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THE SOUTH CHINA SEA SUMMER MONSOON AND THE SEASONAL MODALITY AND WEST EXTENDING OF THE NORTHERN HEMISPHERE PACIFIC SUBTROPICAL HIGH

ZHANG Ren (张 韧)[1], HE Jin-hai (何金海)[2], DONG Zhao-jun (董兆俊)[1] YU Dan-dan (余丹丹)[1]

(1. *Department of Marine Meteorology, Institute of Meteorology, PLA University of Sciences & Technology, Nanjing* 211101 *China;* 2. *Department of Atmospheric Sciences, Nanjing Institute of Meteorology, Nanjing* 210044 *China*)

ABSTRACT: Based on the 4-layer dbl wavelet packet and shannon entropy decomposition /reconstruction method and the NCEP/NCAR daily reanalysis data set, the correlation between the South China Sea summer monsoon and the Northern Hemisphere Pacific subtropical high seasonal modality/shift xvas studied and discussed, and a corresponding summer monsoon frequency-band energy criterion was defined and introduced for diagnosing the Pacific subtropical high's modality/shift. A few new phenomena and correlation between the South China Sea summer monsoon and the Northern Hemisphere Pacific subtropical high were also revealed and presented.

Key words: Pacific subtropical high; South China Sea summer monsoon; wavelet packet; frequency-band energy Criterion

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1 INTRODUCTION

Being one of the important members of Asian monsoon system, the Pacific subtropical high is closely related with monsoon activity with regard to its intraseasonal changes in intensity and east-west shifts in location[1, 6]. As Tao et al. point out in their data analysis, the intensity of Asian summer monsoon is well correlated with the location and activity of the northern Pacific subtropical high — the 500-hPa ridge locates north of 30°N most of the time and splits into two centers in the years of strong summer monsoon; it is mainly south of 30°N, showing as a high pressure ridge extending westward from central Pacific. As what Peng shows in his study[6], the morphology of the Pacific subtropical high is so closely linked with the intensity of summer monsoon that the subtropical high is usually northward, weaker and eastward when the summer monsoon is strong but mostly southward, stronger and westward when it is weak. Apart from north-south oscillations, the Pacific subtropical high can also extend west. There are two modes intraseasonal activity[7]: The first mode shows that again and again, the subtropical high system extends and expands west from central and eastern North Pacific at periods of 20 – 30 days, mostly accompanying the years of weak summer monsoon in Asia; the second mode displays that the system has the same property of movement but sometimes stagnates between 125°E and 155°E, mostly witnessed in the years of strong summer monsoon in Asia. For the westward extension of the Pacific subtropical high, Yu et al.[8, 9] point out in their studies in the 1980's and 1990's that the variation of the high first takes place over the central and eastern Pacific before

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Biography: ZHANG Ren (1963 -), male, native from Emei City of Sichnan Province, Ph.D. professor, mainly undertaking the study of tropical marine weather.

moving west as a form of low-frequency waves. The Japanese Meteorological Agency also notices the westward extension of the subtropical high.

In the studies above, the association between the summer monsoon and subtropical high is all shown to be very significant, though being interpreted in a generalized morphological sense and described quantitatively and yet lacking quantitative discrimination. Recently, some interesting phenomena are found in our analysis of the correlation between the South China Sea summer monsoon and North Pacific subtropical high. First, the results are studied; then the technique of wavelet packet decomposition and reconstruction is used to define an objective and quantitative criterion of frequency domains for the wavelet packet. Diagnostic discrimination is then made possible for the correlation between the South China Sea summer monsoon and North Pacific subtropical high.

2 SOUTH CHINA SEA SUMMER MONSOON AND NORTH PACIFIC SUBTROPICAL HIGH

Both the South China Sea summer monsoon and West Pacific subtropical high are important members of the East Asian monsoon system, the intensity of the former is an essential restraining and governing factor for the activity of the latter. Some cases selected for both strong and weak monsoon years are analyzed in brief.

