The Nonlinear Variation of Annual Average Temperature in the Yangtze Delta and Its Correlation with Global Oscillations

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Abstract—**Climate change has been a major issue for scholars under the background of global warming. Yangtze Delta is one of major economic regions in China. How the temperature of the Yangtze Delta changes in the past decades and if this change has some relation to global climate change? To answer these questions, this paper tries to find the relationship between the temperature's change in the Yangtze Delta and five global oscillations from the point of multiple time scales, by using wavelet regression analysis method. The main findings are as follows: (1) at the larger time scale, like 32-year and 16-year scale, the annual average temperature in the Yangtze Delta presents an increasing trend. But at 8-year and 4-year scale, the temperature fluctuates obviously, and the 4-year scale is much more obviously. (2) The annual average temperature change in the Yangtze Delta associates closely with 5 global oscillations and the correlation becomes better while the time scale enlarged. Moreover, we could find that four oscillation indices (NAOI, PDOI, AOI and AAOI) have an active correlation with the annual average temperature in the Yangtze Delta. But for SOI, the correlation is negative. The reason for these is because of their different formations. Because latitude circulation is the main reason, the oscillations (NAO, AO and AAO) have closer association with the temperature in the Yangtze Delta.**

Keywords- Yangtze Delta; annual average temperature; global oscillations; nonlinear variation; wavelet regression analysis

I. INTRODUCTION

There are five global-size oscillations, namely SO (Southern Oscillation), NAO (North Atlantic Oscillation), NPO (North Pacific Oscillation), AO (Arctic Oscillation) and AAO (Antarctic Oscillation). Their relevant indices could weigh the intensity of oscillations. The response of global or regional temperature to global-size oscillation has been focused by many scholars. Some researcher tells us that five oscillations affect regional climate change, especially temperature variation in China, but among the study in the past, a great number of scholars would like to choose one or two oscillations to research its response to regional climate change [1-4].

Yangtze Delta locates in the eastern coast of China, the edge of Eurasia and the west of Pacific, where is humid subtropical monsoon climate. Oceanic air mass and terrestrial air mass interact in this region. Under the global climatic change background, the temperature in the Yangtze Delta certainly changed. How does the temperature in the Yangtze Delta respond to global warming? This is a very important problem of scientific significance. As temperature is a remarkable index of climate change, research the relationship between the temperature in the Yangtze Delta and global climate change has long-term significance.

The purpose of this paper is to find the relationship between the temperature's variation in the Yangtze Delta and five global oscillations from the point of multiple times scale. The authors firstly show the nonlinear variations of annual average temperature in the Yangtze Delta and the five global oscillations by wavelet analysis, then model the correlations among of them at different time scales by using wavelet regression analysis method.

II. MATERIALS AND METHODS

A. Data

The annual average temperature of Yangtze Delta data source is from the website of China Meteorological Administration. Take the average temperature of the three international meteorological stations (i.e. Shanghai, Nanjing and Hangzhou) as the temperature in the Yangtze Delta.

Southern Oscillation Index (SOI) source is from the website of the National Center for Atmospheric Research. Pacific Decade Oscillation Index (PDOI) is from the website of department of atmospheric science in university of Washington. North Atlantic Oscillation Index (NAOI), Arctic Oscillation Index (AOI) and Antarctic Oscillation Index (AAOI) are from the personal blog of Dr. Li Jianping who is from Chinese Academy of Sciences and majors in atmosphere field.

B. Methodology

In order to identify the nonlinear characteristics and the nonlinear variations of the annual average temperature and its response to global climate change at different time scales, this paper integrated wavelet analysis and regression analysis. First of all, the authors show the nonlinear variations of annual

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average temperature in the Yangtze Delta and the five global oscillations by wavelet analysis and then model the correlations among of them at different time scales by using wavelet regression analysis method.

1) Wavelet analysis: As a time-scale analysis method, wavelet analysis is built based on Fourier analysis. It has good signal characteristics in both low and high frequency [5]. In the low frequency part, it has a lower time resolution and higher frequency resolution. On the other hand, it has a higher time resolution and lower frequency resolution in the high frequency part. It is suitable for wavelet analysis to detect normal signal that contains moment abnormal phenomenon and reveal the components, which is a new method for geography study especially some issues like climate change [6-7].

