Response of the Intensity of Subtropical High in the Northern Hemisphere to Solar Activity

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ABSTRACT

Using the intensity data of each northern subtropical high measured by monthly 500 hPa height charts for the recent 38 years (1954–1991), we calculate their correlations with the monthly sunspot number and monthly solar radio flux at 10.7 cm wave length, respectively. Through strict test, we further confirm a series of high correlations. Next, using a method called the non–integer (year) wave, the significant response of each subtropical high's intensity to solar activity at its main period of 10.9–year length is found. Special attention is paid to that of the eastern Pacific high, the possible mechanism of such sensible response is also analysed.

Key words: Solar activity, Solar constant, Intensity of subtropical high

I. INTRODUCTION

Xu Qun et al. (1984, 1986) and Xu Qun and Jing Long (1986) have ever pointed out that significant positive correlations exist between solar activity and the strength of each subtropical high in the Northern Hemisphere (N.H.), but the data analysed were of 28 years (1954–1981) only. In addition, the auto–correlation inhered in time series had not been removed when above–mentioned correlations were tested for statistical significance. Moreover, to detect the periods in time series only the power spectrum analysis was adopted (Xu, 1986), which now seems to be much limited in the calculation of real periods in low frequency. Hence, it is necessary to extend data and remove the effect of auto–correlations in time series in order to calculate the correlations with more strict test and obtain the real periods in time series by using a better method. Eventually, we may get a more objective estimation for the response of each subtropical high's intensity in the N.H. to solar activity.

II. DATA

We use both the monthly mean area index (MAI) and monthly mean strength index (MSI) to measure the intensity of subtropical high. The MAI is the sum of grid points, of which heights (at the monthly 500 hPa height chart) exceeding 5880 GPM and the MSI is the sum of all larger heights (> 5870 GPM) of grid points. We have sorted out the recent 38 year data (1954–1991) of MAI / MSI for the eastern Pacific high (EPH, 175°–115°W, > 10°N), the western Pacific high (WPH, 110°–180°E, > 10°N), the North Atlantic high (NAH, 0°–80°W, > 20°N) and the Northern Hemispheric high (NH, > 20°N), respectively. For removing the effects of seasonal change, all above MAIs and MSIs have been normalized one month by one month (Xu, 1986).

Solar data are the monthly Wolf's number (W) and 10.7 cm solar radio flux (SF). The data of W in 1954–1980 were observed in the Zurich Observatory. Since January 1981, the

Ws (International Sunspot Relative Number) have been provided by SESC (Space Environment Service Center). Before 1978, the data of 10.7 cm (2800 MHz) solar radio flux (SF) were observed by a radio observatory at Ottawa, from June 1991 onward, the data are obtained at Penticton (also in Canada). All of these data were taken from SESC since 1979, and from a collection of solar terrestrial indices (Zhu, 1982) before 1979 respectively. The SF is a good index to reflect the characteristic of solar activity. Strong SFs are generally associated with the occurrences of large group of sunspots on heliosphere or the outbursts of solar flares. The SF itself is highly positively correlated to the sunspot number (W).

III. CALCULATION OF CORRELATIONS

We have calculated the cross correlations between the monthly W, SF and MAI, MSI of each subtropical high in the N.H. for the recent 38 years (1954–1991) with the latters lagging 0–132 months respectively. In calculation, we have considered the auto–correlations (AC) of each time series. This means when the AC of a certain time series is strong, then the significance of its correlation with other time series will be seriously affected by the number of freedom, which is unequal to the original sample volume of time series. In short, the test of significance for any correlation must consider the inherent persistence in time series, so we should estimate the number of indepedent sample of time series—the effective sample number (Chen, 1982).

According to the AC of time series, the characteristical time scale (τ) between indepedent samples may be obtained as follows:

$$\tau = \sum_{i=-\infty}^{\infty} C_{xx}(i\Delta t) \cdot C_{yy}(i\Delta t) \cdot \Delta t.$$

Hence, the effective number of indepedent samples

$$N = n\Delta t / \tau,$$

where, n is the volume of original sample, Δt is the time lag of sample, C_{xx} and C_{yy} are the ACs of the time series X and Y respectively, both having a time lag of $i\Delta t$ (Chen, 1982). In the tests of significance for all correlations in present work, we generally replace n by N. For the calculated τ_s of correlative time series is mainly concentrated on the interval of 6.5–15.9, then the effective numbers of indepedent samples will be only 1 / 6.5— 1 / 15.9 of n. Hence, in the test of significance at a same level, it demands higher value of correlation due to decreased sample.

