Circulation system complex networks and teleconnections*

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In terms of the characteristic topology parameters of climate complex networks, the spatial connection structural complexity of the circulation system and the influence of four teleconnection patterns are quantitatively described. Results of node degrees for the Northern Hemisphere (NH) mid-high latitude (30° N–90° N) circulation system (NHS) networks with and without the Arctic Oscillations (AO), the North Atlantic Oscillations (NAO) and the Pacific–North American pattern (PNA) demonstrate that the teleconnections greatly shorten the mean shortest path length of the networks, thus being advantageous to the rapid transfer of local fluctuation information over the network and to the stability of the NHS. The impact of the AO on the NHS connection structure is most important and the impact of the NAO is the next important. The PNA is a relatively independent teleconnection, and its role in the NHS is mainly manifested in the connection between the NHS and the tropical circulation system (TRS). As to the Southern Hemisphere mid-high latitude (30° S–90° S) circulation system (SHS), the impact of the Antarctic Arctic Oscillations (AAO) on the structural stability of the system is most important. In addition, there might be a stable correlation dipole (AACD) in the SHS, which also has important influence on the structure of the SHS networks.

Keywords: complex network, structural feature, circulation system, node degree

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1. Introduction

The climate system is an objective physical system, wherein various complex short range and long range connections exist. As such, the system has a complex connection structure.[1−3] The climate system has a relatively stable structure due to the presence of various interior feedbacks and the influence of external conditions. In addition, changes in the interior connection structure of the system cause it to be always dynamically changing, not only asympotically but also sometime abruptly.[4−8] Therefore, we must understand the structural complexity of the climate system from both the variability and the stability of the system.

Since Watts and Strogatz[9] proposed the small world network, which is a network between a regular network and a random network, the topology of complex networks has been applied to many scientific fields, and some research hot points have emerged in complexity study. In a complex network, a node represents a basic cell of the dynamical system, an edge (link) between two nodes represents the interaction between the two nodes, and the network is consisted of a set of those nodes and links. The complex network method may be an adequate method to catch the essence and to effectively feature the interior structures of the interactive systems. Its application has yielded many new insights in different areas of science.[10−12]

Incorporating the complex network theory and the connection of the climate system opens a new direction for studies on the spatial correlation structure complexity of the system. Tsonis *et al.*[1] proposed a way to understand the spatial structure of the climate system from a macroscopic aspect by employing the complex network theory. Gong *et al.*[13] investigated the dynamic statistical properties and the multiple time scale characters of the global sea sur-

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face temperature (SST). In combination with extreme events, Wang *et al.*[14] studied the structural stability conditions for the SST networks. Yamasaki *et al.*[15] explored the responses of the complex networks of the global temperature fields to the El Nino and the La Nina events. Gong *et al.*,[16] Feng *et al.*[6,17] and Zhi *et al.*[18,19] investigated the spatial–temporal scale characters of the global temperature and the height fields of the NCEP/NCAR reanalysis data, thereby establishing a theoretical base for the construction of the complex network for temperature fields. Tsonis and Swanson[2] discussed the structural stability of the climate system by analyzing the effects of the two important teleconnection patterns (the North Atlantic Oscillations (NAO) and the Pacific–North American (PNA) patterns) of the circulation systems on the stability of the system.

The above studies investigated the structural characters of the climate system from a macroscopic aspect, and presented the physical quantities to assess the complexity of the system structure. Nevertheless, there are various teleconnections in the Northern Hemisphere (NH) mid-high latitude (30° N–90° N) circulation system (NHS), such as the Arctic Oscillations (AO), the NAO and the PNA teleconnection patterns, but studies on the effects of the AO on the structural stability of the NHS network and that of Antarctic Arctic Oscillations (AAO) on the structural stability of the Southern Hemisphere (SH) mid–high latitude (30° S–90° S) circulation system (SHS) network are both rarely found in previous research papers. This paper mainly investigates the effects and the relative importance of various circulation teleconnection patterns on the spatial correlation structure stability of the circulation system.

