# Collective behaviour of climate indices in the North Pacific air–sea system and its potential relationships with decadal climate changes*

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(Received 16 June 2011; revised manuscript received 19 August 2011)

A climate network of six climate indices of the North Pacific air–sea system is constructed during the period of 1948–2009. In order to find out the inherent relationship between the intrinsic mechanism of climate index network and the important climate shift, the synchronization behaviour and the coupling behaviour of these indices are investigated. Results indicate that climate network synchronization happened around the beginning of the 1960s, in the middle of the 1970s and at the beginnings of the 1990s and the 2000s separately. These synchronization states were always followed by the decrease of the coupling coefficient. Each synchronization of the network was well associated with the abrupt phase or trend changes of annually accumulated abnormal values of North Pacific sea-surface temperature and 500-hPa height, among which the one that happened in the middle of the 1970s is the most noticeable climate shift. We can also obtain this mysterious shift from the first mode of the empirical orthogonal function of six indices. That is to say, abrupt climate shift in North Pacific air–sea system is not only shown by the phase or trend changes of climate indices, but also might be indicated by the synchronizing and the coupling of climate indices. Furthermore, at the turning point of 1975, there are also abrupt correlation changes in the yearly mode of spatial degree distribution of the sea surface temperature and 500-hPa height in the region of the North Pacific, which further proves the probability of climate index synchronization and coupling shift in air–sea systems.

**Keywords:** climate shift, climate indices network, synchronization, coupling strength

**PACS:** 92.60.Wc **DOI:** 10.1088/1674-1056/21/2/029201

## 1. Introduction

It is well known that an important climate shift was observed over the North Hemisphere climate system (NHS) and in the state of the coupled air–sea system of the tropical and North Pacific in the mid-1970s.[1,2] This abrupt change in recent climate history was characterized by a warming trend over most of the globe in the air temperature. In the background state of global warming, sea-surface temperature (SST) increases over much of the eastern and central tropical Pacific and the coast of western North America while a cooling trend was also detected in the mid-latitude North Pacific. The notable change resulted from the abrupt change and the increase in frequency and intensity of El Niño episodes.[3,4] As the extremely dynamical and complex character of the climate system, the actual physical mechanism of such a climate shift is still not quite clear. So the exact prediction is hard to make due to the complex interactions of different climate dynamics although it is quite essential for human beings.[5−8]

Research about the mid-1970s' climate change focused mainly on linear and nonlinear abrupt change detecting methods, phase or trend changes in air temperature series, climate indices or proxy data series and so on. Wang *et al.*[9] discussed the possibility of the abrupt climate change that resulted from climate warming and suggested the research on abrupt climate change should be further strengthened; Wan and Feng,[10] Gong *et al.*,[11] and Feng *et al.*[12,13] combined the latest research achievements in nonlinear science with the abrupt change detection of the climate system and proposed several theories and meth-

*Project supported by the Special Scientific Research Project for Public Interest, China (Grant Nos. GYHY201006021 and GYHY201106016) and the National Natural Science Foundation of China (Grant Nos. 40930952 and 40875040).

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ods of detecting abrupt climate change in the perspective of dynamic structure characters, such as dynamic correlation factor index, dynamic exponent segmentation algorithm, detrended fluctuation algorithm, permutation entropy algorithm, approximate entropy algorithm, etc., thus opening new possible paths for studying the abrupt change of the dynamic structure of the climate system. Besides, using the running $t$ test, Hou *et al.*,[14] and Xiao and Li[15] quantitatively detected and analysed the inter-decadal abrupt change points of global sea surface temperature fields and revealed the spatial characteristics of inter-decadal abrupt change, the earliest response time and areas, vertically structure, etc. Ma and Fu[16] detected and analysed the drying characteristics of northern China over the past 45 years using the Mann–Kendall method and systematically revealed the inter-decadal spatiotemporal pattern of drying. Mu and Wang[17] demonstrated the possibility of the abrupt change between non-equilibrium states of ecosystem by using a theoretical grass and ecosystem model, forced by a certain external forcing. Most investigations have proved that abrupt changes did exist in the 1960s, the 1970s, the 1990s, etc., among which the climate change of the mid-1970s is especially noticeable. However, it seems that one was not aware that the climate abrupt changes might be the results of complicated interactions of main modes indicated by their indices. Furthermore, it is not quite clear which climate index might play the most important role in the 1970s' climate shift, which is the second, etc., either.

