

## OCEANOGRAPHIC CURRENTS

Wyrтки (1961), based on oceanographic observations made prior to the Naga Expedition, described the physical oceanography of the Southeast Asian Waters. There is a semi-closed circulation within the China Sea itself, forming one or two eddies (Wyrтки, 1961, plates 1b, 2b, 4b, 5b, 6b).

Brinton (1963) divided the area of investigation off the eastern coast of South Viet-Nam in the South China Sea into 3 areas. The first area is the narrow shelf region extending from Nhatrang Bay northward to  $17^{\circ}\text{N.}$ , at the mouth of the Gulf of Tonkin. The second area is the broad Sunda Shelf region, contiguous with the Gulf of Thailand. The third area is the deep oceanic basin of the South China Sea, bounded at its eastern edge by a broad submarine plain from which rise numerous atolls and reefs.

He also pointed out that the abundance of zooplankton in the Gulf of Thailand may be appropriately discussed in relation to coastal regions. These are the regions of high plankton production, directly influenced by the seasonal reversal of the monsoon winds by tidal mixing, and by land drainage. The first region is the shallow northern part of the Gulf, north of Koh Chang,  $12^{\circ}15'\text{N.}$ , in the eastern Gulf and Koh Rad,  $11^{\circ}45'\text{N.}$ , in the western Gulf. The second region is the coastal area of the western part of the Gulf, to a distance of about 70 miles from shore. The third

region is the area along the eastern margin of the Gulf, which encompasses coastal waters of southeastern Thailand, Cambodia, and the southwestern part of Viet-Nam.

LaFond (1963) has given the major results in physical oceanography of the five cruises in the South China Sea of the Naga Expedition. He has given the general regime of water motion and thermal structure, and its variation with the changes in the meteorological regime. The Naga data add much detail to observations of these parameters by Wyrтки (1961) in the South China Sea. The following synopsis is taken from his work:

Cruise S-2, 30 November to 13 December 1959, was conducted during a period when northeast monsoon winds created a southerly flow in the area off the South Viet-Nam coast. These northeast winds were instrumental in piling up surface water against the coast, and caused sinking. There was also some colder water flowing from the north into the area during this winter season which caused the surface temperature near the coast to be colder. At a distance of about 100 miles from the coast, in the central part of the area, the current swung toward an offshore or easterly direction. The computed flow at the farthest offshore stations was to the north which is the reverse of the long-shore current. The boundary, about 150 miles offshore, between these oppositely flowing currents was a zone of convergence.

Cruise S-4, 27 February to 19 March 1960, was carried out toward the end of the northeast monsoon, during the period in which variable winds prevailed. Currents were starting to flow northward, both along the central coast and in some offshore areas, though some of the southerly circulation persisting in some areas was still characteristic of the northeast monsoon. At this season colder water was brought in from the north. Some of this was deflected offshore and caused a partial upwelling in the upper layers. In the northern part of the area this upwelling was supplemented by a south-flowing longshore current. Upwelling was not significant in the shallow shelf water in the southern part of the area.

Cruise S-6, 21 May to 24 June 1960, occurred in the middle of the southwest monsoon period, when winds blew persistently and strongly parallel to the coast in the central part of the area. The current flow was to the northeast with the usual offshore displacement of surface water which resulted in significant upwelling along the coast. The surface water was colder near the coast than in the offshore region. Salinity was higher throughout the central and northeastern parts of the area. This was a consequence of upwelling which reached a maximum during this season.

Cruise S-8, 8 September to 6 October 1960, took place during the change-over period from the southwest to the northeast monsoon winds. There appeared to be a weak

northerly flow in the southern area and a warm southerly set along the northern area. These features created an offshore circulation in the central area, off Nhatrang. The weak and deteriorating upwelling appeared near shore.

Cruise S-10, 10 January to 13 February 1961, occurred when the winds during the northeast monsoon period brought about onshore and southerly displacement of surface water at the near-shore parts. Such southerly flow was optimal for the transport of cold northern water during the winter season. The near-shore water contained discharge from the northern rivers and the Gulf of Tonkin and, coming from higher latitudes, was colder than the adjacent water. About 120 miles offshore there was a reversal of flow, with the current flowing to the northeast on the outer part of the central region.

