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A WAVELET PACKET ENERGY DIAGNOSIS OF SOUTH ASIAN SUMMER MONSOON INFLUENCING ON THE WEST PACIFIC SUBTROPICAL HIGH

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ABSTRACT: Based on the wavelet packet decomposition/reconstruction method and the NCEP/NCAR daily reanalysis data set, the relation between the south Asian summer monsoon and the west Pacific subtropical high seasonal variation was discussed, and a corresponding summer monsoon frequency-band energy criterion was defined and introduced for diagnosing the west Pacific subtropical high. Besides, some existing characteristics and rules about the west Pacific subtropical high were further argued and proofed, a few new phenomena and correlation between the south Asian summer monsoon and the west Pacific subtropical high were also revealed and presented.

Key words: West Pacific subtropical high; South Asian summer monsoon; wavelet packet; energy criterion

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1 INTRODUCTION

An important constituent in the Asian summer monsoon system, the West Pacific subtropical high (simplified as the "High") is closely related with the activity of summer monsoon via the changes in intraseasonal intensity and progression[1 - 8]. Zhang et al[5]. discuss the relationship between seasonal jumps and anomalous location of the High's ridge and onset of low-latitude westerlies and tropical convection in summer, with the finding that the northward jump of the High is closely associated with the onset, northward jump and increase / northward movement — weakened / strengthened tropical convection is linked with a relative northward / southward of the ridge of the High. By calculating of indexes of East Asian summer monsoon and inter-comparing real cases, Peng[6] discovers the High will be usually more northward, weaker and more to the east in the years of strong summer monsoon while otherwise will be true. Tao et al.[7] note in data analysis that the changes in the summer monsoon intensity are well correlated with the location and activity of the High —the 500-hPa ridge is usually north of 30°N and the High is split into two centers while the ridge is usually south of the latitude, extending westwards from the central Pacific where the center of the High stands. Yu et al.[7] compare and study the characteristics of the circulation of two processes of the intraseasonal subtropical High, with the finding that when the High is anomalously northward (July 16 – August 12, 1983) / southward (July 29 – August 16, 1980), differences are large in the location and intensity of the summer monsoon system in Asia.

From the analysis of daily data of the 500-hPa geopotential height field and 850-hPa zonal

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wind field, meaningful corresponding relationship is shown between the South Asia summer monsoon and the High. 1987 was the year of weak summer monsoon, when the zonal wind was relatively weak in the South Asia region and the fluctuation amplitude and process of the westerlies was relatively smooth. Correspondingly, the 5880 geopotential meter (gpm) contour of the High was mainly south of 30°N and the High's center does not change significantly north-south. 1989 was also the year of generally weak summer monsoon, but with significant fluctuation of the westerlies. In contrast, the 5900 gpm contour mainly spans between 26°N and 28°N and the High is generally more southward, though considerable northward jumps and north-south shifts in location occurred. 1986 was the year of strong summer monsoon in South Asia and significant westerlies fluctuations, when the High was more northward in the summer with significant shifts of the High center. 1994 was the year of strong summer monsoon in South Asia but insignificant westerlies fluctuations, when the High is relatively strong and more northward with the center relatively stable in the north-south direction and very limited amplitude of movement.

As shown in the study and data analysis conducted above, the intensity and amplitude of the fluctuation of the South Asia summer monsoon are closely related with the intensity, location and north-south shifts of the High. Lacking quantitative diagnostic description, the relationship, which includes characteristic parameters to depict the activity of the High and monsoon, such as the indexes for the area, intensity, westernmost ridge point, ridge line of the High and index for the summer monsoon, mainly addresses the patterns with which the High or monsoon acts. In addition, as there are multiple periods of activity in the fluctuation of summer monsoon in South Asia (like those of 30 – 50 days and quasi-biweekly oscillations) and existing monsoon indexes are too coarse in the division of frequency structure, it is then necessary to introduce reasonable quantitative indexes to describe the multiplicity in the period of monsoon activity. For this purpose, the current work, on basis of the decomposition and reconstruction of wavelet packets, proposes a diagnostic method to distinguish the energy of frequency domains of the summer monsoon and defines a characteristic value for the domains, with which the location and progression / retreat of the High can then be diagnosed and differentiated.