In this paper, not only the variation of the climate index itself but also the collective behaviours of different climate indices are considered. From the investigation of the coupling function of interaction systems, we try to find out its probable relationship between the observed climate variations in the late 20th century from a new point of view.

## 2. Methods and results

Six major climate indices that we are going to consider here are the Pacific Decadal Oscillation (PDO), the Pacific North America signal (PNA), the Western Pacific Oscillation index (WP), the North Pacific index (NP), the South Oscillation (SO), and El Niño index in area 3 and 4 (NINO 3.4). Data used in this paper are the reanalysis dataset provided by the National Centre for Environment Prediction (NCEP).[18,19] The time series of monthly anomaly values from 1948 to 2009 is available for all indices. Each of these modes has its own mechanism over different geographical regions. These six modes together may have somewhat inevitable relationships with the climate change in the air–sea system of the North Pacific due to their interact dynamics. Traditional abrupt change detection methods, such as moving $t$ test, heuristic segmentation algorithm (briefly BG algorithm), accumulated abnormal method, etc, are always used to detect abrupt climate changes.[20] Here, we use three detection methods mentioned above to investigate the variations of six climate indices themselves. The annual-mean indices are constructed by averaging the monthly indices over the months of December to February considering the stability of the index series.

Figures 1(a)–1(c) show the yearly variation of six climate indices through the traditional abrupt change detection methods: BG algorithm, accumulated abnormal method and moving $t$ test, respectively. From the curves in the figure, four distinct abrupt change points which appear at about the end of the 1960s, in the middle of the 1970s and at the beginnings of the 1990s and the 2000s respectively can be observed from almost all indices no matter which detection method was used. And of these four abrupt change periods, the one that happened in the middle of the 1970s is the most distinct. This is well corresponding to the fact that an important climate shift happened over the North Hemisphere (NH) in the mid-1970s.[14,15]

On the other hand, what we are more interested in is the interactions and the collective behaviours of these climate indices. It is well known that the complex network approach is a compelling perspective and has proven to be useful to analyse the complicated system that is composed of many interacting components such as internet, scientists cooperation net neural network, etc.[21–24] In this paper, we construct a climate network whose nodes are represented by these six major indices; links are represented by the correlation actions between the nodes. In order to describe the correlative character of the connections of these nodes, a way that is commonly used is the mean distance $L(t)$,[25] expressed as

$$L(t) = \frac{2}{N(N-1)} \sum d_{ij}^t, \tag{1}$$

where $t$ is the time in the middle of a sliding window $\Delta t$; $N = 6$; $i, j = 1,\ N$; $d_{ij}^t = \sqrt{2(1 - |\rho_{ij}^t|)}$, and $\rho_{ij}^t$ is the correlation coefficient between nodes $i$ and $j$ in the interval $\Delta t$.[26,27] The absolute value of

correlation coefficient, 1, means well connected relationship between $i$ and $j$ while zero value means the non-connected nodes. And the mean distance can be thought as the average correlation between all possible pairs of nodes in this six-node network. So the lower value of the mean distance means the more synchronizations of network nodes.

