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WAVELET ANALYSIS OF INTERANNUAL VARIATION OF TROPICAL CYCLONES IN GUANGDONG

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ABSTRACT: Climatological laws are studied for the annual frequency of tropical cyclone occurrence and the date of the yearly first landfall, which take place in the Guangdong province or pose serious threats on it from 1951 to 1999, using the data in the *Yearly Book on Typhoons*. A new method that has developed over recent years for the study of temporal sequences, the wavelet analysis, is used, in addition to more common statistical approaches. By analyzing two wavelet functions, MHAT and MORLET, we have compared the results of transformation of the wavelets provided that other conditions remain unchanged. It is discovered that the variance of MORLET wavelet has better indication of primary periods; period-time sequence charts can reflect major affecting periods for individual sections of time; when compared with the original sequence, the chart shows a little shift. On the other hand, such shift is absent in the MHAT wavelet, but its higher frequency part of variance covers up the primary periods to make its variance less predominant as compared to the MORLET wavelet. Besides, the work compares two different assumptions of an amplifying factor *a*. It is found that primary periods can be shown more clearly in the variance when *a* takes the exponential of 2 than it takes values continuously. Studying the annual frequency of tropical cyclones and the date of first appearance for periodic patterns, we have found that the primary periods extracted by this approach are similar to those obtained by wavelet transformation.

Key words: wavelet analysis; annual frequency; date of yearly first tropical cyclone

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1 INTRODUCTION

The spectral analysis was an earlier method used in the study of periodicity of temporal sequences. The shortage is that it is only useful for a whole range of time frequency. Since the 1990's, more efforts have been paid to exploit what is a mathematical "microscope" —the wavelet analysis, which is founded on the non-linearity theory. It gives more detailed account of the internal structure of the time sequence. Its application is wide and used in virtually every trade of industry, ranging from signal identification to seismic waves and in meteorology over recent years. It is noted, however, that most of the study just use the function and not explain why they use it. The current work compares two widely used wavelet functions and different approaches in assuming the value of the amplifying factor so as to have deeper understanding of the nature of the function. In addition, advantages in taking 2 for *a* in actual computation are presented.

2 STATISTIC FEATURES OF TROPICAL CYCLONES MAKING LANDFALL ON OR SERIOUSLY AFFECTING GUANGDONG

Before applying the wavelet transform in studying the interannual variation of tropical

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cyclones, we list the statistical characteristics of the tropical cyclones that have made landfall on or seriously affected the Guangdong province for the comparison and study that follow. In observance of the requirements for routine forecast, the tropical cyclones that are active within 1 degree of latitude from the coast of the province are considered storms having serious effect. Basically, reference [5] presents monthly distribution of these tropical cyclones and spatial distribution of landfall location. It is known therein that the period June through October is the time of maximum probability for the tropical cyclones to appear, whether making landfalls or having serious effect.

2.1 *Monthly distribution*

It is known from Tab.1 that tropical cyclones making landfalls or seriously affecting Guangdong mainly appear in June ~ October, in which July ~ September takes up 70.3% of the total, The probability is relatively large in August and September for the tropical cyclone to make landfall on or seriously affect Guangdong.

Tab.1 Monthly distribution of tropical cyclones making landfall on or seriously affecting Guangdong

Month	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Probability / %	4.2	12.3	21.4	25.9	23.2	8.8	3.4	0.4

2.2 *Interannual variation*

Fig.1 gives the interannual variation curve of these tropical cyclones. There are several points as follows: (1) The tropical cyclone has a well-defined pattern of interannual variation, with the maximum of 9 (1974) and the minimum of 1 (1969), averaging at 5.3 per year in the period of 49 years from 1951 to 1999. (2) The interannual variation is well divided into various stages. From the mid-1950's to mid-1960's, the tropical cyclone had a small amplitude of fluctuation and the number varies between 4 and 7; from the late 1960's to the end of 1970's, its fluctuation became large with significant variation from year to year. It was during the period that the maximum and minimum appearance of tropical cyclone for the 49 years were recorded. The fluctuation was within the normal range in the early phase of 1980's, late phase of 1980's through the beginning of the 1990's but increased again in the late phase of 1990's. The figure tells one interesting fact: Once in every ten years, the annual occurrence of tropical cyclones reduced to a anomalously small number, separately in 1977, 1987 and 1997. The pattern is to be verified. Next is the periodicity analysis of tropical cyclone numbers.