2.1 *Data*

The NCEP/NCAR 500-hPa geopotential height fields and day-to-day reanalysis data based on 850-hPa zonal wind fields (the former for description of the subtropical high and the latter for monsoon analysis) are used, with the duration covering 1980 – 1997. For the intensity and perturbations of the monsoon, gridpoint means over the region of 100°E – 130°E, 5°N – 15°N from June 6th to August 26th are used; for the east-west distribution and westward extension of the North Pacific subtropical high, a time-longitude profile that centers around 30°N and takes average of gridpoints for 27.5°N – 30°N – 32.5°N is used.

2.2 *Summer monsoon intensity and east-west morphology of the subtropical high*

1985 was the year when the summer monsoon was strong over the South China Sea, with the westerly mean averaged over 6 – 8 m/s from May to August. Over a period roughly corresponding to it (from June 16th to August 26th), the bulk of the subtropical high was eastward, the 5900 geopotential height field centered east of 140°E and the 5880 geopotential region was mainly east of 130°E (Fig.1). The monsoon was also quite strong in 1984 (with the average wind speed over 5 – 7 m/s), which was accompanied by relatively eastward location of the subtropical high bulk over the North Pacific in summer (the center of 5880 geopotential meter was mainly east of 130°E, figure omitted).

1992 was the year when the summer monsoon was weak over the South China Sea, with the westerly mean averaged below 4 m/s from May to August. Over a period roughly corresponding to it (from July 10th to August 10th), the bulk of the subtropical high was eastward, the 5900 geopotential height field stayed between 110°E and 130°E and its center was once extending as far as 110°E and beyond (Fig.2). 1995 is also a weak summer monsoon year, in which the subtropical high center was relatively westward, with the 5880 geopotential contour mostly covering areas west of 110°E – 120°E in the middle and late decades of July and August (Figure omitted).

As shown in the analysis above, correlation between the South China Sea summer monsoon and North Pacific subtropical high is roughly like this: When the former is strong / weak, the center of the latter is relatively eastward / westward.

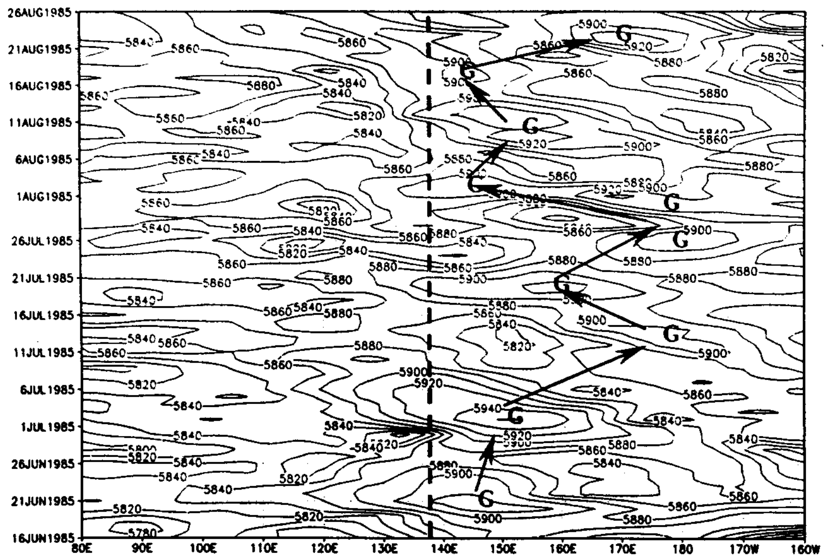

Fig.1 Time-longitude profile at 500 hPa geopotential height over North Pacific from June 16th to August 26th, 1985.

