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Ocean Variability in the U.S. Fishery Conservation Zone, 1976

Julien R. Goulet, Jr. and
Elizabeth D. Haynes, Editors

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U.S. DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary
National Oceanic and Atmospheric Administration
Richard A. Frank, Administrator
National Marine Fisheries Service
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ABSTRACT

Some responses of fisheries resources to natural climate-ocean variability in 1976 are summarized. Emphasis is on the U.S. Fisheries Conservation Zone. Areas in which the United States has an established fishery or commercial interest in a local fishery are also considered. Contributed papers present various aspects of the marine climate in 1976.

Ocean Variability in the U.S. Fishery Conservation Zone, 1976

INTRODUCTION

Julien R. Goulet, Jr.[1]

Ocean variability in the U.S. Fishery Conservation Zone, 1976 is the third volume[2] focusing on the effects of natural ocean variability (including climate scale events) on distribution and abundance of fishery resources. The objectives of this series are:

1. to provide resource managers with an overview and assessment of the status of the environment in terms of large area and long time scale natural processes and their possible effects on marine fishery resources, and

2. to provide researchers with an information source on the ocean properties and processes influencing fishery resources.

These three volumes have been prepared by the program management office of the Marine Resources Monitoring, Assessment, and Prediction (MARMAP)[3] program of the National Marine Fisheries Service (NMFS).

The MARMAP program is a national program of NMFS providing information needed for management and allocation of the nation's marine fishery resources. The program encompasses the collection and analysis of data to provide information on the abundance, composition, location, and condition of the commercial and recreational marine fishery resources of the United States. MARMAP also considers the physical and chemical processes influencing fishery resources.

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[1] Resource Assessment Division, National Marine Fisheries Service, NOAA, Washington, DC 20235.

[2] J. R. Goulet, Jr. (compiler), The environment of the United States living marine resources - 1974. U.S. Dep. Commer., NOAA, NMFS, MARMAP Contrib. 104; J. R. Goulet, Jr. and E. D. Haynes (editors), Ocean variability: Effects on U.S. marine fishery resources - 1975, U.S. Dep. Commer., NOAA Tech Rep. NMFS Circ. 416.

[3] For information, contact Chief, Resource Assessment Division, NMFS, NOAA, Washington, DC 20235.

Changes in physical and chemical properties of the ocean (currents, temperature, nutrients, etc.) and the associated modulation of biological processes directly or indirectly affect not only long-term yields and annual abundances of fish stocks, but also their distribution and availability. Fishery Oceanography, as a subprogram of MARMAP, includes the analysis of physical, chemical, and biological oceanographic data collected during MARMAP and other NMFS surveys and from oceanographic and meteorological operational and research activities of other agencies. Fishery Oceanography provided much of the information incorporated into Ocean Variability in the U.S. Fishery Conservation Zone, 1976.

Editorial Outlook

The areas of interest for Ocean Variability in the U.S. Fishery Conservation Zone, 1976 are the United States' Fishery Conservation Zone, established by P.L. 94-265 (Fisheries Conservation and Management Act of 1976), and the areas of fishery resources outside our Zone in which we have an established fishery or a market interest.

The papers in this document can be categorized as data products, event notices, or topical summaries. Analytic papers, while important for understanding the processes controlling ocean variability and consequent effects on fishery resources, should be submitted to journals with a broader perspective. Preliminary or summarized research results, where appropriate, may be included in the papers contributed to this series.

The data products, event notices, and topical summaries should focus on a limited time interval. The data products should not be selected merely on availability. Rather, products which portray climate-ocean properties or indices of processes should be selected, or developed, for their significance to marine fishery resources. Topical summaries provide overviews of climate-ocean properties and assessment of potential effects on fishery resources. The number of these topical summaries should be increased to present more information on possible environmental influences. In future years we hope to provide the summary to resource managers in a more timely manner. This may involve a small workshop to develop the necessary information, and a distribution of the summary in draft form prior to distribution of the full document as a MARMAP contribution.

We thank our many contributors, who made this volume possible. We welcome criticism, comments, and suggestions for improvement of future volumes in this series.

SUMMARY

Julien R. Goulet, Jr.[1]

The effects of ocean variability on U.S. marine fishery resources can best be summarized within the context of the broad-scale atmospheric and oceanic conditions surrounding our area of interest, the U.S. Fishery Conservation Zone. The variability of the environment within the Zone is controlled by conditions and processes in the overlying atmosphere, at the coast, in the open ocean beyond our Zone, and along the bottom within our Zone. The papers contributed to this document present a synthesis, not necessarily analytic, of the conditions and processes affecting the U.S. marine fishery resources during 1976.

This summary first focuses on the overlying atmosphere, which connects the Atlantic and Pacific Oceans across the North American continent. The conditions at the U.S. coast, in the open ocean beyond our Zone, and along the bottom are summarized in turn. Following this, the responses of marine fishery resources to the variability of their environment are estimated.

Atmosphere

Conditions are considered at the 700 mb level, the height of approximately the lower third of the atmosphere. This is high enough (about 3,000 m above sea level) to be free of surface friction, and thus reflects the large-scale conditions and events taking place in the atmosphere. It is also low enough to be completely within the troposphere, that part of the atmosphere which interacts with the ocean.

Two salient features of the atmosphere in 1976 were the continuation of stronger than average westerly winds over the Northern Hemisphere oceans and a return to lower latitudes of the subpolar low pressure anomaly cells. The variations in westerly wind strength and position influence patterns of upwelling and offshore wind driven transport as well as sea surface temperature distributions. These in turn influence several resource species

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[1] Resource Assessment Division, National Marine Fisheries Service, NOAA, Washington, DC 20235.

such as Atlantic menhaden, Pacific mackerel, and Atlantic sea herring. The strong westerlies have persisted since 1971. However, the high level pressure patterns have undergone drastic changes in their annual averages over the last three years. The 1976 pressure anomaly patterns at 700 mb resemble those of 1974 more closely than those of 1975, but with a few important differences. The Siberian high latitude high pressure cell was much weaker than in 1974. The subpolar low pressure cells were more intense and covered broader areas. The North American continental trough, located over the Great Plains in 1974 and over the Rocky Mountains in 1975, was over the eastern seaboard in 1976. The trough indicated a continental weakening of the subtropical high pressure belt extending across the Atlantic and Pacific. That it was over the eastern seaboard indicated a west coast penetration of Pacific stable high pressure conditions, and consequent California drought. It also indicated more unstable conditions over the eastern seaboard and greater precipitation in that area.

The pattern of seasonal pressure anomalies (differences from 30-yr seasonal averages) showed a striking change from summer to fall in 1976. In 1974 and 1975, the annual average anomalies were dominated by the winter anomalies. In 1976, the fall anomalies were so intense that they dominated the annual average.

Winter 1975-76, with extremely mild east coast conditions, had a zonal distribution of pressure anomalies (the anomalies tended to line up zonally, or along latitude lines). There was essentially no continental trough, whereas 1974 had a trough over the Great Plains and 1975 had a deep trough over the Rockies. By fall 1976, the pressure anomalies had become meridional (the anomalies tended to line up along meridians), indicating extreme wave (north-south) conditions in the actual pressure distributions. Extreme wave conditions preceded both the winter of 1917-18 and that of 1976-77, the two coldest winters of record in the eastern United States.

Haynes (Paper 1) presented a summary of atmospheric circulation during 1976. Dickson and Namias (Paper 2) discussed the interactions between the atmosphere and the sea surface. Summaries of atmospheric conditions over the Pacific (Haynes, Paper 3) and the Atlantic (Goulet and Haynes, Paper 4) also presented the open ocean surface conditions. Chamberlin and Armstrong (Paper 11) presented statistics on the extreme conditions along the east coast in fall 1978 and winter 1977. Quinn (Paper 8) discussed an index of the Southern Oscillation, a phenomenon of the atmosphere in the South Pacific associated with the southeast trade winds. This can be correlated with upwelling along the equator and off the coasts of Chile and Peru, and with the abundance of anchoveta and tuna in those areas.

Coast

Very little information on coastal conditions was compiled for Ocean Variability in the U.S. Fishery Conservation Zone, 1976. Haynes (Paper 16) summarized river runoff into the Middle Atlantic Bight, where the volume flow showed an early spring, peaking in February instead of March or April. There also was extremely high flow in October when precipitation in the Chesapeake drainage basin exceeded 300% of normal. Precipitation exceeded 150% of normal over the entire Appalachian Range in October. This extreme precipitation was associated with the continental trough and extreme wave conditions in the atmosphere. The consequent runoff into the Chesapeake Bay influenced the survival of oyster spat.

McLain (Paper 10) summarized fluctuations in temperature and density at coastal stations from Maine to Florida, Florida to Texas, and Alaska to California. The densities at a tide station at Kiptopeke Beach, VA, at the mouth of Chesapeake Bay, had a large negative anomaly in November, one month later than the extreme flow in the Chesapeake. The early onset of the cold 1976-77 winter was shown by positive density anomalies in New England, a consequence of early freezing and decreased runoff. Negative temperature anomalies in fall 1976 extended along the entire east coast. They began in midsummer south of New Jersey.

Bretschneider and McLain (Paper 5) summarized historical data (1931-75, with some gaps in coverage) showing variations in sea level along the Pacific coast. Unfortunately, the 1976 data were not available to them. Changes in sea level over broad ocean areas can be related to shifts in wind patterns, upwelling regimes, etc., and may be indicative of conditions affecting certain resource species such as Pacific mackerel.

Open Ocean

The conditions in and beyond the Fishery Conservation Zone were summarized by Haynes (Paper 3) and Goulet and Haynes (Paper 4). Dickson and Namias (Paper 2) presented a summary and analysis of the 1976 conditions. The eastern North Pacific, which began 1976 with a smaller reservoir of warm surface water than in previous years, continued to cool. By the end of the year the sea surface temperatures were anomalously cold. Heat storage (average temperature, 0-100 mb) in the Pacific, discussed by Saur (Paper 7) also was lower in 1976 than in 1975.

The central North Atlantic does not have as strong an influence on conditions in the Fishery Conservation Zone as does the eastern North Pacific. It is downwind of the Zone and is isolated from it by a strong frontal system, the Gulf Stream.

The charts of temperature anomaly (McLain, Paper 9) do not show any significant patterns, either positive or negative, in the open ocean waters. Ingham (Paper 12) presented maps of Ekman transport off the Atlantic coast and in the Gulf of Mexico. In 1976, the meridional (north-south) component was generally more negative (more to the south) than the average in the open Atlantic. This indicates a stronger westerly wind component (stronger zonality) than average, which will adversely influence survival of certain species such as menhaden.

Bottom

The bottom does not provide a source of energy or variability in time affecting U.S. marine fishery resources. Nevertheless, in shallower waters at least, the bottom does modify the processes affecting the marine environment. Davis (Paper 22) discussed the bottom waters in the Gulf of Maine and over Georges Bank. There has been a warming trend since 1968, though it was partially reversed in 1975. In 1976, the spring temperatures in the Gulf of Maine and the autumn temperatures, both there and over Georges Bank, resumed their warming trend. This warming in the bottom waters took place despite the cold autumn air temperatures. It may be expected that bottom water temperatures affect the recruitment of bottom dwelling species such as sea scallops or demersal spawning species such as winter flounder and Atlantic herring.

Armstrong (Paper 17) discussed the anomalous bottom anoxic conditions leading to a massive fish kill off New Jersey. Crist and Chamberlin (Paper 19) provided a summary of the bottom temperatures south of New England. No information was available on the broad Bering Sea shelf.

System Responses

How did the environment of the U.S. Fishery Conservation Zone respond to the surrounding variable conditions in 1976? McLain's charts of sea surface temperature anomaly (Paper 9) provide information on scales of one month and 100 km, while Dickson and Namias (Paper 2) presented an analysis on scales of three months and 500 km. The change of anomalies along the Pacific coast from negative at the beginning of the year to positive at the end is noticeable. These changes parallel the opposite changes in the offshore waters of the eastern North Pacific. The sea surface conditions in the Bering Sea, Gulf of Alaska, Gulf of Mexico, South Atlantic Bight, Middle Atlantic Bight, and Gulf of Maine are also charted by McLain and discussed by Haynes (Paper 3) and Goulet and Haynes (Paper 4). The temperature anomalies along the Atlantic coast were positive through July and negative for the remainder of the year. Fast-swimming fish such as tuna congregate in areas and depths where temperatures suit their preferences. Temperatures affect the growth rates of many species.

Nelson (Paper 6) presented the upwelling index along the west coast from the Gulf of Alaska to Baja California. The southern area had extremely low indices in January-February and from September through December. The Gulf of Alaska also had extremely low indices in April-May, July through September, and in November. The California Current region had extremely high indices throughout the year except in April and July-August. These indices provide information on availability of nutrients brought up with upwelled water. Quinn (Paper 8) presented indices of the Southern Oscillation (trade wind relaxation) which tracked the development of El Nino-type activity in the eastern tropical Pacific. Strong El Nino-type activity is detrimental to the growth and abundance of Peruvian anchoveta.

The wind driven transports along the east coast and in the Gulf of Mexico were discussed by Ingham (Paper 12). In February-March the transports were anomalously strong to the southeast along the U.S. east coast. During November-December, anomalously strong southwest transports persisted. In the Gulf of Mexico, anomalously strong northwest transports persisted from October through December. Onshore wind-driven transport is extremely important to survival of Atlantic menhaden larvae.

Gunn (Paper 18) mapped the annual march of the Shelf Water/Slope Water front along several transects off the U.S. east coast. The front in 1976 was significantly more variable than in 1974 or 1975. The energetic state of the front mirrored the energetic state (extreme wave patterns) of the atmosphere and preceeded the cold winter. Deaver (Paper 13) presented the sea surface temperature along the east coast from Florida to Maine. This data set, obtained from airborne radiation thermometry, reflects the early spring and cold autumn of 1976. Cook (Paper 14) presented the changes in water column thermal structure off New Jersey. The early spring of 1976 was also evident in this data set. The nearshore surface salinities were much reduced during spring, and a relatively fresh surface layer sometimes extended beyond the Shelf Water/Slope Water front. (Note the extremely early spring runoff shown by Haynes in Paper 16.) The relative distributions of Shelf Water and Slope Water may be important to overwinter survival of Atlantic herring larvae. Lowered salinities due to high runoff, with associated turbidity, are unfavorable to shellfish.

Smith and Jossi (Paper 20) discussed variations in plankton populations in the Middle Atlantic Bight by season and water mass, and also in a warm core Gulf Stream eddy. Named species may be considered as water mass indicators. Armstrong (Paper 17) discussed the anoxic bottom conditions off New Jersey. This was a response to the early spring warming, with runoff of fresher, lower density water overlying ocean waters and suppressing mixing throughout the water column, and the consequent oxygen depletion by biological activity.

Mizenko and Chamberlin (Paper 15) presented data on the formation of anticyclonic Gulf Stream eddies and their migration through the Slope Water south of New England. Eddies create fast, localized currents which can submerge marker buoys and move lobster and crab traps when the eddies impinge upon the upper continental slope. The total number of eddy days was reduced in 1976 compared with 1975, with the summer quarter showing the greatest reduction. Why the Gulf Stream had a lower energy state, as shown by the number of eddies cast off, compared with the Shelf Water/Slope Water front, is a puzzle.

Rogers (Paper 21) provided an update on the swarming of siphonophores in New England coastal waters. The "lipo," or slime, which fouls fishing nets, was mild in 1976 compared with 1975.

<u>Response of Fishery Resources</u>

What can be said about the response of marine fishery resources to the 1976 status of the environment? We can comment on only a few fishery resources. These comments must be considered only as best estimates rather than as definitive statements.

- The 1976 year class of Pacific mackerel was favored by above-normal upwelling. This has been reflected in the 1977 harvest.

- Larval menhaden were not favored by the wind-driven transport conditions in the Middle Atlantic Bight.

- Recovery of the Peruvian anchoveta fishery may be delayed by the mild 1976 El Nino conditions.

- Anoxia in bottom water off New Jersey had little effect on finfish recruitment, although many adults died. All age groups of shellfish suffered high mortalities.

- Decreased Slope Water on Georges Bank favored herring larvae survival in the fall. Later survival was adversely influenced by the severe winter that followed.

- Extreme runoff in October affected crab recruitment in the Middle Atlantic Bight. The following cold winter also was adverse.

- The October runoff was detrimental to survival of the oyster spat in Chesapeake Bay.

Response to Prior Years

Because marine fishery resources integrate the effects of their environment through their lifetimes, and because the lifetimes of many species are longer than a few years, it is appropriate to comment on 1976 responses to prior years' conditions.

- The continued warming of bottom waters in the Gulf of Maine may adversely affect the recruitment of lobster.

- The catch of Atlantic menhaden was up about 30% in 1976 compared with 1975. The increased catch was not a response to increased fishing effort. This fishery was primarily on the 1974 and 1975 year classes. These year classes were stronger than could have been expected from the wind-driven transport in those years. Was the increased catch a response to increased abundance caused by some as yet unidentified environmental or biological factor? Or was it due merely to the increased availability of fish that were swimming in denser or shallower schools because of some equally unknown influence on their behavior?

- What is the relation between the abundance of summer bottom-spawning, short-finned squid and bottom temperatures on the outer continental shelf and upper slope south of New England? The 1975 year class, fished in the fall of 1976, was 10 times more abundant than normal. The bottom temperatures were about 1C warmer than normal in late spring and early summer. The spawning area of the short-finned squid has not been identified, and so the environmental influences cannot be studied.

- What is the connection between the warming of Georges Bank bottom waters and the reappearance in commercial quantities of sea scallops there? Sea scallop landings declined precipitously in the late sixties. They began increasing in 1974 and reached their 1965 level in 1976. Bottom temperatures in the autumn on Georges Bank fell in the late sixties and have gone through an uneven increase since then. Because sea scallops are harvested at ages greater than four years, a correlation cannot be run between temperatures and landings without obtaining a longer time series of temperature and obtaining lagged correlations. Perhaps the overall warming of Georges Bank bottom waters since 1963 (about 1.5C) is now helping recruitment of sea scallops.

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Paper 1

ATMOSPHERIC CIRCULATION IN 1976[1]

Elizabeth D. Haynes[2]

In the North Atlantic, 1976 was characterized by pressure patterns near normal in position but more intense than usual. The winter storms were severe, but tracked farther north than normal allowing mild conditions to penetrate northward. In June an anomalous and persistent high pressure center settled over western Europe, creating a severe drought for nearly four months. By October, the ridge progressed to the east and the weather returned essentially to normal. At the year's end, winter North Atlantic storms harrassed the shipping lanes.

Surface pressure patterns in the North Pacific also were near normal in position, on the whole, but more intense than usual. Air flow over the area south of the Gulf of Alaska was more zonal than usual until the last quarter, when a persistent ridge along the U.S. west coast forced surface winds to back (rotate counter-clockwise) and become southwesterly. Farther south, north of 20N, surface conditions approximated the long-term (1948-70) mean.

In the equatorial Pacific, wind and pressure patterns resembled those of 1972, with a weakened southeastern Pacific subtropical high, and Southern Hemisphere storms passing to the north of their usual tracks.

At the 700 mb level, winds were much stronger than average all year. Northern Hemisphere flow was primarily zonal the first quarter, with troughs and ridges beginning to develop in April. Deepening continued through the summer, though zonal flow persisted over the North Pacific. A strong blocking ridge became

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[1] This paper is summarized from the Atlantic and Pacific logs in Mariners Weather Log, Vols. 20 and 21; the weather and circulation articles in Monthly Weather Review, Vols. 104 and 105; and contributions in the Proceedings of the NOAA Climate Diagnostic Workshop, NOAA, November 4-5, 1976, Washington, DC.

[2] Resource Assessment Division, National Marine Fisheries Service, NOAA, Washington, DC 20235.

established over Europe throughout the summer. The pattern retrograded in October, with well-developed meridional flow continuing through November. The pattern reverted to more zonal flow conditions by the end of the year.

