The physical oceanography of the Gulf of Thailand, Naga Expedition; Bathythermograph (BT) temperature observations in the Timor sea, Naga Expedition, Cruise S11

Robinson, Margaret K

1974

NAGA REPORT
Volume 3, Part 1

Scientific Results
of Marine Investigations of the South China Sea
and the Gulf of Thailand
1959-1961

Sponsored by
South Viet Nam, Thailand
and the
United States of America

The University of California
Scripps Institution of Oceanography
La Jolla, California
1974

EDITORS: EDWARD BRINTON, WILLIAM A. NEWMAN
ASSISTANT EDITOR: NANCE F. NORTH

Printing of this volume was made possible through the National Science Foundation Grant GN-32570. The NAGA Expedition was supported by the International Cooperation Administration Contract ICAc-1085.

Library of Congress Catalog Card Number: 74-620121

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THE PHYSICAL OCEANOGRAPHY OF THE GULF OF THAILAND, NAGA EXPEDITION

by

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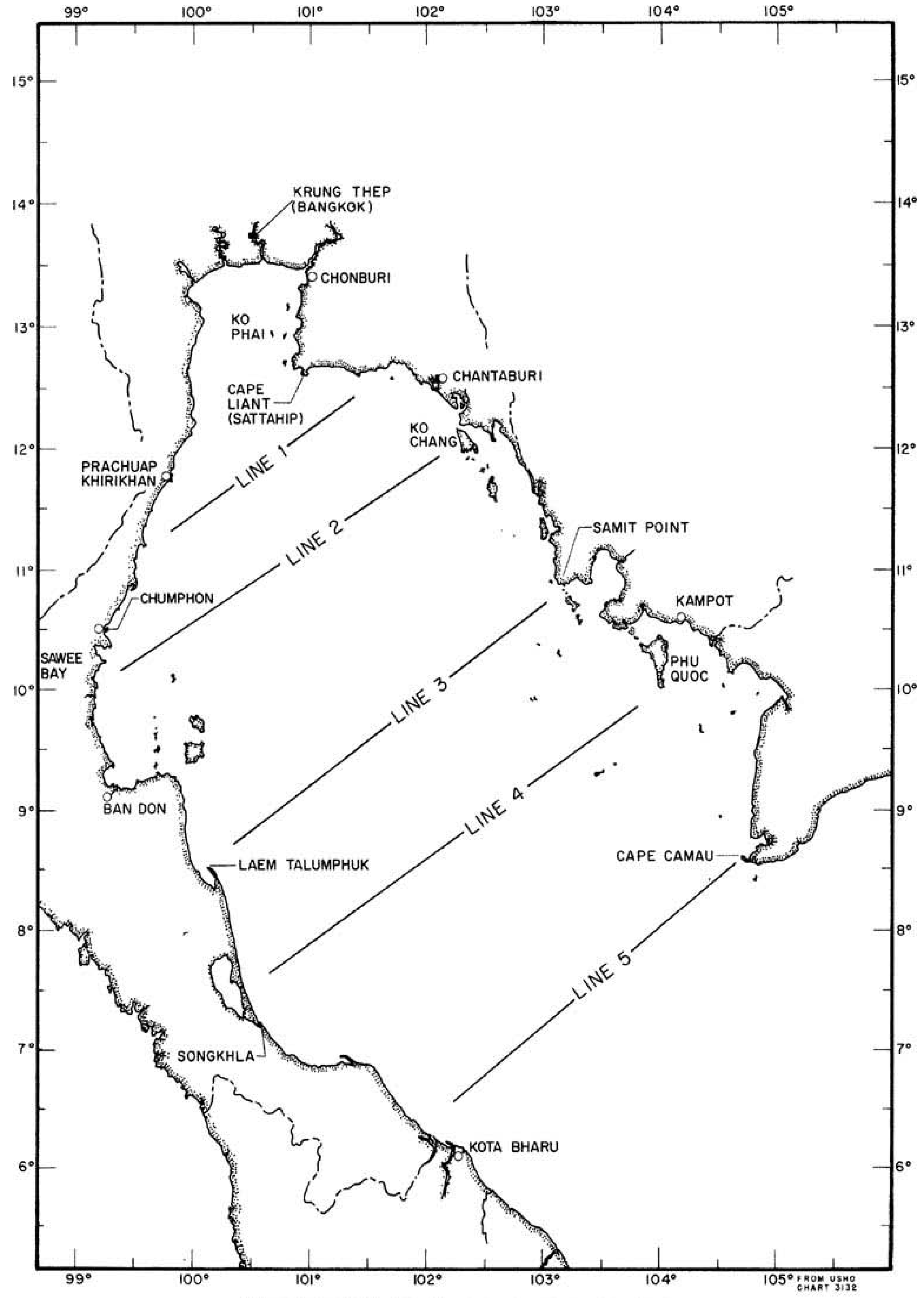

FROM USHO CHART 3132

Chart of the Gulf of Thailand showing Cruise Track Lines

THE PHYSICAL OCEANOGRAPHY OF THE GULF OF THAILAND, NAGA EXPEDITION

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INTRODUCTION AND ACKNOWLEDGMENTS

The Research Vessel *Stranger* of the Scripps Institution of Oceanography, University of California, San Diego, was engaged in the Naga Expedition in the Gulf of Thailand and the South China Sea during the period of October, 1959, to December, 1960. The expedition was jointly sponsored by the Governments of South Viet Nam, Thailand and the United States of America. It had a two-fold purpose; to collect oceanographic, biological and fisheries data and material and to train scientists and technicians from Thailand and South Viet Nam in oceanography and marine biology.

This report is a description of the oceanographic environment in the Gulf of Thailand derived from oceanographic and meteorological data collected for the most part on six cruises in the Gulf between October, 1959, and December, 1960. Five additional cruises were made in the South China Sea between November, 1959, and February, 1961, which will be the subject of a separate report.*

The cruise plans for the Gulf of Thailand were designed to investigate systematically the distribution and variability of the physical properties of the Gulf waters. The station plan consisted of stations located 30 to 40 miles apart on five parallel lines running perpendicular to the east and west coasts of the Gulf. The lines were 60 to 90 miles apart. Figure 1 is a composite plan for the five Gulf cruises which made complete hydrographic measurements. The stations were numbered chronologically on each cruise. Thus, stations at approximately the same location have different numbers on each of the cruises. Within the limits of navigation the primary stations on each line were at the same location on each cruise.

The following physical oceanographic data were collected at each station; reversing thermometer temperatures, salinity and oxygen determinations at standard levels—0, 10, 20, 30 and 50 m—as depth allowed and bathythermograph (BT) temperature observations. The latter were also taken midway between regular stations and at intervals parallel to shore between station lines. Meteorological observations, including wind, air temperature and sea condition, were taken at the time of each BT. Station data and a description of the physical and chemical methods may be found in Faughn (in press). (The various biological data from collections from both the Gulf of Thailand and the South China Sea are described in Volumes 4 and 5 of the Naga publications series.)

The BT slides were photographed at the Scripps Institution of Oceanography, and copies have been distributed to the Royal Thai Navy Hydrographic Office, Bangkok, Thailand, the Oceanographic Institute of Nhatrang, South Viet Nam, and the U.S. National Oceanographic Data Center, Washington, D.C. Copies may be obtained upon request from the Scripps Institution of Oceanography or from the U.S. National Oceanographic Data Center. The individual BT traces will not be published. They have been used, however, together with the reversing thermometer station data, as the basis of the temperature analysis presented in this paper.

Support of the author and personnel who assisted in the preparation of material was by the Office of Naval Research, 1960-64. Publication was made possible by the National Science Foundation. It would be redundant to mention all of the individuals whose work is in some way included in this presentation and whose names appear in Faughn (in press). However, special thanks are due here to Imogene McKinley, Marguerette Schultz and Jean Bye for analysis and processing of BT data and to Janette Larson, Fred Crowe, Bobby J. Thomas and Keiko Akutagawa for their graphic work (all of Scripps Institution of Oceanography).

Special acknowledgment is made to Captain Amporn Penyapol and Lt. Amnuay Scrivirajna of the Royal Thai Navy for their enthusiastic support and gracious friendliness to the author during her stay in Thailand, October, 1962-March 1963, to the UNESCO for their financial support of the visit and to the Royal Thai Navy personnel who provided climatalogical and river flow data.

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*A report on the results of the Naga Expedition, 1959-1961, entitled "Ecology of the Gulf of Thailand and the South China Sea", made to the Government of the United States by the Regents of the University of California, February, 1963 (SIO Ref. No. 63-6) contains the author's preliminary version of the present paper (see also LaFond in the same report).

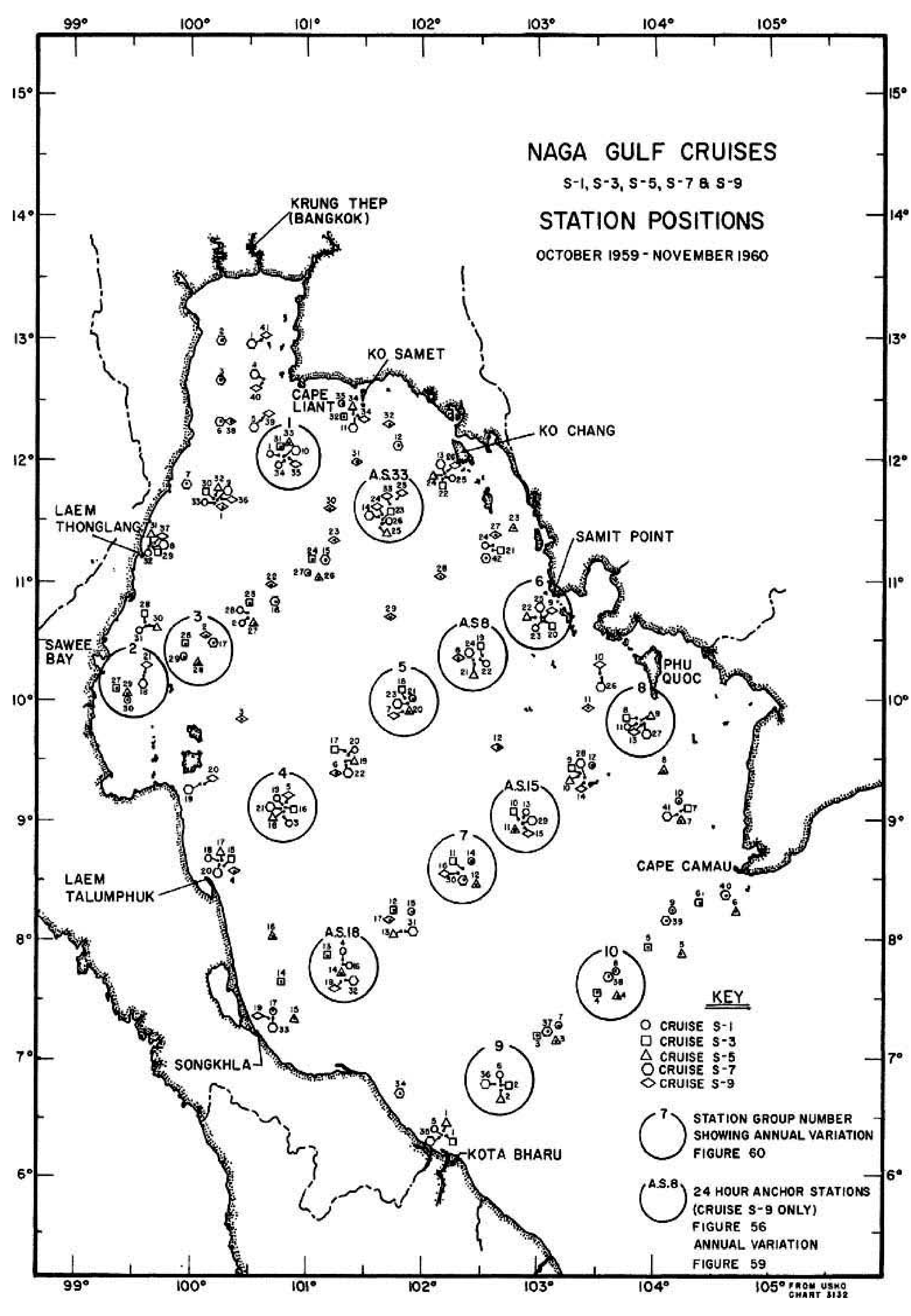
NAGA GULF CRUISES
S-1, S-3, S-5, S-7 & S-9
STATION POSITIONS
OCTOBER 1959 - NOVEMBER 1960
KRUNG THEP (BANGKOK)
KO SAMET
CAPE LIANT
KO CHANG
LAEM THONGLANG
SAMIT POINT
SAWEE BAY
PHU QUOC
CAPE CAMAU
LAEM TALUMPHUK
SONGKHLA
KOTA BHARU
A.S.33
A.S.8
A.S.15
A.S.18
KEY
○ CRUISE S-1
□ CRUISE S-3
△ CRUISE S-5
◎ CRUISE S-7
◇ CRUISE S-9
7 STATION GROUP NUMBER SHOWING ANNUAL VARIATION FIGURE 60
A.S.8 24 HOUR ANCHOR STATIONS (CRUISE S-9 ONLY) FIGURE 56 ANNUAL VARIATION FIGURE 59
99°
100°
101°
102°
103°
104°
105°
15°
14°
13°
12°
11°
10°
9°
8°
7°
6°
FROM USHO CHART 3132

Figure 1.

METHOD OF DATA ANALYSIS

Vertical and horizontal distributions of temperature, salinity and oxygen were constructed from observed, interpolated and extrapolated data points.

In the first step continuous temperature-depth (T-D), salinity-depth (S-D) and oxygen-depth (O2-D) curves were constructed from the hydrographic-cast data at each station. The T-D curve was drawn to conform with the BT trace taken simultaneously. Whenever gradients in salinity and oxygen hydrographic-cast data appeared to be correlated with observed sharp thermocline gradients in the BT data, similar sharp gradients were drawn on the S-D and O2-D curves. The halocline and thermocline, however, did not always coincide, and a sharp halocline could occur in isothermal water (see Figures 16, 17, 59 and 60).

From the T-D, S-D and O2-D curves two sets of values were read and tabulated; 1. Discrete values at the standard levels of 0, 10, 20, 30 and 50 m were used as a basis for construction of horizontal distributions. 2. Depths of occurrence of the iso-values were selected for contouring in both horizontal and vertical section charts. The iso-values selected were; T, 0.5 °C; S, 0.5 ‰ and O2, 0.25 ml/l. The reason for using depths of iso-values to construct vertical distributions rather than discrete values at standard or observed levels is that in the first method it is possible to maintain in the vertical sections the nonlinear gradients which appear on the BT traces and on the (hand drawn) continuous S-D and O2-D curves.

The vertical sections were constructed and are herein presented superimposed on a geographic chart of the Gulf of Thailand. The surface line of each section is a best-fit straight line through the observed hydrographic-station position, and each section is rotated 90° to lie in the plane of the chart. Fortunately, the Gulf is so shallow that the vertical axis of the sections did not exceed the horizontal distance between station lines on the geographic base chart.

The bottom line of each section was constructed from the fathometer-bottom depths recorded on the BT log sheets, amplified where necessary by additional depths from the original fathograms taken along the ship's track (see section on geography of the Gulf of Thailand for further discussion of the bottom topography).

In addition to the sections drawn along the five cruise lines, seven lengthwise sections were constructed to connect the stations between lines (see composite 3-dimensional distribution charts which include three of the lengthwise sections for each cruise, Figures 16, 17, 24, 25, 32, 33, 40, 41, 47 and 48).

In the construction of the vertical sections the isolines were extrapolated to the bottom. These extrapolations are approximations derived from the over-all continuity of the distributions. They were used in the preparation of the horizontal 30- and 50-m charts to provide edge values between the stations and the points where the 30- and 50-m horizontal planes intersect the bottom.

The horizontal charts were constructed using the standard-level interpolated discrete values read from the continuous T-D, S-D and O2-D curves previously described and plotted at the appropriate geographic locations for each cruise.

Between station lines the locations of isolines on the horizontal charts were uniquely defined in space at the points at which the planes of the five crosswise sections and the seven lengthwise vertical sections intersect the selected horizontal planes. In other words the point at which each isoline intersects the surface, 30- and 50-m lines (representing planes) on the vertical sections is the same geographic point through which the isoline must pass on the selected horizontal plane.

The vertical sections were always constructed first, and in general, the horizontal distributions were constrained to agree with the interpretations of the vertical sections where nonlinear gradients were maintained.

As a result of the careful checking for consistency of interpretation and for unique locations of isolines between horizontal and vertical charts, we have felt justified in including interpolations and extrapolations on the charts. The details of the interpolations and extrapolations are obvious, however, because on all charts the observed data points are indicated.

On the vertical sections observed data are indicated by symbols indicating hydrographic-cast depths and the maximum depth of the BT trace. On the horizontal charts interpolated standard-level values are indicated by station-position symbols. The station symbols are omitted where data are extrapolated.

The temperature charts contain more detail than do the salinity and oxygen distributions because of the inclusion of the BT data. This greater detail was carried over to sigma-t charts by computing additional sigma-t values between station lines from the temperature and salinity contours. In particular as many extra sigma-t values were computed at intermediate points as were necessary to retain the tongue-like configurations which appeared on the more detailed temperature charts.

In addition to the above described distribution charts given for the Gulf cruises (S1, S3, S5, S7, S9 and S9A) vertical temperatures sections for the (eastern) Gulf from BT's taken on the underway legs of cruises to the South China Sea (S2, S4, S6 and S10) are also given.

A composite cruise plan, topographic drawings, wind velocity and coastal rainfall charts, various rainfall and river-flow graphs, current-observation diagrams as well as pertinent tables are described in the appropriate places in the discussion which follows.

DISCUSSION

GEOGRAPHY

The Gulf of Thailand is a shallow arm of the South China Sea (Figures 1 and 2) and is open to it at the surface for a distance of 200 miles. The Gulf extends approximately 450 miles. Its greatest width is approximately 300 miles; its greatest depth, in the center, is slightly more than 80 m. The central depression has depths greater than 60 m and extends up the Gulf to within 60 miles of Cape Liant at the southeast corner of the Bight of Bangkok.

Branching out from the central depression are troughs which appear to be narrow, drowned river valleys (Figure 2a). Four large rivers empty fresh water into the head of the Bight of Bangkok, but many smaller rivers flow into the Gulf from both sides. The northeastern coast is generally shallower and flatter than the southwestern coast.

The deeper central Gulf is separated from the South China Sea by two ridges. One extends southwest at depths of less than 25 m for more than 60 miles from Cape Camau. The second and deeper ridge extends northeast off Kota Bharu for a distance of 90 miles at depths of less than 50 m. Subsequent to the Naga Expedition a further survey of the bottom topography in this region was made by the DODO Expedition of the Scripps Institution of Oceanography. In the narrow, deeper channel between the ridges a sill depth of 67 m was observed. These general features of the geography of the Gulf play an important role in the oceanography of the region.

GENERAL OCEANOGRAPHIC CHARACTER OF THE GULF

The Gulf of Thailand may be characterized as a classical two-layered, shallow water estuary on the basis of the distributional charts. Low salinity water which has been diluted by heavy precipitation and fresh water runoff 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 over the 67-meter sill in the entrance channel. This high salinity water fills the deep, central depression below a depth of approximately 50 m. Superimposed on this two-layered system is a complex circulation composed of the wind-driven currents related to the monsoon winds and tidal currents whose velocities in many locations exceed one knot. Neither the northeast nor the southwest monsoon winds were found to be constant in direction or velocity over the Gulf as a whole. The interplay of forces due to the variable winds, tidal currents,* fresh water runoff and excessive precipitation gives rise to localized areas of divergence where low temperature, high salinity water, usually of low oxygen content, is upwelled. These forces alsoestablish areas of convergence where high temperature, low salinity and highly oxygenated water sinks.

The Naga data indicate that the general circulation and physical properties undergo large seasonal as well as shorter period variation. It is possible to infer the direction (but not the magnitude) of the circulation of the water from the slope of the isopleths of temperature, salinity and density expressed in units of sigma-t** in the vertical sections and the intensity of their gradients on the horizontal charts for the surface, 30 and 50 m levels.

Classical oceanography (Sverdrup, Johnson and Fleming, 1942) has shown that ocean currents in the northern hemispheres flow at right angles to the slope of the density surfaces so that the lighter water lies on the right hand of an observer looking in the direction of the current, and the denser water lies on the left hand. In shallow estuarine waters the assumptions upon which current velocities are calculated from the distribution of density based on temperature and salinity observations in the open ocean may not be valid.

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[*] In the relatively small area of the Gulf the tides vary from purely diurnal to semi-diurnal mixed types (Pukasab and Pochanasomburana, 1957).

[**] Sigma-t = ($\rho_{s,\theta,0}$)-1×10^3 where $\rho_{s,\theta,0}$ = density at observed salinity and temperature at atmospheric pressure.

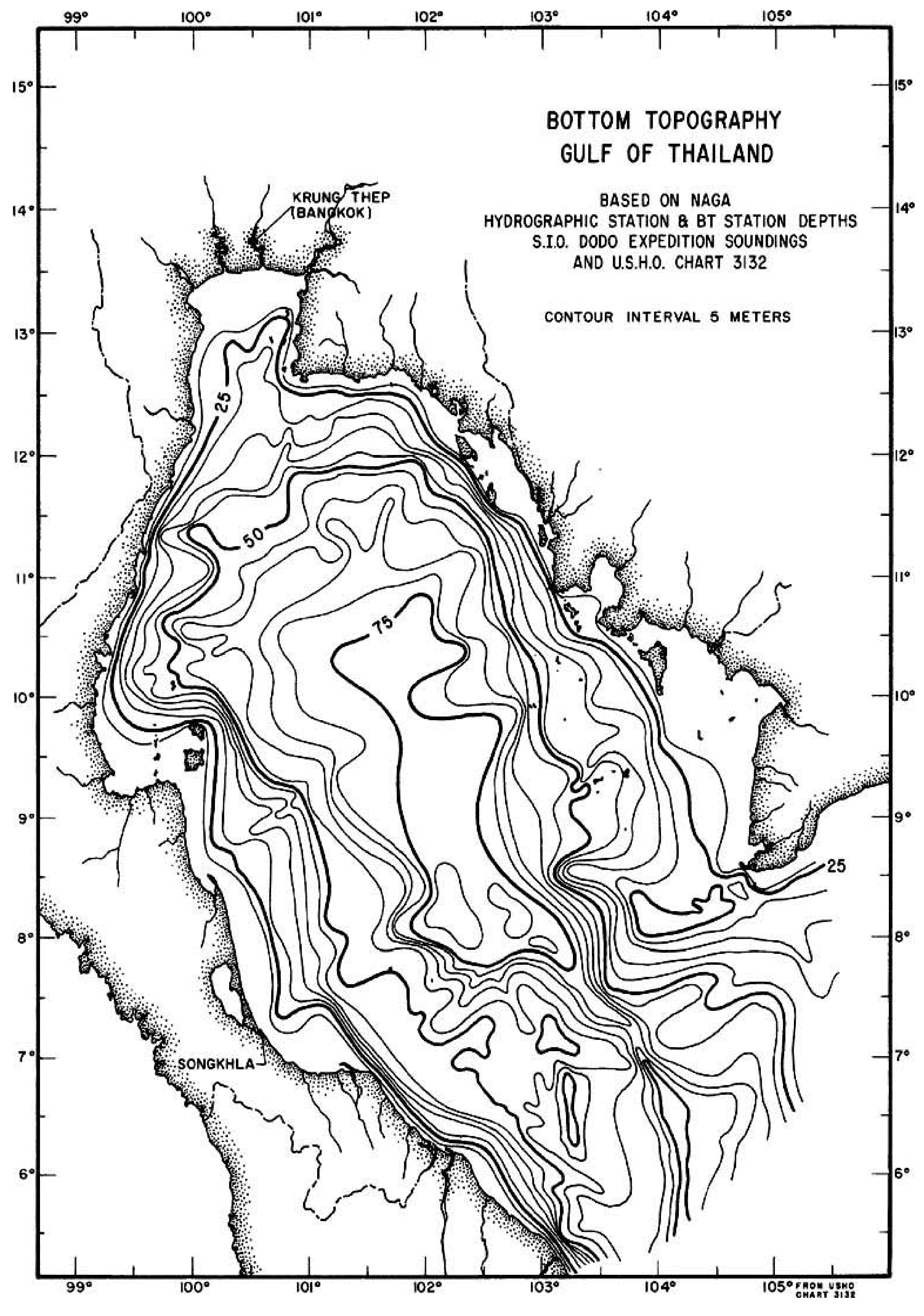
BOTTOM TOPOGRAPHY
GULF OF THAILAND
BASED ON NAGA
HYDROGRAPHIC STATION & BT STATION DEPTHS
S.I.O. DODO EXPEDITION SOUNDINGS
AND U.S.H.O. CHART 3132
CONTOUR INTERVAL 5 METERS
KRUNG THEP
(BANGKOK)
SONGKHLA
25
50
75
25
99°
100°
101°
102°
103°
104°
105°
15°
14°
13°
12°
11°
10°
9°
8°
7°
6°
FROM USHO CHART 3132

Figure 2.

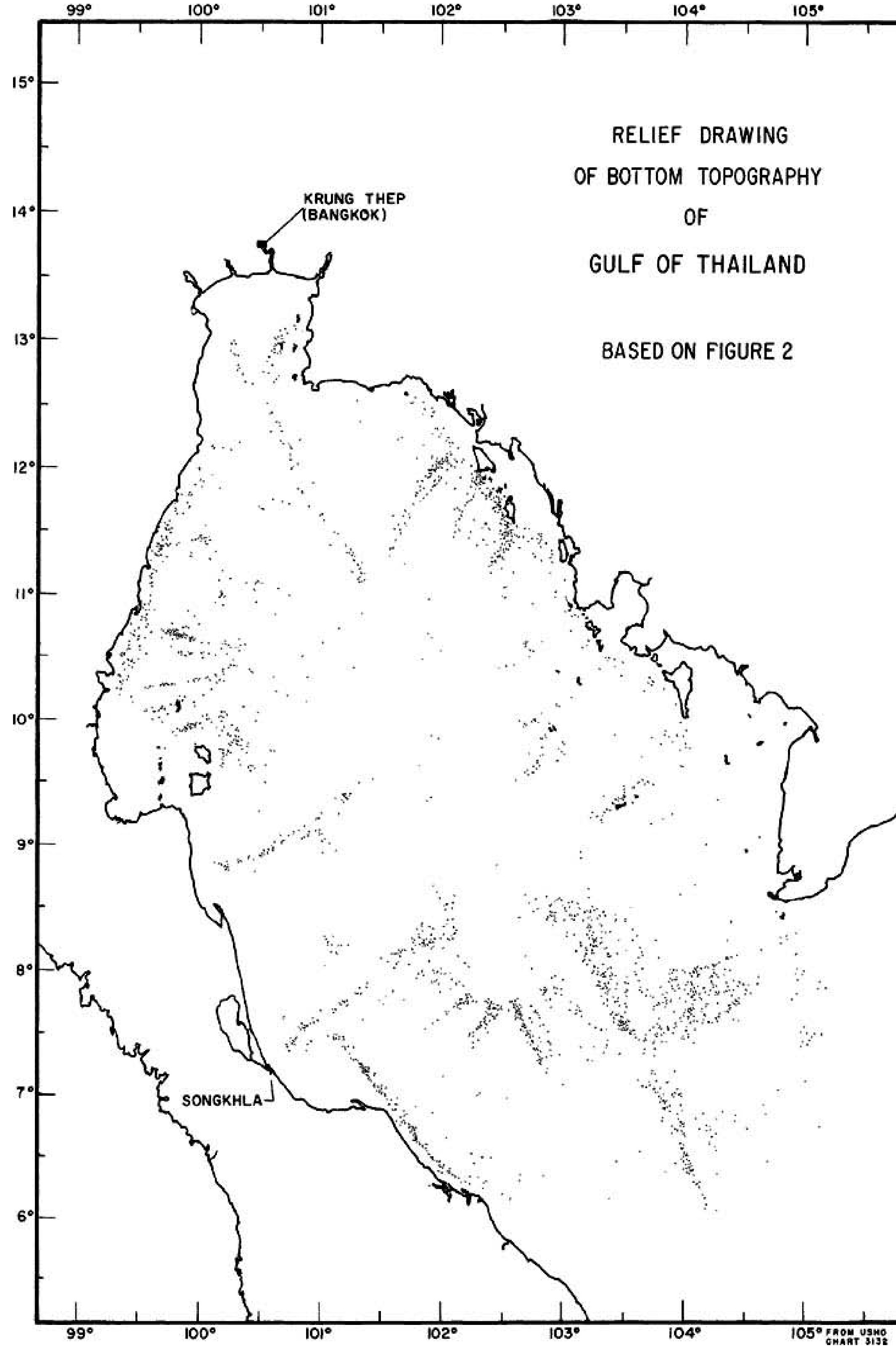
99°
100°
101°
102°
103°
104°
105°
15°
14°
13°
12°
11°
10°
9°
8°
7°
6°
RELIEF DRAWING
OF BOTTOM TOPOGRAPHY
OF
GULF OF THAILAND
BASED ON FIGURE 2
KRUNG THEP
(BANGKOK)
SONGKHLA
FROM USHO
CHART 3132

Figure 2a.

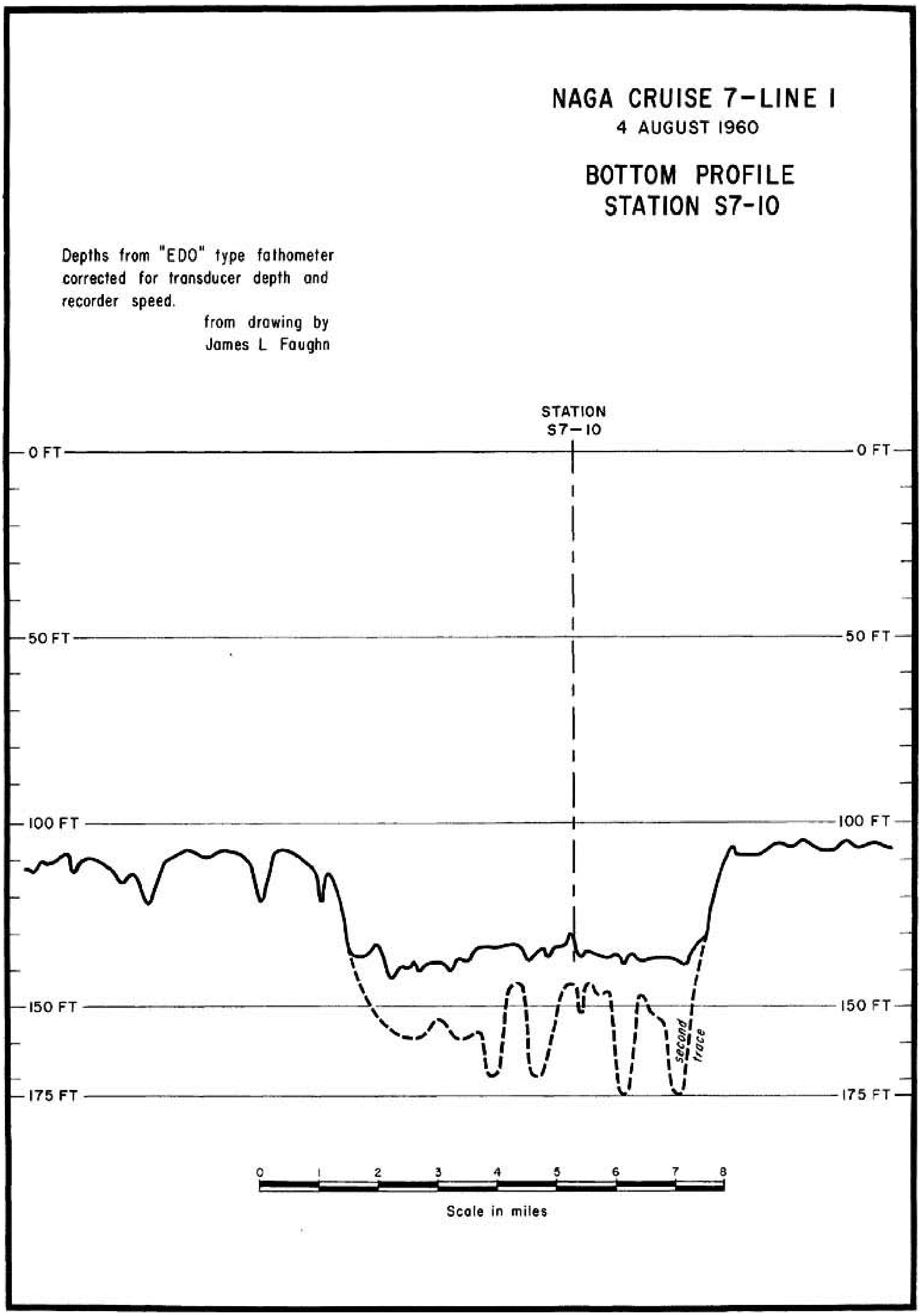
NAGA CRUISE 7-LINE I
4 AUGUST 1960
BOTTOM PROFILE
STATION S7-10
Depths from "EDO" type fathometer corrected for transducer depth and recorder speed.
from drawing by James L. Faughn
STATION S7-10
0 FT
50 FT
100 FT
150 FT
175 FT
second trace
0
1
2
3
4
5
6
7
8
Scale in miles

Figure 3.

However, density distributions do give an indication of the direction of water movements both horizontally and vertically, and density gradients give evidence of relative current strength since horizontal motion must take place if horizontal density differences exist.

Density of a body of water may be changed at the surface by river runoff, precipitation, evaporation and effective incoming radiation. Because of the earth's rotation, winds blowing over the sea surface will transport water at 45° to the right of the wind. The wind may produce areas of coastal upwelling or sinking, convergence or divergence and currents; the wind-induced motion will alter the distribution of density both horizontally and vertically. Wind also alters density by mechanical mixing. In the shallow Gulf of Thailand where strong winds occur such mixing may extend to the bottom or it may be limited at the halocline by the extreme stability of the high salinity deep water at times of light winds.

Wind-induced water motion at 45° to the right of the wind produces the following related vertical motions which affect the density structure of the water column;

Coastal upwelling—surface water is carried away from shore by wind blowing parallel to shore; the deeper water with its own characteristics rises toward the surface,

Coastal sinking—when the wind blows in a direction that causes the surface water to be transported toward shore, the coastal surface water sinks to form a deeper layer of water with surface characteristics.

Open sea divergence—the process where surface water is blown away from an area allowing subsurface water to rise to the surface; may occur in the center of counter-clockwise eddies in the northern hemisphere or between divergent currents (currents flowing away from each other).

Open sea convergence—the process where surface water is blown toward an area from two or more directions and surface water sinks; may occur along a line or in the center of a clockwise eddy in the northern hemisphere or in a region of convergent currents (currents flowing toward each other).

The major component of the circulation in the Gulf of Thailand appears to be wind-induced motion. The monsoon winds over the Gulf, however, are not simply northeast and southwest but vary widely around their primary direction making the interpretation of the results of *in situ* winds more difficult. Examples of wind effects will be pointed out in the discussions of each cruise.

Without wind fresh water river runoff would stay on the surface of the ocean water. In addition to the main channel of the Chao Phya River emptying into the Bight of Bangkok there are also one river to the east, the Klong Dan, draining the same basin and three other rivers draining different regions. These latter are from east to west; Bang Pakong, draining southeastern Thailand, the Tha Chin and Mae Khlong, draining the Bilauktaung Mountains on the western (Burmese) border of Thailand. Both the Naga data and the 1956-57 surface salinity observations compiled by the Royal Thai Navy indicate that river and Gulf water mixing takes place very rapidly in the Bight of Bangkok. In the delta region the penetration of the tides up the rivers is a function of the river flow. In winter at times of low river runoff saline water penetrates the Chao Phya River channel as far north as Bangkok at high tide. The murky, silt-laden fresh water at such times is scarcely three meters thick, and ships' screws churn up the clear saline water lying beneath as they navigate the river (author's observation). There is little mingling of the two water masses at the interface except when mixed by outside forces. Most of the mixing appears to take place beyond the mouths of the rivers where the wind provides the force.

Records of the salinity of the saline water intrusion are not available, but during 1956-57 the highest surface salinity in the region of the Bangkok Bar (13° 25' N) was 31.5 ‰ in April, 1956, and since relatively little mixing takes place in the river channel, the salinity of the deep saline layer can be expected to reach approximately this concentration during reduced river flow.

Rainfall and river flow records have been kept for many years in Thailand. Droughts have occurred frequently allowing salt water intrusion into the delta to cause considerable damage to rice paddies and fruit orchards. For this reason a dam was completed on the Chao Phya River in 1952 at Jayanath, 100 miles

(150 kms) north of Bangkok. A portion of the flood waters are impounded during the rainy season to be released later in the dry season to prevent salt water damage to crops.

River flow along the eastern and western shores of the Gulf of Thailand also reduces surface salinity along shore, but in only one case during the Naga Expedition was low salinity surface water found in mid-Gulf (see discussion of cruise S9).

In order to relate the Naga cruise data of 1959-1960 to the more general climatic conditions of the area, rainfall statistics at locations in Malaysia, Thailand, Cambodia and South Viet Nam have been obtained from World Weather Records, from Monthly Climatic Data for the World and from the Meteorological Department of the Royal Thai Navy. The latter agency also provided river runoff records for the Chao Phya River for 1905-1960. Mekong River flow (recorded at Mukdahan, Thailand, 600 miles from the South China Sea) for the years 1924-64 was obtained from the I.H.O. UNESCO Publication, *Discharge of Selected Rivers of the World, 1971*. While rainfall and river flow data have been collected in Southeast Asia in connection with agriculture, primarily rice and fresh water fish cultivation, these data may also be of great value in the future development of salt water fisheries and the better understanding of the role of rainfall and river runoff in the productivity of these Southeast Asian waters.

Monsoon winds are the dominant factor in the climate of Southeast Asia. The onset of the monsoons varies to some extent, but the southwest monsoon is usually well established in May and ends in September. These winds, having blown across the Indian Ocean and Bay of Bengal, come laden with moisture and bring abundant rainfall to Thailand, Cambodia and South Viet Nam between July and October. Annual rainfall peaks occur at different times at different locations due to the irregular distribution of sea, land and mountain chains, and the prevailing southwest direction of the winds of the Indian Ocean become more variable in speed and direction over Southeast Asian land and water. The annual peaks of the Chao Phya and Mekong Rivers occur August to November. The area drained by the Chao Phya River system is fairly small and simple; increased rainfall over Thailand is reflected in the river flood peak about one month later. Rainfall data from locations around the Gulf coast, where rivers are short and drainage areas small, are good indicators of expected fresh water dilution of near shore Gulf areas.

The influence of Mekong River flow on coastal waters off South Viet Nam is quite different. The Mekong is one of the world's largest rivers. It originates in Tibet and courses most of its distance outside of Southeast Asia before curving toward its delta. Thus, it contains snow melt waters as well as monsoon rainfall on its lower watershed. These two sources, occurring simultaneously, reinforce each other. Measurements of Mekong River flow (at Mukdahan, Thailand) show a peak rate of flow in August and September that is 16-19 times as great as the flow of January to May. How much of this water reaches the South China Sea or Gulf of Thailand and with how much of a time lag and how much sinks into the delta lands can only be guessed at by the reduction of surface salinities in the coastal regions. The time lag is of great importance because, if the river flood does not reach the South China Sea until November, or later, the northeast monsoon will have set in, and low salinity water could be carried south toward the Gulf. If earlier, then it could be carried north along the coast of South Viet Nam and/or offshore into the South China Sea. The coast of central and northern South Viet Nam is essentially rockbound with short rivers and small drainage basins where peak river flow should be only slightly delayed from peak rainfall.

The dry season is that of the northeast monsoon which normally begins in November and ends in February, but occasionally surges of the northeast monsoon may still be experienced in March or even in early April. The period is one of variable moderate winds over the Gulf and mild pleasant temperatures on land.

There are two periods of transition between the opposing monsoons, one of two months' duration (March-April) and one of one month (October). The northeast monsoon winds blow across China and contain little moisture by the time they reach the coastal waters of South Viet Nam and the Gulf of Thailand. The northeast direction is steady over the South China Sea but is variable in the Gulf of Thailand where it is deflected by the Cardamom Mountains. April is the hottest month and brings great discomfort to the inhabitants, especially if the northeast monsoon follows a low-rainfall southwest monsoon year, or if the onset of the rains of the following season is delayed. At these times wells may dry up, and there is little outflow from the short coastal rivers.*

The Meteorological Department of the Royal Thai Navy has also maintained records of the maximum and minimum observed air temperatures throughout their network of weather stations beginning in 1937. Sample values from their records of these extremes at several of the locations, whose rainfall observations are given in Figures 8, 9 and 10 with minima in the month of January during the northeast monsoon and maxima in the transition month of April are as follows; Chiang Mai, 6.0-41.2 °C: Bangkok, 9.9-39.9 °C: Chantaburi, 11.2-38.6 °C: Prachuap Khirikhan, 11.1-39.6 °C: Ban Don, 12.4-39.5 °C: Chumphon, 13.0-39.0 °C: Songkhla, 19.7-37.5 °C.

Data are not at hand concerning the duration or frequency of the extreme cold nor of its effect on the temperature of the Gulf.

The importance of continuous monitoring of air temperature, rainfall, winds and river runoff cannot be overemphasized. An understanding of the interaction of these factors with the sea will be a necessary step in relating the physical environment to the plankton and fish populations. It is to be hoped that the following descriptions of both the meteorological background of the years 1959-61 and the observed conditions in the sea will make possible a better integration with the physical properties of the Gulf, afforded by the careful monitoring by the Naga Expedition, resulting in a more detailed understanding of the influence of fresh water runoff and the upwelling of nutrient-rich waters on the salt water fauna of the Gulf of Thailand.

CLIMATIC BACKGROUND OF THE NAGA EXPEDITION: WINDS, RAINFALL AND RIVER FLOW DURING 1959-1961

Charts showing the wind velocities in the Gulf of Thailand and the South China Sea as observed during the eleven Naga cruises (drawn from Robinson, 1963, and La Fond, 1963 in Ecology of the Gulf of Thailand and the South China Sea) are reduced here to appear in the chronological order of the cruises and include wind observations at underway BT stations in the Gulf as the R. V. *Stranger* sailed through it on the way to South China Sea cruises (Figures 4, 5, 6 and 7). This presentation facilitates the visualization of the changes of direction of monsoon winds on consecutive cruises and their different character in the open South China Sea and the partially closed and somewhat protected Gulf.

Rainfall graphs (Figures 8, 9, 10 and 11) have been prepared for eleven coastal locations in Malaysia, Thailand, Cambodia and South Viet Nam, and at Chiang Mai, Thailand, in the northern highlands of the Chao Phya watershed. These charts contain data for 1959 and 1960. In addition the normals of the 30-year period of 1931-1960 (where available) and the 10-year period of 1951-1960 are plotted on the graphs to relate the Naga Expedition period to the long term climatology. Monthly average rate of flow for the Chao Phya and Mekong Rivers for 1959 and 1960 together with their 30-year and 10-year monthly means (Figure 12) are included for comparison with the rainfall records.

The Naga cruises took place under the following general wind regimes: cruise S1 was in the October transition period: cruises S2, S3, S4, S9 and S10 were during the northeast monsoon (November-March): cruise S5 was during the April transition at the time of maximum air temperatures: cruises S6, S7 and S8 were during the southwest monsoon, S8 extending into the October transition. A summary of the seasons, cruises, observed wind direction and speed, coastal rainfall and river runoff is presented in Table 3.

The rainfall graphs give the total monthly rainfall at each selected location during the Naga cruises and show large year-to-year as well as large monthly and seasonal differences. Minimum rainfall months clearly coincide with the northeast monsoons. Maximum rainfall, however, may come as early as July or as late as

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[*] The author was amazed to find cactus growing near Hua Hin in March, 1961, about ten miles west of the Gulf near 12°30' N.

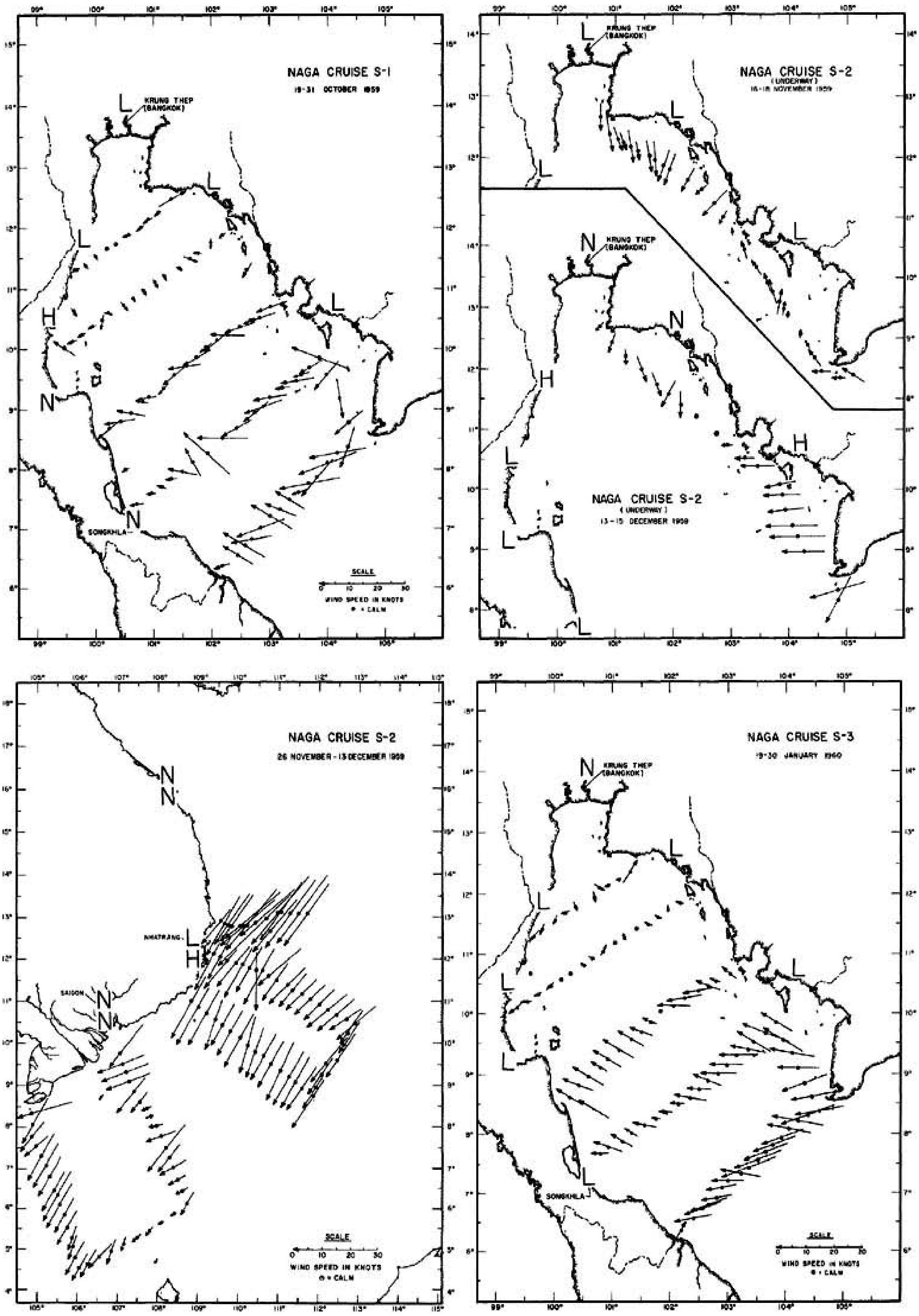

Figure 4. Wind Velocities and Coastal Rainfall.

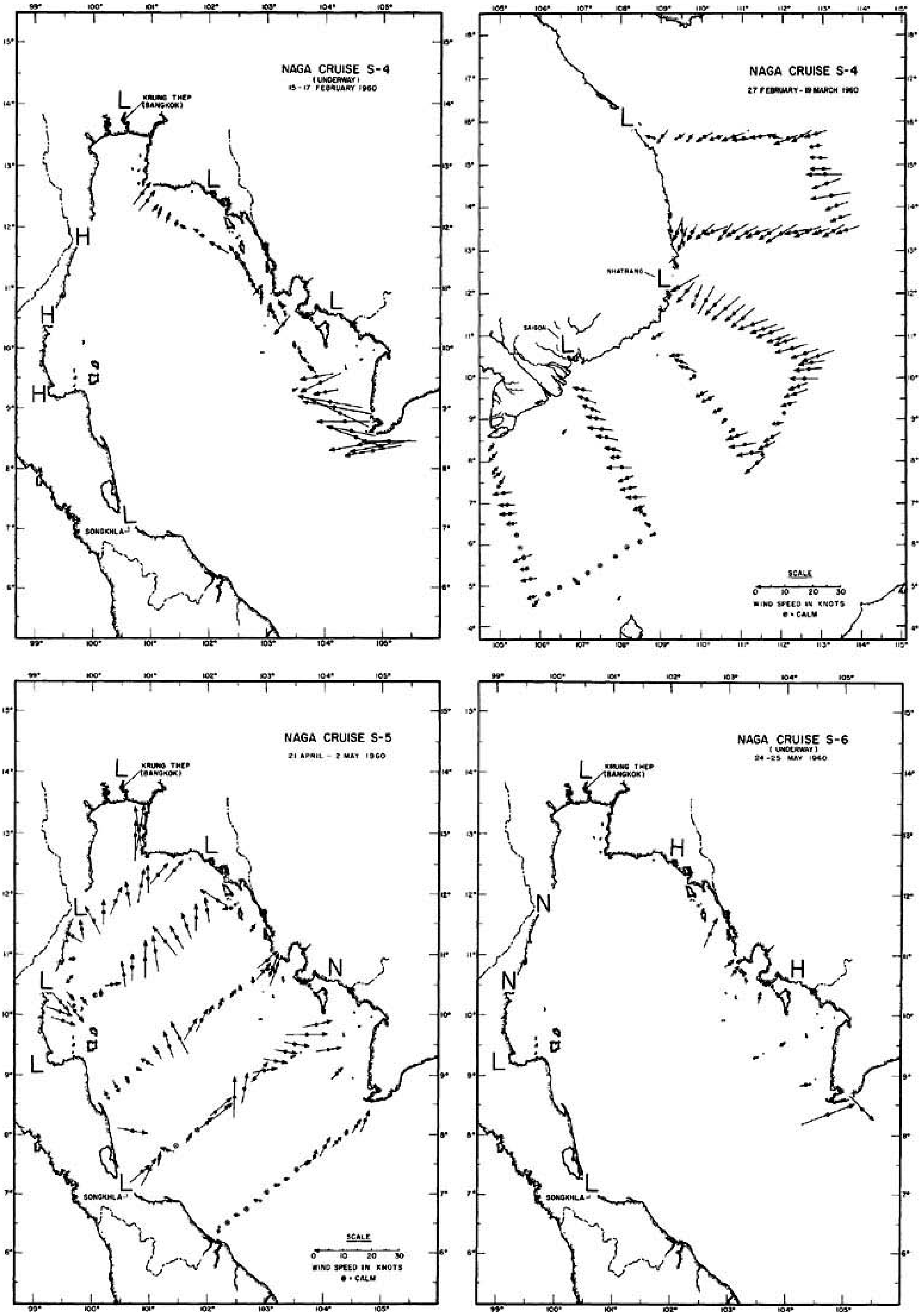

Figure 5. Wind Velocities and Coastal Rainfall.

