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MULTIPLE TIME SCALE ANALYSIS OF CLIMATE VARIATION IN MACAU DURING THE LAST 100 YEARS

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Abstract: The multiple time scale climate changes are studied and calculated with statistical analysis and wavelet transformation on the basis of daily series of observed data over the period 1901–2007 in Macau. The result shows that statistically significant oscillations with 2 to 5 years of period generally exist in the series of climate variables (e.g. annual mean surface air temperature and precipitation as well as evaporation etc.), but with obvious locality in time domain. The variation of annual mean surface air temperature has a quasi 60-year period. The phases of the 60-year variation approximately and consistently match that of Atlantic Multidecadal Oscillation (AMO). The oscillations of seasonal mean surface air temperature in summer and winter have the periods of quasi 30-year and quasi 60-year, respectively. These two periods of oscillations have statistically significant correlation with Pacific decadal oscillation (PDO) and AMO, individually. The multidecadal variations of the precipitation of the annually first flood period and annual evaporation are dominated by periods of quasi 30-year and quasi 50-year, respectively.

Key words: climate change in Macau; wavelet transformation; multiple time scales

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1 INTRODUCTION

Because of its impacts on global and regional economic development, climate change is a focus of attention for the international community. Many studies have been undertaken by climate scientists working in China and abroad. These studies found that in the last 100 years, the global mean surface temperature has experienced a marked increase, the linear trend being 0.074°C/decade[1]. The mean surface temperature for China shows similar warming, but at a rate that is slightly faster than the global mean[2-6]. Whilst there are differences among regions, the time series of China's nationally averaged annual rainfall in the last 50 years exhibits no obvious tendency. On the other hand, the nationally averaged values of climate variables, such as the annual number of sunshine hours, mean wind speed and evaporation, all display obvious downward trends[7].

Climate research usually requires instrumental observations of 100 years or more. Owing to the scarcity of these observations in China in the first 50 years of the 20th century, different investigators have used different methods of interpolation and estimation to reconstruct the missing data. Inevitably this has a bearing on the resulting estimates of the warming rate so that in some cases the differences between estimates can be considerable[8].

The earth's climate system contains many different spatial and temporal scales. Presently, investigations into short-term climate variability are mainly concerned with monthly and intra- and inter-annual time scales. Since the 1990s, wavelet transform has been widely used to analyze the special nature of multiple time scales in climate variability. Many meaningful results have been obtained[9-13]. However, the case of Macau has been less studied. Macau's observing station is located on the western flank of the mouth of the Pearl River Estuary. Continuous records of at least 100 years in length are available from that station for climate variables such as temperature and rainfall. This is rare in southern and even the whole of China. Because of the unique geographical location of

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Macau's observing station, its observations are likely to be less affected by the effects of urbanization[14]. On the other hand, some studies have shown that Guangzhou and Hong Kong temperature and rainfall trends are broadly similar to those of Macau[12,14].

This paper uses wavelet transform to analyze the temporal modes in Macau's temperature, rainfall, sunshine hours and evaporation with a view to better understanding climate variability in Macau and the Pearl River Delta's background atmosphere.

2 DATA AND METHODS

2.1 *Computation of the daily mean temperature*

From the beginning of the 20th century until the 1920s, observations of surface temperature were made 5 times a day in Macau (at 0400, 1000, 1300, 1600 and 2000 LST local time, LST hereafter). Between the 1920s and the early 1950s, observations were made thrice daily (at 0900, 1500, and 2100 LST). Hourly observation began to be made in 1952 and continue to the present day. Since then, the daily mean temperatures are computed from the 24 hourly observations made each day. For the period prior to 1952, the daily mean temperatures are derived via regression in the following way.

First, the 1952-2000 observations are used to derive regression equations with the daily mean temperature as the predictand (i.e., dependent variable) and the 3-times daily (0900, 1500 and 2100 LST) or 5-times daily (0400, 1000, 1300, 1600 and 2000 LST) observations as well as the daily maximum and minimum temperatures as the predictors (i.e., independent variables). One regression relationship is obtained for each month and tested for statistical significance. The pre-1952 daily mean temperatures are then calculated from the corresponding regression equations using the pre-1952 daily observations. Experiments with the 2001-2002 data suggest that with the minimum and maximum temperatures included as predictors, the daily mean temperature estimated by regression can yield an improvement of some 0.3–0.4°C over the estimates from direct averaging (i.e., calculating the average as the simple arithmetic mean of the 5-times daily or 3-times daily observations). Moreover, observations that are missing or likely to be in error are filled or corrected using Hong Kong's temperature records and a regression relationship between Macau and Hong Kong's temperatures. Thus, a time series of daily mean temperature covering the period between 1 January 1901 and 31 December 31 2007 for Macau is constructed.