2.3 *Spatial and intensity distribution of landfalls*

2.3.1 SPATIAL DISTRIBUTION

According to [5], which presents the spatial distribution of tropical cyclone landfalls, we know that they mainly appear in July and September for the eastern part, and from July to September for the western part, of the province. July and August are the two months one would expect to see the landfall in the Pearl River Mouth area. For a yearly first tropical cyclone in May, the area to the east of the mouth is usually where the landfall would appear.

2.3.2 INTENSITY DISTRIBUTION

Of the tropical cyclones making landfall or having serious effect on Guangdong, there were about 50% that had the intensity of typhoon, 17.5% and 23% the intensity of severe tropical storm and tropical depression, respectively, and it was rare for a tropical storm to land. According to Feng [6], for the tropical cyclones affecting Shanghai and the Changjiang River Delta, 76% or more acquired the intensity of typhoon and relatively few were tropical depressions. It is then known that most of the landfalls in southern China are weaker than those in the Changjiang River Delta.

2.4 *Periodicity analysis of annual frequency*

Following the general study of the annual frequency in the above section, we are now turning to the results of periodicity analysis. Fig.2 gives the power spectra corresponding to different periods. A significance test is conducted for the primary periods in which the maximum wavenumber taken is 24.

From Fig.2, we know that the power spectra are the largest in Wave 5 and Wave 7, which correspond to time scales of 9.8 years and 7 year, respectively, each taking up by more than 15%. The secondary largest power spectra are Wave 14 and Wave 16, which are respectively 3.5 years and 3.1 years on the time scale *T*. Wave 19 and Wave 23 are relatively large, having a *T* of 2.6 years and 2.1 years, respectively. According to the *F* test for periodic significance, the 7-year and 9.8 year periods pass the level of *a*=0.05 and the 3.1-year and 3.5-year periods the level of *a*=0.10. It indicates that the annual frequency has the primary periods of 7 and 9.8 years, respectively; the periods of 3.1 and 3.5 years are also of some significance.

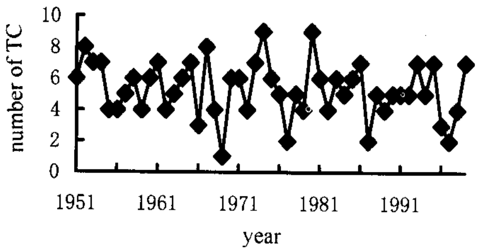


Fig.1 Annual frequency of tropical cyclones

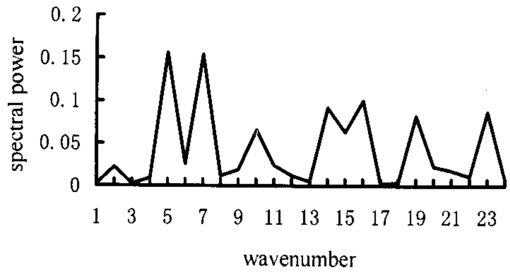


Fig.2 Power spectrum curves corresponding to various periods of the annual frequency of tropical cyclones

2.5 *Interannual variation of yearly first tropical cyclones and analysis of the periodicity*

The ordinate refers to the date when the first tropical cyclone appears for the year. In the way that 1st May is denoted "1" and 2nd May "2", the numerals on the ordinate of Fig.3 are determined. Studying the figure, we know that the date is characteristic of significant interannual variation, with the earliest date shown in the first decade of May (1971 and 1999, for example), latest date in the middle decade of August (1968 and 1975, for example) and the average date on 26th June for the period of 49 years. The figure also tells us that the date of the yearly first tropical cyclone oscillates at both high frequency (like the periods from 1954 to 1961 and from 1964 to 1971) and low frequency (like the periods from 1961 to 1964, early 1970's and late 1980's). It also indicates that the concentrated periods of the year in which the date appears vary from some years to others: it was earlier than average in the 1950's and mid-1960's, later than average from late 1960's to 1970, earlier again in early 1970's and late again from late 1970's to early 1980's, earlier in the middle and late phases of the 1980's and later than average from 1992 to 1998, except in 1994. The date was successively late from 1995 on.

