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On the Mechanism of South China Sea Warm Current and Kuroshio Branch in Winter- - -Preliminary Results of 3-D Baroclinic Experiments

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ABSTRACT

The circulation in the South China Sea was thought to be mainly wind-driven current controlled by monsoons. But recent observations reveal two currents in opposite directions, namely the northeastward South China Sea Warm Current (SCSWC) and the southwestward Kuroshio South China Sea Branch (KSCSB), flowing along the steep continental slope in the northern South China Sea. Surprisingly, the SCSWC flows against the strong northeast monsoon and becomes even stronger in winter.

This may be explained by a "thermodynamic model" based on the intrusion of the Kuroshio through the Bashi Strait. Warm waters extend into the South China Sea in a tongue shape formation along the isobaths of the continental slope and, therefore first, head northwestwards and then bend southwestwards. Hence, the KSCSB is formed by "topography trapping" due to the conservation of potential vorticity. The baroclinic effect due to the strong temperature gradient thus developed by these warm waters against the cold waters near the coast of South China drives the SCSWC strong enough against the monsoon in winter.

Results of 3-D baroclinic (in contrast to barotropic) prognostic numerical experiments are adequate to prove not only these ideas qualitatively but also the existence of cold eddies behind the intruding warm water tongue. Nevertheless further quantitative investigations are required to compare with observations although the circulation in this area is very sensitive to many factors subjected to seasonal and interannual variations.

(Key words: South China Sea, Intrusion of Kuroshio, 3-D Baroclinic numerical experiment, Counter-wind current, Circulation)

1. INTRODUCTION

It was believed that the circulation in the South China Sea is mainly wind-driven current controlled by monsoons (northeast in winter and southwest in summer) according

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to Wyrtki (1961) *et al.* During the sixties and the seventies, however, multi-disciplinary surveys along the Chinese coasts discovered the South China Sea Warm Current (SCSWC) flowing northeastwards along the inner continental slope throughout the whole year. It was surprising that this SCSWC becomes even stronger in winter against the strong northeast monsoon while it is weaker in summer even though the southwest monsoon blows in the same direction (Guan, 1978; 1985). Later,further observations (Qiu *et al*, 1984; Guo *et al*, 1985; SCSIO, 1985) revealed another current flowing almost parallel to the SCSWC but in the opposite direction along the outer continental slope. This was named the Kuroshio South China Sea Branch (KSCSB). These two neighbouring current in opposite directions may be seen from the strong temperature gradients in the horizontal (Figure 1) and from the V-shape temperature profiles in the vertical (Figure 2). Also, it was found that the Penghu Current (PC) flows almost northwards along the southwest coast of Taiwan Island throughout the whole year , but that it is subjected to seasonal variations (Chuang, 1986).

Observations also showed that both the SCSWC and KSCSB decrease as monotonic functions from the surface down to depths (beyond the Ekman layer) near the bottom even in the counter-wind case (SCSIO, 1985). Therefore, there must exist some mechanism of a baroclinic nature other than wind driven processes. From Figures 1 and 2, it can be seen that a band of warm waters with temperatures higher than those of the surroundings lies in between. These warm waters take on a tongue shape due to the intrusion as seen in typical satellite pictures of sea surface temperatures (Figure 3) quoted in (Ye, 1992). Are these warm waters from the Kuroshio?

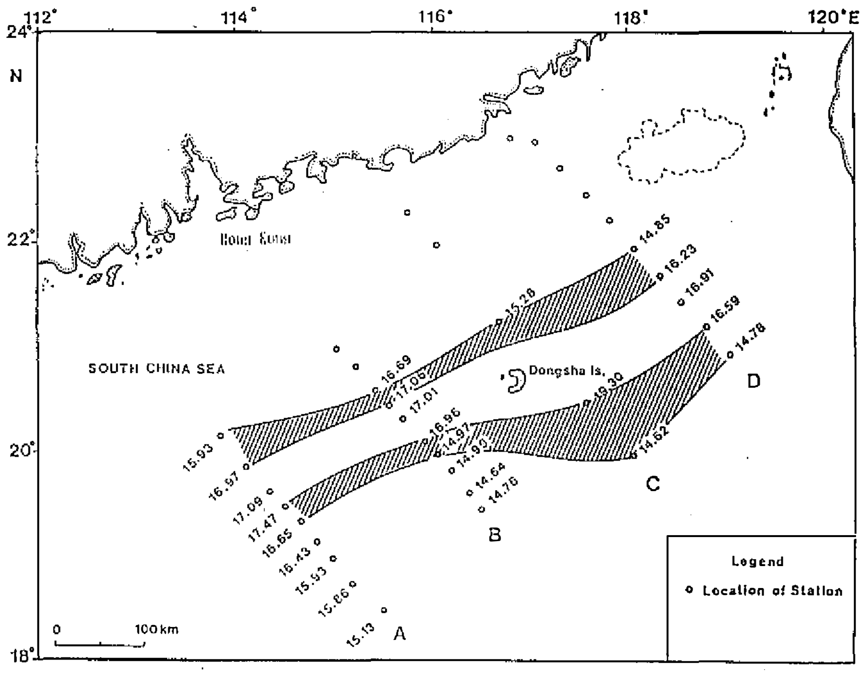


Fig. 1. Strong temperature gradients at the 200 m layer in winter.
Note: Distribution of narrow bands with high temperature in the middle along the continental slope (after SCSIO 1985).