2. Data and methods

2.1. Data

The monthly 500 hPa height data[20] used here were arranged on a grid with a resolution of 5° (latitude) ×5° (longitude). Monthly values at each grid point from 1966 to 2005 are available. This results in 72 points in the east–west direction, 36 points in the north–south direction, and 2592 points in total. These 2592 points were assumed to be the nodes of the height network. The multiple teleconnection patterns in the NHS are more stable in winter half year (from September to February). Therefore, we mainly analyzed the height values $H(j)$ $(j = 1, 2, \ldots, 120)$ from November to January.

2.2. Construction and structural characteristic quantities of circulation system networks

We attempted to construct the complex network of the circulation system based on the correlation between the grid points of the 500 hPa heights. The main ideas were as follows: first, the standardization of the original 500 hPa heights was performed,

$$H'_i(j) = \frac{H_i(j) - \langle H_i \rangle}{\sigma_i}, \tag{1}$$

where $\langle H_i \rangle$ denotes the time mean value of H_i, and $\sigma_i = \sqrt{\langle H_i^2 \rangle - \langle H_i \rangle^2}$. The connection coefficient between arbitrary two grid points C_{ik} (Murirhead, 1982) is

$$C_{ik} = \frac{1}{120} \sum_{j=1}^{120} H'_i(j) H'_k(j)$$
$$(i = 1, \ldots, 2592;\ k = i, \ldots, 2592). \tag{2}$$

The range of C_{ik} is $[-1, 1]$, where $C_{ik} = 1$ denotes a positive full correlation, $C_{ik} = -1$ denotes a negative full correlation and $C_{ik} = 0$ denotes no correlation. The grid points in the height data were assumed to be the nodes in the circulation system connection network. As such, in total $2592(2592-1)/2$ correlation coefficients were obtained from $2592(2592-1)/2$ pairs of nodes. Similar to the case of the temperature connection networks in Gong *et al.*'s paper,[13] if the absolute value of the connection coefficient between two grid points (nodes) was greater than 0.5, the two nodes were considered to have a link; otherwise the two nodes were considered to be unconnected. After all nodes and all links were determined, the intricate interior connections of the 500 hPa height fields were mapped onto a typical complex network.

To show the architecture of the network, it is more appropriate to use the area-weighted number of total links at each geographic location, because the network is a continuous one defined on a sphere. Thus, if a node i is connected with s other nodes at λ_j latitudes, then the degree k_i (area-weighted connectivity) of node i is defined by:

$$k_i = \sum_{j=1}^{s} \cos \lambda_j \Big/ \sum_{j=1}^{2592} \cos \lambda_j. \tag{3}$$

It is known from Eq. (3) that the larger the degree of a node is, the stronger the role of the node is in the circulation system.

If the distance between nodes i and j (number of edges or links through which arbitrary two nodes are connected) is d_{ij}, then the average path length

(L) of the network is defined as the mean value of the distances between all nodes of the network:

$$L = \frac{1}{2592(2592-1)/2} \sum_{i \geq j} d_{ij}. \tag{4}$$

It is known from Eq. (4) that the smaller the average path length of a network is, the shorter the medium process (through which arbitrary two nodes in the network are connected) is, and the more efficient the information transfer in the network becomes.

Suppose that a node i has r_i links, through which it is directly connected with r_i neighbor nodes. The r_i nodes are called the directly connected nodes for node i. Obviously, between the r_i nodes there is a maximum number, $r_i(r_i-1)/2$, for possible links. If the actual links between the r_i nodes is E_i, the clustering coefficient (S_i) for node i is defined as:

$$S_i = 2E_i/r_i(r_i-1). \tag{5}$$

The average value of S_i over all nodes is the mean clustering coefficient (S) of the network. The larger the mean clustering coefficient of a network is, the more distinct the clustering feature of the network is, i.e., the better of the synchronization in the local network.

