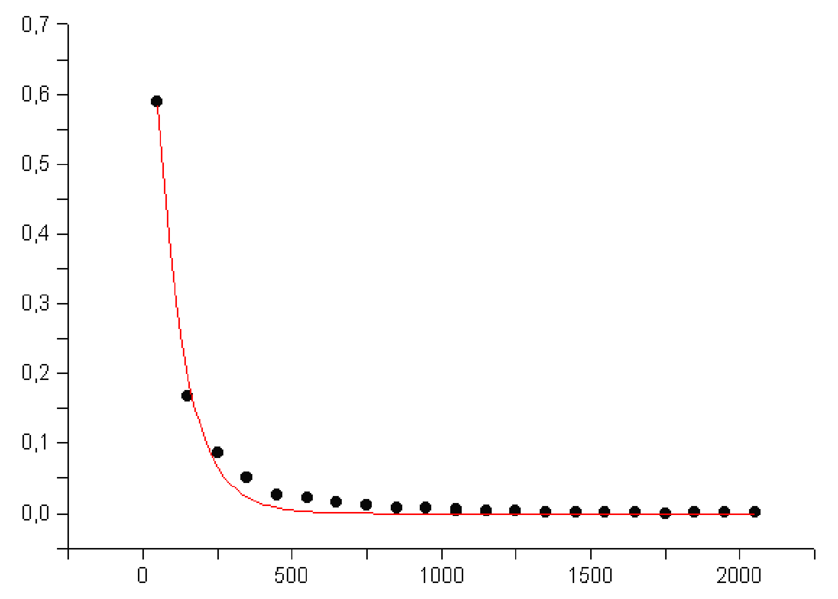


Figure 12 illustrates the occurrence rate of sunspot groups of different areas. The red curve approximates this dependence by exponential distribution.

N(S)=N0+A1exp(-(S-S0)/t1).

Here, N(S) is the number of groups in a given range of areas normalized to the total group number.

The value t1, obviously, determines the relative contribution of the groups with large areas: the larger t1, the more significant the contribution of large groups; with the decrease of t1 increases the relative contribution of small groups.