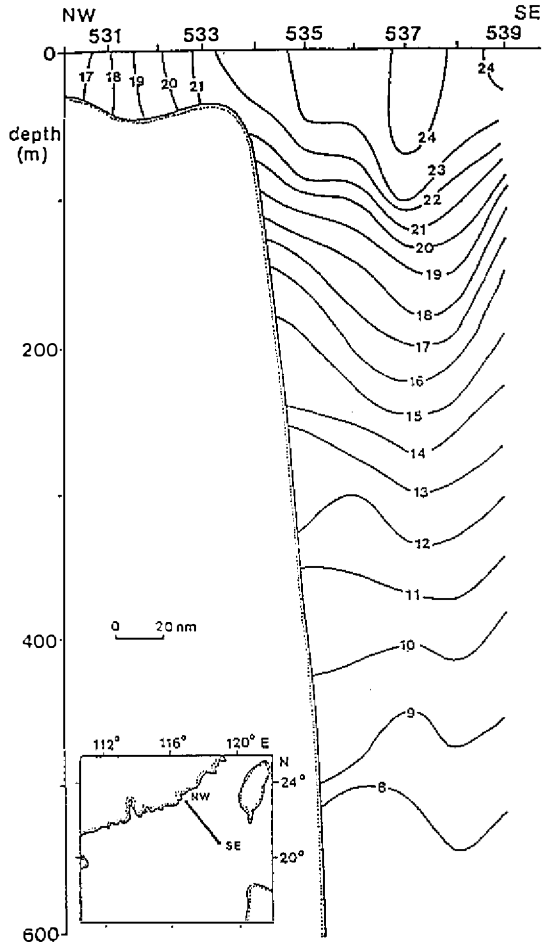


Fig. 2. Temperature profile in Section D, east of the Pearl River estuary.
Note: V-shape profile, indicating two currents in opposite directions (SCSWC and KSCSB) (after SCSIO 1985).

2. INTRUSION OF THE KUROSHIO

Although some authors may still doubt the intrusion of the Kuroshio into the South China Sea, observations have confirmed that it does exist especially in winter.

As for the transport between Luzon and Taiwan (the Bashi Strait), Wyrtki (1961) concluded that there is inflow from the Pacific into the South China Sea in winter and vice versa in summer. But he argued: "A more favorable selection of the stations is impossible, because the Japanese investigations ... were not planned to collect information about water entering and leaving the China Sea. Only comprehensive investigations on this flow could answer the various questions of the hydrography of the China Sea." Later, according to observations of the FRV Cape St. Mary, Chan (1971) pointed out: "Through the Luzon Strait (Bashi Strait), there is a constant inflow of Pacific Water into the South China Sea. ... The maximum inflow from the Pacific Ocean occurs in the NE monsoon season and is considerably reduced in summer."

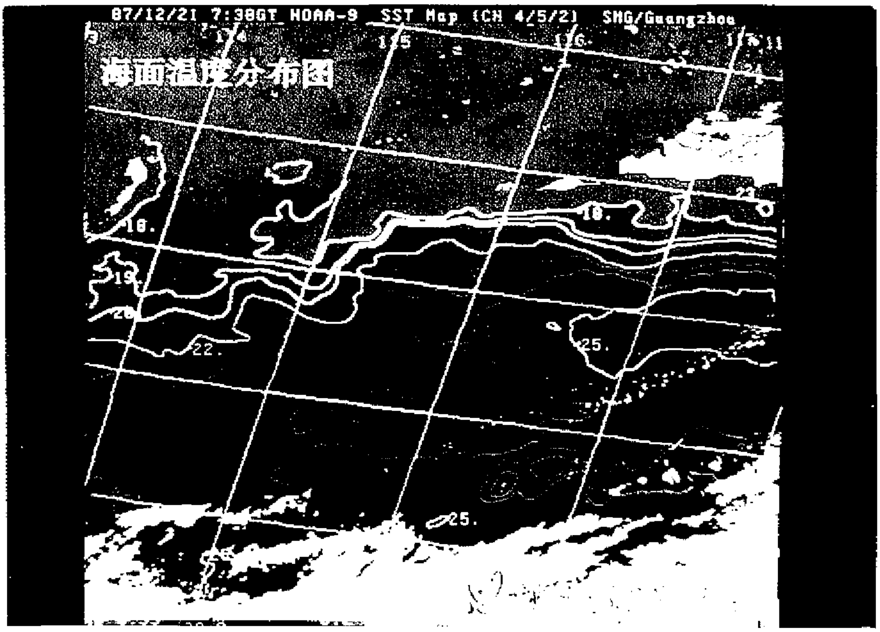


Fig. 3. Satellite picture of sea surface temperature in winter.
Note: Strong temperature gradient about 8°C in 1 degree latitude in the meshes 22-23°N, 116-118°E (after Ye, 1992).