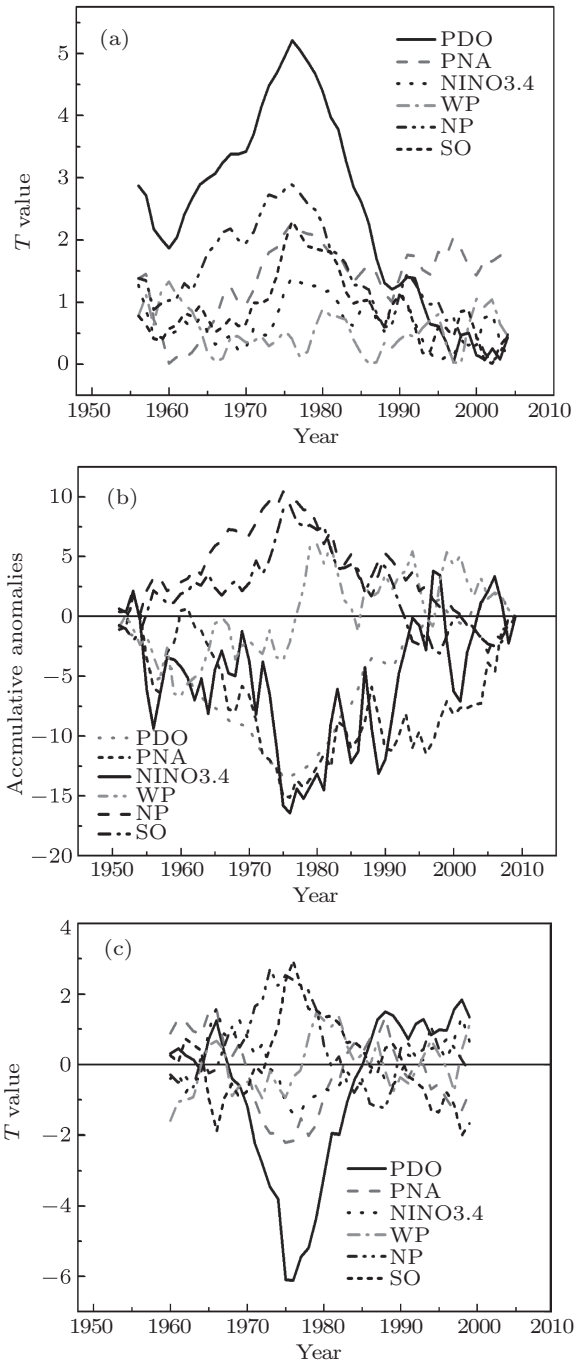



**Fig. 1.** (colour online) Yearly variations of six climate indices through the traditional abrupt change detection methods: BG algorithm (a); accumulated abnormal method (b); moving $t$ test (c). The vertical axis is: $T$ value (a); accumulative anomalies (b); $T$ value (c).

Figure 2 (upper line) shows the mean distance as a function of time. From the curve, four obvious falls of the mean distance $L(t)$ can be observed at the end of the 1960s, in the middle of the 1970s, at the beginnings of the 1990s and the 2000s, respectively. This means well synchronized states in these periods of time. This accords well with the results obtained from the traditional abrupt change detection methods mentioned above.

In the next step, we consider the coupling function of these indices and its probable relationships with their synchronization. Coupling is considered as a measurement of the link strength between the current phase and the future phase of different modes. Therefore, we first try to simplify the original time series by symbolizing the given time series points. We can use a symbolic phase instead of the actual value of the time series by considering only the variation trend of this point and its two nearest neighbours. Just as Table 1 shows, if three points increase sequentially, then we define the middle point as a phase of 0, while a phase of $\pi$ is given if they are decreasing sequentially. Six possible situations and their corresponding symbols are all listed in Table 1 then the originally complex time series can be really simplified by the vectors through this method. The symbolic phases of the time series points are represented by the symbol series $\Phi_n^k$, where $n$ denotes the year and $k$ represents the index. For a given year $n$, the symbolic phase is then defined as the phase vector $\boldsymbol{Z}_n$, whose element $Z_n^k$ is equal to $\exp(\mathrm{i}\,\Phi_n^k)$ correspondingly. Then the vectors such as $\boldsymbol{Z}_n$ and $\boldsymbol{Z}_{n+1}$ construct the matrix $Z$ including all years just as shown below:

$$Z=\begin{pmatrix} \mathrm{e}^{\mathrm{i}\,\Phi_1^1} & \mathrm{e}^{\mathrm{i}\,\Phi_2^1} & \cdots & \mathrm{e}^{\mathrm{i}\,\Phi_n^1} & \mathrm{e}^{\mathrm{i}\,\Phi_{n+1}^1} & \cdots \\ \mathrm{e}^{\mathrm{i}\,\Phi_1^2} & \mathrm{e}^{\mathrm{i}\,\Phi_2^2} & \cdots & \mathrm{e}^{\mathrm{i}\,\Phi_n^2} & \mathrm{e}^{\mathrm{i}\,\Phi_{n+1}^2} & \cdots \\ \mathrm{e}^{\mathrm{i}\,\Phi_1^3} & \mathrm{e}^{\mathrm{i}\,\Phi_2^3} & \cdots & \mathrm{e}^{\mathrm{i}\,\Phi_n^3} & \mathrm{e}^{\mathrm{i}\,\Phi_{n+1}^3} & \cdots \\ \mathrm{e}^{\mathrm{i}\,\Phi_1^4} & \mathrm{e}^{\mathrm{i}\,\Phi_2^4} & \cdots & \mathrm{e}^{\mathrm{i}\,\Phi_n^4} & \mathrm{e}^{\mathrm{i}\,\Phi_{n+1}^4} & \cdots \\ \mathrm{e}^{\mathrm{i}\,\Phi_1^5} & \mathrm{e}^{\mathrm{i}\,\Phi_2^5} & \cdots & \mathrm{e}^{\mathrm{i}\,\Phi_n^5} & \mathrm{e}^{\mathrm{i}\,\Phi_{n+1}^5} & \cdots \\ \mathrm{e}^{\mathrm{i}\,\Phi_1^6} & \mathrm{e}^{\mathrm{i}\,\Phi_2^6} & \cdots & \mathrm{e}^{\mathrm{i}\,\Phi_n^6} & \mathrm{e}^{\mathrm{i}\,\Phi_{n+1}^6} & \cdots \end{pmatrix}. \quad (2)$$

In order to measure the coupling strength between the years, the least square estimator method is used here.[28,29] The estimated vector of the year $n+1$ which is denoted as $\boldsymbol{Z'}_{n+1}$ can be predicted by the least squares predictor

$$\boldsymbol{Z'}_{n+1} = M\boldsymbol{Z}_n, \quad (3)$$

where $M = [Z_{n+1}Z_n^{\mathrm{T}}][Z_nZ_n^{\mathrm{T}}]^{-1}$, with $Z_n$ and $Z_{n+1}$ being the matrices constructed by the columns of $\boldsymbol{Z}_n$ and $\boldsymbol{Z'}_{n+1}$. The coupling strength then can be measured by $\left\|\boldsymbol{Z'}_{n+1} - \boldsymbol{Z}_{n+1}\right\|^2$ and the smaller value means the stronger coupling relationship between years.[30,31]

**Table 1.** Six possible states for the symbolization of the original time series.

| Variation trend of time series | | | | | | |
|---|---|---|---|---|---|---|
| Symbolic phase | 0 | $\pi/3$ | $2\pi/3$ | $\pi$ | $4\pi/3$ | $5\pi/3$ |

Figure 2 (lower line) shows the changes of coupling character of those indices. From the synchronization line, we first take notice of the synchronous state at about 1960 for the network. At the same time, the coupling strength has a decreasing trend, which means the fortified direction of coupling relationship. When the network enters into a new synchronization state again in the middle of the 1970s, the coupling strength begins to decrease again just at this time point. And the same conditions are also observed at about the early 1990s and the 2000s just as the curves show. To sum up, when the network enters into a new synchronization state, the value of coupling strength begins to decrease, which is a symbol of the coupling strengthen just at the same time.