This paper take wavelet decomposition and reconstruction measures for temperature time series and oscillation indices time series as following method. By father wavelet and mother wavelet corresponding transformation, expanding the signal [8]:

$$S_{J,K} = \int X(t)\Phi_{J,K}(t)dt$$

$$d_{j,k} = \int X(t)\Psi_{j,k}(t)dt$$

Where j=1,2，…，J, J is the largest scale, father wavelet and mother wavelet are expressed as following respectively:

$$\Phi_{J,K} = 2^{-j/2}\Phi(\frac{t-2^j k}{2^j})$$

$$\Psi_{J,K} = 2^{-j/2}\Psi(\frac{t-2^j k}{2^j})$$

Father wavelet has the widest support set and suits for the smooth part in the lowest frequency, so it used for trend reconstruction, while mother wavelet is used for analyzing the deviations of trends in the higher frequency.

Signal X (t) can be expressed as following:

$$X(t) = S_J + D_J + D_{J-1} + \ldots\ldots + D_j + \ldots\ldots + D_1$$

where $S_J = \sum_k S_{J,K}\Phi_{J,K}(t)$，$D_j = \sum_k d_{j,k}\Psi_{j,k}(t)$，j=1,2，…，J, usually, X(t) multi-resolution decomposition is:

$$S_{j-1} = S_j + D_j$$

where $\{S_J, S_{J-1}, \ldots\ldots, S_1\}$ is the multi-resolution approximation sequence of signal X(t), and corresponding multi-resolution decomposition is $\{S_J, D_J, D_{J-1}, \ldots, D_j, \ldots, D_1\}$.

In this paper, we use wavelet decomposition and reconstruction for the temperature and the oscillation index at different time scales by the software Matrix Laboratory (short for Matlab). Taking sym8 as wavelet function for the data is discrete variables. In order to get better results of revealing the data's changes, we reconstructed the decomposed signal.

2) Wavelet regression analysis: To understand the relationship between runoff and its related climatic factors, Xu et al. conducted the method of wavelet regression analysis [9-10]. This paper analyzed the relationship between the annual average temperature and the five global oscillations by using this method. The analysis steps are as follows: ① firstly, nonlinear variations of annual average temperature and the five global oscillations were approximated by using wavelet decomposition on the basis of the discrete wavelet transform (DWT) at different time scales; ② then, the statistical relationship between annual average temperature and the five global oscillations were revealed by using regression analysis method based on the wavelet approximation.

III. RESULT AND DISCUSSION

A. Nonlinear variation of the annual average temperature in the Yangtze Delta

To identify the nonlinear variation of the annual average temperature in Yangtze Delta, through wavelet analysis, we got the wavelet reconstruction curves of annual average temperature in Yangtze Delta at four time scales as figure. 1.

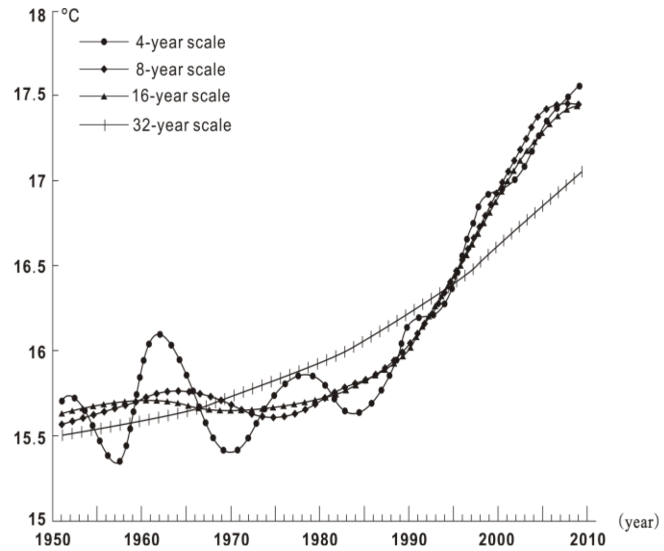

Figure 1. The nonlinear variation of the annual average temperature in the Yangtze Delta at different time scales.