Conducting the analysis of power spectrum in the date of the yearly first tropical cyclones (Fig.4), we know that Wave 4 and Wave 5, or *T* equaling to 12.3 years and 9.8 years, are the most dominant periods, followed by Wave 9 and Wave 10, or *T* equaling to 5.4 years and 4.9 years, i.e. periods of about 5 years. In addition, Wave 15 is one that has relatively large power spectral ratio of waves with *T* of 3.3 years. Specifically, the periods of 12.3 years and 9.8 years have passed the significance test of *a*=0.05 and the period of 5 years or so also reached the significance test of *a*=0.10. It is then known that the yearly first tropical cyclone appear on dates that oscillate at the periods of 12.3, 9.8 and ~5 years.

3 WAVELET ANALYSIS OF ANNUAL FREQUENCY AND DATES OF YEARLY FIRST TROPICAL CYCLONES

3.1 *Methods and principles and wavelet analysis*

For more study of the annual frequency of periodicity of the yearly first tropical cyclones and multi-scale features of the interannual variation as well as more definite reflection of the variation of the annual frequency over the particular time, the wavelet transform is used in different time-scale analysis. In sharp contrast to the periodicity study, which is good at structural analysis for the date in the entire range, the method is capable of probing into a specific window with finer details by studying different scale through the control of the amplifying factor *a*, It is therefore an ideal tool for oscillations of both low and high frequency. It is based on the advantage that the current paper uses two popular consecutive wavelets, MHAT and MORLET, to study, by way of wavelet transform, the interannual variation laws for the annual frequency of tropical cyclones, on the one hand, and have more understanding of the basic nature of the wavelets, on the other. Next are the function expressions for them.

Known as the Mexican hat, the MHAT wavelet has the following generating function of

$$j(t) = (1 - t^2) e^{-\frac{t^2}{2}}$$

The MORLET wavelet is expressed by the generating function as follows:

$$j(t) = e^{-\frac{t^2}{2}} e^{i v t}$$

The discrete wavelet transform is defined as

$$w_f(a,b) = |a|^{-\frac{1}{2}} \sum_{i=1}^{n} f(i)\, j\left(\frac{i-b}{a}\right)$$

in which $j\left(\frac{i-b}{a}\right)$ is the base function of the wavelet, *a* is the scale factor, which is related with the period and frequency, and *b* is the translation factor.

Depicting the power spectrum corresponding to various *a*, the wavelet variance is defined as:

$$w_p(a) = \sum_b |w(a,b)|^2$$

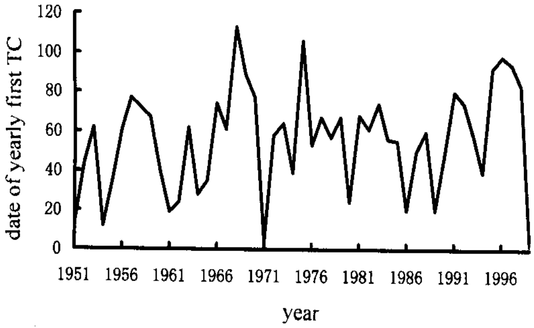


Fig.3 Interannual variation of the date of the yearly first tropical cyclone

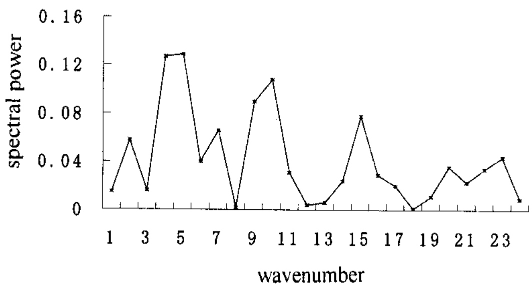


Fig.4 Power spectrum curve for all periods of the yearly first tropical cyclone

Based on the variance corresponding to various a, we study the interannual variation of the annual frequency and the yearly first date of the tropical cyclone as well as the detailed changes in part of the time-frequency ranges. Reference [1] gives theoretic nature of the binary system. The calculations are used to study the difference of a when it assumes two values.

From [4], we have the relation between a of the MHAT wavelet and the period: T=3.974a. For the convenience of work, we take $a = i/3.974$ and $a = 2\times 2^{0.2(i-1)}/3.974$, with the latter taken by the binary system. Following the relation between a and the period, the periods for the two assumptions are respectively $T = i$ and $T = 2\times 2^{0.2(i-1)}$.