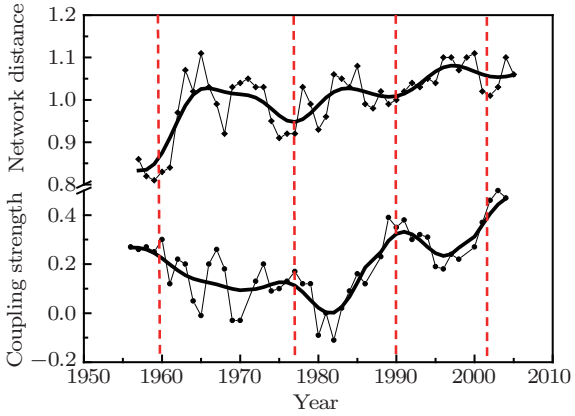



**Fig. 2.** (colour online) Yearly changes of the mean distance of the network (upper line) and the coupling strength between six indices (the lower line). The vertical axis denotes network distance (upper line) and coupling strength (lower line).

From the synchronization and coupling characters of the indices network, we can observe the distinct transitions on the decadal time scale. And the change of synchronous state is always closely related to the coupling strength. These results might reflect some intrinsic mechanism of climate system well related to the major climate changes. Figure 3 shows the annually accumulated abnormal values of SST (a) and 500-hPa height value (b). It is mostly obvious that just at the time point of the mid-1970s, the phase of SST turns from positive to negative on a whole. The same trend is also observed on the annually accumulated abnormal values of 500-hPa height. From the whole time scale of about 60 years, we can also notice some unapparent changes of values trend. For example, the annually accumulated abnormal values of SST and 500-hPa height with negative phases each have the decreasing trend before the 1960s, but after that time point, the negative phases are in the opposite change direction. And among those changes, the one that happened in the middle of the 1970s is most noticeable and important.

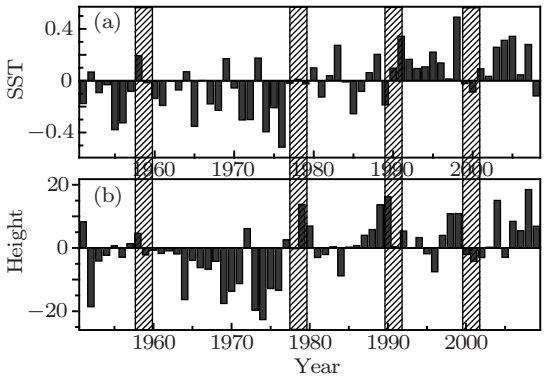



**Fig. 3.** Annually accumulated abnormal values of SST (a) and 500-hPa height value (b).

Empirical orthogonal function technique aims at finding a new set of variables that capture most of the observed variance from the data through a linear combination of the original variables. Empirical orthogonal functions (EOFs) have been introduced in atmospheric science for the discussion of relevant problems in analysing multivariate data in meteorology. In order to make sure whether the abrupt changes are the features of climate index synchronization and coupling behaviours, we apply EOFs to the six climate indices. The variance contribution of first mode of the EOF1 is 75.3%, so this mode represents the main spatial feature of climate indices and other residual information is ignored. Then we construct the new index matrix by using the EOF1 and corresponding temporal coefficients. Figure 4 shows the new index matrix of

EOF1. It is obvious that there is a distinct change around the time point of 1975. There are also small changes around the 1960s, the 1990s, etc. However, the abrupt change in the 1970s is the most significant one. That is to say, the climate shift in the 1970s is a common behaviour of the main modes represented by these six indices, which is quite different from the shifts in other decades.

As demonstrated in previous studies, atmospheric field can be thought as a network of interacting points, while nodes with high degree which are identified as tele-connection or other patterns may play an important role in the network.[32] As is well known, indices of PDO, NINO 3.4 are obtained from SST, so the correlation actions between them might also be contained in the interior correlation actions of the North Pacific SST; while the indices of WP, PNA, SO and NP are obtained from height fields, so correlation actions between them might also be contained in the interior correlation actions of the North Pacific height field. In order to make sure whether the interior correlation actions of North Pacific sea–air system also show abrupt shift features in the 1970s and other decadal periods, we respectively construct the complex networks of SST and 500-hPa height of North Pacific by following the way in Refs. [33]–[35].