Figures 1.1 and 1.2 show anomalies, or departures, of the 700 mb surface from a 30-yr (1941-70) mean height. The annual and quarterly anomalies can be compared to those for 1974 and 1975 (Goulet and Haynes 1978). In general, sea surface temperatures tend to be warmer than normal, and seas calmer, under areas of positive height anomaly, whereas cooler and stormier conditions prevail under areas of negative height anomaly. These interactions in 1976 are more fully discussed by Dickson and Namias in Paper 2.

January - The high and low pressure centers over the North Atlantic were slightly closer together and more intense than average, bringing record high winds and severe storms to western Europe. Positive pressure anomalies extended over the ocean from 20N to 60N.

In the North Pacific the pressure distributions were near normal in position but more intense than usual, and storm tracks tended to be about 5 degrees north of their average locations.

Fast mid-latitude westerlies and a three-lobed wave pattern with broad troughs characterized the 700 mb circulation, with a strong ridge along the U.S. west coast which deflected storms northward to Canada and Alaska.

February - There were more storms than usual in the North Atlantic, and their tracks were far north of normal (the majority of the storms crossed the coast north of Nova Scotia). Surface pressure was normal in outline, but more intense. There was a +14 mb closed high anomaly over western Russia, and a -17 mb anomaly trough paralleling the west coast of Greenland.

Pressure was above normal over all of the Pacific north of 25N, with a +75 m height anomaly at the 700 mb level (+9 mb at the surface) in the center of this area.

The 700 mb wave pattern smoothed this month, with very strong westerly winds a few degrees north of normal. These brought near record high temperatures over all of the United States except the northwest corner.

March - The overall pressure pattern on the North Atlantic was near normal but more intense than usual with a -18 mb anomaly near Iceland and a +11 mb anomaly from 15N to 50N on the central ocean.

The number of storm centers traversing the North Pacific was far above normal. They moved eastward, tracking progressively farther north to the latitude of Seattle, and east of 160W recurved cyclonically, with the majority moving toward and over the Bering Strait. The Aleutian low was far to the east of its usual position. A high pressure cell covered most of the eastern Pacific south of 45N.

The 700 mb pattern of fast zonal flow produced the highest March wind speeds since records began. Record breaking warmth persisted into March over most of the United States.

April - In the North Atlantic, the month was relatively storm free, with storm centers concentrated northwest of a line from Newfoundland to Iceland. A ridge stretched northeastward from the Azores high to 50N, 15W, where pressure was nearly 10 mb higher than normal.

In the North Pacific there were more, but smaller and less intense, low pressure storm centers than normal, and they tracked more nearly east than the normal northeasterly direction. The anomaly pattern was weak, with a negative anomaly trough over the Aleutian Islands associated with the primary concentration of storm tracks.

Fast, zonal 700 mb flow persisted across the Pacific, but a trough developed off the U.S. west coast, a ridge over the Great Plains, a trough off the U.S. east coast, and a pronounced ridge west of Europe.

May - Low pressure storm centers formed farther off the U.S. east coast and were fewer in number than normal, but followed the usual storm tracks across the North Atlantic. There was a -12 mb anomaly centered in the Icelandic low, with a large area of mildly positive anomaly south of 45N.

The number of storms in the North Pacific was near normal, but they were more widely dispersed than usual. The Pacific high and Aleutian low remained stronger than normal.

Mean 700 mb flow across the North Pacific was flat and stronger than normal, while waves developed over the continent with a trough over the U.S. west coast, a ridge in the western United States, and an eastern trough west of the Appalachians. Mean flow over the western North Atlantic flattened and strengthened considerably, while an anomalous low developed above the surface low, and the ridge intensified over Scandinavia.

June - North Atlantic storm paths originated in Ungava Bay, moved southeastward to 50N, 35W, then recurved toward Iceland. None crossed the British Isles or the European continent. A strong ridge north-northeastward from the Azores high brought high temperatures and drought conditions to northwestern Europe.

The western North Pacific was dominated by a strong surface high pressure cell. The pressure gradient was very weak, and the paths of the storm centers were diffuse.

At 700 mb, there was a trough at 175W, and a subtropical ridge over the eastern Pacific, which progressed eastward to bring the west coast trough over the western States. There was an anomalous strengthening of the subtropical jet stream approaching the southwestern United States, while pressures rose to the east. The trough south of Greenland deepened, and the ridge over western Europe strengthened.

<u>July</u> - The North Atlantic was relatively quiet, with diffuse cyclone centers. The sea level pressure pattern was near normal for the month. The few storms that reached Europe did not alleviate the drought or ease the record-breaking heat.

The North Pacific storm tracks were about 5 degrees farther south and more easterly than normal into the Gulf of Alaska. There was an anomalous surface low at 55N, 180W, with lower than normal pressures over the entire eastern North Pacific.

The 700 mb flow over the Pacific was fast and zonal between the Gulf of Alaska low and a strong subtropical high northwest of Hawaii. The western U.S. trough retrograded into the eastern Pacific. Ridging over the Great Plains induced a strong trough over eastern North America. The strong blocking ridge over Europe continued, extending southward from a +55 m 700 mb height anomaly over the North Sea.

<u>August</u> - The major North Atlantic storm centers traveled eastward from the Gulf of St. Lawrence, then curved northeasterly and passed into the Denmark Strait. The usual storm paths south of Iceland and across the British Isles were not followed this month. Hurricane Belle brought heavy rainfall to Long Island and southern New England.

The principal North Pacific storm track was from Japan northeastward into the Bering Sea. The sea level pressure pattern closely matched the climatological mean for the month, although pressures were slightly lower (-5 mb) than normal over the Aleutian chain.

The 700 mb wind flow was zonal between 40N and 50N across the entire Pacific Ocean. Troughs lay over both coasts of the United States, with a ridge over the central States. A deep low over the Davis Strait intensified the drought-producing ridge over western Europe.

September - Extratropical storm activity in the North Atlantic was less frequent than usual this month because of a strong (+13 mb anomaly) surface high in this area. One storm, bred in the Denmark Strait, brought England 4 inches of rain in 24 hours, with winds to 78 knots; it was the worst in 25 years but did not break the drought as the water ran off the dry soil.

In the Pacific, the surface pressure was lower than usual, and the high was displaced westward. The Aleutian low was 7 mb deeper than normal, sustaining strong westerly winds. Hurricane Kathleen, the first tropical cyclone to hit California in 37 years, brought heavy rain to eight western States. Over 2 inches of rain fell in Death Valley, and in the San Joaquin and Imperial Valleys crop losses were severe.

The mean 700 mb circulation showed a three-lobed pattern, with closed lows over the Alaska Peninsula, Baffin Island, and Franz Josef Land. Strong zonal westerlies persisted over the Pacific north of 40N. The trough deepened off California and the downstream ridge lay over the Rockies. The trough over eastern North America deepened. The persistent ridge over Europe retrograded and a trough became established over Scandinavia and the British Isles, extending toward the Azores.

October - Most of the North Atlantic storms occurred in the second half of the month, following the historical tracks from the Gulf of St. Lawrence to south of Iceland or from the U.S. east coast to northern Europe. The pressure centers were near their long-term mean locations, but were more intense than normal. A trough extended from a -12 mb anomaly center over Land's End southeastward across France. A high north of the Black Sea ridged to a +14 mb anomaly over northern Norway. Surface pressure on the North Atlantic west of 50W was within 1 mb of the climatological mean.

There were fewer storms than normal in the Gulf of Alaska. They originated farther east and south than usual and tracked toward British Columbia. The pressure pattern resembled the long-term mean, but with a counterclockwise shifting of centers. There was a -6 mb anomaly center near 50N, 175W, and a +7 mb anomaly center south of Sitka.

At 700 mb the Aleutian low persisted over Bristol Bay, but the Pacific subtropical high, and consequently the area of strong zonal westerlies, retrograded 30 deg of longitude from its position of the previous month, and a strong ridge developed over Kamchatka. The upper air pattern in this area was tighter than normal, and wind flow was more intense. The mean trough over the eastern Pacific intensified, the ridge over the Rocky Mountains persisted, and the trough over the eastern United States deepened. A large area of negative height anomaly, with a -127 m center south of Ireland, extended from Italy to the Great Lakes.

November - The western North Atlantic was rough sailing this month. The major storm tracks ran from near Cape Hatteras to east of Cape Race and toward Iceland, or else recurved into the Labrador Sea. Surface pressure patterns were more intense than normal. The two centers of the Icelandic low were displaced southwestward, while the Azores high was shifted northeastward.

There were fewer, but larger than normal, Pacific storms, originating in the Sea of Japan and tracking northeast into the western Bering Sea, or east to the date line then northeast and north into the Gulf of Alaska. The pressure pattern was much deeper than normal with a significant surface trough extending south between 160W and 155W from a -10 mb anomaly over Bristol Bay. The Pacific high was split into two, with a +8 mb anomaly over western Montana diminishing to the south-southwest towards 30N, 135W, and a +4 mb anomaly center near 30N, 170E.

The 700 mb level showed one major trough paralleling the Asian coast and another extending from Dutch Harbor south-southeast toward 30N, 150W. The normal ridge over the Rockies was higher and sharper than usual, and a trough sloped southwestward from Labrador across the central United States. Flow was west-southwesterly and more intense than normal over the North Atlantic shipping lanes.

December - Normal cyclonic activity occurred from Nova Scotia to the Davis Strait and from Newfoundland through the Denmark Strait, as well as up the U.S. east coast. Four successive storms on this last track battered the grounded oil tanker Argo Merchant, and the fourth one took the Grand Zenith as well.

In the Pacific, storms tracked along the Aleutian chain into the Gulf of Alaska. The low was near its usual position, but was 13 mb deeper than normal. High surface pressure dominated the coast south of British Columbia.

At the 700 mb level, flow was more nearly zonal than in recent months, but with a ridge over the U.S. west coast, a broad trough over the east coast, a high over Iceland with an associated flat ridge, and a low over Scandinavia.

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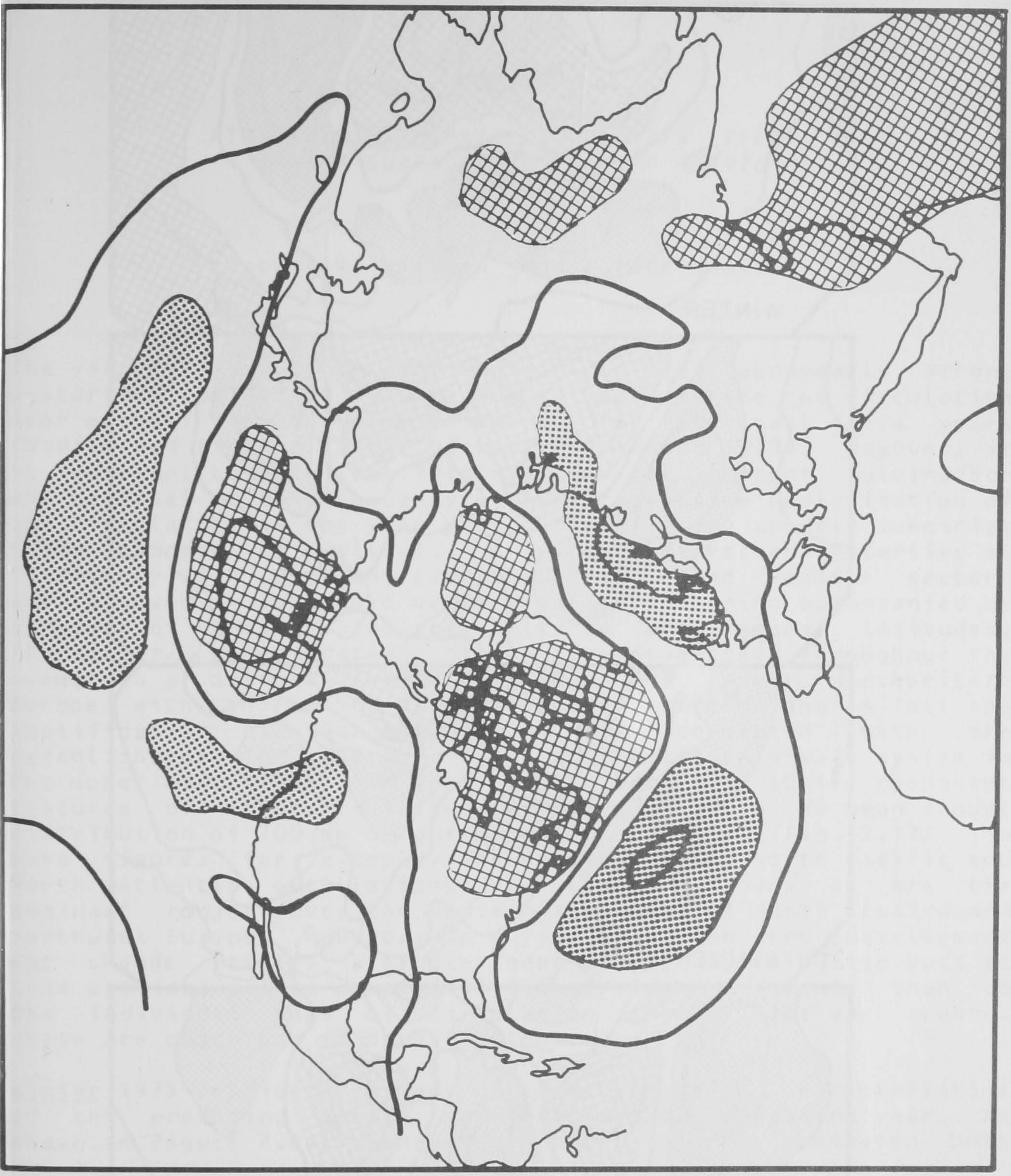

igure 1.1.—Annual mean height anomalies of the 700 mb pressure surface for 1976. Contour interval is 15 m. Hatched shading is <−15 m; stippled shading is >+15 m.

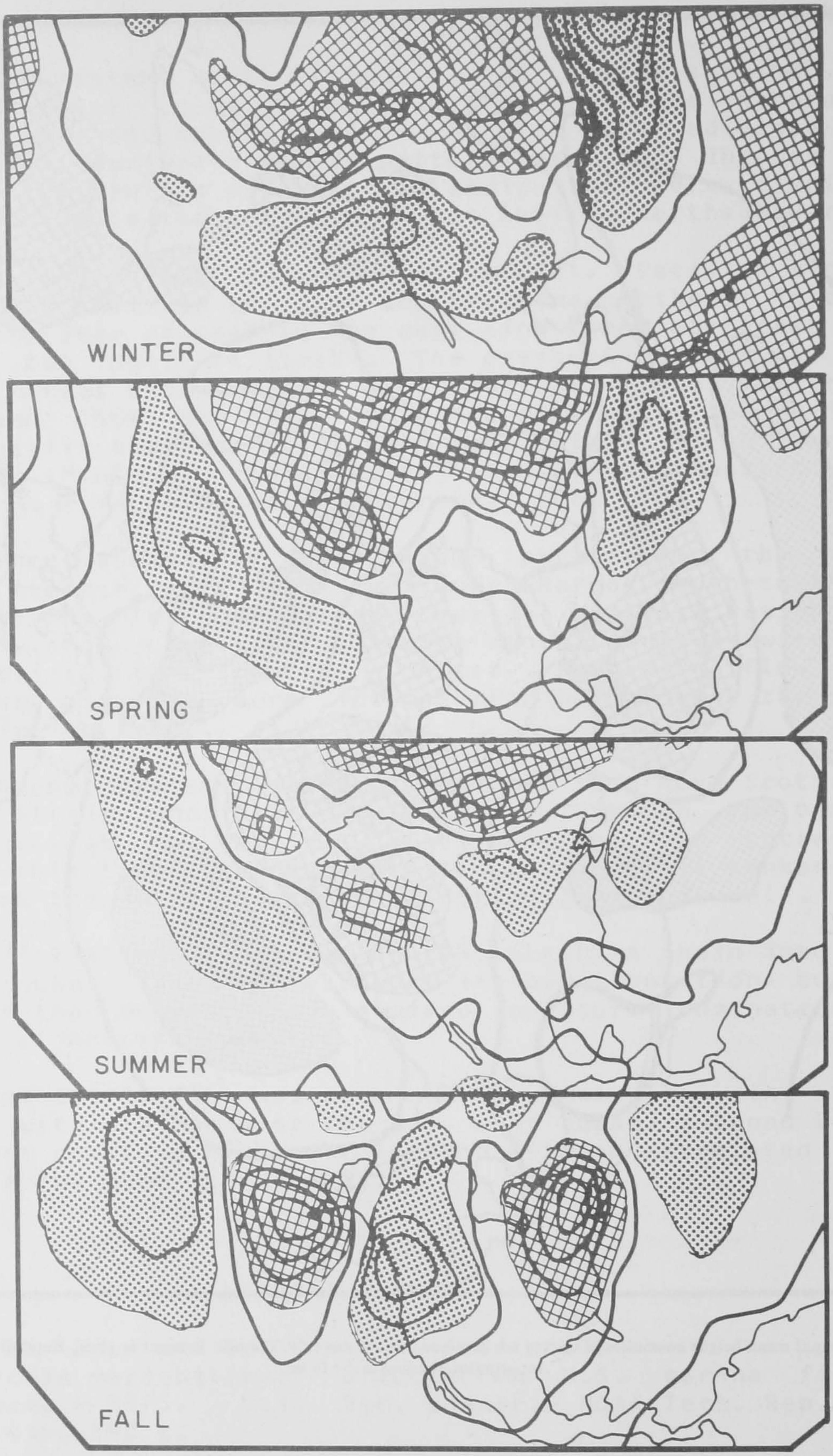

Figure 1.2—Quarterly mean height anomalies of the 700 mb pressure surface for 1976. Contour interval is 15 m. Hatched shading is <−15 m; stippled shading is >15 m.

Paper 2

ATMOSPHERIC CLIMATOLOGY AND ITS EFFECT ON SEA SURFACE TEMPERATURE - 1976

Robert R. Dickson[1] and Jerome Namias[2]

The year 1976 saw the continuation of the abnormally strong westerly flow which has tended to characterize the circulation over much of the Northern Hemisphere for the past five years (Namias and Dickson 1976; Dickson and Namias 1978). However, it is important to note that 1976 also saw the apparent culmination and reversal of this tendency with a progressive amplification of the circulation as the year progressed. We may crudely summarize these changes as follows. A winter of record westerlies at relatively high latitudes over the Atlantic and Pacific sectors was followed by continued westerly vigor in spring accompanied by a return of winds and pressure belts to more normal latitudes. Thereafter, amplification of the flow progressed throughout the summer as a dominant blocking ridge built over northwestern Europe with shortening of wavelengths upstream, and in fall the amplification of the circulation was completed with the establishment, on average, of a full latitude 5-wave system in the upper westerlies. To some extent, each of these component features of the circulation was reflected in the mean annual distribution of 700 mb height anomaly for 1976 (Fig. 2.1); in this figure, for example, the well-developed North Pacific and North Atlantic oscillations are clearly shown, as are the dominant ridges over the western seaboards of North America and northwest Europe. However, in a year when the key development was change itself, a single "mean annual" distribution such as this provides a less meaningful illustration of events than do the individual maps of circulation anomaly for each season. These are described in detail below.