Further, Shaw (1991) confirmed that the above mentioned band of warm waters is from the Kuroshio. Analyzing water masses from the National Oceanographic Data Center (NODC) historical data, he concluded: "An intrusion current developed over the entire continental margin south of China in late fall and winter. The seasonal variation is consistent with the earlier observations. ... Three stages of intrusion. From May to September (summer), the Kuroshio front meanders into the Luzon Strait (Bashi Strait). An intrusion may not exist. Between October and January (winter), an intrusion current begins to form along the continental margin south of China. Finally, the intrusion current decays from February to May, and only isolated pools of the Philippine Sea Water (Kuroshio) can be found. ... The extensive westward movement of the intrusion water at the depth of the salinity maximum is an efficient way of supplying salt and heat to the South China Sea." Actually, this had already proposed the mechanism as to how the KSCSB is formed.

Moreover, the weaker intrusion in summer had been confirmed by Nitani *et al* (1970) (summers in 1965 and 1966), Li *et al* (1987) and other Chinese expeditions organized by the South China Sea Institute of Oceanology, SCSIO (1985). Recently, Pu *et al* (1992) further confirmed the intrusion in various seasons (November 1986, September 1987, April 1988, October 1988 and June 1989) by means of Acoustic Doppler Current Profiler (ADCP) measurements. Their findings were all in agreement with early observations (Chan, 1970).

In addition to the seasonal variations discussed above, it must be emphasizd that the interannual variations are also of importance and sometimes even conceal the seasonal variations. For instance, the Kuroshio transport may be greatly reduced in an El Nino year when almost no intrusion is observed.

Another important phenomenon revealed by observations is that most of the intrusions are at first northwestward bound and then they bend southwestwards from the north part of the Bashi Strait as indicated by many authors, especially Wyrtki (1961) and Pu *et al* (1992). Also, Shaw (1991) pointed out that "An intrusion current developed over the 'entire continental margin' south of China. ..." This may be easily understood since the current transport is "trapped" by the topography and flows along the isobaths of the continental slope as a result of the conservation of potential vorticity (Figure 4). It is concluded that these processes are the mechanisms which form the KSCSB discovered by Qiu *et al* (1984) and Guo *et al* (1985). Also the KSCSB is further reinforced by the northeast monsoon in winter as indicated by Wyrtki (1961) *et al.*

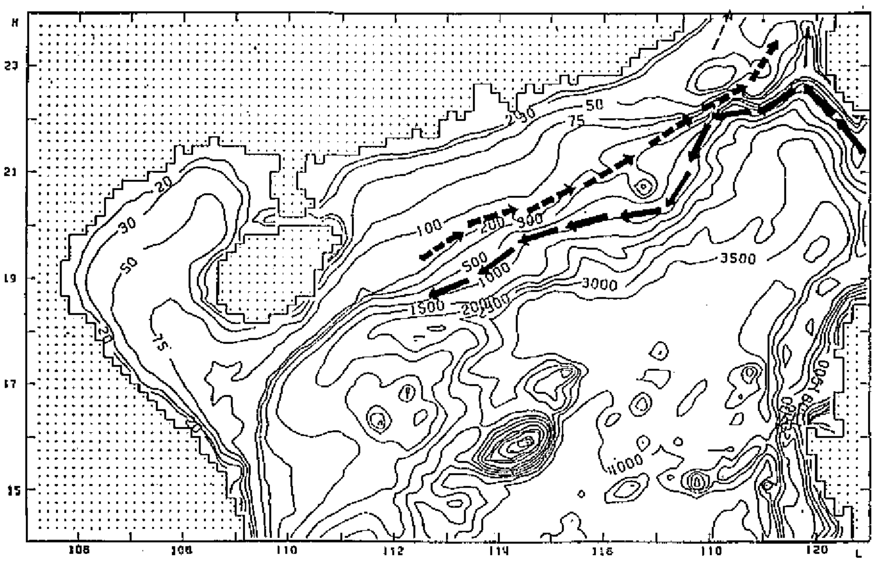


Fig. 4. Sketch of two currents in opposite directions (SCSWC and KSCSB) along the continental slope. (Legend: KSCSB ⟶ SCSWC- - → TWC---→ PC ⟶)

This intrusion is actually a form of gravity density current as studied by Nof and Van Gorder (1988), Griffiths (1986) and Kubokawa and Hanawa (1984), and it is similar to the Tsushima Current formed by the intrusion of the Kuroshio into the Japan Sea as studied by Yoon and Suginohara (1977). Usually, the intrusion flows to the right along the shore, or northward along the west coast of Taiwan Island as is the case in this study, due to the Coriolis effect. But here the Taiwan Strait is so shallow that only a small part is "leaked" to form the northward Penghu Current studied by Chuang (1986) whereas a large part is "trapped" by the topography to form the KSCSB as described above. According to the analytical two-layer model proposed by Nof and Van Gorder (1988), this gravity current may be deduced as $u=\sqrt{2g'D}$, where g' is the reduced gravity, and D is the thickness of the upper layer. This gravity current may even be as strong as 2 m/s in some cases.