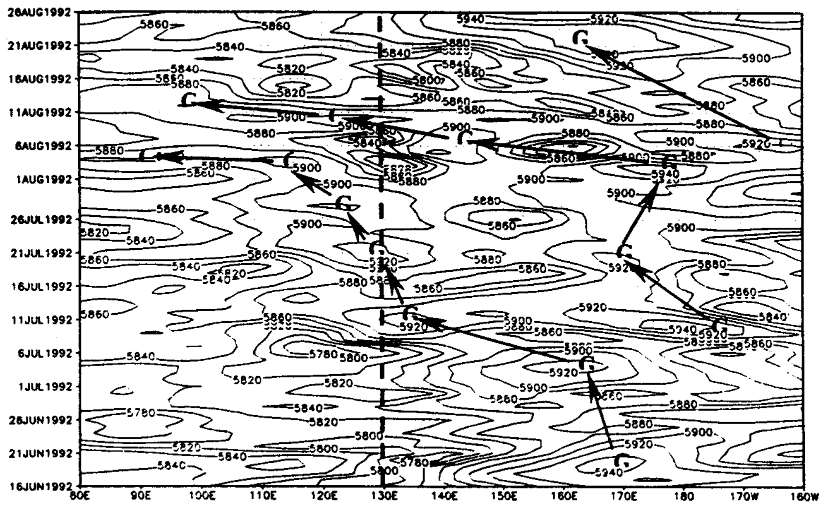

Fig.2 Same as Fig.1 but for the period from June 16th to August 26th, 1992.

2.3 *Summer monsoon perturbations and westward-extending of the subtropical high*

There were large perturbations in the summer monsoon in the South China Sea in 1987. Correspondingly, three significant west-moving processes were found in the year with the North Pacific subtropical high (mid-June – early July, early July – early August, late July – mid-August, as shown in Fig.3), the former two of which were in good lagging response to the summer monsoon perturbations in the South China Sea (June 1st – 20th; June 20th – July 20th). In contrast, in the years of small perturbations or fluctuations (1988, 1993, 1995 and 1997), there were fewer obvious westward extensions of the subtropical high over North Pacific (figure omitted).

As shown in the study above, for the strong perturbations of the South China Sea summer monsoon, the North Pacific subtropical high extends west considerably; for the weak perturbations of the South China Sea summer monsoon, it extends west mildly.

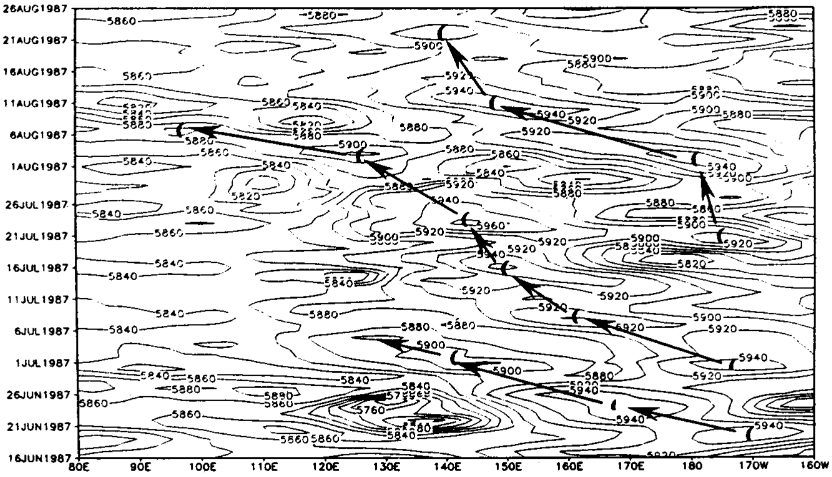

Fig.3 Same as Fig.1 but for the period from June 16th to August 26th, 1987.

3 DECOMPOSITION / RECONSTRUCTION THROUGH WAVELET PACKET AND CRITERIA FOR FREQUENCY DOMAIN ENERGY

The study above has revealed some meaningful phenomena and linkages between the South China Sea summer monsoon and North Pacific subtropical high, but without quantitative description and discriminating standards. Although some of the indexes of the subtropical high, e.g. those of area, westernmost ridge point and ridge line latitude, and the index of East Asia monsoon can be used in reference, they mainly describe the characteristics of the subtropical high or the monsoon itself. In addition, as multiple periods of activity are with the perturbed monsoon itself (like the 30 – 50 day and quasi-by-weekly oscillations) and existing monsoon indexes are too coarse to divide and describe the frequency structure, it is therefore necessary to introduce reasonable indexes to depict the multiple periods of the monsoon activity.

The wavelet analysis is a powerful tool in studying time-frequency signals that are not smooth. By the technique of decomposition by wavelet packets, layers are finely divided in the signal frequency in the form of the binary system. Then the analyzed signals are used to choose auto-adaptive sections of frequency to match the signal frequency spectra. The perturbation intensity and energy distribution are studied separately. In the paper, the technique is used to define characteristics of the energy over frequency domains of the summer monsoon so that the correlation between the South China Sea summer monsoon and North Pacific subtropical high is objectively and quantitatively studied and diagnosed.