3. Results and analysis

3.1. Connection structure features for circulation system networks

Figure 1 shows the degree distribution of the global 500 hPa height fields, in which there are two distinctive degree boundaries near 27.5° N and 27.5° S in the NH and the SH, respectively. Different spatial structural features usually correspond to different underlying dynamic mechanisms; therefore we divide the global 500 hPa circulation system into two subsystems according to the regional features of the circulation system connection network. One of them lies in the tropics, in which nodes are well connected with almost the same high degree, thereby suggesting that the low latitude circulation network is a typical global coupling network. There are direct links between nodes in the typical global coupling network. Therefore, the atmospheric fluctuation information is efficiently transferred in the low latitude circulation system, and changes in height fields are better synchronized. The other one lies in the mid–high latitudes of the two hemispheres, in which the mean node degree is lower than that in the low latitudes and the node degree is not uniform. The node degree is obviously higher in some areas. The higher degree area includes the North Pacific–the North American continent, the Eurasian continent near the Mongolia–Siberia area, the Antarctic region, and the South Indian Ocean between 40° S and 50° S–the Southwest Pacific–the South Atlantic Ocean area. According to the previous studies, the higher degree areas in the NH correspond to the PNA and the EU teleconnection patterns,[21,22] and those in the SH correspond to the AAO[23−25] and the 3-4 waves teleconnection patterns between 40° S and 50° S.[26] It is worth noting that the NAO,[3,27] the NPO and the AO[28] teleconnection patterns are not evident in the NH mid–high latitudes in Fig. 1. This does not indicate that the mean degree distribution is unable to reveal the presence of these patterns or they are not the significant features of the circulation systems. Since those teleconnection patterns can be revealed only in the network of a specific spatial scale range in the NH, those patterns are to certain degree masked out by other patterns, such as the PNA and the EU, in the global scale network.

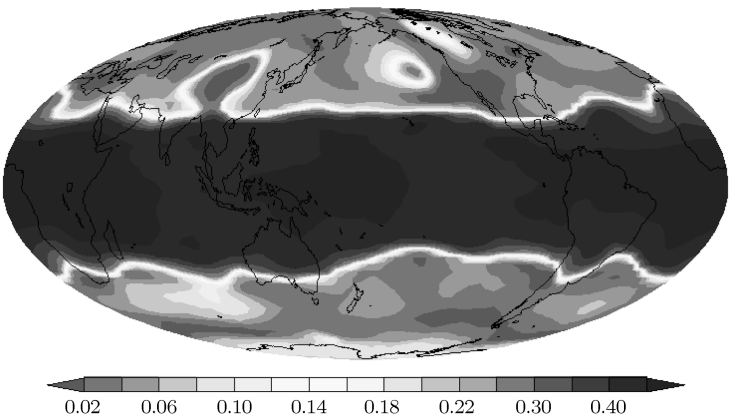


Fig. 1. Degree of node at each geographic location based on the global 500 hPa heights from 1950 to 2004. The uniformity observed in the tropics indicates that each node possesses the same degree. In the extratropics, certain nodes possess a larger degree than the rest. See text for details on how this figure was produced.

In fact, if only nodes north of 30° N latitude are considered, we find that the features consistent with the AO, the PNA, the NAO, and the EU are not only presented but also prominent (Fig. 2(a)). Wallace and Gutzler[19] defined tele-connectivity at each grid point as the strongest negative correlation between all points, and applied the empirical orthogonal function expansion to the geopotential height field to bring out various teleconnection patterns. Because of the requirement of strongest negative correlation (which occurs between a negative anomaly centre and a positive anomaly centre), those approaches can only delineate long-range connections, but are not able to reveal information about the clustering and connectivity at other spatial scales and the strength of the teleconnection patterns in the circulation system. Constructing circulation system connection networks and calculating their node degree distributions are able to bring out major oscillations and major teleconnection patterns of the circulation system. The network approach considers not only the role of the negative correlation but also the role of the positive correlation; therefore, areas with larger node degree in the network are not only teleconnection areas but also strong action areas of the circulation system.