The difference between MORLET and MHAT lies in the fact that the former takes account of phase changes. For the sake of comparison, the amplifying factor for both wavelets takes 2 with the same in other conditions. In other words, $a = 2\times 2^{0.2(i-1)}/1.144$, the period T=1.144a.

3.2 *Wavelet analysis of the annual frequency of tropical cyclones*

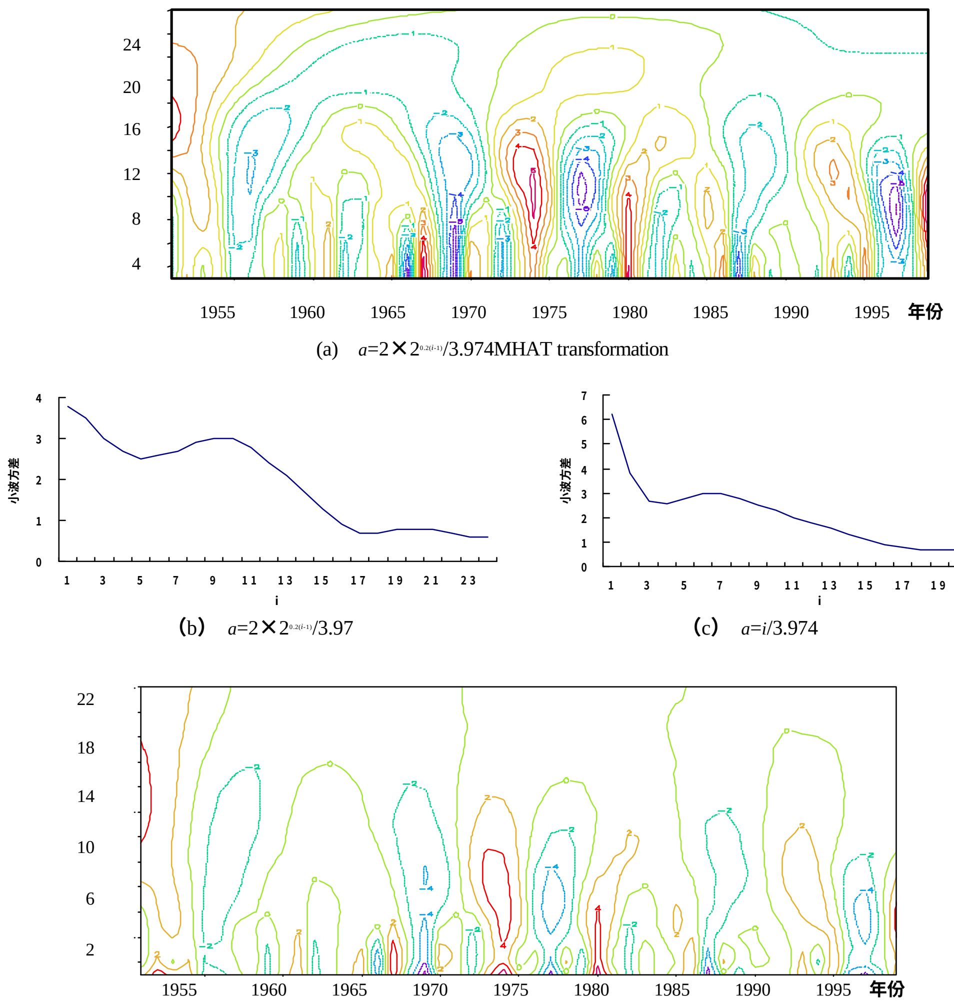
3.2.1 MHAT WAVELET ANALYSIS

Fig.5 (a & d) gives the contours obtained through wavelet transform, which is coordinated with time (year) and temporal scale. Following the relation between the period and scale factor, we know that the figure is reflecting detailed periodic oscillation over the whole or part of the temporal sequence of the annual frequency. Fig.5 (b & c) gives the wavelet variance corresponding to the two value assumptions. The abscissa is the i value (standing for the period) and the ordinate is the variance (×100).

Comparing the wavelet variance with different assumption of value for the amplifying factor in Fig.5 (b & c), we know that the maximum variance occurs at i=10 in Fig.5b and i=7 in Fig.5c except where i is small and yields abnormality. Following the relation between the period T and i, T=7 year correspondingly. It shows the 7-year period is dominant in the annual frequency of the tropical cyclone no matter how the amplifying factor a takes value. All the other periods have relatively small variance. The comparison (Fig.5b & 5c) shows that dominant periods can be more highlighted over the entire range of time frequency and oscillatory anomalies at higher frequency are decreased when a takes 2.