2.2 *Wavelet transform*

The wavelet transform of a time series X_n (n=1, 2, ……, N) is defined as

$$W_n(s) = \sum_{n'=0}^{N-1} X_{n'} \psi^* \left[\frac{(n'-n)\Delta t}{S}\right] \quad (1)$$

where Δt is the sampling interval of X_n, S the scale parameter, and ψ^* the complex conjugate of the wavelet function ψ. Here we use the Morlet wavelet as the basis function for the transform. The Morlet function is given by

$$\psi_0(\eta) = \pi^{-0.25} e^{i\omega_0\eta} e^{-0.5\eta^2} \quad (2)$$

in which η is the non-dimensional time parameter and ω_0 the non-dimensional frequency. We take ω_0 = 6 to make the Fourier period (T) and the scale parameter S almost equal ($T \approx 1.03S$). The scale parameter S is given by

$$S = S_0 2^{j\Delta j} \quad (j=0,\ 1,\ 2,\ \cdots\cdots,\ J) \quad (3)$$

where S_0 is the smallest resolvable scale ($S_0 = 2\Delta t$), and

$$J = \Delta j^{-1} \log_2(N\Delta t/S_0) \quad (4)$$

In the above equation Δt = 1(year), Δj = 0.125, J = 40. In performing the wavelet transform the beginning and end of the time series are padded with zeroes which are removed after the transform. The power of the wavelet spectrum is

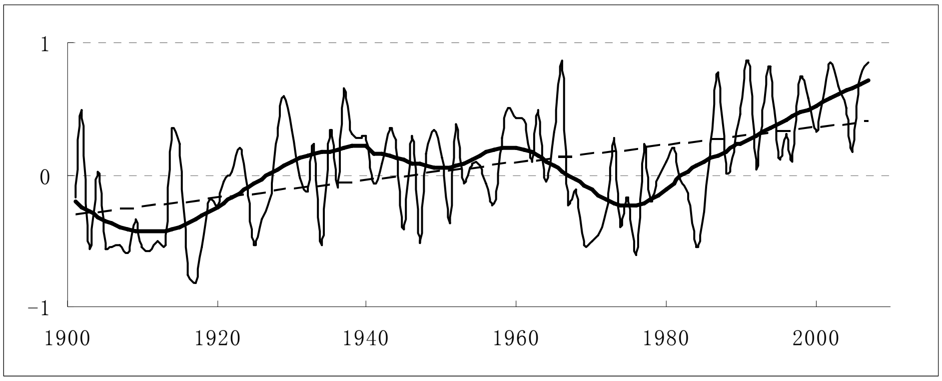
$$E = |W_n(S)|^2 \quad (5)$$

Further details of the wavelet transform are given in Torrence and Compo[11].

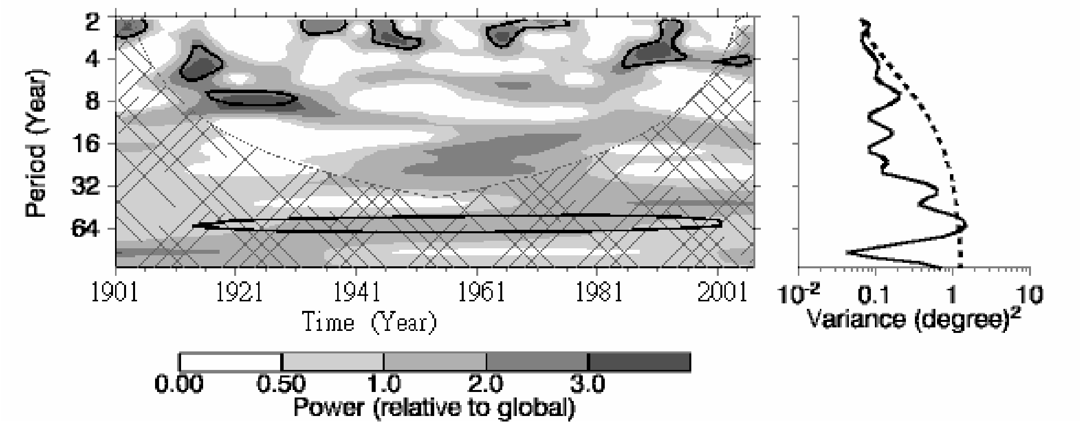
3 ANALYSIS AND RESULTS

3.1 *Temperature*

Figure 1a shows the time series of Macau's mean annual temperature anomaly (relative to the 1961–1990 normal). Analysis of the data shows that between the years 1901–2007, Macau's mean annual temperature has risen by approximately 0.71°C. In terms of trend, this is about 0.066°C/decade, much lower than the global rate given by Intergovernmental Panel for Climate Change (IPCC, 0.071°C/decade). To filter out periods of 20 years or less, we smoothed the mean annual temperature anomaly with a 41-point locally weighted filter[15]. The result is presented as the thick solid line in Figure 1a. It can be seen from this graph that Macau's temperature has a prominent interdecadal variability. There are two distinct cool periods—one in the first twenty years of the twentieth century and the other from the late 1960s to the early 1980s. The 1930s–1940s and the late 1950s to the mid-1960s are two periods when warming clearly took place. The mid-1980s onwards is a third period of rising temperatures. Macau's mean annual temperature thus can be said to exhibit variability on a time scale of several decades. Superimposed on these slow varying background modes are also noticeable interannual oscillations.



(a)



(b)

Figure 1. (a) Macau's 1901–2007 annual mean temperature anomaly (relative to the 1961–1990 normal, in °C) time series (thin line). Thick solid line is the 41-point locally weighted average[15], dashed line the linear trend. (b) Wavelet power spectrum of the annual mean temperature. The gray scale shows the power of the wavelet spectrum relative to the global spectrum. The thick-contours enclosed regions indicate where there is 90% confidence for a red-noise process and the cross-hatched areas are the 'cones of influence'. The small graph on the right shows the global spectrum (solid line) and the 90% confidence line (dashed line) for a red-noise process.