From Table 1 we have:

(1) Although the number of indepedent sample (N) has been reduced by an order of magnitude than original sample (n) under the consideration of AC in time series, the highly positive correlations (reaching 0.05 to 0.01 confidence) still exist between the W or SF and the MAI, MSI of each subtropical high in the N.H. during the recent 38 years, especially the MSIs of the Northern Hemispheric high (NH_2), the eastern Pacific high (EPH_2) and North Atlantic high (NAH_2) are highly correlated ($\alpha < 0.05$) to the previous solar indices (W, SF) with the persistence of about 22, 32 and 21 months respectively.

(2) Both the W and SF have significant positive correlation to the lagging MAI and MSI of EPH, coinciding well with the result of Xu (1986). Special attention is paid to the significant positive correlations ($\alpha < 0.01$) of W and SF persisting in about one year with the EPH_2, which lags for 12–23 months with a correlative peak at the 16–17th month.

(3) Though the correlations of the MAI and MSI of WPH with previous solar indices are

lower than corresponding correlations of EPH, they are still significantly positive ($\alpha <$ 0.05) when the WPH has a lag of about 16 months. In contrast, the maximal correlation between solar activity and the lagging indices of North Atlantic high (NAH_1, NAH_2) appears so late at the 27–29th month (lag of 2.2–2.4 years), coinciding well with the previous result (Xu, 1986) too.

(4) All correlations of SF with each index of subtropical high are larger than the corresponding correlations of W. This manifests that, reflecting the real strength of solar activity, the objectively observed 10.7 solar radio flux (SF) may be preferable to the sunspots (W), which were calculated more or less experimentally.

Table 1. Time Distribution of High Correlations ($\alpha < 0.05$) between SF, W and MAI, MSI of Each Subtropical High in the N.H.

Distribution of high correlations	SF (W)					
	t_{R1}	t_{R2}	T_M	R_M	N	α
NH_1	10—30 (9—30)		17 (17)	0.374 (0.358)	42 (42)	0.02 (0.02)
NH_2	11—32 (11—32)	17, 20,24—27 17, 20,24—27	26—27 (20,27)	0.401 (0.375)	37 (40)	0.02 (0.02)
WPH_1	15—16 (16)		15—16 (16)	0.260 (0.257)	56 (57)	0.05 (0.05)
WPH_2	16 (16)		16 (16)	0.240 (0.231)	67 (67)	0.05 (0.10)
EPH_1	4—27 (4—27)	14—17 (15—17)	16 (16)	0.413 (0.403)	41 (42)	0.01 (0.01)
EPH_2	1—32 (1—32)	11—23 (11—23)	16—17 (17)	0.473 (0.464)	39 (39)	0.01 (0.01)
NAH_1	17—31 (17,21, 24—32)		27 (29)	0.375 (0.360)	34 (35)	0.05 (0.05)
NAH_2	16—36 (17—37)	27,29	27 (29)	0.449 (0.431)	27 (27)	0.02 (0.05)

Note: Numbers in the Table with (without) bracket are the related parameters of high correlations between W(SF) and MAI, MSI respectively; t_{R1} and t_{R2} are the numbers of month with high correlation at the confidence limit (α) of 0.05 and <0.05 respectively. t_{R2} with the real line and dotted line below expresses the numbers of the month with high correlations significant at the 0.01 and 0.02 levels respectively. The R_M and T_M are the maximum value of correlations and the month number of its occurrence respectively, α is a reaching confidence of R_M according to N.

IV. ACCURATE CALCULATION OF THE LENGTHS OF REAL PERIODS

In the researches of connection between solar activity and the strength of subtropical high, it is essential to calculate all main periods of the solar activity and subtropical highs in order to find the possible relationship between them. Power spectrum and harmonical analysis are generally used to calculate the periods included in time series, but their sample points in the section of low frequencies are too few to define the real lengths of periods. As m is the maximum of the time lags, then we can obtain the spectrum estimation of the following period lengths only when $T_k = m / k$ $(0 \leqslant k \leqslant m / 2)$, here k is a positive integer.