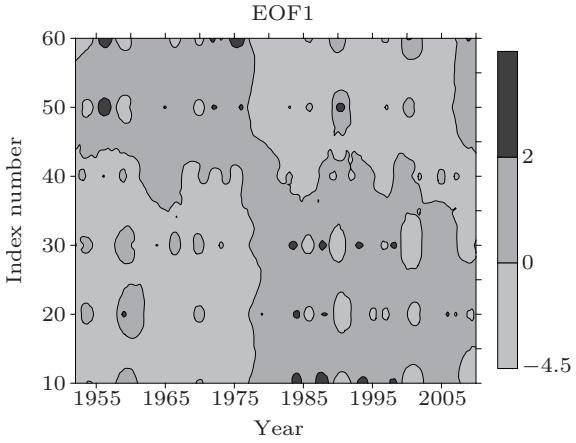



**Fig. 4.** New index matrix constructed by the EOF1 and corresponding temporal coefficients of six indices. The vertical axis denotes index number.

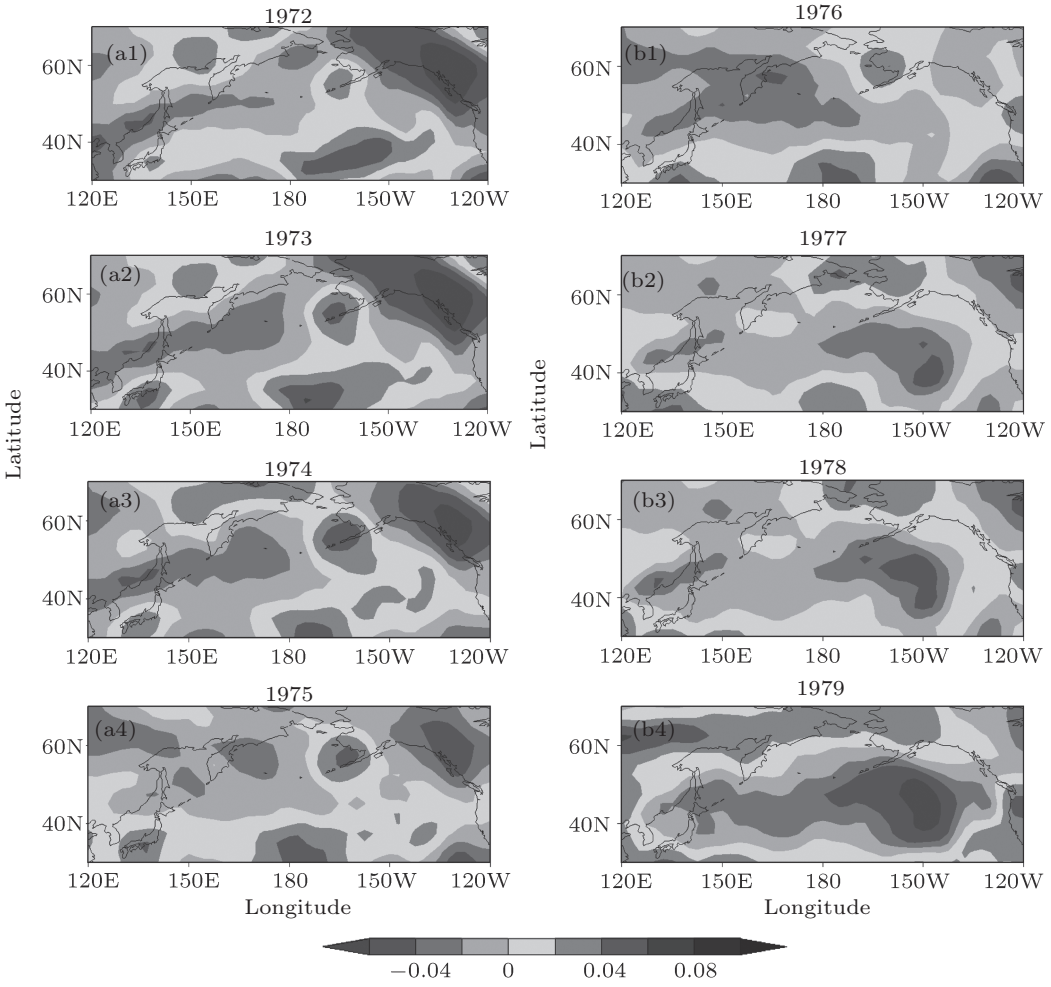



**Fig. 5.** (colour online) Yearly mode of spatial degree distribution of 500 hPa at North Pacific Ocean from 1972 to 1979. The horizontal axis: longitude, the vertical axis: latitude.