From figure 1, the annual average temperature from 1951 to 2008 showed a steady increase trend at 32-year scale, which is the same as the background of global warming. When the time scale down to 16 years, the whole curve still maintains a rising trend, especially during the 1990s, but the oscillation is not very clear, there is a local maximum value (15.6926°C) in 1958 and a local minimum value (15.6507°C) in 1970.At 8 years time scale, the annual average temperature maintains upwards trend and the curve's oscillation increases significantly, the local maximum can be clearly seen in 1965 （15.768°C） and the local minimum in 1974(15.5974℃). When the scale reduces to 4 years further, the curve fluctuates obviously. There are three local maximum (1952, 1962 and 1977) and three local minimum (1957, 1970 and 1985).

During the past 58 years, the annual average temperature of the Yangtze Delta has a clear increase trend especially around the 1990 through our analysis. It accords with the forth evaluating report of IPCC.

B. Nonlinear variation of oscillation indices

By the wavelet reconstruction as mentioned above, we got the similar nonlinear trends for SO, NAO, NPO, AO and AAO respectively.

1) The SOI was in a stable downward trend during the 58 years from the figure above, while the annual average temperature change is opposite at the same time scale, 32-year scale. When the time scale reduces to 16 years, the curve shows fluctuations when it keeps the downward trend. There is a global maximum in 1971(0.1763) and a global minimum in 1990(-0.8994).At the 4-year scale and 8-year scale, the curve oscillates clearly, especially at the 4-year time scale SOI comes to the lowest value in 1993. This phenomenon has close relation to climate warming extreme weather during the 1990s. It shows that when SOI locates a low value and the El Nino is significant, the consequence is the rise of the temperature.

2) At the time scale of 32 years, NOAI exhibits an upward trend at first, reaching the maximum in1995 (0.4636) and then has a slow downward trend. When the time scale decreases to 16 years, there is the same trend as the 32-year scale, but the maximum appears in 1990(0.7688).At 8- year and 4-year time scales, the curve maintains the trend which increases first and then decreases, but the fluctuations are obvious particular at 4-year. At 4-year time scale, the maximum of NAOI appears in 1990(0.9778) and minimum appears in 1968(-0.7576), this is just the opposite condition of SOI, that is, when NAOI is high, SOI is low; the temperature is high in the Yangtze Delta.

3) NAOI increases at first and then decreases at 32-year time scale, which is the same to 16-year, the maximum is 0.4248 in 1993 and 0.7454 in 1990 respectively. This change is very similar with NAOI. At 8- year and 4- year the curves appears oscillation, when they maintain the trend that increases first and then decreases at the same time, but it is less obvious than NAOI, the maximum is 0.9448 in 1983 and 1.2974 in 1985.When the PDOI value is higher, the temperature in Yangtze Delta is higher through the comparison.

4) In two large time scales (32-year and 16-year), AOI increases first and then has a downward trend, which is the same as NAOI and PDOI. The maximum values appears in 2004(0.6178) and 1993(0.6359).When time scale down to 8-year and 4-year, two curves fluctuates obviously but maintains the trend of large time scales, the maximum value both appears in 1989, 0.8828 and 1.2913.The trend of AOI is similar to the annual average temperature of the Yangtze Delta, that is when the AOI is higher, the temperature is higher.

5) AAOI are consistent, all of them appear an upward trend. At 4-year time scale, the oscillation is much more obvious and the global maximum value is 1.887 in 1999. AAO which is the description of oscillation on the Southern hemisphere is far away from Yangtze Delta, but AAOI has a similar change with the annual average temperature in such a global warming background.

C. Correlations between the temperature and oscillation indices

To illustrate the relationship between the annual average temperature variation and the oscillation indices further, we established multiple regression models with wavelet reconstruction value of annual average temperature (dependent variable) and five oscillation indices (independent variables) by stepwise method. The regression equations at different time scales are shown in Table 1.

TABLE I. REGRESSION EQUATIONS AT DIFFERENT TIME SCALES

Time scale	Regression equation	R^2
4-year	*TEMP*=15.943+0.968*AAOI*-1.025*PDOI*-0.690*SOI*	0.749
8-year	*TEMP*=15.935+1.075*AAOI*-1.152*PDOI*-0.661*SOI*	0.867
16-year	*TEMP*=15.567+0.505*AAOI*-6.039*NAOI*-1.159*SOI*+3.363*AOI*	1.000
32-year	*TEMP*=15.910+2.875*AOI*-4.588*NAOI*+0.554*AAOI*	1.000

From the column R Square in the table, the goodness fit of regression equation is increased as the time scale larger, especially in 16 and 32 years the values are close to 1.000, so we would do specific discussion about these two models as followed.