Winter 1975-76 displayed many of the circulation characteristics of the preceding season and indeed of the preceding year. As shown in Figure 2.2, intense subtropical ridges dominated both

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[1] M.A.F.F. Fisheries Laboratory, Lowestoft, Suffolk, England.
[2] Scripps Institution of Oceanography, La Jolla, CA 92037.

the eastern Pacific and north Atlantic, lying well to the north of their normal positions and trending northeastward to cover western North America and the fringes of northwest Europe. Coupled with intense subpolar lows, on average, over Alaska and eastern Greenland, these cells developed polar westerlies of record intensity over the Western Hemisphere, driving mild maritime air into northern North America and Europe, and confining arctic air masses to higher latitudes. Wagner (1977) noted that, in December, "The 700 mb polar westerlies between 55N and 75N over the Western Hemisphere averaged 7.8 m/s, the highest value since records began in 1948, and as much as 5 m/s stronger than normal between 60N and 65N." In absolute terms, the peak zonal wind anomaly was developed between southern Greenland and Scandinavia where the main jet stream axis was deflected far to the north of normal around the Atlantic ridge. In this zone, upper westerly wind speeds averaged 10-15 m/s faster than normal in December (Taubensee 1976a). This pattern of vigorous westerly circulation over both oceans, generally poleward of normal but periodically expanding southward to more usual latitudes, continued throughout the winter. Again, as in previous years, the strong westerlies were largely a feature of the ocean areas and, with a weaker, more meridional flow over the intervening continents, the hemispheric wave pattern as a whole was not without amplitude. Periodically throughout the winter an extensive Asian ridge was able to inject arctic air southward across the western and central Pacific, stimulating intense cyclogenesis there and reinvigorating southwesterly flow across the eastern Pacific (Taubensee 1976a; Wagner 1976a). In January, "Wind speeds across the eastern Pacific and the entire Atlantic averaged 6 to 9 m/s stronger than normal near the maximum axis." (Wagner 1976a). Meanwhile, with intense subtropical ridging over both oceans, the subtropical westerlies (south of 35N) reversed their normal seasonal strengthening trend to weaken from December to more than 3 m/s below normal over the Western Hemisphere in January (Wagner 1976a). Both of these tendencies continued for the remainder of the winter, with temperate westerlies (35N-55N) and subtropical westerlies averaging their second highest and their lowest, respectively, intensities of record in February (Dickson[3] 1976a). Though the situation was somewhat altered in February with the establishment of troughing at the western American seaboard, the U.S. winter as a whole was characterized by intense high latitude westerly flow with ridging in the west bringing drought to the southwest, with frequent chinook winds at the eastern slope of the Rockies, and with mild maritime air across much of the northern part of the country.

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[3] No relation to present author.

With the continuation of the vigorous westerly regime of previous seasons over both oceans, it is perhaps no surprise that the antecedent distribution of surface temperature anomaly (Dickson and Namias 1978) was consolidated rather than destroyed during the winter of 1976. The frequent injections of arctic air over the west and central North Pacific (with associated cyclogenesis, cloud cover, cold front activity, and surface water divergence) combined with high westerly wind speeds to maintain the preexisting belt of anomalously cold water across the full width of the northern North Pacific (Fig. 2.2). In its core area to the east of Japan this cold anomaly exceeded 2F (1.1C). To the south and east of this cold zone the eastern Pacific atmospheric ridge extending between Hawaii and western North America was able to maintain and intensify an area of abnormally warm surface water centered on 30N, 150W. Core anomalies here rose by over 1F (0.6C) from the previous season to +2.1F (+1.2C). Flanking this cell to the eastward, the cool conditions of antecedent seasons continued to prevail along the American seaboard. But, with the ridge aloft extending well inland, the prime stimulus for the earlier cooling (northerly winds and coastal upwelling) was removed. As a result, while still below normal, this coastal strip warmed considerably from the cold conditions observed in the previous fall (Dickson and Namias 1978). At lower latitudes, the North Pacific cold surface conditions extended westward from the coast once more, reflecting the northward displacement of the eastern Pacific ridge and the resulting weakness of the subtropical midtroposphere westerlies, with attendant strengthening of the trade winds at surface level.

As with the Pacific sector, winter temperatures in the western Atlantic were generally cool with an anomaly distribution similar to that of the preceding fall. Building on temperatures already well below normal, centers of intense cooling developed in the Newfoundland area and in the Gulf of Mexico. The former reflected the arctic airflow off the winter continent and the record intensity of wind speeds offshore; the severe but localized cooling in the Gulf of Mexico [-4F (-2.2C) at the core] appears to be at least partly the result of periodic but intense northwesterly flow from the western ridge which brought arctic air and occasional record low temperatures to the Gulf coast in the early part of the winter. Between these two main centers of cooling, a limited area of warm surface water was maintained off the eastern seaboard where the western limb of the Atlantic atmospheric ridge supported an anomalous southerly (from the south) airflow. The narrow, zonal alignment of this ridge, however, meant that this southerly flow and the induced warming were necessarily of limited latitudinal extent.

Many elements of the winter circulation were maintained into spring. As shown in Figure 2.3, faster than normal mid-latitude westerlies continued to prevail in both the Pacific and Atlantic sectors, the product of coupling between intense subpolar lows and strong subtropical highs over each ocean. While, on average, the low height anomaly centers maintained their winter positions over Alaska and southern Greenland, their corresponding ridges moved westward to mid-ocean from the continental margins and returned to more southern latitudes. These movements, coupled with a weakening of the Atlantic ridge from +310 ft (+95 m) at the 700 mb level in winter to +150 ft (+46 m) in spring, along with partial filling of the Greenland low, effected a general weakening of polar westerlies and a shift of their main axis to a more southern path. Once again, as Wagner (1977) points out, the lack of amplitude in the troughs at mid-latitudes meant that arctic air was largely contained at high latitudes in spring with little southward penetration over North America.

It should be noted, however, that the general westerly vigor implied in Figure 2.3 conceals certain periods of more amplified flow within the season. The flow was certainly fast and zonal in March when the temperate westerlies over the Western Hemisphere attained their highest March value since records began (12.3 m/s on average; Taubensee 1976b). Mean anomalies of +5 m/s were observed at 700 mb along the principal wind axis from the Great Lakes to Iceland, with a +12 m/s anomaly south of Greenland. However, although vigorous upper westerlies (+9 m/s anomaly) continued to be generated over the Pacific in April (where injections of arctic and subtropical air around the principal centers of action were generating a strong baroclinic zone), the 700 mb circulation amplified greatly over North America and the Atlantic, and upper wind speeds were slightly below normal when averaged for the Western Hemisphere as a whole (Wagner 1976b, 1977). Flat, faster than normal flow returned, however, to characterize both ocean areas for the remainder of the spring. In the Pacific sector the continued presence of an intense subtropical ridge at higher latitudes than normal, and the strong easterly flow to its south, gave the stimulus for unusually strong typhoon activity over the southwest Pacific.

These developments once again were reflected in the distributions of surface temperature anomaly in spring over the eastern Pacific and western Atlantic (Fig. 2.3). With much continuity in the tendency of the circulation from winter to spring, the season to season changes in sea surface temperature (SST) anomaly are mainly those of detail. The northern Pacific continued to be predominantly cold under its mean trough, although the center of cooling [-2.2F (-1.2C) anomaly in the seasonal mean] was situated close to the Aleutians. To the south of this cold zone an expanding belt of warm surface water marked the clear skies, dry settling air, and oceanic convergence associated with the intense subtropical ridge in its new mid-ocean location. Under its eastern flank, surface warming spread eastward toward the American western seaboard, continuing the erosion of the cold water fringing the coast. At lower latitudes the strong easterly flow around the ridge maintained intense cooling [SST anomaly >-2F (>-1.1C)] westward towards Hawaii.

Changes in Atlantic surface temperature from winter to spring are similarly explicable in terms of the movements of both subtropical ridges. The westward movement, on average, of the Pacific ridge removed the northerly outbreaks that earlier were the source of intense cooling in the Gulf of Mexico. Temperatures there continued below normal, but they increased by over 2F (1.1C) from the previous season. The similar westward expansion of the Atlantic atmospheric ridge brought the expected intensification of warming off the Atlantic states, with anomalies exceeding +1F (+0.6C) over a fairly extensive offshore area. To the northwest of this ridge, however, vigorous offshore westerly flow associated with the upstream trough continued to maintain intense cooling off the Canadian Maritimes and Labrador, in a continuation of the winter situation.

While certain elements of the spring circulation were conserved into summer, the mean distribution of the 700 mb height anomaly for summer (Fig. 2.4) was very much more chaotic than before, with zonal pressure alignments breaking down into patterns of small cells, contributing to a well-amplified mean circulation. As shown in Figure 2.4, a stronger than normal subtropical ridge still extended zonally in mid-Pacific, though its anomalous amplitude was halved. As a result, its eastern margin retracted westward, away from the American coast. To the north of this cell troughing continued ocean-wide so that the intervening westerlies remained anomalously strong (+5 to +8 m/s in July; Wagner 1976c), but the single high latitude trough of spring split into two weaker isolated cells close to the Arctic coast of Siberia and the American North Pacific coasts.

This continuation of anomalous troughing activity, and strong westerly flow at higher latitudes of the North Pacific, brought a further dramatic intensification of cooling in the underlying surface waters. With surface temperatures already well below normal in this zone, the renewed cooling rapidly led to the development of a vast area of subnormal temperatures throughout the western and northern Pacific with core anomalies of -3.5F (-1.9C) and -3.1F (-1.7C) underlying the principal centers of negative height anomaly to the northeast of Japan and off British Columbia. In the southeastern Pacific, equally dramatic changes took place. The weakening and westward retraction of the subtropical ridge meant weaker northerly winds and suppressed upwelling off the American seaboard, finally permitting warm surface conditions to extend eastward to the coast. And with the collapse of their parent cell, the weakening of the trade winds from their previous strength farther south brought a rapid change from cold to warm conditions in the southeastern Pacific, contributing to the development of summer El Nino conditions in the eastern equatorial zone.

Over the North American and Atlantic sectors the key development was the westward retrogression of the dominant centers of action in summer, with a general shortening of wavelengths in the upper westerlies and amplification of the mean flow. From Europe a powerful preexisting block moved westward to settle tenaciously over Britain and assume a dominating role in the Atlantic circulation (Fig. 2.4). With this event and with intensification of troughing activity off the Pacific Northwest, the western Atlantic ridge was encouraged to move inland to east-central North America, leaving only a weak subsidiary cell over the western Atlantic. In the north the persistent mean trough over Greenland also participated in this general retrogression, moving westward while retaining its spring intensity, to become centered, on average, over the Davis Strait. Coupling between this cell and the separated centers of positive height anomaly to its southwest and southeast induced strong, anomalous northwesterly winds from arctic Canada to the Laborador Sea and vigorous, anomalous southwesterly flow at 700 mb from southern Greenland to Iceland and the Norwegian-Greenland Sea. Thus, while the circulation in this sector was much amplified compared to earlier seasons, the polar westerlies retained great vigor in the strong baroclinic zone along the Arctic fringes. In August, for example, when the subpolar trough and the British ridge were both more than three standard deviations from normal intensity, 700 mb level wind speeds were 14 m/s stronger than normal over Iceland (Dickson, 1976b).

With the withdrawal of the preexisting western Atlantic ridge to North America, the causes of ocean warming off the middle Atlantic states and cooling south of Newfoundland were both simultaneously removed so that surface temperatures there became more nearly normal than in former seasons. The strong northwesterly component of airflow from the Canadian arctic was, however, responsible for maintaining the intense cooling off the Labrador coast [anomaly of -3.5F (-1.9C) in the seasonal mean].

The events of *fall* (Fig. 2.5) were apparently of great climatic significance, bringing an end (at least temporarily) to long-established regimes in the atmospheric circulation and in the underlying surface temperature field. Hitherto, for example, the 1970's had been characterized by the extreme vigor of the temperate westerlies over both oceans. In fall, however, the progressive amplification of the circulation was completed with the establishment of a full train of meridional troughs and ridges at mid-latitudes of the Northern Hemisphere. While a deep, full-latitude trough developed in intensity over the central North Pacific, the northerly anomalous circulation along its western flank brought a further increment of cooling to the already chilled surface waters of the northern Pacific, with a core seasonal anomaly of -5.3F (-2.9C) developing south of Kamchatka. To the south of this cell, westerlies still continued to flow vigorously over a restricted sector of the North Pacific, but the broad coast-to-coast sweep of westerlies--so characteristic of recent years--was no longer in operation. Instead, the anomalous tendency was for strong northward flow in the eastern Pacific between the mid-Pacific trough and its response ridge downstream over the American west coast. Already encouraged perhaps by the preexisting distribution of surface temperature anomaly in the easternmost Pacific, which by late summer had featured a strong northward twist of isotherms and an intense anomaly gradient offshore (Fig. 2.4), this southerly airflow was responsible for a further rapid northward extension of warming along the American seaboard, with reduced transfer of sensible and latent heat from the ocean and suppressed coastal upwelling (Nelson, Paper 6). The 1970's thus far had been typified by abnormally warm surface temperatures in the east central Pacific surrounded by cool conditions eastward around the American seaboard. Now, with the cold waters of the northern Pacific becoming encircled to the east by warming at the coast, the SST anomaly distribution for the eastern Pacific as a whole came more closely to resemble conditions of the 1960's than those of the 1970's just described.

In keeping with these developments, the long-established cold-season regime of warm air temperatures in the east of North America and cold in the west also showed signs of reverting to the conditions of the 1960's. The persistent ridge over western North America was able to direct a chill northerly airflow over the central and eastern states as far as the Gulf and Atlantic coasts, bringing extreme low temperatures to all but the western fourth of the country. Depressed south of normal by the western ridge, a vigorous low latitude branch of the jet stream at 200 mb over northern Mexico and the southern United States activated the Gulf of Mexico storm track earlier in the season than is usual (Wagner 1977), while the establishment of a strong baroclinic zone at the Atlantic seaboard contributed to the development of intense storms and strong winds offshore (Dickson and Namias 1976). As the result of these changes, cold surface conditions once more developed and extended across the surface waters of the Gulf of Mexico and western Atlantic (Fig. 2.5).

Finally, Figure 2.6 presents the mean annual distribution of SST[4] anomaly (degrees F) over both the North Pacific and North Atlantic Oceans in 1976 and provides a good general summary of

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[4] SST anomalies for the Atlantic sector were provided by D. R. McLain, Pacific Environmental Group, NMFS, NOAA, Monterey, CA 93940.

the dominant events of that year so far as the oceans were concerned. Over both oceans our attention is immediately drawn to the record extent of colder than normal surface water; in the annual mean, exactly 90% of the 5 degree squares (20N-60N) were below normal temperature in either ocean. In each sector the main zone of intense cooling extended across the northern ocean areas with the center of cooling displaced to the west, reflecting both the antecedent conditions at the close of 1975 and the continuation of the tendency for vigorous westerly flow at high latitudes throughout much of 1976. Farther south, the domains of the strengthened subtropical ridges are marked by zones of minimum cooling or by actual warming in each ocean, while at still lower latitudes, the general strength of the trade winds flowing around these northward-displaced ridges is apparent in the zonal band of cooling at about 20N-25N.

These mean annual distributions are thus dominated by the zonal circulation tendencies which characterized the winter and spring (and antecedent) seasons, rather than by the more amplified flow which prevailed at the close of the year. However, these latter "atypical" conditions were to be of more than passing significance. With surface temperature gradients over the eastern Pacific in fall favoring continued ridging over the Rockies, and with the chilled east favoring maintenance of the east coast trough, the stage was set for the intensification of the fall temperature regime into the record breaking winter conditions of 1977.

ACKNOWLEDGMENTS

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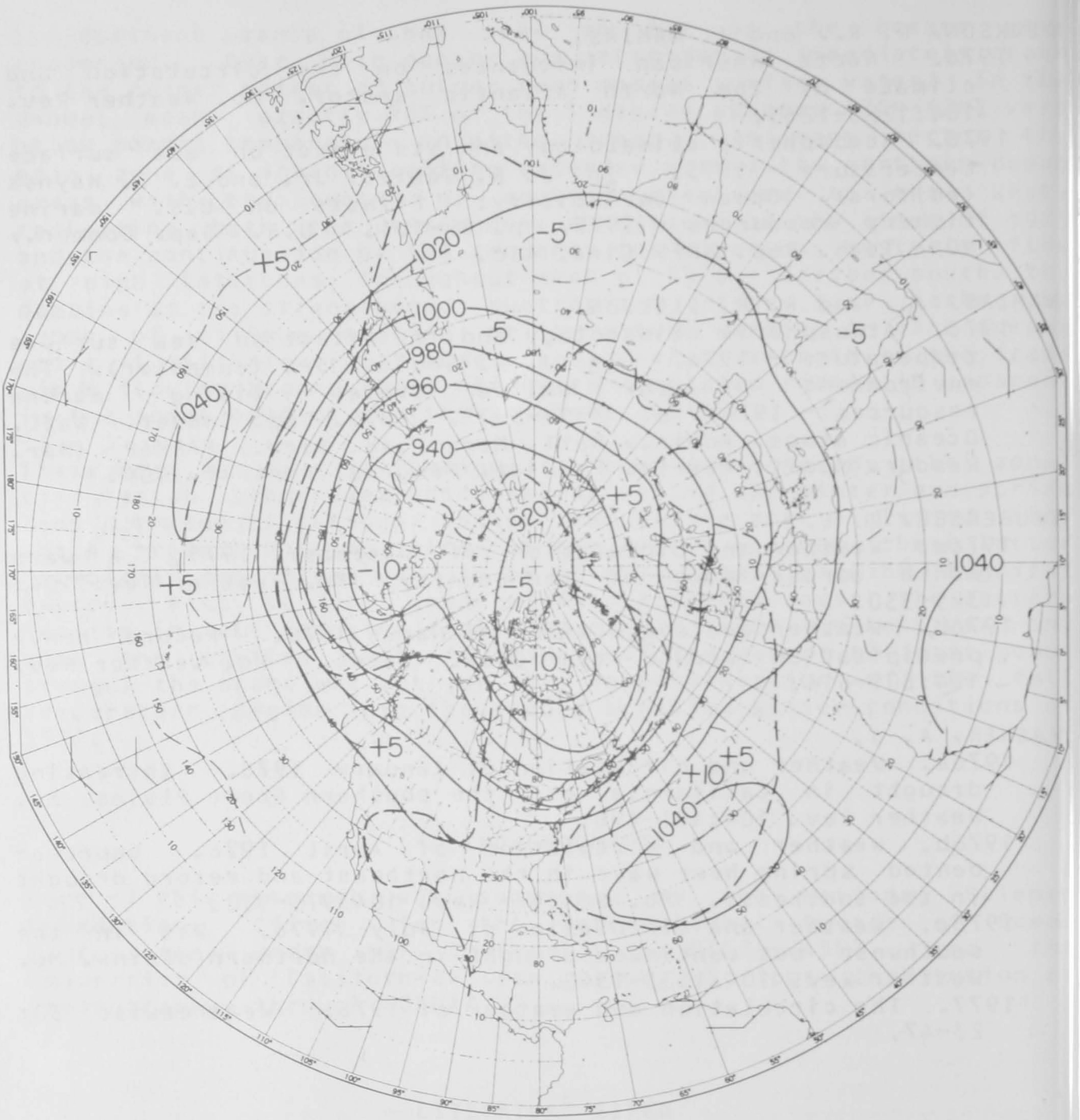


1976 MEAN ANNUAL 700 mb HEIGHT & ITS ANOMALY (feet÷10)

Figure 2.1.—Mean annual height of 700 mb pressure surface and its anomaly (departure from the long-term, 1948-72, mean) in ft/10.

