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The Annual Variation of the Surface Circulation in the South China Sea

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The horizontal and vertical circulations are considered in the South China Sea, based on the 80 years' winds (COADS), 10 years' XBTs (NODC), and about 10 years' sea-level data at Kaoshiung, Taiwan and at Singapore.

The South China Sea is the largest marginal sea in the western North Pacific, which is predominantly governed by the Southeast Asian Monsoons. The principal axis of the Southeast Asian Monsoons is in NE-SW direction between the Bashi Channel (or Luzon Strait) and the Sunda Shelf. The overall direction of the surface currents is coincident with that of the monsoons.

The surface water shows a temperature range of 27° - 30°C in the southern part, and of 24° - 29°C in the northern part of the South China Sea. Due to the excess of precipitation over evaporation over the southern part of the South China Sea, the surface salinity is gradually decreased from the Bashi Channel (S > 34) to the Sunda Shelf (S < 33) (Fig.1). Whereas the thickness of the surface mixed layer in the Kuroshio region varies from 20m to 30m in summer to 80m in winter, it remains within the range between 20m and 50m during the whole year in the South China Sea.

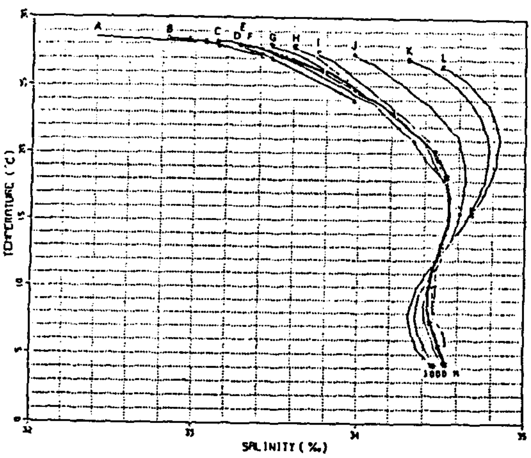

Fig.1. Mean annual T-S curves of the 12 study areas from surface to 1000 m, except areas A(~30 m), B(~50 m), C(~100 m), and D(~800 m).

The horizontal circulation in the South China Sea was well schematized in Wyrtki (1961), in which the Sunda Shelf and the Bashi Channel were set as the open boundaries of the *rectangular channel sea*. Due to the gradient of the cross-axis components of the winds, which are always stronger in the western (continental) side of the channel sea for both monsoons, the resultant cyclonic circulation occurs. The Monsoon Current, flowing through the South China Sea as a whole, changes its direction twice a year with respect to that of the wind stress. The volume transport by the Monsoon Current is about 4 - 6 x 10^6 m^3s^{-1} during winter (NE) monsoon and about 3 - 4 x 10^6 m^3s^{-1} during summer (SW) monsoon. And the resultant horizontal circulation occurs chiefly in winter because the wind stress and its gradient is stronger during the northeast monsoon. He estimated that the transport by the horizontal circulation is between 1 and 3 x 10^6 m^3s^{-1}.

The vertical circulation in the South China Sea results from the piling-up of the sea surface, which causes the vertical displacements of the discontinuity layer and opposite transports at the surface and in the deep layer (Fig.2). During NE monsoon, the surface water flows southwestwards piling up toward the Sunda Shelf due to the narrow and shallow (< 40m) southern opening. Some part of the surface water sinks in front of the shelf and presses down the thermocline, which triggers the lower-layer water to flow in the opposite direction (northeastwards). The reverse flow in the lower layer meets the strong thermal front near the Bashi Channel, where some portion of the lower-layer water is upwelled and pushes up the thermocline, joining the southwestward surface flow. During the SW monsoon, the surface currents are reversed; some of them flows outwards across the Bashi Channel joining the Kuroshio water, some flows back as a part of the surface cyclonic circulation in the northern South China Sea, and some presses down the thermocline near the thermal front. The surface slope toward the thermal front and the reverse vertical circulation during SW monsoon is not so clear as the case of the NE monsoon. But the annual variation of the thermal front near the Bashi Channel and of the thermal structure in the South China Sea shows the indirect evidence of the vertical circulation. The volume transport by the vertical circulation was estimated about 1 x 10^6 m^3s^{-1} from the thermal structure (Jeon, 1990).

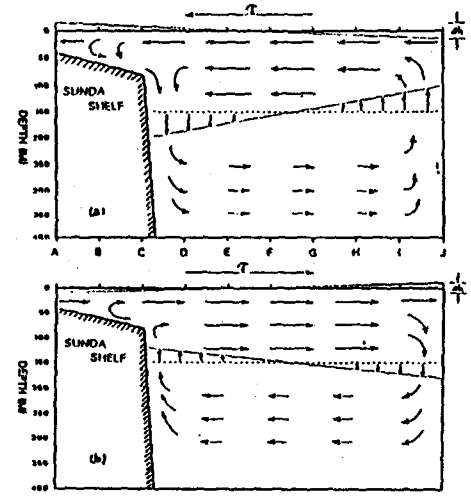

Fig. 2. Schematic diagrams of the vertical circulation (a) during the first half stage of the NE monsoon, and (b) during the first half stage of the SW monsoon.

The annual cycle of the monthly mean sea levels shows opposite patterns between Singapore and Kaohsiung, Taiwan. The monthly mean sea wind stress along the monsoon axis and the sea level difference of Singapore minus Kaohsiung show very similar annual cycles from each other although mean wind stress leads about 12 days in annual harmonics and 22.5 days in semiannual harmonics to the sea level difference (Table 1).

Table 1. Phases and amplitudes of the annual and semiannual harmonics of the mean wind stress (τ) and the sea level difference (SLD; Singapore minus Kaohsiung)

item	frequency	τ	SLD
phase	annual	24°	36°
	semiannual	-52°	-7°
amplitude	annual	59.7 m^2s^{-2}	20.5 cm
	semiannual	11.2 m^2s^{-2}	3.8 cm

Since the amplitude of the annual harmonics is predominant in both parameters, it can be said that the sea surface and the wind stress are still in good linear relationship with the phase difference of about 12 days (Fig.3).

The Bashi Channel is the most significant passage of the water exchange between the South China Sea and the Pacific Ocean. The strong annual cycle of the thermal front in the channel results from the change of the direction and intensity of the vertical circulation, which intensifies the horizontal gradient of the front by upwelling during the NE monsoon, and reduces the gradient by downwelling during the SW monsoon.

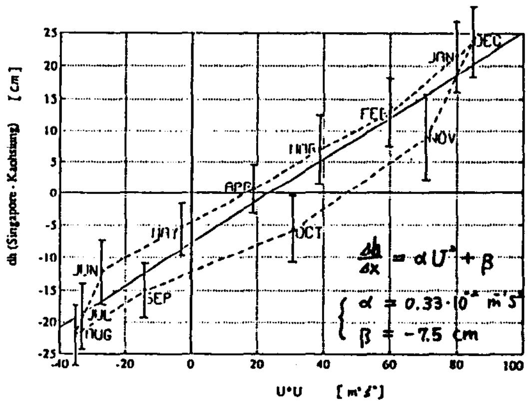

Fig. 3 . Correlation between the mean monthly wind stress along the selected line and the sea level difference (Singapore minus Kaohsiung). The dashed curve shows the annual time-series of the hysteresis of the sea level response to the wind stress. The vertical bars represent the standard deviations of the sea level difference from the monthly means (•).

References

Wyrtki, K. 1961. Physical oceanography of the Southeast Asian waters. *NAGA Rep. 2,* Scripps Inst. Oceanogr., La Jolla, California.

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