RELATIONSHIPS BETWEEN SOLAR ACTIVITY INDICES IN DIFFERENT TIME INTERVALS

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The results of the analysis of long-term changes in the relationship between solar activity indices for 1953-2023 are presented. For this purpose, the 12-month running mean indices *F* 10, *F* 30, *MgII* , *Ri* and *T* were used – solar radio fluxes at wavelengths of 10.7 cm and 30 cm, the ratio of the central part to the wings in the magnesium emission band 276-284 nm, the international sunspot number and the ionospheric index, which is defined from ionospheric data as an analog of the sunspot number. It was found that the entire period of measurements can be divided into intervals 1953-1980, 1981-2012, and 2013-2023, in which the relationships between solar activity indices clearly differ. In the interval 1953-1980, these relationships are stable, i.e., the linear time trend in the dependence of one solar activity index on another is practically absent. In the interval 2013-2023, such trends are usually significant. The boundaries of these intervals (1980 and 2013) approximately correspond to the maxima of the first and last solar cycles in the decreasing activity mode, when the large-scale solar magnetic field and the height of the solar cycle decrease with time. Consequently, the relationships between solar activity indices, including the relationships between the ionospheric index and solar indices, provide additional information about changes in solar cycle regimes and can serve as one of the characteristics of these regime changes.

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1. INTRODUCTION

The extreme ultraviolet (EUV) radiation from the Sun is the main source of heating and ionization of the middle and upper atmosphere [Rees, 1989]. Solar activity indices are used as indicators of EUV radiation from the Sun, including F10, F30, MgII, and Ri - solar radio emission fluxes at wavelengths of 10.7 cm and 30 cm, the ratio of the central part to the flanks in the magnesium radiation band of 276-284 nm, and the international number of sunspots (version 2.0)

[Danilov and Berbeneva, 2023; Laštovička and Burešova, 2023; Laštovička, 2024; Mursula et al., 2024]. The correlation between the annual averages of these indices is very high [Laštovička and Burešova, 2023; Mursula et al., 2024]. However, the relationship between solar activity indices may depend on time [Mursula et al., 2024]. For example, solar radio emission fluxes (at wavelengths from 3.2 cm to 30 cm) increased relative to Ri in the period 1957-2021, and such an increase (linear in time trend) was more significant for relatively long wavelengths: for F3.2 and F30, it was 3% and 20% [Mursula et al., 2024]. These and other connections have shown that the changing relationship between different (for example, photospheric and chromospheric) solar parameters should be taken into account when using the number of sunspots or any other separate parameter in long-term studies of solar activity [Mursula et al., 2024].

Additional information on the relationships between solar activity indices can be obtained if the entire measurement period is divided into intervals with differing trends of the solar activity index, where the variances of trends for each time interval are much smaller than for the entire measurement period of the analyzed indices. Solving this problem using data from moving annual values of indices $F10$, $F30$, Ri, $MgII$ and T was the main objective of this work, where T is an ionospheric index of solar activity. The index T is constructed using experimental data of medians $foF2$ from a series of ionospheric stations to replace the solar index Rz in empirical models in order to ensure minimal errors in calculating $foF2$ using these models, where Rz is the international sunspot number (previous version, which includes the classic Zurich data series) [Caruana, 1990]. It should be noted that $foF2$ can provide important information about both the optimal solar activity indices for $foF2$ and the nature of long-term changes in $foF2$ [Danilov and Berbeneva, 2023; Laštovička and Burešova, 2023; Laštovička, 2024]. Therefore, the index T was included in solving this problem as an indirect index of solar activity, which is determined from $foF2$ data.

Below are the sequentially presented results of solving this problem: relationships of the index Ri with indices $F10$ and $F30$, relationships of the ionospheric index T with all analyzed solar activity indices. For this purpose, moving annual average values of these indices were used in the interval from 01.1953 to 02.2024, which for brevity is designated as the entire measurement period 1953-2023. For the index $MgII$, this interval is 01.1980-02.2024, which is designated as the entire measurement period 1980-2023 for this index.

Below, for brevity, the values $F10$, $F30$, $MgII$, Ri and T are the 12-month running averages of these indices, centered on the given month. Additionally, solar activity indices that are derived from measurements of solar radiation parameters are called solar indices, as distinct from the ionospheric index T, which is based on measurements of $foF2$.