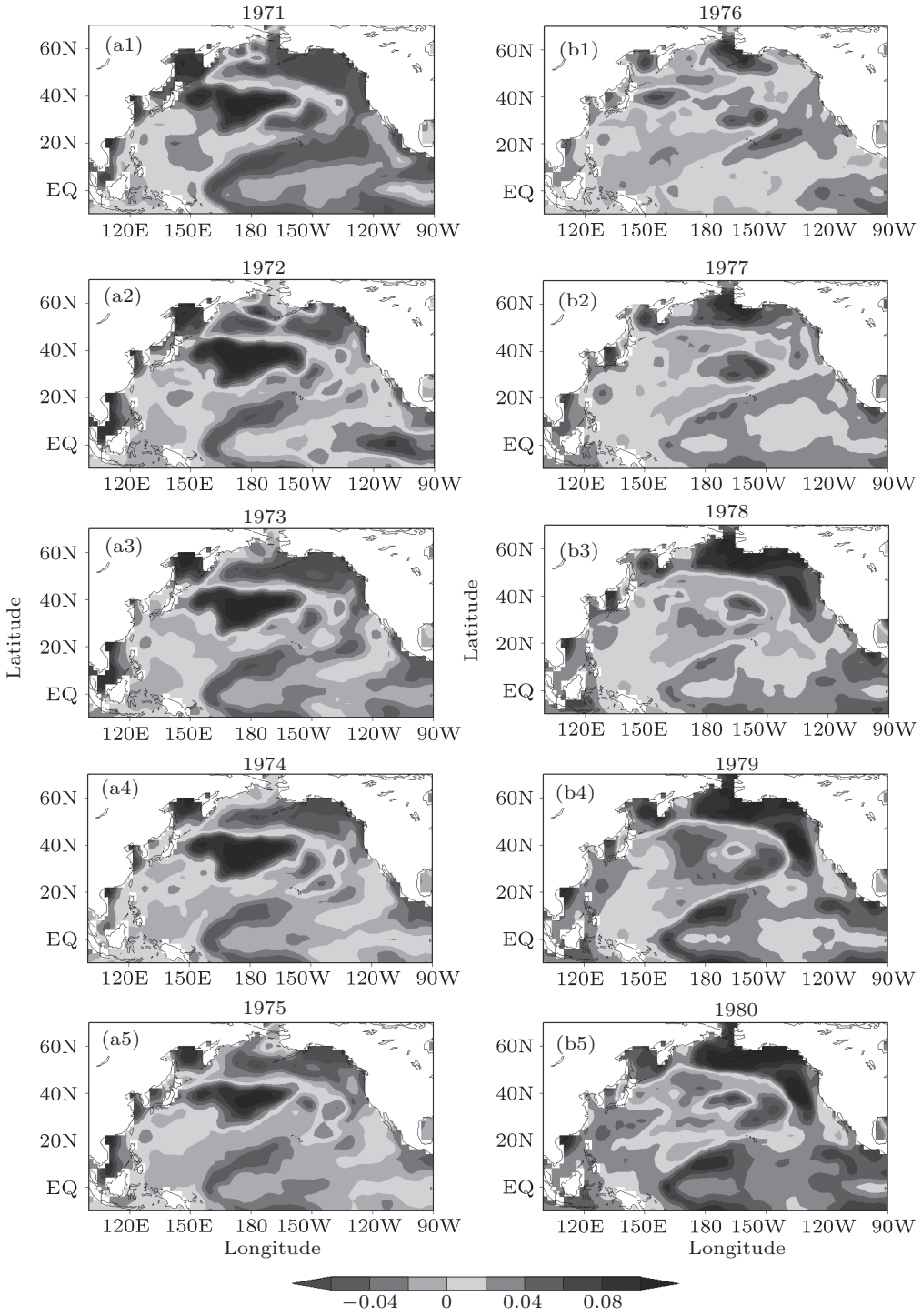



**Fig. 6.** Yearly mode of spatial degree distribution of SST at North Pacific Ocean from of 1971 to 1980. The horizontal axis: longitude, the vertical axis: latitude

Figure 5 shows the yearly mode of spatial degree distribution of 500-hPa height above the North Pacific Ocean from 1972 to 1979. Around the year 1975, the condition in circulation system is that the mode of degree distribution at west part is converted from the pattern of north-strong and south-weak to that of north-weak and south-strong; a similar condition in east part is that the mode converted from the pattern of north-weak and south-strong to that of north-strong and south-weak. This transition might be corresponding to the change of the effect of WP and PNA. A similar situation also happens under the interior action of North Pacific SST system. Figure 6 shows the yearly mode of spatial degree distribution of SST

at North Pacific Ocean from 1971 to 1980. As figure 6 shows, the mode of degree distribution obviously changes around 1975. The mode of degree distribution is converted from weak-strong-weak (north to south) style before 1975 to strong-weak-strong style after that year. This conversion might have close relationships with the changes of the effect of PDO and NINO 3.4. On a whole, the climate system has a distinct adjustment or conversion in the middle of the 1970s and this climate shift is shown not only in the phase change of climate element or indices, but also in the change of indices actions. And the coupling method of different indices can somewhat reflect this character of the climate system from a new aspect.

## 3. Conclusions

In this paper, we construct a climate network of six important indices in the period of 1948–2009 and investigate its intrinsic mechanism. For the purpose of finding the inherent relationships between the important climate shifts and the climate indices, a new method of investigating the synchronization behaviour and the coupling behaviour of index network is used here. The main results are concluded into two aspects. First, the climate network synchronizes four times on this time scale: at the end of the 1960s, in the middle of the 1970s, at the beginnings of the 1990s and the 2000s, respectively. When