Robinson (1963) presented the general features of the physical oceanography of the Gulf of Thailand and the temporal and geographic variations. Particularly important was the upwelling which occurred most strongly along the coast, but varies in location and volume with the seasons. The following synopsis is taken from her work:

The Gulf of Thailand is a shallow arm of the South China Sea. The greatest depth in the central portion of the Gulf is slightly more than 80 meters. The central depression extends into the inner Gulf to within 30 miles of Cape Liant. The deeper part of the Gulf is separated

from the South China Sea by two submarine ridges extending from both sides of the mouth of the Gulf. These two ridges are separated by a channel having a depth at its shallowest point of 58 meters. The northeastern coast of the Gulf is generally shallower and flatter than the southwestern coast.

The Gulf of Thailand may be characterized as a classical two-layered, shallow-water estuary. Low salinity water, which has been diluted by heavy precipitation and fresh water river run-off, flows out of the Gulf at the surface. There is inflow of high salinity relatively cool water from the South China Sea into the Gulf. This high salinity water fills the deep central depression below a depth of approximately 50 meters.

Cruise S-1, 19 to 31 October 1959, was conducted during the transition period between the southwest and northeast monsoons. Upwelling occurred along the eastern side of the Gulf between Phu Quoc Island and Koh Chang, in the north about 30 miles south of Cape Liant, and to a lesser extent on the west coast near Songkla and Kota Bharu. Convergence and sinking took place in the inner part of the west coast, and in the central part of the Gulf.

At the surface there was a counter-clockwise circulation with strong inflow along the east coast and outflow along the west coast. In the central areas very sluggish circulation was indicated. At 30 meters a reversal of flow on the east coast from that at the surface and the development

of a clockwise eddy off Phu Quoc Island were evident. Weak counter-clockwise gyres appeared in the inner and outer sections of the Gulf. At 50 meters there was a strong inflow on the western side which broke down in the central convergence area. A clockwise cell was formed at the eastern portion of the central Gulf and a counter-clockwise cell at the western portion of the inner Gulf.

Cruise S-3, 19 to 30 January 1960, took place toward the end of the northeast monsoon period. Upwelling occurred on the east coast, near Koh Samet, Samit Point and Phu Quoc Island. Convergence and sinking occurred at the central of the Gulf. An isolated pocket of low-temperature water, cooler than  $27^{\circ}\text{C}$ ., was observed at the northwestern corner of the Gulf. This appeared to result from sinking rather than upwelling because the accompanying salinity values in this area were low and the oxygen values high.

The distribution of flow was approximately the same at all levels, with little diminution in velocity with depth. The high salinity water from the South China Sea penetrated into the Gulf, around Cape Camau, for a short distance and flowed out off Kota Bharu on the west coast. A clockwise gyre dominated the central Gulf. The main outflow of water from the head of the Gulf was directed southeastward along the central axis of the Gulf. Along the edges of the main flow, however, eddies developed and return flow occurred both on the east and west sides of

the Gulf. The main flow, however, continued around the gyre to the southeast in the central Gulf, then to the southwest in the outer Gulf, and finally along the west coast paralleling the outflow of high salinity water from the South China Sea.

Cruise S-5, 21 April to 2 May 1960, occurred during the change-over period from the northeast to the southwest monsoon winds. Upwelling was evident in the north about 30 miles south of Cape Liant and along the west coast of the inner Gulf. Residual upwelling from the time of cruise S-3 was persisting along the east coast. Convergence and sinking were evident in the central portion of the Gulf.

A wedge of high salinity water entered the Gulf around Cape Camau, and had sunk below the surface and penetrated to the southwest as far as the center of the Gulf, along the bottom. At the surface there was a narrow inflow along the west coast. Outflow was 30 to 60 miles offshore. A counter-clockwise flow of high salinity South China Sea water entered the Gulf around Cape Camau and flowed out again 40 to 60 miles from the west coast of the Gulf. At 30 meters no evidence of inflow along the west coast was observed. A weak counter-clockwise eddy occupied the northern Gulf, and an even weaker clockwise gyre was noted in the central convergence area. At 50 meters in the southern part of the central basin there was strong inflow on the east, weak outflow on the west, and an extremely weak

clockwise circulation in the upper half of the Gulf.