Now in present work, if $m = 22$ years, we can get spectrum estimations of the following periodic lengths (year) only: 22 / 1, 22 / 2, 22 / 3, 22 / 4, …… i.e., the limited periodic lengths are 22, 11, 7.33, 5.5 year ……). We can see how large intervals appear in the section of low frequencies. If the lengths of the real periods in data exist between the 11 and 22 years, or between the 7.33 and 11 years, then we have no hope to find out these real periods and their actual spectrum peaks by the method of spectrum analysis. Therefore, now we use the non–integer wave method (the NI technique, Schickedanz et al., 1977) in present work. Huang et al. (1984) had ever introduced this method.

The main characteristic of the NI technique is to transform both components $(\mathrm{Cos}\frac{2\pi k}{n}t$, $\mathrm{Sin}\frac{2\pi k}{n}t)$ of a harmonical equation into two variable factors of a linear regression equation, the harmonical coefficients $(a_0,\ a_k,\ b_k)$ then change into the regression coefficients of a new equation. First, we can calculate these regression coefficients from observed data, then obtain the corresponding complex regressive equation for any non–integer wave k $(1 \leqslant k \leqslant n / 2)$ and the square of complex correlation (R_k^2), which is positively proportional to the corresponding power spectrum value of the non–integer wave number k being able to reflect the magnitude of corresponding spectrum value. The F–test may be used to verify the significance of R_k^2.

Now let us calculate the non–integer (year) waves of W and SF from their observed data of 456 months (1954–1991), i.e., to calculate the squares of complex correlations (R_k^2) of all non–integer periods between 2.0 and 38.0 years with the sample interval of only one month. Each R_k^2 will be tested for significance by a statistic F

$$F = \frac{R_k^2 / \gamma}{(1 - R_k^2) / (n - \gamma - 1)}.$$

According to the F–distribution, the freedom of above numerater is γ, while the freedom of denominator is n–γ–1. Now for any k, if $\gamma = 2$, we have $n - \gamma - 1 = 453$. From the table of F–distribution, we find that when $F > 4.7$, a significance of 0.01 confidence is reached.

Fig. 1 shows the distribution of R_k^2 (approximate value of spectrum) of each index in wave length of 40–160 months by the non–integer (year) wave method, which could find out all actual lengths of periods included in time series with any precision. Now we take the resolution as one month. From Fig. 1 and Table 1 we can see that periodical length of the maximal spectrum peak of EPH$_2$(26 months –10.5 years) approximates mostly to the periodical length of corresponding peak of W and SF (131 months–10.9 years), other indices of subtropical highs also have significant spectrum values at the 131th month (all reaching the dotted line of 0.01 level). W has a second peak at the 93th month (7.8 years), but no corresponding responses appear in the spectrum curves of each subtropical high. The variations of W and SF are alike to each other (Fig. 2), the phases of these two curves significantly approximate to the curve of EPH$_2$. Though the area index curve of the subtropical high (WPH$_1$) in the western Pacific contains a periodical effect of the 131 months from solar activity, it still includes some waves of short periods, which are the effects of the 3–5 year cycles of ENSO.