Fig.5a & 5d give the contours obtained through the wavelet transform of the annual frequency. For high-value centers, Fig.5a points to the place in which i=10 (T=7 year) and Fig.5d points to the place in which i=7 (T=7 year). It is an indication that the 7-year periodic oscillation is the dominant period in the variation of the annual frequency.

In the comparison of time sequence and periodicity between two value assumptions for a, we note that all sections of time are more finely structured when a takes 2, which is shown in the



(a) $a=2\times2^{0.2(i-1)}/3.974$MHAT transformation

(b) $a=2\times2^{0.2(i-1)}/3.97$ (c) $a=i/3.974$

Fig.5 MHAT wavelet transform and variance of the annual frequency.

prominence of the central value of dominating periods. For all dominating periods, there are finer portray of positive and negative values on short-term periods of 1 ~ 3 years. One such example could be found in the positive and negative values, as clearly displayed by higher-frequency oscillations between 1990 and 1995.

As shown in the study of Fig.5a, (1) the 7-year low-frequency oscillation is a dominant period, which fits into periods of 1951 ~ 1957, 1973 ~ 1979 and 1985 ~ 1999; (2) the *i* is relatively small that corresponds to the centers of the absolute high values in the 1960's and early 1980's, i.e. they are mainly the oscillation at higher frequency with the dominant period being around 3 years; (3) the present time is in a period of larger annual frequency.

3.2.2 MORLET WAVELET ANALYSIS

Fig.6 gives the wavelet transform and variance by MORLET. The abscissa in Fig.6a & 6b shows that *i* is related with the period and the ordinate is the variance and mode of the real part of the MORLET wavelet; the abscissa in Fig.6c is the year and the ordinate shows that *i* is related with the period. For Fig.6a and 6b, the two curves just show a little difference only when *i*=1, 2 and they are showing consistent tendency but different numerals over other periods. It shows that the real part of MORLET generally substitutes the tendency of the mode. Nevertheless, we also observe that there may be pseudo-phenomena at the short period of the variance of the MORLET real part.

From the mode and the variance of the real part, we find that the value is the largest at *i*=10, or *T*=7, which is the dominant period of the annual frequency of the tropical cyclone; a secondary maximum peak value is found at *i*=13, or *T*=10.5, which corresponds to a period around 10 years. Fig.6b shows that there is a peak value at *i*=4 (*T*=3 years). With the transform of MORLET wavelet, the modes are so distributed that we can clearly identify important periods at about 3, 7 and 10 years, which are similar to the above study of periodicity of the annual frequency of the tropical cyclone.

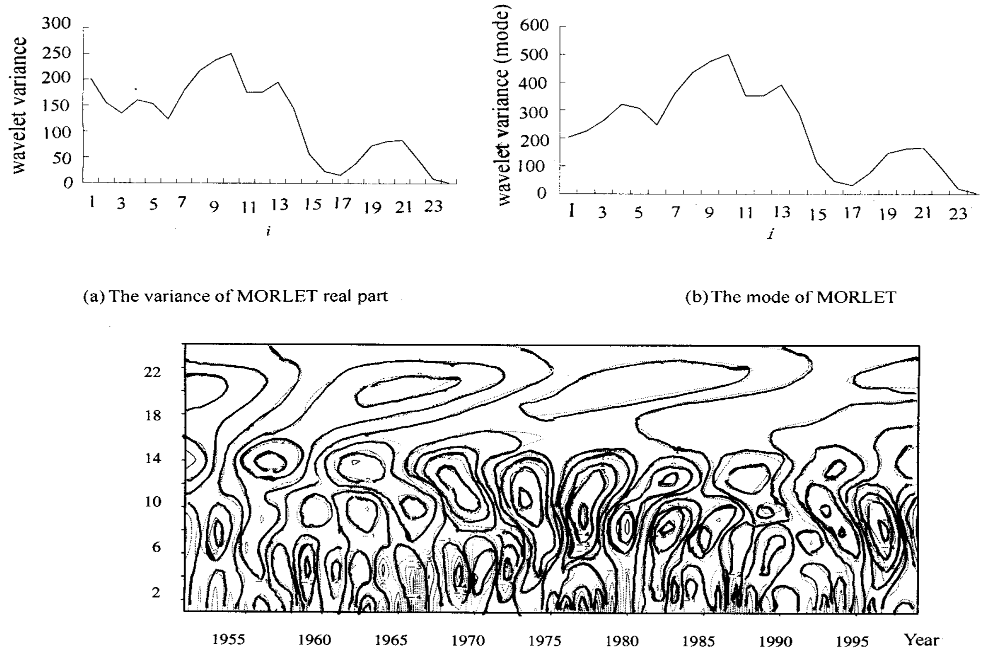
Compared to the variance chart of the MHAT wavelet transformation, the MHAT focuses on the 7-year period and other periods are not shown as clearly in the chart, only that they are reflected in the time sequence and period. In contrast, the variance chart of MORLET is able to show a number of principle periods and improve the pseudo-phenomena on short periods at the same time. The main periods are also well recognized in the period-time-sequence chart.

