Numerical simulation of surface circulation of South China Sea during the last glaciation and its verification*

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In the glacial cycles, a marginal sea may display its "amplifying effect" in environmental changes. An example is the South China Sea (SCS), where the glacial/interglacial contrast of winter sea surface temperature (SST) reaches 6—9℃, far exceeding that at similar latitudes in the Pacific[1, 2]. We speculated that such an "amplifying effect" of SCS must be related to a radical reorganization of the surface circulation during glacial period[3, 4], but this is to be tested and verified. Numerical simulation is one way to test it.

The Ocean General Circulation Model (OGCM) is of great significance for paleo-circulation reconstruction and for trend prediction of its changes. It provides a basic approach for studies of modern circulation system through numerical modeling and an effective way of recognizing the circulation reorganization caused by changes in boundary conditions. Since the water of the SCS has been shallow on its northern, western and southern sides, the glacial sea-level drop by 100—120 m must have turned it into a semi-enclosed gulf, leaving only the Bashi Strait at its northeast corner connected with the open ocean. Meanwhile, the trans-basinal surface currents of the modern SCS, driven by monsoon with alternative directions, must have been replaced by simi-enclosed circulations[3, 4]. For a quantitative estimation of the changes, we have adopted the model used for the modern SCS circulation[5] to simulate the winter (January) and summer (July) surface circulation of SCS during glacial period.

The modeling area extends from 98.75° E to 122.25° E, from 0.25° E to 30.25° E, and $0.5° \times 0.5°$ grid is used. A map showing glacial bathymetry and configurations of the SCS is obtained by subtraction of 110 m (glacial sea level drop) from the modern water depths. The modern wind field is used in our simulation, because of the lack of glacial

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wind regime data from the SCS and the similar wind directions in the SCS between the last glacial maximum and the present time, as shown by the global atmospheric circulation modeling[6]. As to the water exchange between the SCS and the Pacific through the Bashi Strait during glacial period, the inflow and outflow of surface water are assumed to be quantitatively equal. We will show that the general pattern of current directions will remain the same, even if the assumed conditions are changed. The results of our numerical modeling are given in figure 1.

As the modeling shows, the SCS surface circulation at the glacial maximum displays a counter-clockwise pattern in winter (fig. 1(a)) and basically a clockwise pattern in summer, but with local complications (fig. 1(b)). The patterns generally agree well with our speculation[3, 4]. In order to test the reliability of the modeling results, the calculations have been repeated under different conditions. The obtained surface circulation patterns of the SCS remain consistent, whether the entire West Pacific or just the SCS is taken for modeling, or how different wind field data (e. g., wind speed) are used in calculations with the winter and summer monsoon system unchanged. All this shows that the modeling results are well convincing.

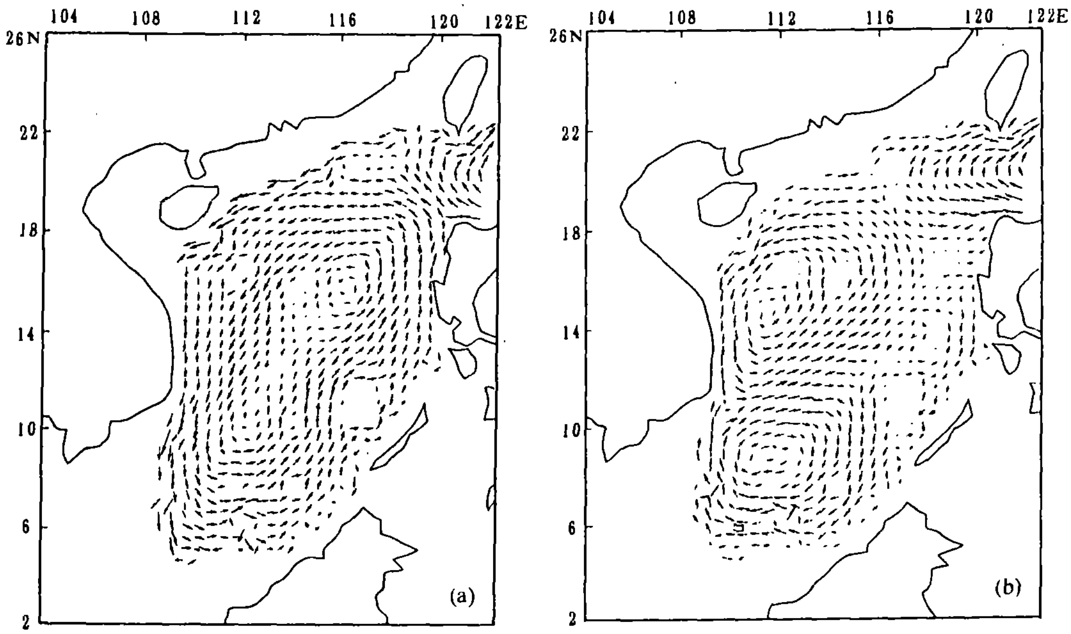

Fig. 1. Numerical simulation of surface currents in the South China Sea at the last glaciation. (a) Winter (January); (b) summer (July).

Nevertheless, an independent data set is requested for a real verification of the circulation modeling. As a rule, paleo-temperature is used for the paleo-circulation test. Amongst the paleo-environmental factors, the calculation of winter and summer SST from the census of planktonic foraminifers based on the paleoecological transfer function is methodologically mature and well recognized. Paleo-SSTs at 10 sediment core sites from various parts of the SCS (talbe 1) have been calculated using Transfer Function FP-12E proposed by Thompson[7] for the West Pacific, and the winter and summer SST distribution patterns of the SCS during the last glacial maximum (about 18—20 ka B. P.) are shown in fig. 2. Although the data of the 10 cores have been provided by different authors, the paleotemperature patterns in fig. 2 look fairly coordinated, implying the rationality of the adopted methods.