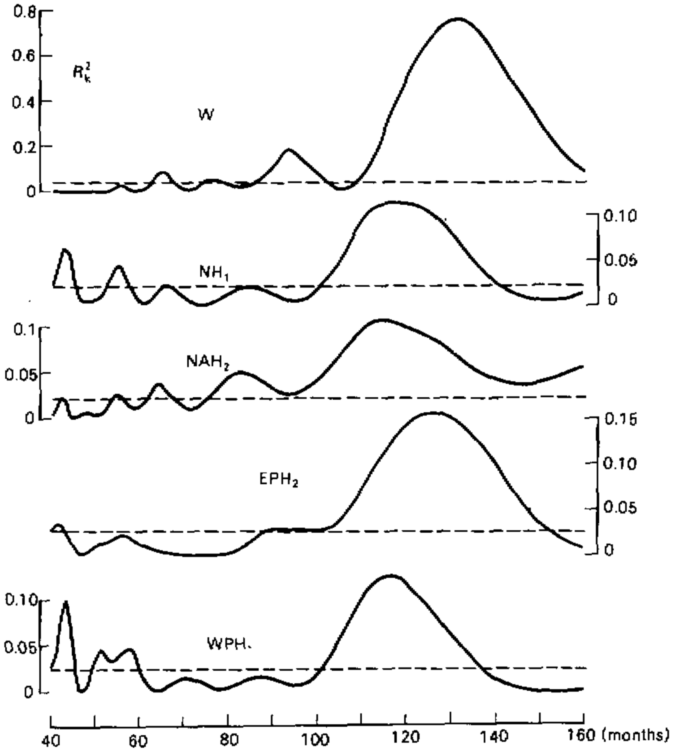

Fig. 1. Time distribution of R_k^2 between solar indices and the MAI, MSI of each subtropical high in wave section of 40–160 months ($k=40, 41,\cdots, 160$). The coordinate denotes the magnitude of R_k^2. Dotted line means that the R_k^2 is significant at 0.01 confidence by the F–test.

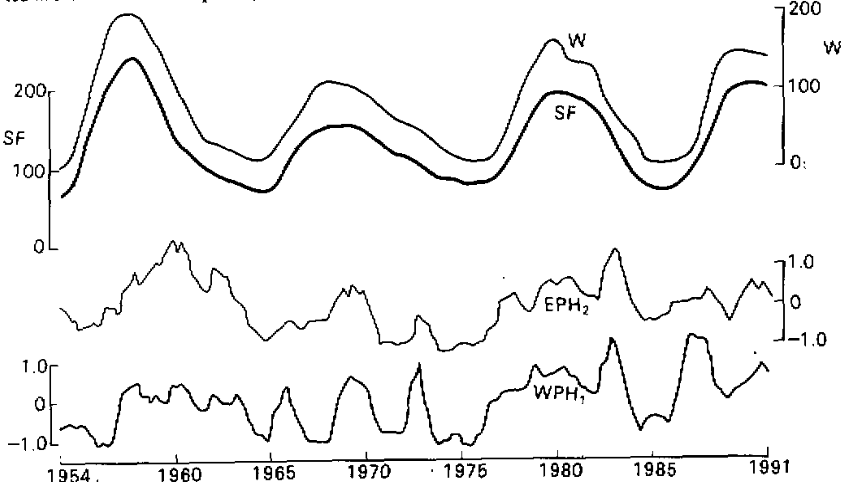

Fig. 2. The 12–month running average curves of W, SF, WPH$_1$ and EPH$_2$ in the past 38 years. The unit of SF is 10^{-22}Wm^{-2}Hz^{-1}. WPH$_1$ and EPH$_2$ are normalized anomaly (unit: 10GPM).

Table 2. The Characteristics of Three Main Periods of Solar Activity and Each Subtropical High in the N.H.

Indice	First period			Second period			Third period		
	T_k	R_k^2	F_k	T_k	R_k^2	F_k	T_k	R_k^2	F_k
W	131, (10.9)	0.758,	707.9	93—94, (7.8)	0.172,	46.9	448—456, (37.3—38.0)	0.068	16.6
SF	131, (10.9)	0.758,	708.0	94, (7.8)	0.190,	53.0	454—456, (37.8—38.0)	0.082	20.2
WPH_1	116, (9.67)	0.127,	33.0	43, (3.58)	0.100,	25.2	456, (38)	0.079	19.5
WPH_2	43, (3.58)	0.095,	23.7	116, (9.67)	0.080,	19.8	456, (38)	0.075	18.4
EPH_1	277—279, (23.1—23.3)	0.167,	45.3	123, (10.3)	0.129,	33.7	57, (4.75)	0.021	4.7
EPH_2	286—291, (23.8—24.3)	0.173,	47.3	126, (10.5)	0.155,	41.5	57, (4.75)	0.023	5.3
NAH_1	405—417, (33.8—34.8)	0.194,	54.6	115, (9.6)	0.092,	23.0	187—195, (15.6—16.3)	0.060	14.4
NAH_2	424—432, (35.3—36.0)	0.205,	58.6	115, (9.6)	0.107,	27.1	195—197, (16.3)	0.084	20.9
NH_1	337—354, (28.1—29.5)	0.205,	58.6	117, (9.75)	0.119,	30.6	42, (3.5)	0.067	16.2
NH_2	339—349, (28.3—29.1)	0.17,	46.5	117, (9.8)	0.099,	24.8	43, (3.58)	0.070	16.9

Note: T_k is the length of period K in months with the corresponding years in parentheses. F_k is a statistic value of period K, showing the corresponding significance of its spectrum value (R_k^2). When $F_k > 4.7$, the spectrum value of period K has reached the 0.01 confidence limit.