2. RELATIONSHIPS BETWEEN SOLAR INDICES

As noted above, the correlation between solar indices is very high; nevertheless, the relationship between them may depend on time. Therefore, it is advisable to divide the entire measurement period into intervals, and determine the average relationship for each interval, for example, of index Y on index X in the form of a stationary regression equation

$$Y(X) = a_0 + a_1 X + a_2 X^2 + a_3 X^3, \qquad (1)$$

where the coefficients of this equation are determined by the data array of Y and X for this time interval. In the next step, identify the linear time dependence (trend) of the residual of index Y from the average relationship Y on X for the given interval:

$$\Delta Y(X) = Y - Y(X) = b_0 + b_1 t, \qquad (2)$$

where $Y(X)$ is defined by equation (1) with constant coefficients a_j and the trend $\otimes Y(X)$ is determined by the change over time of indices Y and X in equation (2).

This procedure of isolating the linear trend $\Delta Y(X)$ as a correction to the dependence $Y(X)$ taking into account the very high correlation between indices Y and X has been used repeatedly. It was applied, for example, to isolate time-linear trends of $foF2$ (in this case $Y = foF2$, X – the solar activity index used) [Danilov and Konstantinova, 2023; Laštovička, 2024].

To select the intervals into which the entire measurement period should be divided, we require that these intervals be about 20 years or more, i.e., large enough to reflect long-term trends of the analyzed indices. Additionally, we require that the variance of the regression equation (2) for each of the selected intervals be significantly less than this variance for the entire measurement period. It will be shown below that the entire measurement period of 1953-2023 can be divided into intervals of 1953-1980, 1981-2012, and 2013-2023. It is noticeable that the last interval is less than 20 years, therefore the results for this interval may be refined as the data array of solar activity indices expands.

Table 1

Table 1 shows the parameters of regression equation (2) for $\Delta Ri(F10)$ and $\Delta Ri(F30)$, i.e., trends of the residual index Ri from dependencies Ri on $F10$ and $F30$. From the data in the table, it can be seen that in the interval 1953−1980, the trends of $\Delta Ri(F10)$ and $\Delta Ri(F30)$ are positive (coefficient $b_1 > 0$), insignificant and very weak. In the interval 1981−2012, the trends of $\Delta Ri(F10)$ and $\Delta Ri(F30)$ are negative, with $\Delta Ri(F30)$ being maximum in absolute value and significant. In the interval 2013−2023, the trend of ΔRi (F 10) is negative, the trend of ΔRi (F 30) is positive, and they are insignificant or weakly significant. For the entire measurement period of 1953−2023, the trends of ΔRi (F 10) and ΔRi (F 30) are negative and significant, with ΔRi (F 30) being maximum in absolute value. The variance, σ^2, of the trend ΔRi (F 30) is greater than for ΔRi (F 10), for the entire measurement period and each of the selected time intervals. The variances of trends ΔRi (F 10) and ΔRi (F 30) for the entire measurement period are at least twice as large as the corresponding variances for each of the selected intervals. The only exception was the interval 1953−1980 for ΔRi (F 10), whose trend was practically absent and insignificant.

Fig. 1

Fig. 2

The nature of changes in trends ΔRi (F 10) can be more clearly seen from the data in Fig. 1. It is evident that not only the variance but also the scatter of data ΔRi (F 10) for the entire measurement interval is much larger than for each of the selected time intervals.

The relatively low dispersion of the regression equation (2) for each of the selected intervals compared to the entire measurement period is largely due to accounting for the dependence Y (X) for each of the selected intervals. In this case, these are the dependencies Ri (F 10) and Ri (F 30). They are shown in Fig. 2. It can be seen that over time there was an increase in the indices F 10 and F 30 relative to the index Ri . Such an increase in F 10 was significant for medium and high solar activity and practically absent for low solar activity. The increase in the index F 30 relative to the index Ri could occur at any level of solar activity. It has been repeatedly noted that the correlation between solar indices is very high [Laštovička and Burešova, 2023; Mursula et al., 2024]. In this case, for the dependence Ri (F 10) in the regression equation (1), the coefficient of determination $R^2 > 0.99$ and $\int^2 < 30$ for any of the selected time intervals. Similarly, $R^2 > 0.98$ and $\int^2 < 45$ for the dependence Ri (F 30).