The db1 wavelet base and Shannon entropy are selected for decomposing and reconstructing a 4-layer wavelet packet. The base displays good orthogonality and strong support and is capable of transforming wavelets continuously and discretely so that signals in various domains of frequency are well reproduced in terms of continuity and abrupt change. For the expressions of wavelet and scale functions and their corresponding forms of extending / shrinking and advection

/ transformation, refer to references [10] and [11].

Main steps of analysis:

(1) First of all, the db1 wavelet base is used to apply 4-layer wavelet packet decomposition to the time sequence signals of the South China Sea summer monsoon to extract characteristic signals for 16 components from low to high frequency at Layer Four (Fig.4). As the work uses day-to-day data, the sampling frequency is 1 for the signal series (times per day).

(2) Then, the decomposition coefficient for the wavelet packet at Layer Four is reconstructed to extract characteristic signals for individual sections of frequency. In view of the fact that the frequency sections are equivalent to band-pass filters with even bandwidth, the following reconstruction relation is followed.

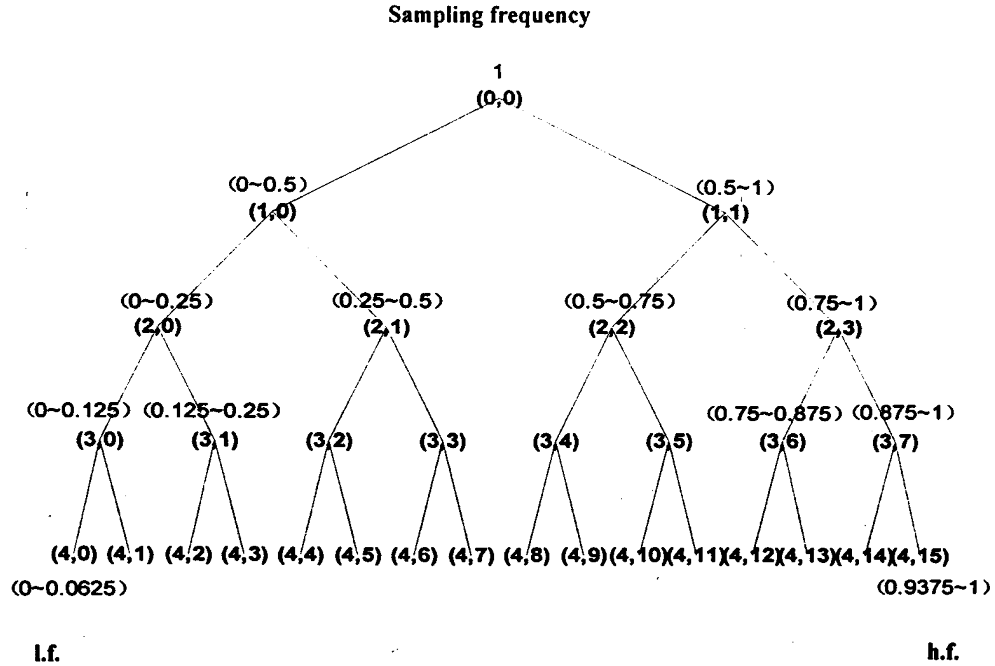

Fig.4 Schematic chart of tree structure of 4-layer wavelet packet decomposition (sampling frequency is 1)

in which S is the signal of real summer monsoon and the actual bandwidth taken up by individual decomposed layers are shown in Tab.1.

Tab.1 Periods of bandwidth for signal components

Signal component	Frequency bandwidth	Corresponding periods / day	Signal component	Frequency bandwidth	Corresponding periods / day
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

Viewing the above structure of frequency-period decomposition, we find that there are very fine bandwidth structure and period resolutions in the decomposition of wavelet for the fourth layer. The decomposition signals for different frequency bands (periods) can have objective reproduction of their structure, intensity and genesis / dissipation.