To further analyze the multiple time scales present in Macau's temperature, we performed wavelet transform on the data. Figure 1b gives the wavelet spectrum of the annual temperature series. Regions of 90% confidence for a red-noise process are enclosed by black contours. The small graph to the right of Figure 1b shows the global wavelet spectrum and the 90% confidence level for a red process (dashed line). It can be seen from Figure 1b that 2-5 year oscillations are readily distinguishable from red noise. Moreover, they are quite strongly localized in the time domain. That is, at the start of the 20th century, the mid-1920s, 1930s and 1940s as well as the mid-1960s, the mid 1980s through to the mid-1990s and even the first decade of the 21st century, the presence of 2-5 year oscillations are comparatively evident, but less so in the vicinity of 1910, 1921, 1941, 1957, 1981 and 2002. In other words, oscillations with a period of 2–5 years have an obvious interdecadal pattern of 10–20 years.

This characteristic is shown more clearly in the scale-averaged power over the 2-5 year band[11] (Figure 2). Additionally, it can be seen from the global wavelet spectrum that the 2-3 year oscillations are statistically significant against the 90% confidence level for red noise. As in the case of Macau, the 2-3 year oscillations are also found in the temperature records of places like Guangzhou[12] and northeastern China[13].

Another notable feature in Figure 1b is that for practically the whole stretch of the time under study (1915 to 2001), the (local) power spectrum of oscillations with a quasi 60-year period is statistically significant with respect to the 90% confidence level for red noise. The reduced variance for the portion of the spectrum before 1915 and after 2001 might be attributed to the edge effects arising from padding with zeroes[11]. Despite this, the global spectrum in the graph to the right of Figure 1b indicates that the quasi 60-year oscillation is significant with respect to the 90% confidence level for red noise. Because of the limited length of the time series, the quasi 60-year oscillation is located within the cone of influence and its spectrum is affected by edge effects. Nevertheless, considering Figure 1a jointly with Figure 1b, we believe that the quasi 60-year oscillation is distinguishable from red noise. Qin and Zhu[6] have shown that for China, oscillations with a quasi 60-70 year period are present in last century's temperature record (1880–1998)[6]. The Macau case is essentially in accord with this.

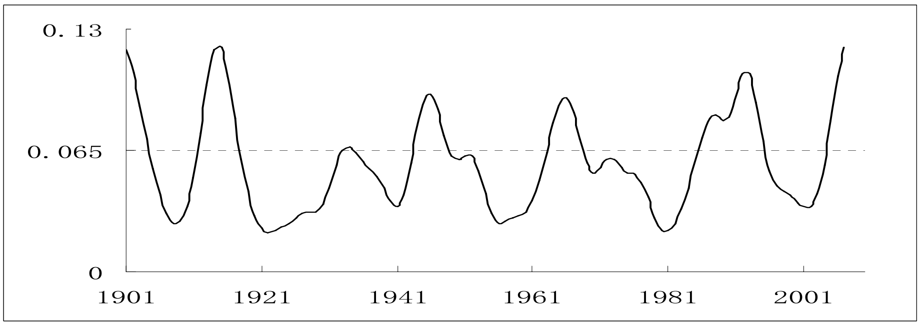
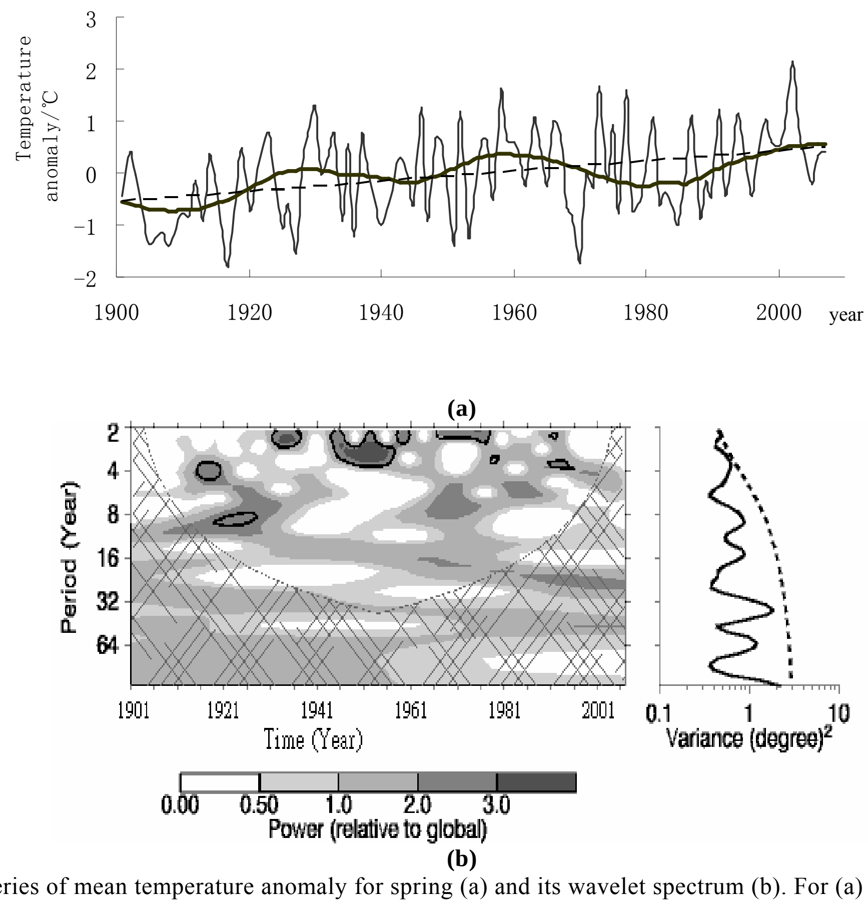


Figure 2. Time series of the scale-averaged wavelet power for the 2-5 year band. Dashed line is the 95% confidence level for red noise.