From Fig.6c, we know that (1) *T*=7 is the most dominant period in the annual frequency of tropical cyclones and those of 3 and 10 years are also playing an important role; (2) the 1950's and 1970's are marked by low-frequency oscillation while the 1960's and early 1980's by 3-year high-frequency; for some years, both the 3-year and 7-year periods are important, such as 1985 ~ 1988.

Fig.5a is generally the same as Fig.6c in the graphic shape and the difference lies in the location of the zero line for every dominant period. For instance, the 10-year time scale has two locations of the zero line in mid-1990's —the MHAT crosses 1995 while the MORLET cuts through 1996. In reality, the year 1995 was a turning point. The MORLET wavelet was deviated by a year. For the 7-year scale, 1962 was a year with the turning point and again the MORLET shifts by a year. The deviation is also evident in other sections of the time. For the 3-year high-frequency oscillation in the late phase of the 1980's, the MHAT indicates negative years for 1987, 1988 and 1989 but a positive year for 1990 while the MORLET shows negatively for 1987, which equals to a year of fewer occurrences of tropical cyclone. It also indicates normal, more and fewer occurrences for 1988, 1989 and 1990, respectively. The fact is that there were normal and fewer occurrences of tropical cyclones in 1988 and 1989, respectively. The deviation of the zero line by 1 year is also found in the 3-year period. The year 1988 is shown as normal in the study of MORLET rather than MHAT, suggesting that the former is capable of reflecting fine internal structure of the higher-frequency oscillation.

Study the variance, we find that the MORLET can reflect not only the dominant periods but the other important periods while the MHAT is good at only revealing the 7-year periodic oscillation. The two wavelets have both advantages and disadvantages. The MORLET wavelet reflects all periods by its variance and shows fine structure of the internal structure of the time sequence. Its disadvantage is that the zero line would shift forward or backward by 1 ~ 2 years in the phase of its real part for some particular years. Being without such shift, the MHAT can only show one dominant period.

From the distribution of the mode of the MORLET wavelet (figure omitted), we can see that the maximum center of the mode is at *i*=10 (*T*=7) and *i*=4, 5 (*T*=3, 3.5), which is similar to the study above.



(a) The variance of MORLET real part (b) The mode of MORLET

(c) The period of the real part and time sequence of MORLET transformation

Fig.6 Wavelet transform and variance of MORLET.

It is clear from the study above that the dominant periods of the annual frequency of the tropical cyclone are around 3, 7 and 10 years. Now we will discuss the climatological tendency of the tropical cyclones affecting the Guangdong province on the scale of 10, 7 and 3 years, with the running mean conducted by T=10, 7, 3.

Fig.7 shows that the number of tropical cyclones fluctuate around 5 on the 10-year scale, which rose for a time in the 1960's but then dropped in the end of the decade and early 1970's, with the late 1970's ~ early 1980's in the low-value zone and a rising trend in the end of 1990's. For the 7-year scale, a rise in the 1950's was followed by a mild fluctuation in the 1960's, with the 1970's in the low-value zone, the 1980's in the fluctuating high-value zone and the middle and late 1990's in the decreasing trend, which began a new rising branch in 1999. For the 3-year scale, the lowest value was in late 1950's, mid-1970's, mid-1980's and mid-1990's. Fluctuating, the rise was in the 1950's and reached the maximum from the end of the decade to early 1960's. The drop