(3) Then, the total energy is sought for the signals of individual frequency bands. Setting that $S_{4j}(j=0,1,2,\cdots\cdots,15)$ has corresponding energy of $E_{4j}(j=0,1,2,\cdots\cdots,15)$, then we have $E_{4j}=\int\left|S_{4j}(t)\right|^2\mathrm{d}t=\sum_{k=1}^{n}\left|x_{jk}\right|^2$, in which $x_{jk}(j=0,1,2,\cdots\cdots,15;k=0,1,2,\cdots\cdots,n)$ is the amplitude of discrete points for the reconstructed signal S_{4j} and n is the point at which samples are taken.

(4) The characteristic energy values are defined for domains of frequency. When the monsoon system (i.e. its intensity and perturbation) is within the normal and abnormal states, no obvious, substantial differences are found in the signal series itself. However, its intensity over specific frequency domains (periods) and energy can be quite different. The calculated characteristic perturbed energy of the monsoon signal over specified frequency domains can indicate or measure the intensity of monsoon perturbation at various periods. They are then compared with observed subtropical high activity so that corresponding relationship is established to diagnose the activity of the subtropical high.

Next, the decomposed and reconstructed signals for individual sections of frequency are used as elements to build a characteristic vector T: $T=[E_{40}, E_{41}, E_{42}, E_{43}, E_{45}, E_{46}, E_{47}, E_{48}, E_{49}, E_{410}, E_{411}, E_{412}, E_{413}, E_{414}, E_{415}]$; when the energy is relatively large, $E_{4j}(j=0,1,2,\cdots\cdots,15)$ is usually large. For the convenience of study, the vector T can also be normalized depending on actual needs. Take

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

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

in which vector T' is a normalized one that depicts characteristic energy over a frequency section of monsoon. Each of the characteristic energy values in the T or T' vector describes different intensity of monsoon perturbation and magnitude of perturbed energy over different domains of frequency (periods).

4 CRITERIA FOR THE FIRST CHARACTERISTIC ENERGY VALUES OF THE SOUTH CHINA SEA

As the monsoon perturbation with periods of 3 or more days takes up about 85% of the total (Tab.2), it reflects the main features of South China Sea summer monsoon variation; short-term perturbations have small variance contribution and weaker influence on the subtropical high when the period is less than 3 days. The characteristic values of decomposed and reconstructed signals for the high frequency of summer monsoon will then not be discussed (same below). When the geopotential meter centers of the 5880 and 5900 contours are east of 140°E, the subtropical high is said to be eastward; when they are west of 120°E – 130°E, it is thought to be westward. Tab.3 compares the characteristic energy values derived for frequency sections of the South China Sea summer monsoon and observed morphology of the high (for a period from June 1st to August 15th every year). As shown in the study, the first characteristic energy values for the South China Sea summer monsoon, which correspond to low-frequency oscillations with periods of more than 16 days, are well correlated with the mean location of the North Pacific subtropical high. With a large (small) first characteristic energy value, i.e. higher than 53 (lower than 53). which is for the year of strong or weak low-frequency summer monsoon perturbation in the South China Sea, the North Pacific subtropical high is active mainly eastward (westward) compared to the normal position. Most of the years diagnostically determined as in Fig.3 agree with the reality, though there are a few years for which the diagnosis is wrong (referred to those with the "*" mark in the table). One such example is found in the case of 1994, when the South China Sea summer monsoon was relatively strong (by having a large first characteristic energy value), the North Pacific subtropical high should have been westward rather than eastward; the other is with the case of 1988, when the summer monsoon was relatively weak (by having a small characteristic energy value), the North Pacific subtropical high should have been eastward rather than westward. It shows that there is close relation between the intensity of South China Sea summer monsoon and the eastward / westward morphology of the North Pacific subtropical high; when other factors or mechanisms take over the main role, however, the link may weaken or disappear all together.

