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NUMERICAL SIMULATIONS OF OCEANIC ELEMENTS IN THE SCS AND ITS NEIGHBORING SEA REGIONS FROM JANUARY TO AUGUST IN 1998

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ABSTRACT: Studies on oceanic conditions in the South China Sea (SCS) and adjacent waters are helpful for thorough understanding of summer monsoons in East Asia. To have a 3-dimensional picture of how the oceanic currents vary, the oceanic elements in the South China Sea (SCS) and its neighboring sea regions in January ~ August 1998 have been simulated by using the improved Princeton University Ocean Model (POM) in this paper. The main results are in good agreement with that of ocean investigations and other simulations. The results show that the SCS branch of the Kuroshio Current is an important part in the north SCS from January to August; the SCS warm current is reproduced clearly in all months except in winter; there always exists a large-scale anti-cyclonic vortex on the right of the Kuroshio Current from January to August. In the model domain, the surface currents of the SCS have the closest relations with the monsoon with an apparent seasonal variation. In addition, the developing characteristics of the SST in the SCS and its neighboring sea regions before and after the summer monsoon onset are also well simulated by the improved POM. Those are the foundation for developing a coupled regional ocean-atmospheric model system.

Key words: regional ocean model; ocean current; summer monsoon

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1 INTRODUCTION

East Asia summer monsoon first breaks out in mid-May in the South China Sea before advancing to the Chinese mainland. The outbreak signifies the onset of the rainy season in eastern China. Works on oceanic elements in SCS and neighboring seas helps understand more of the outbreak mechanism of the SCS monsoon and advance the research on the relationships between air-sea interactions in offshore waters of China and regional climatic changes. Since the 1970's, successive oceanic surveys and large-scale experiments on the international level have broadened the prospects for oceanographic study in China. Specifically, comprehensive investigations and more analysis of the SCS Current, Kuroshio Current, west Pacific currents and Taiwan Straight current have enriched our understanding of the seasonal variation of currents offshore the Chinese coasts (Guan, 1978; Guo, Yang and Qiu, 1985; Fang, Zhao and Zhu, 1992). As most of the known features are viewed partially, it is not easy to reveal a 3-dimensional and whole-view structure of the oceanic circulation. Circulation models for offshore waters are thus developed to fill the gap (Zeng, Li and Ji et al., 1989; Li, Huang and Wang, 1994; Li, Ji and Zeng, 1992). With the on-going study on the SCS monsoon, simulations of oceanic condition on the Chinese offshore waters,

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which is centered around the SCS, have become an integrated part of a broader-scale investigation into the outbreak mechanism of the SCS monsoon, in addition to serving as one of the fundamental work in the development of regional air-sea coupled models.

Using an improved oceanic current model (POM) from the Princeton University, U.S.A. and reanalyzed NCEP data for the SCS monsoon experiment in 1998, the work conducts a simulating study of the oceanic currents, SST, sea surface heights and salinity for January ~ August 1998 over the SCS and neighboring waters, including part of the west Pacific, Bay of Bengal and part of the equatorial Indian Ocean. Special study is also done of the simulations of surface-layer currents and temperature before and after the outbreak of the summer monsoon.

2 BRIEF ACCOUNT OF REGIONAL OCEAN MODEL

POM is a 3-dimensional primitive equations model developed by Blumberg and Mellor (1987) at the Princeton University. Work has been done to improve it (Chu, Huang and Fu, 1996; Chu and Chang, 1997; Qian, Zhu and Wang, 1998). Important improvements include (1) inclusion of computational scheme for the gradient of pressure that gets rid of errors for high accuracy on the basis of complicated oragraphic features on the sea bed in the SCS, (2) adaptation of longitude-latitude horizontal mesh for easy computation and (3) inclusion of solar radiation at both long and short lengths, sensible heat and moisture exchanges to describe air-sea interactions (Levitus, 1982). The POM model adopts the σ coordinates in the vertical direction. To save computational time and increase computational stability, POM splits the barotropic and baroclinic modes of the ocean currents, which use different time steps during the integration. In this work, the time step is set at 60 s for the barotropic mode and 4800 s for the baroclinic mode, according to the size of the horizontal model grids. For the horizontal mesh, the Arakawa C-scheme is used that covers a domain bounded by 75°E ~ 145°E and 5°S ~ 45°N; the grid is spaced at 1°×1° intervals. There are 9 vertical layers with the first layer within top the 40 m of the ocean.