2 DATA

The analysis of daily data of the 500-hPa geopotential height field and 850-hPa zonal wind field (the former is used to describe the High and the latter to analyze the monsoon) is used, which covers the duration from 1980 to 1997. The zonal wind averaged over gridpoints of the region 50°E – 90°E, 5°N – 20°N for the period from June 1st to August 15th is taken to express the changes in the intensity and fluctuations of summer monsoon over the Arabian Sea and Indian Peninsula (simplified as the "Monsoon"); the time-latitude cross section of the geopotential height field centered around 120°E (averaged over gridpoints from 115°E to 125°E) for the period from June 16th to August 30th is used to describe the location and progression / retreat of the High.

3 DECOMPOSITION AND RECONSTRUCTION OF WAVELETS PACKETS AND CRITERION FOR ENERGY IN FREQUENCY DOMAINS

Wavelets analysis is a powerful tool to study unstable time-frequency signals, for it enables fine division of layers of signal frequencies using the binary system and select and match corresponding frequency bands self-adaptively based on the characteristics of the signals it analyzes. As the decomposition and reconstruction of wavelets can accurately address the intensity of the fluctuation and distribution of energy over various periods, the work employs the method to decompose and reconstruct the frequency and periods of the time series signals of the Monsoon and define criterion for energy in corresponding domains of frequency. It is then used to conduct objective and quantitative analysis of the relationship between the Monsoon and the morphology and activity of the High.

The decomposition and reconstruction are carried out with a 4-layer wavelet packet using the base db1 for the daubechies wavelet and shannon entropy. The base has good orthogonality and tight supporting, being capable of transforming continuous and discrete wavelets and displaying the continuity and abrupt-changing of signals over all sections of frequency. For the expressions of db1 wavelet function and scale function and their corresponding shrink / extension and translational / transforming forms, refer to [9, 10]. Next are the main steps of the analysis.

(1) The db1 wavelet base is first used to apply a 4-layer packet decomposition of the time series signals of the Monsoon (it is done following the form of 2^n to decompose the frequency at fixed intervals in which n is the number of layers to be decomposed; it is then possible to fine-divide both high and low frequency signals at the same time and optimum layers to be decomposed can be determined depending on the basic features and empirical knowledge of the objects concerned) to extract separately signal characteristics of 16 components from low to high frequency on the fourth layer (Fig.1). As daily data are used here, the maximum sampling frequency is 1 (times / day) for the signals of the time series.

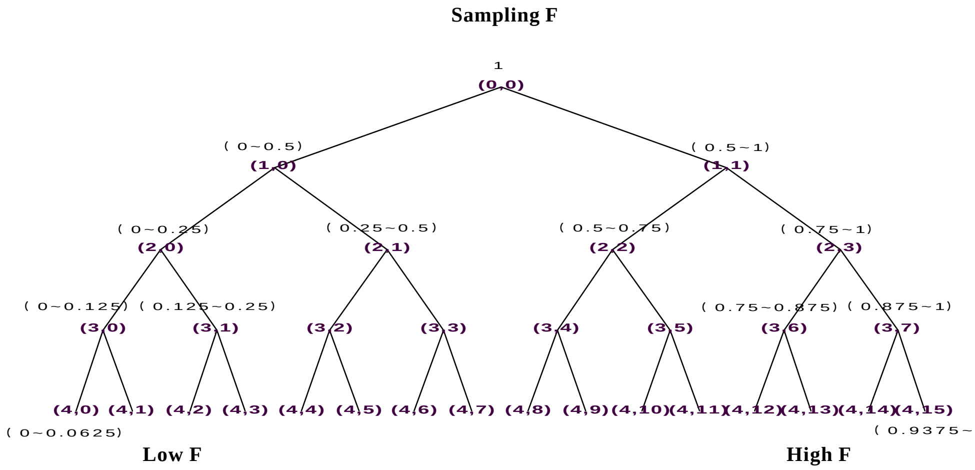

Fig.1 Schematic diagram of tree structure of the 4-layer wavelets packet decomposed (the maximum sampling frequency is 1).