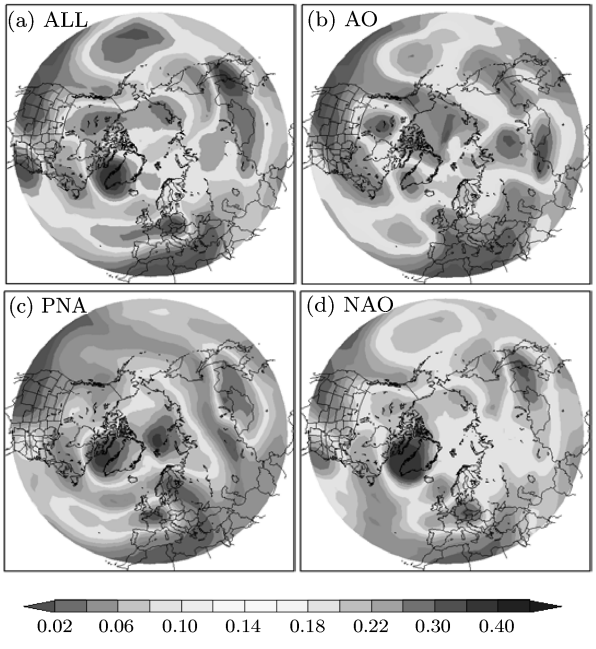


Fig. 2. Node degree distributions for (a) the complete NHS network at 500 hPa and for the NHS network without (b) the AO, (c) the PNA, and (d) the NAO, respectively.

Table 1 lists the structural characteristic parameters for the GS, the NHS, the SHS and the TRS connection networks of the 500 hPa height fields. It can be seen from Table 1 that the GS network has a smaller mean path length and a larger clustering coefficient, which as well as Fig. 1 suggests that the GS network is a typical small world network. That is to say, not only the circulation system is well clustered (such as changes in the height information of nodes are well synchronized in the tropics), but also the information transfer in the system is efficient through some supernodes (i.e., oscillations and teleconnection patterns) in the areas of higher node degree. The mean path length of the GS network is 2.000, indicating that arbitrary two nodes in the network are connected through two intermediate nodes and the height fluctuation information is rather efficiently transferred.

Table 1. Structural characteristic parameters for GS, NHS, SHS and TRS networks.

	$\langle k \rangle$	S	L
GS	0.157	0.665	2.000
NHS	0.098	0.551	3.870
SHS	0.194	0.616	3.369
TRS	0.699	0.903	1.020

In the climate system, some large fluctuations (extreme events) may occur in local areas in a short time, which makes the local areas in a dynamically unbalanced state. For example, anomalous warm (cold) sea surface in the El Nino (La Nina) events in the central–east tropical Pacific usually impacts the atmospheric general circulation through sea–air interactions. Because the circulation system has a small world effect, teleconnections and oscillations rapidly respond to extreme events, then the local strong fluctuation information is rapidly diffused over the whole system, and the system maintains a dynamic balance through self-adjustment.

The NHS and the SHS networks have higher clustering coefficients and smaller shortest path lengths, thus also possessing the typical small world effect. While the TRS network has better clustering property, since its mean shortest path length is 1, and it is a fully coupled network. Therefore, the structural stability of the climate system is robust to local strong fluctuations and to strong external forcing signals. We discuss the robustness of the NH and the SH mid–high latitude systems below.

3.2. Structural stability analysis of circulation system networks

After the removal of a few nodes from the network, if the rest nodes are still connected with each

other (presence of interactions), then it is said that the connectivity of the network is robust against node failure or attack in maintaining the original structure feature. To investigate the robustness of networks, Carlson[29] employed two node-removing strategies: one is randomly removing nodes from the network; and the other is deliberately removing some higher degree nodes. Assuming that the ratio of the removed node number to the total node number of the network is f , then the robustness of the network can be quantitatively delineated with the relationship between mean clustering coefficient S of the network and f. Along the same clue, we plotted a diagram for a random network and the 500 hPa height network robustness (Fig. 3). It can be seen from the figure that under the circumstance of randomly removing some nodes, the GS network (A) still has a higher clustering coefficient (a better connectivity); and under the circumstance of deliberate attacks, the declining rate of the clustering coefficients in the SHS (B) and the NHS (C) networks is obviously larger than that of (A). The rapid decline in the clustering coefficient mainly results from the successive removal of the teleconnection patterns consisted of the nodes with higher degrees. In addition, values of f, above which the clustering coefficient declines to below 0.2 for the 500 hPa height networks, are distinctively larger than that for the random network (D). This further confirms the robustness of the circulation system networks.