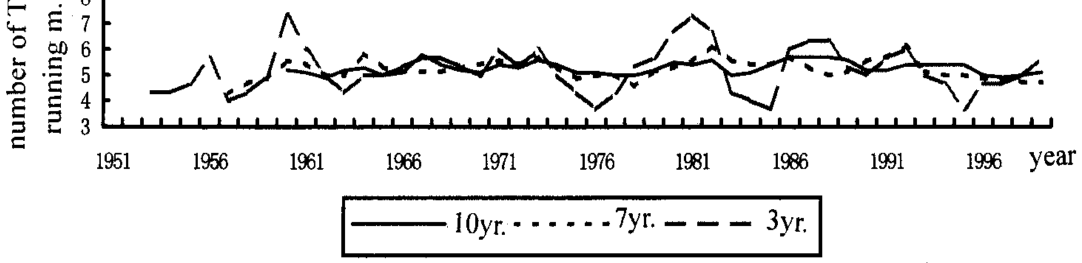


Fig.7 3, 7 and 10 year running mean.

in the number was significant in early 1960's and the fluctuation was mild from the end of 1960's to the 1970's, generally higher than the multi-year mean. After a reduction in the mid-1970's, the number of increase was more than 4. Then it decreased in mid-1980's and the number of tropical cyclones was fluctuating but generally around the mean from the end of the 1980's to early 1990's.

In summary, the annual frequency is of multiple time scales. Sometimes only one of them is playing a major role, like the dominance of the 3-year higher-frequency oscillation in the 1960's and the 7-year lower-frequency oscillation in the 1950's and 1970's. Sometimes several of them are acting together, like the concurrent action by both high and low frequency oscillation in the 1980's.

3.3 *Wavelet analysis of the date of the yearly first tropical cyclones*

Like the annual frequency of the tropical cyclone, periods of 5, 10 and 12 years are also found in the study of the yearly first date of tropical cyclones. Likewise, the MHAT wavelet takes $a = 2\times 2^{0.2(i-1)}/3.974$ and the MORLET wavelet takes $a = 2\times 2^{0.2(i-1)}/1.144$. The period for both wavelets is $T = 2\times 2^{0.2(i-1)}$ following the relation between the period and a.

3.3.1 MHAT WAVELET ANALYSIS

As shown in Fig.8b, the wavelet variance has the peak value at i=11 (i.e. the dominant period T=8 years) and there is another wavelet variance, which is not much different from this one, at i=9 ~ 13 (i.e. the dominant period T=6 ~ 10.5 years). From Fig.8a, we know that the central maximum absolute value is at i=13, or the low-frequency oscillation (T=10.5 years) was playing a dominant role in the end of 1950's and the 1960's; the 3-year high-frequency oscillation took over in the lead in the beginning of 1970's; a period around 5 years became a major feature in the end of 1980's and the 1990's. It is then clear that the interannual variation of the date is also a result of interactions on multiple time scales with stage preferences for both high and low frequency.

3.3.2 MORLET WAVELET ANALYSIS

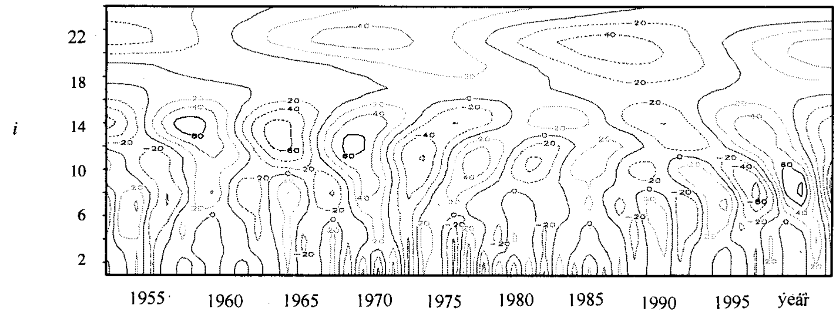
From Fig.8c, we know that the maximum peak of the variance is the most outstanding at i=11 (i.e. T=6 years), followed by a relatively large wavelet variance at i=8 (T=5.3 years) and the secondary extremum is at i=13 (T=10.5 years). In Fig.8d, the maximum centers are at i=12 ~ 13 and i=8, i=10; the 5-year period dominated 1951 ~ 1955, followed by low-frequency oscillation at the period around 10 years in the 1960's, high-frequency oscillation at the period of 3 years from late 1970's to early 1980's; the dominant period changed to that of 5 years from the mid- and late- 1980's to the 1990's.