3 EXPERIMENTAL SCHEME

Two stages are divided for the model integration:

(1) Setting up the equilibrium state of model

In view of insufficient amount of observations of the oceanic circulation, the model treats the lateral boundary by the following ways. The conditions of lateral boundary for the ocean are provided by everyday interpolations of monthly mean temperature and salinity, which are available following Levitus (1982) then the boundary itself is determined by extrapolation of gradient-free ocean currents. Contained in the sea surface boundary are heat exchanges such as the solar radiation at the long and short wavelengths, sensible and latent heat fluxes. Effects of precipitation and sea surface evaporation on the oceanic salinity have not been included.

The integration begins from static oceans. The Levitus-analyzed data of monthly mean temperature and salinity are used as the initial field and the POM is driven by pentad-based wind stress averaged over 1979 ~ 1995 (17 years in all) as extracted from the reanalyzed NCEP data. The air temperature just above the sea surface, which is required in the model integration of exchanges of sensible heat and moisture, are those at the height of 2 m on a pentad basis over the simultaneous period. From January 1, every 30 days are set as a model month, every 360 days a model year. By December 30 in the first year, the model is able to simulate realistically the oceanic elements in winter.

(2) Oceanic conditions of the SCS and neighboring waters in January ~ August, 1998

The integrated results are set as the initial field and the regional oceanic model is driven by the reanalyzed NCEP pentad-based wind stress (determined by day-to-day values) in January ~ August for the period of SCS monsoon experiment in 1998. The sea surface temperatures required in computing the exchange of sensible heat and moisture in the model integration are those (derived from daily data) at the height of 2 m on a pentad basis from January to August.

4 STUDY OF SIMULATIONS FOR JANUARY ~ AUGUST 1998

4.1 *Temporal evolution of ocean currents*

Fig.1a gives the simulated vector charts of the ocean currents in January, April, and July