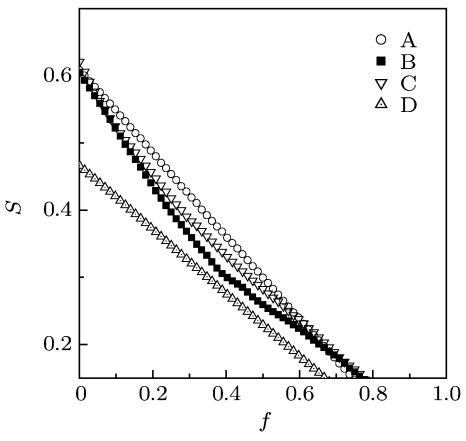


Fig. 3. Robustness of random network and 500 hPa circulation system networks. The clustering coefficient of network (S) against the percentage of nodes attacked (f) under four circumstances: A, random attacks in the GS network; B, deliberate attacks in the SHS network; C, deliberate attacks in the NHS network; and D, random attacks in a global random network.

Obviously, deliberate removal of nodes from a network considerably influences the entire connectivity of the network, resulting in a decline of the stability of the network structure. Therefore, we further analyze the effect of the AO, the NAO, the PNA on the structural stability of the NHS network and the effect of the AAO on the structural stability of the SHS network, respectively. It is observed from Fig. 2(a) that in the NHS network there are multiple superposition areas, wherein the 500 hPa AO, NAO and PNA patterns are overlapped. The correlation among the superposition areas must indicates the characteristic of their common connection information.

3.2.1. Impacts of teleconnection patterns on the stability of the NHS network

To better describe the role of various teleconnection patterns in the circulation systems, we constructed four NHS regional sub-networks. Figure 2(a) shows the geographic distribution of the node degree in the NHS network, from which we can intuitively observe the spatial distributions of the AO, the NAO, the PNA, and the EU patterns; In previous studies, one diagram often gives only one teleconnection pattern. The high and the low values of the node degree of a teleconnection pattern in Fig. 2(a) directly reflect the strength of the pattern in the NHS circulation system. By employing the empirical orthogonal function (EOF) expansion technique, we successively removed the first EOF mode (EOF1 corresponding to the AO pattern; Fig. 2(b)), the second and the sixth EOF modes (EOF2 + EOF6 corresponding to the PNA pattern; Fig. 2(c)), and the third EOF mode (EOF3 corresponding to the NAO pattern; Fig. 2(d)) from the NHS circulation system to investigate the impacts of these teleconnection patterns on the connection structure of the NHS.

Table 2 gives the structural characteristic parameters of the NHS networks for the complete 500 hPa fields and for the 500 hPa fields without the AO, the PNA, and the NAO. We can see that after removing the NAO pattern, the mean degree and the shortest path length of the NHS network reduces 11% and increases 6%, respectively, while the mean clustering coefficient of the network reduces 1%; after removing the PNA, the mean degree and the shortest path length reduces 17% and increases 10%, respectively, while the mean clustering coefficient reduces 2%; and after removing the AO pattern, the mean degree and the shortest path length reduces 30% and increases 18%, respectively, while the mean clustering coefficient reduces 5%. It is evident that after successively

removing each teleconnection pattern, the mean shortest path length always increases, which suggests that the transfer of the fluctuation information in the removed field network must pass through more intermediate nodes than that in the complete field network. In other word, the efficiency of the information transfer in the removed field network is reduced. The reduction in the mean clustering coefficient indicates that after deliberate removal of some nodes from the NHS network, its connectivity is degraded and its structural stability also declines. Meanwhile, after removing the teleconnection patterns, percentage changes in the mean cluster coefficient are obviously smaller than those in the mean node degree and in the mean shortest path length. The reason might be that the removal of the teleconnection patterns mainly destroys long range links in the NHS network, resulting in the increase of the mean path length; while short range links in local areas are far less destroyed. The specific property of the circulation system determines that the long range links between nodes are fewer than the short rang links, the percentage reduction in the clustering coefficient is smaller.

Table 2. Topological statistics of networks before and after excluding the AO, the PNA, the NAO from the NHS network and the AAO from the SHS network, respectively. The Δ_k, Δ_s, and Δ_L denote changes of $\langle k\rangle$, S and L in percentage, respectively.