3. THERMODYNAMIC MODEL

Unlike the mechanism according to which the SCSWC is derived from barotropic wind stress as proposed by some authors, here a thermodynamic model of a baroclinic nature based on the intrusion of the Kuroshio is suggested in this paper.

Early at the same time that the SCSWC was discovered, isotherms were found to be very much concentrated in the sea surface temperatures (SST) near the South China coasts in winter (Ye, 1981) while the SST were almost homogeneous in summer. Later, more precise observations revealed a fine structure where a band of warm waters is present in these isotherms (Figure 1) and which further behaves in a tongue shape manner derived from the intrusion of the Kuroshio as seen from satellite pictures (Figure 3). Here a temperature difference of about 8°C even exists in a distance of 1° latitude as in the meshes 22-23°N, 116-118°E, where the temperature varies from 17 to 25°C. Such a strong front is very rare in actual cases, however.

Thus, strong temperature gradients are developed by these warm waters from the Kuroshio (about 28°C) against the cold waters (about 15°C) near the South China coasts. It is well known that this strong temperature gradient, about 8°C in 1° latitude, gives rise to a strong baroclinic geostrophic effect which drives a strong current. In a Cartesian coordinate system, with x northeastward and y northwestward respectively, a rough geostrophic estimate gives:

$$u(T) = -(dp/dy)/f\rho = -(gh/f\rho)(d\rho/dy) = +0.75\ m/s$$

And the wind drift by a northeast monsoon (10 m/s) yields:

$$u(W) = -0.25\ m/s$$

Thus, the SCSWC surface current amounts to: $u(T) + u(W) = +0.5\ m/s$, which is of the order of magnitude and directed to the northeast, in agreement with observed values as well as those estimated by Guan (1985). It should be noted that in usual cases the counter-wind current exists only as a subsurface current beneath the Ekman layer. But here the SCSWC has its largest value at the surface and decreases as a monotonic function downward near the bottom (SCSIO, 1985). This indicates the baroclinic geostrophic effect is strong enough to overcome the barotropic wind stress. Thus, it may be imagined that the colder the winter, the stronger the SCSWC northeastwards against a stronger northeast monsoon. This was witnessed although in-situ measurements were not possible due to very rough sea states especially in January.

It is easily understood that the strong temperature gradients are much more pronounced in the region east of the Pearl River estuary near the Bashi Strait and weaken in the region west of the Pearl River estuary. Thus, the SCSWC increases in strength from west (near Hainan Island) to east (near Taiwan Strait) and joins the Taiwan Warm Current (TWC) since the TWC may be of a similar mechanism owing to the above mentioned temperature gradient. Hence, the SCSWC in the region west of the Pearl River estuary is, in turn, weakened as well, and is sometimes not very significant as indicated by observations (SCSIO, 1985).

4. NUMERICAL EXPERIMENTS

In order to verify the previous discussions, numerical experiments with the aid of the programs developed in the Institut für Meereskunde, Hamburg (Backhaus, 1985; Hainbucher *et al*, 1987) were done in two phases.

(1) 3-D barotropic model

As a sequence of the previous work (Ye, 1992), 3-D barotropic model was at first applied under open boundary conditions specified so that the inflow from the east (intrusion of the Kuroshio) and outflow to the north (TWC) were allowed. The two currents (SCSWC and KSCSB) in opposite directions were well simulated only when the northeast monsoon was absent as shown in Figure 5(a). It can be seen that the intrusion was "trapped" by the topography and resembled the KSCSB flowing northwestwards at first and then southwestwards along the continental slope. Also there were currents like the SCSWC in the area east of the Pearl River estuary. But when the northeast monsoon was present (Figure 5(b)), only some similar currents existed near the west coast of the Taiwan Strait due to the given outflow to the north from the prescribed open boundary condition. Then no more counter-wind currents off the Pearl River estuary similar to the SCSWC were obtained.