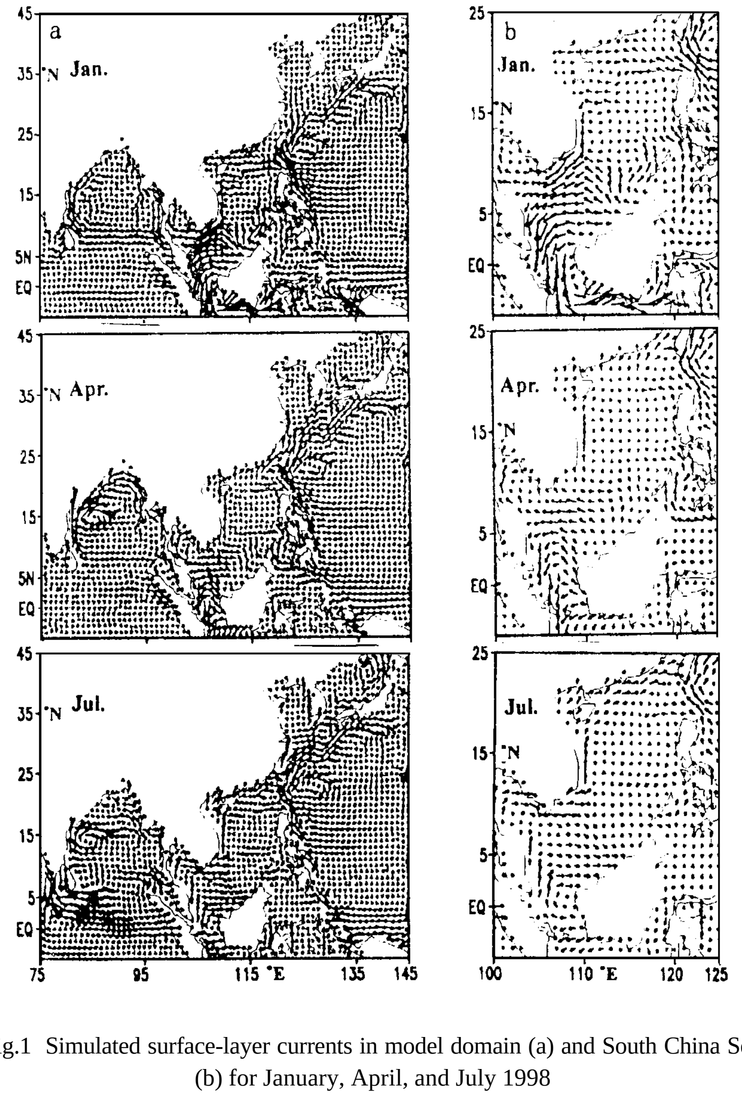

Fig.1 Simulated surface-layer currents in model domain (a) and South China Sea (b) for January, April, and July 1998

(representing winter, spring and summer) 1998. It is seen that changes in the basic patterns are small for the ocean currents over the Philippine Sea. They are composed of the Kuroshio that is traveling westward but recurves to the north meeting the Philippine Islands. The current bulk turns slightly to the west when going north through the Luzon Strait before heading for the northeast to continue the northward advancement; the remainder keeps traveling west through the strait into the SCS and becomes an important member of the current family in the northern part of the sea. It is still a divided issue in the oceanographic community whether the Kuroshio splits a branch into the SCS. Judged from our simulation, the branch current does exist in the SCS, only that the distance with which it stretches into it varies with the month. It can go to waters southeast of the Hainan Island in January but only around 114°E in July. The result remains to be verified against more observations. Over waters east of the Luzon Strait and southeast of the Ryukyu Islands, there is always a large-scale anticyclonic vortex in January through August. Due to limited domain of the model, the simulated vortex is smaller than what it actually is. Offshore currents prevail in those months in the western Bay of Bengal with larger intensity in spring and summer than in winter. In winter the ocean currents flow at a direction just opposite to that in summer. Specifically, they flow westward in January and April but form an east-west-aligned anticyclonic cell between 5°S and 5°N.

To have a clearer view of simulations of surface layer currents of the SCS, Fig.1b is specially presented. It shows that the seasonal variation of the SCS surface currents is significant. In January (Fig.1b), the entire SCS is dominated by a huge cyclonic circulation, in which the northern and southern parts are each controlled by a medium-scale closed cyclonic circulation. Entering the northern SCS through the Luzon Strait, the surface-layer currents travel across the sea and flow out of it by way of the Java Sea to the south. As the winter monsoon is the driving force for the surface-layer currents, the SCS warm currents (Guan, 1978; Guo, Yang and Qiu, 1985) flowing northeastward in the northern part are shielded by those just next to the sea surface. With the weakening of winter monsoon, the SCS warm currents become better-defined in April and July (see Fig.1b—Apr. & Jul.). In the panel for April, the cyclonic pattern of circulation controlling the entire SCS is shown to be less clearly cut. The speed of the warm currents are much smaller than in January for the surface layer as it is a time of weak winds when the northeasterly monsoon is transforming to the southwest monsoon. In the panel for July, however, the surface layer of the SCS is of the steady pattern of summer. It is characterized by a small cyclonic circulation in northern SCS that consists of a medium-scale anti-cyclonic circulation south of 12°N in the SCS and the SCS branch of the Kuroshio, and an inflow from the Java Sea from south of the SCS and a outflow from the southwest to northeast through the Taiwan Strait.