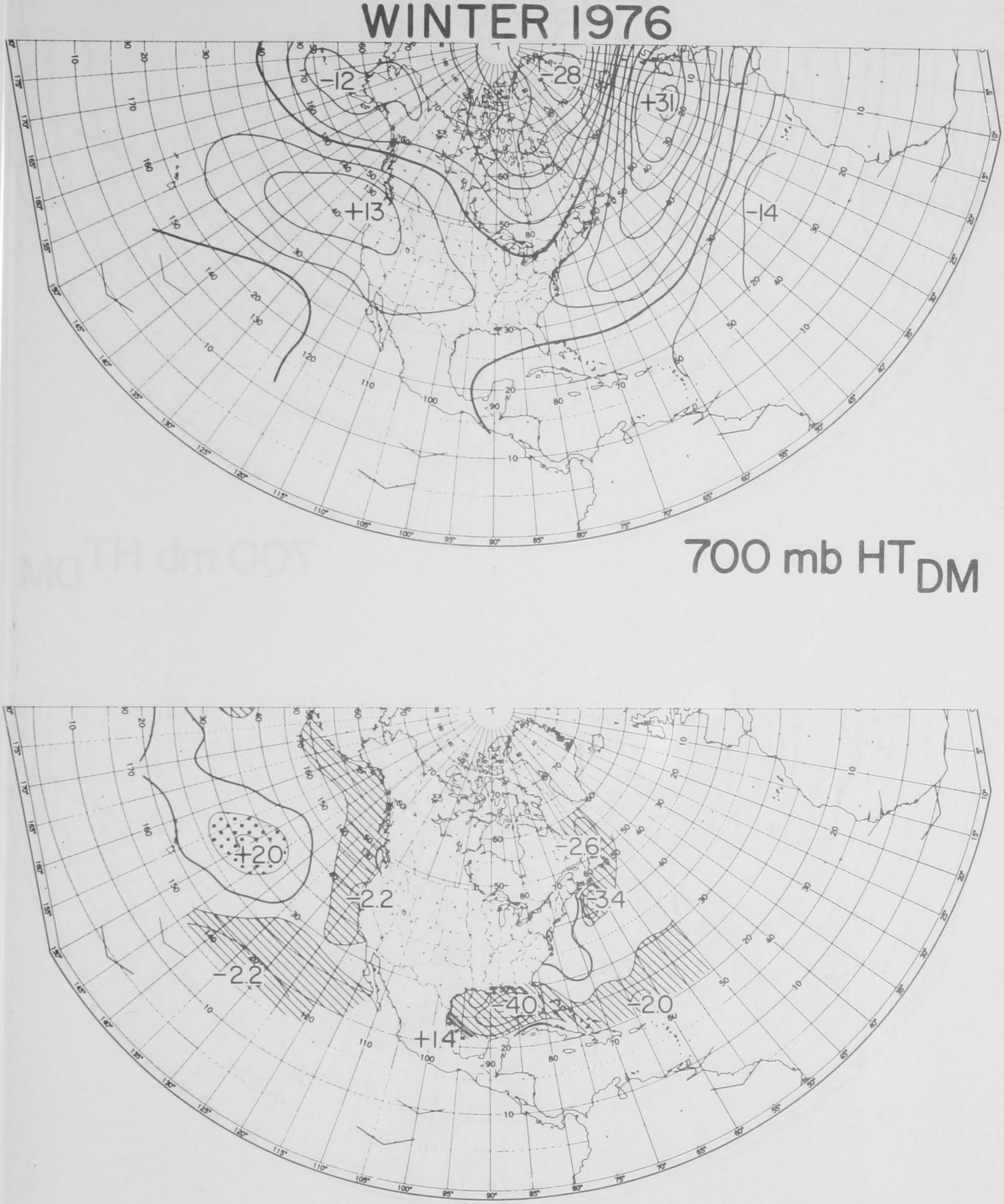
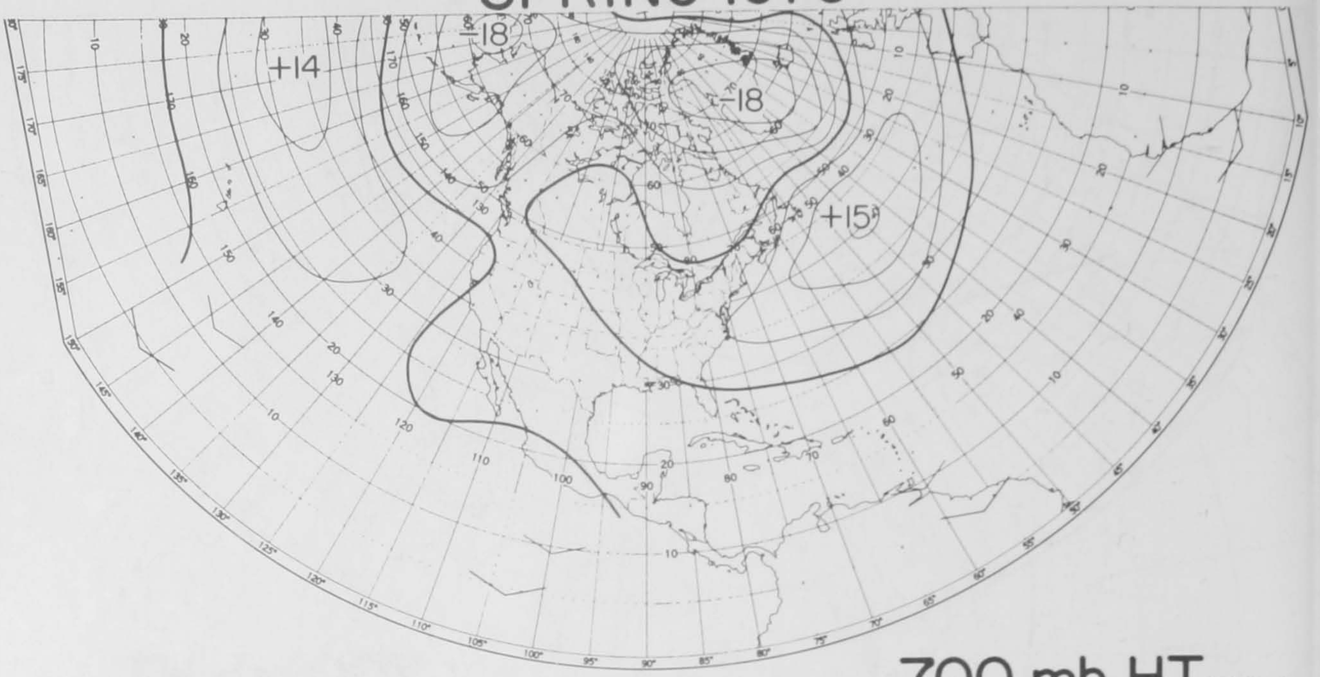


Figure 2.2.—Anomaly (departure from the seasonal mean; base 1947-66) of 700 mb height for winter (December 1975-February 1976) in ft/10 (upper), and anomaly of sea surface temperature for winter in degrees F (lower). Anomalies >+1F are stippled, >−1F are hatched.

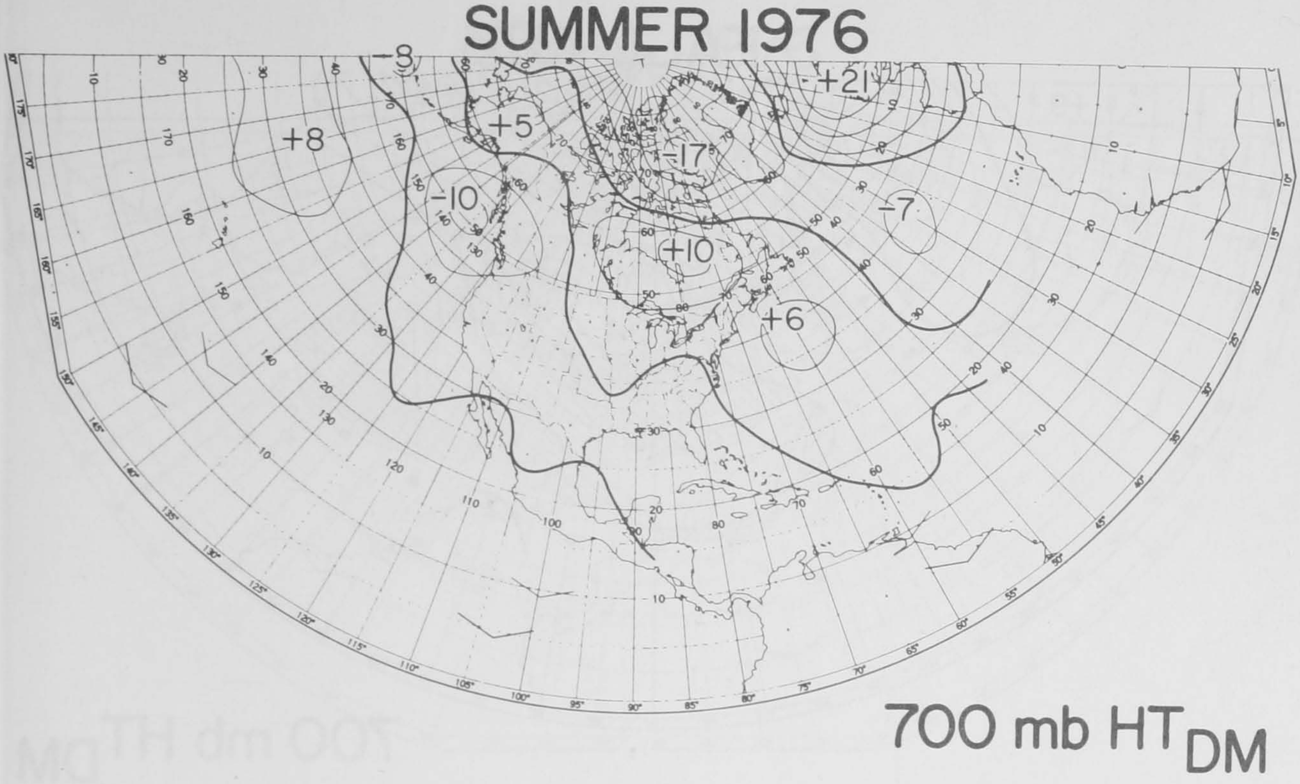
SPRING 1976



700 mb HT_{DM}

SST_{DM}

Figure 2.3.—Anomaly (departure from the seasonal mean) of 700 mb height for spring (March-May 1976) in ft/10 (upper), and anomaly of sea surface temperature for spring in degrees F (lower). Anomalies >+1F are stippled, >−1F are hatched.



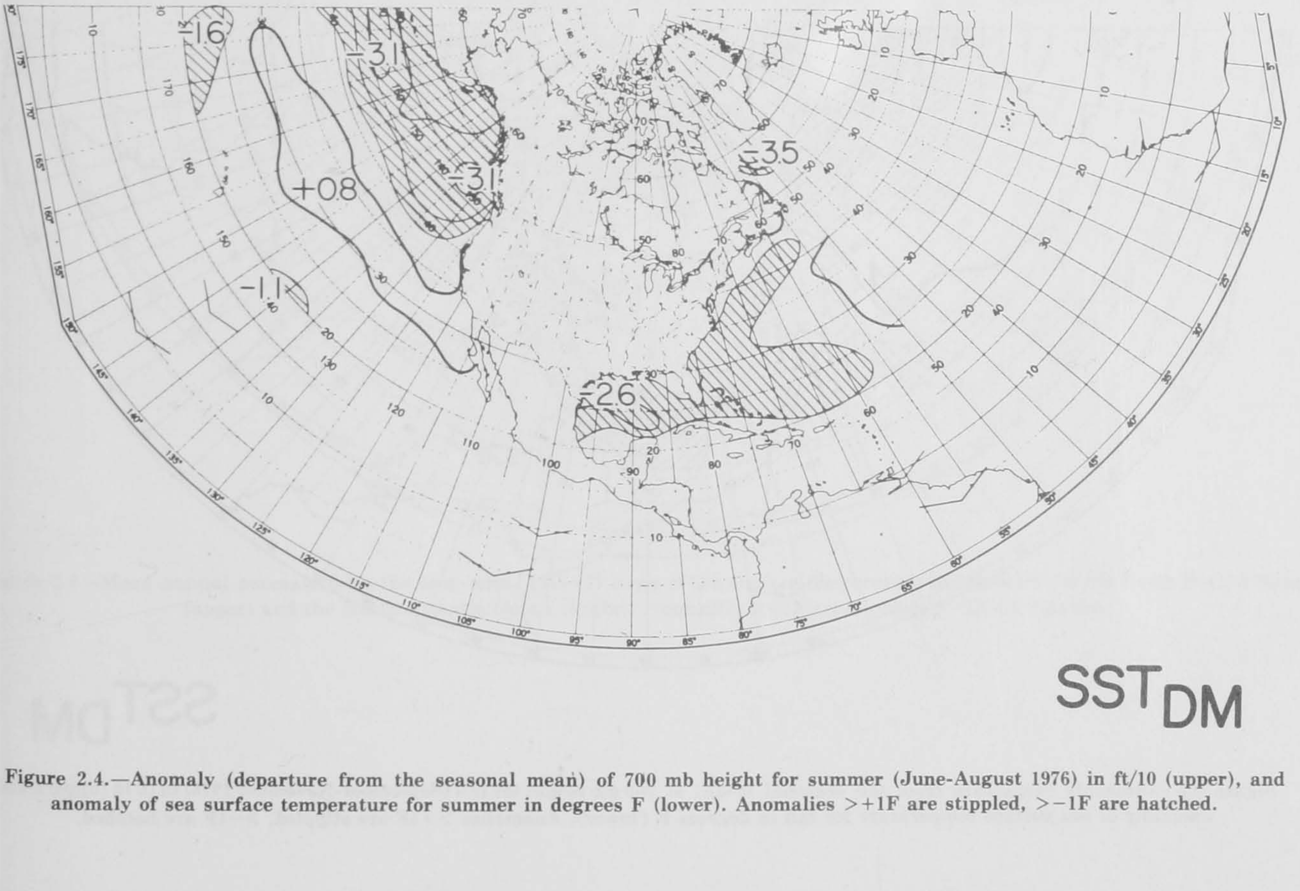


Figure 2.4.—Anomaly (departure from the seasonal mean) of 700 mb height for summer (June-August 1976) in ft/10 (upper), and anomaly of sea surface temperature for summer in degrees F (lower). Anomalies >+1F are stippled, >−1F are hatched.

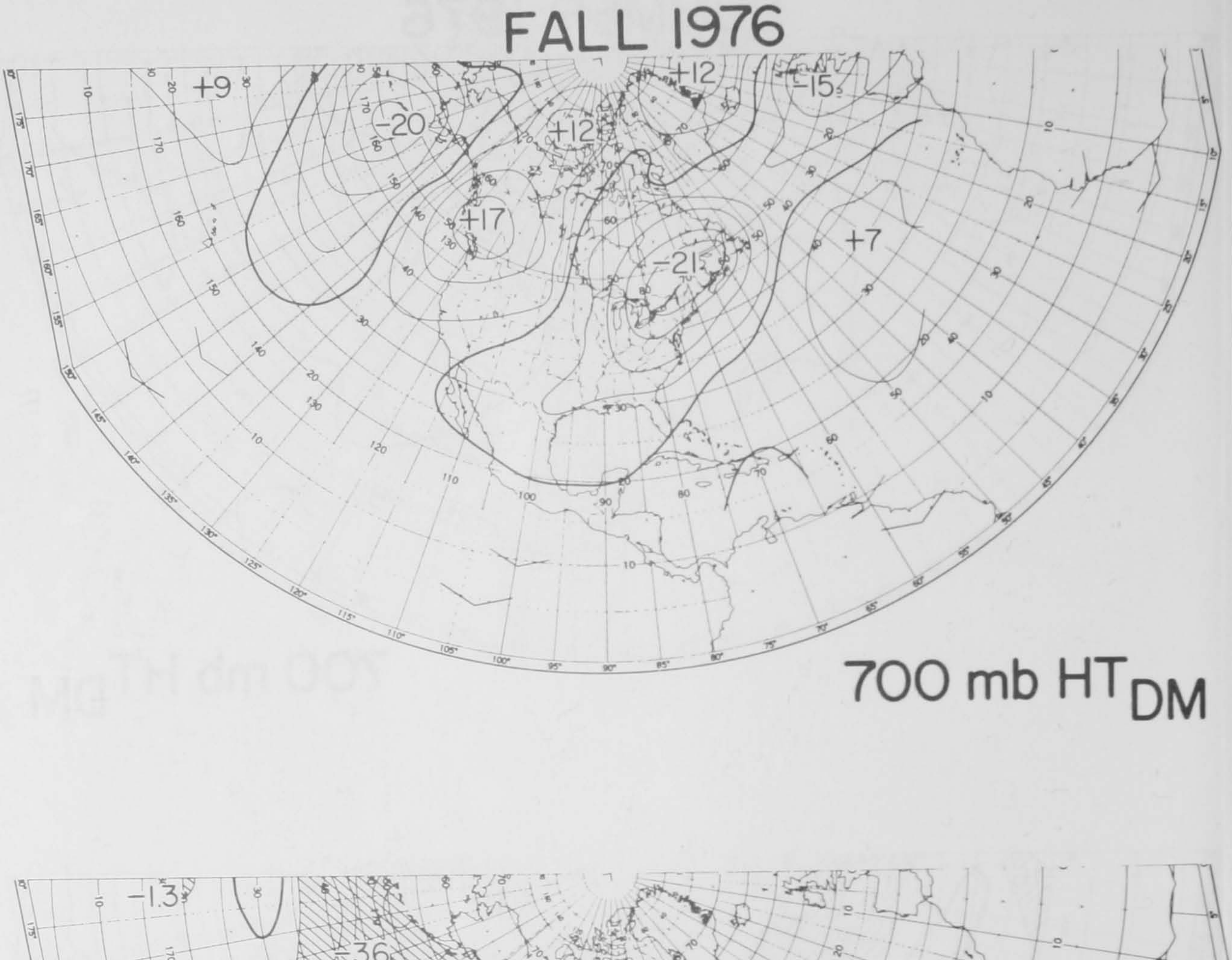


Figure 2.5.—Anomaly (departure from the seasonal mean) of 700 mb height for fall (September-November 1976) in ft/10 (upper), and anomally of sea surface temperature for fall in degrees F (lower). Anomalies >+1F are stippled, >−1F are hatched.

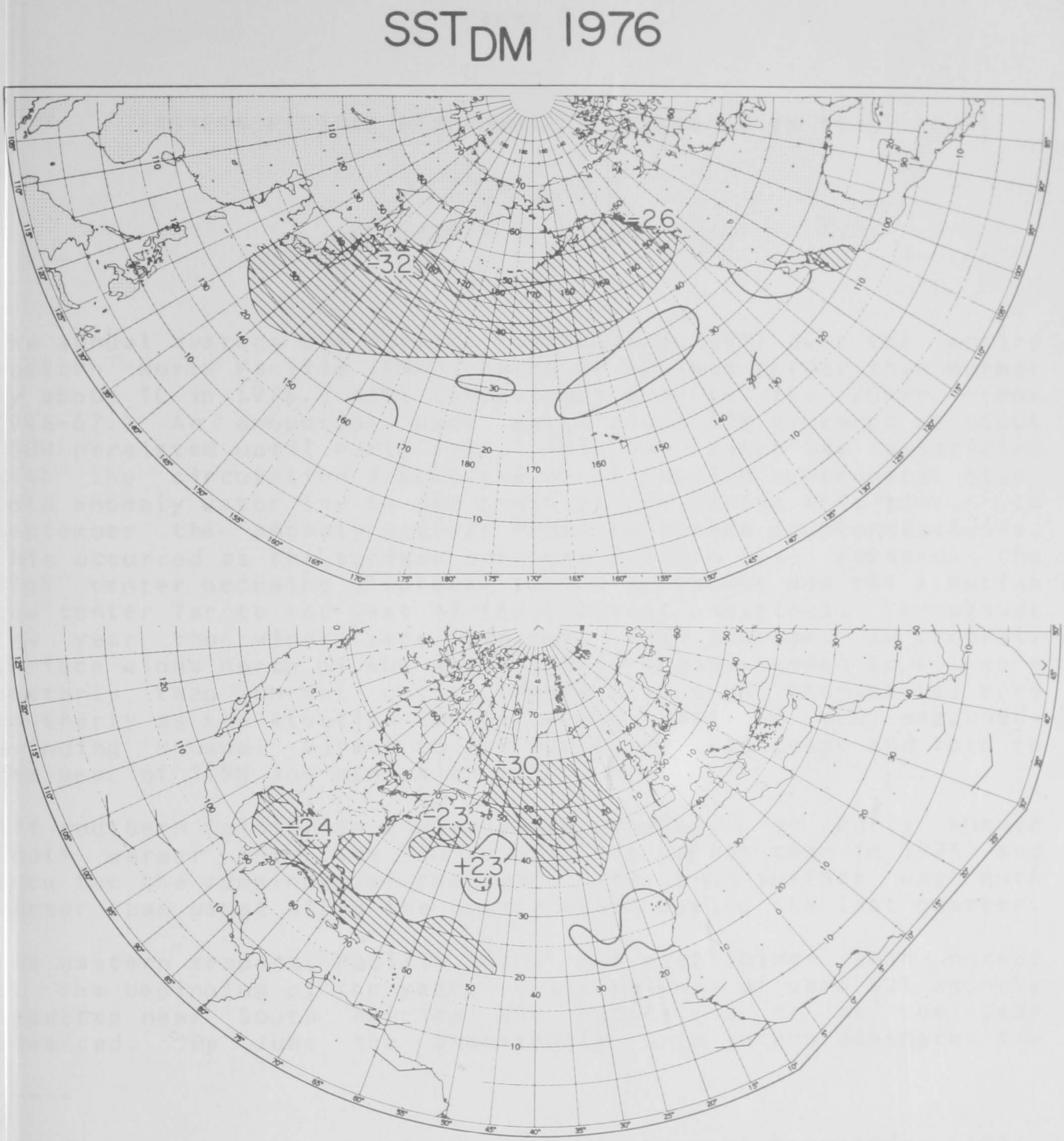


Figure 2.6—Mean annual anomaly from the long-term, 1948-67, mean of sea surface temperature in degrees F for the North Pacific Ocean (upper) and the North Atlantic Ocean (lower). Anomalies >+1F are stippled, >−1F are hatched.