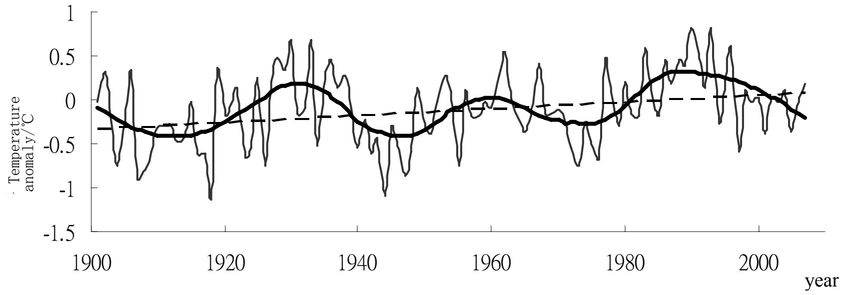
For the four seasons, there are definite differences in the rate of warming. Spring warms the most, followed by winter and with summer the least. The trends for spring, summer, fall and spring are respectively 0.097, 0.038, 0.05, and 0.075°C/decade.

The corresponding wavelet transforms for the four seasons are given in Figures 3 to 6.



(b)

Figure 3. Time series of mean temperature anomaly for spring (a) and its wavelet spectrum (b). For (a) and (b) see Figure 1 for description. See Figure 1 for rest of the caption.



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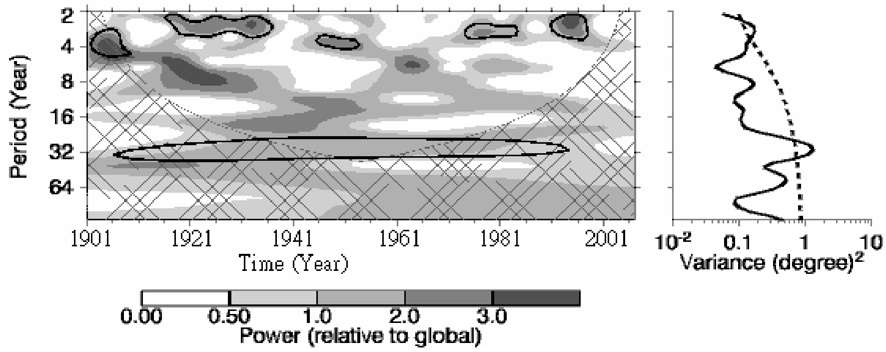
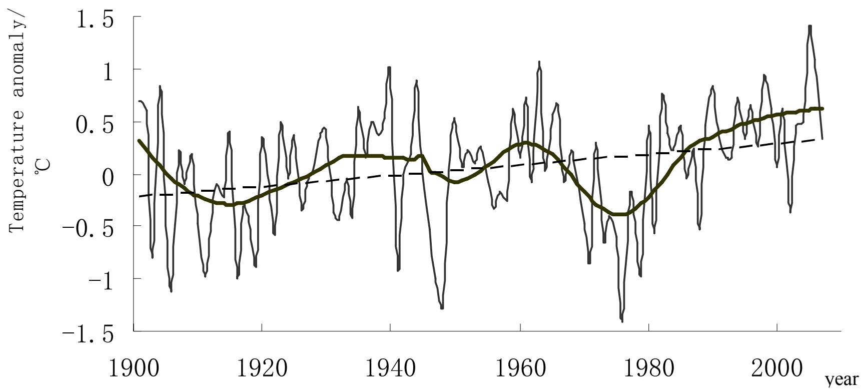
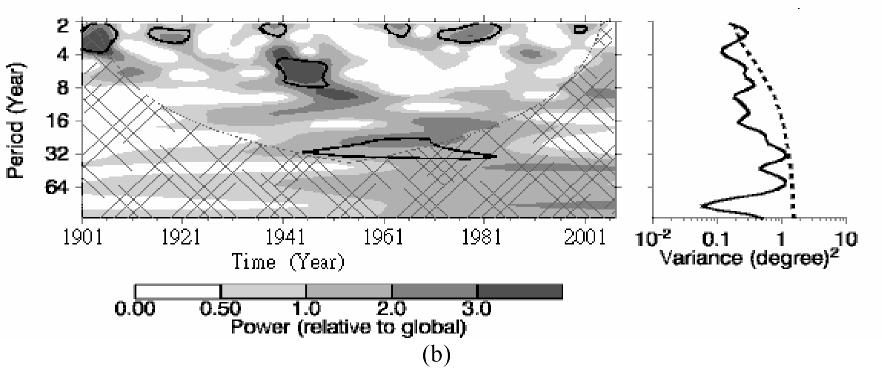


(b)

Figure 4. Same as Figure 3 but for the summer. See Figure 1 for rest of the caption.



(a)



(b)

Figure 5. Same as Figure 3 but for the autumn. See Figure 1 for rest of the caption.

One can see from the thick solid line in Figure 3a that in the case of spring, the 41-point locally weighted average shows three cycles, each with a period of about 30 years. However, the wavelet transform shows that except for the 2-5 year mode (and the concurrent local spectrum of the 11-year cycle in the 1920s), the spectra (both local and global) for all the other time scales do not reach the

90% confidence level with respect to red noise. In other words, there seems to be no statistically significant interdecadal variability in spring's mean temperature (Figure 3b).