		$\langle k\rangle$	(Δ_k)	S	(Δ_s)	L	(Δ_L)
NHS	ALL	0.098		0.551		3.870	
	-AO	0.069	(–30%)	0.527	(–5%)	4.551	(+18%)
	-PNA	0.081	(–17%)	0.541	(–2%)	4.260	(+10%)
	-NAO	0.087	(–11%)	0.545	(–1%)	4.095	(+6%)
SHS	ALL	0.194		0.616		3.369	
	-AAO	0.107	(–45%)	0.550	(–11%)	4.512	(+34%)

Based on Table 2 and the above analysis, we conclude that the impacts of removing the AO, the PNA, and the NAO on the structural stability of the networks are not the same. It can be seen from Fig. 1 that the PNA is one of the major modes of the NH climate system. The PNA dominates in the NH circulation field, and not only affects the NH mid–high latitude circulation, but also is significantly connected with the low latitude circulation. As shown in Fig. 4, after removing the PNA, the number of long range (2000 km–6000 km) links is significantly reduced, while the number of short range (less than 2000 km) links does not change much. Therefore the local clustering feature of the network basically remains the same, and the change in the mean clustering coefficient of the network is small. As such the impact of the PNA on the structural stability of the NHS is smaller. Figures 4(a) and 4(c) show that the NAO is part of the AO, thus it takes a less important role in the NHS compared to the AO. After removing the NAO (Fig. 4(a)), the change in mean clustering coefficient is small, since the removal mainly destroys the 2000 km–6000 km links between the nodes. However, after removing the AO (Fig. 4(a)), features of the teleconnection and the local clustering property of the network are changed in such a way that the entire connectivity of the network is distinctively changed and the stability of the NHS is evidently weakened. Therefore, as far as the effects of the PNA, the NAO, and the AO on the structural stability of the NHS is concerned, the PNA is not the most important one; the NAO is only an important part of the AO; the effect of the AO is most important, and the contribution of the AO to the structural stability is dominant. In addition, the three patterns are mutually connected as a whole, and the failure of any one would significantly reduce the efficiency of information transfer in the network, which is disadvantageous to the dynamic stability of the NHS.

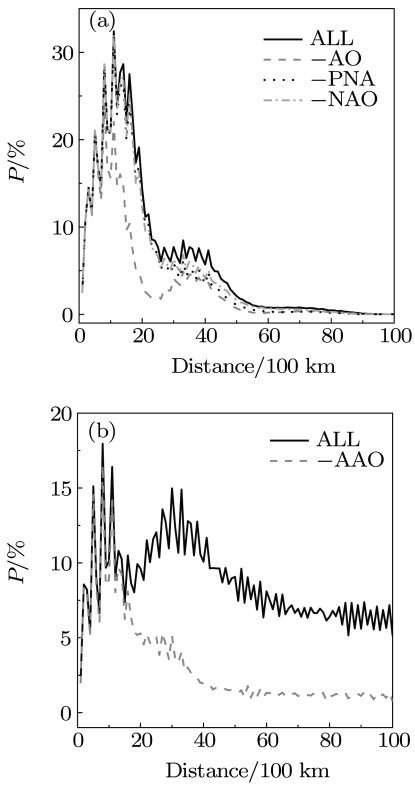


Fig. 4. Mean node degree as a function of the distance between arbitrary two nodes in (a) the NHS and (b) SHS networks.

3.2.2. Impacts of teleconnection patterns on the stability of the SHS network

Likewise, Figs. 5(a) and 5(b) show the node degree distributions of the SHS network with and without the AAO, respectively. From Figs. 2(d) and 5(a), it is clear that the AAO is the dominant mode of the SHS, and its regional mean node degree value is obviously higher than those of other parts of the SHS network. To analyze the impact of the AAO on the SHS network, structure parameters of the SHS networks with (Fig. 5(a)) and without the AAO (Fig. 5(b)) were also calculated (Table 2). It can be seen from Table 2 that after removing the AAO from the complete SHS network, the mean degree of the network reduces 45%, the mean shortest path length increases 34%, and the mean clustering coefficient reduces 11%. So the clustering coefficient suggests that the contribution of the AAO to the stability of the SHS is very important. The removal of the AAO from the SHS network reduces the numbers of the long range and the short range links within 500 km–10000 km (Fig. 4(b)) to different extents, so the small world effect of the network is obviously weakened, while the nearest-neighbor coupling property is distinctively enhanced. It can be observed also from Fig. 5 that the AAO is not only a dominant teleconnection pattern on the hemispheric scale, but also a dominant mode of the SHS.