SPRING 1976

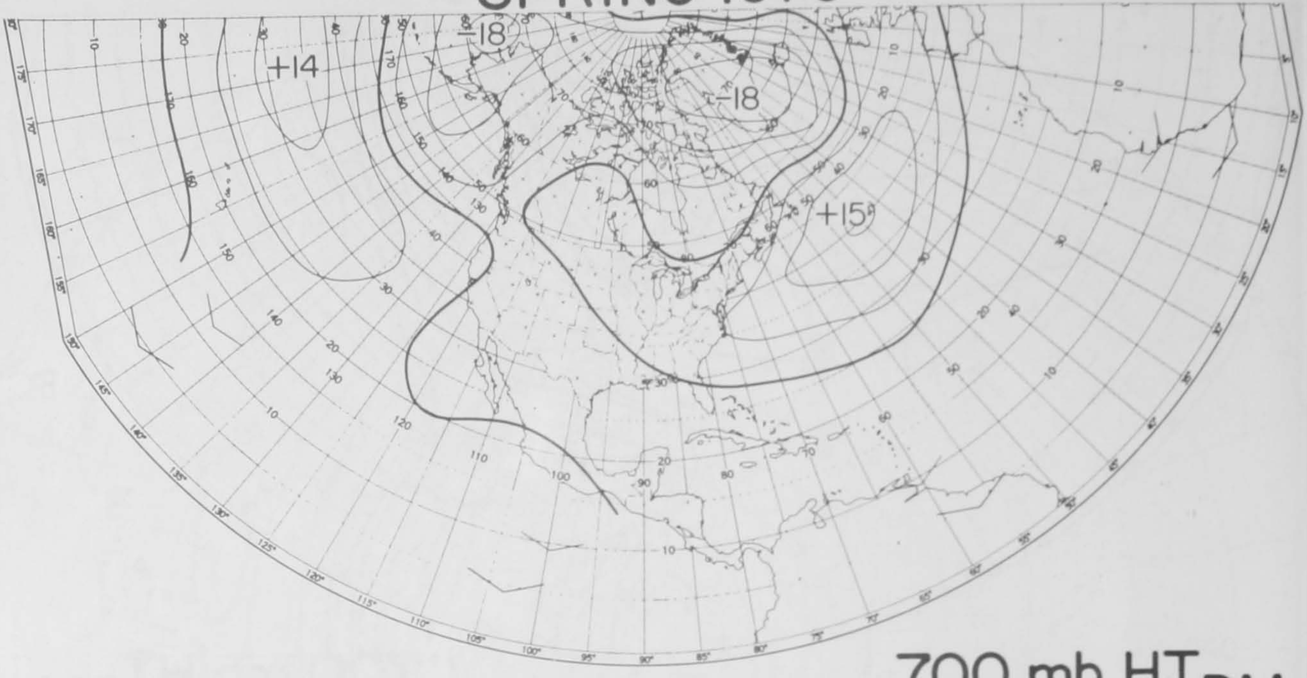
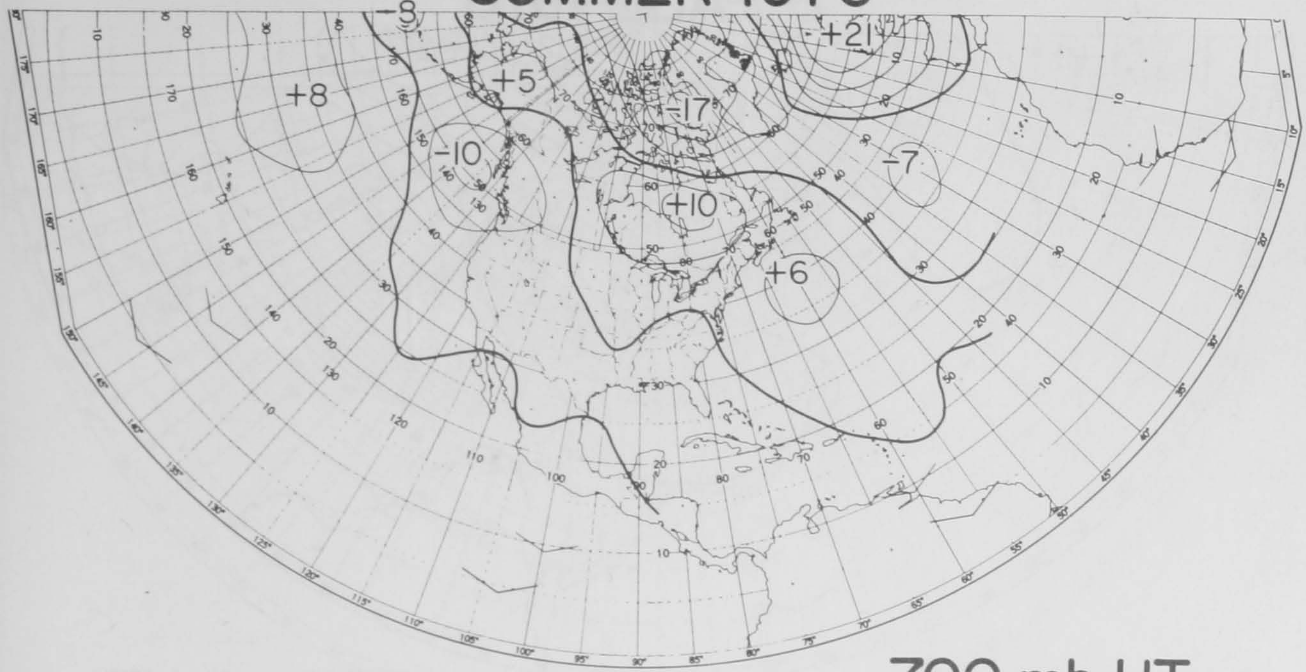


Figure 2.3.—Anomaly (departure from the seasonal mean) of 700 mb height for spring (March-May 1976) in ft/10 (upper), and anomaly of sea surface temperature for spring in degrees F (lower). Anomalies >+1F are stippled, >−1F are hatched.

SUMMER 1976



700 mb HT_{DM}

SST_{DM}

Figure 2.4.—Anomaly (departure from the seasonal mean) of 700 mb height for summer (June-August 1976) in ft/10 (upper), and anomaly of sea surface temperature for summer in degrees F (lower). Anomalies >+1F are stippled, >−1F are hatched.

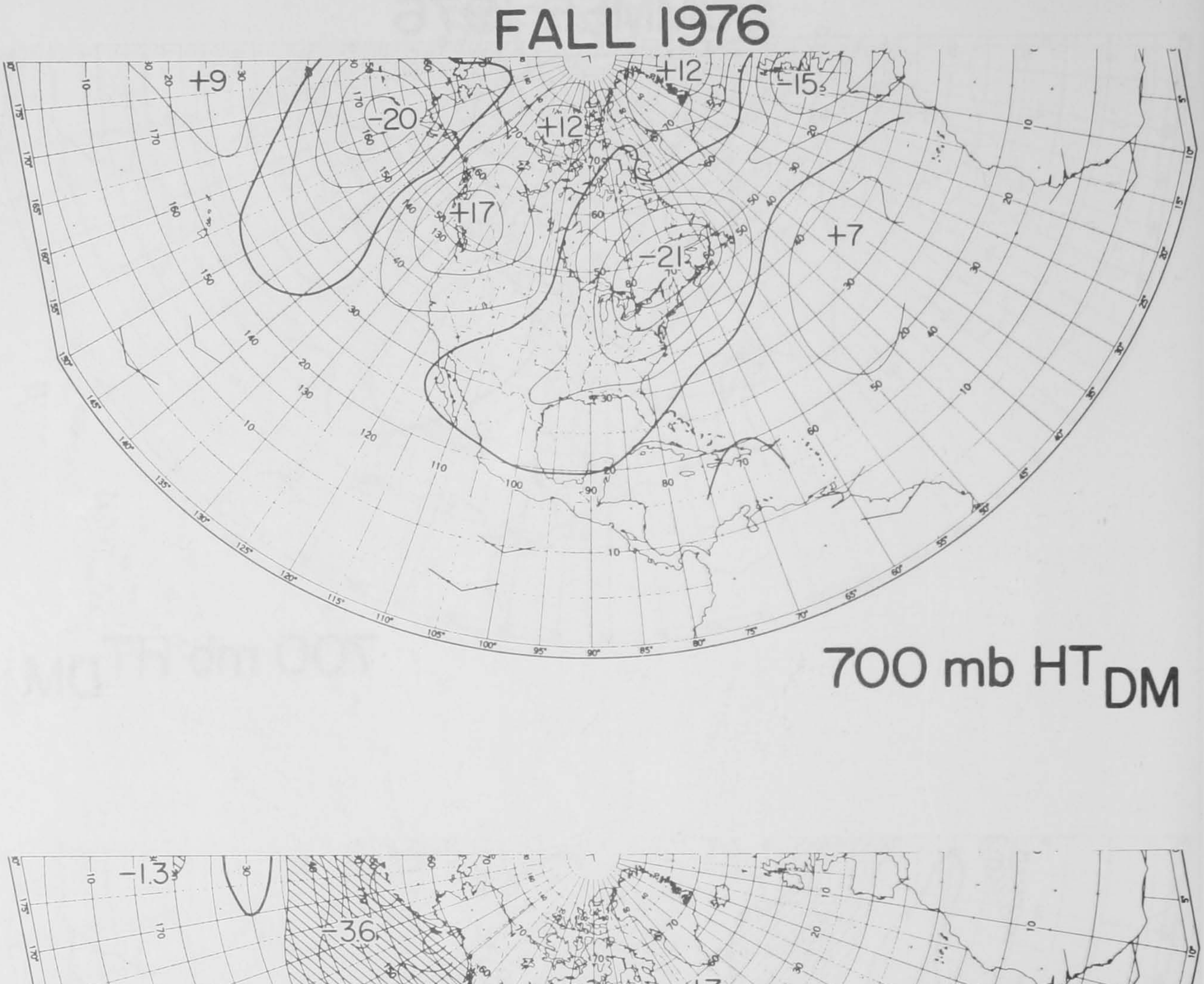
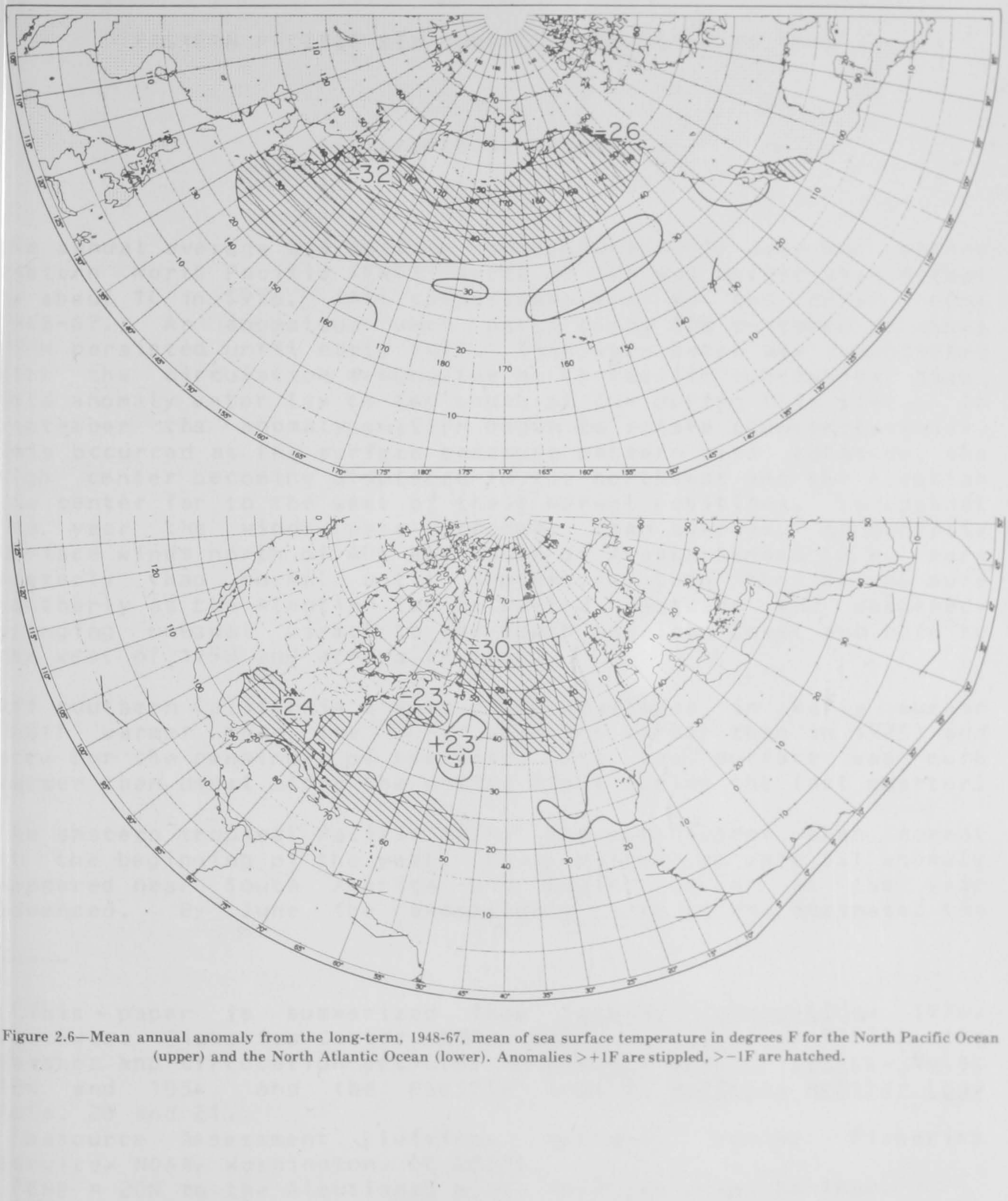


Figure 2.5.—Anomaly (departure from the seasonal mean) of 700 mb height for fall (September-November 1976) in ft/10 (upper), and anomally of sea surface temperature for fall in degrees F (lower). Anomalies $>+1$F are stippled, >-1F are hatched.



SST$_{DM}$ 1976

Figure 2.6—Mean annual anomaly from the long-term, 1948-67, mean of sea surface temperature in degrees F for the North Pacific Ocean (upper) and the North Atlantic Ocean (lower). Anomalies > +1F are stippled, > −1F are hatched.

Paper 3

EASTERN PACIFIC SEA SURFACE CONDITIONS IN 1976[1]

Elizabeth D. Haynes[2]

The annual average sea surface temperature (SST) over the entire eastern North Pacific (ENP)[3] north of 30N was colder than normal by about 1C in 1976. (All comparisons are to the 20-yr mean, 1948-67.) An anomalous warm patch along 30N centered at about 150W persisted until early fall. This warm patch was associated with the circulation around the North Pacific subtropical high. Cold anomaly water lay to the south of 20N during this time. In September the anomaly pattern began to rotate counterclockwise. This occurred as the surface pressure pattern also rotated, the high center becoming displaced to the northeast and the Aleutian low center far to the west of their normal positions. Throughout the year the winds were stronger than average. In general, surface winds north of 40N and south of Alaska tended to be more westerly than normal until September, then they became more southerly as the Aleutian low retreated westward and deepened, bringing unusual warmth to the North American coast and cold to the west of 145W and across to Asia.

Off southern California a warm patch developed in early summer (both warmer than the 20-yr mean and warmer than in 1975) and grew for the remainder of the year. The sea surface was much warmer than usual along the entire coast during the last quarter.

The eastern tropical Pacific (ETP)[4] was much colder than normal at the beginning of the year. Small patches of warm SST anomaly appeared near South America and became larger as the year advanced. By June the anomalously warm waters dominated the

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[1] This paper is summarized from Fishing Information, 1976, Southwest Fisheries Center, NMFS, NOAA, La Jolla, CA 92038; the weather and circulation articles in Monthly Weather Review, Vols. 104 and 105, and the Pacific logs in Mariners Weather Log, Vols. 20 and 21.

[2] Resource Assessment Division, National Marine Fisheries Service, NOAA, Washington, DC 20235.

[3] ENP = 20N to the Aleutians, North American coast to 180W.

[4] ETP = 20S to 30N, American coast to 180W.

equatorial areas east of 120W, and continued to spread for the remainder of the year.

The ocean-atmosphere circulation patterns and the warm SST's during the second half of 1976 resembled those of 1972, a majo El Nino year. The anchoveta fishery was not affected during the first half, but later on the catches were not good north o Callao; the anchoveta were too small. Tuna fishing also was poor near Ecuador from May to November, but improved in December South of 15S, though, fishing was not affected by the warm waters to the north. The normal counterclockwise high pressure circulation with its associated southeast trade winds was weakened by frequent storm passages farther north than usua during the Southern Hemisphere winter. In general, the surface pressure gradient southwest of Peru was flatter than usual fo this time of year. Because SST's remained above normal throug December over most of the ETP, 1976 should be classified as an E Nino year. However, by the last week of the year there wer indications that the El Nino conditions were dissipating.

January - Eastern North Pacific sea surface temperatures droppe seasonally 0.6C-2.2C from December 1975. The SST anomaly patter was similar to that which persisted throughout 1975, with a war (+1C anomaly) pool centered about 30N, 150W in the central ENP and cool (-1C anomaly) water 100 km out all along the Nort American shore to 30N, and westward south of that latitude Strong surface pressure gradients between the deep Aleutian lo and a strong ridge off the U.S. west coast caused strong sout to southwest winds north of 30N and east of 165W to 135W. Storm tracking south of the Aleutian Islands were more intense tha usual, and by increased mixing may be responsible for increasin the negative SST anomaly in this area.

Except for small isolated patches, the ETP was significantl cooler than normal, reaching -3.3C anomaly at 15N, 95W of Guatemala and at 7N, 93W. Temperatures over the tuna fishin grounds south of 20N and east of 110W were mostly below normal and the fishing fleet was widely scattered. The extensive area of negative SST anomalies were associated with strong an persistent northerly winds. Off southern Baja Californi temperatures were slightly above normal and fishermen made goo catches in this area.