Thus, the relationships between solar activity indices have changed over time. For an approximate accounting of these changes, the entire measurement period was divided into relatively large intervals, within which this relationship was considered constant, and the additional dependence of this relationship on time was taken into account using linear trends of residuals for each of the selected intervals. In turn, the choice of time intervals was determined by the conditions: they should be more than 20 years, the variance of the trend for each interval should be much less (by 2 times) than its variance for the entire period of index measurements. The intervals 1953−1980, 1981−2012, and 2013−2023 for the trends ΔRi (F 10) and ΔRi (F 30) satisfied the listed criteria, which determined the choice of these intervals. The interval 2013−2023 is too short, therefore the results of trend estimates for this interval, including the value of the coefficient b_1 in equation (2), are preliminary.

Standard characteristics of solar activity cycles are sunspot numbers, in this case, these are the *Ri* indices – international sunspot numbers (version 2) [Hathaway, 2015]. For the interval 1953−2023, they are shown in Figure 1. From the data in Figure 1, it can be seen that the heights of solar cycles decreased over time for cycles 21−24. The boundaries of the selected intervals (1981 and 2013) are located in the area of the maximums of cycles 21 and 24, i.e., at the beginning and end of the decreasing cycles. Consequently, changes in the nature of the relationships between solar indices are due to the peculiarities of long-term changes in solar activity cycles and can serve as an additional indicator of such cycle changes. Cycle 25 was the first cycle with increased height after a series of decreasing cycles. The restructuring in the nature of the relationships between solar activity indices occurred at the maximum of the previous cycle, i.e., earlier than the beginning of cycle 25. Analysis of possible causes of such anticipation of events is beyond the scope of this work. Nevertheless, it is noted that the first spots of a new cycle appear long before the minimum, i.e., earlier than the spots of the previous cycle disappear. Cycles seem to exist simultaneously, but at different latitudes. This gave rise to the assumption that the true length of the cycle is not 11, but 15–17 years [Harvey, 1992; Obridko, 2008; Martin, 2024].

The conclusion that changes in the nature of relationships between solar indices can serve as an additional indicator of trends in solar cycle changes, including the direction of these changes, is the main result of this work. Additional information about the properties of solar activity indices can be provided by analyzing the relationship between the ionospheric index T and solar indices $F10$, $F30$, *Ri* and *MgII*. The results of this analysis are presented below.

3. RELATIONSHIPS BETWEEN THE IONOSPHERIC INDEX AND SOLAR INDICES

Analysis of the relationships between the ionospheric index T and solar indices $F10$, $F30$, *Ri* or *MgII* is based on regression equations (1) and (2), where $Y = T$, $X = F10$, $F30$, *Ri* or *MgII*. Therefore, for example, $\Delta T(F10) = T - T(F10) = b_0 + b_1 t$ gives a linear time trend of the residual of index T, from which the average dependence of T on $F10$ for a given interval is excluded using regression equation (1) in the form of a polynomial $T(F10)$.

Table 2.

Table 2 shows the parameters of the regression equation (2) for $\Delta T(X)$, where $X = F10$, $F30$, Ri or $MgII$, for the selected intervals 1953−1980, 1981−2012 and 2013−2023 and the entire measurement period 1953−2023. The exception is the $MgII$ index, for which measurements in the first time interval are absent. From the data in Table 2, it follows that for the interval 1953−1980, the trends of $\Delta T(X)$ are positive ($b_1 > 0$), but they are low in magnitude and insignificant. For the interval 2013−2023, all trends of $\Delta T(X)$ are negative and significant ($F10$, $F30$) or weakly significant (Ri, $MgII$), for the trend $\Delta T(F10)$ they are maximum in absolute value. For the intermediate interval 1981−2012, the trends of $\Delta T(X)$ differ: for $\Delta T(MgII)$ it is practically absent ($b_1 = -0.002$ 1/year, $R^2 = 2\cdot10^{-5}$), for $\Delta T(F30)$ and $\Delta T(MgII)$ they are negative and significant, for $\Delta T(F10)$ and $\Delta T(Ri)$ they are positive, but low in magnitude and insignificant. For the entire measurement period 1953−2023, the trends of $\Delta T(F30)$ and $\Delta T(MgII)$ are negative and significant, the trends of $\Delta T(F10)$ and $\Delta T(Ri)$ are weakly significant and in absolute value they are approximately 3 times smaller than the trend of $\Delta T(F30)$. From these data, it follows that the details of the trends $\Delta T(X)$ for different indices may differ. Nevertheless, common to them is the absence of significant trends $\Delta T(X)$ in the interval 1953−1980, and the existence of significant negative trends $\Delta T(X)$ in the interval 2013−2023, which are mostly significant. This allows us to assert that the time intervals identified based on the analysis of solar indices relationships are also essential for the relationships of the ionospheric index T with solar indices, and 1981 and 2013 are the boundaries of intervals with differing properties of the ionospheric index trends $\Delta T(X)$.