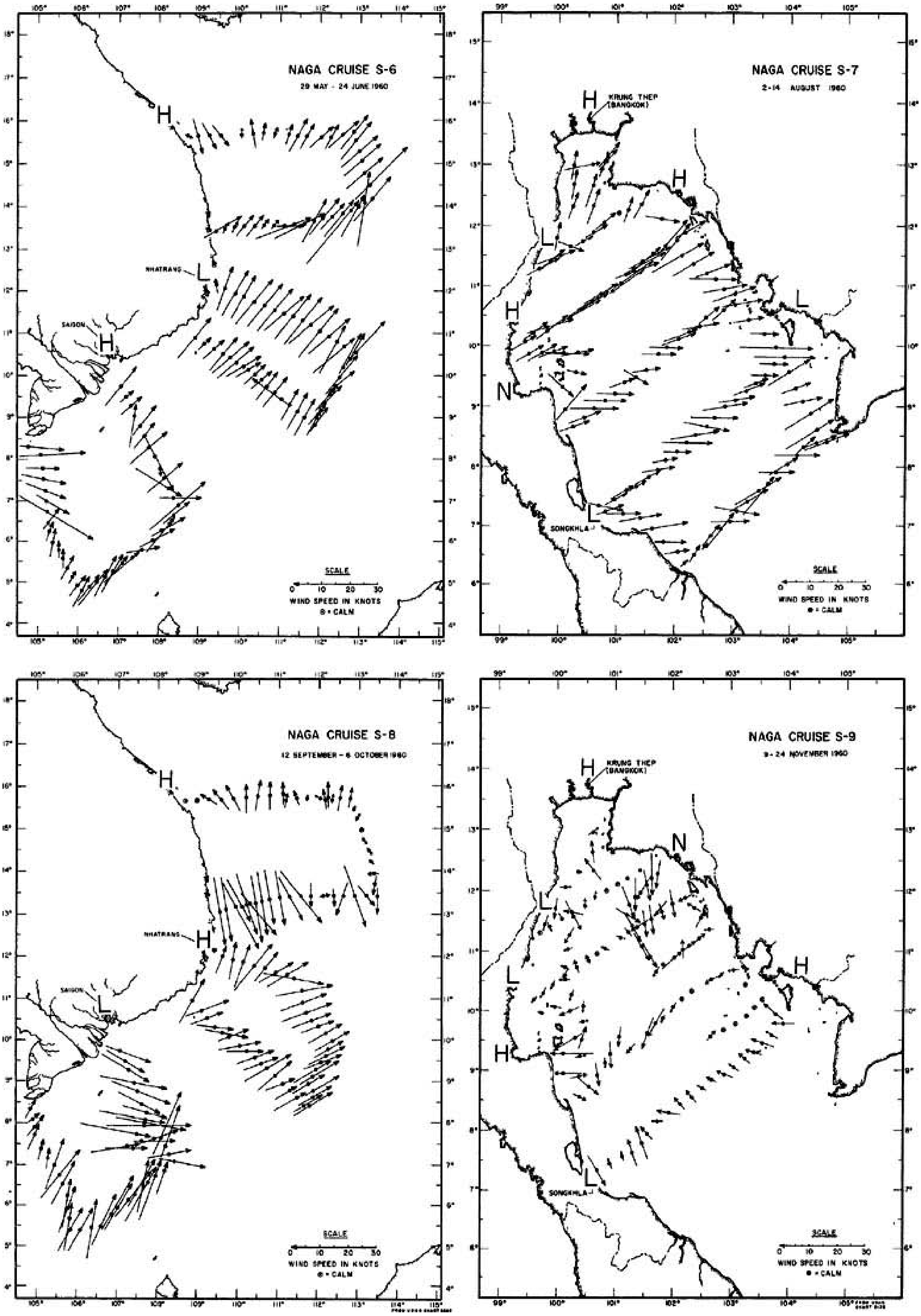

Figure 6. Wind Velocities and Coastal Rainfall.

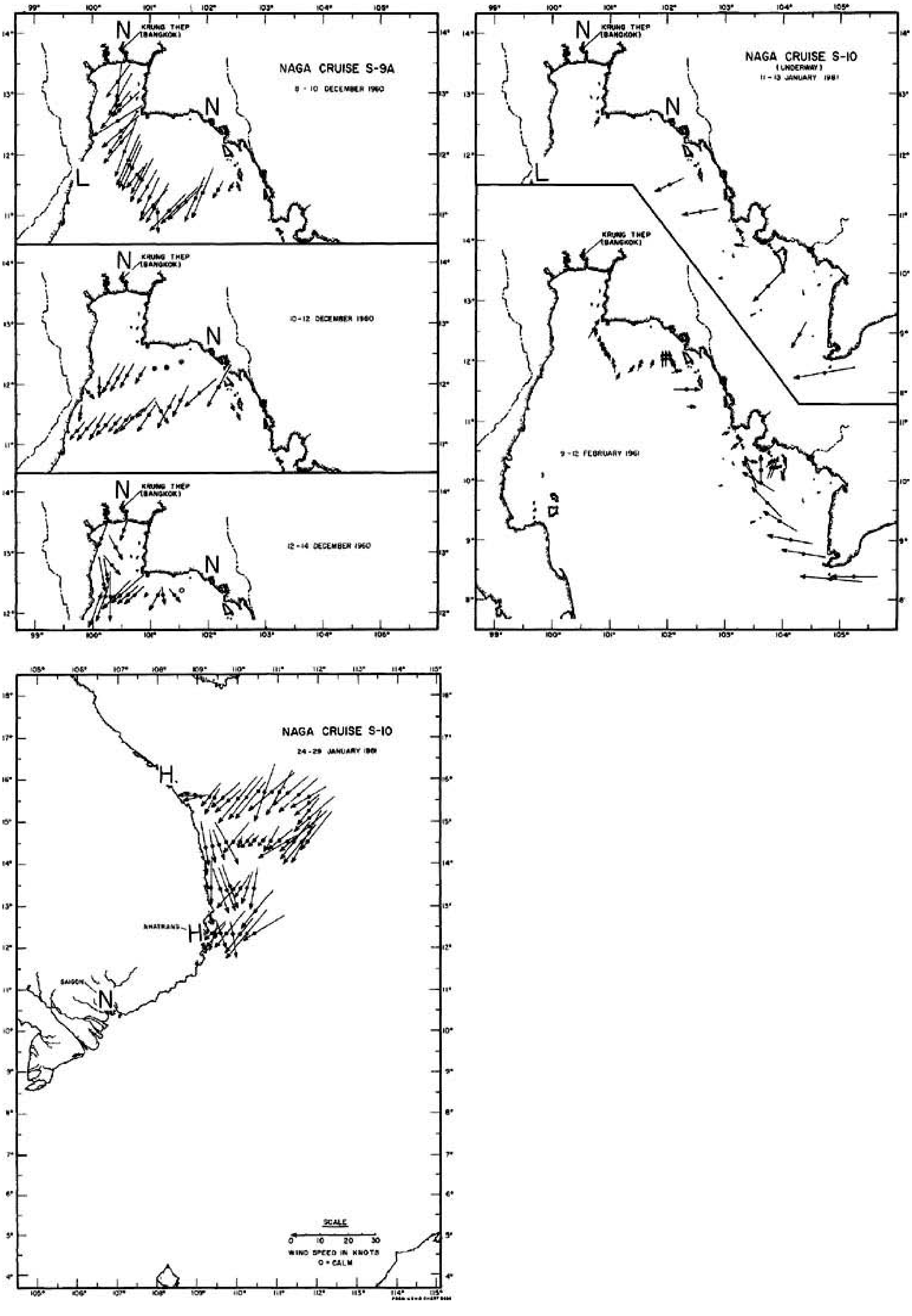

Figure 7. Wind Velocities and Coastal Rainfall.

November. Locations with late rainfall maxima frequently had secondary peaks earlier in the season, June to August. The three stations along the Malaysian-Thai peninsula, Ban Don, Songkhla and Kota Bharu, all had maxima in November. September and October were the times of maximum rainfall at most of the other selected locations. It is surprising that the heaviest rainfall comes at the end of the southwest monsoon.

Total monthly rainfall at Bangkok in 1959 and 1960 is compared with the monthly minimum and monthly maximum (from 30-year records) in Figure 13.

The maximum rate of flow of the Chao Phya River (measured at Wad Tha Hard and at Nakorn Sawan, Thailand) occurred during October in 1959 and in 1960 and is in agreement with that of the long period means (Figure 12). The maximum rate of flow on the Mekong River (measured at Mukdahan, Thailand) occurred in September, 1959, and in August, 1960, although both months were of very high flow in both years. Evidence of this runoff will be discussed below.

Mean flow on the Chao Phya, averaged over different periods are shown in Figure 14. The 5-year means (1959-60) were much lower than the 10-, 20-, and 30-year means.

The annual average of flow for the Mekong and Chao Phya Rivers for the years 1931-1960 are compared with total annual rainfall at Saigon and Bangkok for the same period in Figure 15. These comparisons show that annual rainfall at the coastal locations cannot be used to predict river peak or low runoff. When comparisons are made for year-to-year trend or for rainfall and river flow above or below their own 30-year normals, agreement is no better than expected by chance; i.e. 14 out of 30 for Bangkok-Chao Phya, 13 out of 27 for Saigon-Mekong. The year to year trends of the rivers' flow also agrees 14 out of 30. The only comparisons between the two rivers which shows better than chance agreement is for the years which are above or below their own 30-year average flow. In this case there was agreement in 22 of the 30 comparisons.

From 1954 to 1960 the flow on both rivers was below the 30-year normal. Between 1935 and 1952 there were only three years when Mekong River flow was below normal; 1936, 1940 and 1944. Very low flow also occurred between 1931 and 1934. Departures from normal were not nearly so extreme on the Chao Phya. After the low-flow years of 1931 and 1932 above normal or normal flow occurred in all but four years (1936, 1940, 1941 and 1946) between 1933 and 1953. The good climatic agreement between the outflow of the two rivers indicates that river flow which integrates the total precipitation over the entire river watersheds is the best indicator of climatic year-to-year changes.

The annual average of the maximum flow year and of the minimum flow year and the monthly average of the maximum flow month and of the minimum flow month (from 30-year records) for both rivers are given in Table 1.

TABLE 1
RIVER FLOW IN m^3/sec

		Mekong		**Chao Phya**
Annual Average	Max. year (1937)	9637	(1942)	1735
	Min. year (1931)	6321	(1932)	486
Monthly Average	Max. month (Sept., 1937)	30,582	(Sept., 1942)	5343
	Min. month (Apr., 1960)	1044	(Apr., 1959)	22

For the Mekong the annual average of the maximum flow year was 1.5 times as large as that of the minimum year; the maximum monthly average was 29.2 times as high as that of the minimum month. For the Chao Phya the annual average of the maximum flow year was 3.6 times as large as that of the minimum year; the maximum monthly average was 242 times as great as that of the minimum month.

Notwithstanding the enormous flow of the Mekong River, surface salinity in the South China Sea as observed on the Naga Expedition was everywhere greater than 33‰ except in a narrow band along the South Viet Namese coast where less than 33‰ water can be attributed to Mekong and other river flow.

In the Gulf of Thailand, however, surface salinities were in general between 32‰ and 33‰ except where diluted by river runoff, increased at the surface by upwelling or from intrusion of South China Sea high salinity water into the mouth of the gulf and into the deep central trough. Therefore a criterion of 32‰ is used to distinguish rainfall and river runoff characteristics in the Gulf.

Although flow data are available for the Chao Phya River only in the Gulf, Naga cruise data indicates that contributions of fresh water from rivers emptying into both sides of the Gulf are sufficient to maintain salinities of less than 33‰ there even during the northeast monsoon period:

The Naga Expedition made only a limited number of hydrocasts in the Bight of Bangkok. All were made on cruises S7 (August, 1960) and S9 (November, 1960). Table 2 is a comparison of the salinities obtained at the northernmost Naga stations with those at the same sites in 1956 and 1957 taken from charts published by the Royal Thai Navy Hydrographic Department. Also included from the Thai data is the lowest salinity found in August and November at any of the four river mouths at the head of the Gulf. The lowest river mouth salinities were observed in the month of October; i.e., 6.00‰ in October, 1956, 1.00‰ in October, 1957.

TABLE 2
BIGHT OF BANGKOK SALINITIES

	Naga Expedition 1960			Royal Thai Navy Hydro. Dept. 1957		1956	
Month & Naga Station No.	**Station Location N**	**E**	**S ‰**	**Chart S ‰ At Naga Loc.**	**Lowest River Mouth ‰**	**Chart S ‰ At Naga Loc.**	**Lowest River Mouth ‰**
August,					15.00		8.00
S7-1	12°59'30"	100°35'15"	33.17	30.50-30.75		29.00-30.00	
S7-2	12 59 00	100 15 00	33.29	32.00-32.25		31.50-32.00	
S7-3	12 40 00	100 15 00	33.00	31.50		32.00-32.50	
S7-4	12 40 00	100 35 30	33.05	31.50-31.75		31.50-32.00	
November					19.00		8.00
S9-41	12 59 00	100 36 00	32.28	28 00-28.50		31.50	
S9-40	12 39 00	100 36 13	32.21	31.50		31.50	

Even at the peak of river flood, mixing of the emergent fresh water occurs so rapidly that special and intensified simultaneous surveys in this area are required for meaningful biological interpretation. Special attention should also be directed to the west coast of the South Viet Namese peninsula to determine the extent of flooding from various canals and rivers; the Song Cai Lon in the Baie de Rach-Gia, the Song Ong Doc and the Cua Song Bay Hap system. The contribution of runoff from this coast and of Mekong flood waters moving around Cape Camau into the Gulf are undoubtedly of prime importance to the biological productivity there.

From a consideration of rainfall and river runoff data one would expect low salinity surface water of less than 32‰ to occur in those periods not monitored by the Naga cruises;

1. off the east coast from Chantaburi to Kampot and possibly extending to Cape Camau from June to November,

2. off Prachuap Khirikhan, Chumphon and Ban Don from October to January,
3. off Songkhla and Kota Bharu from November to January,
4. central Gulf from September to November,
5. head of Gulf (north of 13 ° N) in all months.

River water not only diminishes the salinity, but it enriches the nutrient properties of the water and thus the biological productivity. Wind, on the other hand, can either enrich or diminish the nutrient content and productivity of the water because it is the major force causing vertical and horizontal circulation.

The series of wind, rainfall and river flow graphs point out the climatic variability surrounding the Gulf of Thailand and along the western shores of the South China Sea and indicate how important continuous climatic monitoring is if there is to be a full understanding of the relation between climate and the variability of fauna and flora of these waters.

Reference to these charts will be made in the following discussions of the surface and subsurface properties of the Gulf of Thailand waters observed on the Naga cruises.

Sea water is enriched not only by runoff from rivers but also by the upwelling of deep water which has been enriched by the decomposition of organic and inorganic wastes which descend through the water column to the bottom. During this process oxygen is consumed, and if depletion is sufficient, the water may become uninhabitable to organisms. It is important for biologists studying the shallow Gulf of Thailand to know to what extent its deeper water is reoxygenated by convergence and sinking and how often oxygen-poor deeper water is replaced. Biological collections may then be related to the oxygen distribution for a better understanding of the relative importance of nutrient enrichment by upwelling and oxygen depletion by decomposition.

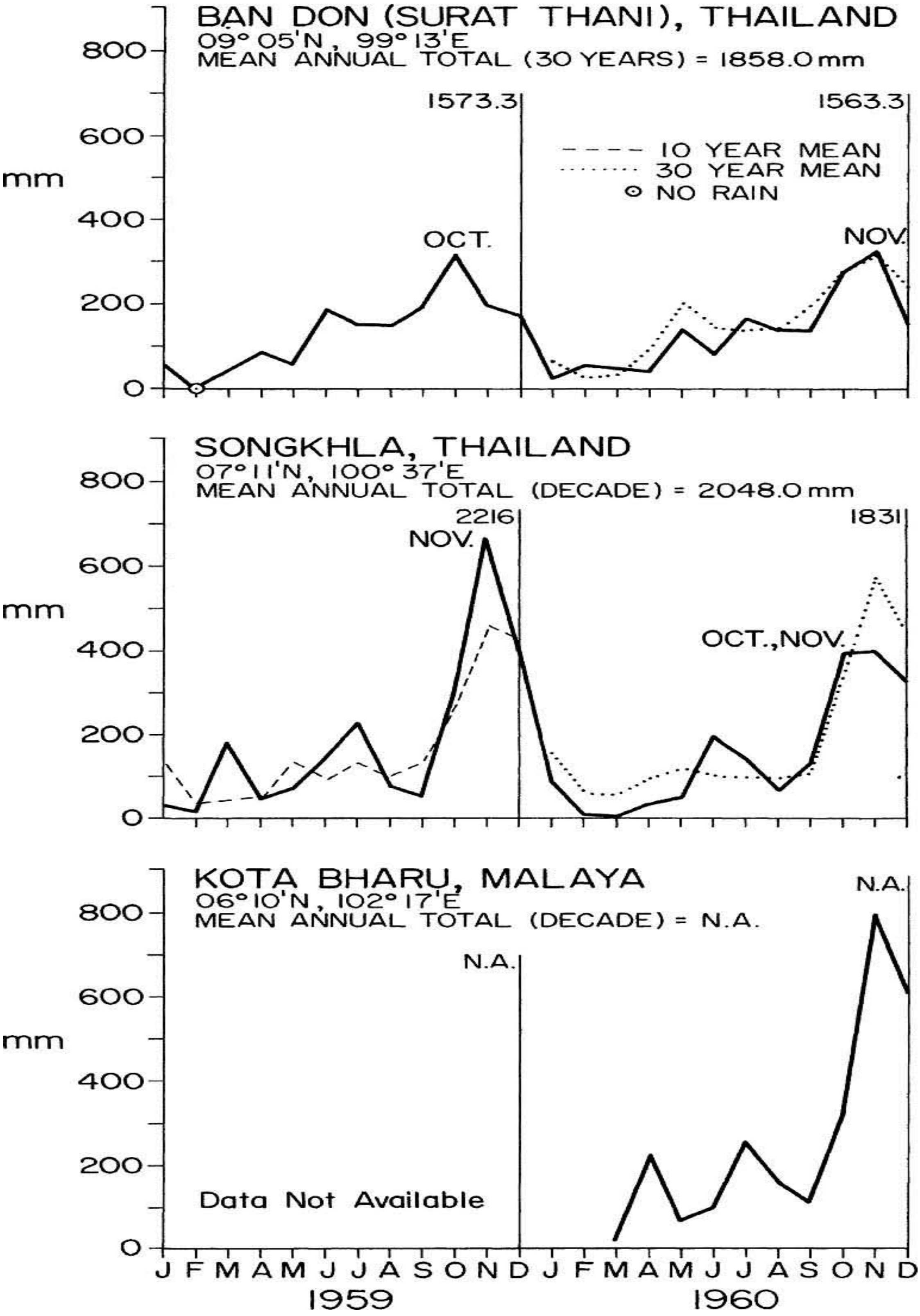

Figure 8. Monthly Rainfall.

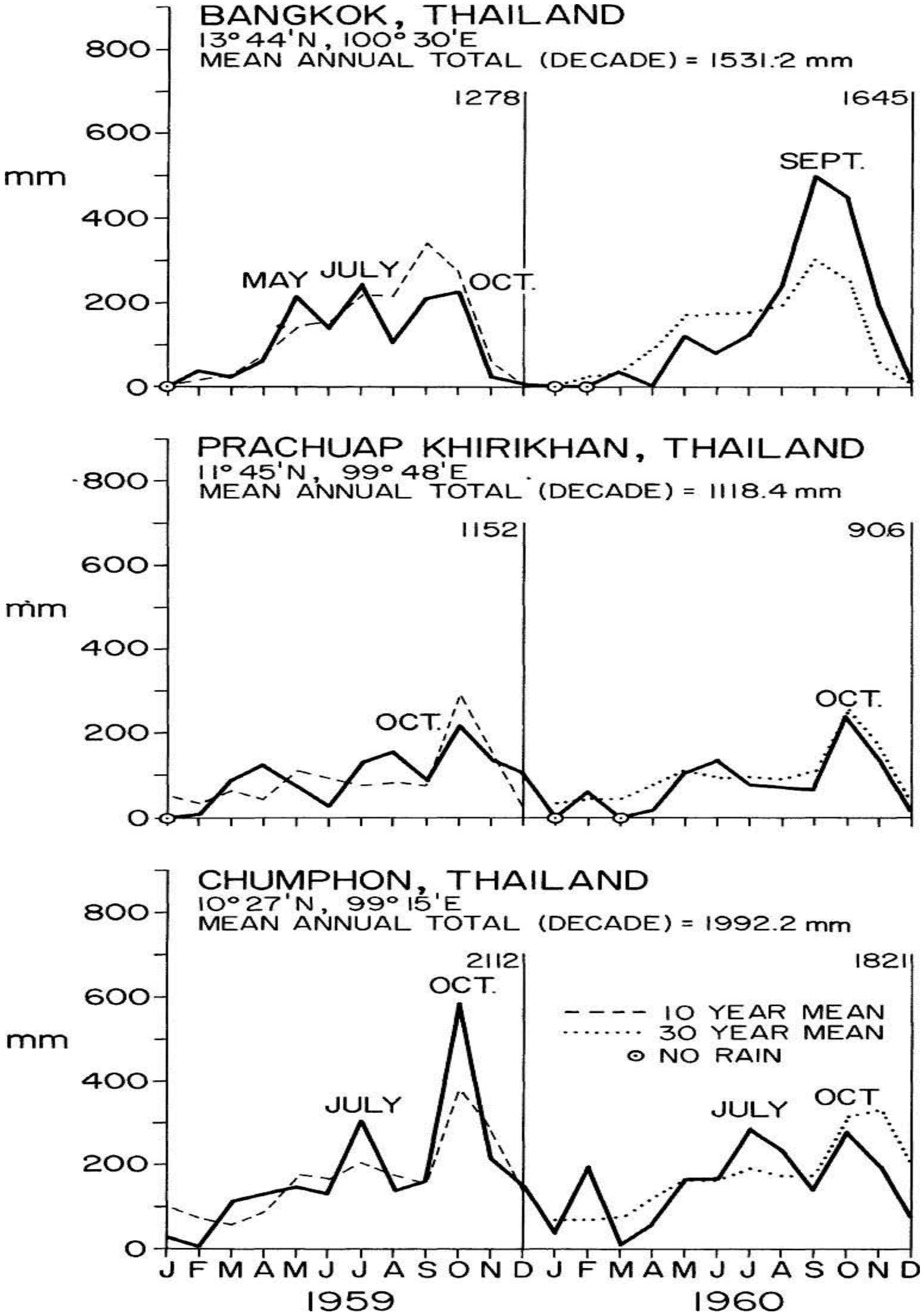

Figure 9. Monthly Rainfall.

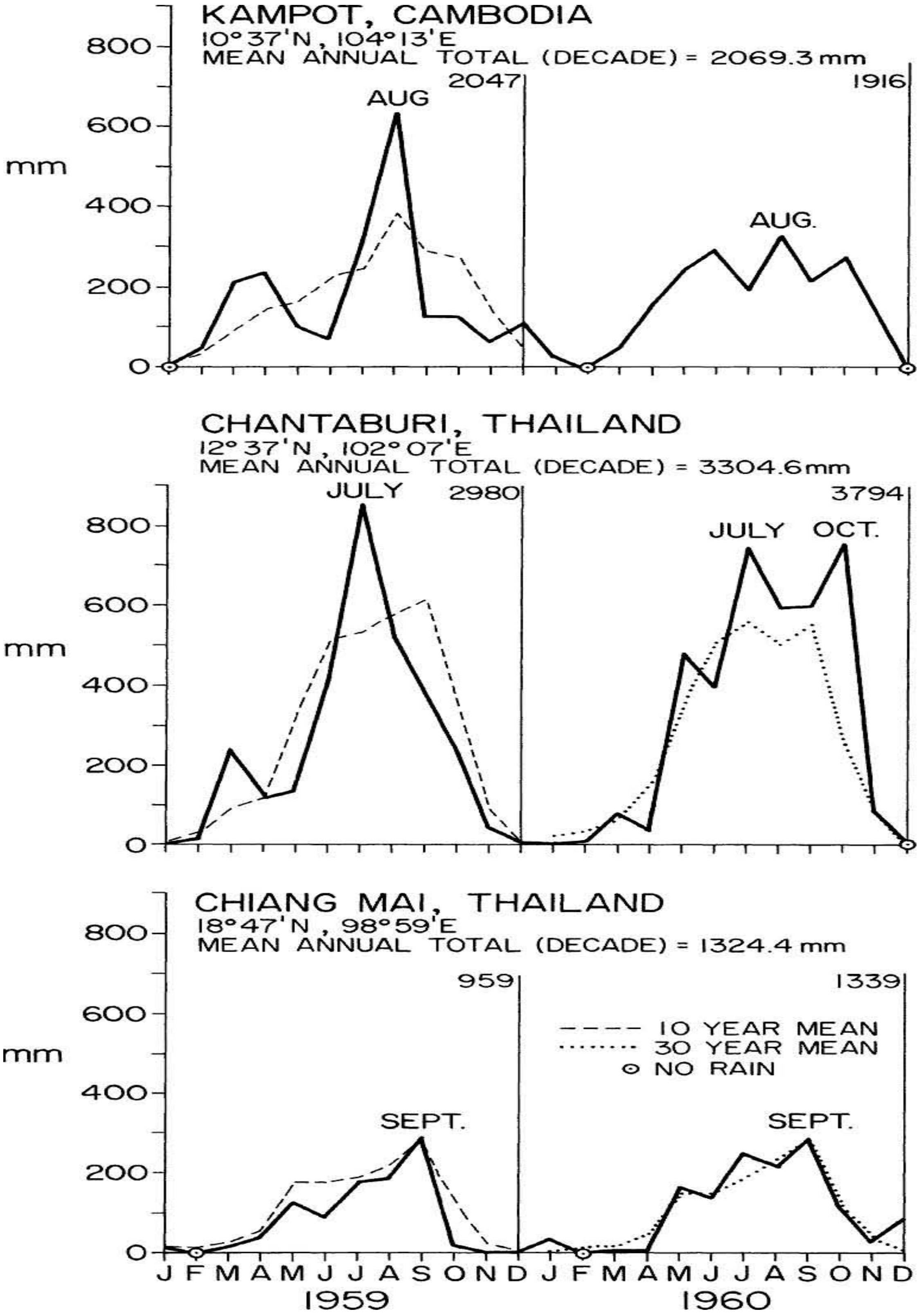

Figure 10. Monthly Rainfall.

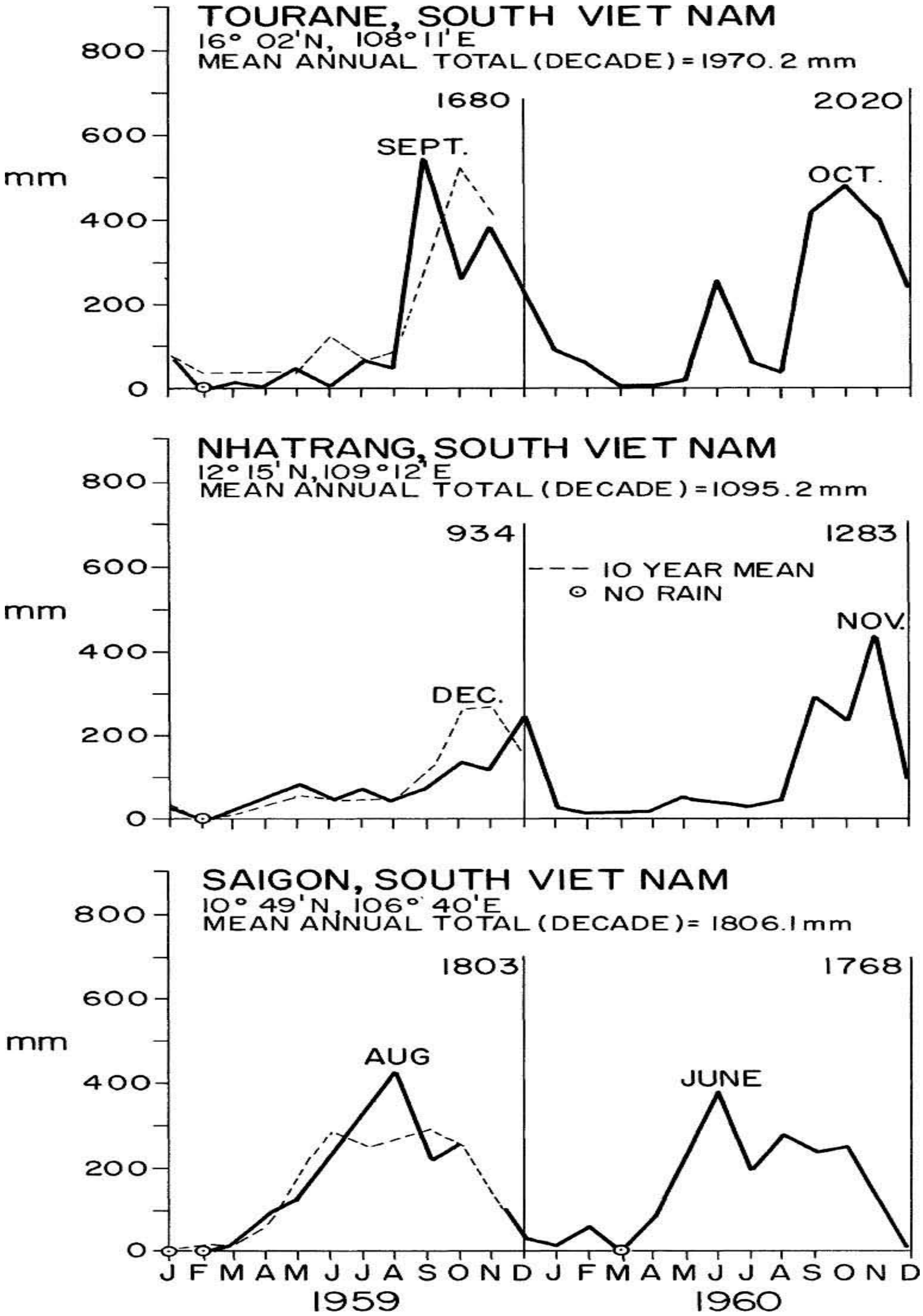

Figure 11. Monthly Rainfall.

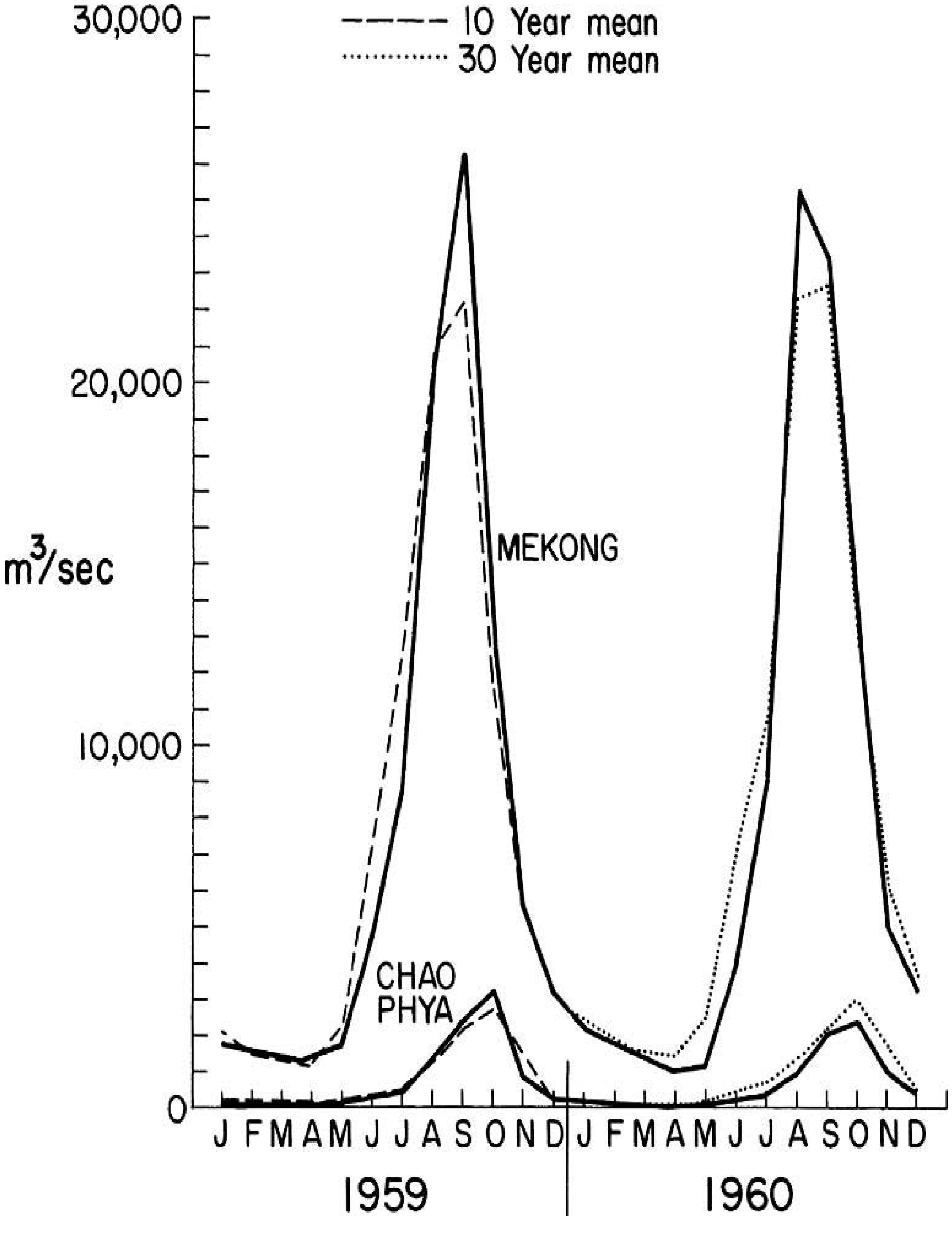

Figure 12. Mekong and Chao Phya Monthly Average Flow (1959-60) and Long Term Means.

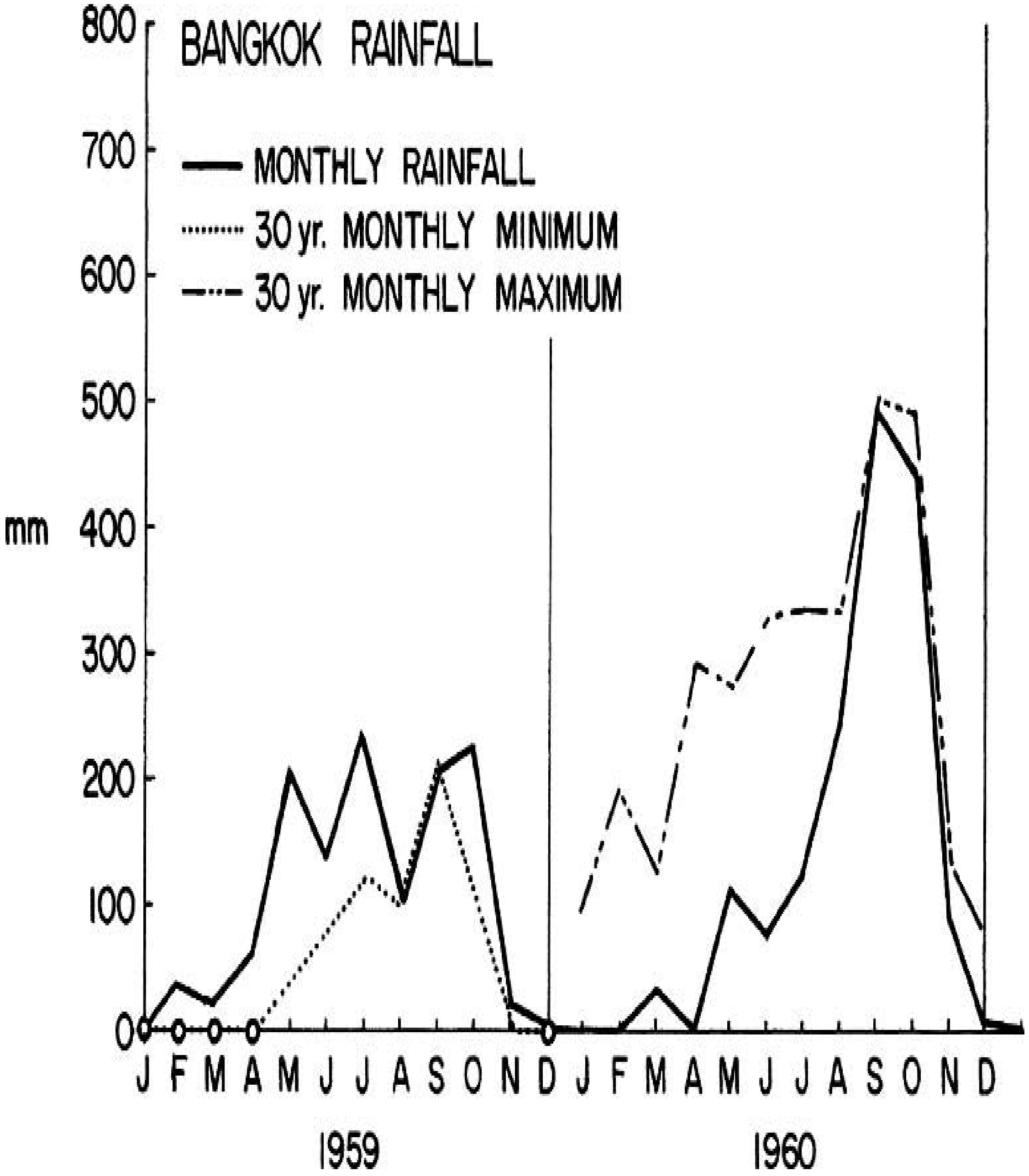

Figure 13. Bangkok Rainfall; monthly, 30-yr. monthly maxima and minima.

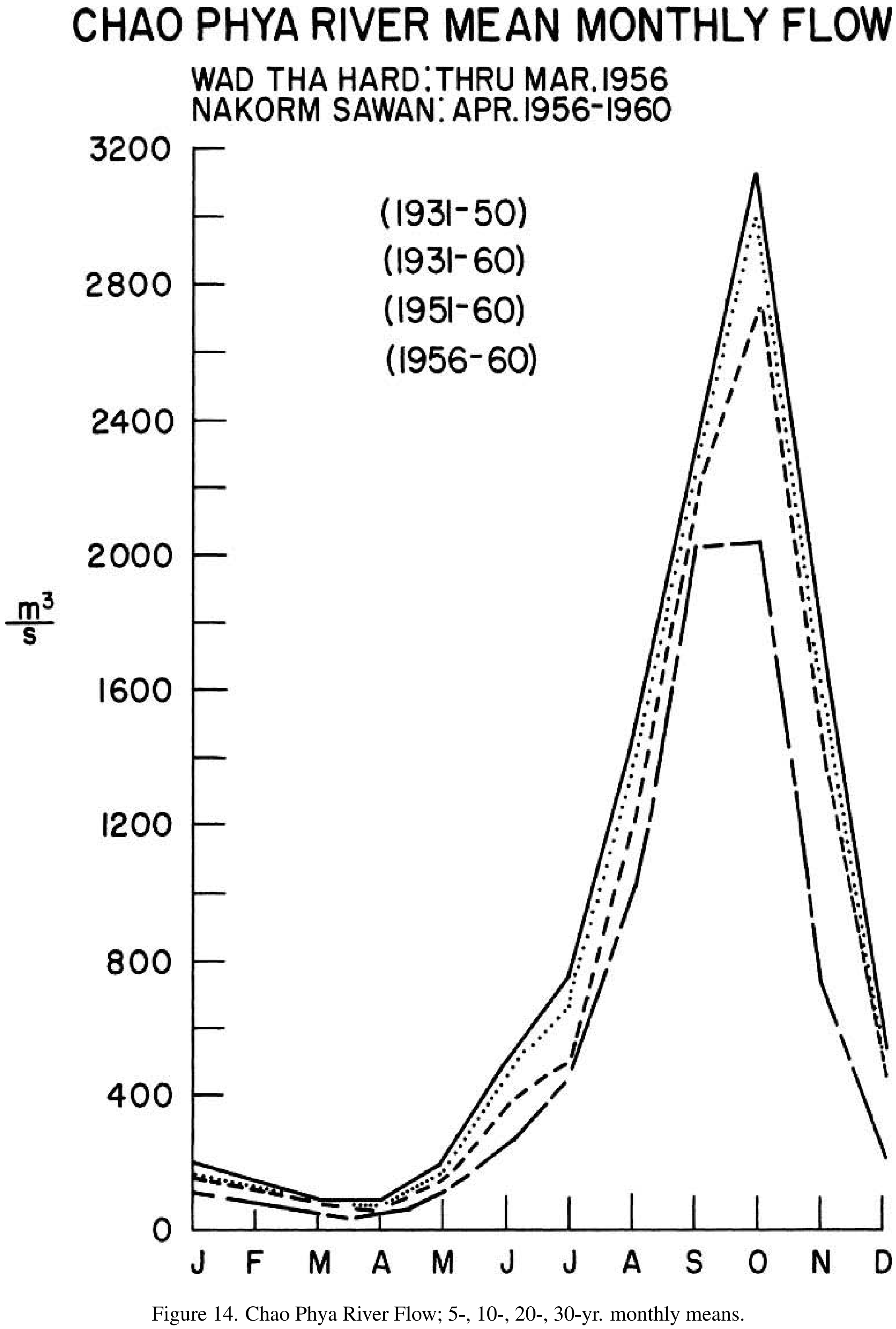

Figure 14. Chao Phya River Flow; 5-, 10-, 20-, 30-yr. monthly means.

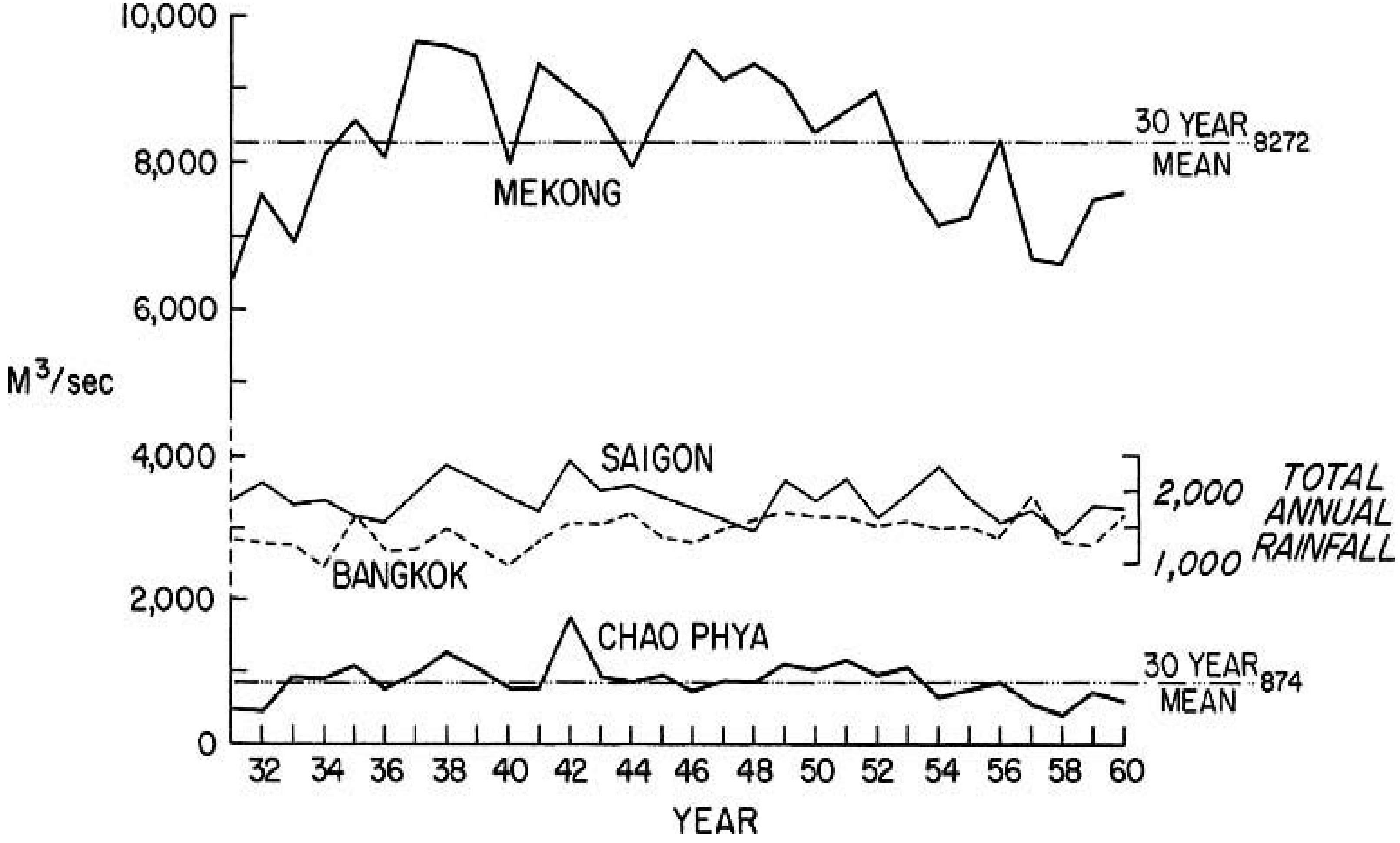

Figure 15. Comparison; annual river flow average with total annual rainfall.

TABLE 3

SUMMARY OF NAGA CRUISES; WINDS, RAINFALL, RIVER RUNOFF

Seasonal Wind Regime	Naga Cruise	Date	Survey Area	Cruise Lines	Wind Direction	Wind Speed (Knots)	Monthly Rainfall (mm)	Mean River Runoff (m^3/sec)
Transition (Fall)	S- 1	Oct 19-31, 1959	Gulf	1-2	Var.	0-11	(Oct) PK-220; C -586	CP 2,297 (max)
				3-5	WE, E, SE	2-22	(Oct) K -127; BD-316	M 13,222
Northeast Monsoon	S- 2	Nov 16-18, 1959	Gulf	1-3	NW, NE	5-12	(Nov) B - 21; PK-134	CP 341
				3-5	SW, W	2- 9	(Nov) K - 67	M 5,667
	S- 2	Nov 26- Dec 13, 1959	S.C.S.	1-3	NE	13-36	(Nov) T -382	
							(Dec) S - 31	M 3,158
				4-5	NE, E	2-21		
	S- 2	Dec 13-15, 1959	Gulf	1-3	E	0-10	(Dec) B -t ; PK-104	CP 230
				3-5	N, NW, NE	5-20	(Dec) K -110; So-399	
	S- 3	Jan 19-29, 1960	Gulf	1-2	Var., SW	0- 9	(Jan) P, B, Cb-0	CP 114
				3-5	E, SE	3-21	(Jan) C - 29, BD- 52	
							(Jan) K - 0	M 2,205
	S- 4	Feb 15-17, 1960	Gulf	1-3	SW, SE	1-10	(Feb) B - 0; C -199	CP 91
				3-5	E, SE	2-24	(Feb) K - 0	M 1,789
	S- 4	Feb 27- Mar 19, 1960	S.C.S.	1-3	E, NE	1-13	(Feb) N - 15; T - 53	CP 44
				4-6	NE, E	0- 9	(Feb) S - 54	M 1,375
Transition (Spring)	S- 5	Apr 21- May 2, 1960	Gulf	1	S, SE, SW	2-16	(Apr) B - 2; Cb- 37	
				2	S, SE, SW, NW	0-13	(Apr) C - 60	CP 30
				3	NW, SE, SW	2-13	(Apr) BD- 42	
				4	W, SW, S	0-14	(Apr) S - 71; K -154	M 1,004
				5	Var.	0- 8	(Apr) KB-230	
	S- 6	May 24-25, 1960	Gulf	2-3	SW	4-11	(May) PK-108; Cb-482	CP 83
				3-5	SW, W, NW	4-19	(May) So- 49; K -247	M 1,182
Southeast Monsoon	S- 6	May 29- Jun 24, 1960	S C S.	1	S, SE	3-15	(Jun) T -255	CP 204
				2	N, NW	0-29	(Jun) N - 42	M 3,901
				3-4	SW, W	5-22	(Jun) S -383	
				5-6	NW, W, SW	3-30		
	S- 7	Aug 2-14, 1960	Gulf	Bangkok Bight	S, W	9-13	(Aug) B -244	CP 924
				1-5	SW, W	0-26	(Aug) So- 64; Cb-593	M 25,294
Transition (Fall)	S- 8	Sept 12- Oct 6, 1960	S.C.S.	1	S, SE	0-11	(Sep) T -429	
				2	NW	0-26	(Sep) N -298	CP 2,032
				3-6	SW, W	0-30	(Sep) S -233	M 23,377
Northeast Monsoon	S- 9	Nov 9-24, 1960	Gulf	Bight	S, SW	4- 9	(Nov) B - 94	CP 936
				1	Var.	0- 7	(Nov) Cb-100; PK-135	M 4,952
				1a, E2, 2E, 2a	W, WE	0-14		
				W2, W3, S2-3	Var.	0-16	(Nov) C -197; BD-327	
				E3, 3a	Var.	0- 4		
				4	E, SE, NW	0-10	(Nov) K -143; So-395	
							(Nov) KB-800	
	S- 9a	Dec 8-14, 1960	Gulf	Bight	NE, N, NW	7-17	(Dec) B - 10	CP 379
				1-2	NE, NW	0-21	(Dec) PK- 2; Cb- 0	M 3,207
	S-10	Jan 11-13, 1961	Gulf	1-3	SW, E	4-13	(Jan) B - 0; Cb- 20	CP 139
				3-5	NE, E	5-22	n.a.	M 2,183
	S-10	Jan 24-29, 1961	S C.S.	1-4	E, NE, NW	4-22	(Jan) T -129; N - 48	
							(Jan) S - 2	
	S-10	Feb 9-12, 1961	Gulf	1-3	SW, SE, W	0- 9	n a	CP 80
				3-5	E, SE	2-22		M 1,758

Bangkok	B	Kota Bharu	KB	Chantaburi	Cb
Prachuap Khirikhan	PK	Tourane	T	Chao Phya	CP
Chumphon	C	Nhatrang	N	Mekong	M
Ban Don	BD	Saigon	S	Not available	n.a.
Songkhla	So	Kampot	K	Trace	t

CRUISE S1, OCTOBER 19-31, 1959, GULF OF THAILAND

The first Naga cruise took place in the transition month of October, 1959. The Cardamom Mountains appear to be the cause of the two wind regimes observed in the Gulf on cruise 1 and on later cruises during the northeast monsoon months. There is usually a different wind speed and direction south of Point Samit extending in most cases the width of the Gulf. Variable light winds were observed north of Point Samit along lines 1 and 2. South of Point Samit northeastern winds were already dominant along lines 3 and 4 with eastern and southeastern winds along line 5 and the western coast. Velocities reached 22 knots on a few stations.