Off Ecuador the equatorial ocean front began to weaken toward th end of the month. Slightly positive SST anomalies occurred of the Gulf of Guayaquil. Tuna fishing was exceptionally good i this area.

February - Seasonal cooling of the ENP occurred at a near norma rate, with temperatures dropping up to 1C from January values except off California and Baja California where SST's ros slightly. The anomaly pattern closely resembled that of January, although the area of positive anomaly contracted and moved northward slightly and the area of anomaly greater than -1C also decreased. Below normal temperatures continued off the North American west coast.

Along the western boundary of the Peru Current, SST's increased 1C to 2C since last month from 5N to 20S between 85W and 115W. Warm anomalies of up to +3C occurred inshore of this area. This above normal warming was associated with a Southern Hemisphere high pressure system which was weaker than usual. The equatorial front between 85W and 95W was very weak. SST's in this area exceeded 26C and the fleet made exceptionally good catches of yellowfin tuna.

During this month northerly winds from the Gulf of Mexico frequently penetrated the Gulf of Tehuantepec and the Costa Rican fishing grounds. Strong winds and rough seas caused very bad fishing weather up to 500 miles south and west of these areas. SST's were lowered as much as 3C by wind mixing. The Gulf of Panama also experienced extensive wind mixing of surface layers and below normal surface temperatures.

A severe earthquake occurred in Guatemala on 4 February. At 0930 GMT that day, at 14N24', 94W25', the ship Unique Fortune reported, "Vessel suddenly jumped twice, shuddered violently in calm sea."

March - Seasonal cooling continued over the ENP; SST's dropped up to 1C since last month and approached the annual minimum. The anomaly pattern continued similar to last month's except that the -1C anomaly pool centered at 25N, 135W in February disappeared. Winds associated with low pressures in the Gulf of Alaska were stronger than normal.

In the ETP sea surface warming is expected in March. However, the fishing grounds southwest of Baja California experienced cooling greater than 1C, and fishing decreased due to rough weather. Most of the fleet shifted to south of 20N where the SST's were up to 1C above normal.

Tuna fishing was very good south of the Galapagos Islands where SST anomalies were positive. Above normal warming occurred off Ecuador and offshore of Peru, the +1C anomaly areas showing up clearly in NESS satellite charts from infrared data and from ship reports. South of 10S and east of 78W, SST's have been up to 1C below normal along the coast of Chile for many months.

April - Sea surface temperatures over most of the ENP increased only slightly from the March minimum values, and dropped up to 0.6C between Baja California and Hawaii, creating a large area of

-1C anomaly water. Anomalies of -1C showed also south of the Aleutians and off the coast of Oregon. A strong surface pressure gradient north of 40N caused stronger than normal westerly winds which contributed to the below normal heating in this area.

There were large areas of up to -2C anomaly water centered at 10N, 100W and at 10N, 140W. In both areas, above normal northeast trade winds and cloud cover persisted most of the month, leading to more vertical mixing and less heating than usual for April. There were much smaller areas of up to +3C anomaly water west of Guayaquil to 90W.

Along the equator east of 120W, upwelling was diminished and the surface was warmed by solar heating in very light wind conditions. South of 10S along the coast of Peru, upwelling in the Peru Current maintained below normal SST's during the month.

<u>May</u> - Sea surface temperatures increased at a below normal rate over the entire ENP this month. Greatest warming, up to 1.7C, occurred off the coasts of Washington and Oregon out to 400 miles offshore. The SST anomaly pattern was similar to that of the previous month, but the area of warm anomaly decreased somewhat and the area of >-2C cold anomaly increased significantly.

There was a strong surface high pressure cell centered near 35N, 145W and a deeper than normal Aleutian low, causing strong winds; the northwesterly winds west of the low contributed to lowering the SST's southeast of the Alaskan Peninsula, while southerly winds east of the low warmed the surface off the Pacific Northwest.

Extensive warming occurred along the equator east of 115W. Positive SST anomalies were >+2C in four areas where upwelling was weaker than normal. The warm offshore water moved closer to the coast of Peru from the equator to 10S than in any month since December 1972 when El Nino reached its maximum intensity. The normal surface high pressure center off the coast of Chile and Peru was weakened this month by the passage of frequent storms.

In the fishing grounds north of the equator, SST's increased faster than normal. In the area east of 110W, the large negative anomalies of March decreased to near normal this month.

<u>June</u> - Sea surface temperatures increased by up to 4.4C over the entire ENP due to seasonal warming. The areas of >-1C anomaly decreased greatly, and a small patch of >+1C anomaly appeared off southern California. Between 30N to 45N and 140W to 170W, temperatures that were up to 1.7C below normal last month increased to above normal values due to decreased cloud cover (increased solar radiation) and lighter winds (decreased latent and sensible heat flow from ocean to atmosphere). Cold anomalies

decreased also in the Gulf of Alaska. A strong surface high pressure area occupied the entire ENP, bringing strong northwesterly winds from Vancouver Island to central California.

In the ETP, east of 120W, SST's increased at above normal rates north of the equator and increased markedly in the Southern Hemisphere. The SST's were higher here than in any June since 1972, a major El Nino year. The positive SST anomalies from 10N to 10S, east of 120W to the coast and south to below Pisco, Peru, were larger than those of June 1965, an El Nino year. There was a marked reduction of low stratus, because of the decreased air-sea temperature contrast, and an increase in cumuliform cloud clusters, with low barometric pressures, frequent frontal passages, and disruption in the southeast trade winds in this area usually dominated by the southeastern Pacific high.

Tuna fishing off Ecuador decreased sharply as the water temperature rose. In the Northern Hemisphere tuna fishing was very good, especially on the Albatross Plateau and northwestward after Hurricane Annette moved through early in the month. West of 120W tuna fishing was better than usual in water slightly warmer than normal with light winds and seas.

<u>July</u> - Seasonal warming caused SST's to increase over the entire ENP. The warm anomaly pool in the central ENP moved 20 deg southward, and a small warm patch appeared off Oregon due to decreased northerly winds and less intense upwelling.

Sea level pressures were up to 7 mb lower than normal over the entire ENP. Strong surface pressure gradients caused above normal westerly winds, resulting in increased evaporative and conductive cooling and vertical mixing. A large area of anomaly >-2C appeared along the 45th parallel and into the Gulf of Alaska.

Along the equator the SST's showed a tremendous area of anomalous warming, especially east of 120W. Normally the temperatures in July decrease 1C or more in this area. Warming appeared in the Peru Current, typifying an El Nino year. Below normal surface pressures and surface winds south of the equator to 20S and east of 110W were associated with an unusually weak subtropical high pressure center off South America. Low pressure centers and fronts frequently passed eastward through this area which normally is dominated by high pressure, weakening the southeast trade winds here.

Southwest of Baja California the tuna catch was good in waters warmer than normal.

August - Except for a small patch off northern California, the entire ENP north of 35N was anomalously cold, up to -3.5C in spots near 45N, 175W. SST's increased during the month, but at below normal rates. A band of slightly (0C-1C) warmer than normal water persisted across the ETP from 25N to 35N except near Baja California where upwelling increased due to northwesterly winds.

Sea level pressures were near normal in pattern but with a slightly stronger gradient, resulting in above normal westerly winds north of 40N.

The equatorial band of warm SST anomalies reached +4.5C and extended south along the coast to below Pisco, Peru. The subtropical high pressure center was displaced, and the southeast trades were interrupted by passing storms. Toward the end of the month the normal high pressure pattern became reestablished.

Six tropical depressions formed in the area from 10N to 15N and 100W to 120W where SST's were above 29C. Two of these developed into hurricanes which moved through the fishing grounds south of the Revillagigedo Islands. Southwest of the storms' paths winds and seas were unusually light where the southeast trade winds were interrupted, and tuna fishing was exceptionally good. The heavy cloud cover associated with the storms created small areas of negative SST anomaly.

September - Sea surface temperatures in the ENP decreased seasonally by 0.5C to 1.7C over most of the Gulf of Alaska and down the west coast to southern California. Small increases occurred over a large area between Baja California and Hawaii. The anomalously cold area spread southward to 33N, but a patch of +1C anomaly appeared at 23N, 125W. Sea level pressures were up to 8 mb below normal with a strong Aleutian low pressure system and strong westerly winds.

In the ETP the area of warm anomaly increased greatly, centered on about 5S and extending from offshore of Ecuador and Peru to 150W. Although the low level atmospheric circulation returned to normal early in the month and the southeast trade winds became reestablished, a succession of low pressure centers moved across the southeast Pacific at lower latitudes than usual later in the month and again disrupted the normal wind flow along the coast from the equator to 15S. There was only a very small area of upwelling immediately offshore of Guayaquil and some south of Pisco.

Four tropical storms formed over the waters warmer than 29C south of Mexico and moved northwestward, one doing considerable damage in southern California.

October - A large and intense low pressure system settled over Bristol Bay this month, bringing storms with unusually high winds and severe weather. Wind mixing of the ocean surface layer caused SST's to drop at twice the normal seasonal rates throughout the ENP west of 130W and north of 30N. South of a line southwestward from San Francisco and east to the coast, above normal SST's were associated with persistent surface high pressure, light cloud cover, and low winds.

Positive SST anomalies covered almost the entire ETP. North of 10S and east of 135W SST's were significantly above normal. Light winds and warm seas aided fishermen in this area. The area of above normal temperatures in the ETP was greater than in any month since January 1973, which marked the end of the 1972 El Nino condition.

Three small areas of negative anomaly occurred off Chala and Lobitos, Peru, and at 8N, 97W. Above normal winds and extensive cloud cover associated with weather fronts moving through this area kept the surface layers well mixed, and upwelling was active south of 15S along the coast.

November - Seasonal cooling was weaker than normal over most of the ENP. Cold anomalies receded slightly along the U.S. and Canadian coasts under the influence of an anomalous high over the Northwestern States and its associated light southerly winds and clear skies. A deep and persistent low over the Aleutian chain at 165W caused strong winds and rough seas. It dominated weather conditions across the entire western Pacific north of 35N and brought anomalous cooling to the Hawaiian Islands.

Seasonal warming progressed along the coast of South America under less than normal cloud cover. Anomalously warm seas prevailed offshore 10 deg north and south of the equator to 180W and beyond. In the Gulf of Tehauntepec SST's were 1C to 2C below normal as the result of strong northerly winds and cold outbreaks which carried across from the Gulf of Mexico.

December - Sea surface cooling of the ENP proceeded at less than the normal rate, thus diminishing the area of negative SST anomaly. North of 30N, surface winds were more southerly than normal, blocked to the east by a high pressure ridge off the northwestern U.S. coast.

The Aleutian low was much deeper (-13 mb anomaly) than normal, and slightly southeast of its usual position. Storminess associated with this low caused considerable ocean mixing, and below normal SST's prevailed west of 150W.

The ETP continued anomalously warm, with a very small area of upwelling alongside the coast of Peru. This pattern resembled that of the two recent El Nino years; the warm areas were slightly more extensive than in December 1965 and not so large as in December 1972. The subtropical high rressure system was frequently weakened by passing weather fronts. Also, cloud cover and surface winds over the ETP were much below normal.

Paper 4

SEA SURFACE CONDITIONS IN THE WESTERN NORTH ATLANTIC IN 1976[1]

Julien R. Goulet, Jr. and Elizabeth D. Haynes[2]

This summary essentially is limited to the area off the U.S. east coast from Florida to Nova Scotia and about 1,000 km offshore. The Gulf of Mexico is mentioned briefly also.

In general, the sea surface off the eastern seaboard was warmer than usual through July, then tended to be slightly cooler than average. In January, there was cooler than normal water immediately surrounding Cape Hatteras, but this was soon dispelled by warm air and mixing during the warmest February in a century. This warmth continued through the spring. As the summer advanced the sea surface warmed seasonally, but at a lower rate than usual, so that the warm anomalies became smaller until in August the sea surface was cooler than normal in the Middle Atlantic Bight and essentially average elsewhere except south of Nova Scotia where warm anomalies persisted through the year. The weather was mild until late in the year, as storms tracked far north of normal. Very few crossed the coast south of Newfoundland until October. There were several severe storms up the U.S. east coast during the last quarter.

Except for Maine and Florida, the entire country was warmer than normal during the winter of 1975-76 (December-February). Warm conditions continued through spring, although not quite so markedly. Summer was cool almost everywhere except Maine, which remained warmer than usual. Autumn (September-November) was

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[1] This paper is summarized from gulfstream, Vol. II; the Atlantic logs in Mariners Weather Log, Vols. 20 and 21; the weather and circulation articles in Monthly Weather Review, Vols. 104 and 105; Gulf Stream analysis charts, Environmental Products Group, NESS, NOAA, Washington, DC 20033; temperature anomaly charts, Pacific Environmental Group, NMFS, NOAA, Monterey, CA 93940 (see McLain, Paper 9); airborne radiation thermometer charts, Coast Guard Oceanographic Unit, Washington, DC 20590 (see Deaver, Paper 13).

[2] Resource Assessment Division, National Marine Fisheries Service, NOAA, Washington, DC 20235.

cooler than normal east of the Continental Divide. Cooling was rapid in December east of the Mississippi. There was a complete absence of tropical storms in the Gulf of Mexico and Caribbean Sea due to the unseasonable intrusion of cold air aloft and the stronger than normal high-altitude westerlies.

January - The entire Gulf of Mexico and the western North Atlantic (WNA) were seasonally colder than last month. The Middle Atlantic Bight and the Gulf of Mexico were also significantly colder than average. Warmer than average temperatures were found offshore of the continental shelf from 30N to the offing of the Gulf of Maine. There was also a large patch of colder than average temperatures southeast of Nova Scotia. The central Atlantic area was not significantly above or below average.

The Gulf Stream and slope front positions were far less convoluted than they had been for the past several months. Eddy activity also was much reduced. A large meander was present in the South Atlantic Bight at the end of the month, though it was not present one week earlier. A faint eddylike feature at 37N, 73W was the remains of a warm core, anticyclonic eddy which had been extensively studied (Bisagni 1976). It was picked up at 39N30', 64W20' in July 1975 and followed for nine months. It moved westward until December, and then moved erratically southwestward until it finally disappeared in March 1976 at the edge of the shelf off the Delmarva Peninsula. A warm eddy at 40N, 66W was first observed near the end of January. Cloud cover prevented its earlier discovery, but strong positive temperature anomalies in that area indicated that it had formed earlier in the month. A cold eddy at 33N, 74W was observed forming in the last half of the month.

Storm centers crossed the U.S. east coast farther north than usual, only one passing south of Cape Hatteras (near Charleston, SC). Another crossed the lower Chesapeake Bay, and the rest passed farther north. The Grand Banks received a full measure of severe storms this month.

February - The Gulf Stream was slightly offshore of its historical mean position for the month. Most of the western North Atlantic was warmer than normal, but with a -5C anomaly cold patch at about 41N, 60W, and a cold remnant south of Cape Hatteras. The Gulf of Mexico was up to 2C below normal. The sea surface temperature (SST) was seasonally colder, in the WNA, than last month by 0.5C to as much as 6.7C, while the Gulf was slightly warmer than last month.

Eddy activity more than doubled this month from last month, from one anticyclonic and one cyclonic eddy at the end of January to two anticyclonic and four cyclonic eddies in late February (west of 55W). The Shelf Water/Slope Water front also appeared more convoluted, although data were limited. A Shelf Water excursion pushed southeast off the shelf abreast of Savannah, displacing the Gulf Stream. This excursion may have lasted up to two weeks, but cloud cover and differing interpretations do not allow complete definition. The SST anomaly off savannah was strongly negative, indicating that the feature was persistent.

More storms than usual this month passed far north of normal and battered the North Atlantic shipping lanes. The U.S. coast south of Cape Cod was nearly storm free. One strong extratropical cyclone moved rapidly up the Piedmont early in the month, grounding an oil barge in Chesapeake Bay on the 1st and a ship in Searsport, ME, on the 2nd. This storm raced northward and reached Davis Strait on the 4th.

March - The western North Atlantic in general was warmer than normal, with a small cold anomaly patch remaining southeast of Nova Scotia. A tongue of cold water also wandered off the shelf east of Cape Charles, an expansion of the Savannah negative anomaly of February. Seasonal warming was general throughout the Gulf of Mexico, though the anomalies remained negative except for small areas along the northern coast. Warming and cooling was uneven and indefinite in the WNA.

Eddy activity continued to increase, showing one anticyclonic and five cyclonic eddies at the end of the month, plus the remains of the anticyclonic eddy (ACE 5) studied by Bisagni (1976). The Gulf Stream moved slightly north during the month and became much more convoluted.

Storms off the U.S. east coast formed farther east than normal, and only one actually crossed the coast south of Long Island. This was a minor storm over Cape Hatteras. The major fishing grounds were nearly storm free.

April - The Middle Atlantic Bight area and eastward was up to 3C warmer than usual, with near normal temperatures to the south, and significant positive anomalies north of 35N. A loop of warm Slope Water abutted the Gulf Stream at 37N, 72W, perhaps a consequence of reabsorption of an anticyclonic eddy. The pool of anomalously cold water southeast of Nova Scotia moved slightly eastward and deepened to greater than -4C anomaly. The sea surface in general was seasonally warmer than last month by 0.5C to about 2C, though there was slight cooling in the area southwest of Bermuda. The coastal positive anomalies in the Gulf of Mexico spread, while the central Gulf remained colder than normal.

Although the number of Gulf Stream eddies decreased to only one small cyclonic one at 34N30', 68W20' by the end of the month, the Shelf Water/Slope Water front was extremely convoluted and confused, as was the Gulf Stream front. Towards the end of the month warm tongues extended east of the Gulf Stream at 30N and 33N, perhaps precursors to cyclonic eddy activity.

The number of storms was far below normal, resembling a summer month in the WNA. The storm tracks were concentrated north of Nova Scotia with only one crossing the coast to the south. A brief, severe extratropical storm caused the loss of the drilling rig _Ocean Express_ while under tow in the Gulf of Mexico.

May - Although almost the entire WNA area under consideration was warmer this month, the change was seasonal, and the warm SST anomalies decreased in extent and intensity. An area of negative anomalies east of the Gulf Stream from 30N to 35N is a possible consequence of increased cyclonic eddy activity. The Gulf of Mexico was almost entirely colder than normal with positive anomalies only off Florida and in the loop current area.

There were three small cyclonic eddies and one larger anticyclonic eddy, broken from a large Gulf Stream meander on 10 May, present at the end of the month. The Gulf Stream flowed smoothly to off Cape Charles, then began to meander downstream. However, the meanders diminished in size as the month advanced. The Slope Water/Shelf Water front was tortuous with incursions and excursions north of 37N.

Again this month there were fewer storms, and these farther off the coast and farther north, than usual. One extratropical storm developed in the central Gulf, crossed northern Florida, and then followed the Gulf Stream across the Atlantic.

June - The entire Atlantic area was 1 or 2 deg warmer than last month, as expected for the season. Positive SST anomalies diminished slightly, and -3.3C anomalies appeared off the mouth of Chesapeake Bay. Negative anomalies were found southeast of the Bay to east of the Gulf Stream and southeast of Nova Scotia. The Gulf of Mexico was colder than normal over its entire area.

Eddy activity was apparently much reduced this month, though excessive cloudiness prevented clear satellite pictures of the Gulf Stream area. The Coast Guard airborne radiation thermometer (ART) flights, also interrupted by bad weather, portrayed the west wall of the Gulf Stream generally following the 180 m isobath to Cape Hatteras, then bearing off northeastward to 37N and there turning toward the east to 71N, the limit of observations. There were also convoluted temperature patterns off Chesapeake Bay west of the Gulf Stream. Portions of the Gulf Stream, Slope Water, and Shelf Water regions were pictured by satellite late in the month. Strong meandering activity was found between 70W and 60W. One small cyclonic eddy was plotted in _gulfstream_ at 36N, 70W, its 29 May position, unsupported by

SST anomaly or other evidence.