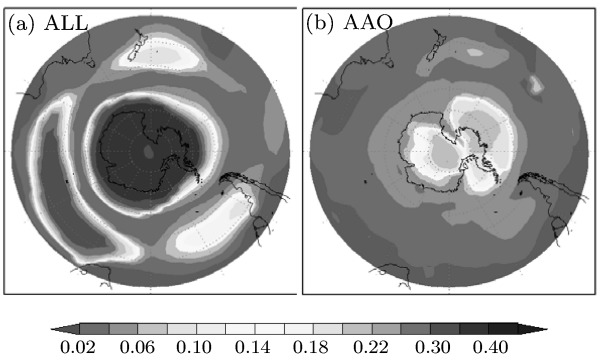


Fig. 5. Node degree distributions for (a) the complete SHS network at 500 hPa and (b) the SHS network without the AAO

3.2.3. Impacts of Antarctic Dipole patterns on the stability of the SHS network

Figure 6(b) shows that there are two high node degree areas in Antarctic after removing the AAO from the complete SHS network. Few works have focused on these two areas. The empirical orthogonal function (EOF) analysis is a well known procedure in the atmospheric sciences, which decomposes a signal into modes (EOFs) of variability. Each mode explains some of the variance observed in the data. The first EOF explains most of the variance, and so on. In order to confirm the existence of these two high degree areas, we excluded the first mode of original height field data of mid–high latitude of South Hemisphere and constructed the residual height field. Figure 6(a) shows the first mode (EOF1′). The positive and the negative centres in the EOF1′ are well correspond to the two high degree centres in Fig. 5(b). Then we excluded the EOF1′ of the residual height field to remove the two high degree centres in Antarctic (Fig. 7). After the removal of the EOF1′, the mean degree and the mean clustering coefficient of the Antarctic network are 0.070 (reduced 34%) and 0.534 (reduced 3%), respectively. So, the two high degree centres have important influence on the stability of the correlation structure and on the transfer of the fluctuation information. Figure 6(b) shows the second mode (EOF2) of the original height field data (S60°–S90°). Obviously, the positive and the negative centres are also well consistent with the two high degree centres in Fig. 5(b). Figure 8 shows the temporal series of the EOF1′ and the EOF2. The correlation coefficient is −0.81, which pasts the 0.01 confidence test. Figure 9 shows the winter mean height field (S60°–S90°, from 1971 to 2000). There are a couple large value centres in the Antarctic area, which are also consistent with the two high degree centres in Fig. 5(b). So, the two high degree centres in the Antarctic area might be a stable correlation dipole and be independent of the AAO. This dipole shows synchronous positive correlation and might be one of the most important components of the mid–high latitude South Hemisphere system. For convenience, we call these two high degree centres as the Antarctic correlation dipole (AACD).

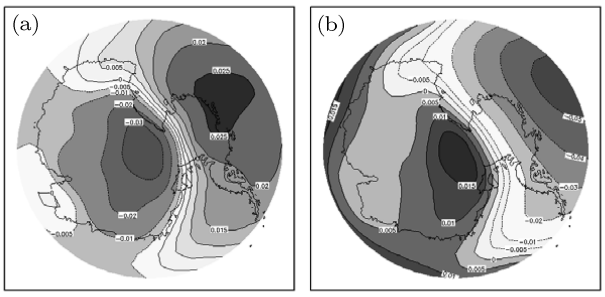


Fig. 6. EOF modes of mid–high latitude of South Hemisphere at 500 hPa. (a) The first mode (EOF1′) of the residual height field, (b) the second mode (EOF2) of the original height field data (S60°–S90°).

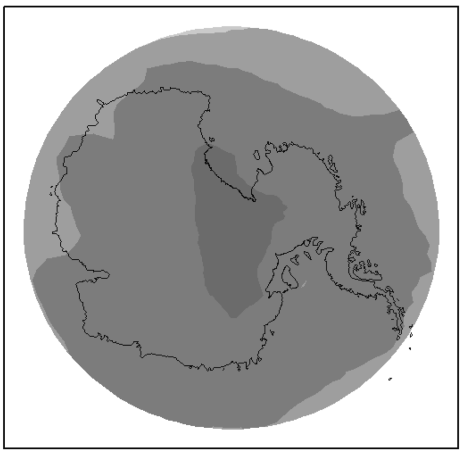


Fig. 7. Node degree distribution for the Antarctic circulation network at 500 hPa without the AACD.