During this month rainfall at the locations near the Gulf coast was normal at Ban Don (316 mm) and Songkhla (298 mm), lower than normal at Prachuap Khirikhan (220 mm) and Bangkok (225 mm) and higher than normal at Chumphon (586 mm). It was raining on stations 6a, 8b, 9 (line 5), 14, 14b, 15, 15a, 16 (line 4), and there was a slight drizzle on station 24 (between lines 2 and 3). In this month of maximum river runoff from the Chao Phya system and very high rainfall, low surface salinities (32‰) were observed along both coasts, and the 32‰ line was pushed south to the neck of the Bight of Bangkok (Figure 20). The ship's station rainfall did not dilute open Gulf salinities below 32.5‰.

In the composite, vertical and horizontal charts (Figures 17, 18 and 20) the low salinity surface water can be seen to be confined to a layer less than 10 m thick except in two places: at the west end of line 2 where the low salinity water extended to the bottom (40 m) and on the east end of line 4 where it reached 20 m. Water of high salinity (above 33‰) and low temperature (below 28°C) filled the central trough. This body of water was also associated with low oxygen values on lines 2 and 4, but in the center of lines 3 and 5 the oxygen content at 50 m was greater than 4.0 ml/l.

Criteria for evidence of vertical motion in the Gulf for each of the cruises will be as follows:

> divergence, upwelling—slope of isolines rises toward the surface as the coast is approached; salinity above 33‰ found above 30 m,
>
> convergence, sinking, downwelling—slope of isolines descends from surface; low salinity, high oxygen water found below 30 meters; subsurface temperature inversions.

In the vertical sections there is evidence of upwelling of high salinity, low oxygen water around the eastern side of the Gulf on lines 3 and 4 between Phu Quoc Island and Point Samit. The 30 m salinity distribution indicates some upwelling along the west coast between Songkhla and Kota Bharu. Low oxygen values were also observed at 30 m in this area. The 30 m salinity distribution and the dome seen in the salinity isolines in the vertical sections indicate upwelling had occurred at the center of line 1 (station 34) about 30 miles south of Cape Liant and on line 2 (stations 26 and 28). Very low oxygen values (2.72 and 2.65 ml/l) were observed below 45 m (Figure 19) at these two stations associated with salinities of 33.31 and 33.73‰. Low oxygen water was not observed in the shallower depths on line 1. Oxygen poor water (2.74 to 3.05 ml/l) was also found near the bottom along the entire length of line 4.

There was piling up and downwelling of fresh, highly oxygenated water on the west end of line 2 near Sawee Bay.

On the west end of line 3 near Laem Talumphuk a temperature inversion appeared at the bottom where water of high salinity, temperature and oxygen had previously sunk beneath the cooler fresh water runoff. Intermediate depth temperature inversions (Figures 16, 18) and high oxygen values suggest that convergence and sinking had taken place also along the central part of line 3.

The relation of the upwelling and sinking areas to the observed wind distribution is not altogether clear. The upwelling off Kota Bharu and Cape Liant may be residual from the southwest monsoon regimes while that on the east coast was just beginning with the onset of the northeast monsoon (see also discussion on page 103). The low salinity pile up at the west end of line 2 may be due to lack of wind and to the exceedingly high rainfall and runoff that occurred in the area. There are convergent winds on lines 2 and 3, but winds on line 2 are so weak that they hardly seem sufficient to account for the convergent sinking seen on line 3 which may instead be associated with convergent horizontal flow.

The horizontal circulation was inferred from the horizontal charts of temperature, salinity and sigma-t (Figures 20, 21 and 22).

At the surface the density distribution indicates a counter-clockwise circulation with inflow along the east coast and outflow along the west coast. In the central areas the very slight density gradients indicate sluggish, if any, net circulation. At 30 meters the density distributions indicate a reversal of flow on the east coast from that at the surface and the development of a clockwise eddy off Phu Quoc Island. A weak counter-clockwise gyre appeared in the inner section of the Gulf. The strong density gradient at the west end of line 2 is associated with pile up of fresh water. At 50 meters the density gradients were greater than at 30 meters and in the central Gulf greater than at the surface. They indicate inflow on the western side that broke down into a convergence zone at line 4. A clockwise cell was present on the eastern portion of line 3 and a counter-clockwise cell on the western side of line 2.

The horizontal oxygen distributions at each level (Figures 20, 21, 22) are in agreement with the inferred circulation.

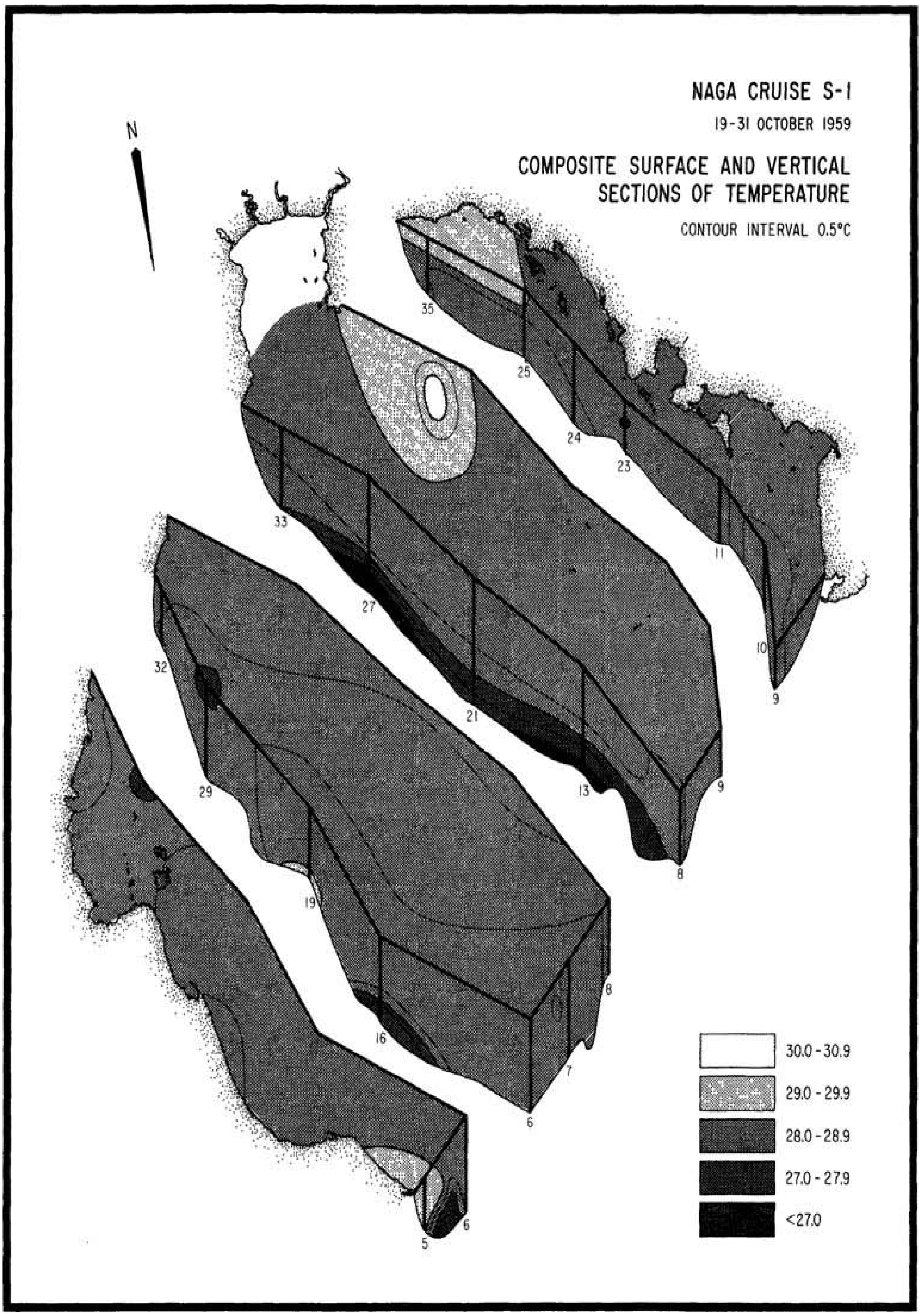
NAGA CRUISE S-1
19-31 OCTOBER 1959
COMPOSITE SURFACE AND VERTICAL SECTIONS OF TEMPERATURE
CONTOUR INTERVAL 0.5°C
N
35
25
24
23
11
10
9
33
27
21
13
9
8
32
29
19
16
8
7
6
5
6
30.0 - 30.9
29.0 - 29.9
28.0 - 28.9
27.0 - 27.9
<27.0

Figure 16.

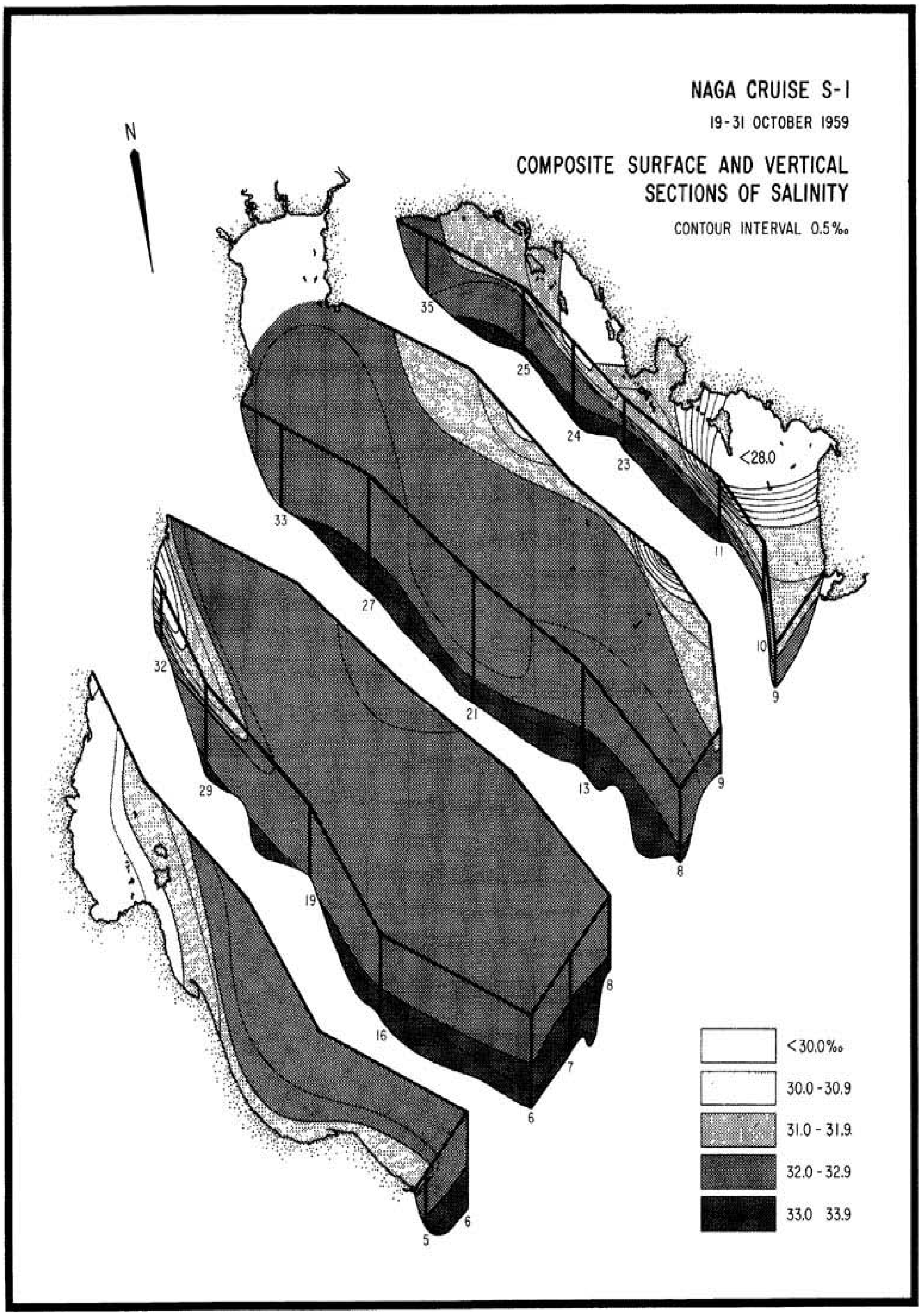
NAGA CRUISE S-I
19-31 OCTOBER 1959
COMPOSITE SURFACE AND VERTICAL SECTIONS OF SALINITY
CONTOUR INTERVAL 0.5‰
N
35
25
24
23
<28.0
11
10
9
33
27
21
13
9
8
32
29
19
16
8
7
6
5
6
<30.0‰
30.0-30.9
31.0-31.9
32.0-32.9
33.0 33.9

Figure 17.

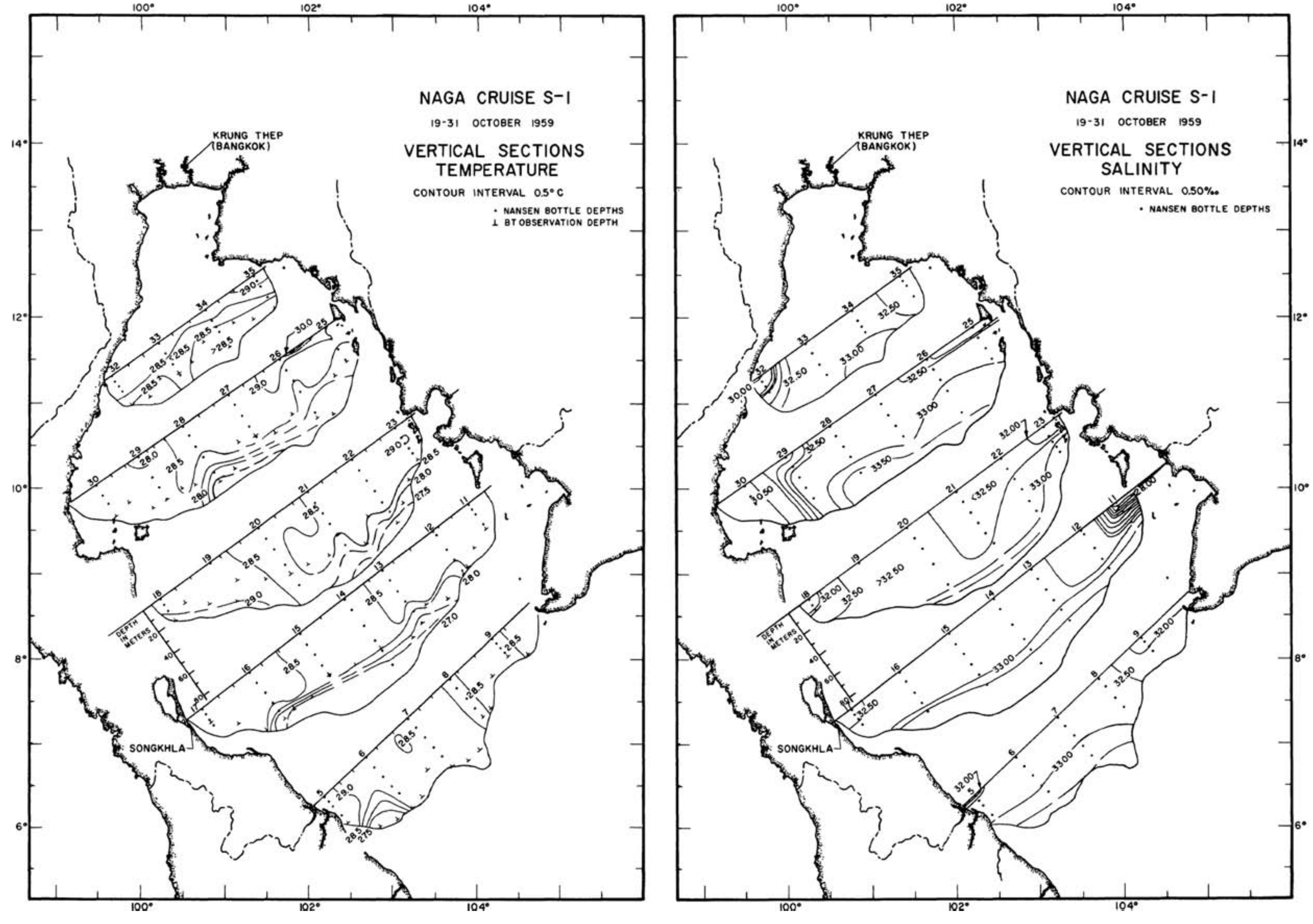
NAGA CRUISE S-I
19-31 OCTOBER 1959
VERTICAL SECTIONS
TEMPERATURE
CONTOUR INTERVAL 0.5°C
• NANSEN BOTTLE DEPTHS
⊥ BT OBSERVATION DEPTH
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
20
40
60
80
100°
102°
104°
14°
12°
10°
8°
6°
NAGA CRUISE S-I
19-31 OCTOBER 1959
VERTICAL SECTIONS
SALINITY
CONTOUR INTERVAL 0.50‰
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS

Figure 18.

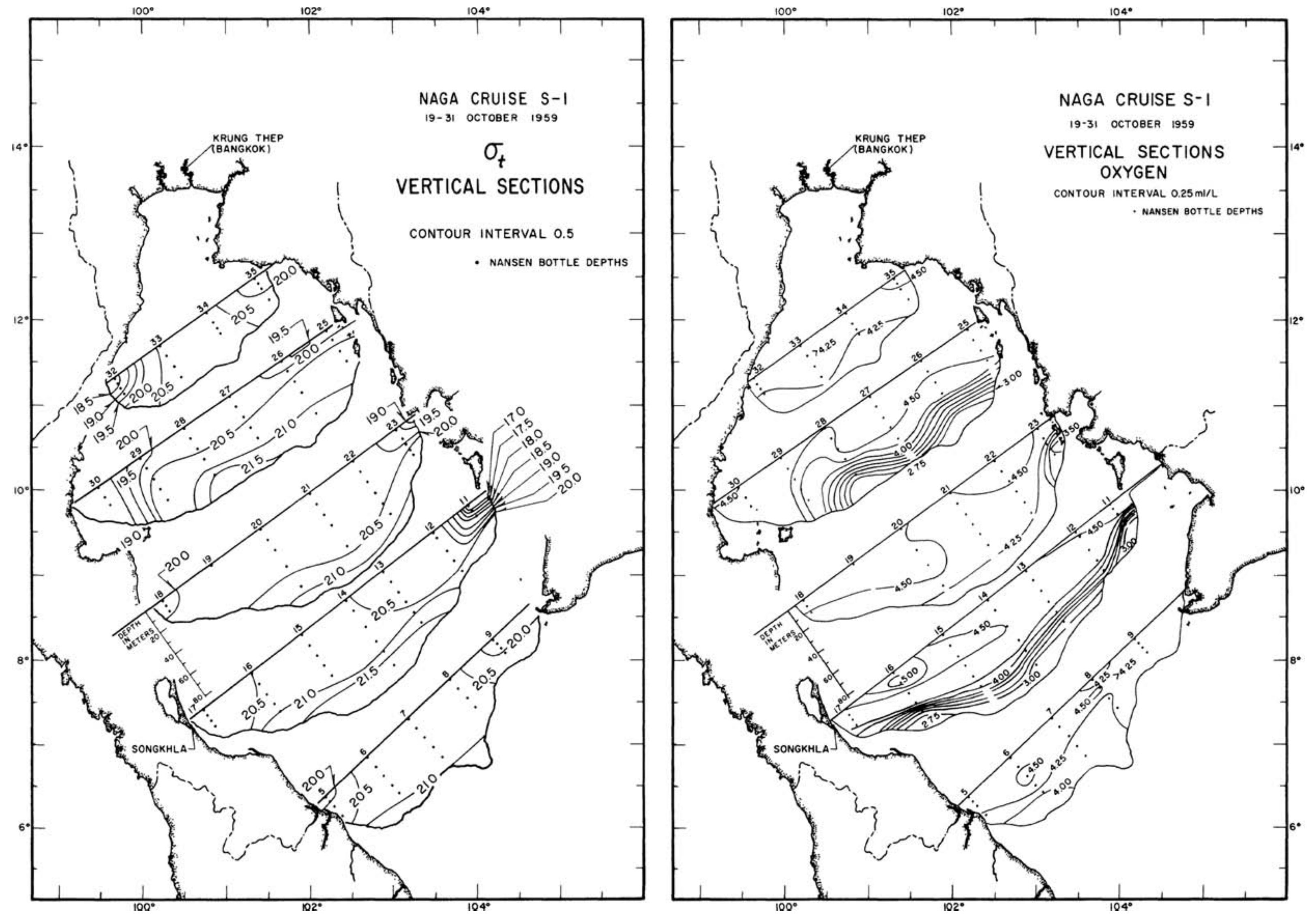
NAGA CRUISE S-1
19-31 OCTOBER 1959
σ_t
VERTICAL SECTIONS
CONTOUR INTERVAL 0.5
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
20
40
60
80
100°
102°
104°
14°
12°
10°
8°
6°
NAGA CRUISE S-1
19-31 OCTOBER 1959
VERTICAL SECTIONS
OXYGEN
CONTOUR INTERVAL 0.25 ml/L
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS

Figure 19.

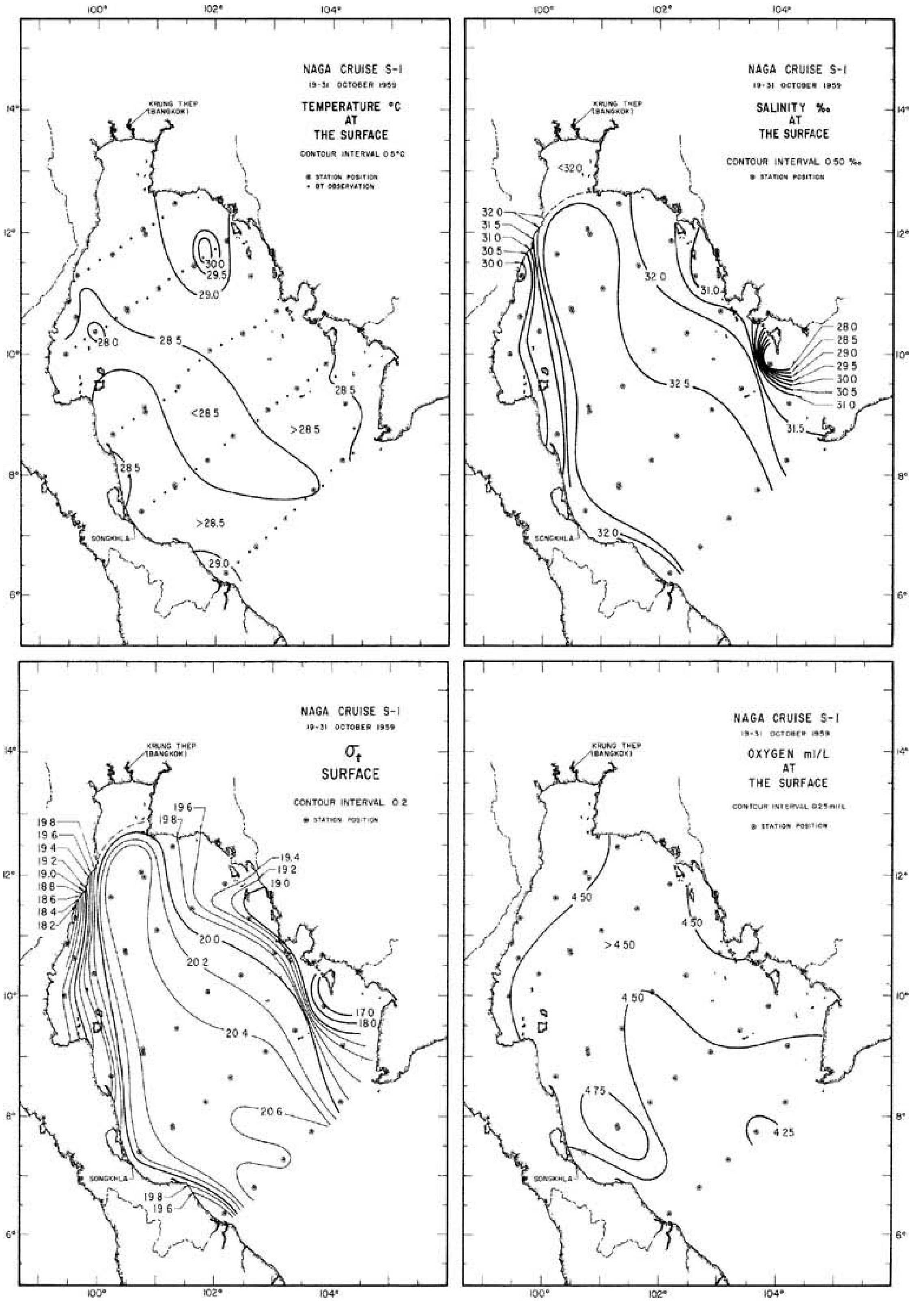

Figure 20. Horizontal Distributions at Surface.

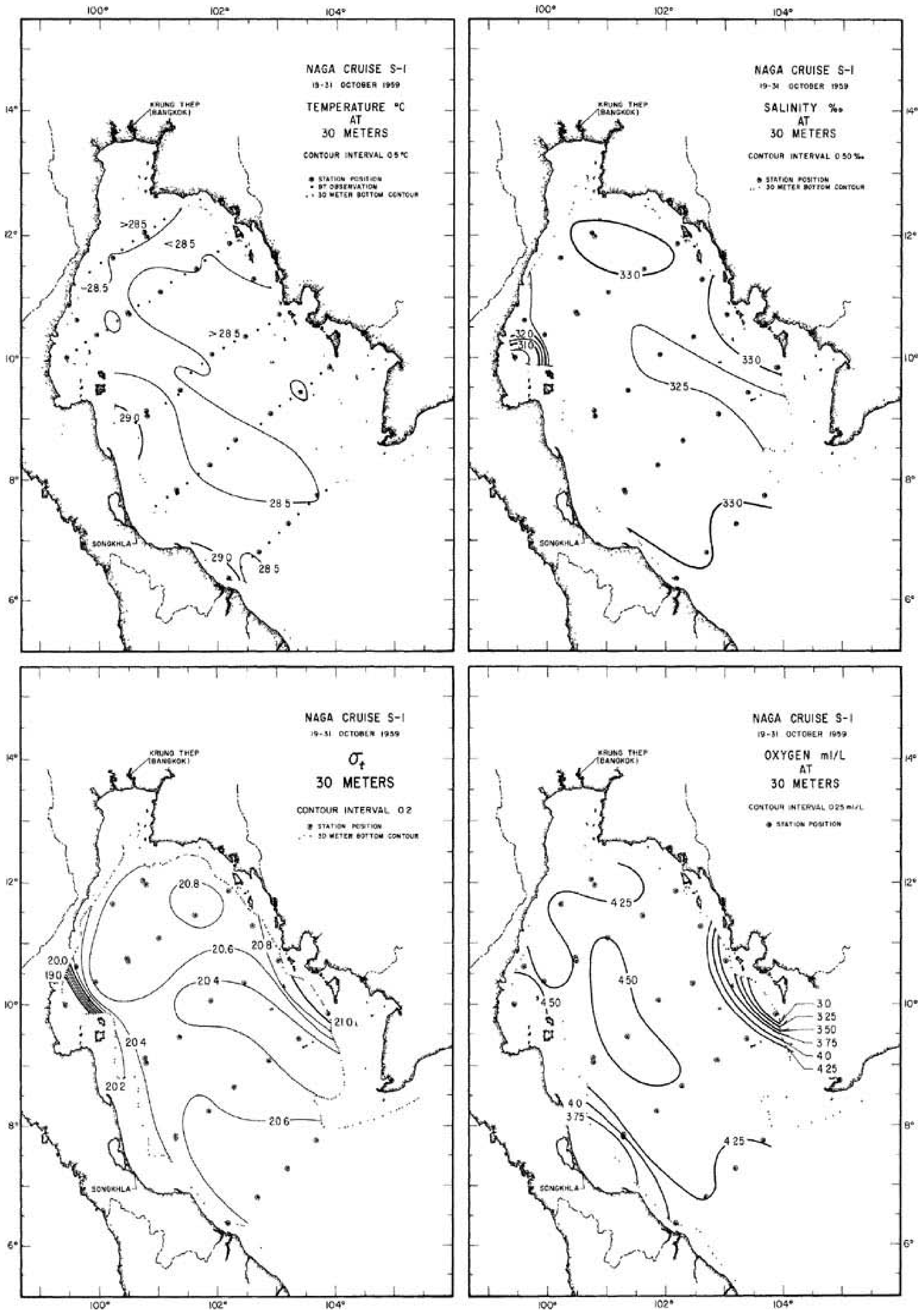

Figure 21. Horizontal Distributions at 30 m.

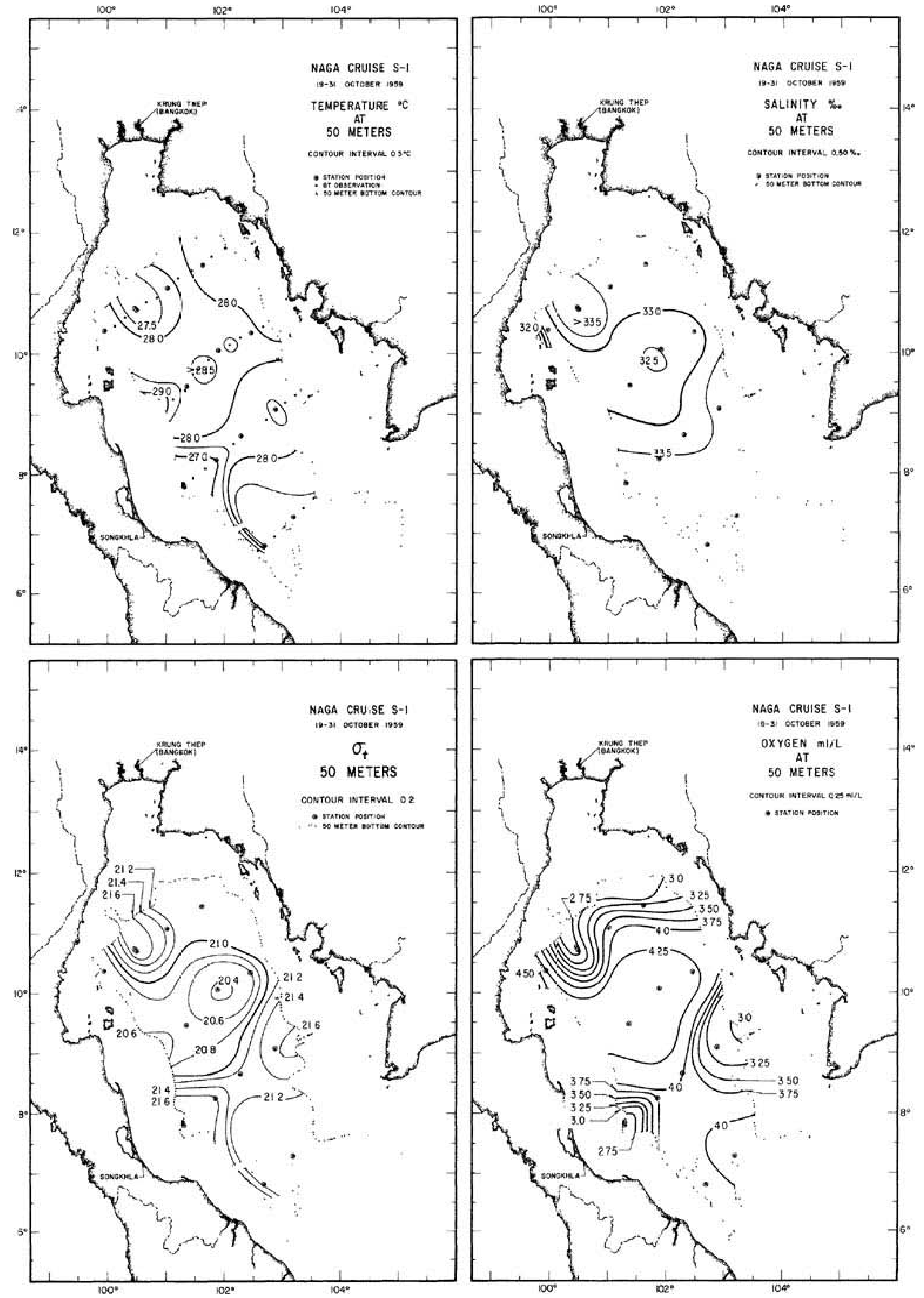

Figure 22. Horizontal Distributions at 50 m.

CRUISE S2, November 16-18,1959, Gulf of Thailand,
November 26-December 13, South China Sea,
December 13-15, Gulf of Thailand.

The winds on the November Gulf leg of cruise S2 were north and northeast as far south as Point Samit with speeds of 5 to 12 knots; to the south the winds shifted to the southeast at speeds of 2 to 9 knots.

Rainfall during November, 1959, was lower than normal at Prachuap Khirikhan (134 mm), Bangkok (21 mm), Chumphon (218 mm) and Kampot (67 mm), but salinities were not observed on this leg. When the ship entered the South China Sea the northeast monsoon was in full swing with speeds up to 36 knots. On line 4 and on the connecting line from 4 to 5 wind speeds less than 5 knots occurred, and there were some slight shifts in direction. Monthly rainfall was normal at Tourane (218 mm) and Saigon (31 mm) in December, 1959, and higher than normal at Nhatrang (242 mm) and Kampot (110 mm). Mekong River runoff was greatly diminished from the October high. On this cruise only at inshore station 32 of line 5 just east of Cape Camau was a salinity of less than 32‰ observed at the surface. This shallow shelf station showed 31.46‰ at the surface and 32.94‰ at 20 m—the bottom bottle. This dilution appears to be from the Mekong River outflow carried south and kept near shore by the northeast winds. Surface salinity at station 19 somewhat farther offshore from Saigon was 33.31‰ with little dilution apparent. The typical offshore surface salinities in the South China Sea ranged from 33.19 to 33.80‰. At depths between 50 and 100 meters water reached salinities greater than 34‰, but water of such high salinity did not appear at shallow shelf stations. However, at two offshore stations, 12 and 23, surface salinities less than 33‰ were observed.

The return trip through the Gulf on this S2 cruise again indicated the effect of the land configuration on wind direction. On this leg east winds were observed as far north as Point Samit followed by weak north, northwest and northeast winds. Rainfall at the Gulf coast locations in December, 1959, was normal at Bangkok (T) and Chantaburi (2 mm), lower than normal at Chumphon (146 mm), Ban Don (172 mm) and Songkhla (399 mm) and higher than normal at Prachuap Khirikhan (104 mm) and Kampot (110 mm).

The temperature profiles (Figure 23) along the ship's track on cruise S2 through the Gulf, November 16-17, 1959, indicate a considerable change in the water column from those recorded on cruise S1. Water of temperature greater than 29 °C had been observed on cruise S1 at the surface in the northeast corner of the Gulf extending out to line 2. This water must have been mixed with the high salinity water upwelled in the area in order to raise the density sufficiently for this mixed water to sink below the surface where it was observed along the track in November as a temperature inversion between Cape Liant and Point Samit. The highest subsurface temperature was 29.7 °C. By the time of the return trip one month later, December 13-15, 1959, the temperature inversions had become less pronounced; temperatures had decreased leaving little subsurface water higher than 29 °C. Decreasing temperature with depth, that is, isothermal conditions, prevailed at both ends of the track with the lowest temperature of 26.9 °C observed off Cape Camau and a sharp temperature gradient of 1.5 °C across water entering the Gulf.

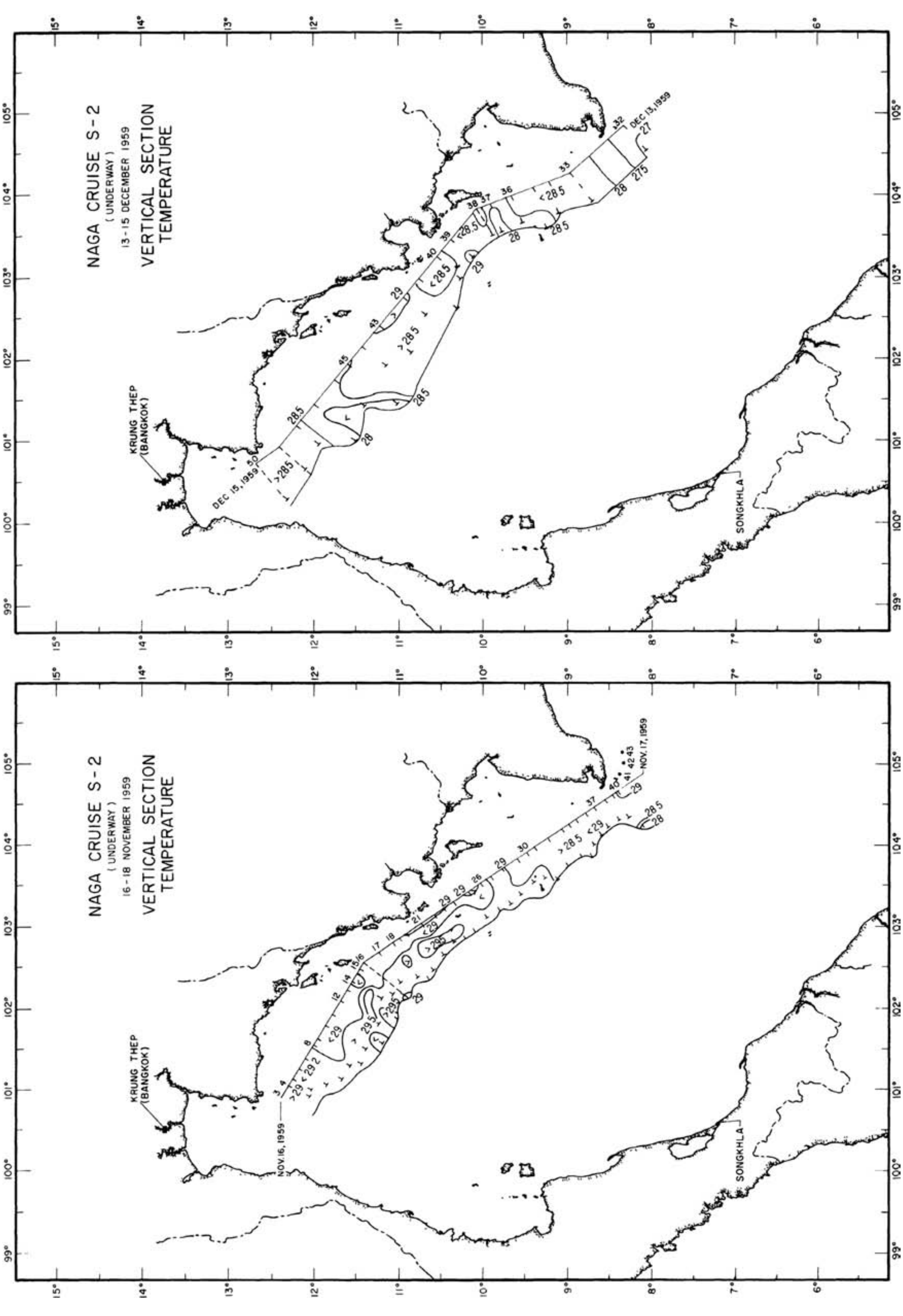
NAGA CRUISE S-2
(UNDERWAY)
13-15 DECEMBER 1959
VERTICAL SECTION
TEMPERATURE
KRUNG THEP
(BANGKOK)
SONGKHLA
DEC 15, 1959
DEC 13, 1959
NAGA CRUISE S-2
(UNDERWAY)
16-18 NOVEMBER 1959
VERTICAL SECTION
TEMPERATURE
KRUNG THEP
(BANGKOK)
SONGKHLA
NOV. 16, 1959
NOV. 17, 1959

Figure 23.

CRUISE S3, JANUARY 19-30, 1960, GULF OF THAILAND.

During cruise S3 the observed winds were similar in strength but more consistently eastern than during cruise S1 (Figure 4). They were weak and variable on lines 1 and 2 in the inner Gulf. On most of line 5 the winds were northeast shifting toward the east along the east coast and most of the central portions of lines 3 and 4 and to the southeast as the ship approached the west coast of the Gulf. Wind speeds on these lines ranged between 10 and 20 knots, averaging greater than 10 knots.

Rainfall during January, 1960, at the Gulf coast locations was normal at Bangkok (0), higher than normal at Kampot (25 mm), lower than normal at Chantaburi (1 mm), Prachuap Khirikhan (0), Chumphon (36 mm), Ban Don (24 mm) and Songkhla (88 mm). In spite of the fact that January is a month of low rainfall and moderate river runoff, central Gulf surface salinities were lower than on any of the other cruises. Salinities greater than 32‰ remained in the northeast below Sattahip and Chantaburi, the main outflow of low salinity water coming south along the western shore. A wedge of high salinity surface water greater than 33.5‰ southwest of Cape Camau was transported by the southeast winds into the mouth of the Gulf, but a remnant of the low salinity water found on cruise S1 was observed at station 7 north of Cape Camau between lines 4 and 5.

The vertical sections (Figures 26 and 27) and the horizontal distributions (Figures 28, 29 and 30) of cruise S3 indicate little wind-induced upwelling. On the east end of line 3 the slope of the isolines indicates some upwelling tendency which may be a residual effect previously noticed on cruise S1. However salinities and temperatures were lower and oxygen values higher in this area on cruise S3 than on cruise S1.

In the area south of Cape Liant salinities greater than 33‰ were again found on line 2 (station 23), the 33.5‰ salinity water found above 40 m. Oxygen values decreased rapidly below 20 m to 1.19 ml/l at 46 m. The areal extent of the high salinity water observed on cruise S3 was smaller than on cruise S1; the deep salinities were lower (33.53‰), the oxygen values lower and the temperatures approximately the same.

The high salinities and low oxygen concentrations observed on line 2 were not found at any depth on line 3 and only below 50 m on line 4. On cruise S3 the lowest oxygen concentration (1.94 ml/l; salinity of 32.91‰) at 50 m was observed in the center of the trough. On cruise S1 the lowest oxygen concentrations were on the slopes of the trough, yet oxygen was depleted to less than 3.05 ml/l along the full length of line 4.

Convergence and downwelling appear to have effected the distribution of properties along portions of lines 3 and 4 similarly to that described for cruise Sl.

The high salinity (33.5 to 33.95‰), high oxygen (4.25 to 4.57 ml/l) water observed on line 5 was an intrusion at all depths of well-mixed South China Sea water.

On all lines temperature inversions with depth were found. Density distributions, however, were stable. The surface water appears to have been cooled by the lower air temperatures associated with the north winds, but complete mixing had not yet taken place.

The horizontal circulation determined from cruise S3 horizontal temperature, salinity and sigma-t distributions (Figures 28, 29 and 30) differed from that of cruise S1. The circulation was dominated at all levels by an intrusion of homogeneous high salinity, low temperature water from the north and east around Cape Camau. This water did not penetrate into the Gulf as far as line 4, but instead flowed out of the Gulf slightly west of the center of line 5. The main outflow of water from the head of the Gulf was southeastward along the central axis of the Gulf where it diverged beyond line 2, one eddy curving sharply east then north. The main flow curved first sharply west and north and then again curved sharply southward out of the Gulf along the west coast. This portion of the circulation system contained water of much lower salinity than that of the eddy at the head of the Gulf or of the intrusion of South China Sea water. The convergence of the waters from two different sources accounts for the redoubled course of direction of flow of the low salinity water. Circulation at 30 and 50 meters was similar, but both levels lacked the dominant flow to the southeast down the axis of the Gulf suggested by the surface distributions.

Horizontal oxygen distributions at all levels are in agreement with the inferred circulation.

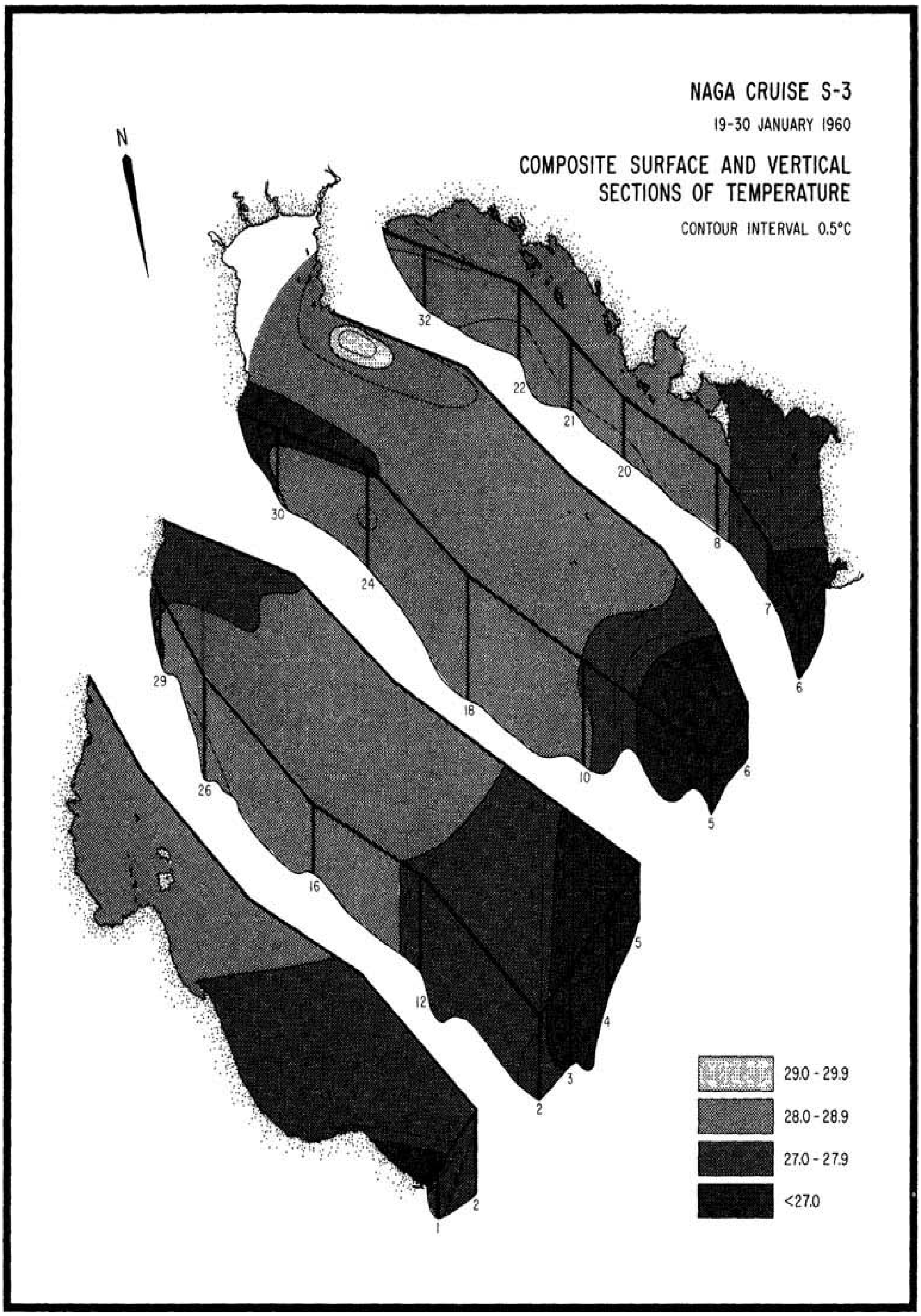
NAGA CRUISE S-3
19-30 JANUARY 1960
COMPOSITE SURFACE AND VERTICAL SECTIONS OF TEMPERATURE
CONTOUR INTERVAL 0.5°C
N
32
22
21
20
8
7
6
30
24
18
10
6
5
29
26
16
12
5
4
3
2
1
2
29.0 - 29.9
28.0 - 28.9
27.0 - 27.9
<27.0

Figure 24.