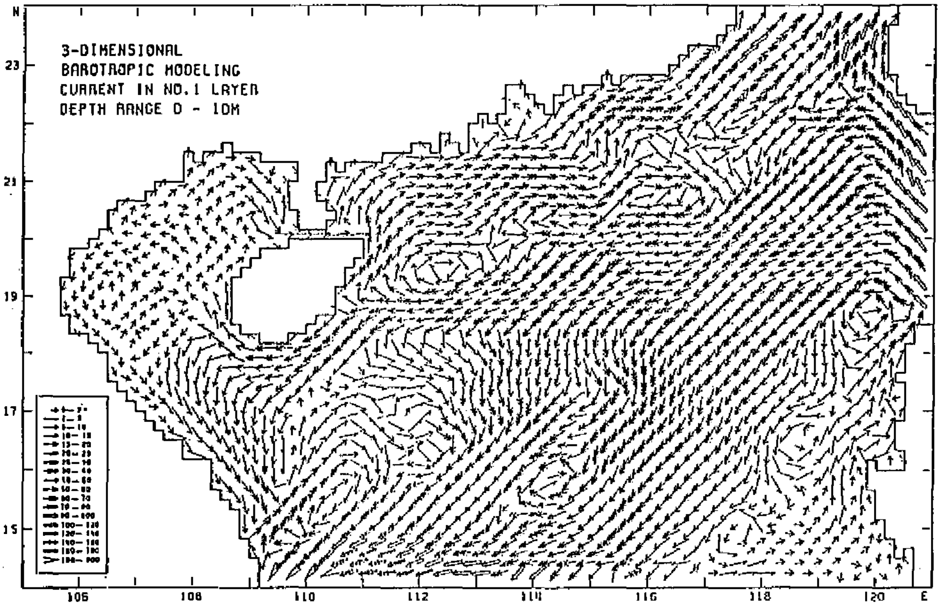
(2) 3-D baroclinic prognostic model

Here the 3-D baroclinic prognostic program was applied. In contrast to the barotropic model described above, the inflow from the east (Bashi Strait) could be automatically derived from the baroclinic effect with warm waters intruding into cold waters if the temperatures at the open boundaries were fixed to be warm at the east, say 28°C at upper layers as prescribed according to the temperature profile of the Kuroshio (Nitani, 1970). The initial conditions were so chosen that the sea surface temperature in winter were assumed to increase from 14°C to 27°C southwards (from 24°N to 14°N) and temperatures at different layers were adjusted according to Levitus (1982) data. As an example, in Figure 6 (a,b,c,d), the warm waters from the Kuroshio, down to a depth of 50 m with a temperature of 28°C, intruded in sequence for 6, 9 ,12 and 25 days respectively in tongue shape manners, also again "trapped" by the topography. Thus the simulated KSCSB flows along the continental slope, at first northwestwards and then southwestwards in good agreement with observations as described above. The intrusion took about 12 days to reach the area off the Pearl River estuary in these experiments suggesting a reasonable transition period of about half-a-month for the seasonal variations.

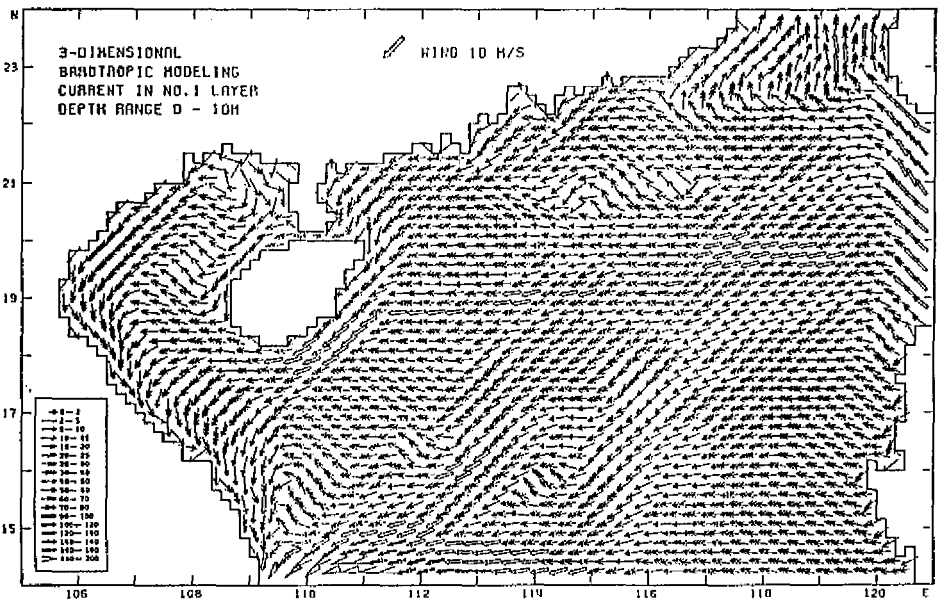
The isotherms were very concentrated near the west coast of the Taiwan Strait and became less concentrated westwards suggesting the SCSWC increases eastwards in strength as mentioned in the previous discussions. In contrast to the barotropic program, here the SCSWC still existed (Figure 7) with monotonic decreasing strengths from the surface downwards even though a strong northeast monsoon (10 m/s) was present in this experiment.

While the warm waters were intruding along the continental slope westwards, an eddy composed of cold waters was gradually formed around an area west of the Bashi Strait. This eddy seemed equivalent to that which had been proposed based on some authors' observations. As an alternative, this may also have been derived from either upwelling or instability.

It should be emphasized that in these prognostic baroclinic numerical experiments, in contrast to those of the barotropic model, no steady states are neccessary. It has already been seen from Figure 6 that if the intrusion continued until infinity, the whole South China Sea would be filled with warm waters. Obviously, however, this could never happen in reality. The temperature field in the South China Sea chosen in the initial conditions stated above is the coldest case and is subjected to change to warmer cases during a time scale of months, and thus further intrusion is no longer possible.