Tab.2 Percentage of individual periodic waves of the South China Sea summer monsoon in total variance by perturbation (unit in %; range of computation: June 1st – August 15th)

period / d	> 16	8. – 16	5.6 – 8	4 – 5.6	3.2 – 4	others
Mean for 1980 – 1997	43.697	15.217	9.435	13.172	3.468	15.011

Tab.3 Vectors of characteristic energy of the decomposed and reconstructed South China Sea summer monsoon wavelet for various frequency domains (range of computation: June 1st – August 15th)

year	Central location of observed subtropical high	Diagnosed results from characteristic values	Periods for vectors of characteristic energy of wavelet for various frequency domains (first 5 characteristic values)				
			> 16 d	8 – 16 d	5.6 – 8 d	4 – 5.6 d	3.2 – 4 d
1994	120 – 140 °E	eastward *	61.318	11.639	11.259	10.216	2.425
1985	140 – 160 °E	eastward	60.769	20.445	9.715	11.632	3.994
1982	140 – 160 °E	eastward	60.674	14.057	7.771	17.083	3.443
1984	150 – 170 °E	eastward	54.669	16.657	11.980	13.003	3.964
1981	150 – 170 °E	eastward	53.735	19.552	9.965	17.967	2.652
1996	130 – 150 °E	westward	52.794	13.160	10.979	9.955	5.215
1990	130 – 150 °E	westward	52.484	14.390	8.046	10.682	1.968
1986	120 – 140 °E	westward	52.140	13.912	14.393	13.575	2.240
1997	130 – 150 °E	westward	48.611	9.686	11.544	14.142	3.350
1989	130 – 150 °E	westward	42.437	18.966	13.288	12.653	3.390
1987	130 – 150 °E	westward	41.986	23.201	11.709	7.625	6.002
1991	120 – 140 °E	westward	39.429	25.287	13.052	12.407	4.419
1993	140 – 160 °E	westward *	39.195	13.717	4.622	16.090	3.010
1992	120 – 140 °E	westward	38.633	9.128	6.818	20.080	4.210
1980	130 – 150 °E	westward	36.386	16.191	4.910	8.069	2.512
1988	160 – 180 °E	westward *	31.114	13.061	7.045	16.125	3.246
1983	120 – 140 °E	westward	29.862	13,551	6.051	15.956	2.632
1995	130 – 150 °E	westward	14.223	8.954	7.728	8.117	3.084

5 CRITERION FOR THE SECOND CHARACTERISTIC ENERGY VALUES OF SOUTH CHINA SEA SUMMER MONSOON

Analyzing the time-longitude profile of the 500-hPa geopotential height field centered around 30°N and eastward / westward movement with time of geopotential height centers higher than the 5880 contour, we know that the eastward / westward movement of the subtropical high can roughly be divided into two types: one extends much westward and the other moves within a relatively small range. The second characteristic energy value for decomposed and reconstructed wavelet helps us analyze the corresponding relation between the perturbed summer monsoon and the westward extension of the subtropical high. As shown in the result of comparison (Tab.4), the characteristic value (for the quasi-biweekly perturbation with periods 8 – 16 days) is closely related with the westward extension of the Pacific subtropical high. When the former is larger (than 15) and smaller (than 15), which correspond to the years of strong and weak quasi-biweekly activities of the South China Sea summer monsoon, the North Pacific subtropical high will extend significantly westward and remains stationary, respectively. Except for a few isolated years that have wrong diagnosis, the subtropical high is consistent with the corresponding relation described above in other years.

Tab.4 Vectors of characteristic energy of the decomposed and reconstructed South China Sea summer monsoon wavelet for various frequency domains (range of computation: June 1st – August 15th)