(2) Then, the coefficient for the wavelet packet at the fourth layer is reconstructed to extract signal characteristics for individual frequency domains. Based on the fact that frequency sections decomposed from the wavelet packet are equivalent to band-pass filters with homogeneous bandwidth. The relation of the decomposition and reconstruction is expressed by

$$S = \sum_{j} S_{4j} (j = 0,1,2,\cdots\cdots,15)$$

where S is the signal of real summer monsoon and percentages of individual decomposed layers taking up in bandwidth are shown in Tab.1. From the decomposed frequency – period structure, we note that the 4-layer decomposed wavelets packet shows very fine bandwidth structure and resolution of periods. It is then seen that the decomposed signals of the frequency bands (periods) as shown above are relatively objective and accurate in depicting changes in the intensity and fluctuation.

Tab.1 Periods of bandwidth corresponding to signal components.

Signal components	Frequency bandwidth	Corresponding periods / days	Signal components	Frequency bandwidth	Corresponding periods / days
S_{40}	0.000～0.0625	≥ 16.0	S_{48}	0.500～0.5625	1.8～2.0
S_{41}	0.0625～0.125	8.0～16.0	S_{49}	0.5625～0.625	1.6～1.8
S_{42}	0.125～0.1875	5.6～8.0	S_{410}	0.625～0.6875	1.5～1.6
S_{43}	0.1875～0.250	4.0～5.6	S_{411}	0.6875～0.750	1.3～1.5
S_{44}	0.250～0.3125	3.2～4.0	S_{412}	0.750～0.8125	1.2～1.3
S_{45}	0.3125～0.375	2.6～3.2	S_{413}	0.8125～0.875	1.1～1.2
S_{46}	0.375～0.4375	2.3～2.6	S_{414}	0.875～0.9375	1.06～1.1
S_{47}	0.4375～0.500	2.0～2.3	S_{415}	0.9375～1.000	1.0～1.06

(3) The total energy is sought for individual bands of frequency

Setting the energy is $E_{4j}(j=0,1,2,\cdots\cdots,15)$ for $S_{4j}(j=0,1,2,\cdots\cdots,15)$, then we have

$$E_{4j}=\int\left|S_{4j}(t)\right|^2\mathrm{d}t=\sum_{k=1}^{n}\left|x_{jk}\right|^2$$

where $x_{jk}(j=0,1,2,\cdots\cdots,15;k=0,1,2,\cdots\cdots,n)$ is the value of amplitude for the discrete point of the reconstructed signal S_{4j} and n is the point at which samples are taken.

(4) Characteristic values are defined for the energy in domains of frequency. When the monsoon system (i.e. wind speed or fluctuation of monsoon) is in a normal or abnormal state, the signals of time series may not be substantially different from each other as the signals of corresponding frequency domains (periods) are sending confusing messages. In fact, however, the magnitude and intensity of fluctuation energy may be completely different for individual domains (periods) of monsoon signals. For instance, significant differences could exist in the 30-50-day or quasi-biweekly oscillations if the monsoon is in a normal or abnormal state. Through the calculation of characteristic values of fluctuation energy for independent frequency domains of the monsoon signals, the intensity of monsoon fluctuation can be effectively displayed or measured for all domains of time and frequency so that linkages between Monsoon fluctuation and High activity over individual periods of frequency are established.