Storm tracks were almost entirely north of 40N, with only one storm crossing the coast of Maine. The tracks curved northward between Greenland and the Faroes, and none crossed the British Isles or western Europe.

July - The Gulf Stream this month closely followed the 180-m depth contour to Cape Hatteras, slightly inshore of its climatological mean position. Northeast of the Cape it followed the mean track to 70W, then meandered slightly downstream. The cyclonic eddy at 35N, 70W moved 2 deg westward during the month. There was much mixing of Slope and Shelf Waters during the month. Early in the month tremendous meanders and eddies developed, but all were apparently resorbed by the Gulf Stream.

All SST's increased seasonally during the month, but the warm anomalies diminished. A strong warm spot reached a +5C anomaly at 41N30', 64W30', with smaller positive anomaly values north of 39N from 55W to the American coastline. The rest of the Atlantic area was near normal for the month. The Gulf of Mexico remained anomalously cold.

Storm activity was below normal this month, and most storms tracked west of the British Isles.

Over the Fourth of July weekend, masses of dead fish were reported off Sandy Hook, NJ. Fisheries investigations (Armstrong, Paper 17) determined the cause to be an anoxic water mass, brought about by natural weather conditions, which expanded southward to Atlantic City, NJ, by mid-August, and by mid-September covered half of the Middle Atlantic Bight. Estimates were that up to 50% of the commercial fish stocks might be lost this year due to this phenomenon.

August - The Gulf Stream this month was fully seen by satellite imagery west of 60W. It flowed very smoothly along its historical mean track for the month to 67W, then made a dip to the south followed downstream by a larger one to the north.

Two small cyclonic eddies persisted through the month, both moving about 150 km southwestward. A large (250 km diameter) anticyclonic eddy at 39N30', 67W originated on 25 August as a pinched off meander. A minor warm core eddy at about 38N30', 72W30' shows on the ART isotherms as well as in the satellite analysis. The central ocean waters continued to warm at the surface this month, but SST's over the continental shelf dropped due to tropical storm activity. In 1975, by contrast, seasonal warming persisted through August. Significant cold anomalies, on the order of -1.5C, appeared in the Middle Atlantic Bight.

Extratropical storms were concentrated from the Canadian Maritimes to the Denmark Strait, with a few storms crossing from Alaska to Greenland.

There were no ART flights east of Savannah, GA, due to tropical storms. The U.S. east coast had no extratropical storms this month, but Hurricane Belle passed from Cape Hatteras to Long Island on the 9th and 10th. The Gulf of Mexico continued slightly colder than normal. It spawned the weak tropical storm Dottie, which crossed the southern tip of Florida and turned up the 80th meridian to Charleston.

<u>September</u> - Almost the entire North Atlantic surface area over the shelf cooled 1C to 2C this month. The warm anomaly area south of Nova Scotia expanded, but south of 40N, and in the Gulf of Mexico, the SST's were average or slightly cooler than normal.

The <u>gulfstream</u> pictures a mildly meandering Gulf Stream for this month, with three cyclonic eddies and two anticyclonic eddies. Satellite imagery intermittently pictured very complex eddy and meandering activity. Cloud cover prevented proper definition, but the patterns changed rapidly through the month, ending with the quieter conditions portrayed in <u>gulfstream</u>. In the middle of the month there were four anticyclonic eddies, one cyclonic eddy, and one cyclonic loop. There also were large patches of entrained Shelf Water and of mixed Shelf/Slope Water. One week later only one anticyclonic eddy was found, along with two cyclonic eddies and the one large cyclonic loop. There were still large patches of mixed Shelf/Slope Water, and the the Shelf Water/Slope Water front was extremely convoluted.

The only tropical storm in September remained completely east of 61W. Only one storm was found relatively near the U.S. coast, and that one was still offshore of the Gulf Stream. None crossed the coast south of Newfoundland, and most storms tracked north between Iceland and the Davis Strait. In 1975, by contrast, there were three major hurricanes; the extratropical storms tracked farther south and then between England and Iceland. There were no storms in the Gulf of Mexico in September 1976.

<u>October</u> - The warm anomaly area south of Nova Scotia persisted, but the remainder of the Atlantic coastal area was not significantly warmer or colder than normal. The <u>gulfstream</u> shows large areas of positive anomaly, while the temperature anomaly charts show large areas of negative anomaly. In the Gulf of Mexico, SST's were significantly cooler than normal.

The Gulf Stream is pictured in <u>gulfstream</u> flowing smoothly, with two major anticyclonic eddies. A cold core eddy at 32N, 74W was entirely surrounded by warm Sargasso Sea Water which reached to 100 km from Cape Hatteras. The large warm eddy at 39N, 69W persisted, entraining Shelf Water on its eastern edge. The smoothness of the Gulf Stream front is partly due to poor definition caused by cloud cover.

Storm tracks moved farther south this month, and several storms passed up the U.S. east coast bringing winds above 70 kn (36 m/s), tornadoes, heavy rains, and flooding from South Carolina northward. The trawler Lana Carol sank with a full load of scallops off Barnegat Light on the 31st. Coast Guard helicopters rescued the crew. The laden dragger Patricia Marie, homeward bound to Provincetown within sight of other vessels, was lost with all hands (Schwadron 1977).

A storm developed on a cold front on the 16th, 350 km southwest of New Orleans, moved east-northeastward across northern Florida the next day, and raced along the classical storm track offshore to Nova Scotia and beyond on the 18th. There was a second, milder storm in the western Gulf at the end of the month. The majority of the storms tracked significantly more easterly than in September, reaching the area between Greenland and Spain.

November - Due to surface mixing from intense cyclonic activity, the warm anomalies disappeared this month, and the sea surface was colder than normal nearly everywhere. Anomalies of about -3.5C occurred in the middle Atlantic Bight. The Gulf of Mexico continued about 1.5C colder than usual for the month.

Between 50 and 60 km southeast of Cape Hatteras, SST's rose 8C from west to east across the west wall of the Gulf Stream. Both the ART and the gulfstream pictured an anticyclonic Gulf Stream loop in the South Atlantic Bight. Due to cloud cover, eddy and meander observations were not clear. There was at least one anticyclonic eddy at 39N, 70W30', and there may have been two more farther east. Last month's cyclonic eddy, with a noticeable warm ring, persisted at 35N, 71W.

There was a succession of storms off the U.S. east coast this month. The first formed near Norfolk on the 5th, and in 24 hours was over Nova Scotia. The second formed off Cape Hatteras on the 8th, paralleled the first slightly to the east, and reached Newfoundland the next day. Two more storms crossed New England. At the end of the month a broad frontal area extended from the western Gulf of Mexico northeast to Nova Scotia. A succession of frontal waves and the long fetch of westerly winds created high seas and swells all along the front. The USCGC Taney rescued the crew from a sinking shrimp boat 450 km northeast of Norfolk. A storm which formed in the Gulf of Mexico on the 13th under the influence of this storm system reached northern Greenland in six days.

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The only tropical storm in September remained completely east of 61W. Only one storm was found relatively near the U.S. coast, and that one was still offshore of the Gulf Stream. None crossed the coast south of Newfoundland, and most storms tracked north between Iceland and the Davis Strait. In 1975, by contrast, there were three major hurricanes; the extratropical storms tracked farther south and then between England and Iceland. There were no storms in the Gulf of Mexico in September 1976.

<u>October</u> - The warm anomaly area south of Nova Scotia persisted, but the remainder of the Atlantic coastal area was not significantly warmer or colder than normal. The <u>gulfstream</u> shows large areas of positive anomaly, while the temperature anomaly charts show large areas of negative anomaly. In the Gulf of Mexico, SST's were significantly cooler than normal.

The Gulf Stream is pictured in <u>gulfstream</u> flowing smoothly, with two major anticyclonic eddies. A cold core eddy at 32N, 74W was entirely surrounded by warm Sargasso Sea Water which reached to 100 km from Cape Hatteras. The large warm eddy at 39N, 69W persisted, entraining Shelf Water on its eastern edge. The smoothness of the Gulf Stream front is partly due to poor definition caused by cloud cover.

Storm tracks moved farther south this month, and several storms passed up the U.S. east coast bringing winds above 70 kn (36 m/s), tornadoes, heavy rains, and flooding from South Carolina northward. The trawler Lana Carol sank with a full load of scallops off Barnegat Light on the 31st. Coast Guard helicopters rescued the crew. The laden dragger Patricia Marie, homeward bound to Provincetown within sight of other vessels, was lost with all hands (Schwadron 1977).

A storm developed on a cold front on the 16th, 350 km southwest of New Orleans, moved east-northeastward across northern Florida the next day, and raced along the classical storm track offshore to Nova Scotia and beyond on the 18th. There was a second, milder storm in the western Gulf at the end of the month. The majority of the storms tracked significantly more easterly than in September, reaching the area between Greenland and Spain.

November - Due to surface mixing from intense cyclonic activity, the warm anomalies disappeared this month, and the sea surface was colder than normal nearly everywhere. Anomalies of about -3.5C occurred in the middle Atlantic Bight. The Gulf of Mexico continued about 1.5C colder than usual for the month.

Between 50 and 60 km southeast of Cape Hatteras, SST's rose 8C from west to east across the west wall of the Gulf Stream. Both the ART and the gulfstream pictured an anticyclonic Gulf Stream loop in the South Atlantic Bight. Due to cloud cover, eddy and meander observations were not clear. There was at least one anticyclonic eddy at 39N, 70W30', and there may have been two more farther east. Last month's cyclonic eddy, with a noticeable warm ring, persisted at 35N, 71W.

There was a succession of storms off the U.S. east coast this month. The first formed near Norfolk on the 5th, and in 24 hours was over Nova Scotia. The second formed off Cape Hatteras on the 8th, paralleled the first slightly to the east, and reached Newfoundland the next day. Two more storms crossed New England. At the end of the month a broad frontal area extended from the western Gulf of Mexico northeast to Nova Scotia. A succession of frontal waves and the long fetch of westerly winds created high seas and swells all along the front. The USCGC Taney rescued the crew from a sinking shrimp boat 450 km northeast of Norfolk. A storm which formed in the Gulf of Mexico on the 13th under the influence of this storm system reached northern Greenland in six days.

December - The SST's were not strikingly unusual this month. They tended to be slightly cooler than average north of Cape Hatteras, with some warm anomaly water associated with the warm-core eddies. The Gulf of Mexico continued cool.

The Gulf Stream showed a meander east of Charleston associated with the persistent cold eddy surrounded by a ring of warm water at 33N, 75W. A warm eddy also persisted at 39N, 72W. No others could be seen because of clouds. The Shelf Water/Slope Water front in the Middle Atlantic Bight was ragged with incursions and excursions.

A storm formed in South Carolina on the 7th, but was of little consequence in the western North Atlantic. Another formed off Georgia on the 15th, the day the *Argo Merchant*[3] ran aground. It tracked rapidly northeastward, bringing high winds and rough seas to the Nantucket Shoals area and preventing the Coast Guard from salvaging the oil.

Another storm, from the midwest, crossed the Maine coast on the 21st, affecting the same area with air temperatures in the teens (<-7C) and below, and causing gales from Maine to Virginia. Another midwestern storm crossed New Jersey on the 28th and turned northeastward, adding its fury to the shipping lanes. The Panamanian tanker *Grand Zenith* was last heard from 55 km from Cape Sable. No trace of the ship has been found.

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1977. Loss of dragger and her crew is stunning blow to Provincetown. Natl. Fisherman 57(9):25A, 31A.

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[3] Surveys in the area of the *Argo Merchant* spill have shown mortalities and deformities among developing cod and pollock embryos, noticeable decreases in the abundance of sand lance larvae, and oil contamination of zooplankton. Studies are continuing; preliminary findings have been released in: The ARGO MERCHANT Oil Spill, NOAA Special Report, U.S. Dep. Commer., March 1977.

Paper 5

ANOMALIES OF MONTHLY MEAN SEA LEVEL ALONG THE WEST COASTS OF NORTH AND SOUTH AMERICA

Dale E. Bretschneider and Douglas R. McLain[1]

INTRODUCTION

Measurements of mean sea level provide a source of long-term information concerning ocean processes. The data series of hourly tidal height measurements are unique among marine data series, in that they have been obtained inexpensively, over relatively long periods, at many fixed locations worldwide.

Many investigators have examined fluctuations of sea level at single stations, or relationships among small groups of stations. Roden (1960, 1963, 1966) used spectral and statistical methods to examine the interrelationships among sea level, temperature, and atmospheric pressure at selected stations along the west coast of North America. Saur (1972) examined sea level differences between the Hawaiian Islands and the California coast as an index of broad-scale changes in geostrophic flow in the California Current system. For fisheries assessment purposes, however, monitoring of ocean changes requires groups of stations covering larger areas. The stations examined in this report extend along the west coasts of North and South America from Massacre Bay, Attu, in the Aleutian Islands, to Caldera, Chile.

DATA

Most of the monthly mean sea level data in our data base were obtained from the University of Hawaii.[2] These data were updated

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[1] Pacific Environmental Group, National Marine Fisheries Service, NOAA, Monterey, CA 93940.

[2] We thank K. Wyrtki and B. Kilonsky, Department of Oceanography, University of Hawaii, who assembled these data and provided us with a tape copy.

and expanded with data from other sources.[3] All data were converted to centimeters.

For this report, tide stations most representative of open ocean conditions were selected. Although many tide gage stations examined in this report are located on piers in sheltered coastal harbors, stations subject to highly variable local tidal conditions common to large river mouths (such as Astoria, OR), large shallow bays (such as Alameda, CA), and straits or sounds (such as Ketchikan, AK), were generally not included. Additional criteria for station selection were a long, continuous data record, a constant tidal reference datum, and an even distribution of stations with distance along the coast. The stations selected and their locations are shown in Figure 5.1.

The processes affecting sea level are complex. In addition to the well-understood tidal or astronomic forces, sea level is affected by:

1. Changes in the average density of the water column.

2. Changes in distribution of atmospheric pressure over the ocean surface (resulting, in part, in variations in large scale wind patterns).

3. Variations in speed of alongshore components of ocean currents.

4. Changes in total mass of ocean water resulting from accretion or melting of glaciers.

5. Subsidence or emergence of the land upon which the gage is located.

The relative importance of these processes varies from station to station.

For ocean monitoring in support of fisheries assessment, we are interested in fluctuations with periods of months to years. For this reason the data are presented in terms of monthly means which remove the principal diurnal and semidiurnal periodicities from the data. Fluctuations with periods longer than months or years can be reduced by comparing the data with a 19-yr mean. This compensates for the nodal tide, which results from the changing declination of the moon over a period of 18.61 years. The nodal tide has a much greater "potential," or effect, than do

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[3] Permanent Service for Mean Sea Level, Berkenhead, U.K., and National Ocean Survey, NOAA, Washington, DC 20852.

other long-period, astronomically induced, harmonics observed in tidal data (Lisitzin 1974). We did not, however, remove very long-period fluctuations such as those caused by isostatic glacial responses (as at Yakutat, AK) or fluctuations related to land subsidence or uplift (such as at Balboa, CZ).

Our objective is to compare temporal fluctuations of sea level along much of the eastern Pacific coast for eventual comparison with fishery fluctuations. In order to allow comparison between stations and to flag unusual events, the data are presented as monthly mean anomalies or departures of a given month from its long-term mean. The long-term means used in this report were for the 19-yr period, 1949-67. The tidal reference datum differs from station to station. Computation of anomalies at each station allows comparison in time between stations having different datum levels.

Pattullo et al. (1955) found that in temperate and tropic latitudes (between about 40N and 40S) changes in the specific volume of the water column were responsible for most of the nontidal variation in recorded sea level. Atmospheric pressure effects were found to account for only a small part of the recorded changes in sea level. This situation is not true, however, in higher latitudes. Lisitzin and Pattullo (1961) found that north of 40N much of the variation in sea level results from changes in distribution of atmospheric pressure over the ocean. This "inverted barometer" effect can be removed from the data in high latitudes by adjusting sea levels for departures of atmospheric pressure from a long-term mean.

There is evidence that fluctuations in atmospheric pressure are quickly followed by compensating changes in sea level so that the total pressure on the sea floor remains very nearly constant. This isostatic adjustment is thought to occur over a range of several thousand miles and within a time span of several days. Thus, the ocean can be considered to approach isostatic equilibrium with atmospheric pressure for periods of a month or more. Assuming the average pressure over the oceans remains constant, if the pressure difference between two stations changes, the sea surface slope will change to compensate for this difference so that there will be no net change in the distribution of pressure on the sea floor (Pattullo et al. 1955; Saur 1972).

Pressure effects were removed from the data by correcting sea levels to a long-term mean atmospheric pressure in the vicinity of the tide gage. This compensates for both the normal seasonal cycle and the monthly pressure anomaly. Monthly mean sea level pressure data were obtained from the World Weather Record series, Monthly Climatic Data for the World, from CCEA,[4] or computed from monthly mean pressure fields obtained from FNWC.[5]

Normal atmospheric pressures at each station were obtained by averaging monthly pressures for the entire period of record. The effects of monthly variations from this long-term pressure mean were removed from sea level measurements by applying a correction of 1 cm in sea level for each millibar deviation in atmospheric pressure. Sea level data for all stations north of Mazatlan were corrected in this manner, with resultant small decreases in the range of sea level anomalies. Pressure deviations south of Mazatlan were on the order of one millibar or less, not large enough to warrant correction because sea level measurements have a typical error of about 1 cm.

DISCUSSION

The anomalies of corrected monthly mean sea level (Figs. 5.2-5.6) exhibit remarkably coherent patterns in time and space. Perhaps the most striking feature of the time series is the long-term persistence and wide distribution of high sea level during the period 1957-59. Evidence of anomalously high sea level extends from Caldera, Chile, to Adak, AK. Similar periods of anomalously high sea level can be seen in 1940-41 and 1971-73, and to a lesser extent in 1951-52 and 1965-66.

The simultaneous occurrence of these changes over such vast distances suggests a relation to large-scale oceanic or atmospheric disturbances. The periods of anomalously high sea levels were also periods of anomalously warm sea surface temperatures and are associated with El Nino occurrences in the eastern tropical Pacific (Quinn 1976, 1978).

Such environmental changes can have dramatic effects on marine fisheries. Along the coast of Peru, for example, large changes in the distribution and abundance of anchoveta result from adverse oceanographic conditions associated with El Nino periods. These conditions, combined with heavy exploitation, have resulted in a decline of the fishery and have had major economic impact. Radovich (1961) documented many changes in the distribution of marine populations along the coast of California during the warm water periods 1940-41 and 1957-59 which were associated with high sea levels. He found a general northerly shift of southern

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[4] Center for Climatic and Environmental Assessment, Environmental Data Service, NOAA, Columbia, MO 65201.

[5] Fleet Numerical Weather Central, U.S. Navy, Monterey, CA 93940.

species and an increase in yellowtail and bonito populations off California. Changes of sea level related to fluctuating coastal circulation may be associated with variations in year class strengths of marine populations due to changes in larval transport.

In his investigation of low frequency sea level oscillations, Roden (1966) found a high coherence in sea level fluctuations measured by tide gages located within similar macroenvironments, such as those located within the Gulf of Alaska or within the California Current area. Even stations with dissimilar exposure, such as those with gages located on the open coast compared to those with gages located in enclosed bays, yielded similar results if the stations were within the same macroenvironment. We now examine fluctuations of sea level in groups of stations having similar oceanographic environments.