It is not possible to compare these simulations with the actual fields for there are not any observations of ocean currents for 1998. The regional ocean model (POM) is able to simulate the basic features of surface-layer current fields in January ~ August, when compared with previous observations (Guan, 1978; Guo et al., 1985) and simulated results by Zeng, Li and Ji et al. (1989), Li, Huang and Wang (1994), and Li, Ji and Zeng (1992).

Ocean currents at the depth of 300 m flow with speeds and seasonal variation smaller than those in the surface layer (figure omitted). To be more specific, the currents in the SCS flow in from the Pacific Ocean through the Luzon Strait and flow out through the Sulu Sea; currents obviously flow westward in equatorial Indian Ocean in January, April, and July; offshore currents are still dominant over western Bay of Bengal; a large-scale vortex is well-defined over waters east of the Luzon Strait and southeast of the Ryukyu Islands, though with velocity smaller than the surface layer.

4.2 *Temporal evolution of SST fields*

Fig.2 is the simulated surface-layer sea temperature in the model domain. It is seen that it is relatively low in January and zones ≳ 28°C are located in the Philippine Sea, Bay of Bengal and parts of the west Pacific warm pool (as shown by the shaded areas in the figure, same below). In April, the temperature rises over the entire simulated oceanic region and zones ≳ 28°C are distributed over the entire Bay of Bengal, central and southern SCS and the Philippine Sea, together with some degree of increase over mid-latitude waters. In July, zones ≳ 28°C connect over northern SCS and the Philippine Sea and much beyond. The contour ≳ 28°C has by now extended northward to 32°N to arrive in the East China Sea and the Yellow Sea.

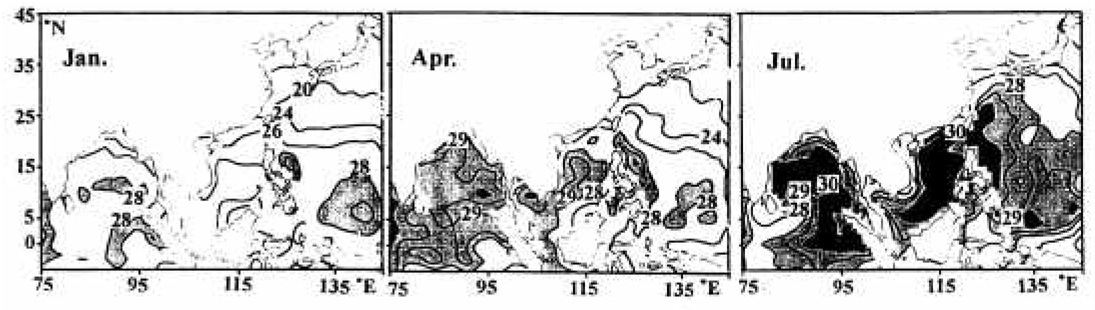

Fig. 2 Simulated surface-layer temperature in the model domain for January, April, and July 1998 (unit: °C)

Fig.3 gives the spatial fields and time coefficients derived by EOF decomposition (Panel d, after normalization) using monthly SST by NCEP (a), simulated day-to-day surface-layer sea temperature for this period (b), and observed day-to-day air temperature at the height of 2 m over corresponding regions, January through August 1998; the variance shows a 99% contribution. It is