A characteristic vector $\boldsymbol{T}$ is constructed using decomposed and reconstructed signals for individual domains of frequency:

$$\boldsymbol{T}=[E_{40},E_{41},E_{42},E_{43},E_{44},E_{45},E_{46},E_{47},E_{48},E_{49},E_{410},E_{411},E_{412},E_{413},E_{414},E_{415}]$$

When the energy is relatively large, $E_{4j}(j=0,1,2,\cdots\cdots,15)$ is usually large, too. For convenient analysis, the vector $\boldsymbol{T}$ is normalized depending on actual needs. Taking

$$E=(\sum_{j=0}^{15}\left|E_{4j}\right|^2)^{\frac{1}{2}}$$

$$\boldsymbol{T'}=[\frac{E_{40}}{E},\frac{E_{41}}{E},\frac{E_{42}}{E},\frac{E_{43}}{E},\frac{E_{44}}{E},\frac{E_{45}}{E},\frac{E_{46}}{E},\frac{E_{47}}{E},\frac{E_{48}}{E},\frac{E_{49}}{E},\frac{E_{410}}{E},\frac{E_{411}}{E},\frac{E_{412}}{E},\frac{E_{413}}{E},\frac{E_{414}}{E},\frac{E_{415}}{E}]$$

T is the normalized characteristic vector of energy over domains of the Monsoon frequency. For ***T*** or ***T'*** , each of the characteristic value of energy respectively stands for the intensity and energy of the Monsoon over the said domains of frequency (periods).

4 FIRST CHARACTERISTIC ENERGY VALUE AND NORTH-SOUTH MORPHOLOGY OF THE WEST PACIFIC SUBTROPICAL HIGH

Eighteen years (1980 – 1997) of the Monsoon and High are calculated and examined in comparison experiments. As monsoon fluctuations for periods over 3 days take up about 90% of the total (Tab.2), they show main features of the variation of South Asia Monsoon; short-term fluctuation below 3 days have smaller variances and weaker effect on the High, which will not be discussed (same below).

Tab.2 Percentages of fluctuations of individual periods of the Monsoon in total variance of signals (duration of calculation: June 1 – August 15)

Periods	> 16 d	8～16 d	5.6～8 d	4～5.6 d	3.2～4 d	< 3d
Mean for 1980 – 1997 / %	61.8028	6.7004	6.8697	8.9619	7.2694	8.3957

Tab.3 gives the characteristic vectors S_{40}, S_{41}, S_{42}, S_{43}, S_{44} for the frequency domains of the wavelets packet for the mean zonal wind in the Monsoon region and state of the High in summer and comparisons of differentiation results. It is divided by the mean location of the ridge —the High is said to be northward if its 5880 gpm center or 5900 gpm coverage stays north of 30°N but considered southward if they remain south of 30°N. From the table, we note that the first characteristic energy value of S_{40}, or low-frequency fluctuations, take up the majority of the energy for monsoon activity. The magnitude of the value is well associated with the years of northward / southward location of the High observed. As shown in the calculation results, if the characteristic value is large (>103), the High is northward in summer; if it is small (<103), the High is southward. It is then reasonable to take 103 as the critical value of the first characteristic energy value, which can be used to tell whether the High is northward or southward. Tab.3 gives the results of such diagnostic differentiation. It shows that except for a few years (1980, 1988 and 1993) for which the diagnosis goes wrong (those labeled with asterisks), what is differentiated for the 15 years agrees generally well with the High observed.

Tab.3 uses the time series for yearly periods from June 1 to August 15. As the Monsoon is active over roughly the same as the High is, the differentiation outcome is only diagnostically meaningful. In view of forecast needs, the characteristic vector ***T*** is calculated over an annual period from June 1 to July 31 instead of one from June 1 to August 15. The calculated characteristic value of summer monsoon frequency domains for the same years are listed in order according to the magnitude of the first characteristic value (which describes low-frequency activity of the Monsoon with periods longer than 16 days). As shown in the results, the High is mostly northward in summer in years with the latter higher than 90 (the critical value) and otherwise is true (Tab.4).