year	Activity status of subtropical high	Diagnosed results from characteristic values	Periods for vectors of characteristic energy of wavelet for various frequency domains (first 5 characteristic values)				
			> 16 d	8 ~ 16 d	5.6 ~ 8 d	4 ~ 5.6 d	3.2 ~ 4 d
1991	Large W. Extension	Large W. Extension	39.429	25.287	13.052	12.407	4.419
1987	Large W. Extension	Large W. Extension	41.986	23.201	11.709	7.625	6.002
1985	Small movement	Large W. Extension*	60.769	20.445	9.715	11.632	3.994
1981	Large W. Extension	Large W. Extension	53.735	19.552	9.965	17.967	2.652
1989	Large W. Extension	Large W. Extension	42.437	18.966	13.288	12.653	3.390
1984	Large W. Extension	Large W. Extension	54.669	16.657	11.980	13.003	3.964
1980	Large W. Extension	Large W. Extension	36.386	16.191	4.910	8.069	2.512
1990	Small movement	Small movement	52.484	14.390	8.046	10.682	1.968
1982	Small movement	Small movement	60.674	14.057	7.771	17.083	3.443
1986	Large W. Extension	Small movement *	52.140	13.912	14.393	13.575	2.240
1983	Small movement	Small movement	29.862	13.551	6.051	15.956	2.632
1993	Small movement	Small movement	39.195	13.717	4.622	16.090	3.010
1996	Large W. Extension	Small movement *	52.794	13.160	10.979	9.955	5.215
1988	Small movement	Small movement	31.114	13.061	7.045	16.125	3.246
1994	Small movement	Small movement	61.318	11.639	11.259	10.216	2.425
1997	Small movement	Small movement	48.611	9.686	11.544	14.142	3.350
1992	Large W. Extension	Small movement *	38.633	9.128	6.818	20.080	4.210
1995	Small movement	Small movement	14.223	8.954	7.728	8.117	3.084

In contrast to the years in which the subtropical high remains stationary, not only the second but the third characteristic energy values, which correspond to 5.6 – 8 – day periodic perturbations of the summer monsoon, tend to be small; for some years in which the subtropical high extends significantly, the second characteristic value is relatively small while the third one is relatively large (as in the cases of 1986 and 1996). In other words, the quasi-biweekly perturbation is weak but the 5 – 8 – day periodic perturbation is strong. Consequently, the third characteristic energy value is also diagnostically important for indication of the westward extension of the North Pacific subtropical high. Applying the weighting coefficients of 0.60 and 0.40 to the second and third characteristic energy values of the monsoon for weighting average, we have a criterion for integrated characteristic value, which more appropriately shows the corresponding relation between perturbed summer monsoon and east / ward activity of the North Pacific subtropical high. In other words, for the years when the monsoon is strong / weak at the periods of 8 – 16 days and 5 – 8 days, the subtropical high usually responds by moving obviously to the west or staying where it is, with errors occurring only in the cases of 1980, 1985 and 1992. Exceptions do appear with the above differentiating procedure. For instance, the summer monsoon was relatively strong in 1985, though with insignificant westward extension of the subtropical high (Fig.1); the summer monsoon was relatively weak in 1992, though with significant westward extension of the subtropical high (Fig.2). It shows that multiple factors are affecting the west-extending of the subtropical high so that the monsoon perturbation is a major factor in most of the years while other factors may be the key in the rest.

6 CONCLUDING REMARKS

Based on the 4-layer db1 wavelet packet and shannon entropy decomposition /reconstruction method and the NCEP/NCAR daily reanalysis data set, the correlation between the South China Sea summer monsoon and the Northern Hemisphere Pacific subtropical high seasonal modality/shift was studied and discussed, and a corresponding summer monsoon frequency-band energy criterion was defined and introduced for diagnosing the Pacific subtropical high's modality/shift. A few new phenomena and correlation between the South China Sea summer monsoon and the Northern Hemisphere Pacific subtropical high were also revealed and presented. Main results are as followed.

a. Into the correlation analysis for the monsoon and subtropical high the method of wavelet packet decomposition and reconstruction is introduced and an objective and quantitative criterion for summer monsoon energy over frequency domains is defined. The qualitative description of the summer monsoon activity is thereby decomposed to quantitative calculation that is relatively accurate. By setting a critical characteristic value as the differentiating index, the diagnosis and prediction of the east / west morphology of the summertime North Pacific subtropical high and its westward extension are thus added with another method of analysis and standard of differentiation.

b. As shown in the study, the intensity of the South China Sea summer monsoon (i.e. low-frequency activity with periods more than 16 days) correspond with the eastern / western locations of the subtropical high center. When the summer monsoon is strong (weak), its location is usually eastward (westward).

c. As also shown in the study, the summer monsoon perturbations (i.e. weekly and biweekly oscillations with periods of 5 – 8 days and 8 – 16 days) are closely related with the westward extension of the North Pacific subtropical high in summer. When the former is strong, the latter usually responds by having significant extension; when the former is weak, the latter is mostly small in the amplitude of movement of its center.

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