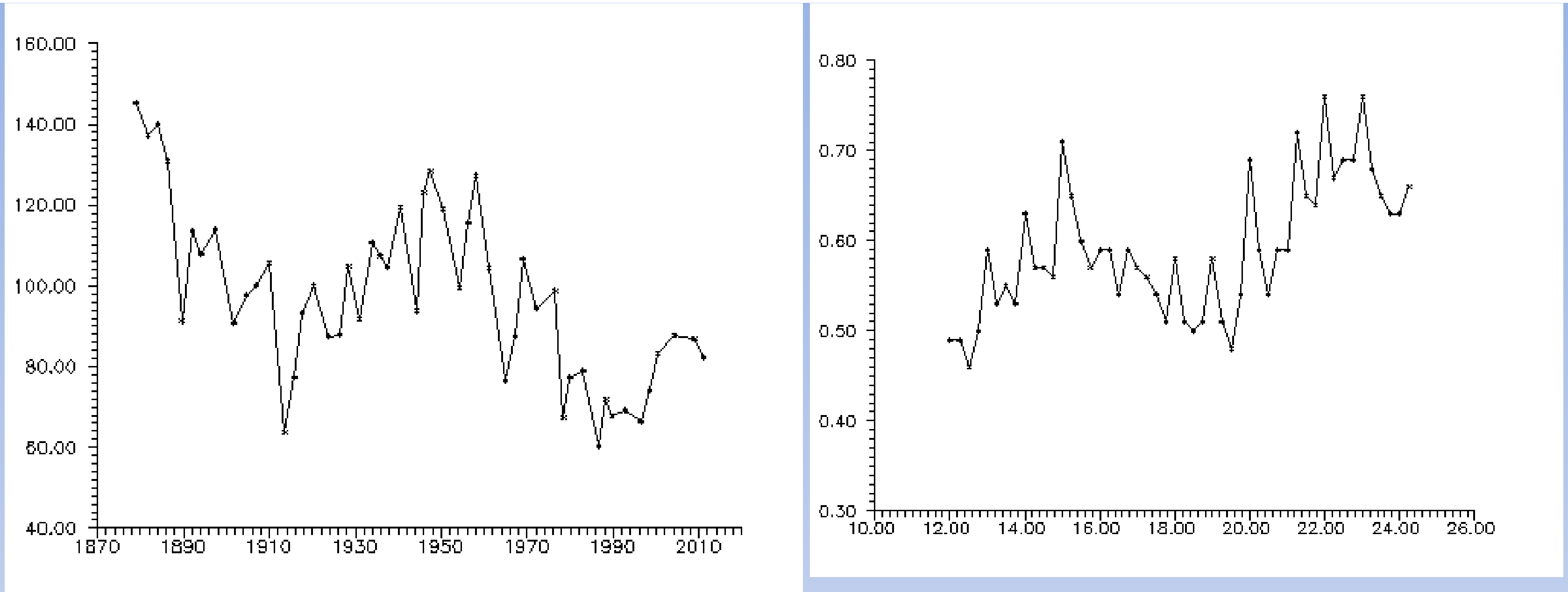


Figure 13 shows the time variation of t1 (left) and fraction of small groups (right). One can see that the relative contribution of sunspot groups of different size changes significantly with time, displaying evidence of a secular cycle with a period of about 80 years. The contribution of large groups increases during the high cycles 18 and 19 and during a fairly high cycle 11 at the abscissa origin. The minimum values of t1 are observed in a very low cycle 14 and a moderate cycle 23. On the whole, we can say that the first thirty years of the past century were characterized by increased contribution of small spots. At the end of the period under consideration, beginning with cycle 20, one can see a gradual decrease in t1, which suggests that the relative number of small spots began to increase again. This agrees with (Nagovitsyn et al., 2012) and (Bludova et al, 2013) and contradicts the conclusions made by Lefèvre, L.; Clette, F. (2011).

On the whole, it is of fundamental importance that the proportion of sunspots of different sizes reflects a certain long-term variation in the sunspot formation activity. It might be expected that this proportion would change over an 11-year cycle. In fact, however, we are dealing with some secular mechanism, which affects precisely the small sunspots.

Small sunspot groups are usually considered to be the early stage of the group evolution. It is believed that some groups simply vanish before growing large. However, this is not quite true. The appearance of small sunspots is controlled by one, perhaps, very long-term process, while the further evolution of the group depends on another process associated, probably, with the subphotospheric dynamo.

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Note that the central part of the spot, i.e., its umbra, also obeys some long-term mechanism. It occupies greater part of the group in the periods when small spots are more numerous. Note, however, that the value of q in 1929 was higher than normal for the spots of all sizes! This means that the increase in q was caused not only by the increased number of small sunspot groups but also by some other as yet unknown factor.

It is also significant that with the growth of the group, the relative contribution of the umbra decreases reaching its standard value of 0.18 obtained by Waldmeier. This is the value given in handbooks

The increase in q in the early 1930-ies can be related to the revealed though as yet unexplained anticorrelation between the observed rotation rate of the Sun and the corresponding Wolf number maximum. It turns out that the solar rotation rate was higher in the 1930-ies, i.e., in the period of low activity cycles (Hathaway and Wilson, 1990; Obridko and Shelting, 2001; Badalyan, 2011). It was in the epoch of low cycles from 1915 to 1940 that we observed a decrease in the effective rotation period of the Sun (i.e., an increased angular rotation rate). Moreover, it was revealed (Antalov´a, 1986) that the differential rotation rate decreased in the zones where the integral sunspot area was larger.

Let us recall that Eddy, Gilman, and Trotter (1976) revealed from the old sunspot sketches by Johannes Hewelius that the rotation rate of the Sun in the equatorial zone in the period 1642-1644 was by 3 – 4% higher than in the first half of the 20th century. At the same time, the rotation rate at the latitude of 20◦ and higher was the same as in the first half of the 20th century. This means that the differential character of the solar rotation was much more pronounced. However, this conclusion was questioned by Abarbanell and Wöhl (1981) .

Note that the Maunder minimum might have been a manifestation of the reduced area of sunspots. As a result, the observations with low–resolution facilities available in the 17th century (to say nothing of the naked-eye observations) gave an impression that the number of sunspots decreased. Besides, the small spots usually cause weak geophysical disturbances. Therefore the sunspot numbers determined from indirect evidence (e.g., aurora observations) must have been underestimated.

Thank You for attention !