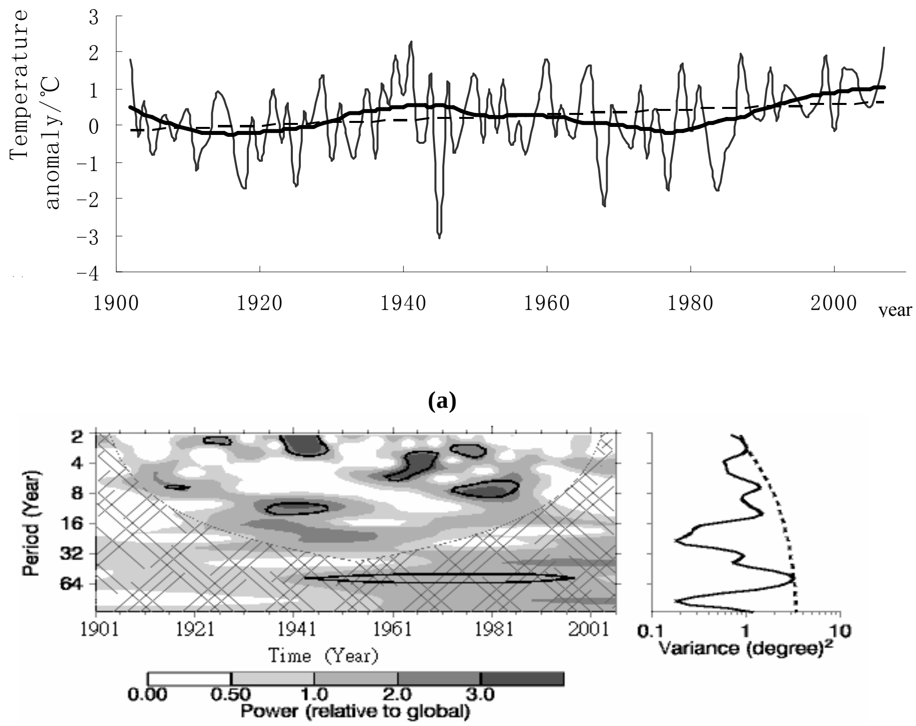


Figure 6. Same as Figure 3 but for the winter. See Figure 1 for rest of the caption.

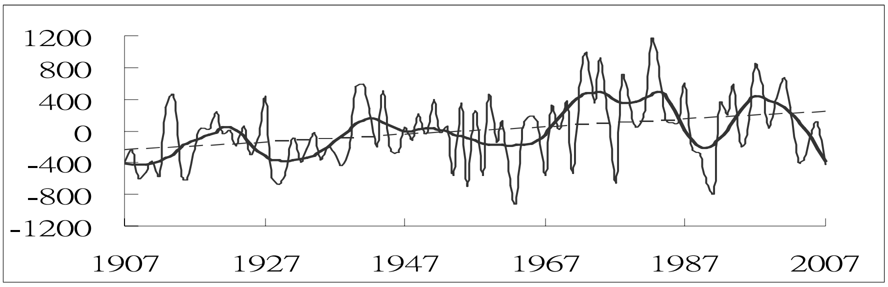
In the case of summer, the annual mean temperature after smoothing by a 41-point locally weighted average (thick solid line, Figure 4a) displays 3 distinct cycles with a quasi 30-year period between cycles. Wavelet transform indicates that the 2-5 year oscillations as well as quasi 30-year oscillations are statistically significant against the 90% confidence level of red noise (Figure 4b). That is, apart from the 2-5 year cycle, on the interdecadal time scale summer's mean temperature also possesses a quasi 30-year periodicity. This is where summer's mean temperature is distinctly different from that of spring.

Autumn is similar to summer in that the temperature data reveal statistically significant 2-5 year and quasi 30-year oscillations. However, before the 1940s and after the 1980s these quasi 30-year oscillations are relatively weak in the sense that they are not distinguishable from red noise at the 90% confidence level (Figure 5). Presently it is not clear whether this reduction in variance is due to padding by zeroes[11].

In respect of winter, it can be seen from Figure 6 that like the other three seasons, the 2-5 year oscillations are the most pronounced as well as statistically significant. They are also quite strongly localized in time. However, winter differs from summer and autumn in that the quasi 30-year oscillations are not statistically significant. In their place there seems to be quasi 60-year oscillations whose local spectrum between the 1940s and the late 1990s is statistically significant against the 90% confidence level of the red noise spectrum (Figure 6b). Moreover, the 41-point locally weighted average winter temperature also discloses an obvious 2-cycle pattern with a quasi 60-year period from cycle to cycle (Figure 6a). The existence of a statistically significant quasi 60-year periodicity in the winter mean temperature can therefore be inferred.