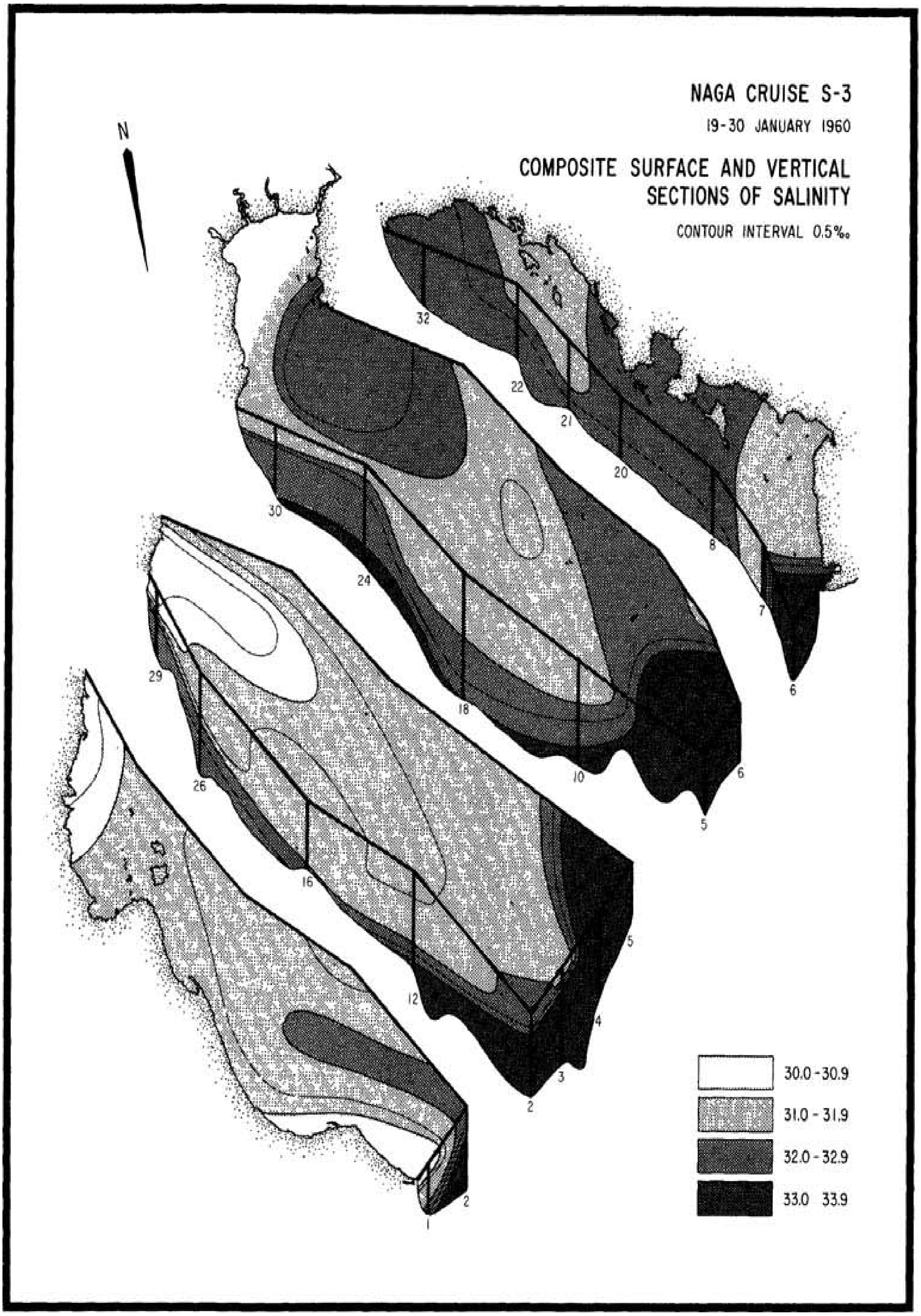
NAGA CRUISE S-3
19-30 JANUARY 1960
COMPOSITE SURFACE AND VERTICAL SECTIONS OF SALINITY
CONTOUR INTERVAL 0.5‰
N
32
22
21
20
8
7
6
30
24
18
10
6
5
29
26
16
12
5
4
3
2
1
2
30.0-30.9
31.0-31.9
32.0-32.9
33.0 33.9

Figure 25.

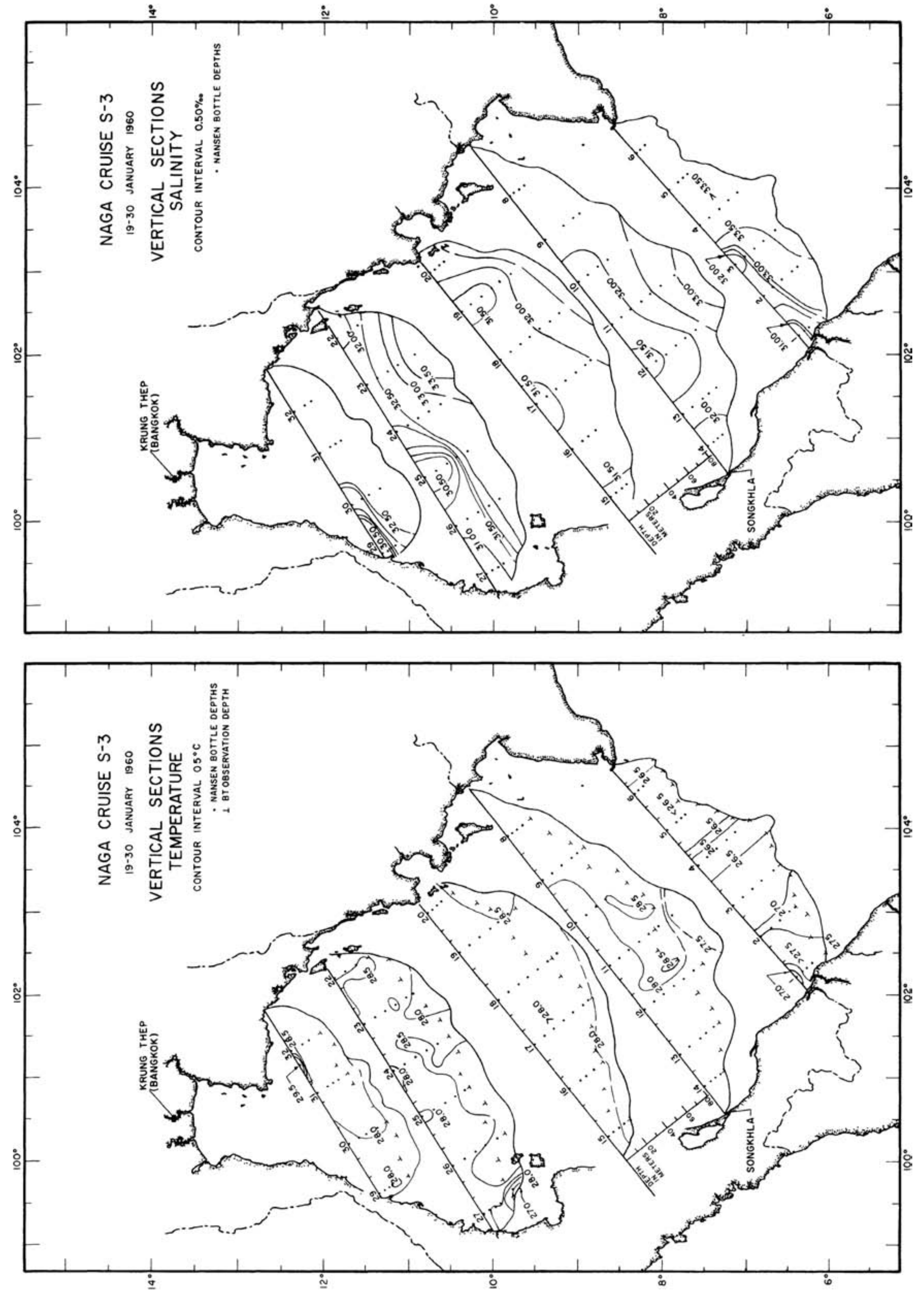
NAGA CRUISE S-3
19-30 JANUARY 1960
VERTICAL SECTIONS
TEMPERATURE
CONTOUR INTERVAL 0.5°C
· NANSEN BOTTLE DEPTHS
⊥ BT OBSERVATION DEPTH
NAGA CRUISE S-3
19-30 JANUARY 1960
VERTICAL SECTIONS
SALINITY
CONTOUR INTERVAL 0.50‰
· NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
20
40
60
80
100°
102°
104°
6°
8°
10°
12°
14°

Figure 26.

]

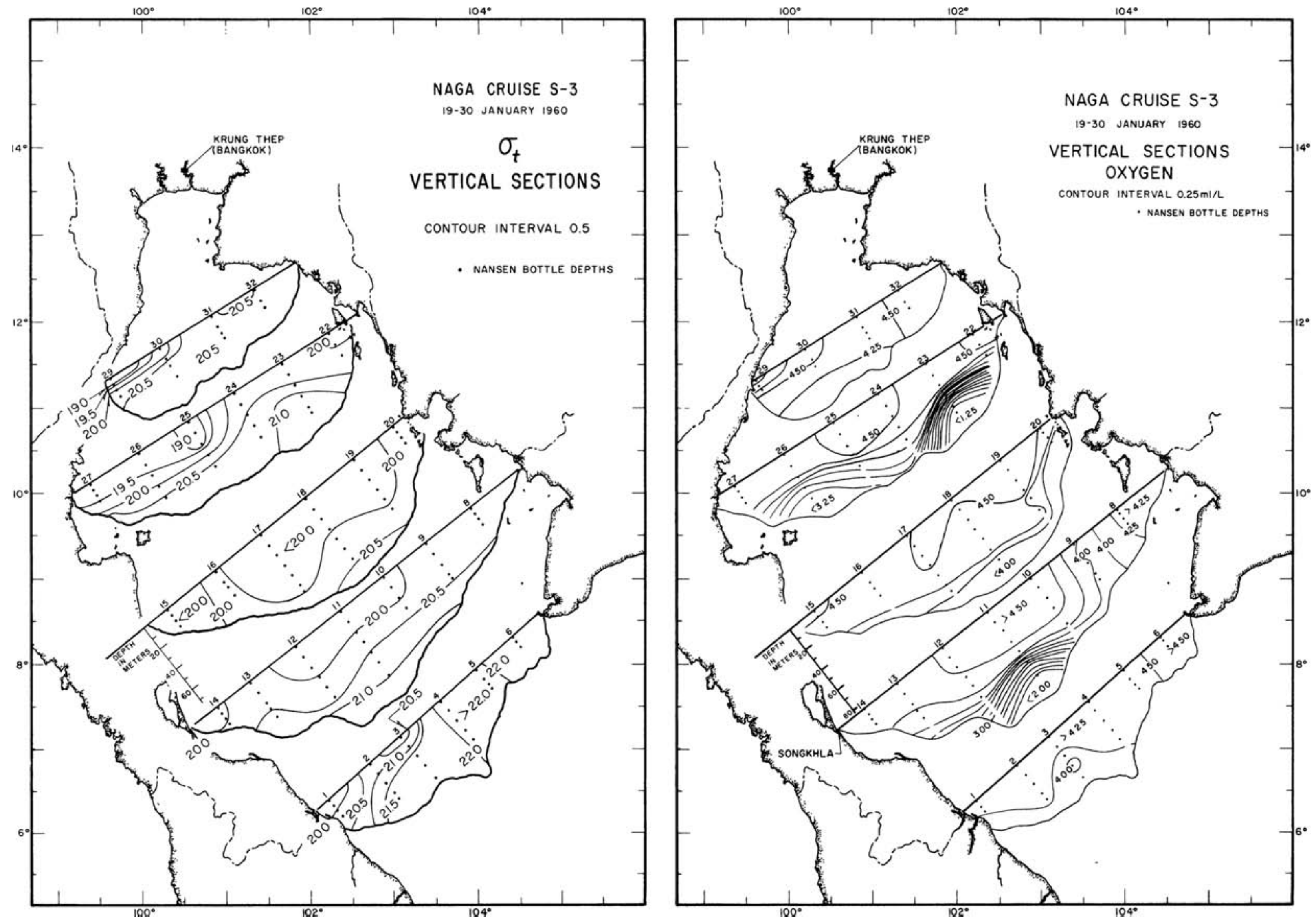
NAGA CRUISE S-3
19-30 JANUARY 1960
σ_t
VERTICAL SECTIONS
CONTOUR INTERVAL 0.5
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
DEPTH IN METERS
NAGA CRUISE S-3
19-30 JANUARY 1960
VERTICAL SECTIONS
OXYGEN
CONTOUR INTERVAL 0.25ml/L
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
100°
102°
104°
14°
12°
10°
8°
6°

Figure 27.

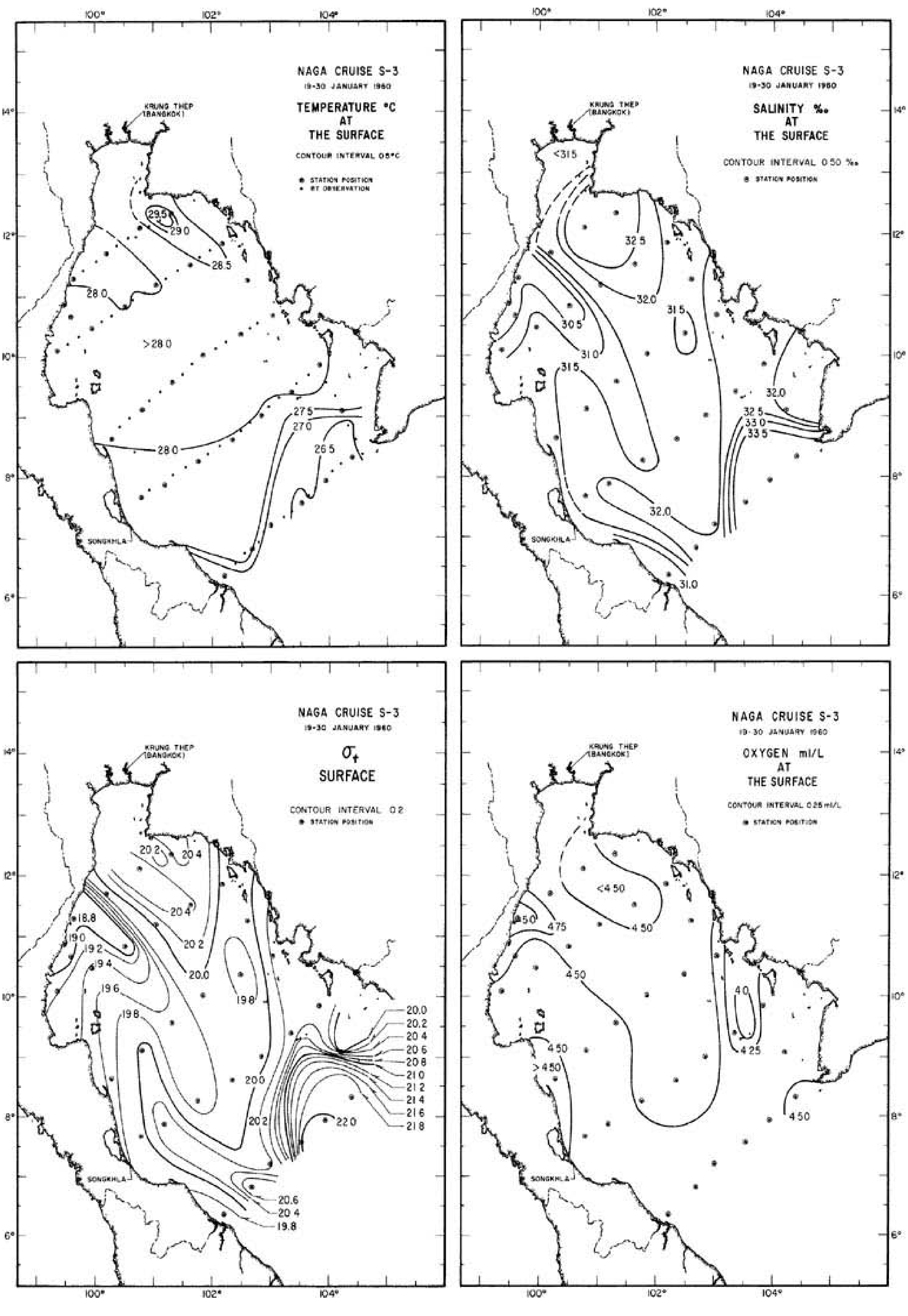

Figure 28. Horizontal Distributions at Surface.

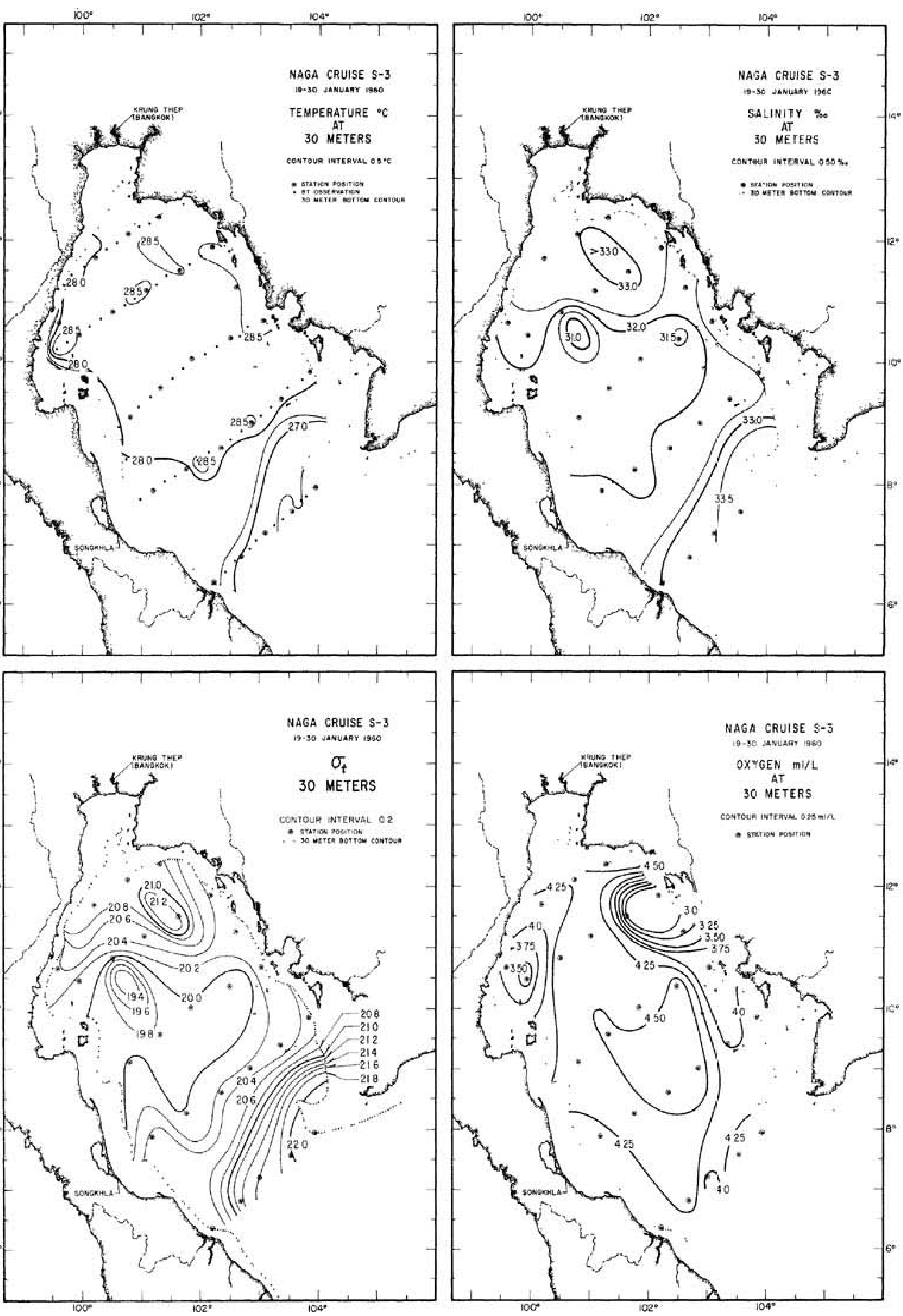

Figure 29. Horizontal Distributions at 30 m.

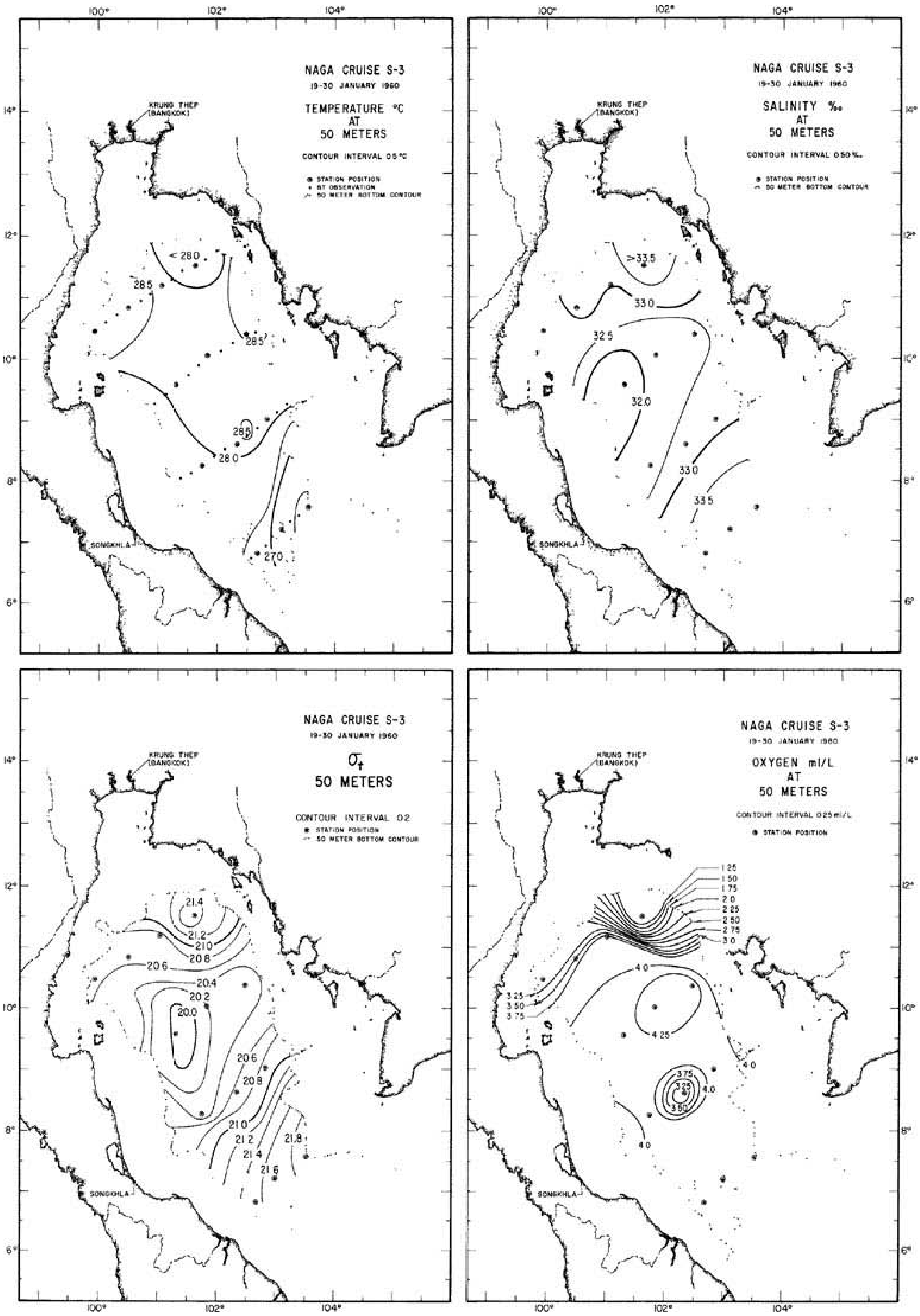

Figure 30. Horizontal Distributions at 50 m.

CRUISE S4, February 15-March 19, 1960, South China Sea
(February 15-17, Gulf of Thailand Underway Stations)

On cruise S4, February, 1960, the winds at underway stations in the eastern Gulf were northeast off Sattahip at 10 knots, decreased to less than 3 knots and changed direction to southeast near Ko Chang. As the ship approached Cape Camau wind speeds increased up to 20 knots and the direction shifted to the east.

Rainfall at Gulf coastal locations for February were lower than normal at Bangkok (0), Chantaburi (10 mm), Kampot (0) and Songkhla (8 mm), higher than normal at Prachuap Khirikhan (62 mm), Chumphon (199 mm) and Ban Don (59 mm). The wind observations from near Cape Camau suggest that further intrusion of high salinity water from the South China Sea might be expected between Cape Camau and Kota Bharu, but no salinities were taken on this leg of the cruise.

Winds in late February and early March, 1960, at the South China Sea stations on cruise S4 were less intense than on any other cruise in this area. On the northern three lines wind speeds were 10-15 knots, on the southern three lines 5 knots-calm. The wind direction along the northern lines was predominantly northeast varying some to the east; along the southern lines they were mainly from the east. At none of the three closest inshore stations on each line was surface salinity of less than 33‰ found. In this month of low rainfall and low river runoff with South China Sea water being transported toward shore by the northeast and east winds (where the coast trends to the southwest) no dilution of surface salinities was observed. Rainfall at the coastal locations along the east coast of South Viet Nam at this time was lower than normal at Nhatrang (18 mm), Tourane (15 mm) and Saigon (0).

The vertical temperature section (Figure 31) through the eastern Gulf based on the underway BT's taken enroute to the South China Sea reveal a structure similar to that seen on cruise S2 in December, 1959. Temperature inversions beneath the surface at approximately the same temperatures as on cruise S2 still remained in the area between Cape Liant and Point Samit. Temperature decreased with depth at the north end of the track; isothermal conditions prevailed from Phu Quoc to Cape Camau. In this area the sharp temperature gradient had increased to more than 2 °C with minimum observed temperatures of 25.4 °C near the Cape. Higher salinities at subsurface depth must have continued to prevail southeast of Cape Liant.

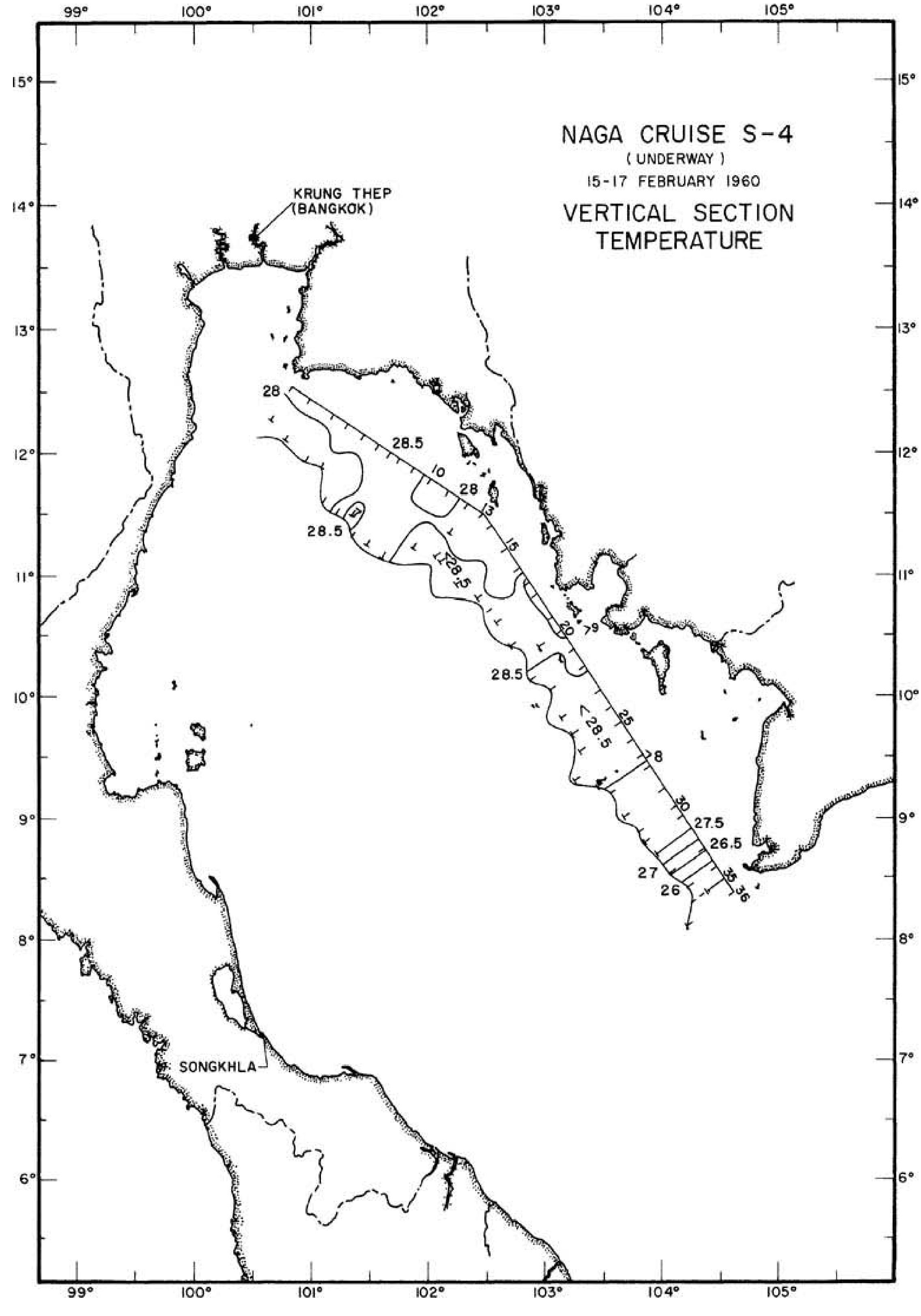
NAGA CRUISE S-4
(UNDERWAY)
15-17 FEBRUARY 1960
VERTICAL SECTION
TEMPERATURE
KRUNG THEP
(BANGKOK)
SONGKHLA
28
28.5
10
28
13
15
28.5
28.5
20
9
28.5
25
<28.5
8
30
27.5
26.5
27
26
35
36
99°
100°
101°
102°
103°
104°
105°
15°
14°
13°
12°
11°
10°
9°
8°
7°
6°

Figure 31.

CRUISE S5, APRIL 21-MAY 2, I960, GULF OF THAILAND.

In late April, 1960 (cruise S5) a monsoon transition month, not only were the winds variable, but there was a shift to strong south, southeast and southwest winds on the inner lines 1 and 2, mid-Gulf changes in wind direction from northwest to southeast to southwest on lines 3 and 4, and minimum speeds from southwest on line 5 between Cape Camau and Kota Bharu in contrast to the situation on cruises S1 and S3 where winds were strongest on lines 4 and 5, very weak and variable on lines 1 and 2.

Rainfall during April was below normal at all the Gulf coastal locations; Bangkok (2 mm), Prachuap Khirikhan (17 mm), Chumphon (60 mm), Ban Don (43 mm), Songkhla (35 mm) Chantaburi (37 mm) and Kampot (154 mm). Although normals are not available for Kota Bharu, 230 mm rainfall was recorded there for April, indicating an early onset of rain on both sides of the southern part of the Gulf.

The surface salinity picture (Figures 33, 36) is in great contrast to that on cruise S3. Surface salinities less than 32‰ remained in an "S" shaped area beginning along the eastern shore from station 23 between lines 2 and 3 and extending to the eastern stations 9, 10 and 11 on line 4, across mid-Gulf on line 3 (stations 18, 19, 20) with a tongue reaching to Kota Bharu through station 14 on line 4 and station 2 on line 5. To the east on line 5 the high salinity wedge seen on cruise S3 had increased to values greater than 34‰. This intrusion cannot be accounted for by the weak southeast winds observed in the area. Instead this high salinity water, first seen in this area on cruise S3 in January, 1960, must have intruded into the Gulf during a previous period of high velocity northeast winds.

Temperatures above the thermocline were everywhere higher than observed on any of the other cruises. All surface temperatures exceeded 30 °C; 31.56 °C was observed at station 23. Diurnal heating at the surface was evident in several places when wind speeds were low. A sharp thermocline was developed over most of the area between the warm low salinity surface water and the deeper, higher salinity water. A sharp temperature and salinity front was observed north of Cape Camau.

The vertical profiles of temperature, salinity, sigma-t and oxygen (Figures 34 and 35) indicate that residual upwelling persisted at the eastern end of lines 3 and 4. Oxygen concentrations as low as 1.35 ml/l were observed on line 3. Low oxygen concentrations were found in the western part of the trough on line 4, but in the center of the trough oxygen was as high as 4.02 ml/l at 58 m with a salinity of 33.99‰ in contrast to 1.94 ml/l and 32.91‰ on cruise S3 at this location. These changes indicate that a renewal of the deep waters in the trough had occurred as well as the surface-to-bottom penetration of the wedge of high salinity water southwest of Cape Camau.

The salinity distribution suggests that upwelling may have begun on the west end of line 2. In the Cape Liant region the bottom bottle on station 33 on line 1 in the upwelling area was at 18 m with an observed salinity of 32.72‰, considerably higher than at adjacent stations, but not as high as observed at deeper levels on cruises S1 and S3. Salinity reached 32.65‰ at 46 m in the adjoining area on line 2, also considerably lower than in this area on cruise S1 and S3, but again higher than at adjacent stations on cruise 5.

Convergence and downwelling were again evident in the central regions of lines 3 and 4 similar to the situation on cruises S1 and S3.

The horizontal distribution charts of temperature, salinity and sigma-t (Figures 36, 37 and 38) suggest the following circulation patterns: A wedge of high salinity water with values above 34‰ had entered the Gulf at the eastern end of line 5, lay below the surface at line 4, but extended as far as the center of line 3 along the bottom. In the inner Gulf there appears to have been a weak counter-clockwise eddy at the surface which was better developed at 30 and 50 meters. The general circulation was southward along the east coast to line 3, across to the west central portion of the Gulf between lines 3 and 4, along the edge of the high salinity instruction and out of the Gulf about 60 miles east of the coast. Sigma-t distributions suggest a weak counter-flow along the west coast.

Horizontal oxygen distributions at each level (Figures 36, 37 and 38) are in accordance with the inferred circulation.

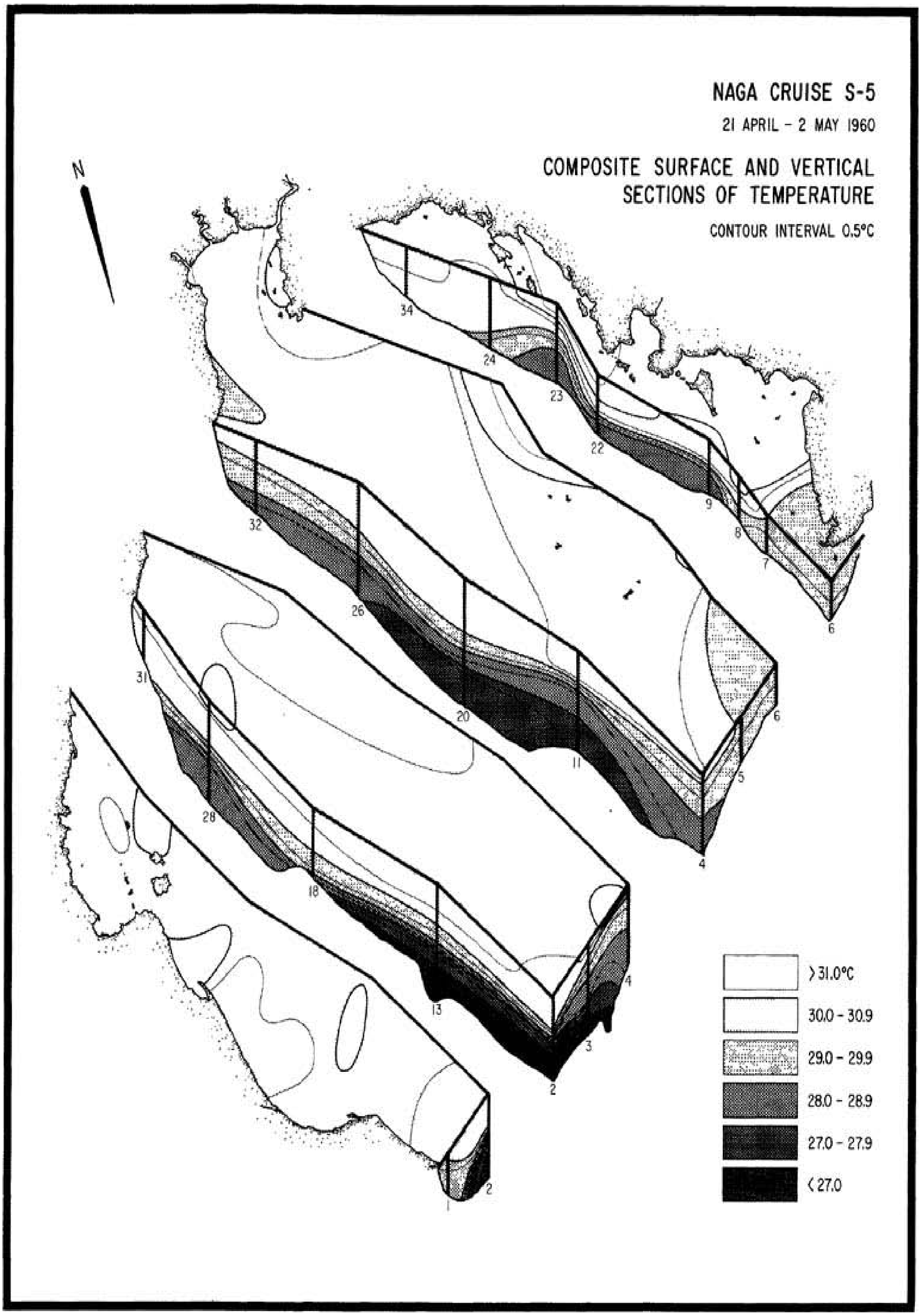
NAGA CRUISE S-5
21 APRIL - 2 MAY 1960
COMPOSITE SURFACE AND VERTICAL SECTIONS OF TEMPERATURE
CONTOUR INTERVAL 0.5°C
N
34
24
23
22
9
8
7
6
32
26
20
11
6
5
4
31
28
18
13
4
3
2
1
2
>31.0°C
30.0 - 30.9
29.0 - 29.9
28.0 - 28.9
27.0 - 27.9
<27.0

Figure 32.

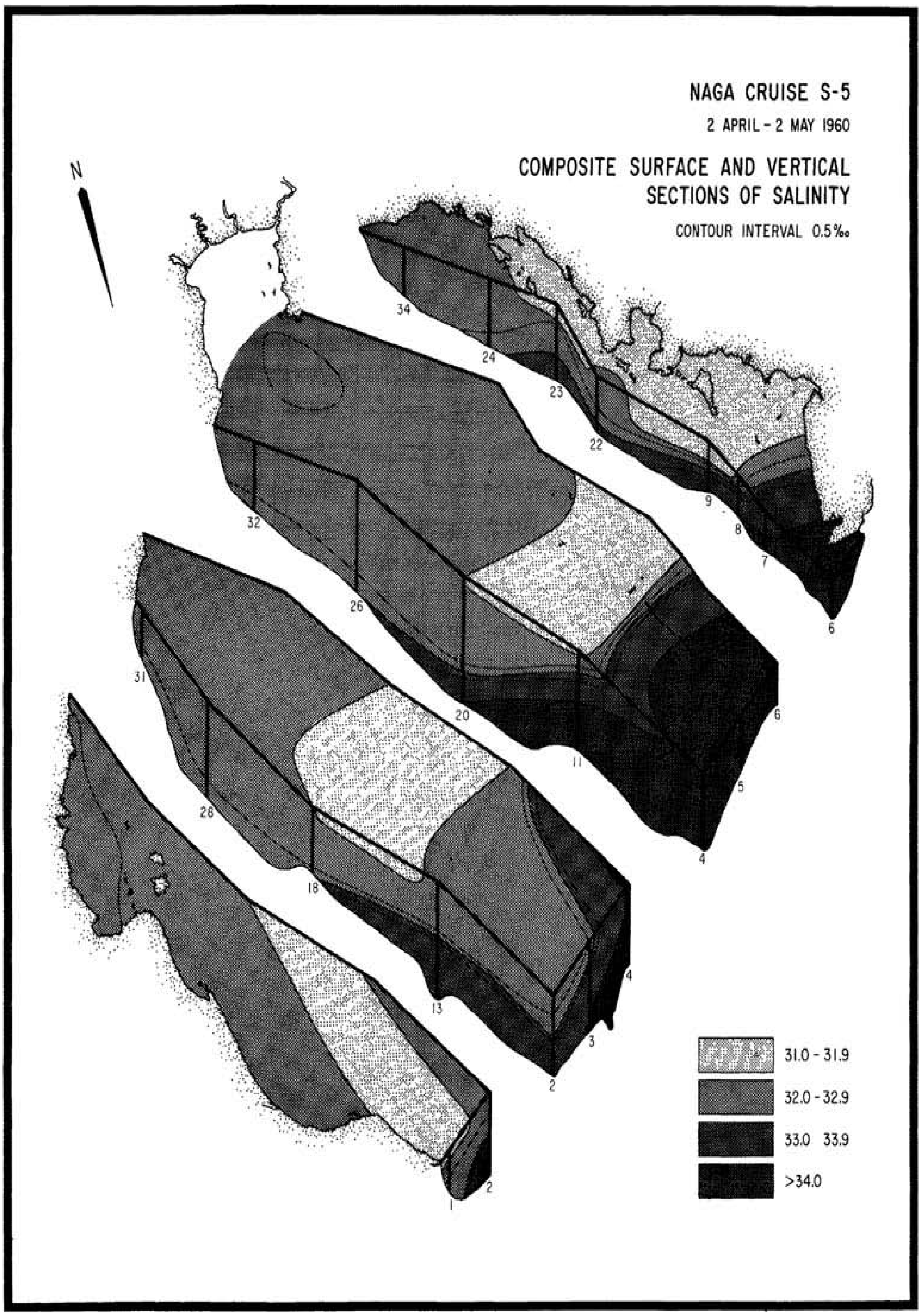
NAGA CRUISE S-5
2 APRIL - 2 MAY 1960
COMPOSITE SURFACE AND VERTICAL SECTIONS OF SALINITY
CONTOUR INTERVAL 0.5‰
N
34
24
23
22
9
8
7
6
32
26
20
11
6
5
4
31
28
18
13
4
3
2
1
2
31.0 - 31.9
32.0 - 32.9
33.0 33.9
>34.0

Figure 33.

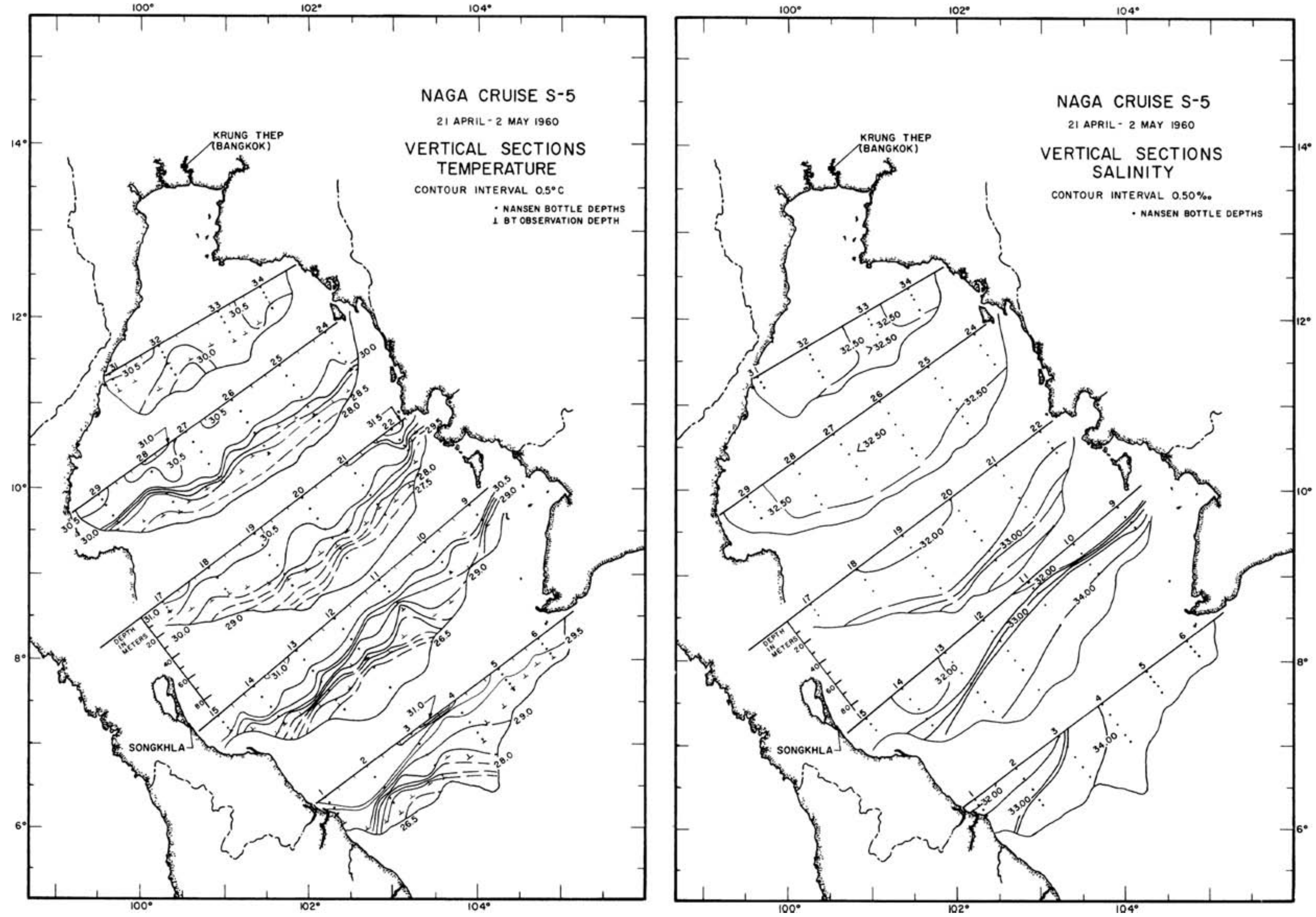
NAGA CRUISE S-5
21 APRIL - 2 MAY 1960
VERTICAL SECTIONS
TEMPERATURE
CONTOUR INTERVAL 0.5°C
• NANSEN BOTTLE DEPTHS
⊥ BT OBSERVATION DEPTH
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
20
40
60
80
100°
102°
104°
6°
8°
10°
12°
14°
NAGA CRUISE S-5
21 APRIL - 2 MAY 1960
VERTICAL SECTIONS
SALINITY
CONTOUR INTERVAL 0.50‰
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
32.00
32.50
>32.50
<32.50
33.00
34.00

Figure 34.

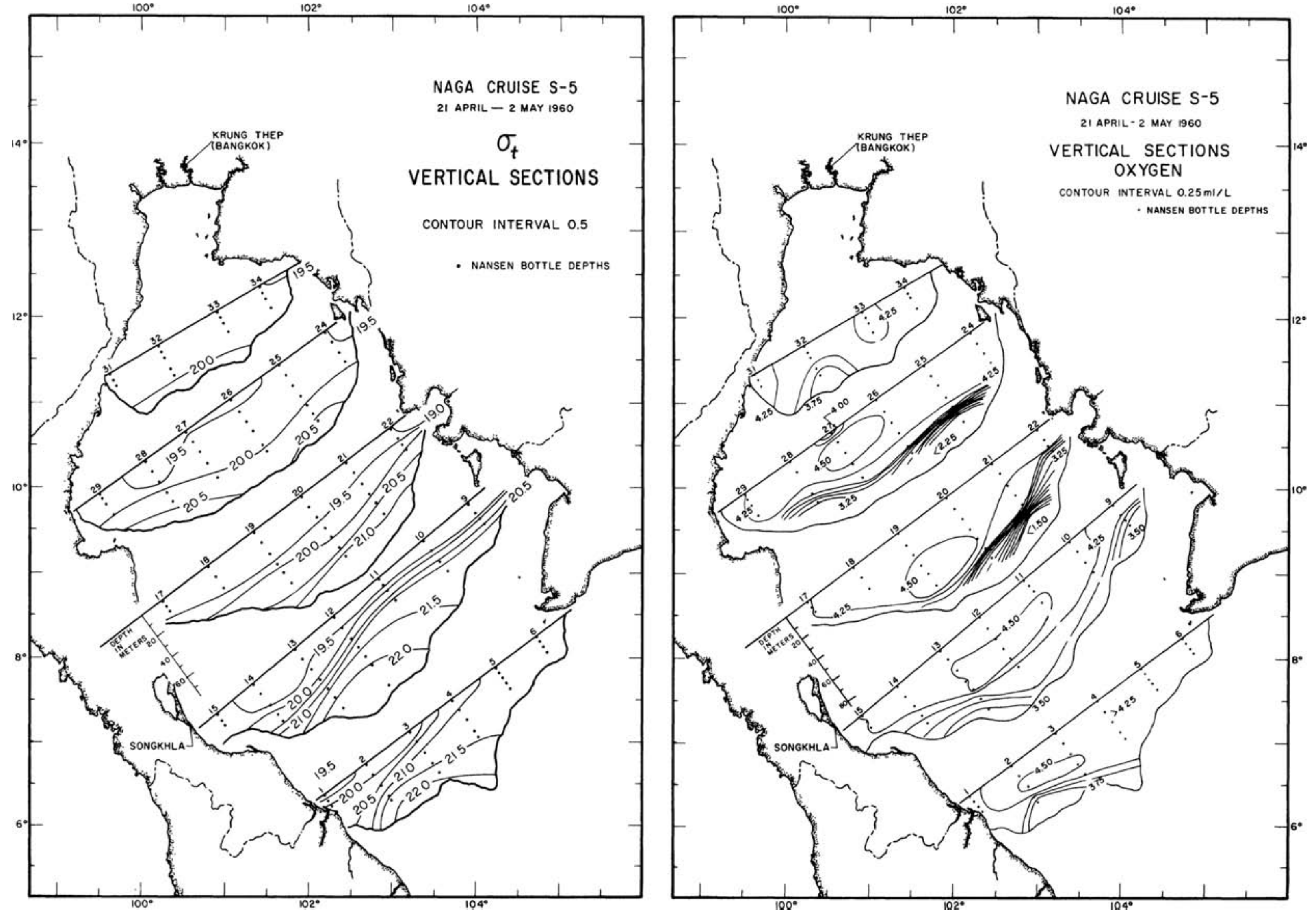
NAGA CRUISE S-5
21 APRIL — 2 MAY 1960
σ_t
VERTICAL SECTIONS
CONTOUR INTERVAL 0.5
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
20
40
60
80
100°
102°
104°
14°
12°
10°
8°
6°
1
2
3
4
5
6
9
10
11
12
13
14
15
17
18
19
20
21
22
24
25
26
27
28
29
31
32
33
34
19.0
19.5
20.0
20.5
21.0
21.5
22.0
NAGA CRUISE S-5
21 APRIL - 2 MAY 1960
VERTICAL SECTIONS
OXYGEN
CONTOUR INTERVAL 0.25 ml/L
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
<1.50
<2.25
3.25
3.50
3.75
4.00
4.25
>4.25
4.50

Figure 35.