As compared with Tab.2, the results of two methods of diagnostic differentiation are exactly the same (i.e. except for the three years of 1980, 1988 and 1993 for which the diagnosis goes wrong (labeled with asterisks), though the years listed according the magnitude of characteristic values are slightly different. It shows that the low-frequency fluctuations at periods longer than 16 days as detected for June and July can be objective descriptors of how the High looks like in the north-south direction in the time. As the duration of calculation of characteristic monsoon values is ahead of that of the High morphology, the differentiation results are both diagnostic and predictive over some period of validity.

Tab.3 Differentiation of characteristic energy values of frequency domains in the wavelets packet for the Monsoon (duration of calculation: June 1 – August 15; it is between June 16 and August 30 for the state of the High)

year	Observed state of the High	Results of characteristics differentiation	Periods for the characteristic values of energy of frequency domains in the wavelets packet				
			> 16 d	8～16 d	5.6～8 d	4～5.6 d	3.2～4 d
1994	northward	northward	115.240	16.453	6.860	6.495	2.467
1984	northward	northward	111.973	14.681	11.262	16.578	2.137
1980	southward	northward *	109.804	8.373	12.153	13.142	4.210
1986	northward	northward	107.514	25.358	13.728	14.246	4.688
1993	southward	northward *	106.059	12.686	10.218	15.710	3.396
1990	northward	northward	105.102	8.031	11.536	15.318	2.903
1981	northward	northward	104.322	20.234	13.825	11.222	2.477
1985	northward	northward	103.556	10.788	11.471	15.739	2.492
1991	northward	northward	103.396	8.948	13.094	19.048	2.066
1996	southward	southward	101.958	27.220	16.903	13.798	6.102
1992	southward	southward	100.375	17.729	14.823	17.197	4.613
1982	southward	southward	99.762	13.973	12.543	18.913	3.342
1988	northward	southward *	97.136	16.879	9.926	12.254	2.700
1989	southward	southward	96.690	21.790	12.541	12.426	3.098
1983	southward	southward	96.492	14.562	10.938	19.933	3.763
1997	southward	southward	96.270	18.472	11.932	5.371	3.249
1995	southward	southward	94.369	16.803	9.576	10.285	2.310
1987	southward	southward	90.926	8.070	7.876	13.608	2.990

For the calculation of the characteristic vector ***T***, the period is further put forward to May 15 – July 15. As shown in the result, the critical value is about 80 for the first characteristic energy value. When it is larger than 80, the High is northward; when it is smaller than 80, the High is southward. Except for the years of 1980, 1988 and 1991, the differentiation is basically correct (table omitted). It shows that similar restraints and correlation are present between low-frequency activity over the period and the morphology of the High afterwards. By determining the characteristics of the energy of low-frequency activity of the Monsoon during the period, we can infer the basic morphology of the High with some degree of assurance.

As shown in the above calculation and comparison, the characteristic values of the first frequency domain energy based on the decomposed and reconstructed wavelets packet are objective indicators of basic morphology of the High in summer. The mechanisms and dynamic significance are to be studied in future research.

5 SECOND CHARACTERISTIC ENERGY VALUES AND NORTH-SOUTH ACTIVITIES OF THE HIGH

Analyzing the time-latitude cross section of the 500-hPa geopotential height field near 120°E for differences in 5880 gpm and 5900 gpm among the years, we note that eight out of 18 years (1980 – 1997) witness active north-south shifts of the High (the center location of which has significant oscillations in the north-south direction, figure omitted) and the other ten years see stable High (the center location of which does not change much in the same direction). Column Five in Tab.5 presents it. Similar diagnostic study with the method of characteristic energy values for frequency domains have also shown that the magnitude of the second characteristic energy value (corresponding to the quasi-biweekly oscillation of the Monsoon at periods between 8 and 16 days) is well correlated with the north-south shifts of the High in summer. When it is larger than the critical value of 15, the year will be associated with active north-south shifts of the High; when it is smaller than 15, the year will be associated with stable position of the High (Tab.5). In other words, in the years of strong / weak quasi-biweekly oscillations of summer monsoon in South Asia, the high in western Pacific will be relatively active / stationary. Except for a couple of years (1991 and 1997, which are marked by asterisks), when obvious incorrect differentiation occurs, most of the results are generally consistent with reality.