Among the regression equation at 16-year, it excluded the variable PDOI. According to the principle of stepwise regression analysis, we could find that as the AAOI increased, the temperature increased, then the variables NAOI and SOI came to the equation would make the temperature decreased, at last, the temperature would increase when the AOI came into the equation. From this model, we could conclude AAO, NAO, SO and AO have a greater impact for the annual average temperature in the Yangtze Delta, but it is less to PDO.

At 32-year time scale, AOI has the highest correlation value with the annual average temperature and could make the temperature increased. On this basis, the temperature would decrease as the affect of NAOI. Last, the temperature would increase slightly as AAOI enters the regression equation. In this model, AO, NAO and AAO have significant impact for the annual average temperature.

Through the analysis of two regression equation, we found AO and AAO had the closer relationship with the annual average temperature than NAO, SO and PDO have the least relationship.

Solar radiation and underlying surface are two factors for the Yangtze Delta temperature variation, in addition air circulation. AOI reflects the strength of westerly winds in mid-latitudes, when AOI is high, the subtropical is strong, mid-latitude circulation is strong and then it would lead to the increase of the Yangtze Delta temperature [11]. Although AAO describes the oscillation in high latitudes of the Southern

Hemisphere and its geographical location is far from the Yangtze Delta, it has the similar change with the annual average temperature in the Yangtze Delta. AAOI is the indicator of the westerly winds in the Southern Hemisphere mid-latitude regions, similar to AOI. When AAOI increases, the strength of the Southern Hemisphere westerly wind increases, mid-latitude circulation becomes strong and this will result in temperature of the eastern Pacific Ocean increased, El Nino is significant and then the temperature in Yangtze Delta increased.

NAO involves two large pressure centers Iceland low pressure and Azores high pressure, which both had direct impact on westerly winds. In summer, when NAO is strong, subtropical high in the Northern Hemisphere is strong and its location is north, mid-latitude circulation is strong [12], consequently, the temperature in Yangtze Delta increases. The result is opposite when NAO is weak. In winter, when NAO is strong, the winter Siberian High and East Asian monsoon weakened, it leads the temperature of Asian continent increased [13]. The condition is opposite when NAO is weak. So no matter summer or winter, when NAOI value is high, the temperature in Yangtze Delta is also high.

In addition to the three high-latitude, SO and PDO could affect the temperature in the Yangtze Delta at the same time. When SOI is low, the North Pacific subtropical high moves to high latitude, this would lead to the westerly winds developed. The western equatorial Pacific warm water will expand east, the eastern Pacific sea temperature will increase and El Nino occurs which will make the temperature in increased in this atmosphere circulation [14]. PDOI is the description of surface sea temperature of the Pacific Ocean, when it locates a represent high value, the sea temperature of eastern Pacific also locates a high value and then the Yangtze Delta temperature will increase as the El Nino occurs.

IV. CONCLUSIONS

Summarizing the research result, we elicit the conclusions of this study as following:

1) At large time scales, such as 32-year and 16-year, the annual average temperature, NAOI, PDOI, AOI, and AAOI had a rising trend but SOI. When NAOI, PDOI, AOI, AAOI had high values and SOI located a low value, the annual temperature is represent high. On the opposite side, when NAOI, PDOI, AOI, AAOI had low values and SOI located a high value, the annual temperature is represent low. As the time scale decreased, the entire oscillation index maintained the trend of large time scales, in addition appeared obvious fluctuation and their global maximum or minimum appeared around 1990. At the same time, the temperature of the Yangtze Delta appeared rapid increase.

2) All the oscillation indices had significant correlation with the annual average temperature, NAOI, PDOI, AOI and AAOI had positive correlation with the annual average temperature but SOI. AOI, AAOI and NAOI this high latitude oscillations had closer relation with the annual average temperature by the analysis of two better regression models.

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