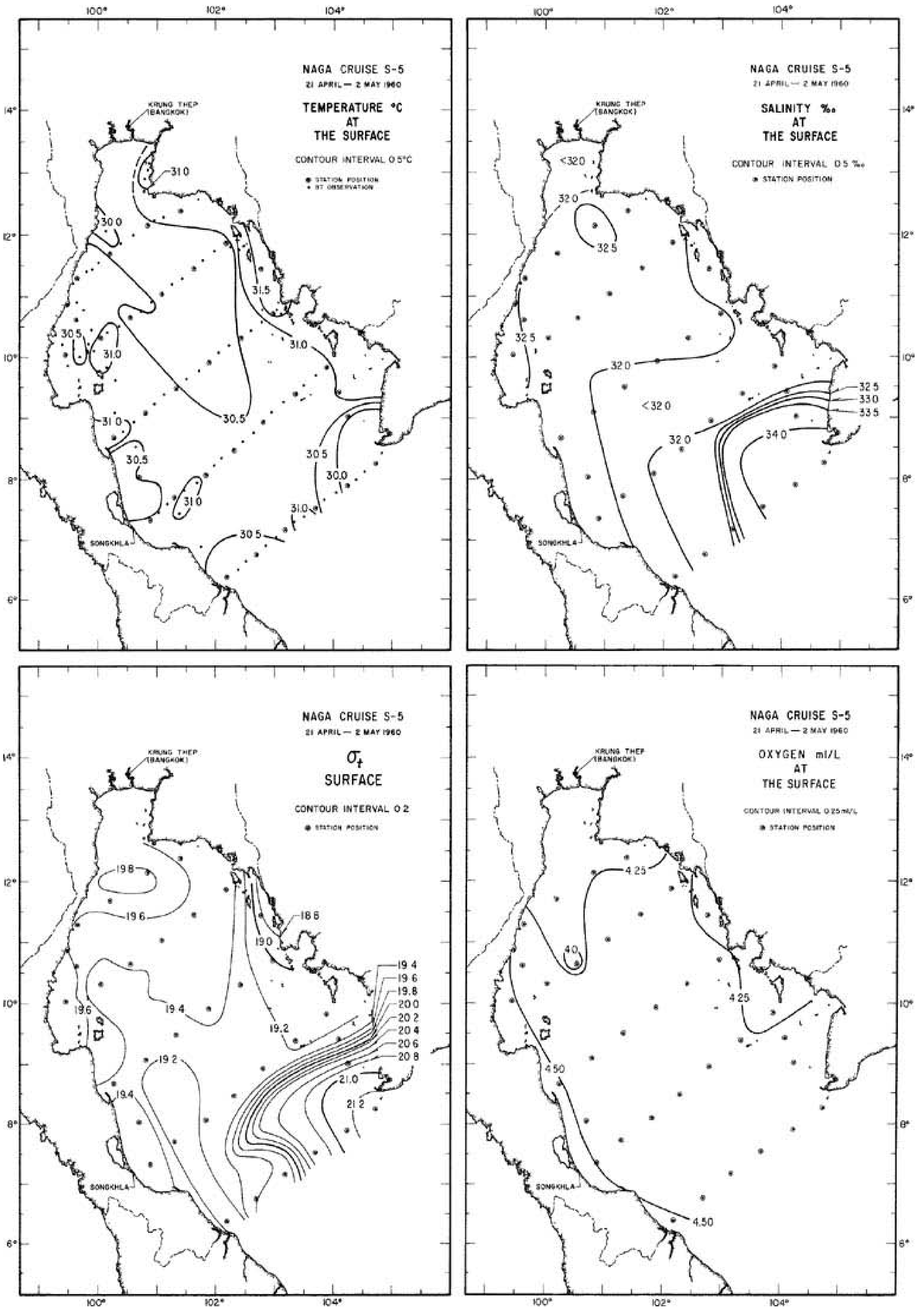

Figure 36. Horizontal Distributions at Surface.

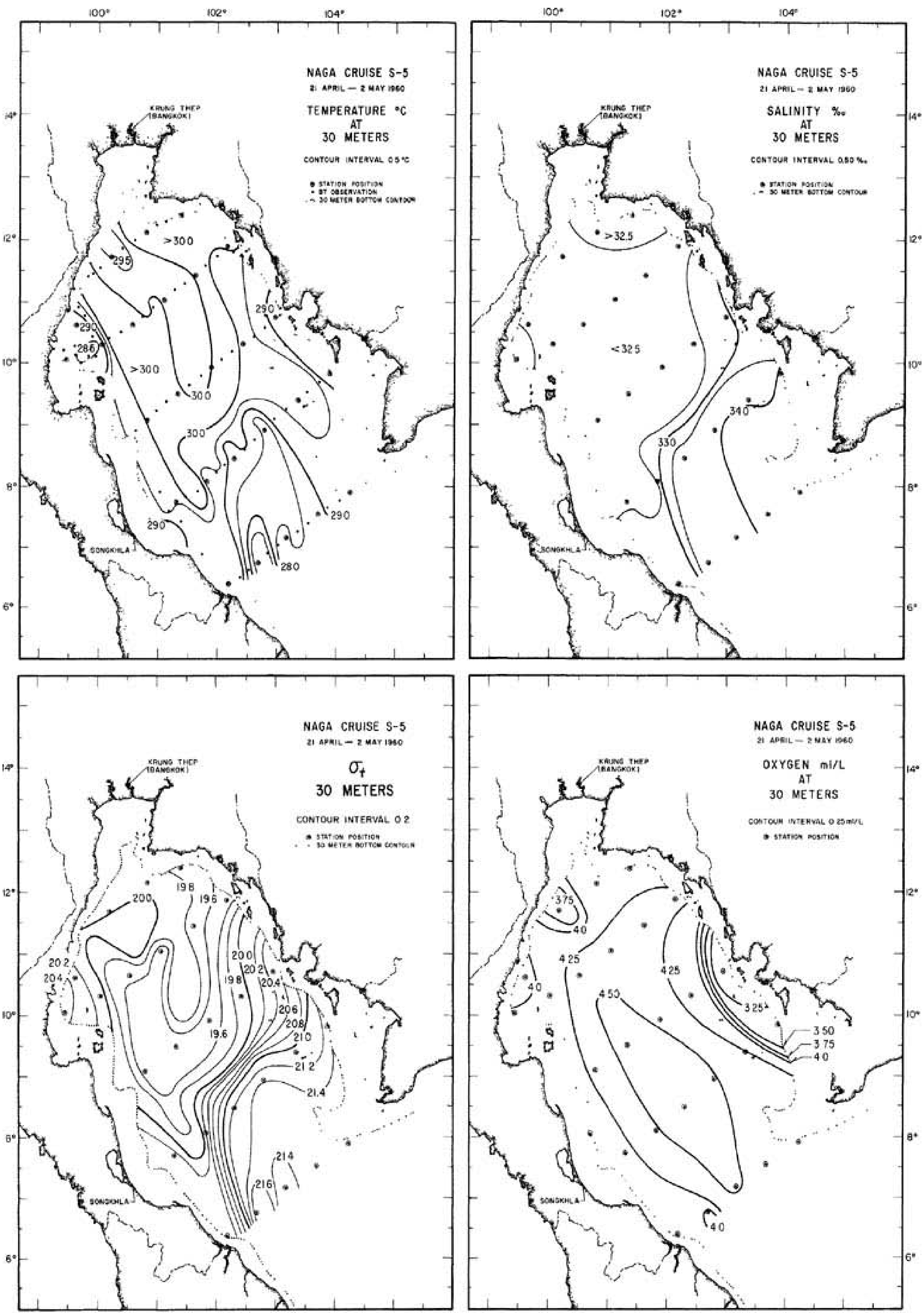

Figure 37. Horizontal Distributions at 30 m.

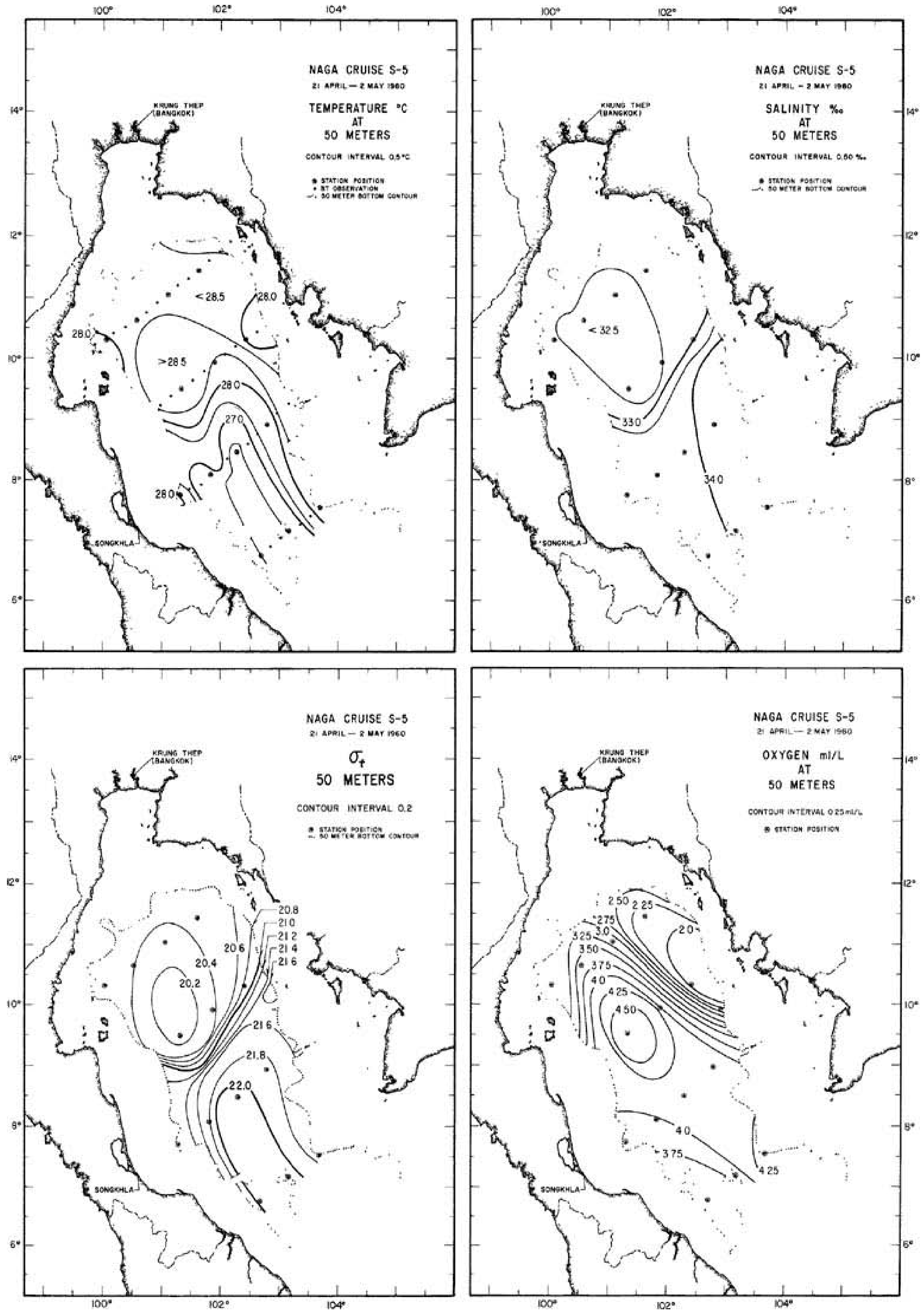

Figure 38. Horizontal Distributions at 50 m.

CRUISE S6, May 24-June 24, 1960, South China Sea
(May 24-25, Gulf of Thailand Underway Stations)

Cruise S6 took place at the beginning of the southwest monsoon. The few wind observations taken in the Gulf on May 24-25, 1960, were southwest in direction but very weak until the ship approached Cape Camau with the exception of 10 knot southwest winds off Ko Kut. Rounding the Cape the ship encountered first a 20 knot west wind then a 12 knot northeast wind. Rainfall at Gulf coastal locations in May was normal at Prachuap Khirikhan (135 mm) and Chumphon (163 mm), lower than normal at Bangkok (139 mm), Ban Don (82 mm) and Songkhla (194 mm) and higher than normal at Chantaburi (482 mm) and Kampot (247 mm) where the monsoon rains came earlier than on the western side of the Gulf.

As the *Stranger* proceeded north along the east coast of South Viet Nam, and continuing to June 24, 1960, the winds were predominantly from the southwest at 25-30 knots although variation in strength and direction was observed. Near shore on line 1 winds were northwest. South of Cape Camau (line 6), and occasionally elsewhere, winds were west or northwest. Monthly rainfall for June of 1960 was higher than normal at Tourane (255 mm) and Saigon (229 mm), less than normal at Nhatrang (42 mm). The nearest-to-shore stations on line 5 (station 29) and on line 6 (station 42) had surface salinities slightly less than 33‰, namely 32.98 and 32.94‰. Also station 32, the fourth from shore on line 5, had the lowest surface salinity observed on cruise S6, 32.38‰. This low salinity water could have been carried there at 45° to the right of the southwest winds, but, if so, it indicates that the high wind speeds in this area had just begun, in order for this low salinity surface water to have persisted. The logs do not indicate occurrence of local rain, another possible explanation for the low observed salinity, but rainfall observations were not always recorded.

Temperatures along the enroute underway track in the Gulf (Figure 39) showed that the high temperatures observed in April and May on cruise S5 still prevailed with surface temperatures near or above 30 °C. No temperature inversions were observed; low surface salinities would be expected at this time based on rainfall data (no hydrographic casts were made on this leg).

Although no cruise took place in July, 1960, it should be noted as the month of maximum rainfall for the year at Chantaburi (854 mm) and at Chumphon (308 mm), and in both cases it was higher than the normal. Other stations with higher than normal rainfall for the month were Ban Don (166 mm) and Songkhla (145 mm). Kota Bharu (260 mm) had a secondary rainfall peak at the same time. Bangkok (127 mm) and Kampot (184 mm) as well as the three east coast South Viet Nam locations had lower than normal monthly rainfall; Tourane (64 mm), Nhatrang (31 mm) and Saigon (184 mm).

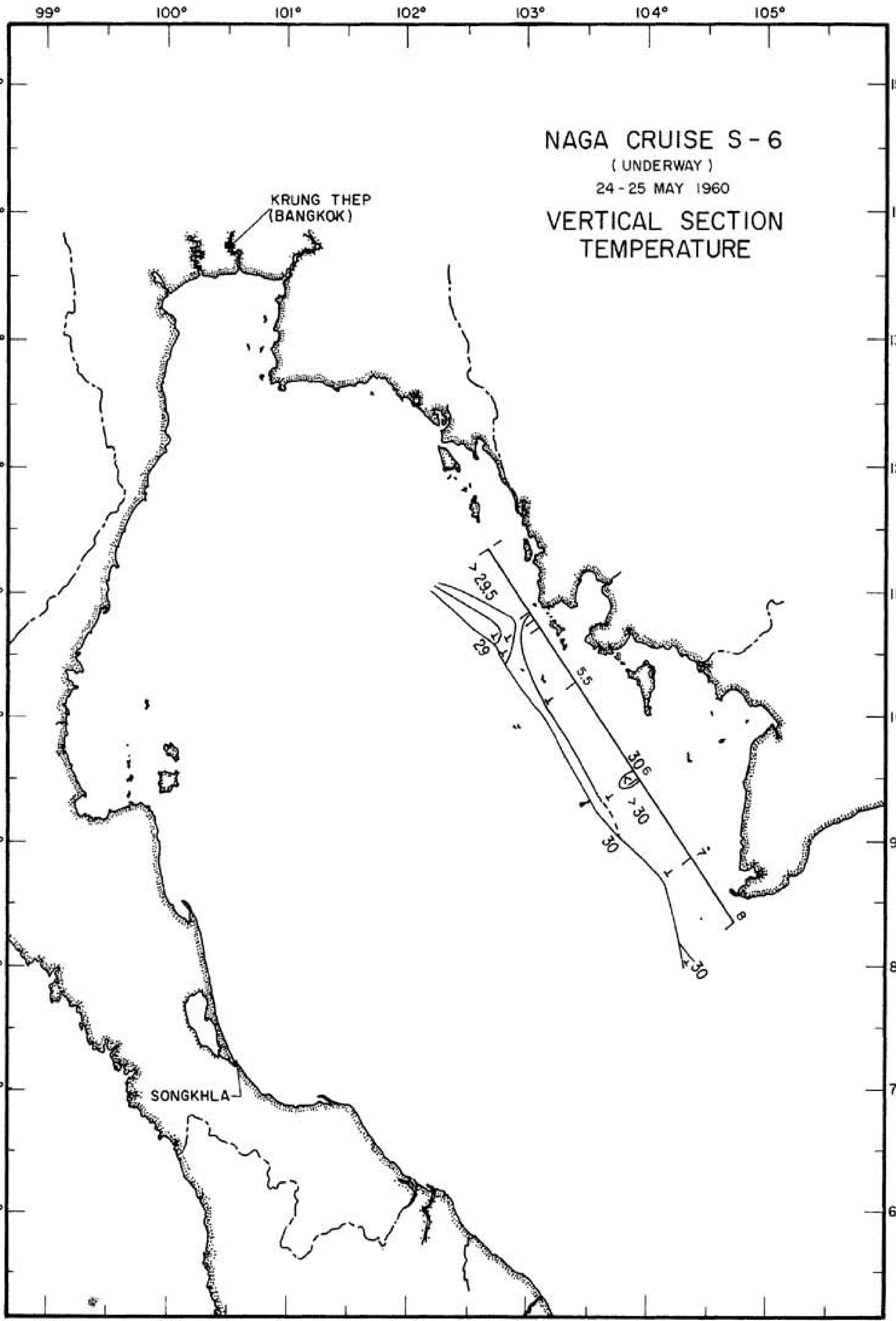
NAGA CRUISE S-6
(UNDERWAY)
24-25 MAY 1960
VERTICAL SECTION
TEMPERATURE
KRUNG THEP
(BANGKOK)
SONGKHLA
> 29.5
29
5.5
30.6
> 30
30
7
8
30
99°
100°
101°
102°
103°
104°
105°
15°
14°
13°
12°
11°
10°
9°
8°
7°
6°

Figure 39.

CRUISE S7, AUGUST 2-14, 1960, GULF OF THAILAND

Cruise S7 was the only Gulf cruise that took place during the height of the southwest monsoon season, and winds observed on this cruise were therefore vastly different from those observed on all other Gulf cruises. Wind direction varied from south to west. At the head of the Gulf wind direction was mainly from the south; on lines 1 and 2 from the southwest; on lines 3 and 4 from due west and on line 5 from both west and southwest. Wind speeds exceeded 10 knots at all but four stations and usually ranged between 15 and 26 knots.

Although August is a high rainfall month, rain was observed on only eight stations; 1, 19, 25, 26, 27, 27a, 29 and 33. No surface salinity dilution was evident in the salinities at stations 1, 19, 29 and 33, but very low salinities were observed at stations 25, 26, 27 and 27a along the east coast of the Gulf. Increased river runoff, strengthened by high rainfall at Chantaburi in July and August, must have been involved in producing the low surface salinities along the east coast since they occurred at a number of stations where no rain fell at station time and lowest salinity values occurred at near shore stations. Rainfall during August was higher than normal at Bangkok (244 mm), Chantaburi (593 mm) and Chumphon (232 mm), normal at Ban Don (166 mm) and lower than normal at Prachuap Khirikhan (70 mm), Songkhla (130 mm) and Kampot (327 mm). No significant dilution of surface salinity from rainfall or runoff was observed along the west coast or in mid-Gulf. Instead salinities greater than 33‰ were observed for the first time at the surface beyond the mouth of the Gulf. On previous cruises upwelling or divergence had brought 33‰ water to the 30 m depth. On cruise S7 the up welled water reached the surface in the region south of Cape Liant on line 1 where high salinity water was found at depth on all previous cruises, but on this cruise the high salinity water extended to the west coast, as far south as Chumphon and north into the Bight of Bangkok. The high salinities in the Bight of Bangkok are surprising when rainfall and river runoff alone are considered since both were increasing toward the September peaks. However, the composite and vertical distributions of properties (Figures 41 and 42) indicate that high salinity water which upwelled south of Cape Liant and along the west coast must have been transported into the shallow water of the Bight by the strong southwest and south winds against the outflowing fresh water causing an extremely sharp salinity gradient between these inner stations and the rivers' mouths (see page 27). At 13° N (stations 1 and 2) surface salinities of 33.39 and 33.17‰ were observed with values increasing slightly with depth. At station 8 near Laem Thonglang surface salinities reached 33.70‰ at 18 m 33.79‰.

Upwelling also occurred along the west coast north of Songkhla where water of salinity 33.10‰ was found at the surface on station 33. Water of salinity greater than 34.00‰, which was observed on cruise 5 on line 5 intruding into the Gulf south of Cape Camau from surface to bottom as well as in the deep trough on lines 3 and 4, was found to have shifted to the west side of the deep central basin and was no longer present at the surface.

Convergence and downwelling appeared again in mid-Gulf on lines 2 and 3 in roughly the same area as on previous cruises. Again this seems to be a result of convergent flow rather than direct wind effect.

The circulation as inferred from the horizontal distributions of temperature, salinity and sigma-t (Figures 44, 45 and 46) shows a strong flow into the Gulf along the east coast at the surface and at 30 meters and a strong northward flow along the west coast. There appears to be some outflow from the Gulf on the west end of line 5 at all levels associated with a counter-clockwise circulation southwest of Cape Camau. At 50 meters the strong density gradient between water masses divides the circulation into two cells, the inner clockwise and the outer counter-clockwise gyres, with convergent flow at the east side of the Gulf and divergent flow on the west side between the two gyres. While it is not possible to speak quantitatively of flow velocities, it is possible to calculate roughly the minimum speed with which water of salinity 33.5‰, observed at a depth of 60 m in mid-Gulf at station 20 on cruise S5, would have to travel to reach to the surface on line 1 on cruise S7; i.e., approximately 130 nautical miles in 96 days or 1.4 nautical miles per day.

The horizontal oxygen distributions at all levels (Figures 44, 45 and 46) were in agreement with the inferred circulation.

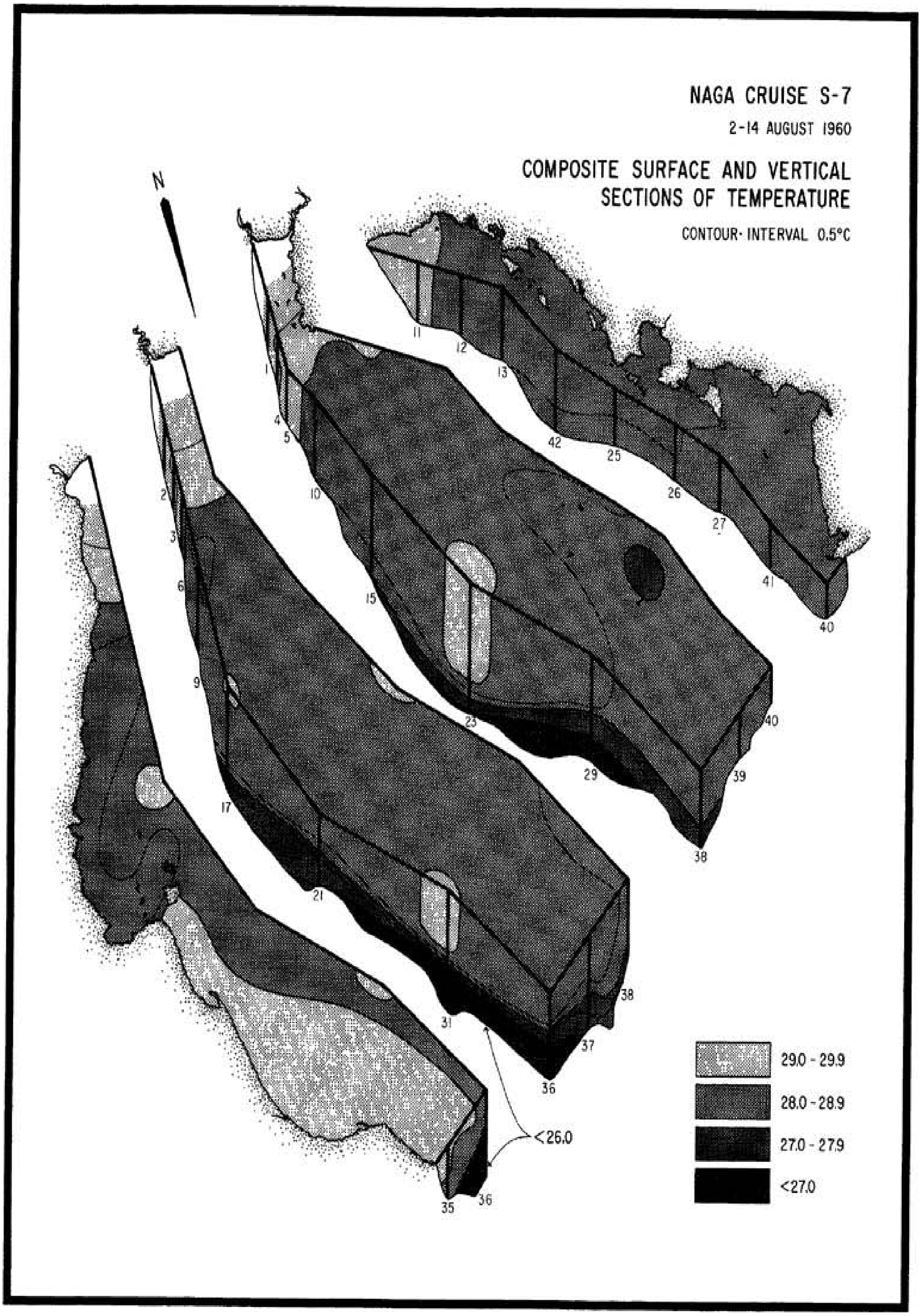
NAGA CRUISE S-7
2-14 AUGUST 1960
COMPOSITE SURFACE AND VERTICAL SECTIONS OF TEMPERATURE
CONTOUR· INTERVAL 0.5°C
N
11
12
13
42
25
26
27
41
40
1
4
5
10
15
23
29
40
39
38
2
3
6
9
17
21
31
38
37
36
35
36
<26.0
29.0 - 29.9
28.0 - 28.9
27.0 - 27.9
<27.0

Figure 40.

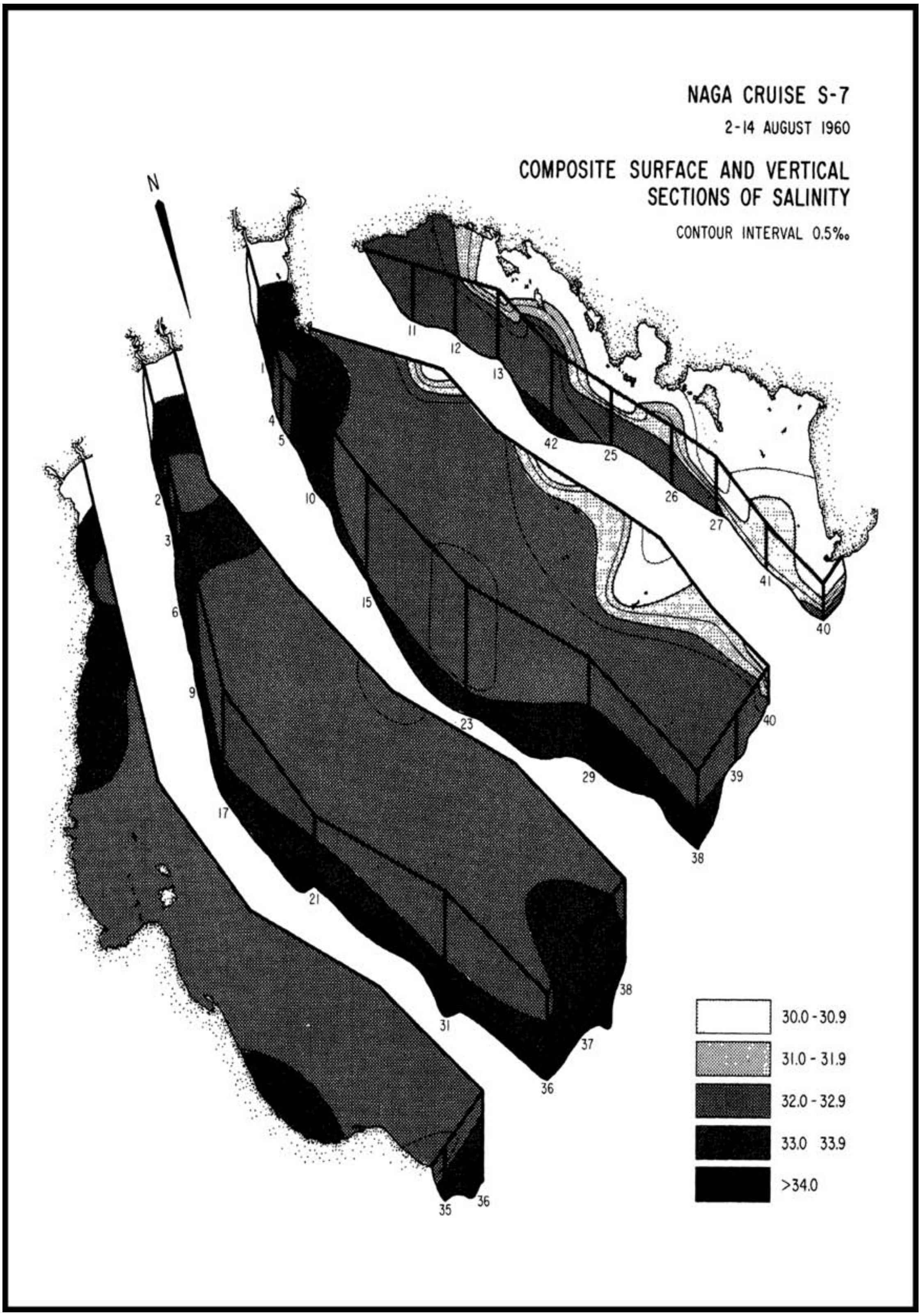
NAGA CRUISE S-7
2-14 AUGUST 1960
COMPOSITE SURFACE AND VERTICAL SECTIONS OF SALINITY
CONTOUR INTERVAL 0.5‰
N
1
2
3
4
5
6
9
10
11
12
13
15
17
21
23
25
26
27
29
31
35
36
36
37
38
38
39
40
40
41
42
30.0 - 30.9
31.0 - 31.9
32.0 - 32.9
33.0 33.9
>34.0

Figure 41.

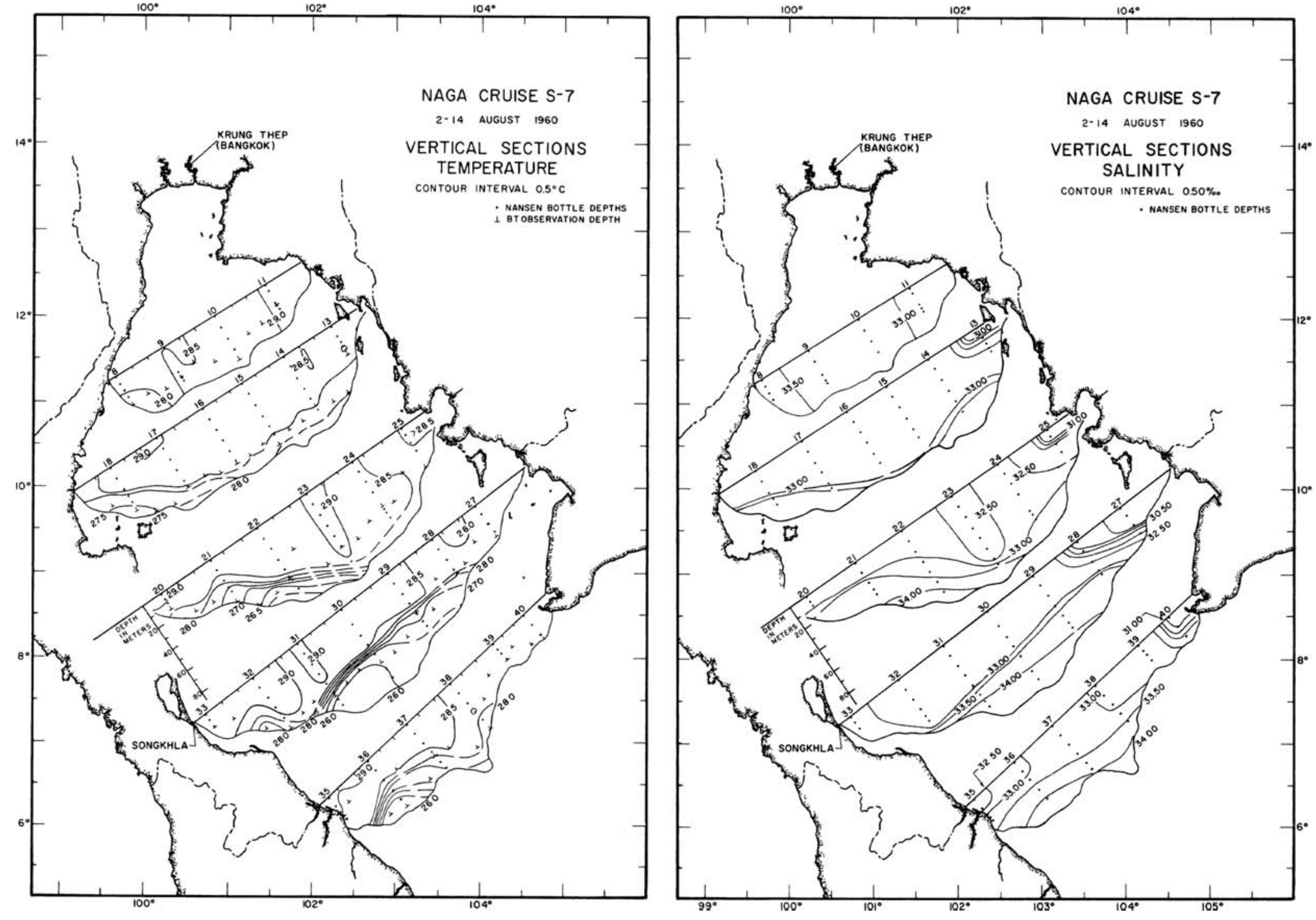
NAGA CRUISE S-7
2-14 AUGUST 1960
VERTICAL SECTIONS
TEMPERATURE
CONTOUR INTERVAL 0.5°C
• NANSEN BOTTLE DEPTHS
⊥ BT OBSERVATION DEPTH
NAGA CRUISE S-7
2-14 AUGUST 1960
VERTICAL SECTIONS
SALINITY
CONTOUR INTERVAL 0.50‰
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
20
40
60
80
99°
100°
101°
102°
103°
104°
105°
6°
8°
10°
12°
14°

Figure 42.

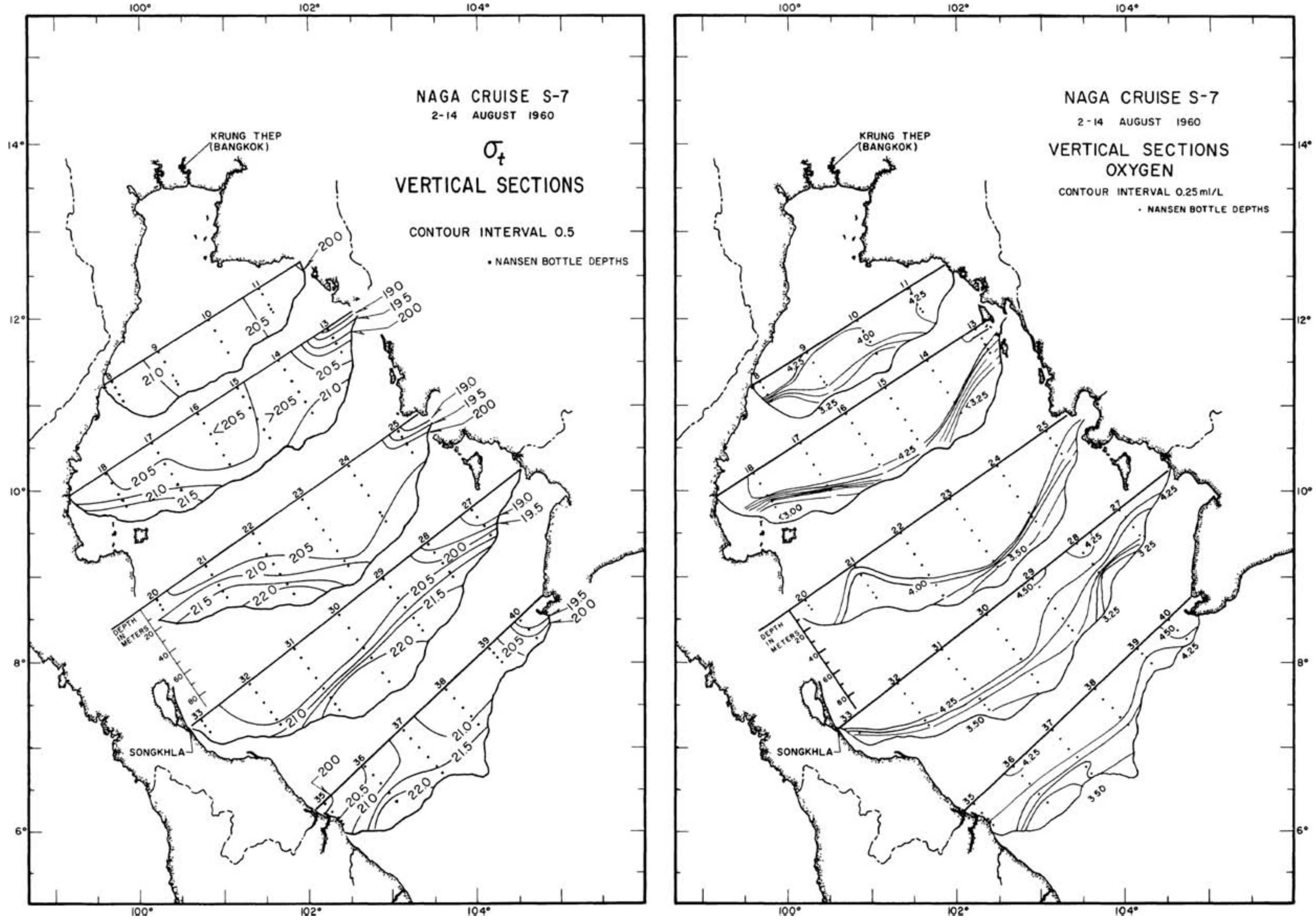
NAGA CRUISE S-7
2-14 AUGUST 1960
σ_t
VERTICAL SECTIONS
CONTOUR INTERVAL 0.5
• NANSEN BOTTLE DEPTHS
NAGA CRUISE S-7
2-14 AUGUST 1960
VERTICAL SECTIONS
OXYGEN
CONTOUR INTERVAL 0.25 ml/L
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH IN METERS
20
40
60
80
100°
102°
104°
14°
12°
10°
8°
6°

Figure 43.

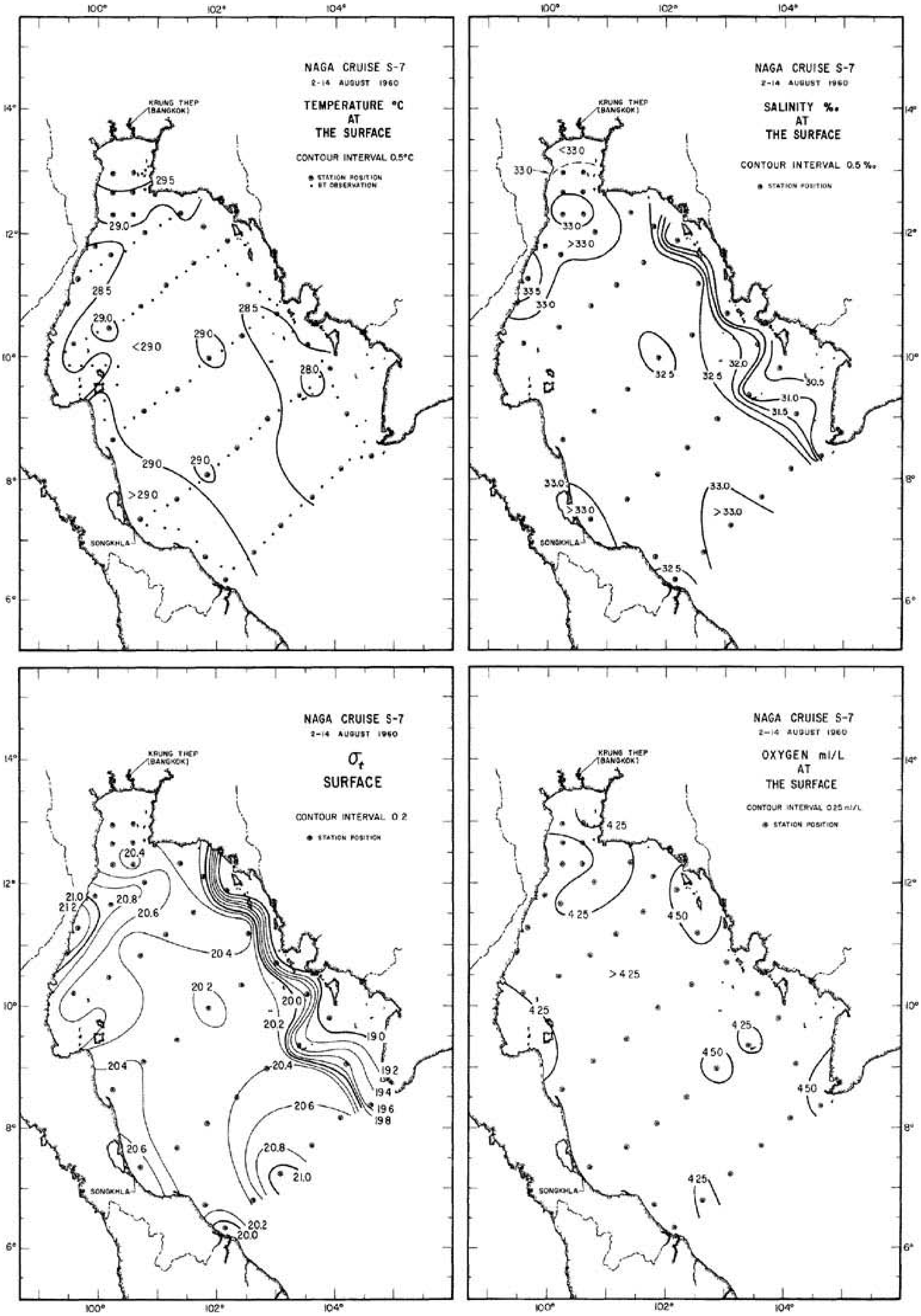

Figure 44. Horizontal Distributions at Surface.

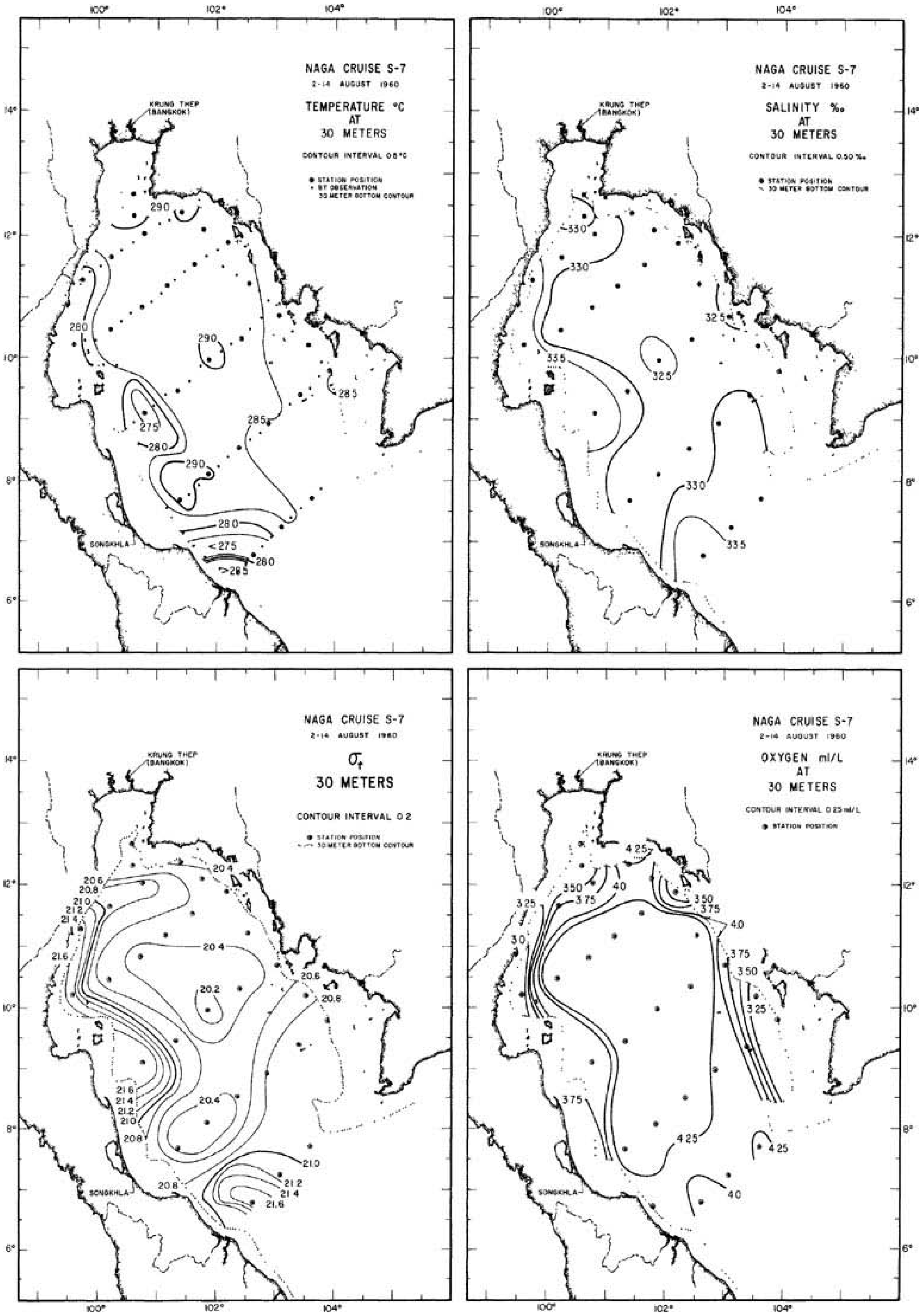

Figure 45. Horizontal Distributions at 30 m.

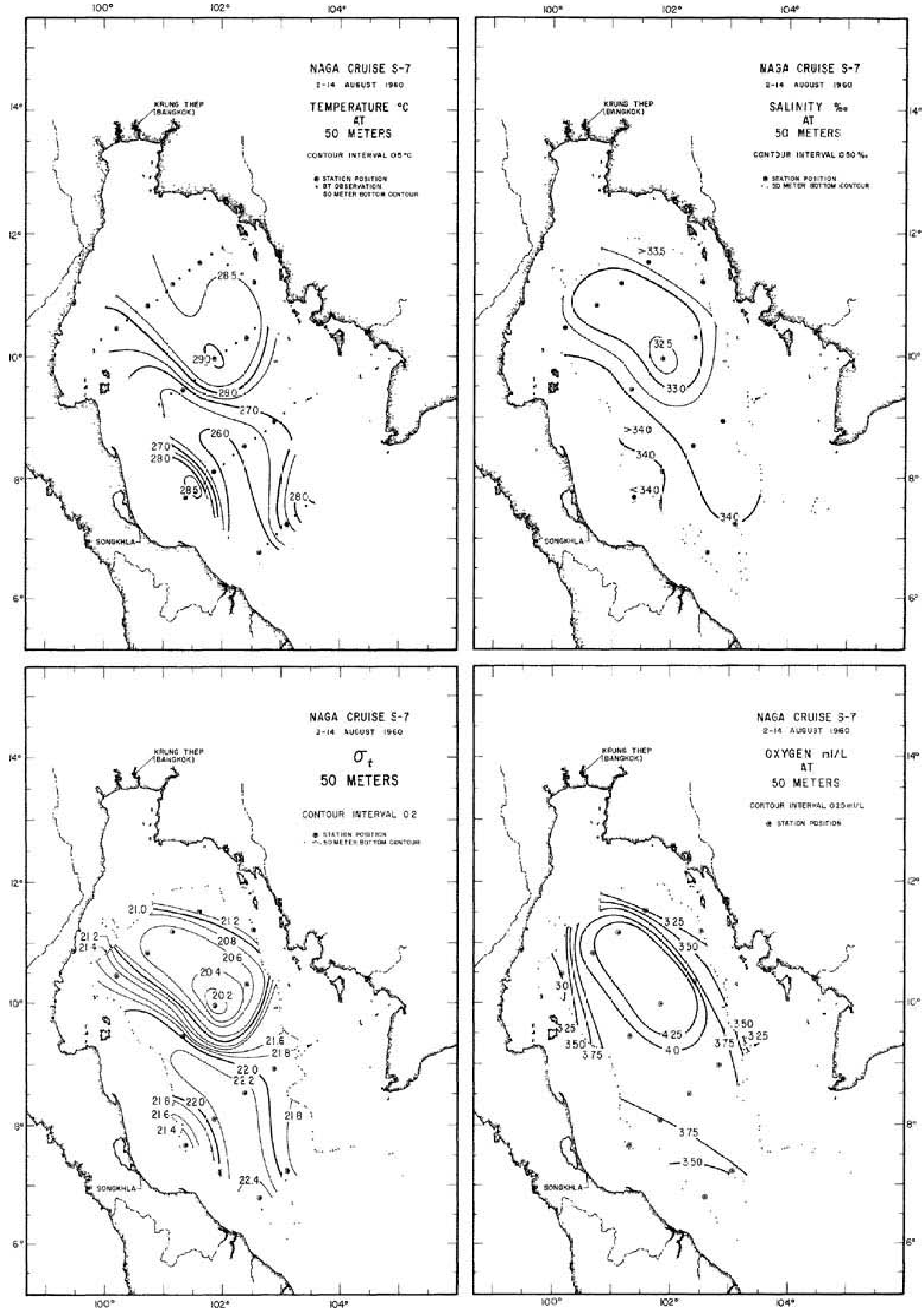

Figure 46. Horizontal Distributions at 50 m.

CRUISE S8, SEPTEMBER 6-OCTOBER 8, 1960, SOUTH CHINA SEA

(No temperature or salinity observations made in the Gulf of Thailand.)

Cruise S8 began during September, 1960, the last month of the southwest monsoon, and extended into the transition month of October in which there were changes of wind speed and direction along the cruise track in the South China Sea. Winds were light coming from south to southeast on line 1 and the connecting line toward line 2. On line 2, however, strong west and northeast winds were observed. On line 3 winds changed back to the prevailing southwest direction. On the inshore part of lines 4 and 5 winds were from the west, but on line 6 they were again more southern. On the two southern lines wind speeds remained 15-25 knots.

Monthly rainfall at Tourane (429 mm) and Nhatrang (298 mm) was higher than normal in September, but in October, although rainfall was high (480 mm and 223 mm respectively), both sites had less than the normal for the month. Saigon had less than normal rainfall (233 mm) in September and normal (246 mm) in October. The Mekong River flow was higher than the 30-year normal for September and October, 1960, but the total flow for 1960 was below the 30-year mean. The effect of the heavy river runoff and rain can be seen in the surface salinities of the near shore stations. All nearshore stations from lines 2 through 6 had surface salinities less than 33‰. On lines 3 and 5 the low salinity water extended beyond the second station on the line. The less than 33‰ water was between 10 and 19 m thick. All but the north and northeast winds of line 2 would have a tendency to transport water away from shore. The lowest salinity, 30.66‰, was observed at nearshore station 29 on line 5; 31.59‰ was observed at station 43 on line 6 just off Cape Camau. At these same locations on cruise S6 in June, 1960, at the beginning of the southwest monsoon salinities were 32.98 and 32.94‰.