From Table 2 we have:

(1) The variation of solar activity has three main periods, the most significant period is 10.9 years (131 months), then 7.8 years and 37–38 years in sequence. Anyhow the R_k^2 and F_k of the 131–month period are significantly larger than the corresponding values of other two periods. Moreover, no responses of the 7.8–year period are found in the variations of each subtropical high. Therefore, our analysis will concentrate on the effects of the 10.9–year period in solar activity.

(2) The mainly prevailing periods of subtropical high indices are as follows:

① The period of about 10 years; ② the 23–24 year period; ③ the 34–38 year period; ④ the 3.5–4.8 year period. The first three periods are associated possibly with solar activity. The 23–24 year period may be connected with the double 11–year oscillations of the sunspot's magnetic fields. The 34–38 year period possibly is a kind of Brückner period. Eeigenson (1963) indicated that the relation between the sun and tropospheric atmosphere is not certain to be linear (quoted from Zhang, 1976), so the quasi–century period of solar activity may directly produce the Brückner period of atmospheric circulation, the length of which is about a half of the quasi–century period, including three or four 11–year periods. Now we have also obtained the significant 38–year period from the long year data of W and SF, further supporting above point.

(3) The lengths either the first period in NAH or the third period in WPH are about 34–38 years, belonging to the same Brückner period of about 35 years.

(4) The 3.5–4.7 year short period is prevailing in the strength indices of the WPH, EPH and NH. This just reflects the significant influences of the Southern Oscillation, which also modulates the intensity of the Northern Hemispheric high (NH), through affecting the strengths of the WPH and EPH. Anyhow, its influence on the North Atlantic high is not significant.

The following discussion will be focused on the effect of the 10.9–year (131–month) solar oscillation on each index of subtropical highs in the N.H.. A feasible way is to see whether the spectrum value at the 131–month for each index of subtropical highs reaches the significant level of the F–test, hence the R_k^2 values at the 131–month of each index of subtropical highs and their corresponding F_k are listed in Table 3.

Table 3. The Spectrum Significance of Each Index of Subtropical Highs in the N.H. at the Main Period (131–Month) of Solar Activity

Index	R_k^2	F_k	α
WPH_1	0.057	13.8	0.01
WPH_2	0.039	9.2	0.01
EPH_1	0.112	28.7	0.01
EPH_2	0.147	39.1	0.01
NH_1	0.070	17.0	0.01
NH_2	0.061	14.6	0.01
NAH_1	0.053	12.8	0.01
NAH_2	0.069	16.7	0.01

From Table 3, it can be seen that all indices of subtropical highs contain the significant influence from the main period (131–month) of solar activity. Arranging the F_k by its magnitude, the most significant influences of the 131–month period occur successively at the following indices:

a. The strength index of the eastern Pacific high (EPH_2),

b. The area index of the eastern Pacific high (EPH_1),

c. The area index of the northern hemispheric high (NH_1),

d. The strength index of the North Atlantic high (NAH_2) and so on.

Though the positive correlations between the indices of the western Pacific high (WPH_1, WPH_2) and preceding solar activity are not very significant (Table 1), in Table 3, the solar activity in main period (131–month) still has notable influence.

V. CONCLUSION AND DISCUSSION

1. Through a strict test with the consideration of auto–correlations in time series, both indices (the sunspot number and 10.7 cm solar radio flux) of solar activity still show a series of significant positive correlations with the area / strength indices of subtropical highs in the N.H. with 1–2 years lag especially the strength indices of the Northern Hemispheric high, the

eastern Pacific high and North Atlantic high are significantly positively correlated to the intensities of preceding solar activity with the persistence of 22, 32 and 21 months, respectively.

2. The area / strength indices of the eastern Pacific high have the most sensitive positive response to the intensities of solar activity in preceding 1–2 years, especially in preceding 16–17 months. The intensity of the North Atlantic high also responds significantly positively to the preceding solar activity, but the time of largest response of the NAH delays to the 3–5th month of two years later.