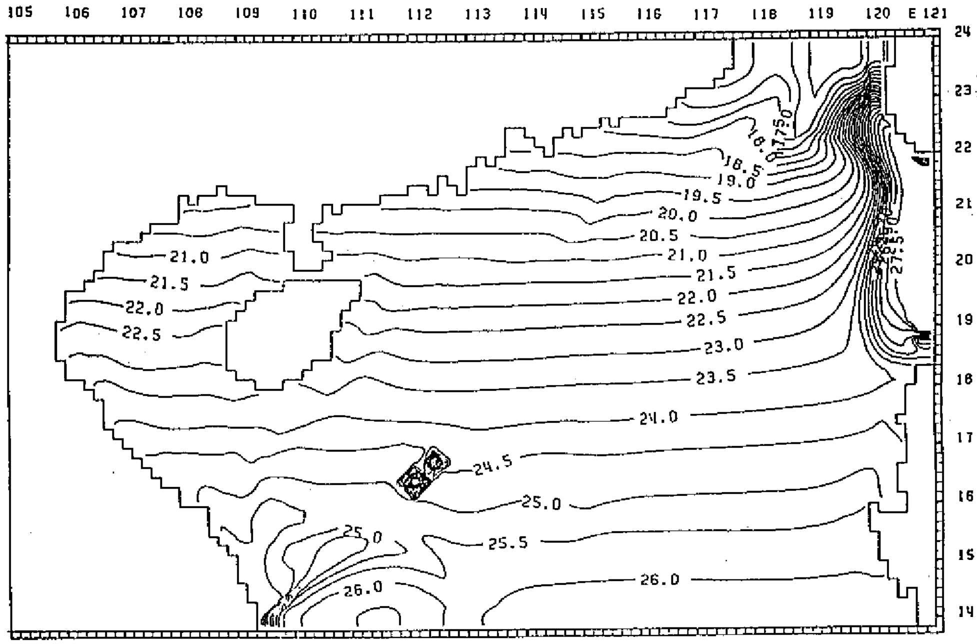


(a)

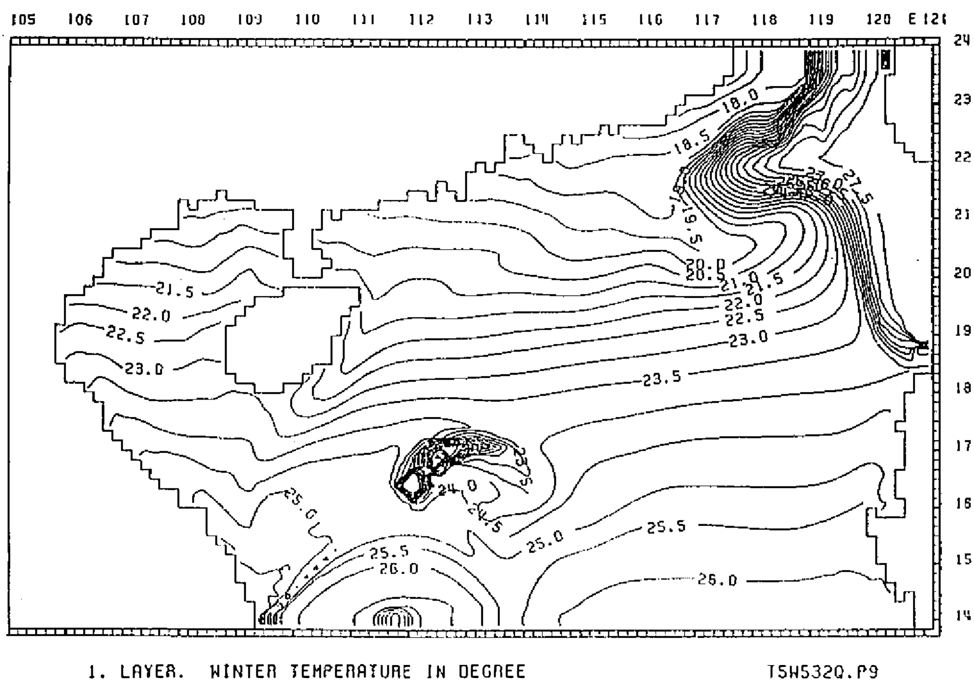


(b)

Fig. 5. Circulation in the northern South China Sea by 3-D barotropic model (a) without wind field; (b) with wind field of the NE monsoon. Open boundary conditions: inflow from east (Kuroshio); outflow to north (TWC).