CRUISE S9, NOVEMBER 9-24, 1960, GULF OF THAILAND

Cruise S9 took place in November, 1960. Line 5 was omitted from the itinerary and two additional half lines located between the standard lines were occupied in the east half of the Gulf.

Winds were highly variable in speed and direction although the northeast monsoon is normally well developed by November. Strongest winds were observed in the eastern parts of lines la and 2 and on the connecting line toward line 2a with speeds of 5-10 knots from a dominantly northern direction. Along the west coast in mid-Gulf there were winds of similar speeds which varied in direction from northeast, east to north and northwest. Winds on the east ends of lines 3 and 3a were mostly calm or less than 3 knots. On line 4 the winds were light east to southeast except off Songkhla where northwest winds at 12 knots were observed.

A few rain squalls occurred during this cruise, but no rainfall was recorded during the time the stations were occupied.

The rains did not stop abruptly in November at the beginning of the northwest monsoon although they were much less than in September and October except at Ban Don (327 mm), Songkhla (395 mm) and Kota Bharu (800 mm) where the maximum for the year fell. In November Bangkok (94 mm), Ban Don and Kampot (143 mm) had higher than normal rainfall, Chantaburi (100 mm) had normal and Prachuap Khirikhan (135 mm) and Chumphon (197 mm) had less than the normal rainfall for the month. The high November rainfall on the west side of the Gulf is reflected in the low surface salinity along that coast with the minimum near Ban Don. However, the lowest salinity was observed at station 15 on line 4 in mid-Gulf, and a large body of water of salinity less than 32‰ was observed on the east end of line 4 where light or calm winds would allow it to persist. What was the source of this water? In October, 1959, on the station at the east end of line 4 a surface salinity of 27.00‰ was observed, but the salinity had increased to greater than 32‰ at the second station on the line. The runoff appears to have come from drainage from the east coast between Phu Quoc and Cape Camau. On cruise S8, as previously mentioned, surface salinity as low as 31.59‰ was found just south of Cape Camau in early October, 1960, but the southwest winds would not have transported the Mekong River outflow into the Gulf. However, if the northeast monsoon had already developed along the coast of South Viet Nam and over the Gulf between Cape Camau and Kota Bharu since the time of cruise S8, low salinity surface water could have come around Cape Camau into the Gulf. Wyrtki (1961, plate 5a) shows a southwestward flowing monsoon current already developed along the South Viet Nam coast by November which could bring low salinity water south and into the mouth of the Gulf although possibly not as far north as line 4. Yet the presence of the lowest salinity water in mid-Gulf rather than near shore is puzzling. Station 15 (Figure 49) where these low salinities were observed was an anchor station occupied for 24 hours. Surface salinities remained between 29.00-29.47‰ the entire time while 10 m salinities were between 29.46-29.70‰ and 30 m salinities were below 32‰ (31.28-31.78‰). In order for this large body of low salinity water to have persisted away from its land source a considerable period of low wind speeds must have occurred. Most observations on the eastern half of lines 3 and on line 3a reported no wind. On line 4 between the east coast and station 15 winds ranged from 2-7 knots with higher speeds near the coasts. It is unfortunate that line 5 was omitted from this cruise because an enormous amount of rain (800 mm) fell at Kota Bharu during November, 1960, and it might have been possible that low salinity water extended across the mouth of the Gulf although such was not the case on any of the previous cruises in the northeast monsoon periods. The higher wind speeds in the southwest Gulf might have raised the surface salinity in this area by mixing.

Another contrast between the salinity distribution found on cruise S9 compared with that on cruises S1 and S3 is the occurrence of a high salinity cell in mid-Gulf on lines 2 and 3. This may be an example of open sea divergence and upwelling under a pattern of divergent winds whose strength was not sufficient to bring the 33‰ water to the surface in this area where on previous cruises convergence and sinking were observed. Stronger divergent winds would need to have preceded this cruise to account for the observed distributions. However the oxygen content of this water was high, near or above 4.25 ml/l, and the deep 33.5‰ salinity lines are relatively low and do not indicate any vertical disturbance of the deeper low oxygen water. An alternate explanation for the presence of this high salinity water in mid-Gulf is that it is the remnant of the high salinity upwelled water found at the head of the Gulf on cruise S7 which had moved downstream without dilution aided by the divergent winds in that area, but not caused by them. Temperature and oxygen concentrations at the head of the Gulf are very close to those observed on cruise S7. On all cruises the central part of the Gulf has minimum motion with in-and-out flow confined mainly to the coastal areas. This situation would also aid the preservation of a dense, homogenous body of water as long as it had moved into an area where deep, denser high salinity water lay beneath and until it was diluted at the surface by mixing with the nearby low salinity water or sank in a convergence area spreading out on its own density surface.

On cruise S1 no water of salinity greater than 33‰ was found at the surface and on cruise S3 such water occurred only in the wedge entering the Gulf around Cape Camau.

The vertical distribution of temperature, salinity, sigma-t and oxygen (Figures 49 and 50) indicates less pronounced areas of upwelling along the eastern coast than on cruises S1 and S3. Low oxygen concentrations were observed at the east ends of lines 2a, 3 and 3a at shallow depths. The deeper waters in the trough below 50 m had oxygen concentrations between 2.05 and 2.53 ml/l.

During this cruise, as well as cruises S1 and S3, frequent temperature inversions were observed. Density distributions, however, were stable.

Horizontal circulation was inferred from the horizontal distribution charts of temperature, salinity and sigma-t (Figures 51, 52 and 53). Horizontal oxygen distributions at each level were in accordance with the inferred circulations.

The density distribution at the surface does not clarify the source of the low salinity water on line 4, but it is apparent that the source was Mekong River water from one or both sides of the South Viet Nam peninsula with a clockwise circulation around the low density core. There was a counter-clockwise gyre around the high salinity cell in mid-Gulf and strong outflow along the west coast. The situation was similar at 30 m with little or no gradients in the central areas. At 50 m the gradients increased. The densest water was found in mid-Gulf on line 2 indicating the onset of upwelling in the northern part of the Gulf. At this level inflow was indicated along the western coast, outflow along the eastern shore.

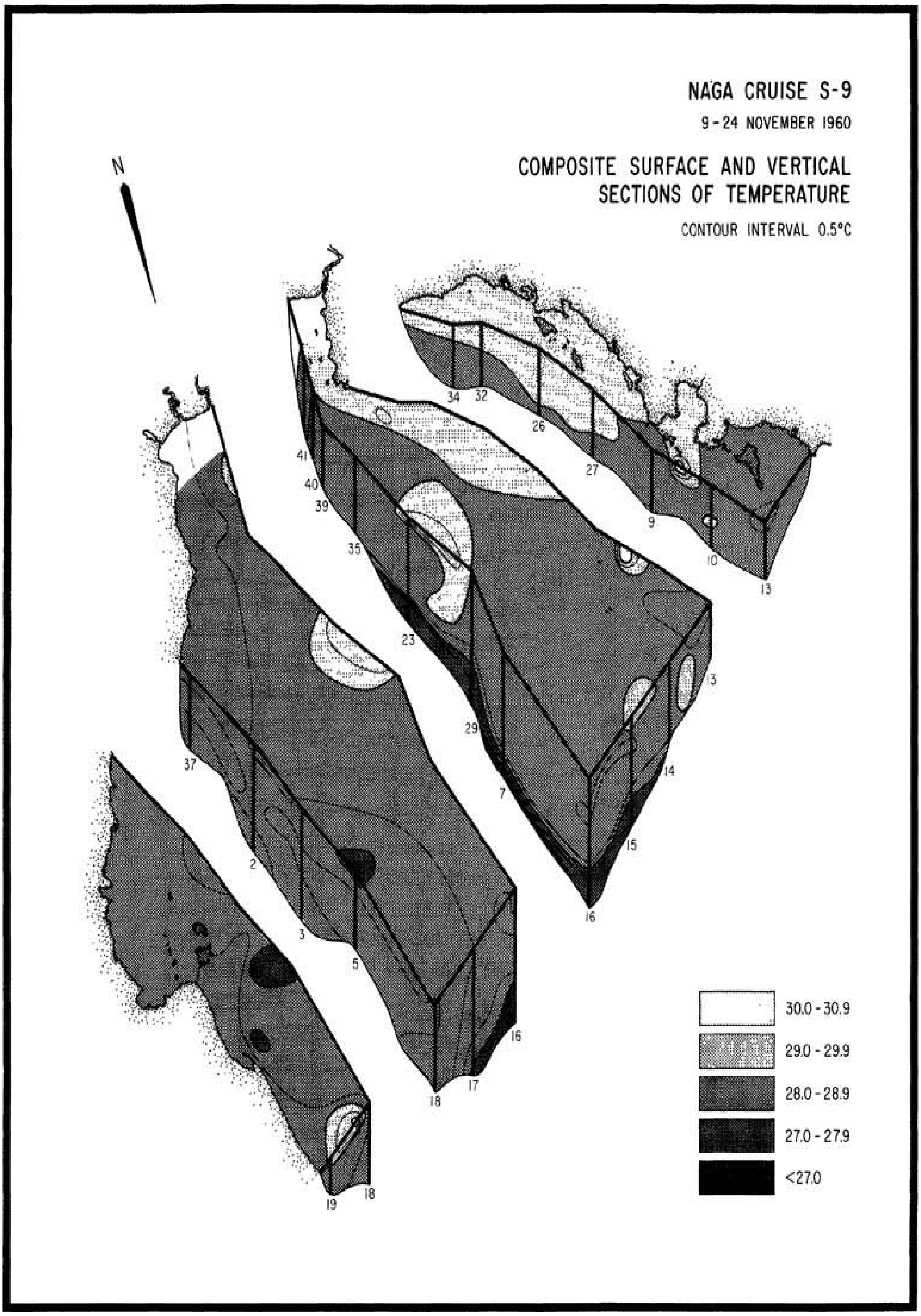
NAGA CRUISE S-9
9 - 24 NOVEMBER 1960
COMPOSITE SURFACE AND VERTICAL SECTIONS OF TEMPERATURE
CONTOUR INTERVAL 0.5°C
N
34
32
26
27
9
10
13
41
40
39
35
23
29
7
13
14
15
16
37
2
3
5
18
17
16
19
18
30.0 - 30.9
29.0 - 29.9
28.0 - 28.9
27.0 - 27.9
<27.0

Figure 47.

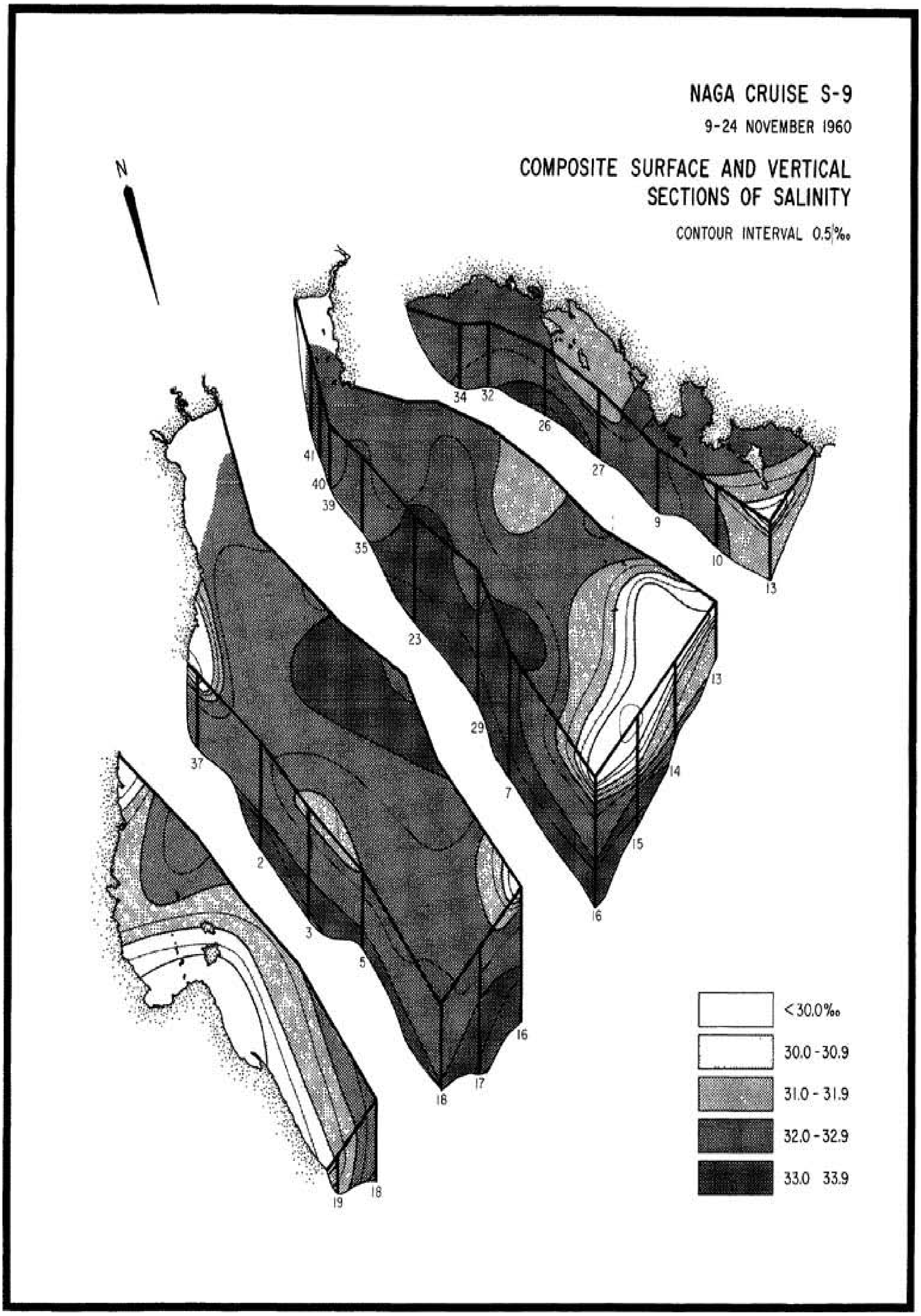
NAGA CRUISE S-9
9-24 NOVEMBER 1960
COMPOSITE SURFACE AND VERTICAL SECTIONS OF SALINITY
CONTOUR INTERVAL 0.5‰
N
34
32
26
27
9
10
13
41
40
39
35
23
29
7
13
14
15
16
37
2
3
5
18
17
16
19
18
<30.0‰
30.0 - 30.9
31.0 - 31.9
32.0 - 32.9
33.0 33.9

Figure 48.

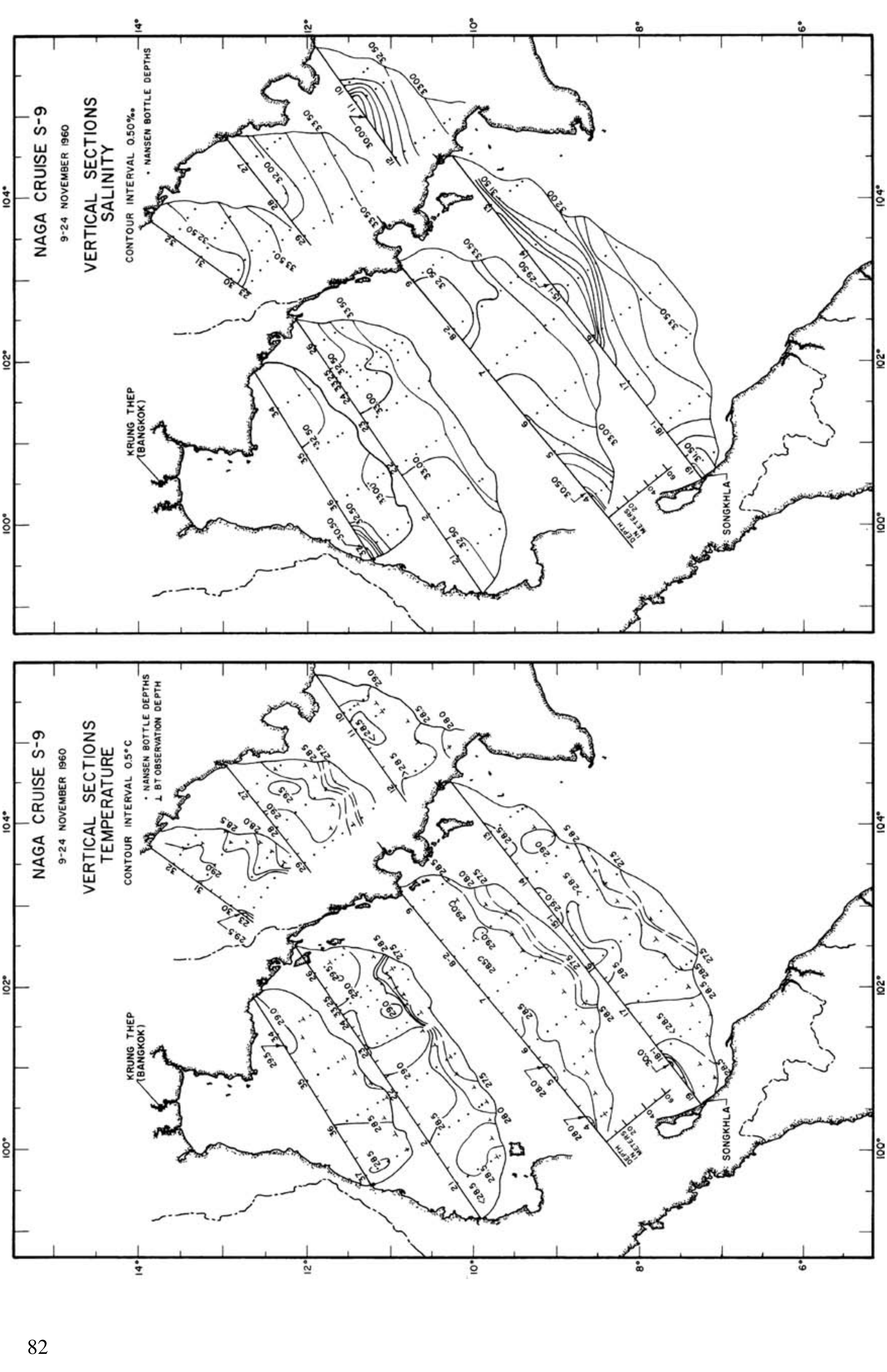
NAGA CRUISE S-9
9-24 NOVEMBER 1960
VERTICAL SECTIONS
TEMPERATURE
CONTOUR INTERVAL 0.5°C
• NANSEN BOTTLE DEPTHS
⊥ BT OBSERVATION DEPTH
NAGA CRUISE S-9
9-24 NOVEMBER 1960
VERTICAL SECTIONS
SALINITY
CONTOUR INTERVAL 0.50‰
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH METERS
20
40
60
14°
12°
10°
8°
6°
100°
102°
104°

Figure 49.

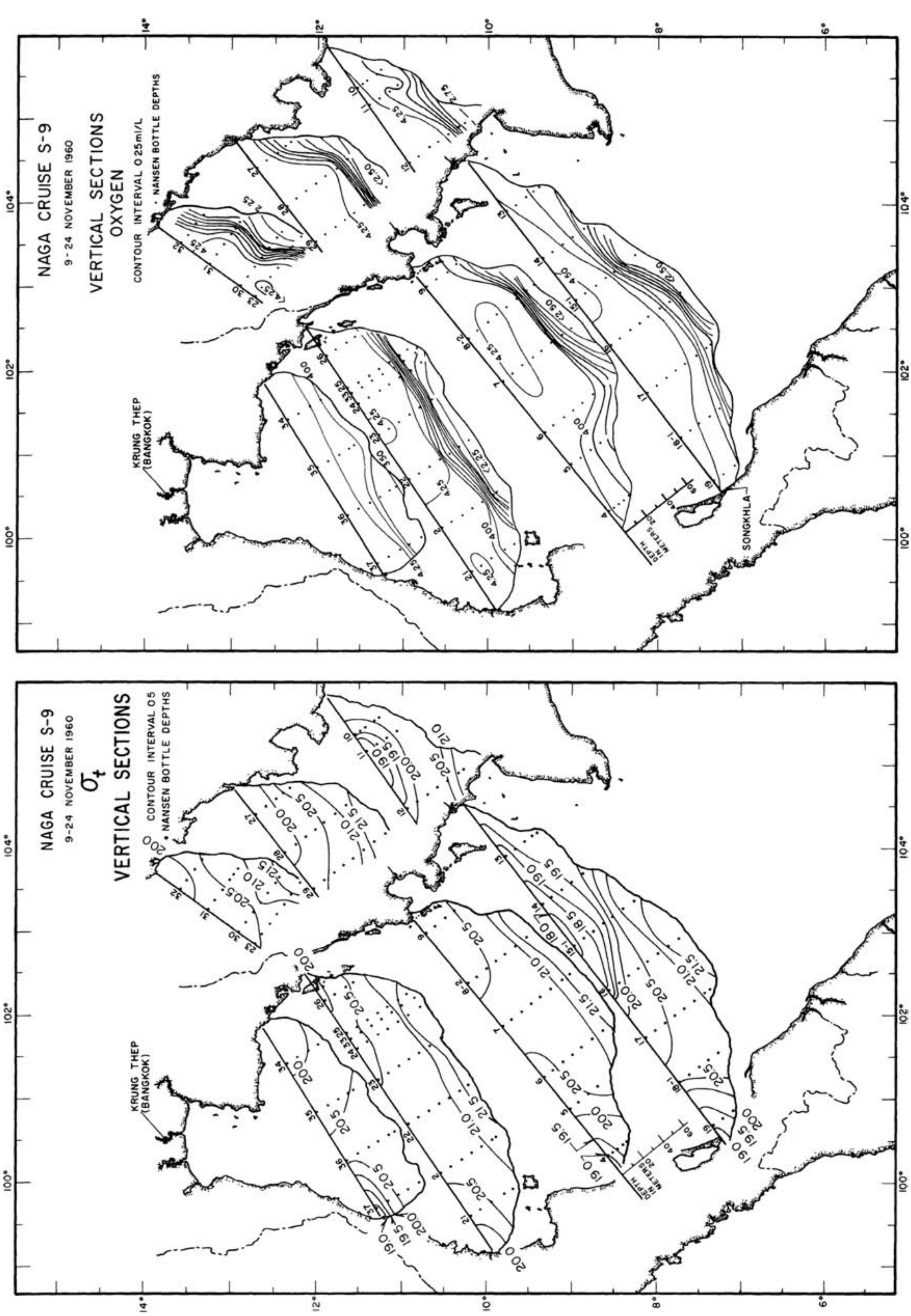
NAGA CRUISE S-9
9-24 NOVEMBER 1960
VERTICAL SECTIONS
OXYGEN
CONTOUR INTERVAL 0.25 ml/L
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
SONGKHLA
DEPTH METERS
NAGA CRUISE S-9
9-24 NOVEMBER 1960
σt
VERTICAL SECTIONS
CONTOUR INTERVAL 0.5
• NANSEN BOTTLE DEPTHS
KRUNG THEP (BANGKOK)
DEPTH METERS
14°
12°
10°
8°
6°
100°
102°
104°

Figure 50.

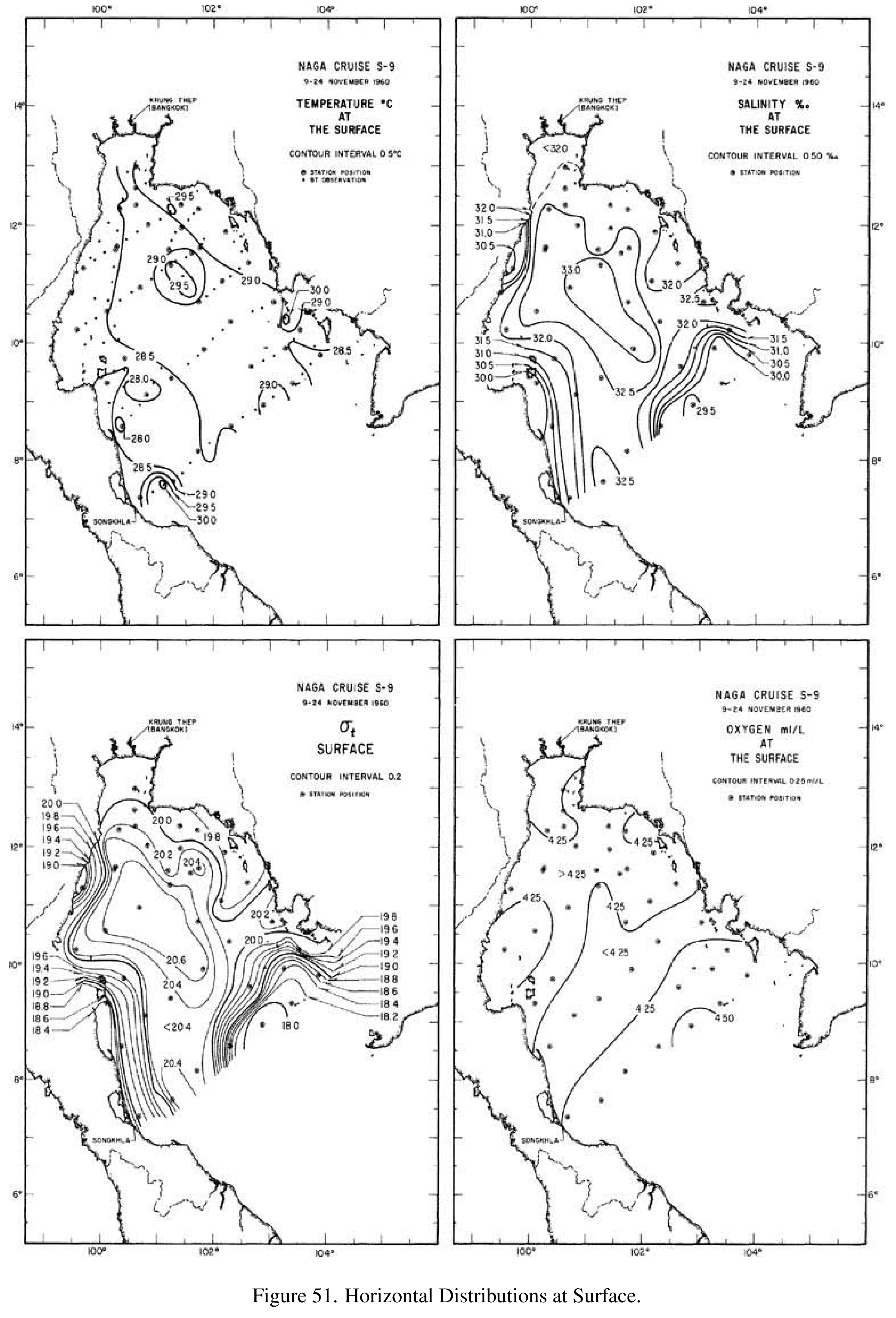

Figure 51. Horizontal Distributions at Surface.

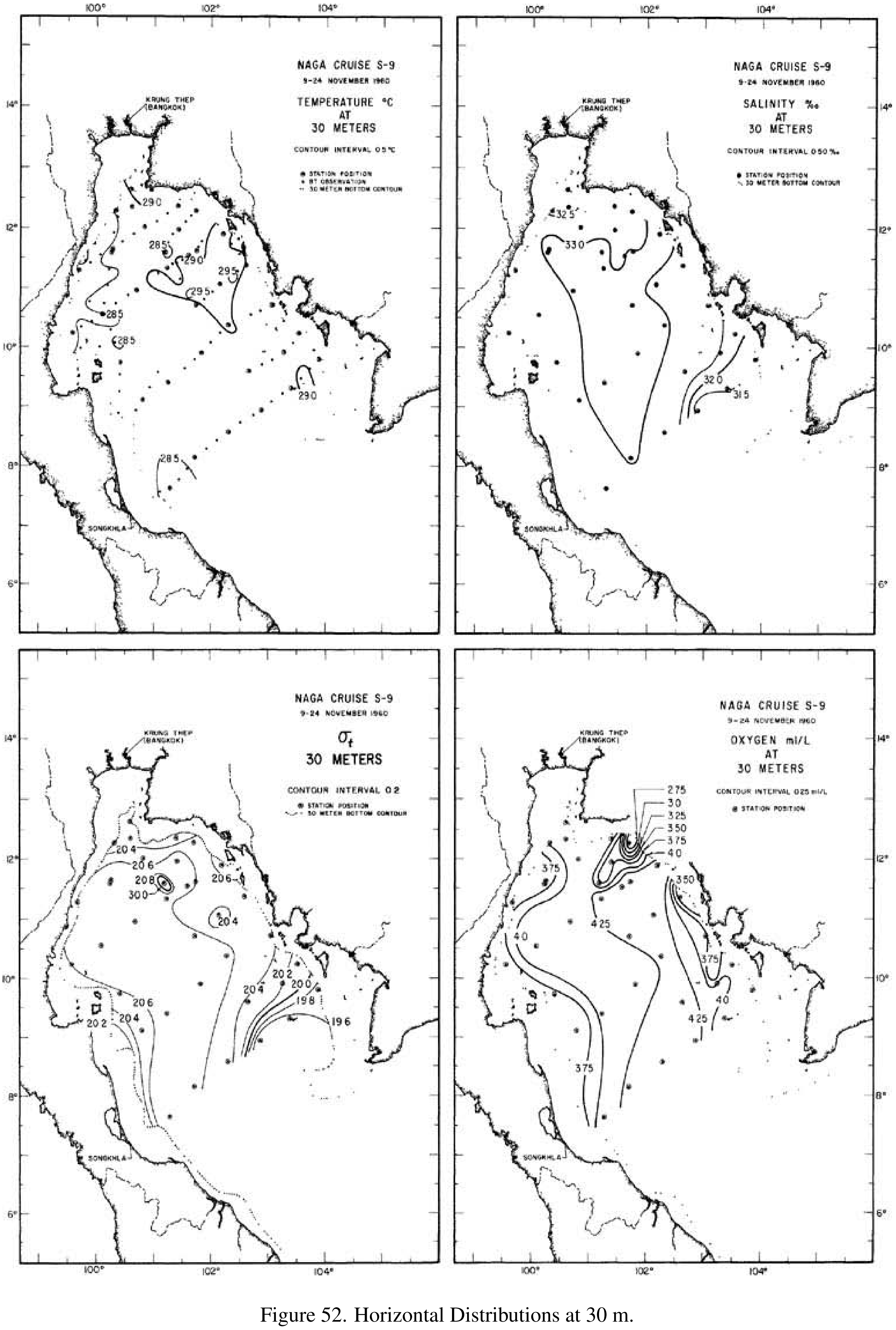

Figure 52. Horizontal Distributions at 30 m.

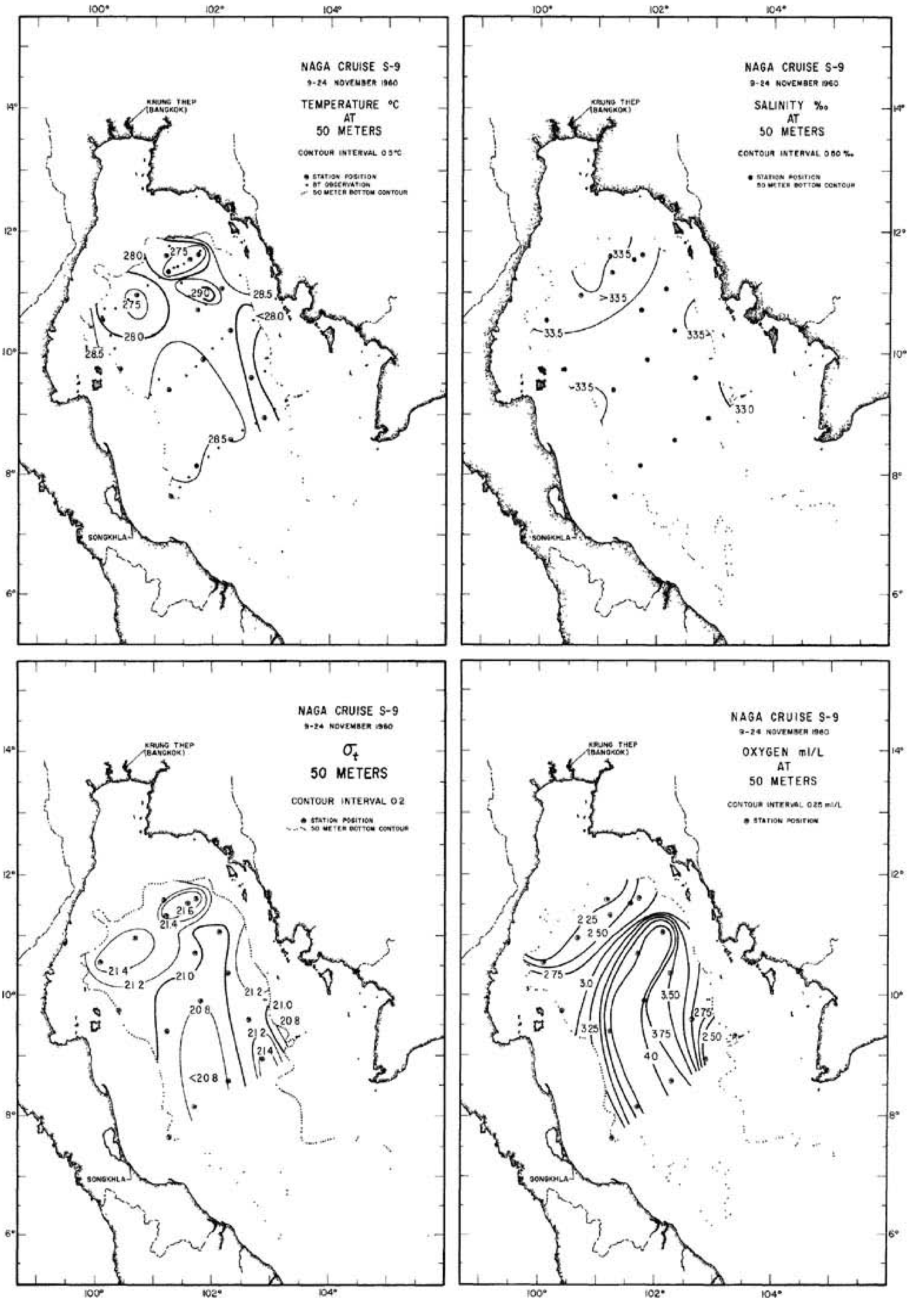

Figure 53. Horizontal Distributions at 50 m.

CRUISE S9A, DECEMBER 8-14, 1960, (NORTHERN) GULF OF THAILAND.

Cruise S9A in December, 1960 covered the inner Gulf and two northern lines intensively but made only meteorological and BT observations and biological collections. Winds in the upper Gulf were more constant in speed and direction than those on cruise S9 with dominant northeast winds of 10-15 knots in the inner Gulf on the first leg, somewhat less in speed on the second leg and more variable in both speed and direction on the third leg. Rainfall during December was normal at Bangkok (10 mm) and Chantaburi (0) and less than normal at Prachuap Khirikhan (2 mm). Winds in this area in December, 1959, (underway observations on cruise S2) had been primarily northwest with one north and one northeast observation; speeds were less than in 1960.

The vertical temperature distributions (Figure 54) were similar to those observed during cruise S9 and were also characterized by temperature inversions. Salinities probably were similar to those on cruise S9 because of the lack of rainfall and reduced river runoff.

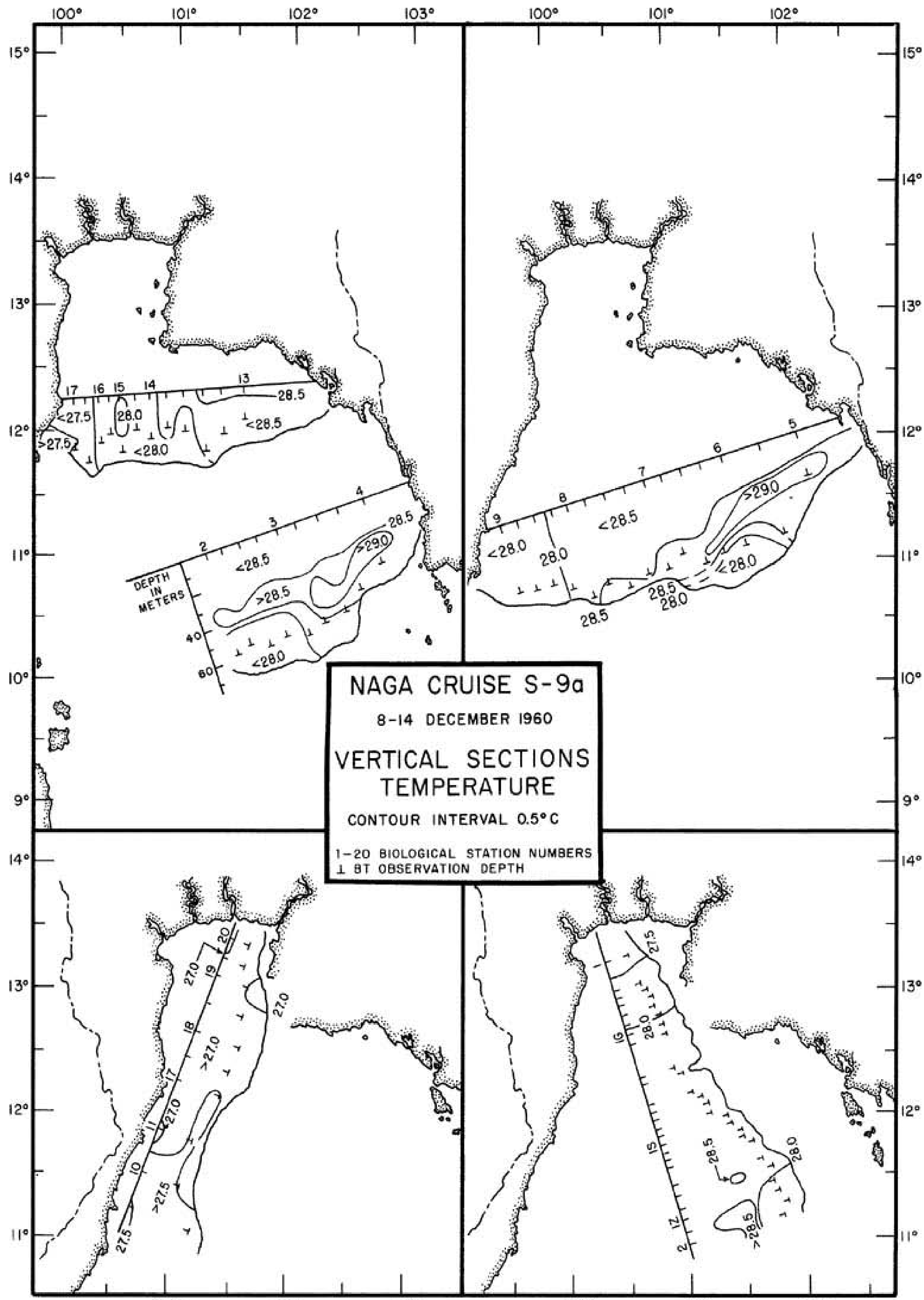
NAGA CRUISE S-9a
8-14 DECEMBER 1960
VERTICAL SECTIONS
TEMPERATURE
CONTOUR INTERVAL 0.5° C
1-20 BIOLOGICAL STATION NUMBERS
⊥ BT OBSERVATION DEPTH
100°
101°
102°
103°
15°
14°
13°
12°
11°
10°
9°
17
16
15
14
13
<27.5
28.0
28.5
<28.5
>27.5
<28.0
1
2
3
4
5
6
7
8
9
10
11
12
16
18
19
20
DEPTH IN METERS
40
60
>28.5
>29.0
27.0
>27.0
27.5
>27.5
>28.5

Figure 54.

CRUISE S10, January 11-13, 1961, Gulf of Thailand,
January 13-February 9, South China Sea,
February 9-12, Gulf of Thailand.

The underway wind observations on the Gulf leg of cruise S10 in January, 1961, were east and northeast with variable speeds of 2-20 knots with the maximum off Cape Camau. The South China Sea portion of S10 in January covered only the two northern lines completely and the near-shore halves of lines 3 and 4. Winds were dominantly northeast with some northwest winds near shore. Speeds ranged 5-30 knots. Monthly rainfall was higher than normal at Tourane (129 mm) and Nhatrang (48 mm), lower than normal at Saigon (2 mm) and Prachuap Khirikhan (20 mm) and normal at Bangkok (0) and Chantaburi (20 mm). Surface salinities were less than 33‰ at each of the three northern near-shore stations (1, 13 and 14) in the South China Sea.

On the return leg of S10 through the Gulf to Bangkok in February, 1961, there were strong 20 knot east winds as the ship rounded Cape Camau, southeast to south as it neared Phu Quoc. Towards the north they were very light south or southwest except for a 6 knot southeast wind off Sattahip and a 10 knot west wind off Ko Kut. The wind pattern closely resembles that of cruise S4 (February, 1960) with the sharp change in speed and direction north of Point Samit. Rainfall and salinity data are not available for this period.

The temperature structure along the Gulf cruise (Figure 55) track in January, 1961, (cruise S10) was much simpler than that in December, 1959, (cruise S3) or February, 1960, (cruise S4). The intense temperature gradient entering the Gulf beyond Cape Camau was greater (26.2 to 28 °C) than on cruise S2, somewhat less and not quite as sharp as on cruise S4 (25.4 to 27.5 °C). Temperatures were isothermal or decreased with depth except one observation.

On the return leg through the Gulf in February, 1961, the water temperature front near Cape Camau was much less developed than on any of the above cruises. Between Point Samit and Cape Liant, where weak winds were observed, the surface temperatures were 0.5 to 1.0 °C lower than those observed on cruise S4, and, while some temperature inversions were observed, they too were smaller. Because February is a month of expected low rainfall and minimum river runoff, salinities along the track might be expected to have ranged between 32 and 32.5‰.

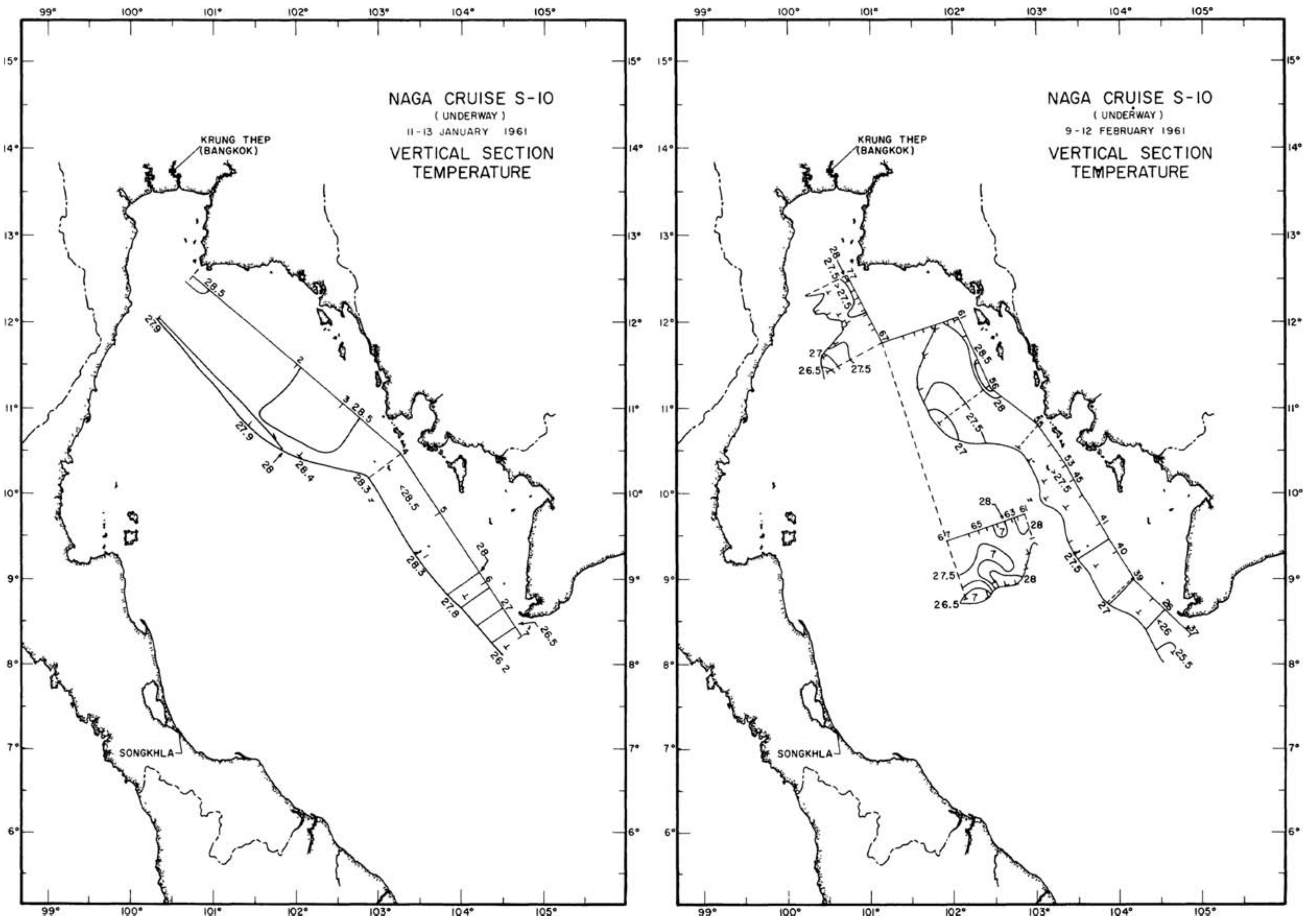
NAGA CRUISE S-10
(UNDERWAY)
11-13 JANUARY 1961
VERTICAL SECTION
TEMPERATURE
KRUNG THEP (BANGKOK)
SONGKHLA
28.5
27.9
2
3 28.5
27.9
28
28.4
28.3
<28.5
5
28
28.3
6
27.8
27
26.5
26.2
NAGA CRUISE S-10
(UNDERWAY)
9-12 FEBRUARY 1961
VERTICAL SECTION
TEMPERATURE
KRUNG THEP (BANGKOK)
SONGKHLA
28
77
27.5
>27.5
67
27
26.5
27.5
61
28.5
56
28
27.5
27
55
53
45
>27.5
28
63
61
65
28
27.5
28
26.5
41
40
27.5
39
27
26
<26
37
25.5
99°
100°
101°
102°
103°
104°
105°
15°
14°
13°
12°
11°
10°
9°
8°
7°
6°

Figure 55.

CURRENTS OF THE GULF OF THAILAND

Three related groups of current measurements have been taken in the Gulf of Thailand. The first was collected during cruise S9 in November, 1960, on the Naga Expedition when four 24-hour anchor stations at selected locations were occupied for a study of the diurnal variation of temperature, salinity and surface currents. The second group was collected by the USS *Serrano* in March and November, 1961, using current meters. These two sets of observations are reported and discussed here. The third group of observations, which were made in November, 1964, at two stations at the mouth of the Gulf by the RV *Argo* returning from the DODO Expedition to the Indian Ocean, is reported in Faughn and Taft, 1967.

A. Diurnal Variation of Temperature, Salinity and Surface Currents Observed on Cruise S9.

During cruise S9 four 24-hour anchor stations were occupied, the locations of which are shown on Figure 1. Hydrographic casts were made at 3-hour intervals and BT and surface current measurements at hourly intervals. According to J.L. Faughn, Captain of the RV *Stranger*, the current measurements were made in the following manner;

> "The direction and rate of movement of surface currents were observed at hourly intervals over a lunar tidal day at each of the four anchor stations. The weather and sea conditions were uniformly favorable for anchored operations except during an occasional squall when the wind attained speeds of 25–40 mph for short periods of time. The vessel rode quietly and, usually, to the prevailing surface current. At each station the depth of water was approximately 30 fathoms, and the vessel was anchored with 75 fathoms of chain to the starboard anchor.
>
> "Current speed was determined by observing the rate of separation between the anchored vessel and a freely drifting spar. Current direction was determined by simultaneous observations of the angular position of the spar relative to the centerline of the ship and of the true heading of the ship. After the manner of the ancient "CHIP LOG", a light line of suitable length, knotted at selected intervals and tended from the vessel, was attached to the spar. In operation the spar was carefully lowered into the water over the stern of the vessel and the line was payed out as the spar drifted clear downstream. The distance from the spar to the first knot in the line was selected to permit the spar to get well clear of the turbulence in the water caused by the vessel before the knot passed the point for observation. When, in the judgment of the observer, the motion of the spar had stabilized, a stop-watch was started on the instant a knot in the line passed the observation point. After the watch was started, the observer kept count of the knots as the line was payed out, and, after a reasonable number had passed, usually ten, he stopped the watch. At this instant, observations were made of the position of the spar and of the ship's heading for determination of drift direction. The current speed was then computed from the distance traveled in the interval clocked. Values accepted for each hour's record represent the average of three successive determinations following closely one on another by this method.
>
> "As a check on the probable accuracy of the method employed, both for determination of current speed and direction, an additional drift spar of somewhat different design was employed at the last station. The underwater portion of the latter spar was increased in size to present a larger drag area to the current, and a light-weight, small-diameter section about three feet long was added above. No line was attached to the second spar; instead, the above-water section was clearly marked at two vertically separated points. Over a period of an hour and fifteen minutes with the spar drifting freely away from the ship, observations of the angular distance between the marks were made at frequent intervals using a marine sextant. From the known spacing between the marks and the observed vertical angle the horizontal distance to the spar from the observer was determined. Using this information and the recorded time of each observation, the rate of drift was determined. The direction of current flow by the second method was determined by direct observation of the true direction of the spar from the bridge of the vessel. These results were compared with the corresponding data obtained during the same period

by the first method. Observed variations in the results thus compared were insignificant."
(See also Faughn, in press.)

Strong tidal periodicities were present in the surface current observations (Figure 56). The vector diagrams of the currents at each station vary considerably. All stations were in the region where mixed semi-diurnal and diurnal tides are to be expected (Pukasab and Pochanasomburana, 1957). The differences in surface current at the four locations, therefore, depends upon the extent to which the wind-driven or geostrophic currents were dominant. The resultant direction of flow at each station, however, was consistent with the general circulation inferred from the density distributions.

The T-D and S-D envelopes of curves in Figure 56 also show large diurnal variations, but even more remarkable is how much the envelopes differ from one another notwithstanding the fact that the observations were taken near to each other both in time and space. The oscillations in depth of the thermocline and halocline appear to be primarily of tidal period although additional random changes were also present.

At Anchor Station 33 on line 2, thirty miles southwest of Ko Chang in the northern Gulf, surface current speeds and directions varied from southwest 0.1 kt to northeast 0.2 kt to southwest 0.3 kt. The semi-diurnal tidal component was dominant.