3.2 *Rainfall variability*

Macau's mean annual rainfall is 1873 mm. As can be seen in Figure 7a which shows the time variation of Macau's annual rainfall anomaly, for the record (97 years) as a whole rainfall in Macau has been increasing. The trend is approximately 47 mm/decade, or 2.5%/decade with respect to the mean. From Figure 7b which gives the results of the wavelet analysis for Macau's rainfall anomaly, it can be seen that between the 1950s and the early 2000s, there is a very clear oscillation with a period of about 2–5 years. In addition between the mid-1970s and the mid-1990s the presence of an 11-15 year oscillation can be discerned. However, there seems to be no other modes of interdecadal variability. If one now focuses on the rainfall anomaly in the annually first flood season (April to June), one can readily note from the 41-point locally weighted average (Figure 8a) that there are three cycles with a quasi 30-year period between cycles. At the same time, Figure 8b shows that between the 1930s and the mid 1980s, the local spectrum obtained for these quasi 30-year cycles are statistically significant with respect to the 90% confidence level of the red noise spectrum. The same can be said for the global spectrum. The above results demonstrate that rainfall in the annually first flood season possesses statistically significant quasi 30-year oscillations. Furthermore, as in the case of the annual rainfall, analysis of the rainfall data for the annually first and second flood seasons collected in the last 50 years reveals the existence of statistically significant 2-5 year oscillations in the annually first flood season (Figure 7b) as well as the second flood season (Figure omitted). However, the statistically significant quasi 30-year cycle found in the annually first flood season is not detected in the second flood season rainfall (Figure omitted).



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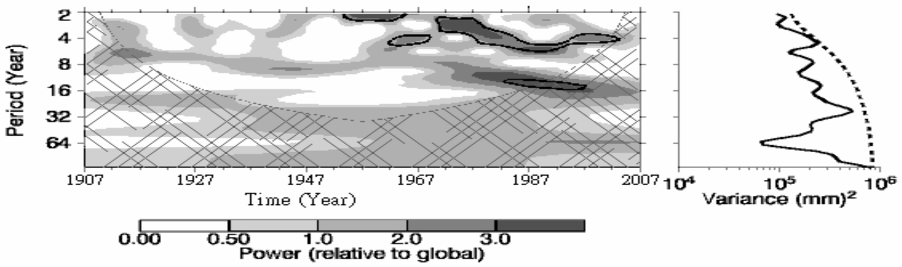
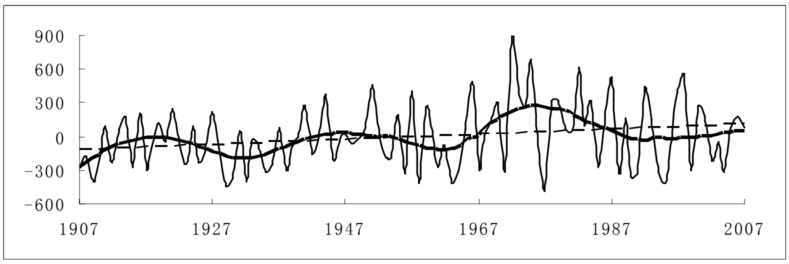


(b)

Figure 7. Time series of annual rainfall anomaly (a) and its wavelet spectrum (b). In (a) the thin solid line is the interannual variation, thick solid line the 21-point locally weighted average and dashed line the trend. All units are in mm. See Figure 1 for rest of the caption.



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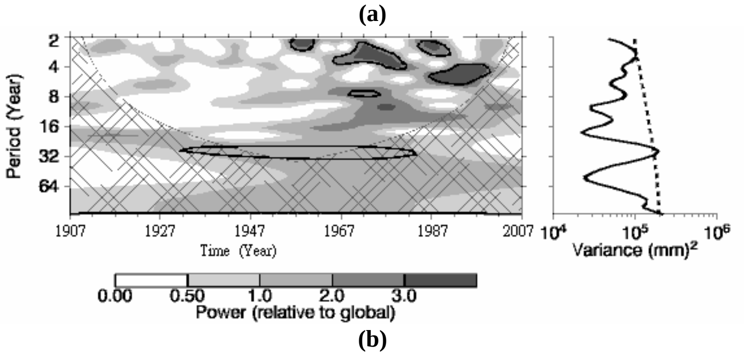
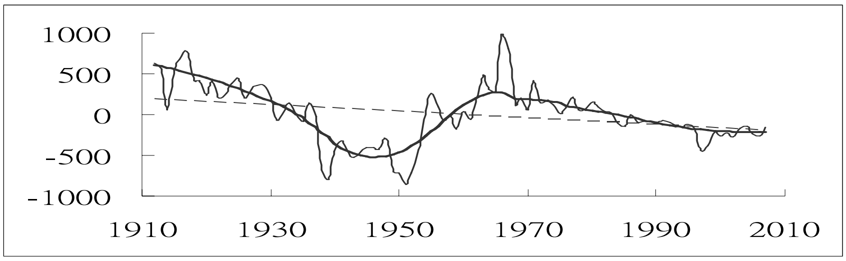


(b)

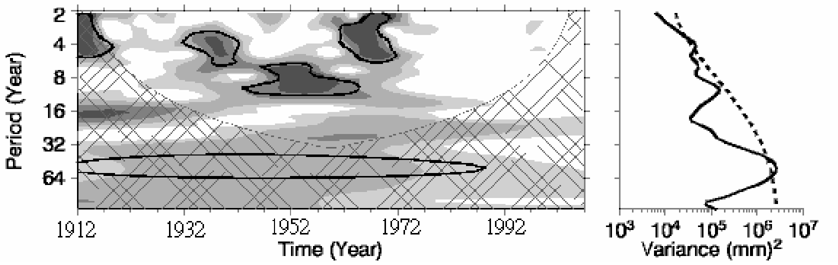
Figure 8. Time series of annually first flood season rainfall anomaly (a) and its wavelet spectrum. See Figure 1 for rest of the caption.