Cruise S-7, 2 to 14 August 1960, was conducted when the southwest monsoon was well developed. During this period the most intense upwelling was observed centered along the west coast, north of Songkla. Upwelling was also observed at the northwestern corner and in the neck of the Gulf. Sinking occurred in the middle of the center and outer Gulf.

The inferred circulation at the surface showed flow into the Gulf along both coasts with convergence and pile-up at the neck. A counter-clockwise circulation was in effect south of Cape Camau, with main outflow of Gulf water approximately 60 miles east of Kota Bharu. There was a weak clockwise gyre in mid-Gulf, and a small portion of the counter-clockwise gyre at the mouth of the Gulf. At 30 meters there was an extremely weak clockwise gyre. At 50 meters the clockwise circulation of the inner Gulf and counter-clockwise gyre of the outer part of the Gulf were observed.

Cruise S-9, 9 to 24 November 1960, was carried out when the northeast monsoon period began. Upwelling occurred along the middle portion of the east coast. This was the period of greatest river run-off and low salinity surface water was also observed along both eastern and western shores.

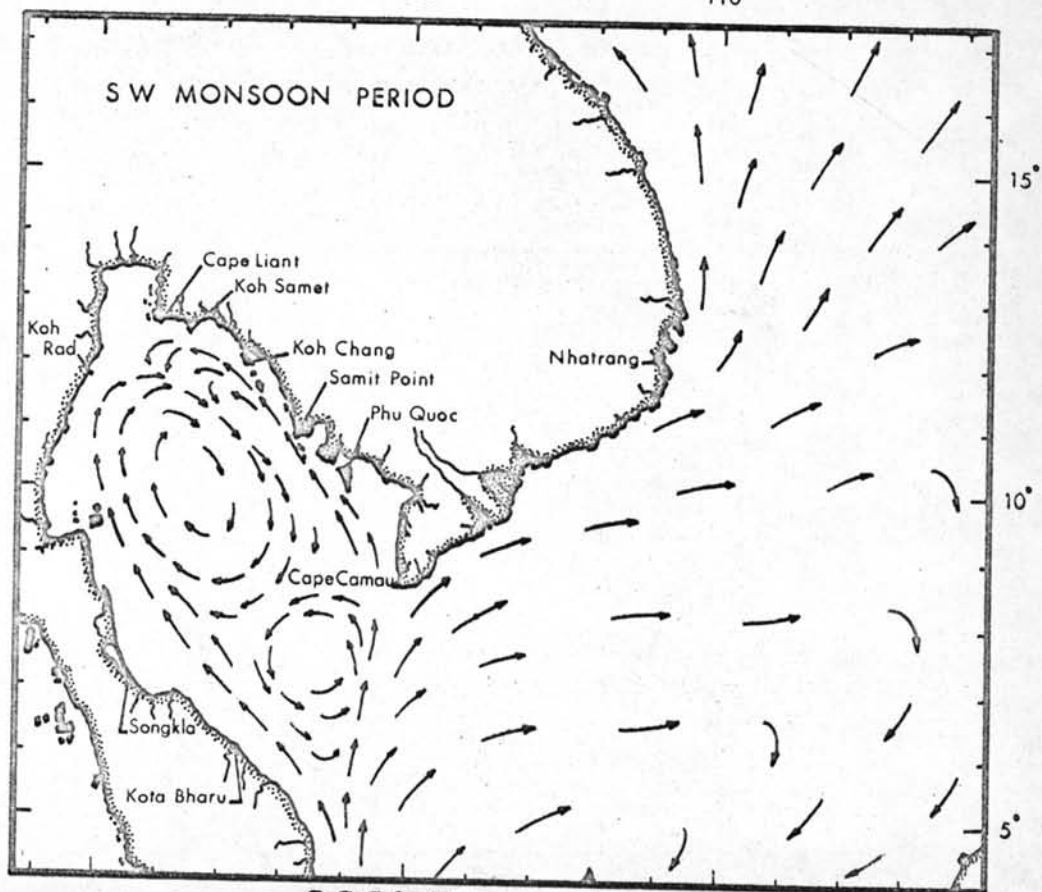
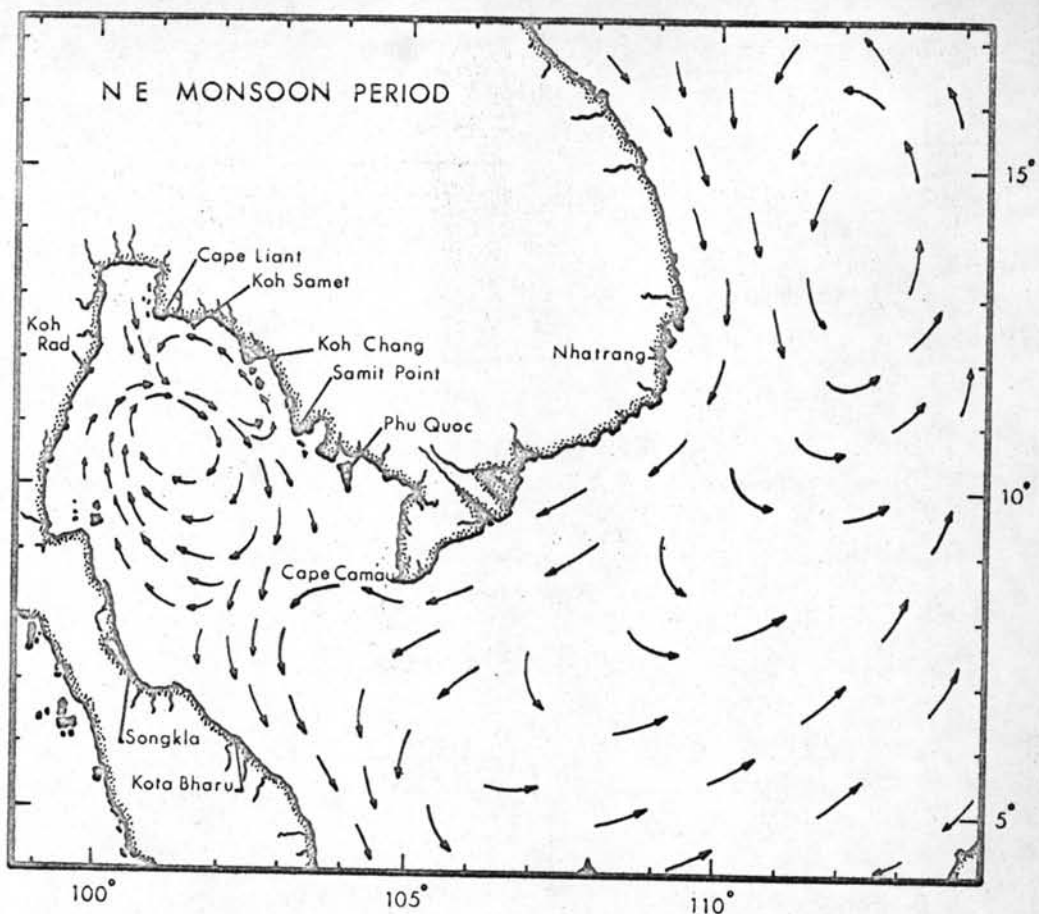
The low salinity water which sunk at the center of the



outer Gulf came around Cape Camau from the south coast of South Viet-Nam. At both the surface and at 30 meters there was a narrow outflow from the Gulf along the western shore. Northward and northeastward inflow was evident across the outer Gulf from the western to the eastern sides. Within 60 miles of Phu Quoc Island there was a divergence which the main flow proceeded northward along the east coast and the balance turned into a clockwise eddy south of Phu Quoc. There was very weak circulation in the central areas, particularly at 30 meters. At 50 meters there was inflow along the western coast, outflow along the eastern coast, and a secondary counter-clockwise cell in the northern half of the Gulf.

## MAPS

Oceanographic currents during the northeast and southwest monsoon periods (modified from LaFond, 1963; Robinson, 1963; Wyrтки, 1961).



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