The break in the slope at the thermocline and halocline was sharp although a few T-D curves show a small temperature decrease above the principal thermocline. The top of the thermocline was also slightly shallower than the top of the halocline. Both varied approximately 5 m in depth.

The range of temperature and salinity at standard levels for the four anchor stations is given in Table 4. At Anchor Station 33 the ranges at the standard levels were largest at the surface and were high at 30 m. However, at the non-standard level of 45 m, the curves show maximum ranges.

TABLE 4

24-HOUR RANGE OF TEMPERATURE AND SALINITY AT ANCHOR STATIONS

Depth	A.S. 33		A.S. 8		A.S. 15		A.S. 18	
	Range		Range		Range		Range	
	T°C	S°/oo	T°C	S°/oo	T°C	S°/oo	T°C	S°/oo
0	0.35	0.36	0.30	0.08	0.49	0.47	0.54	0.17
10	.13	.07	.05	.07	.10	.24	.14	.02
20	.11	.10	.07	.23	.07	.30	.10	.05
30	.27	.25	.63	.38	.08	.46	.05	.05
50	.03	.14	.43	.32	.07	.07	.03	.06

At Anchor Station 8, fifty miles southwest of Samit Point, the surface currents varied in speed and direction from northwest 0.6 kt to north 0.2 kt to northeast 0.2 kt to east 0.3 kt and finally to southwest 0.5 kt. Tidal periodicity was primarily semi-diurnal.

The T-D and S-D curves show complicated inversions with depth. There was a double thermocline and a double halocline, the depths of which varied by approximately 5 m during the 24-hour period. These station curves are extremely good examples of the strong horizontal and vertical gradients in temperature and salinity which occur in the Gulf along water mass boundaries. The diurnal ranges at standard levels indicate maxima at 30 m. The curves, however, indicate maximum salinity ranges would occur at the non-standard level of 35 m.

Conditions at Anchor Station 15 in the center of line 4 were different. Surface currents were dominantly northwest 0.3 to 0.5 kt and west 0.1 to 0.3 kt. While the principal tidal component was semi-diurnal, the approximately 90° shift in direction was a result of the influence of the mean circulation.

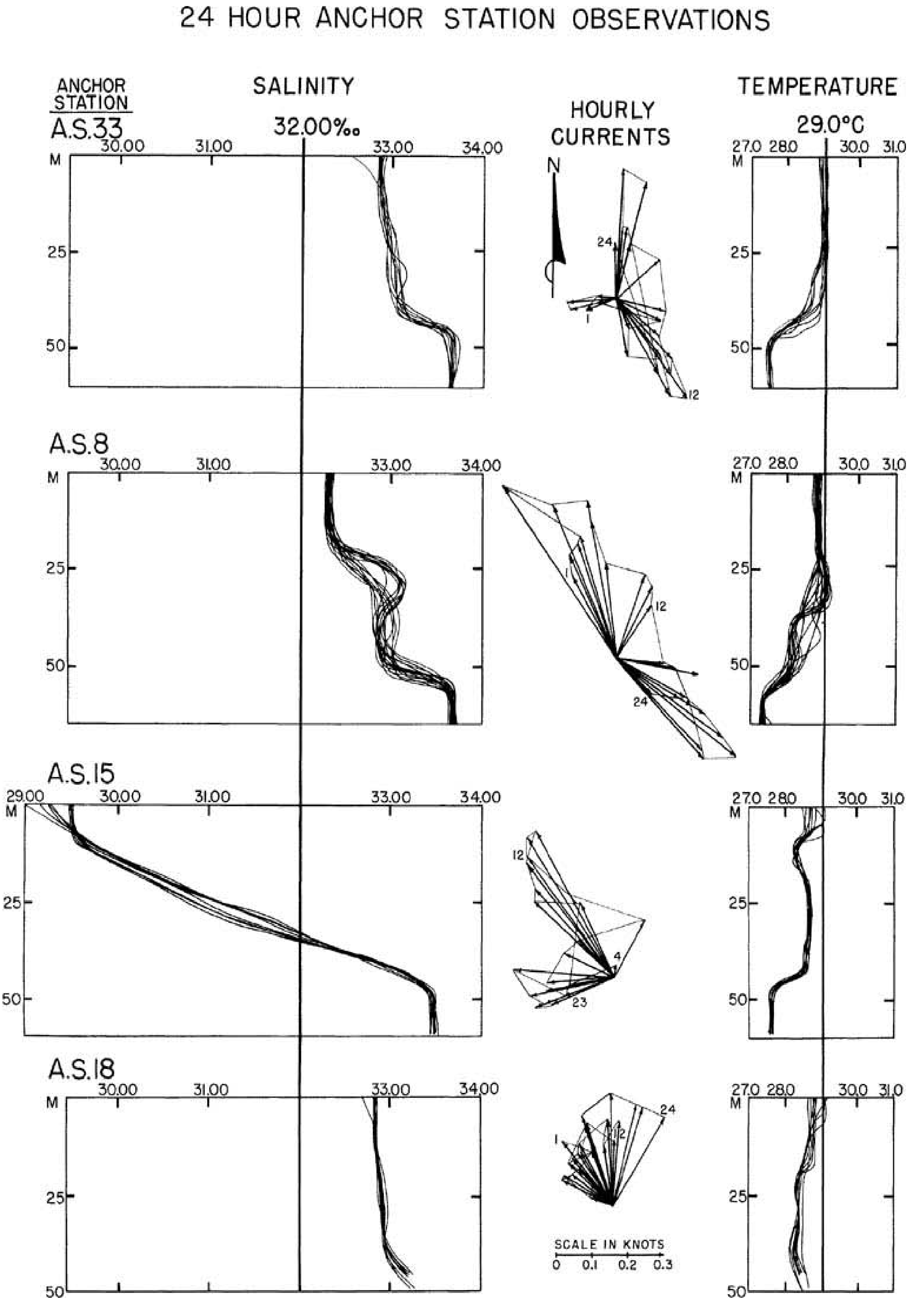
24 HOUR ANCHOR STATION OBSERVATIONS
ANCHOR STATION
SALINITY
32.00‰
HOURLY CURRENTS
TEMPERATURE
29.0°C
A.S.33
A.S.8
A.S.15
A.S.18
29.00
30.00
31.00
33.00
34.00
27.0
28.0
30.0
31.0
M
25
50
N
1
12
24
4
23
SCALE IN KNOTS
0
0.1
0.2
0.3

Figure 56.

TABLE 5

COMPARISON OF RESULTANT VECTOR CURRENT VELOCITIES AND AVERAGE SCALAR CURRENT SPEEDS

	DEPTH - METERS																						
	0	3	6	7	9	12	15	18	20	21	23	24	27	30	34	36	38	39	42	45	46	47	50
STATION 1A - March 26-27, 1961 - 26 Hours																							
Vectors:																							
Direction (°)	352	030	045		065	084	074	053		030													
Current Vel. (kts)	12	11	12		.09	12	.08	07		.03													
Scalars:																							
Av Current Speed (kts)	.14	.20	25		25	.26	.24	.27		24													
STATION 2 - March 13-14, 1961 - 27 Hours																							
Vectors.																							
Direction (°)	334	320	067			103		143				161		120	191								
Current Vel (kts)	19	11	.08			.08		10				.08		05	02								
Scalars																							
Av Current Speed (kts.)	28	.32	47			49		.47				42		36	30								
STATION 3 - March 14-15, 1961 - 26 Hours																							
Vectors.																							
Direction (°)	060	071	085			079		105				095		123	106								
Current Vel (kts)	22	25	.28			.26		12				04		06	04								
Scalars.																							
Av Current Speed (kts)	.25	31	42			40		27				27		26	.23								
STATION 4 - March 21-22, 1961 - 25 Hours																							
Vectors																							
Direction (°)	017	027	036		042	042	024	040		039		032		016		347	030						
Current Vel (kts)	37	.42	46		41	.35	29	.28		.18		22		08		08	05						
Scalars.																							
Av Current Speed (kts)	42	48	53		47	40	34	.35		31		30		.28		.20	.13						
STATION 5 - March 19-20, 1961 - 29 Hours																							
Vectors.																							
Direction (°)	296	301	301			300		311				305		308		327		338	324		324		340
Current Vel (kts)	41	40	37			37		37				40		44		35		18	13		11		05
Scalars.																							
Av Current Speed (kts)	44	42	39			39		39				.42		47		38		21	18		15		09
STATION 6 - March 16-17, 1961 - 26 Hours																							
Vectors																							
Direction (°)	314	336	056		075	074	323	137		035		084	092	093									
Current Vel (kts)	13	09	06		09	.10	.04	.04		01		08	06	04									
Scalars																							
Av Current Speed (kts)	16	.25	.26		.29	.29	.27	.26		22		23	27	18									
STATION 7 - March 18-19,1961 - 26 Hours																							
Vectors																							
Direction (°)	274	296	302			266		229				316		344		350			310	236		229	
Current Vel. (kts)	20	17	17			08		.08				05		12		12			11	07		09	
Scalars																							
Av Current Speed (kts.)	22	32	32			28		28				31		29		30			28	28		.29	
STATION 8 - November 8-9, 1961 - 24 Hours																							
Vectors																							
Direction (°)				104			164				162												
Current Vel (kts)				15			33				15												
Scalars																							
Av Current Speed (kts)				26			34				21												
STATION 9 - November 9, 1961 - 5½ Hours																							
Vectors																							
Direction (°)				257					198											191			
Current Vel (kts.)				42					35											49			
Scalars																							
Av Current Speed (kts)				49					38											38			
STATION 9 - November 10, 1961 - 5 Hours																							
Vectors																							
Direction (°)				336					118											147			
Current Vel (kts)				28					47											80			
Scalars																							
Av Current Speed (kts)				48					51											93			
STATION 10 - November 10-11, 1961 - 15 Hours																							
Vectors																							
Direction (°)				148					136								160						
Current Vel (kts)				05					06								08						
Scalars																							
Av Current Speed (kts)				22					22								19						

The S-D curves are dominated by an extreme halocline between 10 and 50 m with an increase from 29.47 to 33.75 ‰ in 40 m. In the upper 10 m when the salinity was constant there was considerable temperature variability. At the tip of the halocline a slight temperature inversion occurred, but between 24 and 45 m, the main part of the halocline, the temperature was essentially isothermal. Finally, between 45 and 50 m a sharp decrease in temperature occurred corresponding to the bottom of the halocline. Beneath 50 m homogeneous low temperature, high salinity water was found.

At Anchor Station 18, thirty miles from Songkhla, at the western end of line 4 diurnal variation in currents and water properties was at a minimum. The direction and speed of the surface current was primarily northwest and north 0.1 to 0.3 kt. The tidal component was largely masked by the dominant northwest flow toward the upper Gulf, but the direction change represents expected semi-diurnal characteristics.

B. USS *Serrano* Current Observations in the Gulf of Thailand, March and November, 1961.

The USS *Serrano* collected current observations in the Gulf of Thailand during March and November, 1961, using Model III and Model IV Roberts Current Meters. Recordings were made by chronograph or Brush records, and reduction of the data was carried out in accordance with E.R. Roberts (1952).

The tabulated current-meter data were given to the author by Mr. Claude I. Coffey, U.S. Naval Oceanographic Office, who supervised the observational program at sea. The procedure used was as follows:

> The ship would head upwind, drop and pay out the bow anchor and chain, and then lower a stern anchor on 3” nylon line. The ship would then steam ahead, retrieving bow chain until a satisfactory scope on each was obtained. Based on local time, a meter was lowered on the hour, starting just below the surface and continuing at various intervals to the bottom. Generally speaking, a complete lowering was made in approximately twenty minutes. The values are considered average for that hour. The following measures were taken to insure over-all reliability of the data:
>
> The Roberts Current Meters were calibrated in the David Taylor model Basin tow tank just prior to use. During the surveys the meters were raised to deck level at least once per hour to check the condition of the impeller bearings, freedom of movement to the connecting ball bearing swivel and the frame trunnions. Several daily intercalibration checks between different meters were routinely made.

Operating conditions were favorable, especially during the March survey. Between 15:00 and 23:00 hours on November 10, 1961, however, in the middle of station 9 a local squall occurred and wind speeds up to 17 kts were observed. Heaving of the ship necessitated retrieval of the stern anchor, and current observations were interrupted for a period of 15 hours. During station 10, also, the ship was anchored by bow anchor alone. Therefore, the reliability of observations at stations 9 and 10 is less than at the other stations.

In Figure 57 the current data at all depth levels are summarized in vector diagrams superimposed on a map of the Gulf of Thailand to indicate the geographical location of the stations. Each vector in this figure was obtained by constructing the vector sum of all pairs of readings, assuming that the readings represented average conditions over one hour. Also shown in Figure 57 are resultant wind vectors corresponding to the same period of time as the current observations. Examples of the progressive vectors with resultant vectors omitted are shown in Figure 58.

In Table 5 the resultant vector-current velocities are compared with the average scalar current speeds. The ratio of these two values is a measure of the semi-diurnal tidal effect in the current measurements.

Currents in the Gulf of Thailand are a complex mixture of tidal, wind-driven and density currents. The tides in the Gulf of Thailand vary from diurnal to semi-diurnal with inequalities-to-mixed diurnal and semi-diurnal types. In addition seiches have been observed with periods of approximately 40 minutes (Pukasab and Pochanasomburana, 1957).

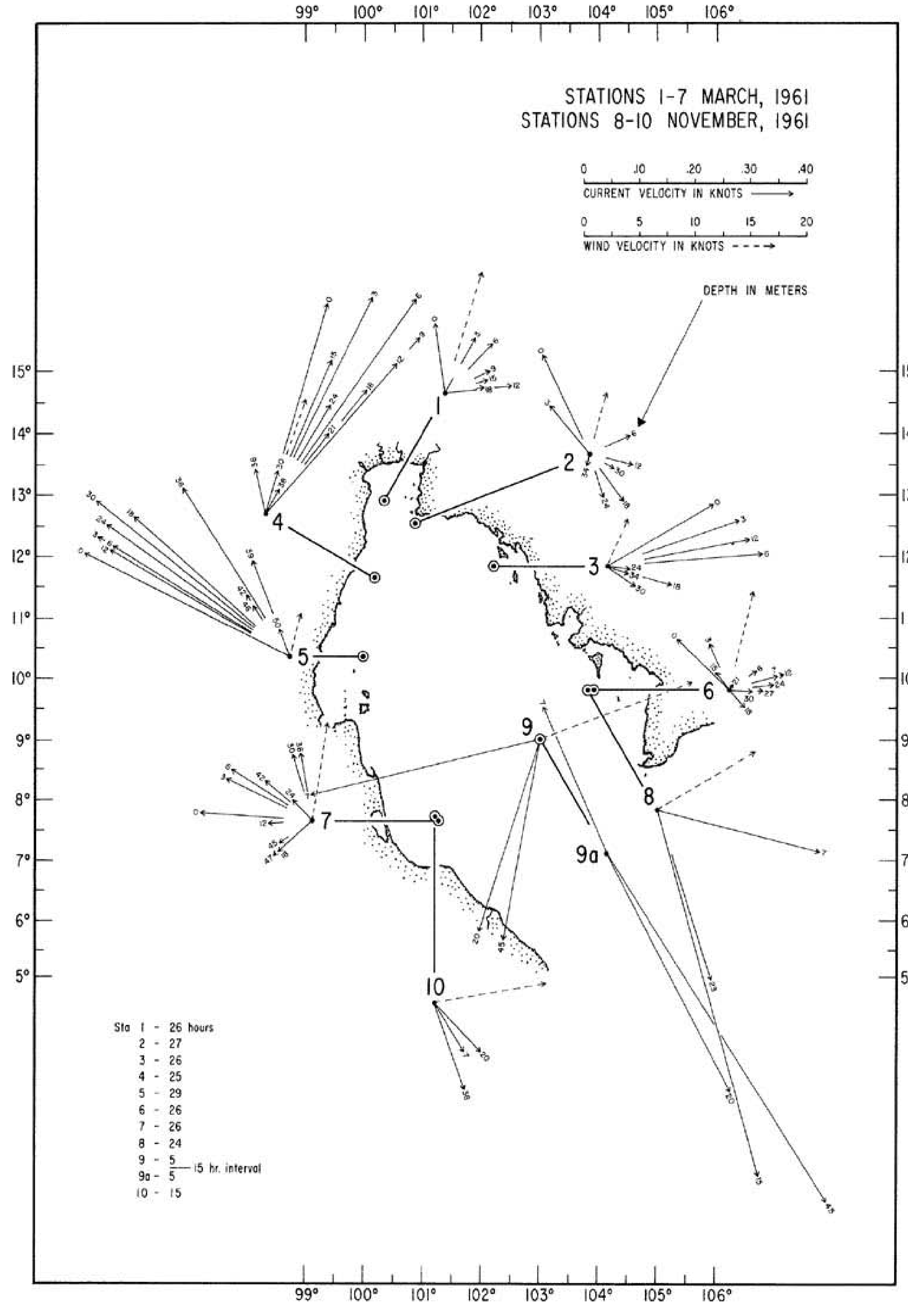

Figure 57. Vector Diagrams of Currents at Ten U.S.S. *Serrano* Stations.

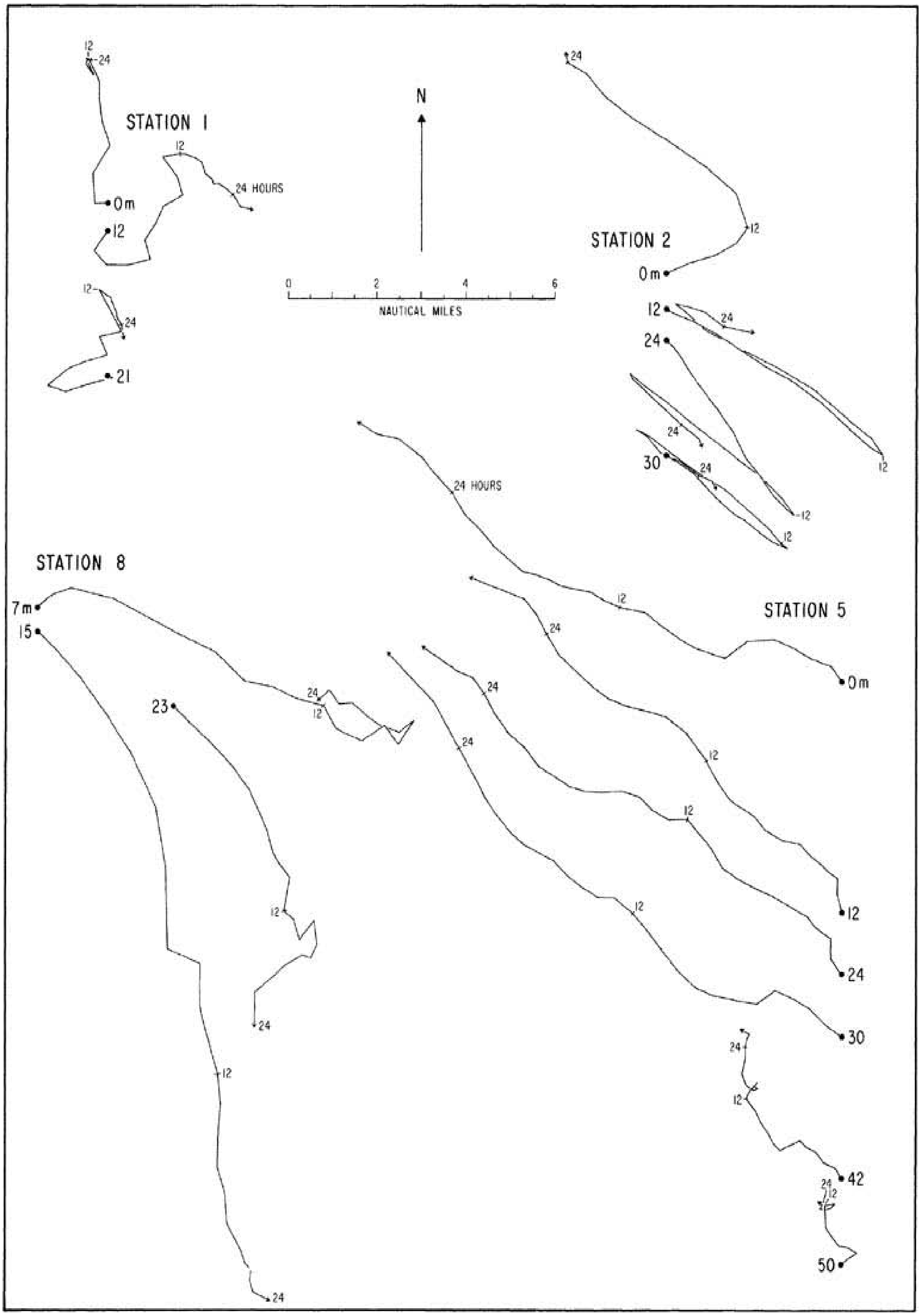

Figure 58. Progressive Vectors of Four U.S.S. *Serrano* Stations.

Stations 4 and 5 are in the area where diurnal tides are dominant. Stations 2, 3, 6, 7, 8 and 10 are located where semi-diurnal types prevail. Station 1 is in an area dominated by semi-diurnal tides with inequalities. At station 9 the break in the record makes tidal inferences impossible. Stations 6 in March and 8 in November were occupied at practically the same location. In November the tidal periodicity appears to have been diurnal while in March it was predominantly semi-diurnal. These contrasts of the mixed diurnal and semi-diurnal tidal types are related to different stages of the tide.

It is difficult to generalize concerning the change of direction and speed of the velocity vectors with depth. At stations 1, 2, 6 and 7 the highest speed occurred at the surface; at the other stations, at intermediate depths except at station 9 where the maximum speed was observed at 45 m—the greatest depth. The average speed at this depth during the second part of station 9 was 0.93 kts, and the highest individual observation was 1.4 kts. While the observations during the second part of station 9 may be less reliable than during the first part due to the ship's motion, the average speeds at 7 m were essentially the same during both parts of the station. This suggests that the increased speed at the 20 and 45 m levels during the second part was real even if the absolute values are somewhat in error.

The surface current vector is to the right of the wind vector at only one of the March stations, station 3. In all of the other March stations the surface current vector was to the left of the wind vector, the angles varying from 3 to 95°. The implication of these facts is that the direction of the observed currents was not primarily dependent upon the simultaneous local winds.

Surface current measurements were not made at stations 8, 9 and 10 in November, 1961. The 7-meter current vectors on stations 8 and 10, as well as the March 6-meter vectors at stations 1, 2, 3, 4 and 6, are to the right of the wind vectors at angles varying from 15 to 65° (average = 44°). Below the surface the shifts in current direction at increasing depths were to the right 63‰ of the time.

The progressive vectors at the surface at stations 1 and 2 (Figure 58) are of quite different character than those beneath the surface. These differences may be related to velocity shear associated with the strong gradients in the vertical density distribution that are indicated by the distribution of temperature and salinity observed on the Naga Expedition. At station 5 the progressive vectors between the surface and 30 m are similar. At 42 and 50 m velocities were greatly diminished. At station 8 the character of the vectors is markedly different at the three levels. There was no tidal influence evident at 15 m; changes in direction were small throughout the period of observation. At 7 m there were major directional changes after 15 and 18 hours; at 23 meters changes occurred after 15, 16, 18 and 22 hours, but the changes were in different directions at the two levels. On stations 4, 5, 8 and 9 prevailing currents associated with the wind or the density distribution appear to have dominated over the tidal effects. The current speeds at some stations varied by more than 1.0 kt; at others (stations 5 and 7) the speeds remained relatively constant. Table 6 tabulates the maximum and minimum current speeds observed at each of the stations. The maximum observed current speed was 1.7 kts at 15 m on station 8.

TABLE 6
MINIMUM AND MAXIMUM OBSERVED CURRENT SPEEDS (KTS)

	Station 1		Station 2		Station 3		Station 4		Station 5		Station 6		Station 7		Station 8		Station 9		Station 10	
Depths	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
0	0	.7	0	1.0	0	.8	0	1.0	.3	.6	0	.4	0	.5						
3	0	.7	0	1.1	0	.6	0	.9	.3	.5	0	.5	0	.6						
6	0	.7	0	1.0	.2	.5	.3	1.0	.2	.5	0	.5	0	.5						
7															.2	1.0	.3	.7	.2	.8
9	0	.7					0	.8			0	.6								
12	0	.5	0	1.0	.2	.6	0	.7	.2	.6	0	.6	0	.5						
15	0	.7					0	.7			0	.6			.2	1.7				
18	0	.7	0	1.0	0	.5	0	.7	.2	.5	0	.6	0	.5						
20																	.2	.8	.2	.8
21	0	.6					0	.7			0	.5								
23															.2	.8				
24			0	1.0	0	.5	0	.7	.3	.5	0	.5	0	.6						
27											0	.5								
29							.6	.6												
30			0	.8	.1	.5	0	.5	.3	.6	0	.5	0	.6						
34			0	.8	0	.4														
36							0	.5	1	.8			0	.5						
38							0	.5											.2	.8
39									0	.5										
42									0	.5			0	.5						
45													0	.5			.2	1.4		
46									0	.4										
47													0	.5						
50									0	.3										

VARIATION OF TEMPERATURE AND SALINITY AT FOUR ANCHOR STATIONS AND TEN ADDITIONAL SELECTED LOCATIONS IN THE GULF OF THAILAND.

The diurnal variation at the four anchor stations may be contrasted with the annual variation at the same locations by a comparison of the diurnal envelopes with T-D and S-D curves from data of cruises S1, S3, S5 and S7 (Figure 59). While these cruises did not cover the entire year, they did cover the months of extreme conditions according to meteorological records (see discussion of climatic background).

In Table 7 the range of temperature and salinity at the four anchor stations during the five cruises is tabulated.

TABLE 7
RANGE OF TEMPERATURE AND SALINITY AT ANCHOR STATIONS DURING FIVE NAGA CRUISES

Depth	A.S. 33 Range		A.S. 8 Range		A.S. 15 Range		A.S. 18 Range	
m	T°C	S°/₀₀	T°C	S°/₀₀	T°C	S°/₀₀	T°C	S°/₀₀
0	1.90	0.86	2.57	1.31	2.68	3.65	3.10	1.05
10	2.09	.58	2.22	1.21	2.63	3.23	2.87	1.11
20	2.10	.77	2.22	1.16	.95	3.25	2.82	1.11
30	1.84	1.03	1.67	1.14	.72	2.52	2.34	.73
50	.96	.95	.55	.54	1.72	1.50	(1.3)*	(1.1)*

* Extrapolated

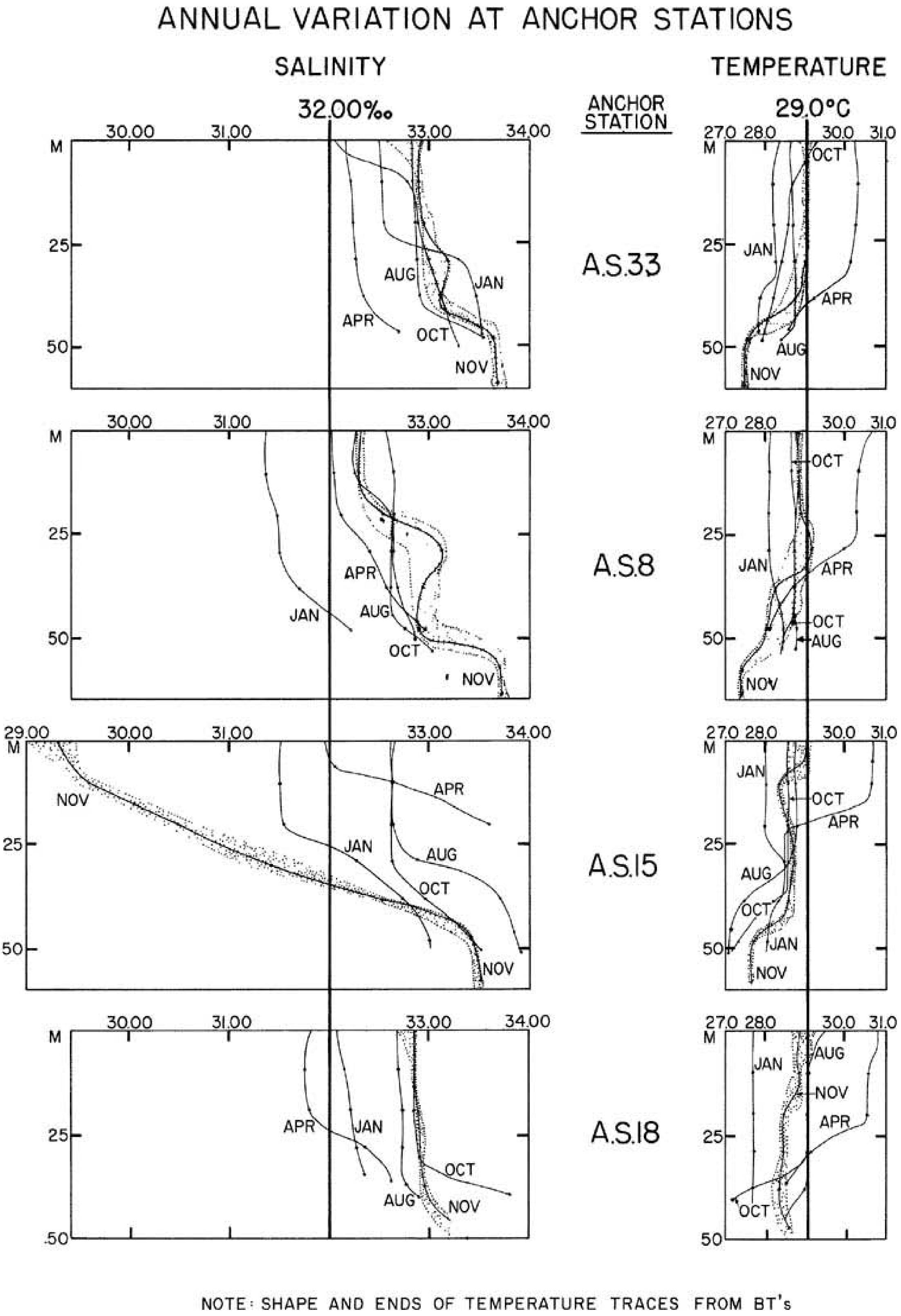
ANNUAL VARIATION AT ANCHOR STATIONS
SALINITY
TEMPERATURE
32.00‰
ANCHOR STATION
29.0°C
29.00
30.00
31.00
33.00
34.00
27.0
28.0
30.0
31.0
M
25
50
.50
A.S.33
A.S.8
A.S.15
A.S.18
JAN
APR
AUG
OCT
NOV
NOTE: SHAPE AND ENDS OF TEMPERATURE TRACES FROM BT's

Figure 59.

At each of the four anchor stations January temperatures were lowest: August, October and November temperatures were similar to each other and intermediate, and April temperatures were markedly the highest between the surface and 30 m. Below 30 m the situation was different. At stations 8 and 33, the eastern stations, the minimum temperatures beneath 30 m occurred in November during the northeast monsoon when upwelling occurred in the eastern Gulf. At station 15 the lowest temperatures were in August although in October they were almost as low. At station 18 the lowest temperatures occurred in October, but the August observation did not penetrate as deep. Figures 16 and 40 suggest that low temperatures persisted in the central deep from August through October.

The variation in salinity was greatest at station 15. It is noteworthy that at each of the four selected localities a different annual cycle of salinity distribution was observed. Minimum salinities occurred in January, April and November while maximum salinities were noted in April, August and November. Because of these large differences within the Gulf, a relatively small area, it cannot be assumed that these curves define a stable annual salinity cycle; large year-to-year differences, as well as annual differences, can be expected.

Variability in the annual cycle of both temperature and salinity is further illustrated by observations at ten additional stations in the Gulf (Figure 60) located as indicated in Figure 1. These observations were selected to demonstrate changes taking place throughout the year in upwelling areas (Locations 1, 2, 3, 4, 6, 8, 9); convergent and deepest areas (Locations 5, 7); areas affected by river discharge and precipitation (Locations 1, 6, 7, 8) and the area where South China Sea water intrudes both at the surface and at depth (Location 10). In Table 8 are tabulated the observed ranges of temperature and salinity at the selected station locations.

ANNUAL VARIATION AT SELECTED LOCATIONS

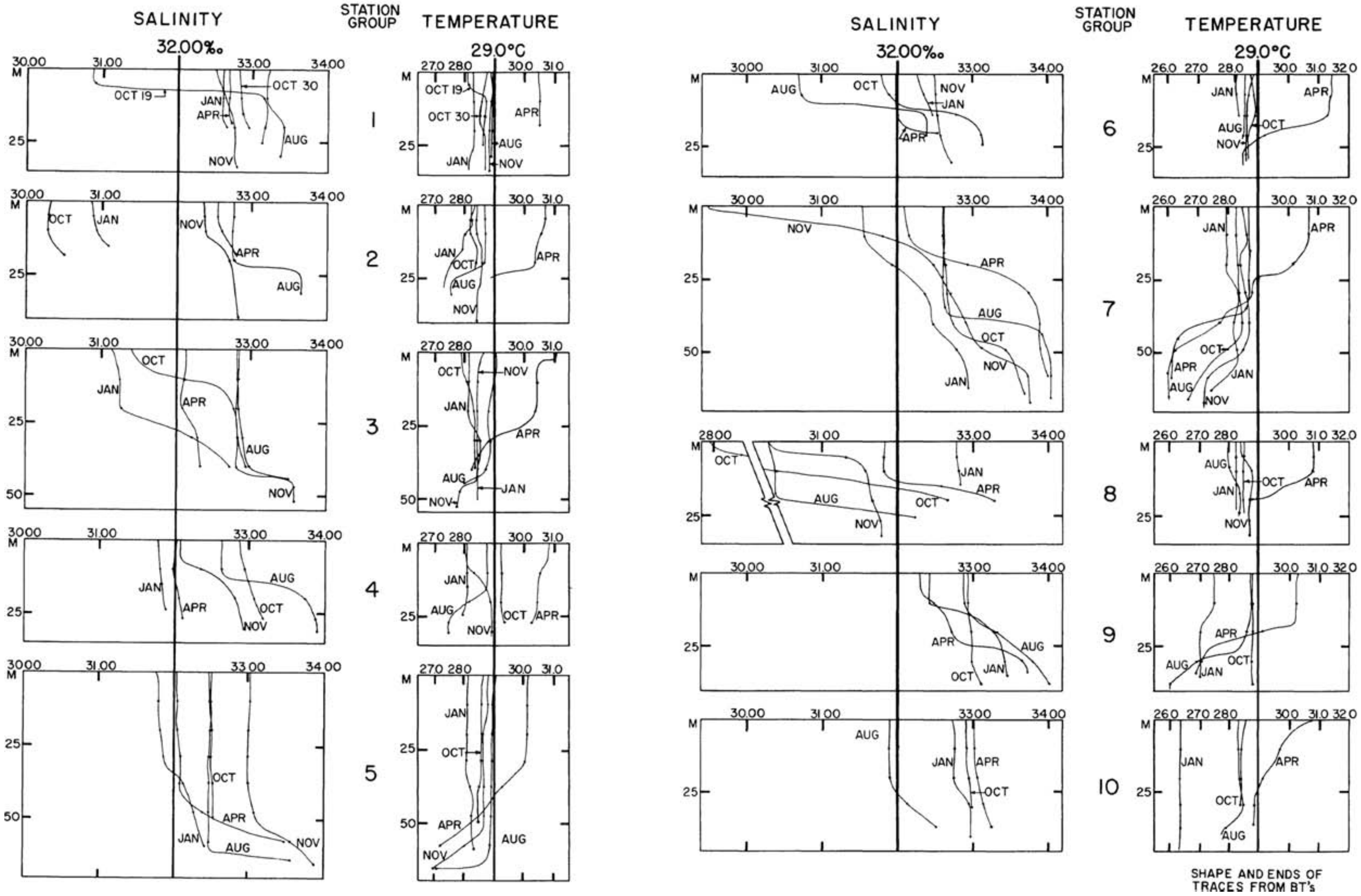

Figure 60.

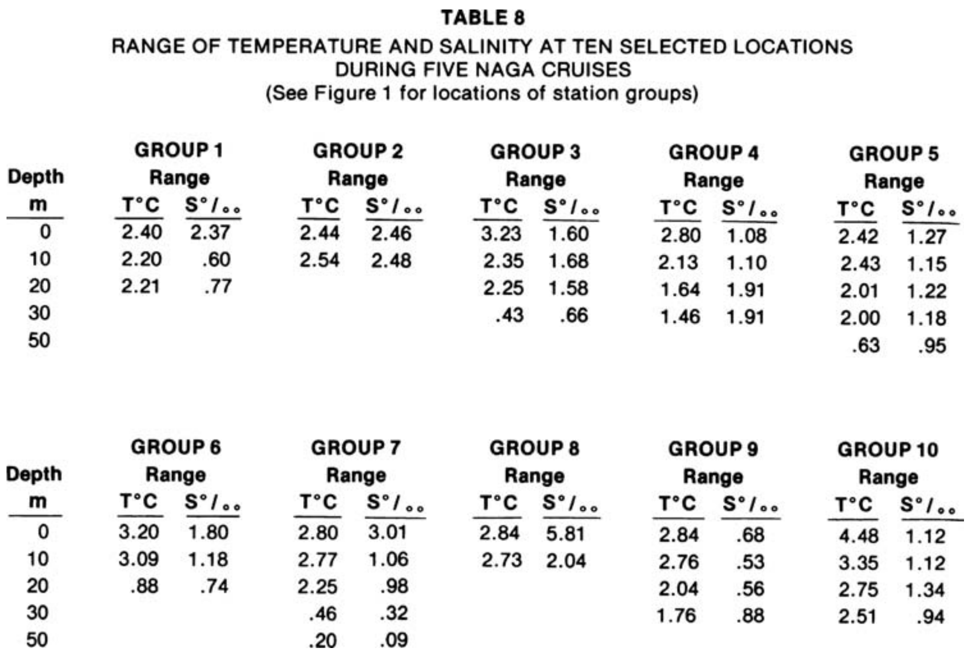

TABLE 8
RANGE OF TEMPERATURE AND SALINITY AT TEN SELECTED LOCATIONS DURING FIVE NAGA CRUISES
(See Figure 1 for locations of station groups)

Depth	GROUP 1 Range		GROUP 2 Range		GROUP 3 Range		GROUP 4 Range		GROUP 5 Range	
m	T°C	S°/₀₀	T°C	S°/₀₀	T°C	S°/₀₀	T°C	S°/₀₀	T°C	S°/₀₀
0	2.40	2.37	2.44	2.46	3.23	1.60	2.80	1.08	2.42	1.27
10	2.20	.60	2.54	2.48	2.35	1.68	2.13	1.10	2.43	1.15
20	2.21	.77			2.25	1.58	1.64	1.91	2.01	1.22
30					.43	.66	1.46	1.91	2.00	1.18
50									.63	.95

Depth	GROUP 6 Range		GROUP 7 Range		GROUP 8 Range		GROUP 9 Range		GROUP 10 Range	
m	T°C	S°/₀₀	T°C	S°/₀₀	T°C	S°/₀₀	T°C	S°/₀₀	T°C	S°/₀₀
0	3.20	1.80	2.80	3.01	2.84	5.81	2.84	.68	4.48	1.12
10	3.09	1.18	2.77	1.06	2.73	2.04	2.76	.53	3.35	1.12
20	.88	.74	2.25	.98			2.04	.56	2.75	1.34
30			.46	.32			1.76	.88	2.51	.94
50			.20	.09						

Location 1 is represented by curves plotted for the station near the probable drowned river channel south of Cape Liant (Figure 2a). With the exception of station 1 on cruise S1, both temperature and salinity changed only slightly with depth at Location 1 in contrast to the highly stratified structure of other upwelling areas where the upwelled water did not reach the surface. When these data are not related to data from neighboring stations the only clue to the unusual upwelling condition is that the salinity below 10 m is at all times greater than 32.5‰. In geographical context salinity at this location is seen to be always higher than at nearby stations.

From these illustrations it can be seen that the strongest upwelling occurred along the western coast in August and on the northeastern coast in January and October. Downwelling occurred in all months in the central part of the Gulf (Locations 5, 7), was frequently observed on the east coast (Location 8) and occasionally on the west coast (Location 2). The annual cycles in salinity and temperature in the deep waters of the central Gulf below 50 m differed between Locations 5 and 7. Runoff and precipitation in October decreased the surface salinity at Location 8 near Phu Quoc Island to 27.77 ‰, the minimum salinity observed during the Naga Expedition.

The three areas where the most intense upwelling occurred are: 1. on the west coast near Sawee Bay, 2. on the east coast off Samit Point, and 3. southwest of Cape Liant. These areas are of primary importance in the study and determination of biological productivity in the Gulf; it is to be expected that particular attention will be paid to these areas in future oceanographic programs. The areas of upwelling along the east and west coasts of the Gulf, discussed above, could be located from the distribution of a single property—temperature, salinity or oxygen. The third area, southwest of Cape Liant, could not be located without observations of salinity. During the five Naga Gulf cruises on which hydrographic casts were made this area was characterized primarily by high salinity relative to neighboring areas. It may be of interest to note that, when the salinity data were first examined, the occurrence of the high salinities in this northern area far from the mouth of the Gulf suggested inaccuracies in the data.

There was no obvious route by which water of such high salinity could have reached this locality so far from a possible southern source. Yet, when relatively high salinities were found in the area during all the cruises, a search for a possible explanation was made. Captain Faughn made a detailed examination of fathograms which had been taken along, and transecting, line 1. His study of these fathograms revealed a 6-mile wide trough, probably a drowned river channel, that cuts across the shallow shelf south of Cape Liant and extends into the central deep (Figures 2, 2a and 3). This trough provides a pathway along which the high salinity water can penetrate into the inner Gulf, there to be upwelled under proper wind conditions. The finding of this trough, the existence of which was inferred from the distribution of salinity on the Naga cruises, is an example of the close relationship between bottom topography, distribution of physical properties and the monsoon winds.

The ranges of temperature, salinity and oxygen which occur in the Gulf are of importance in understanding the faunal distributions. These ranges are summarized by cruise in Tables 9 through 13. The absolute maxima and minima observed during the cruises are tabulated in Table 14.

HORIZONTAL AND VERTICAL RANGES OF TEMPERATURE, SALINITY AND OXYGEN

TABLE 9

CRUISE S 1

	Temperature °C					Salinity °/oo					Oxygen ml/l				
Depth in Meters	Max.	Sta. or BT	Min.	Sta. or BT	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz Range
0	30.2	25B	27.8	29	2.4	32.99	6	27.77	11	5.22	4.89	16	4.18	8	.71
30	29.0	18B	28.2	29B	0.8	33.04	7	<30.50*	30	2.54	4.72	20	3.05	11	1.67
50	<29.0*	19A	<26.8	15A	2.2	33.54	15	32.50	21	1.04	4.46	20	2.72	26	1.74
>60	28.8	6	26.7	14	2.1	33.67	14	<33.00*	20	.67	<4.37*	20	2.92	14	1.45
Vertical Range	30.2	25B	26.7	14	3.5	33.67	14	27 77	11	5.90	4.89	16	2.72	26	2.17

TABLE 10

CRUISE S 3

	Temperature °C					Salinity °/oo					Oxygen ml/l				
Depth in Meters	Max.	Sta. or BT	Min.	Sta. or BT	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz. Range	Max.	Sta	Min	Sta.	Horiz. Range
0	29.9	31B	26.2	5B	3.7	33.75	4	30.06	25	3.69	5 01	29	4 13	9	.88
30	28.8	26B	26.2	6	2.6	33.95	4	31.49	19	2.46	4.63	19	2.88	23	1 75
50	28.8	25A	26.5	3B	2.3	33.53	23	31.73	17	1.80	4.34	18 19	1.19	23	3.15
>60	28.0	17	26.4	4	1.6	>33.98	4	>31.73	17	2.25	3.76	18	1.94	11	1 82
Vertical Range	29.9	31B	26.2	6	3.7	33.98	4	30.06	25	3.92	5.01	29	1.19	23	3.82

TABLE 11

CRUISE S 5

	Temperature °C					Salinity °/oo					Oxygen ml/l				
Depth in Meters	Max.	Sta. or BT	Min.	Sta. or BT	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz. Range
0	31.7	22A	29.5	6	2.2	34.24	6	31.61	1	2.63	4.44	31	3.94	27	.50
30	30.5	33A	27.1	2	3 4	34.16	4	32.04	26	2.12	4.73	19	3 76	2	97
50	29.0	19A	26.5	13	2.5	33.92	12	32.28	19	1.64	4.60	19	1 35	21	3 25
>60	< 28.0*	3B	< 26.5*	13	1 5	33.99	12	< 32.50*	26	1.49	4.04	12	< 1.50*	21	2.54
Vertical Range	31.7	22A	26.5	13	5.2	34.24	6	31.61	1	2.63	4.73	19	1.35	21	3 38

* Extrapolated Values.

HORIZONTAL AND VERTICAL RANGES OF TEMPERATURE, SALINITY AND OXYGEN

TABLE 12

CRUISE S 7

Depth in Meters	Temperature °C					Salinity °/oo					Oxygen ml/l				
	Max.	Sta. or BT	Min.	Sta. or BT	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz. Range
0	29.4	35 35B	28.0	27A 27B	1.4	33.70	8	30.30	27	3.40	4.64	29	4.16	28	.48
30	29.0	31B	27.1	36	1.9	33.89	21	32.43	23	1.46	4.44	15	2.87	18	1.57
50	29.0	23	26.0	30A	3.0	34.01	31	32.45	23	2.36	4.37	15	3.06	14	1.31
>60	<28.5*	23	26.0	31	2.5	34.04	30	33.49	23	.55	4.31	23*	3.53	31	.78
Vertical Range	29.4	35B	26.0	31	3.4	34.04	30	30.30	27	3.74	4.64	29	2.87	18	1.77

TABLE 13

CRUISE S 9

Depth in Meters	Temperature °C					Salinity °/oo					Oxygen ml/l				
	Max.	Sta. or BT	Min.	Sta. or BT	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz. Range	Max.	Sta.	Min.	Sta.	Horiz. Range
0	30.1	18A	27.9	4	2.2	33.04	22	29.00	15-6	4.04	4.61	15-1	4.13	9	.48
30	29.5	27B	28.3	17B	1.2	33.33	30	31.28	15-2	2.05	4.36	23 25	2.61	32	1.75
50	29.0*	28A	27.4	23B	1.6	33.76	24	33.13	7	.63	4.23	28	2.27	23	1.96
60	28.5*	6B	26.9	7	1.6	33.86	7	33.30	17	.56	3.75	6	2.29	7	1.46
Vertical Range	30.1	18A	26.9	7	3.2	33.86	7	29.47	15-1	4.39	4.61	15-1	2.27	23	2.34

TABLE 14

MAXIMUM, MINIMUM AND RANGES OF OBSERVED TEMPERATURE, SALINITY AND OXYGEN DURING FIVE NAGA CRUISES

Depth	TEMPERATURE °C			SALINITY °/oo			OXYGEN ml/l		
	Max.	Min.	Range	Max.	Min.	Range	Max.	Min.	Range
0	31.7	26.2	5.5	34.24	27.77	6.47	5.01	3.94	1.07
30	30.5	26.2	4.3	34.16	30.50	3.66	4.73	2.61	2.12
50	29.0	26.0	3.0	34.01	32.28	1.73	4.60	1.35	2.25

* Extrapolated Values.

SUMMARY, DISCUSSION AND RECOMMENDATIONS

Data of temperatures, salinities and oxygen concentrations obtained by the RV *Stranger* on the Naga Expedition of 1959-1961 in the Gulf of Thailand are presented here graphically in various figures and tables and are discussed in terms of the geography and general oceanographic character of the Gulf. The vertical and horizontal distributions of these factors, and especially the surface salinities, are integrated with the wind speeds and directions as observed by the Expedition and with the rainfall and river runoff at various coastal locations as recorded for the period in several weather records. The Gulf is clearly defined in physical terms as an estuary; the water mass movements for the period of the Expedition are seen as sequential responses to these particular physical terms in the context of classical oceanography.

The Naga Expedition was unique in being the joint enterprise of the governments of three nations; South Viet Nam, Thailand and the United States of America. It was primarily an exploratory survey; i.e., a pilot program, whose findings should "lead to an understanding of the oceanography of the region, including the circulation, methods of enrichment, primary productivity, and to the nature, distribution and abundance of the important marine resources" (Faughn, in press). Representation of the physical and chemical data from the selected sites of the Gulf of Thailand, as here presented in three dimensions for a period of one and a half years, forms a sketch from which an identity clearly begins to emerge. This is remarkable in that it is drawn from the work of so many people. Characteristic of both a sketch and an exploration is the immediate suggestion and provocation to refine further the details; i.e., to re-phrase earlier questions more precisely and to pose new ones. A broad outline of some of these questions and their interrelationships is suggested below. It is clear from the collective efforts of all the participants of the Naga Expedition that great progress in the understanding and conservation of marine resources can come out of the recent and on-going investigations being carried out by nations bordering Southeast Asian waters of which the Naga Expedition was a part.

In retrospect the Naga Expedition paid insufficient attention to land-sea interactions and near-shore processes, particularly the effects of runoff and the dry season on physical and biological processes. The following questions require more attention to these processes:

1. How important is the physical oceanography of the Gulf of Thailand, especially the Mekong Delta, including the western South Viet Nam peninsula with respect to the utilization of the area as a breeding and/or grazing ground for fish:
    a. primary; plankton feeders (anchovies, herrings), aquatic plants and mud feeders (mullets), filter feeders and scavengers (invertebrates) and small predators,
    b. secondary (predaceous and scavenger); directly (within the delta and its channels) and indirectly (peripheral; i.e., on the above listed emergent population).
2. Essentially the same question above as applied to the Chao Phya River System, and to a lesser extent to the small river systems on the east and west coasts of the Gulf.
3. What are the seasons and the seasonal variations for each of the above systems:
    a. delta floods: when do the maximum and the minimum flooding occur each year; what is the variation of the annual maximum over a long period; what factors (rainfall, snowmelt, dams) are influencing the variation?
    b. oceanic: what factors are seasonally consistent (predictable); how predictable are these factors; what factors are NOT consistent (predictable); what is the effect of these (predictable or unpredictable) oceanic factors (T, S, O_2, water mass movements) on the fishes and/or other segments in the food chain?
4. Careful attention should be given to special or unusual features of the coast of the Gulf; i.e., types of land drainage (bare rock, lush growth, etc.), harbor and bay flushing, near-shore sudden drop-offs.

By careful correlation of such information it would eventually be possible to establish which factors in the Gulf are actually affecting fish productivity; i.e., is the enormous quantity of sediment which annually issues into the sea from the Mekong River actually of great benefit to the diatom-fish food chain, and if so, is it consistently so, or is it at certain seasons or situations a deterrent; is fish-species distribution, as indicated by annual catches, predictable given certain limited physical (meteorological and oceanographic) data, thus eliminating the laborious time consumming and costly necessity of biological (plankton) analysis; what lies within the power of the peoples of Southeast Asia to control and to preserve the biological productivity of the seas of this area.