Fig. 3.

The features of trends $\Delta T(X)$ during the selected time intervals can be seen more clearly from the data in Fig. 3. It is evident that the data scatter relative to the trends $\Delta T(X)$ is quite large. Nevertheless, for all the considered trends $\Delta T(X)$, common patterns are clearly distinguished: weak positive trends in the interval 1953-1980 and significant negative trends in the interval 2013-2023.

4. DISCUSSION

It is believed that the Sun's magnetic field is the main cause of solar activity variability, including changes in this activity with the solar cycle [Svalgaard and Hansen, 2013; Balogh et al., 2014; Hathaway, 2015]. Observational data of the Sun's magnetic field showed that the increase in the magnetic moment of the solar dipole from 1915 to approximately 1980 was replaced by a decrease [Obridko and Shelting, 2009], and this decrease apparently continued until the end of solar cycle 24 with an abnormally large decrease in the global magnetic field of the Sun during cycle 23 [Petrie, 2024].

The observed decrease in solar cycles from 21 to 24 corresponds to such a decrease in the large-scale magnetic field of the Sun. From the data in Figure 1, it follows that in the interval 1980-2012, the sunspot numbers Ri decreased with time relative to the solar radio emission fluxes (F 10 and F 30): the trend ΔRi (F 10) = $Ri - Ri$ (F 30) was negative and the ratio $C = Ri / Ri$ (F 10) decreased with time, where Ri (F 10) is the F 10 index converted to the Ri scale using the regression equation (1). Such a decrease in the ratio C is more significant for high or increased solar activity (Fig. 2). Based on qualitative analysis, it was found that the decrease over time of the ratio $C = Ri / Ri$ (F 10) is associated with a decrease in the large-scale magnetic field of the Sun: the observed decreases in cycle heights and reductions in the ratio C at cycle maxima for solar cycles 21-24 are caused by the same reason [Livingston et al., 2012; Svalgaard and Hansen, 2013]. The decrease in the ratio C with a decrease in the Sun's magnetic field, apparently, is characteristic specifically for low solar cycles. This allowed us to assert that in cycles 21-24, the Sun transitioned to a new regime of low activity [Svalgaard and Hansen, 2013]. It should be noted that 1980 is one of the boundaries where there is a change in the nature of the relationship between solar activity indices (see Figures 1-3) and the transition of the solar cycle to a low activity regime, including a decrease in the large-scale magnetic field of the Sun and the height of the solar cycle over time. The other boundary, 2013, corresponds to the maximum of the last of the low solar cycles and a strong change in the nature of the relationship between each of the analyzed pairs of solar activity indices (see Fig. 1 and Fig. 2).

Thus, the relationships between solar activity indices in certain time intervals are one of the characteristics of changes in solar cycle regimes, including the transition to a low activity regime, when there is a decrease over time in the large-scale magnetic field of the Sun and the height of the solar cycle.

It should be noted that the main purpose of this work was to divide the entire period of measurements of solar activity indices into intervals longer than 20 years, in which the characteristics of the relationships between solar activity indices were distinctly different. As a result, these intervals became 1953−1980, 1981−2012, and 2013−2023. The interval 2013−2023 is too short to obtain reliable estimates of such relationships, so they are preliminary for this interval.

5. CONCLUSIONS

The results of the analysis of long-term changes in the relationship between solar activity indices for 1953−2023 are presented. For this purpose, one-year moving averages of the indices $F10$, $F30$, $MgII$, Ri and T were used – solar radio flux at wavelengths of 10.7 cm and 30 cm, the ratio of the central part to the wings in the magnesium emission band 276–284 nm, the international sunspot number (version 2.0), and the ionospheric index, which is defined from ionospheric data as an analog of the sunspot number. The following conclusions were obtained.