Tab.4 Same as Tab.3 but with the calculation covering the period from June 1 to July 31 for the Monsoon

Case years	Real state of High	Results of differentiation	Periods for characteristic energy vectors of wavelets packet (the first five)				
			> 16 d	8～16 d	5.6～8 d	4～5.6 d	3.2～4 d
1994	northward	northward	104.610	10.439	11.723	9.440	3.149
1984	northward	northward	100.869	7.400	9.591	12.884	4.273
1980	southward	northward*	100.529	11.796	8.219	11.784	4.667
1993	southward	northward*	94.983	8.330	7.971	15.917	3.287
1986	northward	northward	94.849	21.859	10.521	4.090	5.522
1990	northward	northward	94.493	10.158	6.957	9.442	3.124
1985	northward	northward	93.546	8.372	5.170	7.693	1.983
1991	northward	northward	92.317	11.053	12.383	16.265	2.208
1981	northward	northward	91.057	14.370	7.762	10.323	4.652
1996	southward	southward	87.942	28.576	16.968	13.443	6.909
1992	southward	southward	87.918	19.258	13.639	14.396	5.946
1982	southward	southward	87.138	12.585	13.679	4.746	5.152
1995	southward	southward	86.882	16.587	10.708	7.389	3.490
1988	northward	southward*	86.460	16.350	12.164	8.781	4.460
1989	southward	southward	86.359	23.648	8.457	9.604	4.533
1987	southward	southward	86.322	10.787	6.300	5.351	3.499
1983	southward	southward	84.046	17.457	10.786	7.318	4.902
1997	southward	southward	83.543	12.820	6.659	11.989	3.844

For the purpose of prediction, the period of characteristic energy values calculation is shortened to a time between June 1 and July 31. As shown in the result, the High exercises active north-south shifts in summer in years when the critical value is larger than 14 for the second characteristic energy value but remains stationary in years when it is smaller than 14 (Tab.6). Except for the three years (1983, 1991 and 1994, which are marked with asterisks), differentiation is generally correct. The order of magnitude in terms of particular cases and characteristic values vary from year to year.

As shown in the results above, the magnitude of the characteristic energy values of the quasi-biweekly oscillations of the Monsoon in June – August and in June – July diagnostic and predictive (with limited period of validity) to the north-south shifts of the High. If the calculation period is further put forward to a period between May 15 and July 15 and corresponding critical value for the second energy is taken to determine how the High shifts north-south, the result will be much poorer (errors occur in seven of the years differentiated). It is shown that leading characteristic Monsoon values are not an efficient diagnostic or predictive tool for the activity of the High (table omitted).

Tab.5 Same as Tab.3 but with the calculation covering the period from June 1 to August 15 for the Monsoon