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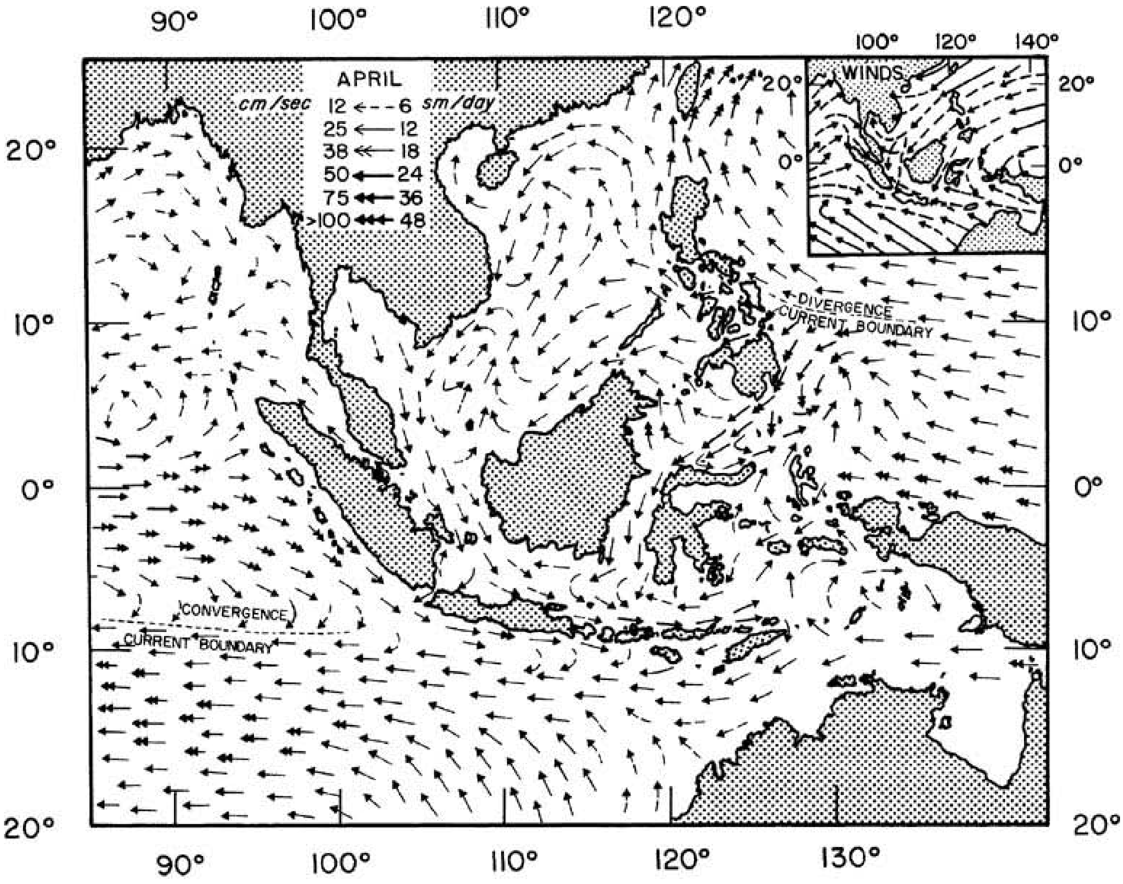

Surface Currents and Winds in April
(re-drawn from Wyrtki, 1961)

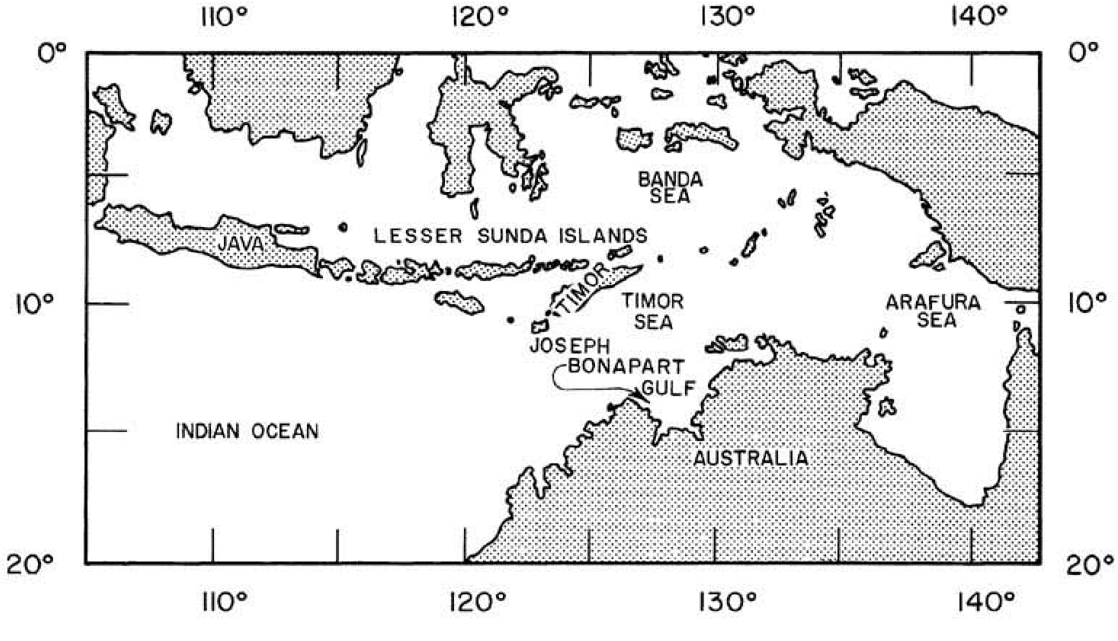

Chart of the Area

BATHYTHERMOGRAPH (BT) TEMPERATURE OBSERVATIONS IN THE TIMOR SEA, NAGA EXPEDITION, CRUISE S11

by

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BATHYTHERMOGRAPH (BT) TEMPERATURE OBSERVATIONS IN THE TIMOR SEA, NAGA EXPEDITION, CRUISE S11

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BATHYTHERMOGRAPH (BT) TEMPERATURE OBSERVATIONS IN THE TIMOR SEA, NAGA EXPEDITION, CRUISE S11

by

Margaret K. Robinson

INTRODUCTION

The R. V. *Stranger* of the Scripps Institution of Oceanography carried out an extensive geophysical survey of the Timor Sea between March 29 and April 24,1961, (van Andel and Veevers, 1967) following the completion of the major oceanographic observational programs in the Gulf of Thailand and the South China Sea. During the survey, closely spaced bathythermograph (BT) temperature and wind velocity observations were made. Observed wind velocities, vertical temperature sections along the cruise tracks and horizontal distributions of temperature at standard depth levels based on BT data are the subject of this report. These observations provide a detailed description of the temperature structure of the Timor Sea and complement the more general one given by Wytrki (1961).

BACKGROUND

In Volume 2 of the NAGA Reports Wyrtki (1961) summarized the general oceanographic characteristics of the Timor Sea, including the wind systems and surface circulation, the physical properties of water in the surface layer, the water masses in the deep basin and the tides. Since the material presented here consists only of temperatures recorded during a period of one month, little can be added to Wyrtki's general discussion of seasonal circulation. However, for the readers' convenience and for a general picture of conditions to be expected at this season, we quote several of his pertinent descriptions:

1) of monsoon winds: "In March the southeast trades of the Indian Ocean extend further northwards and eastwards, while over the Timor and Arafura Seas northwest winds still prevail. Over the China Sea the northeast monsoon has weakened.
   In April the equatorial trough moves quickly to the north and lies over the equator. The southeast trades reach to about 5° S, that is, toward the north of the Lesser Sunda Islands, where it is normally called the southeast monsoon."
2) of surface currents [The frontispiece of this paper includes a chart of the Surface Currents and Winds in April re-drawn from Wyrtki (plate 2a) and a chart of the area relevant to the descriptions.]: "In the Timor Sea a current to the southwest prevails during the whole year, its axis runs close to the coast of Timor. From April to September the current reaches to the Australian coast, although its velocity decreases in that direction. From October to March a weak current towards the northeast is formed off the Australian coast under the influence of winds from the southwest. The Timor Current takes its water from October to April out of the current flowing along the north coast of the Lesser Sunda Islands to the east, which turns around the eastern end of Timor. Only at the time of the full development of the southeast monsoon is the Timor Current supplied by water out of the upwelling region in the Arafura and eastern Banda Seas."

General information concerning the surface layer, extracted from Wyrtki's charts is as follows:

The average annual variation of temperature in the homogeneous surface layer is 4-5°C over the range of 26 to 31°C. From August through October the thickness of this homogeneous layer is approximately 20 m; the average depth of the maximal density gradient is greater than 140 m, and the average thickness of the discontinuity layer is greater than 100 m (distance between the 15° and 23°C surfaces).

The annual variation of surface salinity based on observations in the years 1950-1955 is 0.5‰; the average surface salinity in these years was 34.4‰.

The average annual rainfall is approximately 1000 mm. Evaporation exceeds precipitation from April through September in the Timor Sea.

Wyrtki's extensive discussion of the properties of the deep water circulation are omitted here except to note that observations from the "Snellius" and "Samudera" hydrographic stations in the deep Timor Trough indicate that the deep waters are a mixture between Pacific Ocean and Indian Ocean waters (Wyrtki, plate 38).

Tides in the Timor Sea are of the mixed prevailing semi-diurnal type. Amplitude of the semi-diurnal tide ($M_2 + S_2$) is between 100 and 200 cm; amplitude of the diurnal tide ($K_1 + O_1$) is 40 to 60 cm.

DISCUSSION

WINDS

The Timor Sea lies at 9° to 13° South and 123° to 131° East between the Island of Timor and the northwest coast of Australia. This region is dominated by the southeast trade winds from April to October, but because of the topography of the region, the dominant southeast wind direction, which occurs over the Arafura Sea to the east, becomes more variable over the Timor Sea, and in April there are almost equal amounts of wind from northeast, east and southeast (H.O. Pub. No. 107, 1955). In January and February the winds over the Timor Sea are primarily from the northwest, and March is a month of transition between these winds and the deflected southeast trades of April.

In Figure 6A is shown the observed wind velocities as they occurred during the NAGA cruise, S11. Time continuity of the changes can be followed more readily by referring to the Cruise Track* in Figure 1B. There were a few northwestern winds on Line I in early April, but anomalous western winds were observed between Stations 100 and 121 on Line III and in the Joseph Bonapart Gulf, a possible topographic effect. Elsewhere, the winds were predominantly from the east, southeast or northeast. Wind speeds rarely reached 20 mph, the average being about 10, although many were less than 5 mph. These detailed observations are in general agreement with Wyrtki (1961) and H.O. Pub. No. 107 (1955).

VERTICAL TEMPERATURE SECTIONS

In Figures 2 through 5 are presented the vertical temperature sections constructed along the cruise lines shown in Figure 1A. The bottom topography in these charts was drawn to conform with van Andel and Veevers' (1967) chart. Over the Timor Trough, which is at the east end of the Sunda Trench and measures as deep as 1752 fathoms, a 250-meter BT was used, but observations did not always penetrate to this depth. The sections were constructed by reading the specific depth on the BT trace where the integral isotherm values occurred in order to preserve the actual gradient.

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* Editors' Note: A complete chronological station index for Cruise S11 is given in Volume 1 (Faughn, J.L., NAGA Report Series, in press) in which those stations here numbered as S11A-153 through S11A-192 and S11B-1 through S11B-11, respectively, bear these same designations, but those here numbered as Sll-1 through Sll-195 are there designated S11A-V165 through S11A-V377.

The temperatures in the trough, generally, ranged from 29.1° to 30.2°C at the surface and from 12.4° to 13.3°C at 250 meters. On the shelf the temperatures ranged from 30.0° to 31.3°C at the surface. In some of the deep areas on the shelf temperatures of 21° and 28°C were observed at depths of 150 meters. The highest temperature at the greatest depth, still on the shelf, was observed at Station 182 on the section along Line XI (Figure 5) where a temperature of 25.5°C was observed between 180 and 230 meters.

On most of the sections there is evidence of surface heating. In general, this occurred at times of low wind speed, or calm. Also, April, an inter-monsoon month, is typically a period of minimum cloud cover. If the upper limit of the thermocline is defined as the depth at which the temperature has decreased by 1°C, then it may be said to have occurred usually between 25 and 50 meters but occasionally as deep as 75 meters. Oscillations in the depth of the thermocline along the sections were frequently as great as 25 meters.

HORIZONTAL TEMPERATURE DISTRIBUTIONS

Figures 6B through 9B include the horizontal temperature distributions for the surface, 25, 50, 75, 100, 150 and 200 meters, respectively. Bottom contours on the horizontal distribution charts have been taken from van Andel and Veevers' (1967) definitive bathymetric chart based on data collected on this NAGA Expedition.

The temperatures on the Australian side were higher at all levels than those over the trough and along the Timor coast. This distribution of temperature would indicate flow to the southwest in accordance with geostrophic balance which requires that the warm, less dense water be on the left side of a density current in the southern hemisphere. Such an interpretation is in agreement with Wyrtki's current charts (1961).

The horizontal range of temperature in the Timor Sea varied from 3°C at the surface to 2°C at 25 meters, to 6°C at 75 and 100 meters, then decreased to 3°C between 150 and 200 meters when the isolated deep areas on the shelf are disregarded.

The surface temperatures observed on this cruise were, in general, 1 ° to 2°C higher than the April mean sea surface temperatures in the Timor Sea shown by Wyrtki (1961). Only near the Timor coast were the temperatures as low as his mean. Wyrtki's values are probably biased by the fact that most of the hydrographic cast data on which his summary was based were from stations in the cooler, deep trough area of the Timor Sea.

CONCLUSION

The closely spaced BT observations taken during NAGA Cruise S11 have provided an excellent detailed picture of the temperature structure in April, 1961, in the little known area of the Timor Sea. The distributions are in general agreement with inferences made from scattered hydrographic cast data primarily collected by the "Snellius" Expedition of 1929 (van Riel et al, 1950) and recently summarized by Wyrtki (1961).

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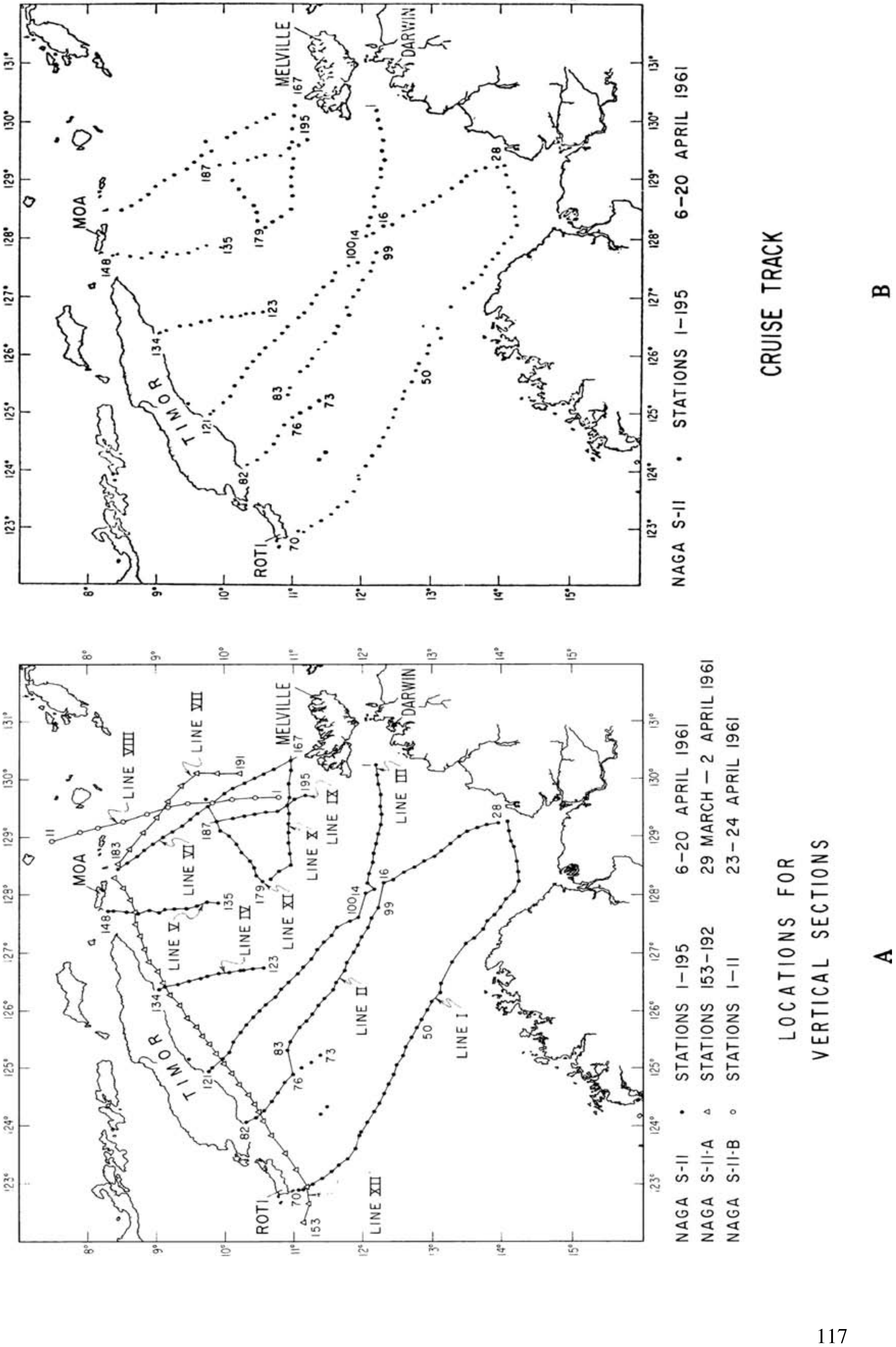


LOCATIONS FOR VERTICAL SECTIONS

A

CRUISE TRACK

B

Figure 1

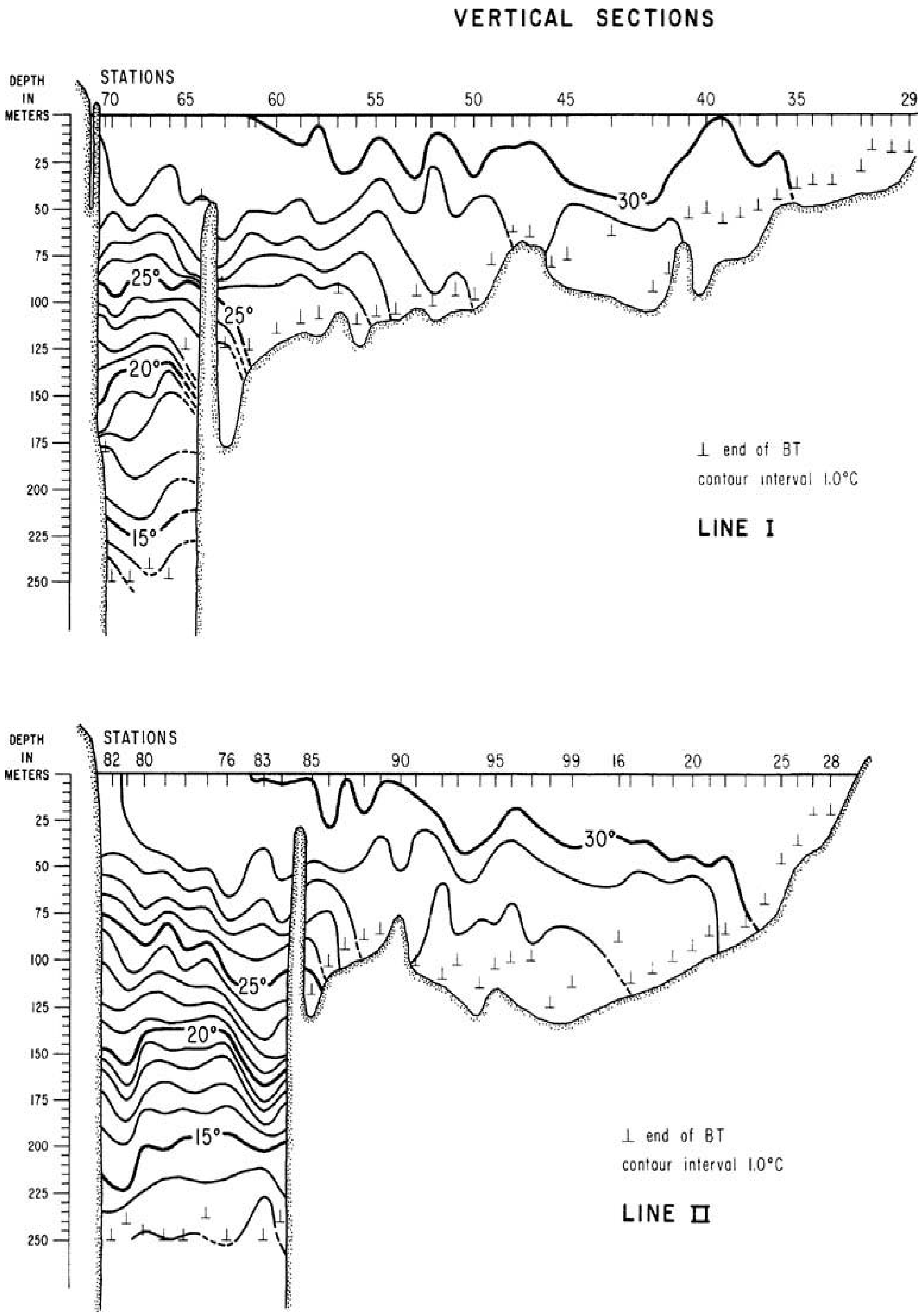

VERTICAL SECTIONS
DEPTH IN METERS
25
50
75
100
125
150
175
200
225
250
STATIONS
70
65
60
55
50
45
40
35
29
30°
25°
25°
20°
15°
⊥ end of BT
contour interval 1.0°C
LINE I
DEPTH IN METERS
25
50
75
100
125
150
175
200
225
250
STATIONS
82
80
76
83
85
90
95
99
16
20
25
28
30°
25°
20°
15°
⊥ end of BT
contour interval 1.0°C
LINE II

Figure 2

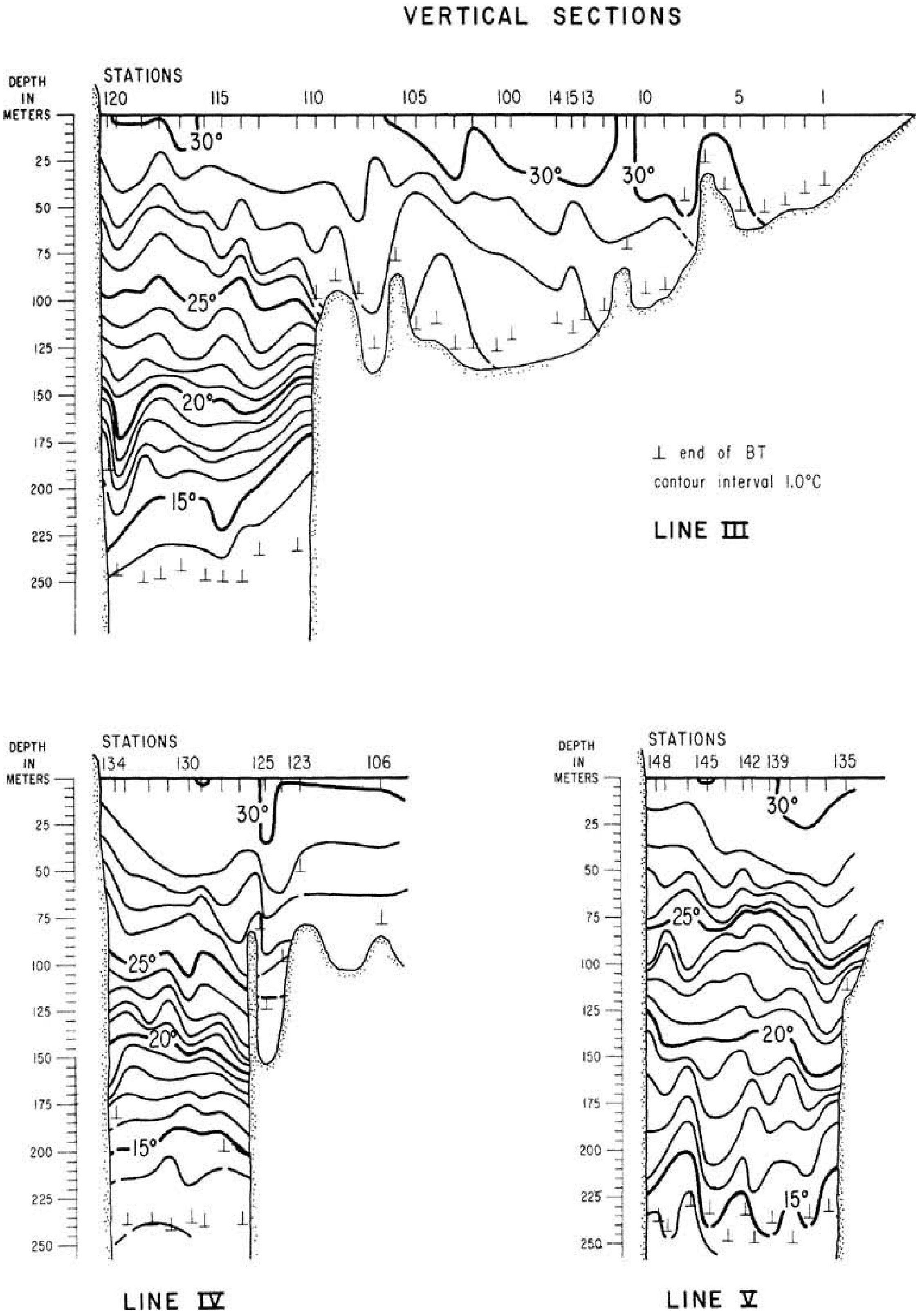

VERTICAL SECTIONS
DEPTH IN METERS
STATIONS
120
115
110
105
100
14 15 13
10
5
1
25
50
75
100
125
150
175
200
225
250
30°
25°
20°
15°
⊥ end of BT
contour interval 1.0°C
LINE III
DEPTH IN METERS
STATIONS
134
130
125
123
106
30°
25°
20°
15°
LINE IV
DEPTH IN METERS
STATIONS
148
145
142
139
135
30°
25°
20°
15°
LINE V

Figure 3

VERTICAL SECTIONS

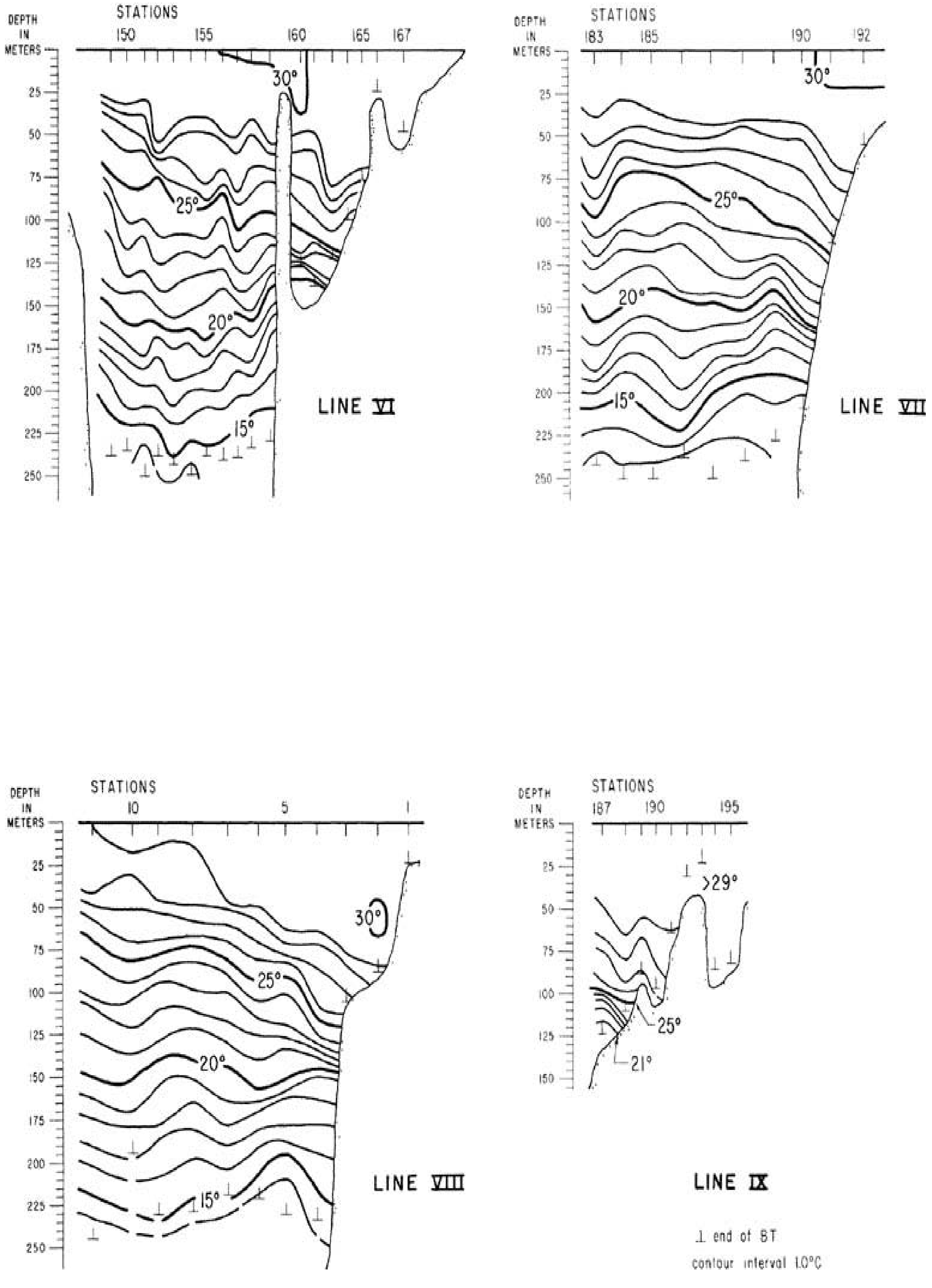


Figure 4

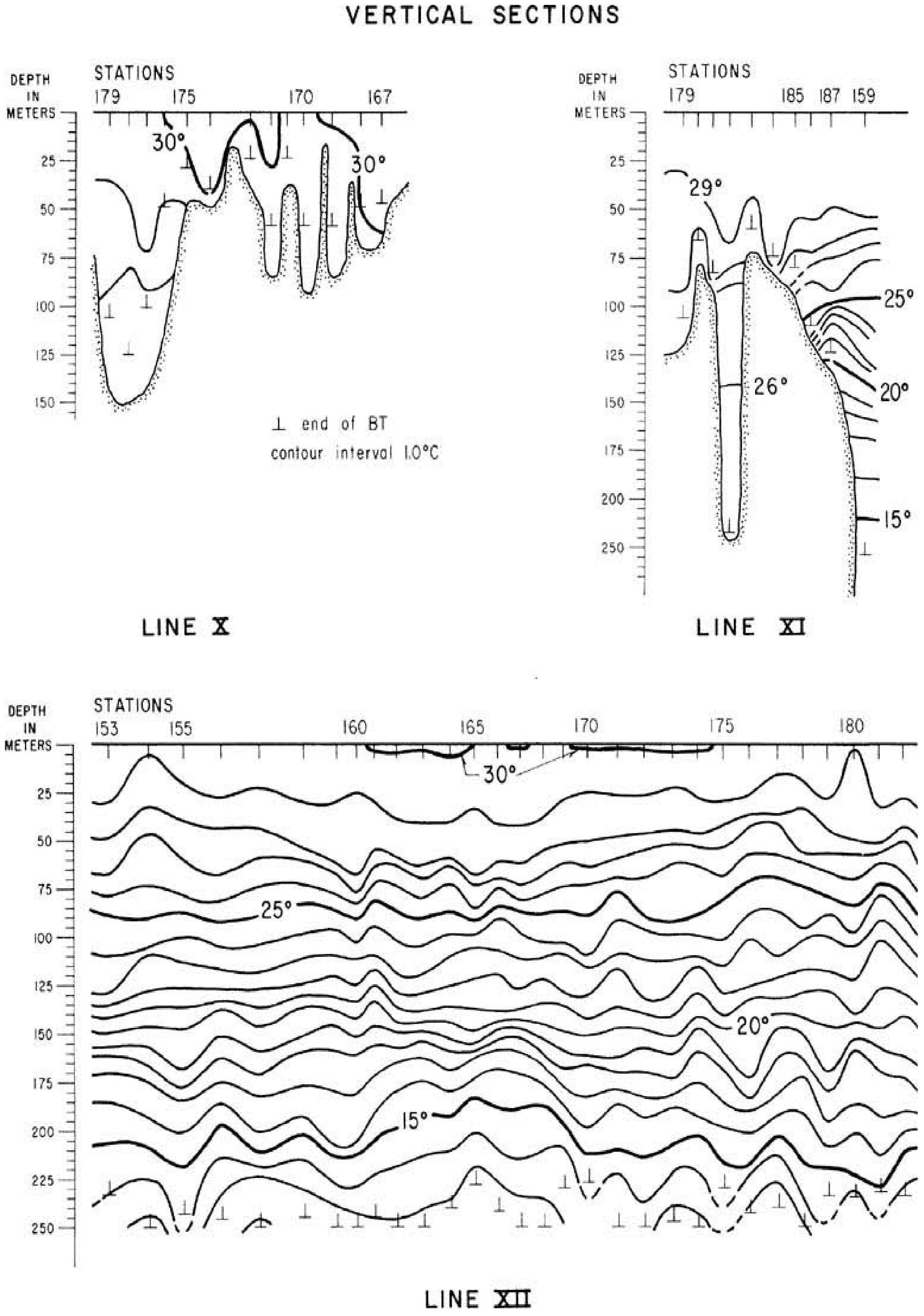
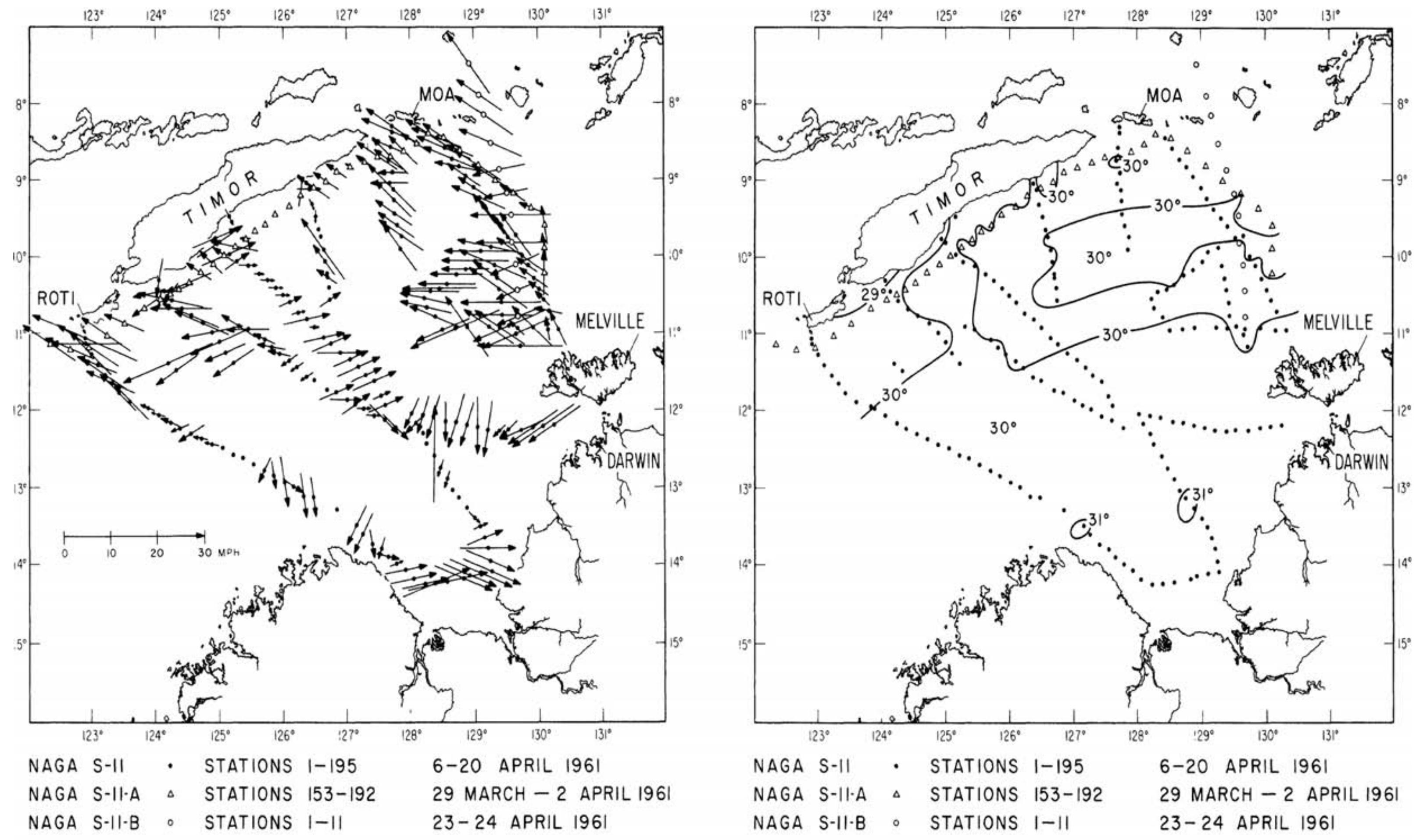

VERTICAL SECTIONS
DEPTH IN METERS
STATIONS
179
175
170
167
30°
30°
25
50
75
100
125
150
⊥ end of BT
contour interval 1.0°C
LINE X
185
187
159
29°
26°
25°
20°
15°
175
200
250
LINE XI
153
155
160
165
180
30°
25°
20°
15°
225
LINE XII

Figure 5



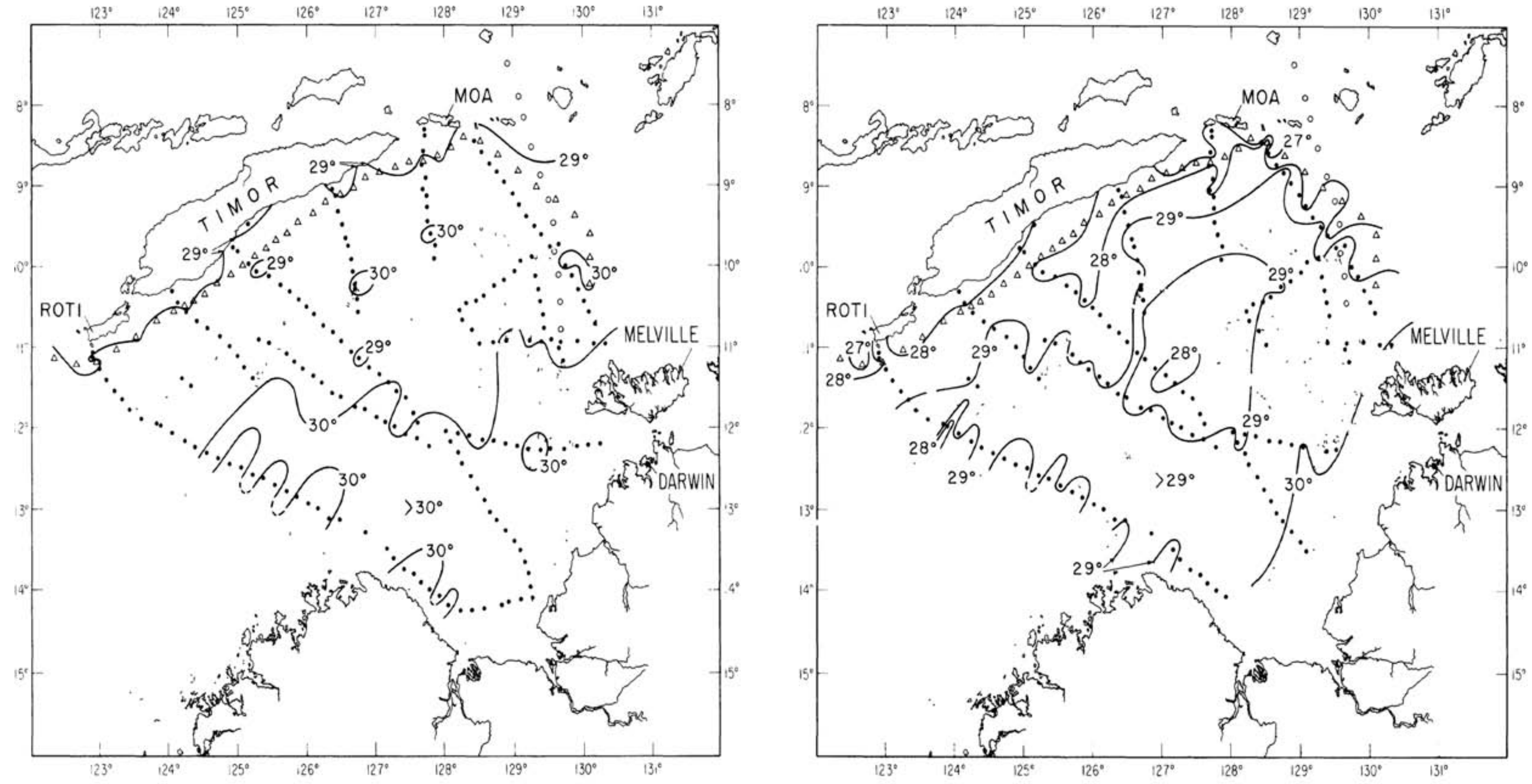
WIND VELOCITY

A

TEMPERATURE °C
AT THE SURFACE

B

Figure 6



NAGA S-II • STATIONS I–195 6–20 APRIL 1961
NAGA S-II-A △ STATIONS 153–192 29 MARCH – 2 APRIL 1961
NAGA S-II-B ○ STATIONS I–II 23–24 APRIL 1961

TEMPERATURE °C
AT 25 METERS

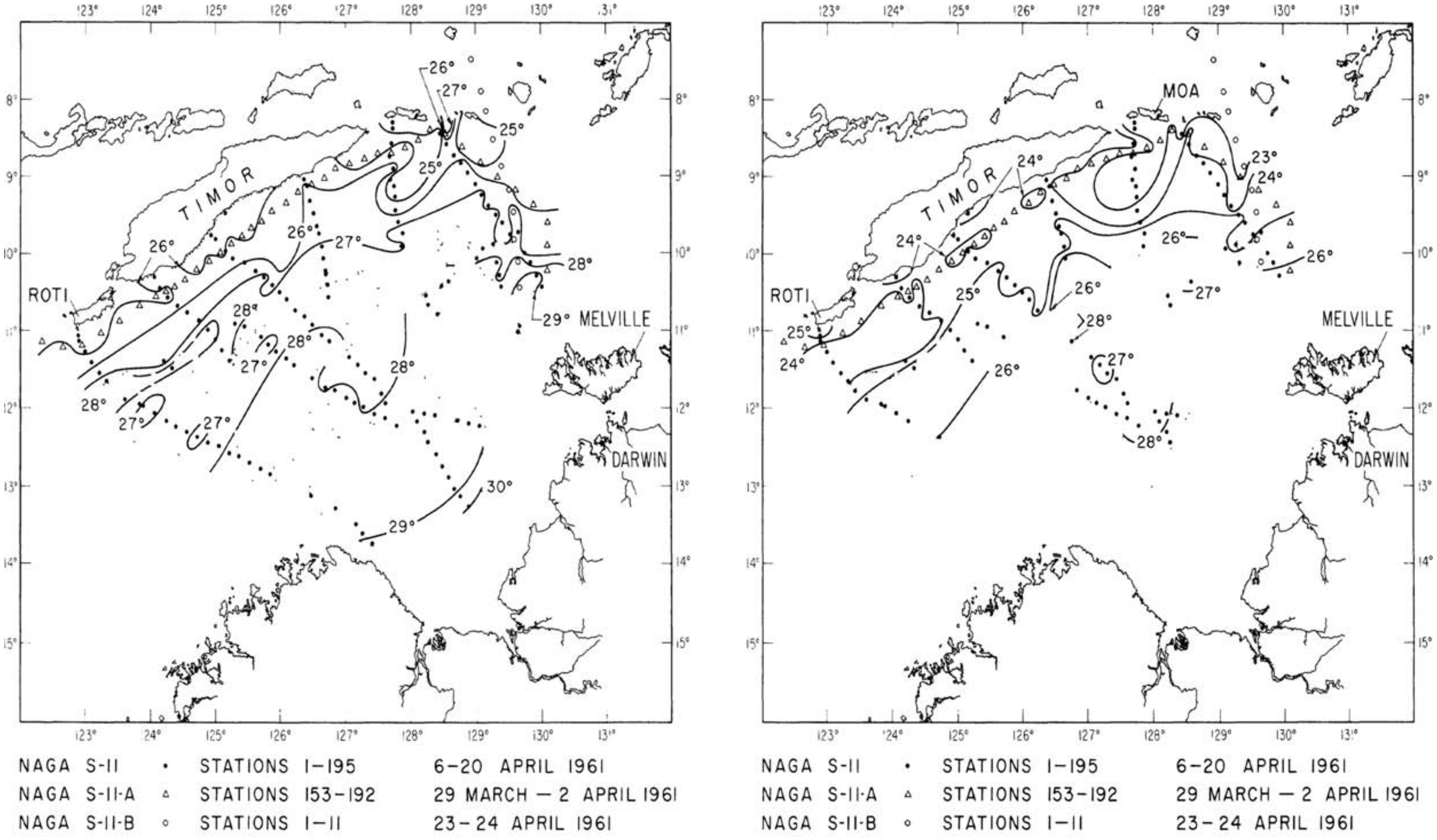
A

NAGA S-II • STATIONS I–195 6–20 APRIL 1961
NAGA S-II-A △ STATIONS 153–192 29 MARCH – 2 APRIL 1961
NAGA S-II-B ○ STATIONS I–II 23–24 APRIL 1961

TEMPERATURE °C
AT 50 METERS

B

Figure 7



NAGA S-II • STATIONS 1–195 6–20 APRIL 1961
NAGA S-II-A ▵ STATIONS 153–192 29 MARCH — 2 APRIL 1961
NAGA S-II-B ○ STATIONS 1–11 23–24 APRIL 1961

TEMPERATURE °C
AT 75 METERS

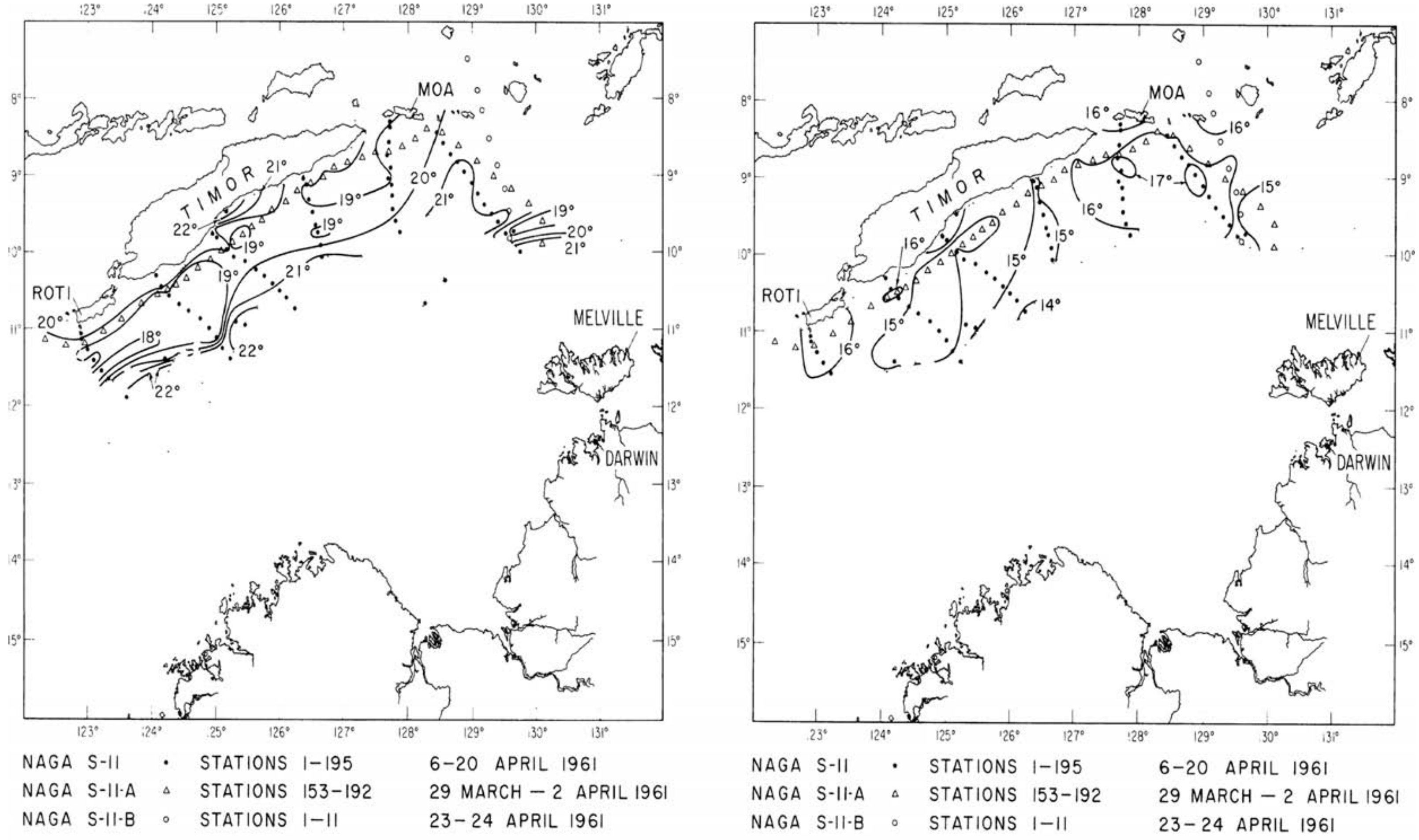
A

NAGA S-II • STATIONS 1–195 6–20 APRIL 1961
NAGA S-II-A ▵ STATIONS 153–192 29 MARCH — 2 APRIL 1961
NAGA S-II-B ○ STATIONS 1–11 23–24 APRIL 1961

TEMPERATURE °C
AT 100 METERS

B

Figure 8



TEMPERATURE °C
AT 150 METERS

A

TEMPERATURE °C
AT 200 METERS

B

Figure 9