3.3 *Annual evaporation*

Between 1912 and 2007, Macau's annual evaporation is 1106 mm. The time series of Macau's annual evaporation anomaly is shown in Figure 9a. From the 41-point locally weighted average (represented by the thick solid line in this figure), it can be noted that annual evaporation anomaly has two evident cycles with an interdecadal scale of about 50 years.



(a)



(b)

Figure 9. Time series of annual evaporation anomaly (a) and its wavelet spectrum (b). See Figure 1 for rest of the caption.

From the 1910s to the 1930s, the anomaly is positive and downward. Between the 1930s and the 1940s, it becomes negative, attaining a minimum in the 1950s. This is followed by a period of increasing annual evaporation with the anomaly returning to positive in the early 1960s and reaching a maximum in the mid 1960s. From the mid-1960s annual evaporation again starts to fall, and the anomaly once more reverts to negative from the mid-1980s. Overall, the trend displayed by the annual evaporation data (96 years) is downward. The rate of decline is 4.2%/decade (relative to the mean for the entire record). This rate is consistent with that of China as a whole[7]. It can be observed from Figure 9b that present in annual evaporation are statistically significant oscillations with 2-5 and quasi 50-year periods. The 2-5 year oscillations are strongly localized in the time domain. They generally appear in the three time periods 1912–1919, 1932–1940 and 1962–1972 before fading out after the early 1970s. In addition to the 2-5 year and quasi-50 year oscillations, statistically significant quasi 6-12 year oscillations can also be observed between the early 1940s and the early 1960s.

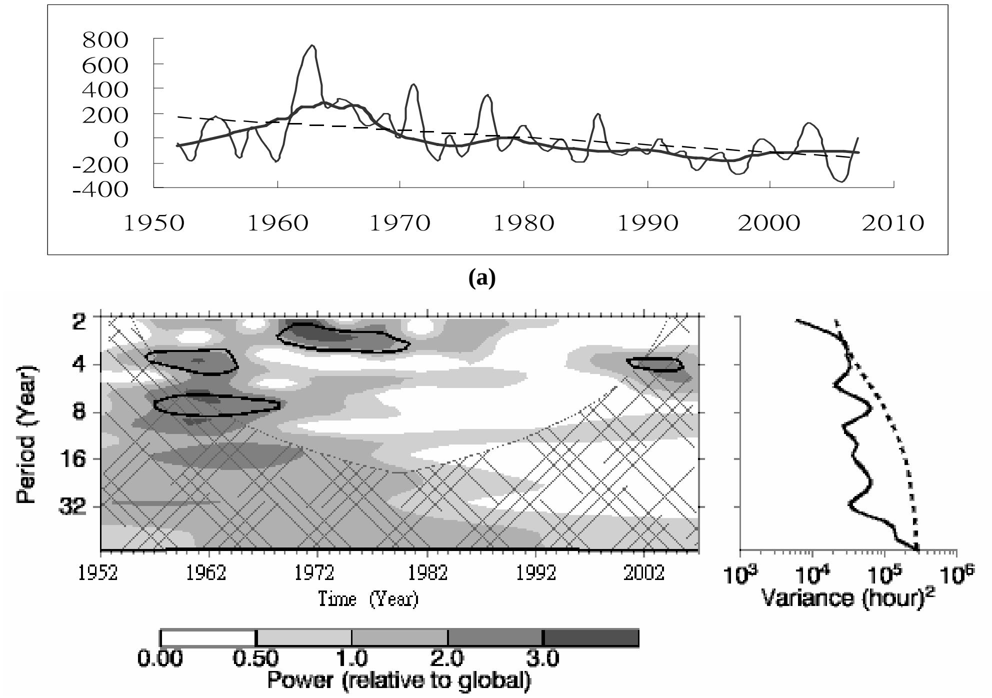
3.4 *Number of sunshine hours*

The mean annual number of sunshine hours computed from Macau's observations made between 1952–2007 is 1887. The annual number of sunshine hours in Macau has been decreasing since the mid-1960s. This can be seen in Figure 10 which gives the time variation of the anomaly. The trend is consistent with the global one as well as China's. In particular, between 1952–2007 the linear trend is –60h/decade. This is much higher than the national one[7]. Comparing Figure 10a with Figure 9a one sees that the trends for annual evaporation and number of sunshine hours are very similar. This seems to suggest that the variability in annual evaporation is predicated mainly on the variability in the number of sunshine hours. Furthermore, wavelet transform indicates that between the mid-late 1960s and the end of the 1970s as well as in the first few years of the 2000s, in the time series of the number of sunshine hours there are statistically significant oscillations with a period of approximately 2–5 years. Additionally, between the mid-1950s and the late 1970s, oscillations with a period of approximately 7–8 years are also statistically significant (Figure 10b).

4 DISCUSSION

Short-term climate variability is critically affected by solar and volcanic activity as well as anomalous sea surface temperatures. A number of studies have shown that there exists in the Atlantic an oscillation with a multi-decadal time scale called the Atlantic Multidecadal Oscillation (AMO). AMO is closely related to multidecadal climate variability in some major regions in the world such as North

America, Europe and the Indian sub-continent[16-18]. Using a coupled ocean-atmosphere model with sea surface temperatures constrained to follow the observed AMO cycle, Zhang et al.[19] was able to show that after eliminating the trends, the modeled Northern Hemisphere mean surface temperatures exhibit low-frequency multidecadal oscillations with amplitudes and phases that are similar to the multidecadal variability in the actually observed mean. Presently, there seems to be few studies on the relationship between AMO and climate variability in China and Asia. Zhang et al.[20] found that on a time scale of several decades, there is an association between the Pacific Decadal Oscillation (PDO) and the AMO. The climate systems of the Indian and Pacific oceans are forced by AMO via teleconnection between the tropical and the temperate zones[21]. Through numerical modeling, Lu et al.[22] and Wang et al.[23] found that variability in the East Asian Monsoon is related to AMO.