Case years	Real state of High	Results of differentiation	Periods for characteristic energy vectors of wavelets packet (the first five)				
			> 16 d	8～16 d	5.6～8 d	4～5.6 d	3.2～4 d
1996	active	active	101.958	27.220	16.903	13.798	6.102
1986	active	active	107.514	25.358	13.728	14.246	4.688
1989	active	active	96.690	21.790	12.541	12.426	3.098
1981	active	active	104.322	20.234	13.825	11.222	2.477
1997	stationary	active*	96.270	18.472	11.932	5.371	3.249
1992	active	active	100.375	17.729	14.823	17.197	4.613
1988	active	active	97.136	16.879	9.926	12.254	2.700
1995	active	active	94.369	16.803	9.576	10.285	2.310
1994	active	active	115.240	16.453	6.860	6.495	2.467
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1982	stationary	stationary	99.762	13.973	12.543	18.913	3.342
1993	stationary	stationary	106.059	12.686	10.218	15.710	3.396
1985	stationary	stationary	103.556	10.788	11.471	15.739	2.492
1991	active	stationary*	103.396	8.948	13.094	19.048	2.066
1980	stationary	stationary	109.804	8.373	12.153	13.142	4.210
1987	stationary	stationary	90.926	8.070	7.876	13.608	2.990
1990	stationary	stationary	105.102	8.031	11.536	15.318	2.903

As shown in the diagnostic and differentiation results, the method based on the second characteristic energy values of the Monsoon is quite objective in describing and differentiating the north-south movement of the High, and reveals good correlation and corresponding relationship between high / low intensity of the quasi-weekly oscillations at periods of 8 – 16 days and active / stationary north-south movement of the High. Work remains to be done on its governing mechanism and dynamics.

Tab.6 Same as Tab.3 but with the calculation covering the period from June 1 to July 31 for the Monsoon

Case years	Real state of High	Results of differentiation	Periods for characteristic energy vectors of wavelets packet (the first five)				
			> 16 d	8～16 d	5.6～8 d	4～5.6 d	3.2～4 d
1996	active	active	87.942	28.576	16.968	13.443	6.909
1989	active	active	86.359	23.648	8.457	9.604	4.533
1986	active	active	94.849	21.859	10.521	4.090	5.522
1992	active	active	87.918	19.258	13.639	14.396	5.946
1983	stationary	active *	84.046	17.457	10.786	7.318	4.902
1995	active	active	86.882	16.587	10.708	7.389	3.490
1988	active	active	86.460	16.350	12.164	8.781	4.460
1981	active	active	91.057	14.370	7.762	10.323	4.652
1997	stationary	stationary	83.543	12.820	6.659	11.989	3.844
1982	stationary	stationary	87.138	12.585	13.679	4.746	5.152
1980	stationary	stationary	100.529	11.796	8.219	11.784	4.667
1991	active	stationary *	92.317	11.053	12.383	16.265	2.208
1987	stationary	stationary	86.322	10.787	6.300	5.351	3.499
1994	active	stationary *	104.610	10.439	11.723	9.440	3.149
1990	stationary	stationary	94.493	10.158	6.957	9.442	3.124
1985	stationary	stationary	93.546	8.372	5.170	7.693	1.983
1993	stationary	stationary	94.983	8.330	7.971	15.917	3.287
1984	stationary	stationary	100.869	7.400	9.591	12.884	4.273

5 CONCLUDING REMARKS

In our study of the correlation between the Monsoon and the High, a method of decomposition and reconstruction of the 4-layer wavelet packets is introduced and defined based on db1 wavelet base and the shannon entropy. The relationship between the Monsoon and the morphology and north-south shifts of the High is discussed. The results both provide evidence for our data analysis and existing research findings and reveal some new phenomena.

(1) The diagnostic and differentiation method is objective, quantitative and physically illustrative and able to turn an overall qualitative presentation of the Monsoon activity into a relatively concrete quantitative diagnosis.

(2) The magnitude of the second characteristic energy values of the Monsoon in the current and preceding periods (depicting low-frequency activity at periods above 16 days) is well correlated with the north-south morphology of the High in summer — the High is usually northward / southward in the years of strong / weak low-frequency activity of the Monsoon.

(3) The magnitude of the second characteristic energy values of the Monsoon in the current and preceding periods (depicting low-frequency activity at periods between 8 to 16 days) is well correlated with the north-south morphology of the High in summer —the High is usually active / stationary in the years of strong / weak quasi-biweekly fluctuations of the Monsoon.

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