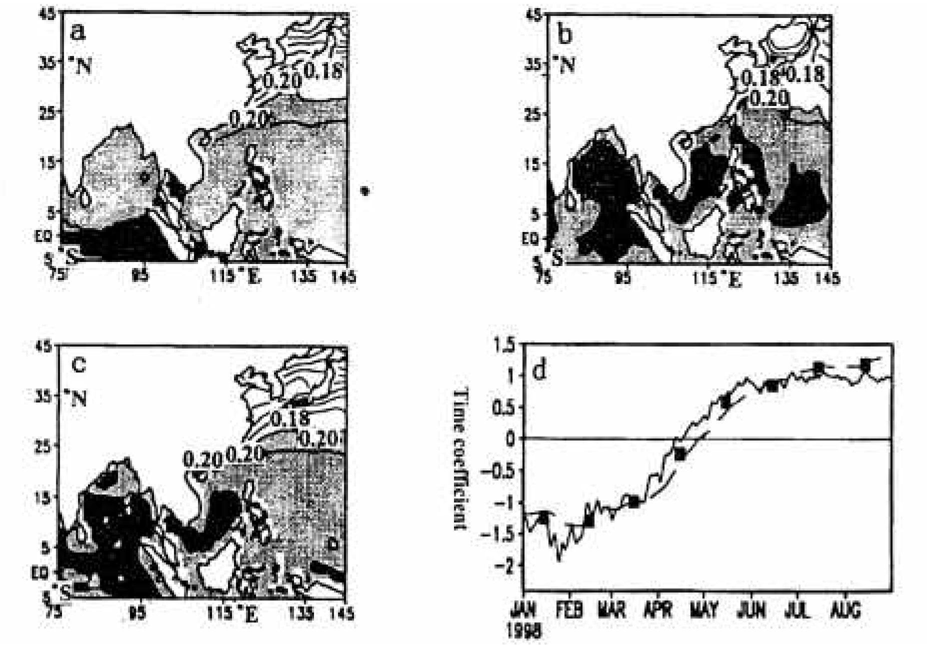

Fig.3 The first spatial (a: NCEP 1998 SST, b; simulated SST; c: observed air temperature at 2 m height) and time coefficients of EOF (d: after standardization. Long dashed line: simulated SST; solid line: observed air temperature at 2 m height; solid blackened frame: NCEP monthly SST from January to August 1998)

then clear that the simulation yields a spatial sea temperature pattern of high to the south versus low to the north with homogeneous distribution over low latitudes and a trend of warming over the entire oceanic region in spring and summer. It is consistent with the real situation 1998. The distribution of middle and high values in the low-latitude waters (Fig.3b) is similar to the observed air temperature at the height of 2 m (Fig.3c). It is probably the consequence of using a forced ocean model for the height. Fig.4 is the difference between simulated surface-layer temperature and observed SST over the region of the SCS in January, April and July, which indicates more of

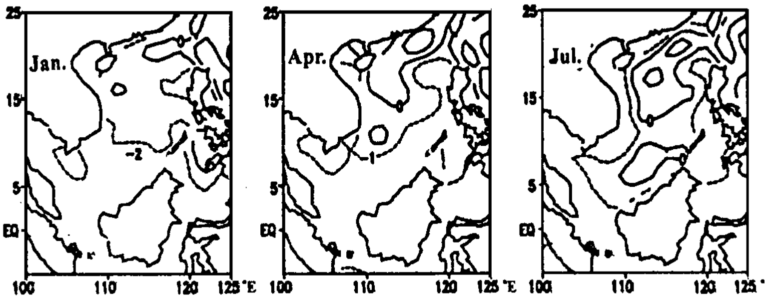

Fig.4 Differences between the simulated SST and observed SST in the South China Sea for January, April, and July.

the simulation of surface-layer temperature in the region. As shown in Fig.4, the difference between them decreases with the duration of integration, being the maximum in January, reducing a little in April and the minimum in July. The reason why the simulation is more agreeable with the observation with the lapse of integration time is: it is the first phase of the experiment rather than the observation for December 30, 1997 that determines the initial SST distribution and the model requires time to adopt to it.