(a)

(b)

Figure 10. Time series of sunshine hour anomaly (a) and its wavelet spectrum (b). See Figure 1 for rest of the caption.

Recently, we have explored the possible connection between AMO and climate variability in Macau. Shown in Figure 11 is the time series of the detrended 41-point locally weighted average of Macau's annual mean temperature anomaly and AMO. It can be seen that the two time series vary almost in step, and both show a quasi 60-year period. The correlation between the two time series is as high as 0.67 (statistically significant at the 1% level). The above analysis thus seems to suggest that on a multidecadal time scale, Macau's mean annual temperature is closely related to the AMO. It was pointed out in a previous section that there are considerable differences in the interdecadal variations in the annual mean seasonal temperatures. This implies that there should be definite differences in the degree of association with the AMO from season to season. Winter is found to have the highest correlation coefficient with AMO (0.47), and summer the lowest, 0.21 (Figure omitted). In summer the weather in southern China is dominated by the subtropical high and other tropical systems which are more directly influenced by variations in Pacific's sea surface temperature. Figure 12 shows summer's PDO index and the low-frequency oscillations in Macau's annual mean summer temperature anomaly. Their cycles are very much alike. The correlation between the two time series is 0.54, statistically significant at the 5% level. As in the case of Macau, interdecadal variations in Yunnan Province's mean annual summer temperature follow quite closely that of the PDO[24]. Why is Macau/East Asia's climate related to AMO? Through what physical processes does AMO affect climate variability in China and East Asia? These are the topics for further study.

5 CONCLUSIONS

(1) Macau's climate variables such as annual mean temperature, seasonal mean temperature, annual rainfall, the annual number of sunshine hours as well as annual evaporation are all found to have statistically significant 2-5 year oscillations.

These oscillations are also found to be localized in time. In particular, the 2-5 year oscillations in the annual mean temperature have an interdecadal variability of 15–20 years.

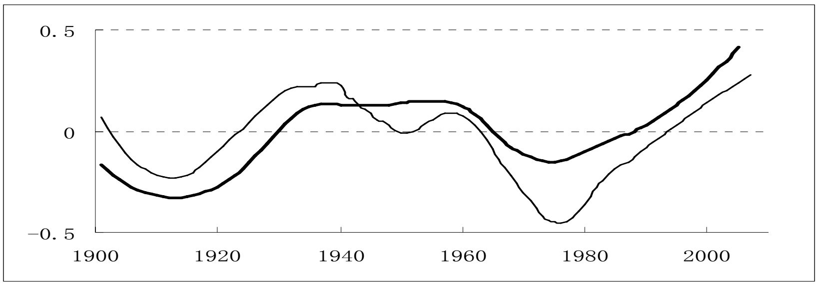


Figure 11. Time series of Macau's annual mean temperature anomaly (thin solid line) and AMO (thick solid line). Both series have been smoothed with a 41-point locally averaged filter.

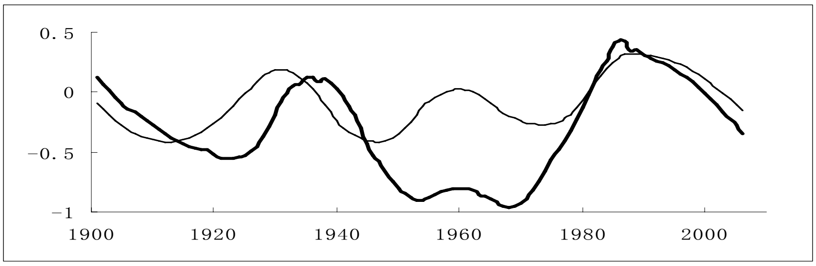


Figure 12. Time series of Macau's annual mean summer temperature anomaly (thin solid line) and the summer PDO (thick solid line). Both have been smoothed by a 41-point locally weighted average.

(2) Moreover, the annual mean temperature has a statistically significant oscillation with a quasi 60-year period. This oscillation is found to move more or less in phase and is highly correlated with the AMO. The correlation between this 60-year oscillation and AMO is a high 0.67.

(3) Seasonal mean temperatures exhibit distinct differences in their variability. On the interdecadal time scale summer's mean temperature displays a quasi 30-year periodicity, and winter's a quasi 60-year periodicity. These periodicities seem to be respectively related to the PDO and AMO respectively, and the relationships are statistically significant. Autumn's situation is similar to that of summer, but spring seems to have no statistically significant interdecadal variability.

(4) The record shows that despite a falling trend in the most recent 10 years, Macau's annual rainfall has been generally increasing in the last 101 years. Moreover, a statistically significant quasi 30-year oscillation can be found in the annually first flood season.

(5) In the last 56 years, the annual number of sunshine hours in Macau has been falling and at a rate that is markedly higher than the national average for China.

(6) There is a quasi 50-year oscillation in Macau's annual evaporation. As in the case of sunshine hours, beginning from the 1970s a linearly downward trend can be seen in annual evaporation.

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