1. The entire measurement period can be divided into intervals 1953−1980, 1981−2012, and 2013−2023, in which the relationships between solar activity indices are distinctly different. In the interval 1953−1980, these relationships are stable, i.e., the linear time trend in the dependence of one solar activity index on another is practically absent. In the interval 2013−2023, such trends are usually significant. In this interval, the trend $\Delta T(X) = T - T(X)$ is negative for $X = F10$, $F30$, $MgII$ or Ri, where $T(X)$ is the average for a given interval dependence of T on X.

2. The boundaries of these intervals (1980 and 2013) approximately correspond to the maxima of the first and last solar cycles in the decreasing activity mode, when there is a decrease over time in the large-scale magnetic field of the Sun and the height of the solar cycle. Consequently, the relationships between solar activity indices, including connections between the ionospheric index and solar indices, provide additional information about the changing regimes of solar cycles and can serve as one of the characteristics of these regime changes.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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Table 1. Parameters of the regression equation (2) for ΔRi (F 10) and ΔRi (F 30): coefficient of this equation b_1 in 1/year, coefficient of determination R^2 and variance σ^2 for intervals 1953–1980, 1981–2012, 2013–2023 and the entire measurement period 1953–2023.

1953–1980			1981–2012			2013–2023			1953–2023		
b_1	R^2	σ^2	b_1	R^2	σ^2	b_1	R^2	σ^2	b_1	R^2	σ^2
(F 10)											
0.08	0.016	27.4	–0.13	0.115	11.7	–0.45	0.111	17.2	–0.24	0.364	44.0
(F 30)											
0.17	0.040	42.9	–0.45	0.387	27.3	0.115	0.004	32.9	–0.49	0.532	89.3

Table 2. Parameters of the regression equation (2) for ΔT (X), where $X = F$ 10, F 30, Ri or $MgII$: coefficient of this equation b_1 in 1/year, coefficient of determination R^2 and variance σ^2 for intervals 1953–1980, 1981–2012, 2013–2023 and the entire measurement period 1953–2023.

1953–1980			1981–2012			2013–2023			1953–2023		
b_1	R^2	σ^2	b_1	R^2	σ^2	b_1	R^2	σ^2	b_1	R^2	σ^2
ΔT (F 10)											
0.09	0.072	06.9	0.014	0.002	10.5	–0.91	0.494	09.0	–0.08	0.170	13.6
ΔT (F 30)											
0.17	0.099	16.6	–0.20	0.233	11.5	–0.41	0.287	04.4	–0.27	0.580	22.1
ΔT (Ri)											
0.05	0.013	14.4	0.104	0.08	10.4	–0.45	0.094	20.3	0.096	0.150	22.2
ΔT ($MgII$)											
-	-	– 0.00	–0.00	0.000	13.5	–0.52	0.133	18.6	–0.27	0.36	20.9

Figure captions

Fig. 1. Time variations in years of the *Ri* index (upper panel), values of $\Delta Ri\ (F\,10)$ and their linear trends (broken and straight lines, respectively) for the intervals 1953–1980, 1981–2012, 2013–2023 (middle panel) and the entire analyzed measurement period 1953–2023 (lower panel). Points – values of *Ri* at the boundaries of these intervals.

Fig. 2. Dependence of the *Ri* index on $F\,10$ and $F\,30$ for time intervals in years 1953–1980 (thick lines), 1981–2012 (thin lines) and 2013–2023 (dashed lines).

Fig. 3. Time variations in years of values $\Delta T\ (X)$ and their linear trends (thin and thick lines) for intervals 1953–1980, 1981–2012, 2013–2023, where $X = F\,10$, $F\,30$, *Ri* or *MgII* .