From the simulated SST fields for the depth of 300 m in January ~ August (figure omitted), we know that it is much cooler in deep depths than in the surface layer with ill-defined seasonal variations. Zones of high SST cover waters east of Taiwan and south of Japan with the central core $>$ 15°C. The large-scale anti-cyclonic vortex, which is previously shown to be active east the Luzon Strait and southeast of the Ryukyu Islands, are of warm nature. They are caused by surface-layer warm water converging and sinking towards the vortex center in response to the terrestrial Coriolis force in the environment of anti-cyclonic circulation in the ocean. There is not much variation in the SST in the Bay of Bengal. The South China Sea SST is one of the lowest in the model domain, being around 10°C ~ 12°C.

Some consistent findings are also noted between the simulated sea surface roughness and salinity and the observations. They are not presented here due to limitation of text.

4.3 *Analysis of simulations of surface-layer currents and temperature before and after the outbreaks of 1998 summer monsoon*

As indicated in the analyzed field observations (Chen and Zhu, 1999) during the South China Sea Monsoon Experiment (SCSMEX), the summer monsoon is weaker than normal and set in at a time later than the average. The outbreak was in the 5^{th} pentad of May. For the climatological mean, the SCS summer monsoon begins in the middle of May when the southerly is the dominant wind controlling the SCS. In the middle of May, 1998, the SCS, except for areas south 5°S, was still controlled by the easterly due to a more westward location of the subtropical high. It was not until late May that the high moves eastward and leaves room for the southerly to take over most of the

SCS waters (figure omitted).

Fig.5 is the vector chart of simulated surface-layer ocean current for the early period (a), middle period (b), and late period (c) of May. It shows the evolution of the surface-layer currents in the simulations before, during and after the outbreaks of the SCS summer monsoon in 1998. The figure shows that the inflow, which is present in the surface layer in the early pentad of May, did not result in the formation of an anti-cyclonic pattern of current circulation; the prevalent easterly intensifies the current leaving the shore over waters southwest of the Borneo. It also shows that it was not until in the middle pentad of May that a small-scale anti-cyclonic pattern of circulation appeared in southern SCS, though with small extent and weak intensity; by late May, it expanded to 10°N and intensified. The study shows that the surface-layer currents in the SCS waters are closely related with the monsoon, i.e., the former quickly responds to the latter. The trajectory is studied of a buoy "ARGOS", which drifted in May 1 ~ July 1 in southern SCS during the 1998 SCSMEX. On May 26, the buoy suddenly changes the direction of drifting from west to east (Li, 1999). It may signal a turning point of the surface-layer currents in the southern SCS, being consistent with the observations.

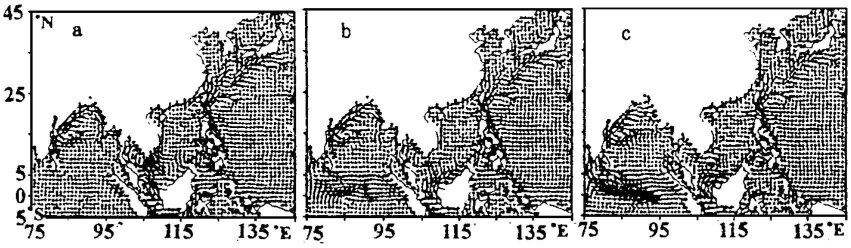

Fig.5 Simulated surface-layer current in the model domain for the first, second and third dekad of May 1998.

Fig.6 gives the surface-layer temperature of the reanalyzed data before (period averaged over

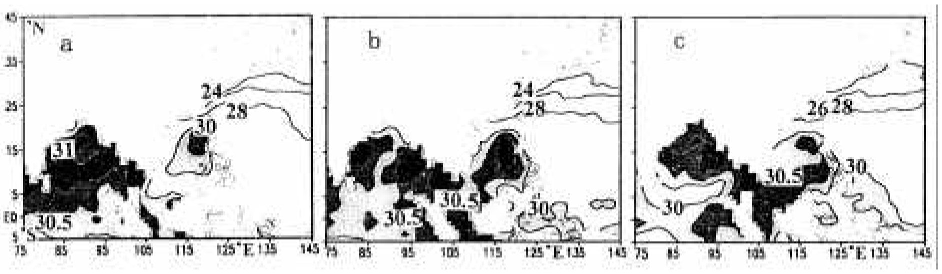

Fig.6 The NCEP SST before (a), during (b), and after (c) the onset of the SCS summer monsoon