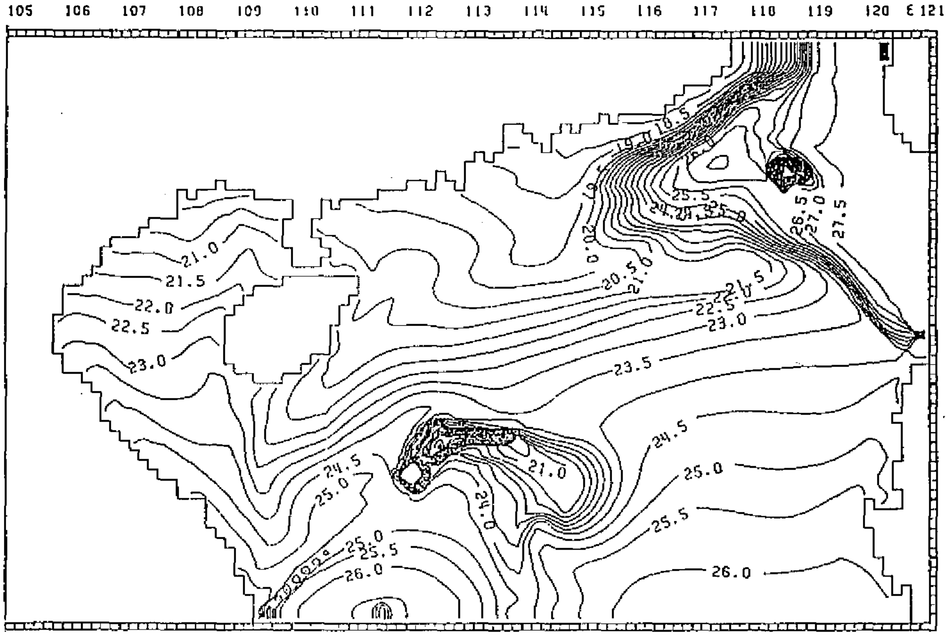


(a)

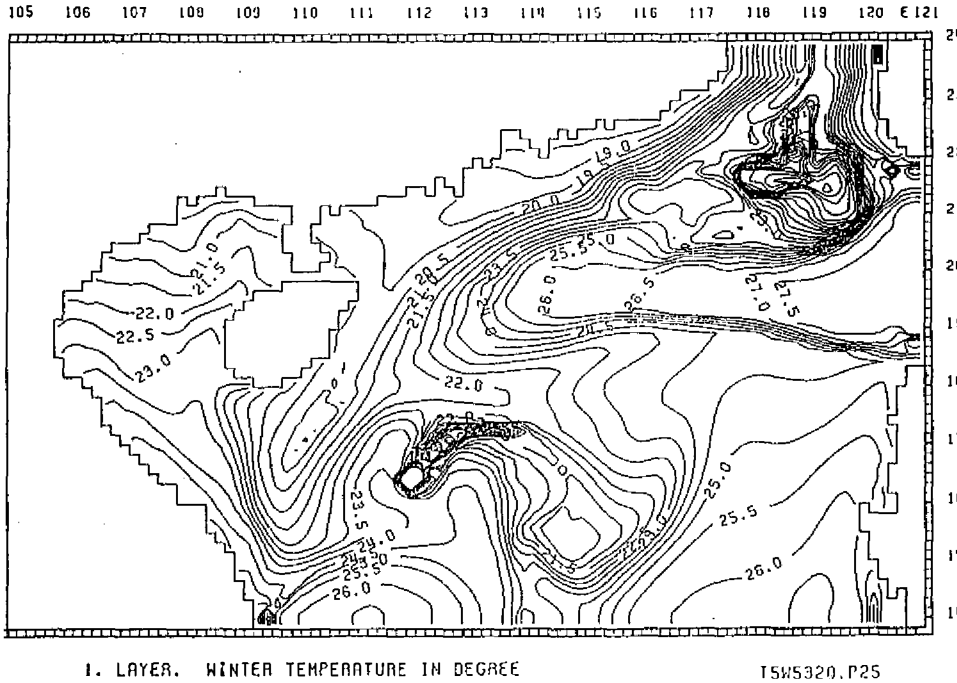


(b)

Fig. 6. Intrusion of Kuroshio warm waters in a tongue shape in sequence after (a) 6 days, (b) 9 days, (c) 12 days, and (d) 25 days.
Note: Concentrated isotherms and an eddy around an area west of the Bashi Strait.



(c)



(d)

Fig. 6. (Continued)

Results of these numerical experiments (Figure 7) were only adequate to verify the above ideas qualitatively but not quite satisfactory enough to compare them with observations quantitatively. For instance, the tongue of warm waters was too wide while observations showed it should be a band of narrow width. The KSCSB is too strong (larger than 1 m/s in most cases). Further studies, therefore, need to be undertaken.