Table 1 Ten sediment cores used for paleo-SST reconstruction of the South China Sea at glaciation

Core	Location	Water depth/m	Core length/cm	Reference
V36-3	19°01′ N, 116°06′ E	2 809	1 215	[3]
V36-6	19°47′ N, 115°49′ E	1 579	1 263	Feng *et al.*, 1988
V36-8	20°03′ N, 115°43′ E	1 304	1 207	[10]
SO49-8KL	19°11′ N, 114°12′ E	1 040	955	[3]
N204	18°13′ N, 110°56′ E	180	440	[11]
GGC-11	11°53′ N, 118°20′ E	2 165	145	[8]
NS88-11	9°56′ N, 115°37′ E	880	433	[12]
RC12-350	6°33′ N, 111°13′ E	1 950	1 129	[13]
NS86-43	7°02′ N, 110°24′ E	1 763	300	[12]
SCS12	7°42′ N, 109°18′ E	543	120	new data

The North Pacific polar front migrated southwards at the last glaciation and, hence, the southern limit of the Arctic/Subarctic water influence shifted about 10 degrees of latitude to the south[8]. Accordingly, the Temperate Water Mass occupying 25°— 30° N at present must have also shifted southwards at glaciation to ca. 20° N, the latitude of the Bashi Strait[3]. This means that the Pacific water entering the SCS through the Bashi Strait was lower in temperature[4, 9]. In winter, the cooler water flowed westward first following the counter-clockwise surface circulation of the SCS (fig. 2 (a)), leading to a lower temperature in the northern part of the SCS. In summer, the cooler water entering the SCS flowed first to the south together with the clockwise circulation (fig. 2(b)), causing a lower water temperature in the east. The paleo-SST reconstruction based on planktonic foraminiferal data has proved these patterns. As seen from fig. 2(c), the glacial winter SST of the SCS increases from 17.5℃ off the Pearl River mouth (station V36-6) to 23.0℃ in the southwest of the SCS (station NS 86—43), with a significant N-S SST gradient of 5.5℃, but much less in E-W direction (less than 3℃ in the northern part and about 1℃ in the southern; see fig. 2(c)). By contrast, in glacial summer the SST difference between the north and south was insignificant. If the average paleo-SSTs are calculated from the 4 stations south of 10° N and the 5 stations north of 18° N separately, the difference between north and south turns out to be as minor as 0.1℃, whereas the paleo-SST difference between the easternmost (GGC-11, 24.9℃) and westernmost (SCS 12, 27.7℃) stations reaches 2.8℃ (fig. 2(d)). Compared with the standard errors of Transfer Function EP12-E (1.46℃ for winter and 2.48℃ for summer), the above discussed N-S winter SST gradient of the glacial SCS and the E-W summer SST gradient surpass the standard error, while the E-W

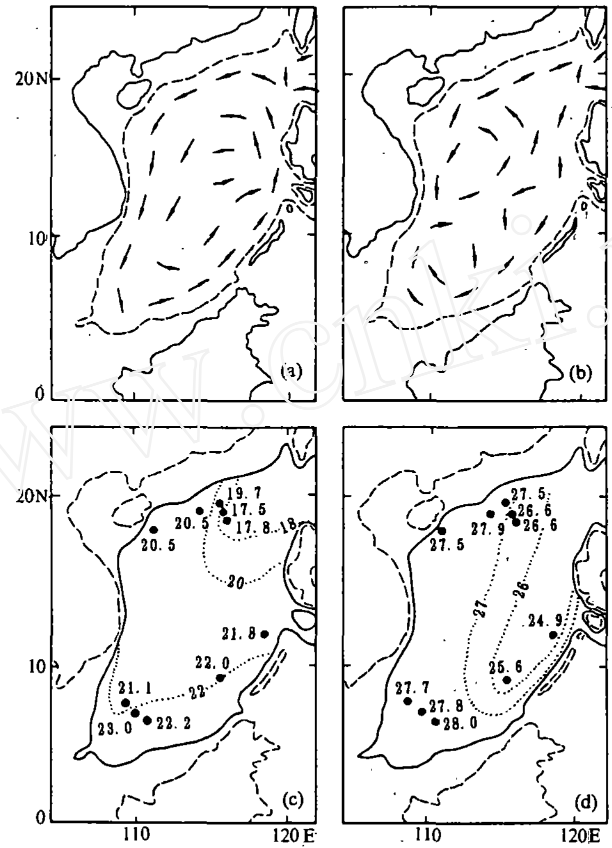

Fig. 2. Comparison between surface circulation and temperature distribution in the South China Sea during the last glaciation. Surface circulation: (a) winter, (b) summer, based on results of numerical simulation with simplifications; surface temperature: (c) winter, (d) summer, based on planktonic foraminiferal census calculated using transfer function.

gradient for winter and N-S gradient for summer are below or close to the standard error, suggesting nice correspondency between the paleo-SST patterns and the modeling results of circulation.

To sum up, our numerical simulation has proved the great difference between the glacial and interglacial surface circulations of the SCS, and the paleo-SST reconstruction has proved the results of simulation. The reconstruction of the SCS glacial circulation is of great significance for our understanding of the specific features of marginal seas in environmental evolution and their influence on the bordering land.

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