the network enters into the synchronization state, the value of coupling coefficient begins to decrease just at the time point, which means a symbol of the strengthened coupling. These corresponding relationships are associated with the annually phase or trend change of abnormal values of North Pacific SST and 500-hPa height value. Second, from the synchronization line and the coupling line, we can see that the changes that happened at the beginnings of the 1990s and the 2000s are not very significant, while the changes in the middle of the 1970s are noticeable and prominent. This result is consistent with the fact that the most important climate change is the one that happened in the mid-1970s in resent hundred years. Besides, the abrupt change in the mid-1970s might be corresponding to the dynamical changes in the climate system, while the abrupt changes in the 1990s and the 2000s are just corresponding to the phase changes in climate system.[15,36] So the other changes seem not very remarkably with respect to those in the mid-1970s, although they do exit and are also very important actually.

The new index matrix constructed by the EOF1 and corresponding temporal coefficients of six indices further prove the possibility of the 1970s' climate shift in climate indices; beside, we all observe the distinct changes at the time turning point of 1975 of the yearly spatial degree distribution of the North Pacific SST system and 500-hPa circulation system, which further prove the possibility of climate shift in climate index coupling. In a word, the new method of synchronization and the investigation of coupling characteristics between indices can well reflect the major climate shifts of the complex climate system.

Tsonis *et al.*[28] showed that the major climate modes tend to synchronize at some coupling strength in the North hemisphere air–sea system; however they did not show a similar behaviour to that in the North Pacific air–sea system. In this paper it is further proved that the synchronization and coupling behaviour at the time point of climate shift also existed in a regional climate system; besides, this behaviour is also consistent with the synchronization behaviours in SST and 500-hPa height.

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