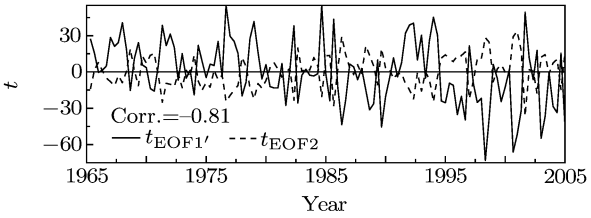


Fig. 8. The temporal series of EOF1′ and EOF2.

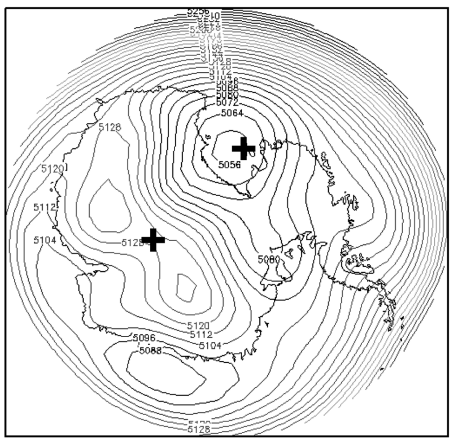


Fig. 9. The winter mean height field (S60°–S90°, 1971–2000).

4. Conclusion

The complex network approach was applied to the 500 hPa height data in this paper by taking data gridpoints as nodes of the network and the connection coefficients of a node with other nodes as its links. The spatial connection structural complexity of the circulation systems was quantitatively described in terms of the characteristic parameters of the network topology, such as mean node degree, mean clustering coefficient and mean shortest path length. On the whole, the circulation system connection networks calculated have a smaller mean path length and a larger mean clustering coefficient, thus possessing the typical small world effect. The node degree distribution for the GS suggests that there are two distinctive boundaries near 27.5° N and 27.5° S in the NH and the SH, respectively. Different spatial structural features frequently correspond to different underlying dynamic mechanisms. Therefore, based on the regional character of the GS, we divided the GS into a low latitude circulation sub-system and two mid–high latitude circulation sub-systems. The low latitude sub-system network mainly shows a global coupling property, while the mid–high sub-system networks possess typical small world effect.

The node degrees of the NHS and the SHS networks obtained are able to visualize relevant teleconnection patterns previously found in the two hemispheres and to quantitatively describe the strengths of the teleconnections in the NHS and the SHS, respectively. The computational results of the node degree for the NHS networks with and without the AO, the NAO, and the PNA demonstrate that the presence of the teleconnection patterns greatly shorten the mean shortest path length of the networks, thus being advantageous to the rapid transfer of the local fluctuation information over the network and to the maintenance of the NHS stability. Removing the AO and the NAO from the NHS distinctively reduces the numbers of the short range and the long range links of the circulation system and obviously increases the mean path length of the network, leading to a remarkable reduction in the efficiency of the information transfer within the network. Therefore, for the NHS, the impact of the AO on the NHS connection structure is most important, the impact of the NAO is the next important, and the PNA is a relatively independent teleconnection pattern, whose role in the NHS is mainly manifested in the connection between the NHS and the TRS. For the SHS, the impact of the AAO on the structural stability of the system is most important, and the removal of the AAO from the SHS network reduces the mean degree by 45% and increases the mean path length by 34% in comparison with the corresponding values for the complete SHS network. Therefore, the AAO is most important, to which one should pay attention in considering the SHS. In addition, there might be a stable correlation dipole (AACD) in the Antarctic area, which is independent of the AAO. The AACD shows synchronous

positive correlation and might be one of the most important components of the mid–high latitude South Hemisphere system. After removal the AACD, the mean degree and the mean clustering coefficient of the Antarctic network reduces 34% and 3%, respectively.

Tosnis *et al.*[3] showed the roles of the PNA, the NAO in the NHS, but the AO, the structural complexity of SHS have not been discussed. This paper extends the work of Tosnis *et al.*, and the AO, the structural complexity of SHS, the AAO, and the AACD are all discussed.

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