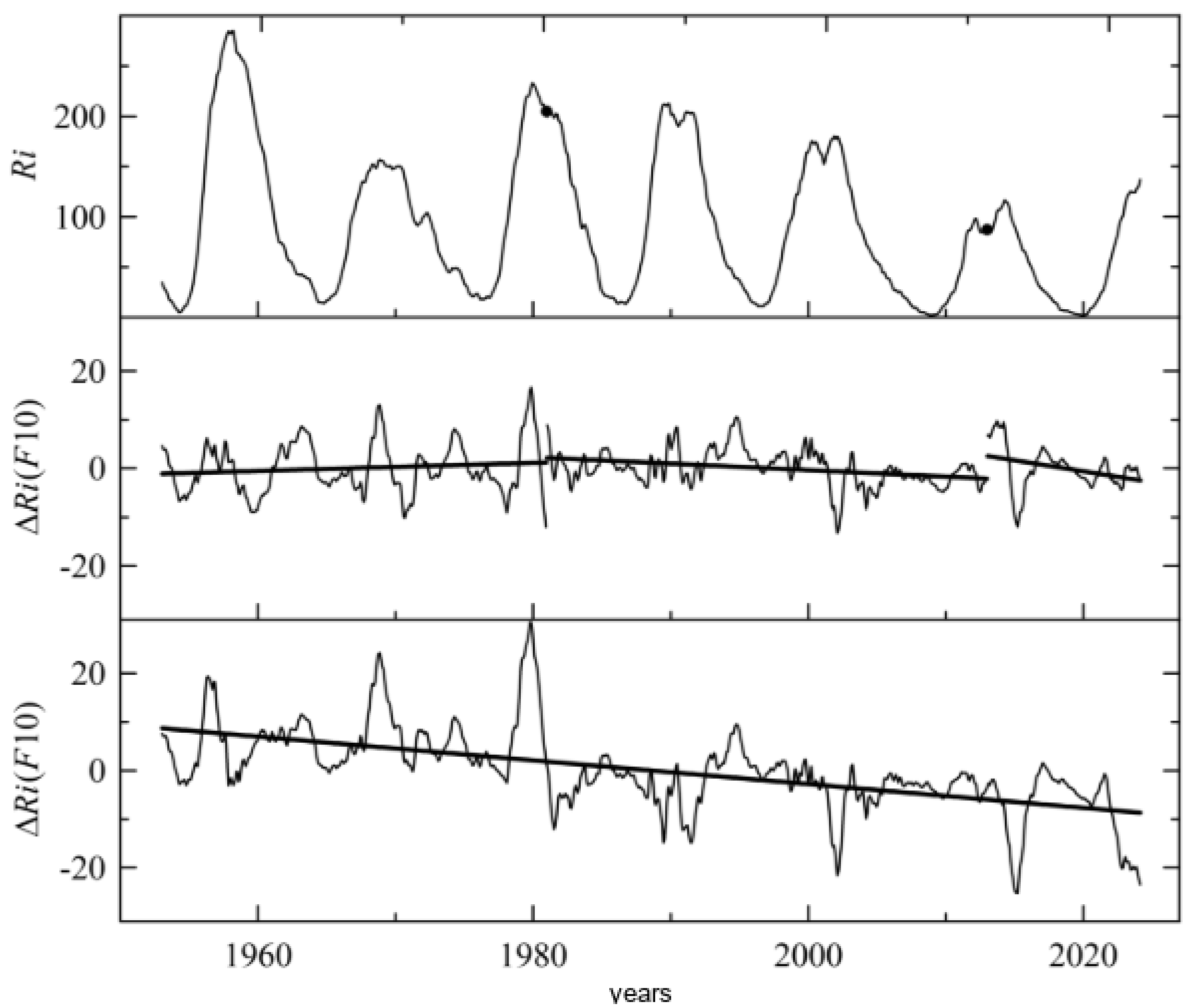

Fig. 1.

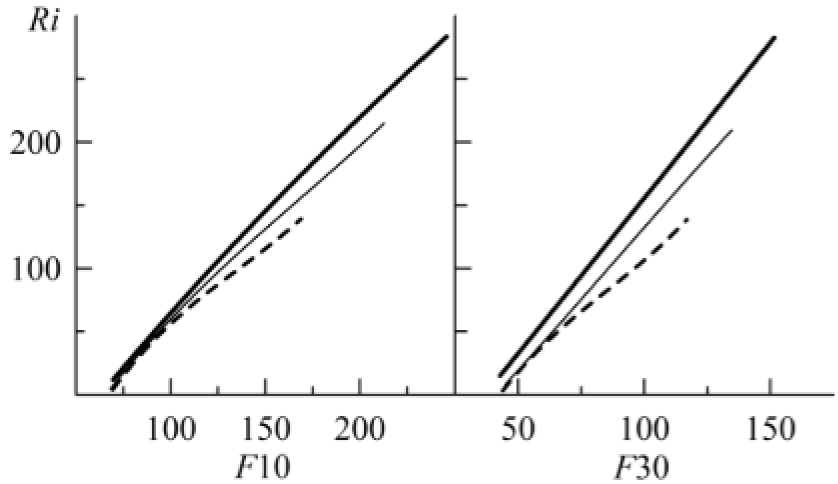

Fig. 2.