Comparing two wavelet transform yields the conclusion as follows:

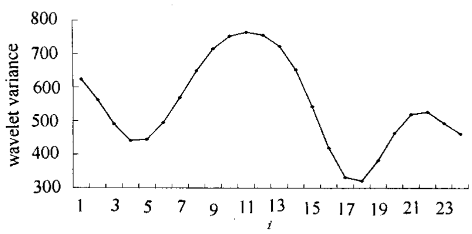
(1) The period of the MORLET wavelet variance is different from the dominant periods in the MHAT analysis in that the former highlights the 5 ~ 6-year period while the latter the 10.5-year period. By studying the whole range of time, we find that the 5-year period dominates from 1951 to 1955, the 10-year period in the end of 1950's and the 1960's, 5- and 3- year periods the 1970's and the beginning of the 1980's and the 5-year period in the end of 1980's and the 1990's. The analysis of both wavelets have indicated that the 5-year and 10-year periods may be two dominant periods of the interannual variation of the yearly first date of tropical cyclones.

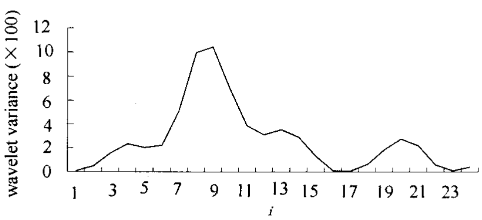
(2) Studying Fig.8 (a & d), we find that the MHAT shows low-frequency oscillation but the MORLET gives a short 3-year period for the same range from 1955 to 1960. In fact, if the 10-year scale is applied, the year 1958 should be of positive value and having a late date of the

yearly first tropical cyclone; if the 3-year scale is applied, the year should be of negative value and having an early date. From the observation that the first tropical cyclone in 1958 occurred earlier than normal, we infer that the MORLET wavelet gives more details than the MHAT, especially in the analysis of high-frequency oscillation.



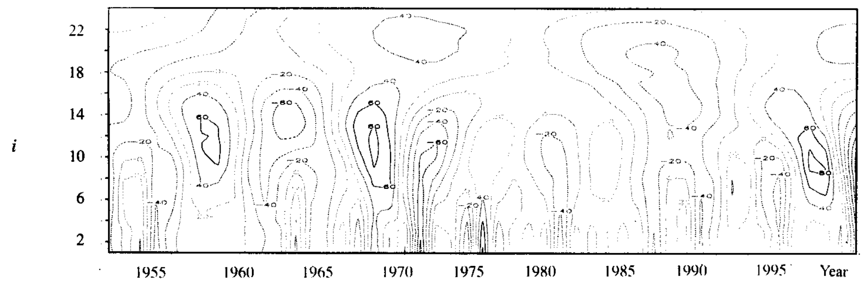
(a) The variation of MHAT wave let of the first TC.





(b) The variance of MHAT of the yearly first TC

(c) The variance of MORLET of the yearly first TC



(d) The transformation of MORLET of the yearly first TC

Fig.8 Wavelet transform of the date of the yearly first tropical cyclone.

4 CONCLUDING REMARKS

a. For the annual frequency of the tropical cyclone, the dominant periods obtained through the analysis of periodicity and wavelet are about 7, 3 and 10 years.

b. High and low oscillations of the annual frequency appear in specific concentrated parts of the year. The interannual variation is also of interactions on multiple time scales. Low-frequency oscillations of the 7-year period dominated the 1950' s and 1970' s; high-frequency oscillation of the 3-year period were mostly seen in the 1960' s and 1980' s; both high and low frequency oscillations were playing the role in some years (like 1985 ~ 1988); and the low-frequency oscillation returned to the lead in the mid- and late- stages of the 1990' s.

c. The dominant periods of the yearly first date of the tropical cyclone is about 5 and 10 years. Like the annual frequency, the yearly first tropical cyclone also vary with time preference and interact on multiple time scales.

d. By comparing different assumptions of value for *a*, we have proved that it is more significant for it to take the exponential of 2 than any direct taking, which enables more detailed description of the time sequence.

e. The MORLET and MHAT wavelet transforms have advantages of their own. The former enables more detailed description of the time sequence, with its variance contribution showing more significantly (outstandingly) the dominant periods (time scales). However, the zero line has some displacement on the time sequence-period chart.

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