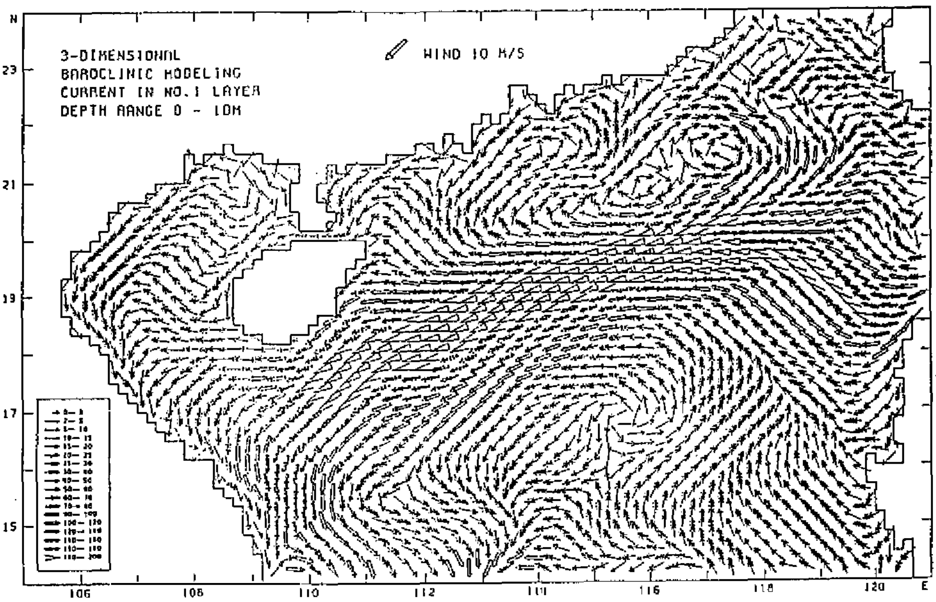


Fig. 7. Circulation in the northern South China Sea in winter. by the 3-D baroclinic prognostic model with a strong NE monsoon. Open boundary conditions: warm waters in the east.

5. CONCLUSIONS

By analyzing historical data and observational results, taking into account the "thermodynamic model" together with the 3-D baroclinic prognostic numerical experiments, it can be concluded that the circulation in the northern South China Sea is mainly a density current derived from the baroclinic thermodynamic effect in contrast to the general surface circulation in the South China Sea mainly driven by barotropic wind stress:

(1) The "Kuroshio South China Sea Branch" (KSCSB) is formed by the intrusion of warm waters through the Bashi Strait into the cool South China Sea "trapped" by the topography due to conservation of potential vorticity. Thus it flows at first northwestwards and then southwestwards;

(2) The "South China Sea Warm Current" (SCSWC) is driven northeastwards by the geostrophic effect from the strong temperature gradient developed by the intruding warm waters from the Kuroshio against the coastal cold waters south of China. It then becomes even stronger against the strong northeast monsoon in winter;

(3) There exist the "Taiwan Warm Current" (TWC) and the "Penghu Current" (PC), both almost northward, along the west and the east coasts in the Strait of Taiwan respectively and cold eddies formed west of the Bashi Strait;

(4) All these processes are subjected to significant seasonal and interannual variations and are sensitive to many factors, like the transport, temperature, and structure of the Kuroshio, and the temperature field, and wind field of the South China Sea;

(5) The present results of the 3-D baroclinic prognostic numerical experiments are only good enough to verify the above ideas qualitatively, but not quite satisfactory enough to compare them with observations quantitatively. Further improvements must be made.

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APPENDIX
A Brief Introduction to the 3-D Baroclinic Numerical Model Employed in the Present Study

For many years numerical models have been developed in the Institut fuer Meereskunde, Universitaet Hamburg (IfM H) as a major interest. The author is lucky to have been invited to apply them to study problems in South China as joint cooperative projects.

The circulation dynamics are formulated by the Navier-Stokes equations which include the conservation of momenta, the continuity equation, the conservation of temperature and salinity, the equation of state of sea water with some approximations. These are: Sea water is considered an incompressible fluid; Reynold stresses are parameterized with K-theory; Hydrostatic approximation is applied to the horizontal momemtum equations and only the vertical coomponent of the Coriolis acceleralation is considered. In this study, the right-hand Cartesian coordinate system was used.

Water elevation is allowed and wind stressis considered at the surface, and bottom friction is treated at the sea bed as usual. No normal flow is allowed at the lateral land boundary. Also no heat transport and no salinity flux are permitted across the seabed and the lateral land boundary.

The Arakawa C finite difference grid is employed with a semi-implicit algorithm SOR scheme in order to save computer time and memory.

In the present study, open boundaries for a barotropic model were so chosen to allow for outflow to the north (the Taiwan Strait) and inflow from the east (the Bashi Strait) according to reasonable transports from observations. And finally, the wind stress of the northeast monsoon was applied.

For the baroclinic model, an inflow from the east was derived automatically by warm waters in the upper layers at the eastern boundary as chosen according to the temperature profile of the Kuroshio. This simulated the warm Kuroshio waters intruding into the cold South China Sea in winter. The initial condition was assumed with respect to a temperature field of the South China Sea in winter with reference to the Levitus historical data. In a prognostic model, the temperature field of the South China Sea was changed with the intrusion of the Kuroshio in seequence, but no steady state should be reached as finaally the whole South China Sea would be filled with warm waters in contradiction to realistic cases.

Salinity was assumed to be constant throughout this study as its influence is of minor importance.