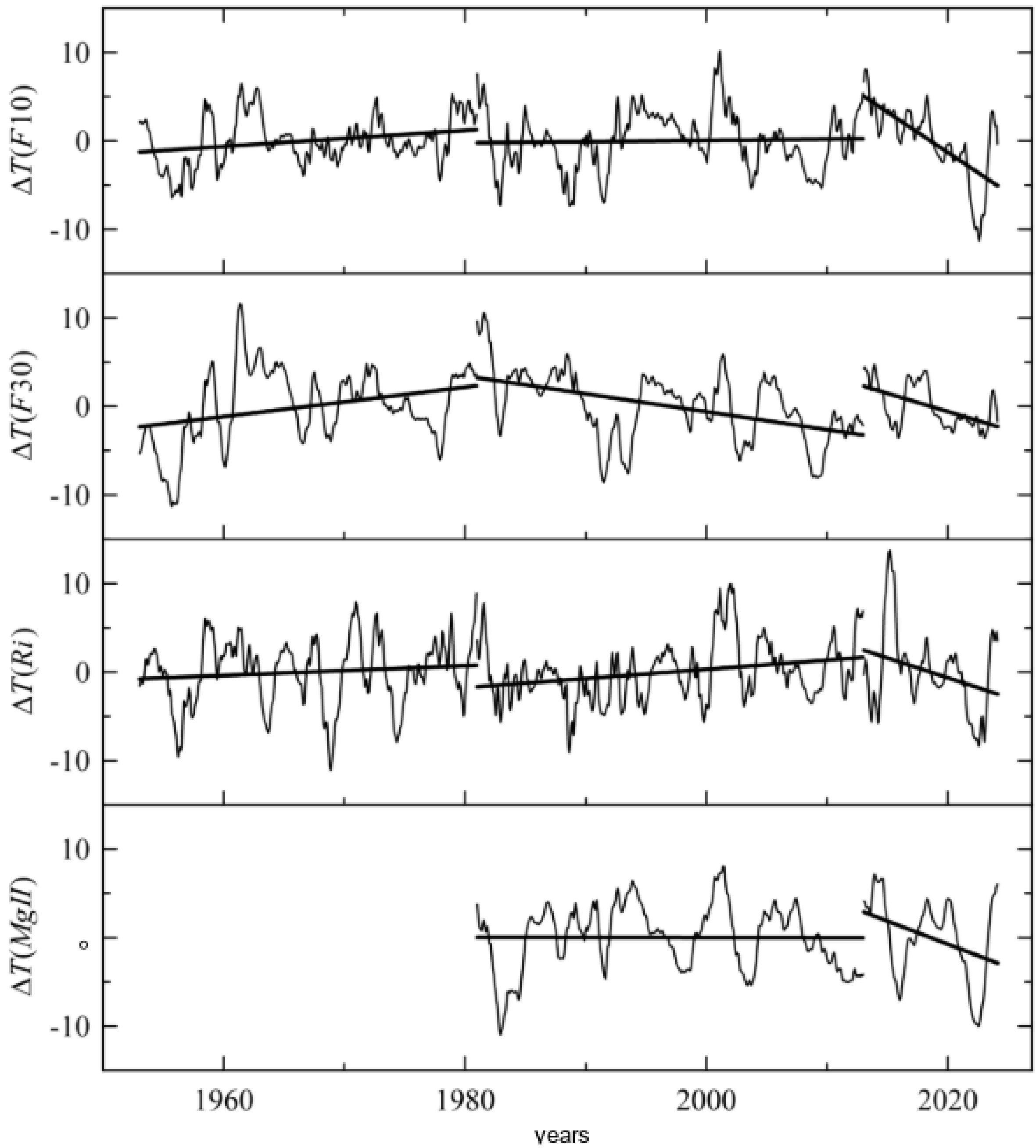

Fig. 3.