3. The 10.7 cm solar radio flux has a higher relationship with the strength of each subtropical high in the N.H. than that of the sunspot number, also demonstrating that the former may be a better index for reflecting the intensity of solar activity.

4. Using an analytic technique of the non–integer (year) wave, we find that all indices of subtropical highs in the N.H. are significantly influenced by the main period (10.9–year) of solar activity.

5. The western Pacific high, the North Atlantic high and both indices of solar activity contain a same period of about 34–38 years, showing that the source of this Brückner period may be an influence from the low frequency oscillation of solar activity.

6. It is possible that the 3.5–4.8 year periods existing in the Northern Hemispheric high, the eastern and western Pacific high are influenced deeply by the intensity of the Hadley cell in the equatorial Pacific through the variable phases of ENSO.

7. The annual frequency of the Etesian wind in Athens of the past 70 years (1891–1961) had a significant positive correlation (reaching 0.001 confidence) to the annual number of sunspots, whereas the former was modulated by the interannual oscillation of the strength of summer North Atlantic high (Carapiperis, 1962, quoted from Herman et al., 1978). This result coincides well with our present work, which shows that during a period of strengthening solar activity, the North Atlantic high is tending to intensify with its eastern ridge expanding eastward, then the Etesian wind will prevail over Athens.

8. The tropopause heights of some stations located in the tropical Pacific show a significant interannual change, coinciding well with those of the 11–year solar cycle (Gage et al., 1981; Reid et al., 1983). It is evident from the Fig. 6 of Reid and Gage (1983) that the sunspot numbers of 1952–1973 had a very high correlation with the tropopause's potential temperatures of some stations located in the tropical Pacific a year later. Owing to the significant barotropy for the anomaly of atmospheric circulation, above discovery coincides well with our present result.

9. A statistical analysis of the past 231–year data indicates that the summer floods in the middle–lower reaches of the Yangtze River occur at the peak years (0—+2 years) of the solar activity 11–year cycle (Xu, 1986) usually. An analysis of historical data in the lower reaches of the Yangtze River also presents the same conclusion (Wu, 1981). Above findings agree well with the present work, which means the strong solar activity will cause strong western Pacific high with its west ridge point stretching more westward, then the strong warm moist southwest wind from the Bay of Bengal will benefit plenty of rain in the middle–lower reaches of the Yangtze River during rainy season.

10. Recent detections from satellite (Wilson, 1988; Schatten, 1988) indicate that the solar constant observed at the top of the atmosphere is correlated significantly positively to the intensity of solar activity (such as the sunspot number). Connected with the present result, following conclusion may be drawn:

Accompanying with an increase (decrease) in solar activity, the earth–atmosphere system will receive more (less) solar radiation. This difference exists clearly in the vast regions at low latitudes. Much solar radiation will be stored over the subtropical zone with clear sky. From this point, present study is more reasonable as follows. The detection of satellite manifests that with the variation of solar activity, the changes of the ultraviolet (UV) radiation are larger than those of the visible radiation. It is convincible that the UV radiation in the wave length of 300–400 nm has an oscillation of about 2% magnitude, for the UV radiation with its wave lengths >330 nm is reduced only slightly by atmospheric ozone. Over sea surface with clear, dry atmosphere, it is more easy to detect the corresponding change of solar radiation following the variation of solar activity (Blocker et al., 1983). We believe that the vast subtropical ocean (especially of the eastern Pacific) just belongs to these kinds of regions. Clear, dry atmosphere dominated by the subtropical anticyclone will benefit the mixed layer beneath ocean successively storing the anomaly of cumulative heat, which is produced by the changes of solar activity— solar constant. Through affecting the sea surface temperature anomaly, above.heat anomaly will modulate the anomaly fields both of the atmospheric temperature and pressure aloft. Owing to more than a month is needed for the modulation of atmospheric temperature –pressure field to the change of heating field of underlying surface, it is reasonable that after a lag of only 1–4 months, the strength and area indices of the eastern Pacific high will begin closely to respond to the change of preceding solar activity. Their positive correlations reach a peak of the 0.01 confidence when the formers have a lag of 16–17 months (see Table 1). This is sufficient to show that the strength of anticyclone over the eastern subtropical Pacific is an indicator of atmospheric circulation responding most sensitively to the intensity of preceding solar activity.

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