May 10 ~ 16), during (period averaged May 17 ~ 23), and after (period averaged over May 31 ~ June 6) the outbreak of the SCS monsoon in 1998. Fig.7 is the simulations for similar sections of time in an attempt to compare the changes in surface-layer temperature and the difference between the simulation and observation before and after the outbreak of the monsoon in the SCS. As shown in Fig.6 for the observed SST, it is higher than 28°C in waters south of 25°N while the Bay of Bengal and most of the equatorial waters to its south are higher than 30°C, some even reaching 31°C, in all of the three sections of time. Before the outbreak of SCS monsoon, the SST is not as high in the SCS areas and the warm pools of the tropical western Pacific as in the Bay of Bengal, but acquires a comparable magnitude at the time of the outbreak, with the highest SST of 30°C ~ 30.5°C within the western Pacific warm pools in the model. Examining the simulation (Fig.7), we know that the regional ocean model is successful in reproducing warm-SST regions of the SCS and the Bay of Bengal before and after the summer monsoon outbreak in the SCS in 1998. The simulation is close to reality for there is consistent amplitude of warm temperature and SST tends to be higher in the Bay of Bengal than in the SCS in the pre-onset period but stays more or less the same as it shifts to the post-onset period of the summer monsoon. The simulations have points that fall short of expectation, one being cooler SST than reality in the warm pools of the equatorial western Pacific, which may be accountable by the fact that this region happens to be near the model boundary, the other being a more westward back-flow region of the Kuroshio simulated that causes a cooler SST there, due to limitation of model domain.

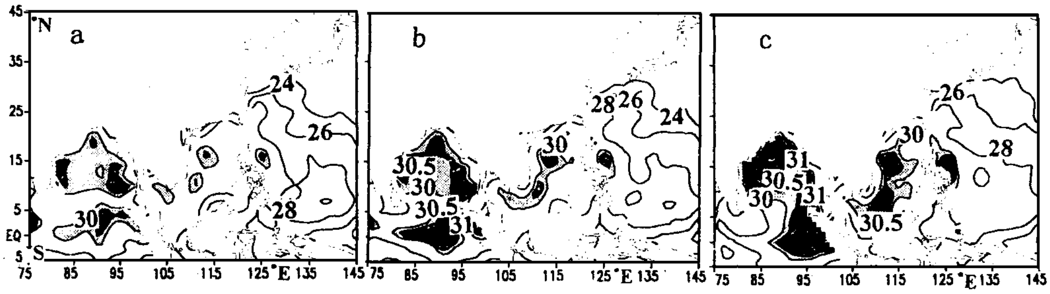

Fig.7 Same as Fig.6 but for simulated results

5 CONCLUDING REMARKS

a. The model starts integration from a stationary oceanic state. Under the condition of pentad-mean wind stress in the course of 360 model days, the winter pattern of oceanic state has covered the SCS and neighboring waters. It is a sign that POM is indeed capable of modeling the annual variation of oceanic elements.

b. Using a wind-stress-driven ocean model for January ~ August 1998, basic features of the SCS branch of the Kuroshio, a large-scale anti-cyclonic warm vortex to the right and warm SCS currents as well as the close links between SCS ocean currents and the summer monsoon, are simulated.

c. With the addition of a number of heat fluxes on the sea surface, the improved POM can have a comprehensive forecast of the seasonal variation of SST in the model waters January through August. The forecast is especially satisfactory concerning the evolution of the surface-layer temperature in the SCS and neighboring waters just around the outbreak of the Southwest Monsoon. The POM is then selected as an ocean model for the regional air-sea coupled model system, which paves the way for next experiments.

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