Aleutian Islands

Sea levels in this area are quite variable. Significant long-term lower sea levels can be seen at Adak (1943-51) and Attu (1952-53). In contrast to the low sea levels observed at Adak and Attu in 1952-53, Unalaska, Kodiak, and Yakutat show anomalously high values, with a peak in early 1953. There seems to be little correlation between Attu and neighboring stations. This suggests that sea level at Attu, which is located in an area of relatively free exchange between the Pacific Ocean and Bering Sea, may respond to a different combination of environmental processes than sea level at Adak, Unalaska, or Kodiak. It is interesting to note that Attu is the only station of the 25 examined that did not show anomalously high sea levels in 1957-59. Unalaska had small anomalies through 1956 and strong positive anomalies during 1957-59. In contrast, the periods 1964-67 and 1971-74 exhibit strong negative anomalies. This suggests long-term fluctuations in the ocean environment near Unalaska.

Gulf of Alaska - Pacific Northwest

Kodiak has the shortest record of observations in the series. It was included to fill a gap between widespread stations. It shows surprisingly small variations in sea level with extremes in 1957-58 and 1961-62. A weak positive anomaly with a peak in early 1958 is evident.

The Yakutat gage, located in a harbor, is subject to salinity changes due to increased river runoff during summer months (Favorite 1974). The trend of decreasing sea level seen in the series for this station results from land uplift due to isostatic glacial rebound. Strong negative anomalies are evident during 1955-56, 1961-62, and 1971-72. Surprising small positive anomalies are seen during 1958. Favorite (1974) has shown that annual mean sea level anomalies at Yakutat were well correlated with mean annual wind stress transport anomalies in the Gulf of Alaska during the period 1950-59.

Fairly persistent long-term sea level anomalies with short-term fluctuations can be seen at Sitka, Prince Rupert, Tofino, Neah Bay, and Crescent City. Sea level fluctuations are remarkably coherent among these stations, considering the 1800 km along the coast between Sitka and Crescent City. Major periods of high sea level are seen during 1940-41 and 1957-59. Low sea level periods include 1955-56, late 1961-early 1962, and 1964. A significant period of anomalously low sea level is evident at Prince Rupert between the years 1947 and 1951.

California Current

Sea level data from San Francisco, Avila Beach, Los Angeles, and La Jolla also exhibit similar fluctuations. Periods of high sea level are noticeable during 1941, 1951-52, 1957-59, and 1972-73 at all stations. Periods of high sea level during 1969 were observed at San Francisco and Avila. Periods of low sea level occurred at all stations during 1955 and early 1956 and during 1964. A strong trend of rising sea level in relation to land occurred at all stations in this group.

Mexico - Central America

Mazatalan, Manzanillo, Acapulco, Balboa, La Union, and Buenaventura show similar patterns of sea level fluctuations. Periods of high sea level correspond very well with El Nino conditions (Quinn 1976, 1978). All stations exhibit very high sea levels during 1941-42, 1957-59, and, to a lesser extent, 1965-66. Extremely high levels were noted during 1972-73. The anomaly at Manzanillo for December 1972 measured 28.8 cm, one of the largest in the entire series. Anomalously low sea levels were seen in 1949-50, 1955, and 1967. The station at Balboa shows a trend of rising sea level which Roden (1963) attributed to land subsidence.

Peru Current Region

Talara, Callao, Matarani, Antofagasta, and Caldera also show remarkably coherent fluctuations in sea level. Like the group of stations to the north, periods of high sea level correspond well with El Nino conditions. The 1941-42 period of high sea levels is evident at Matarani. The 1957-59 and 1965 periods of high sea levels are seen at all stations in this region. During 1972, a period of extremely high sea levels occurred at Talara peaking at 36.5 cm in December 1972. A maximum anomaly of 34.4 cm was measured at Talara during November 1974. It is interesting to note the sharp spike of extremely low sea level that occurred just before the 1974 period of high sea level at Talara. Anomalously high sea levels are also evident at Callao during 1972. Periods of low sea level occurred at all stations in this group during 1949-50, 1954-56, and 1966-67.

CONCLUSION

Anomalies of monthly mean sea level observations along the west coast of North and South America persist for periods ranging from several months to two years or longer and are coherent in space for hundreds of kilometers. Anomalous "events" can be traced along the coast from Chile to Alaska and may be related to coastal circulation processes which may in turn affect larval drift and reproductive success of marine organisms. Certainly the major periods of anomalously high sea level during 1941-42, 1957-59, and 1972 were associated with unusual changes in the abundance or distribution of many marine species. It is hoped that further research on the factors affecting sea level will lead to a better understanding of ocean circulation processes and their effects on populations of marine organisms.

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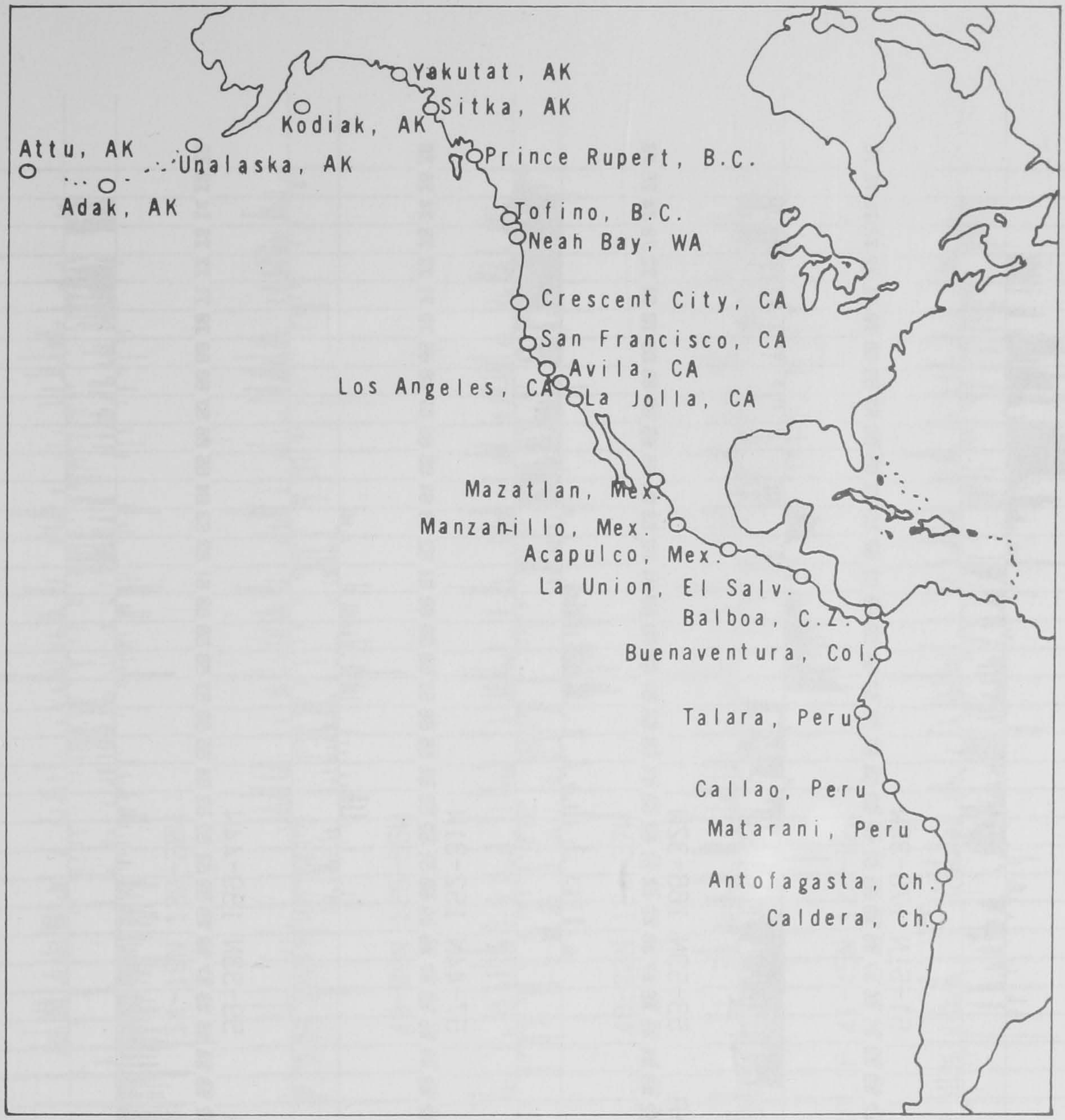


Figure 5.1.—Selected tide stations along the west coast of North and South America.

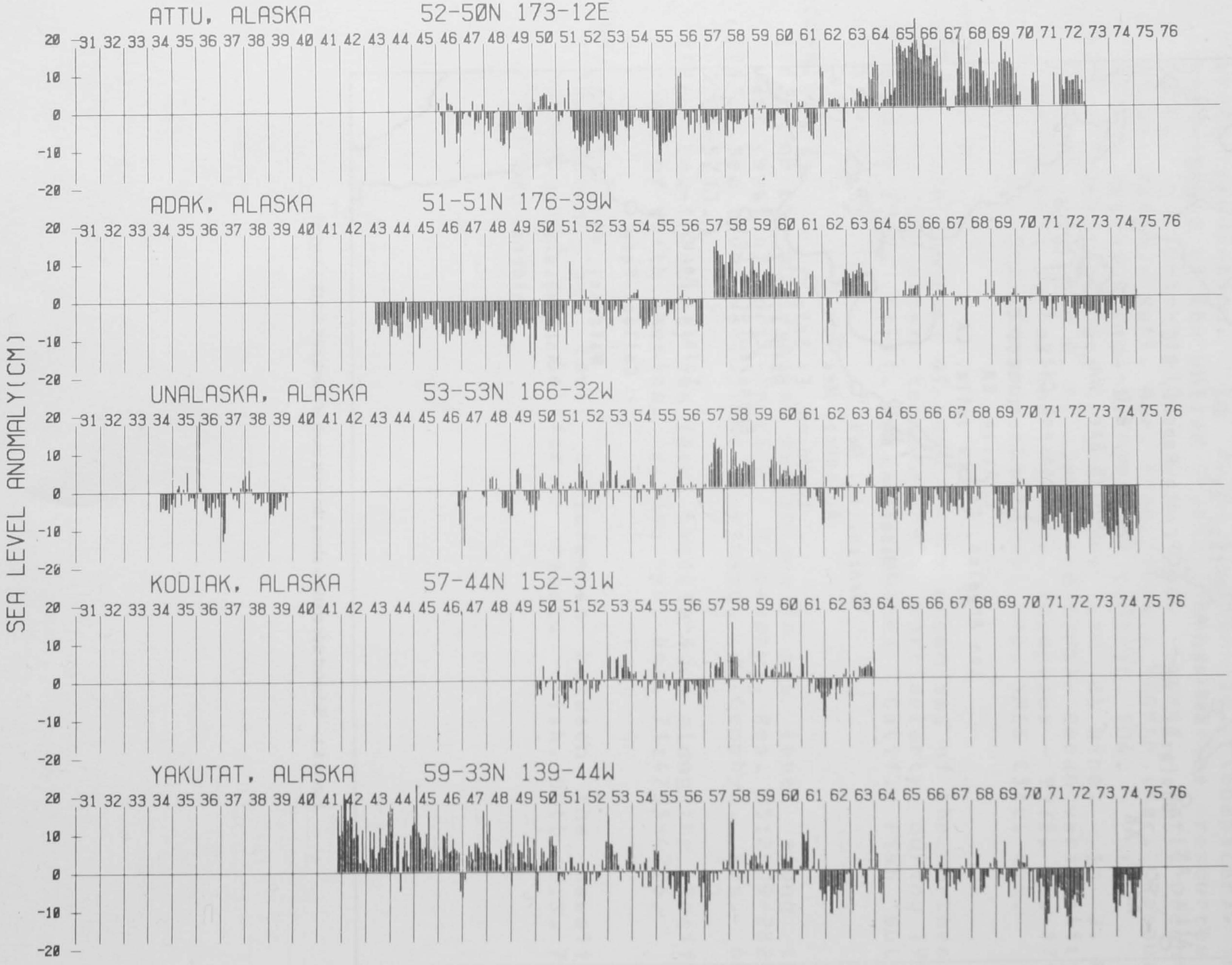


Figure 5.3.—Anomalies of mean sea level for stations in the Aleutian Islands and Gulf of Alaska.

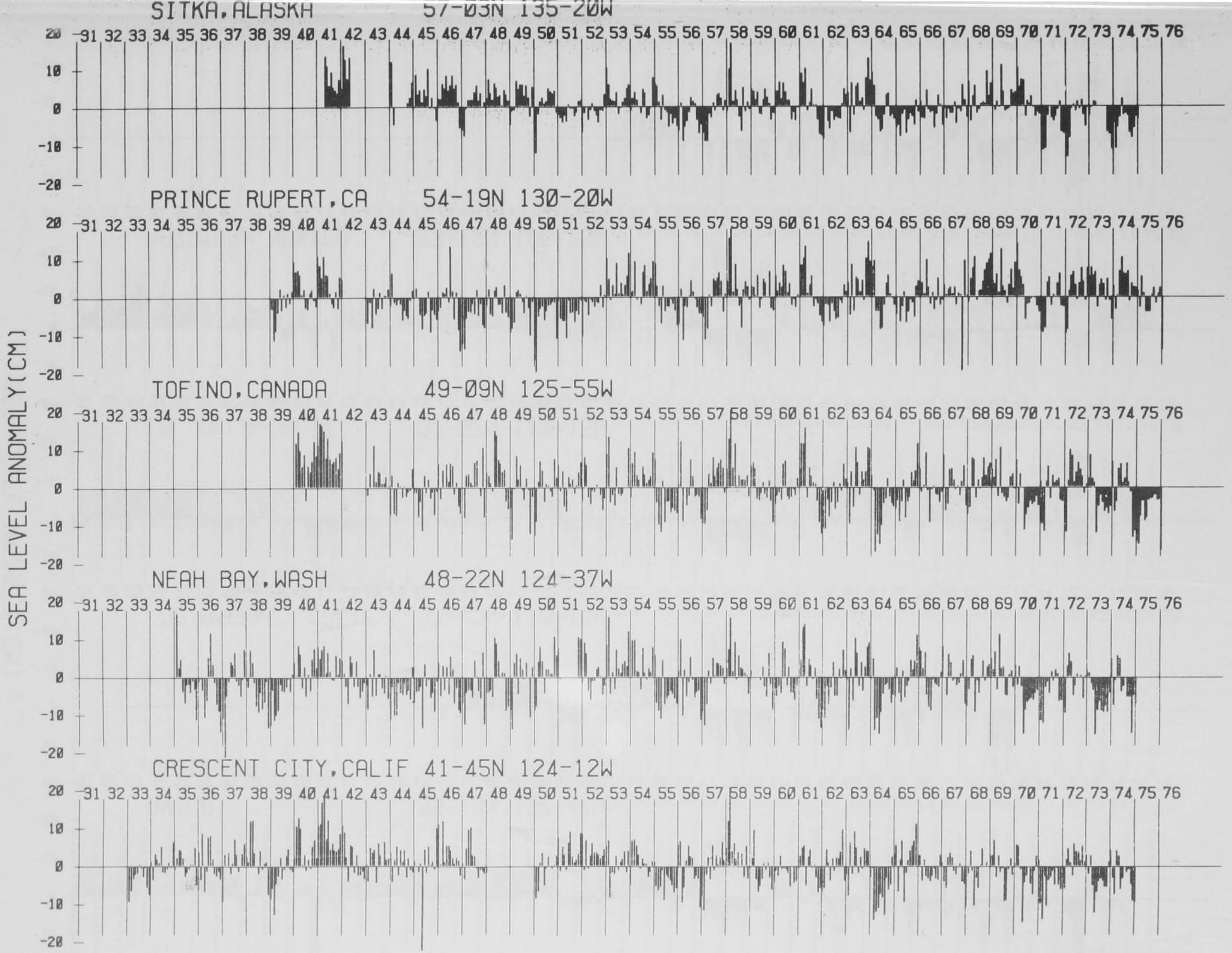
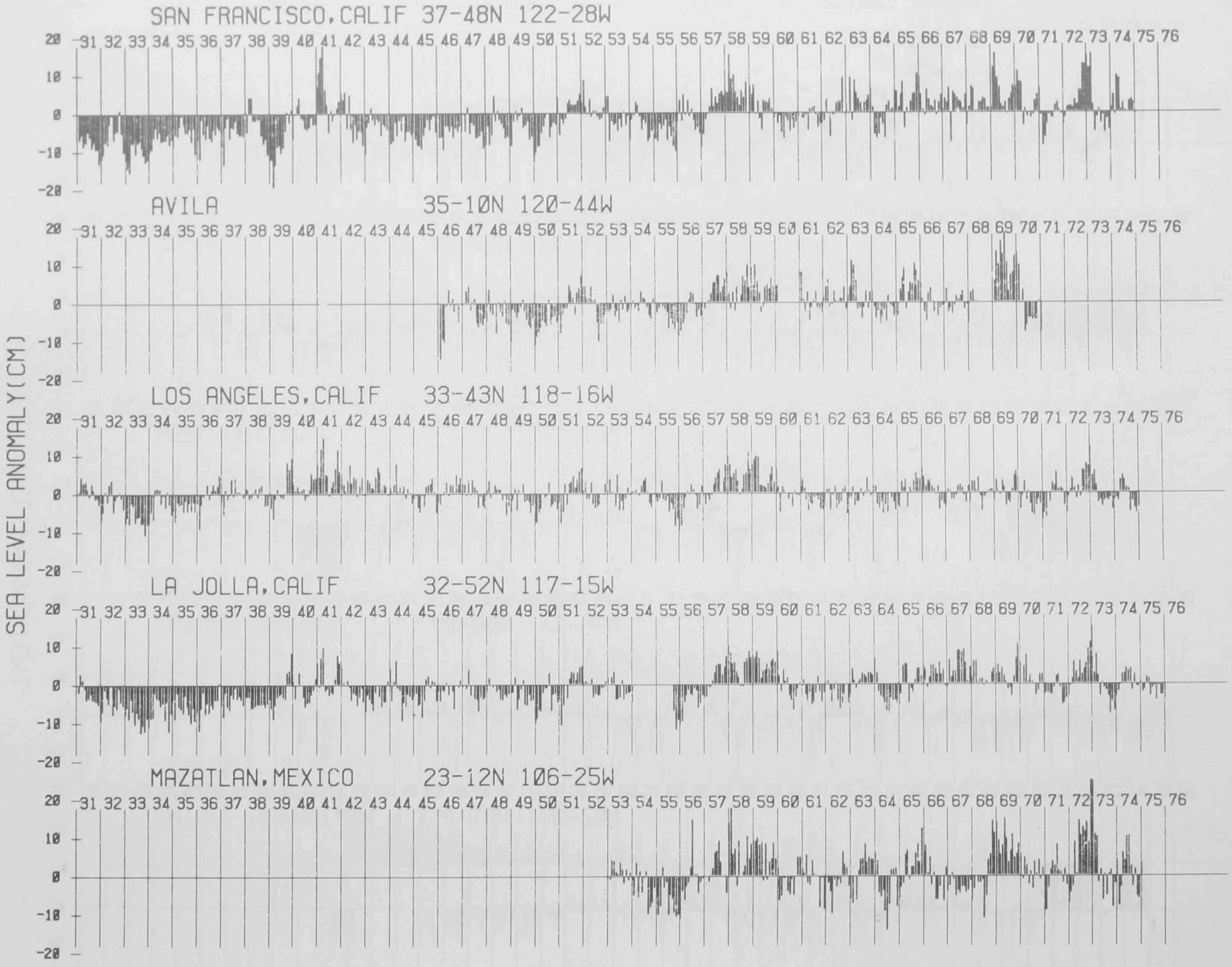


Figure 5.3.—Anomalies of mean sea level for stations in the Gulf of Alaska and Pacific Northwest.


SAN FRANCISCO, CALIF 37-48N 122-28W
AVILA 35-10N 120-44W
LOS ANGELES, CALIF 33-43N 118-16W
LA JOLLA, CALIF 32-52N 117-15W
MAZATLAN, MEXICO 23-12N 106-25W
31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76
20
10
0
-10
-20
SEA LEVEL ANOMALY(CM)

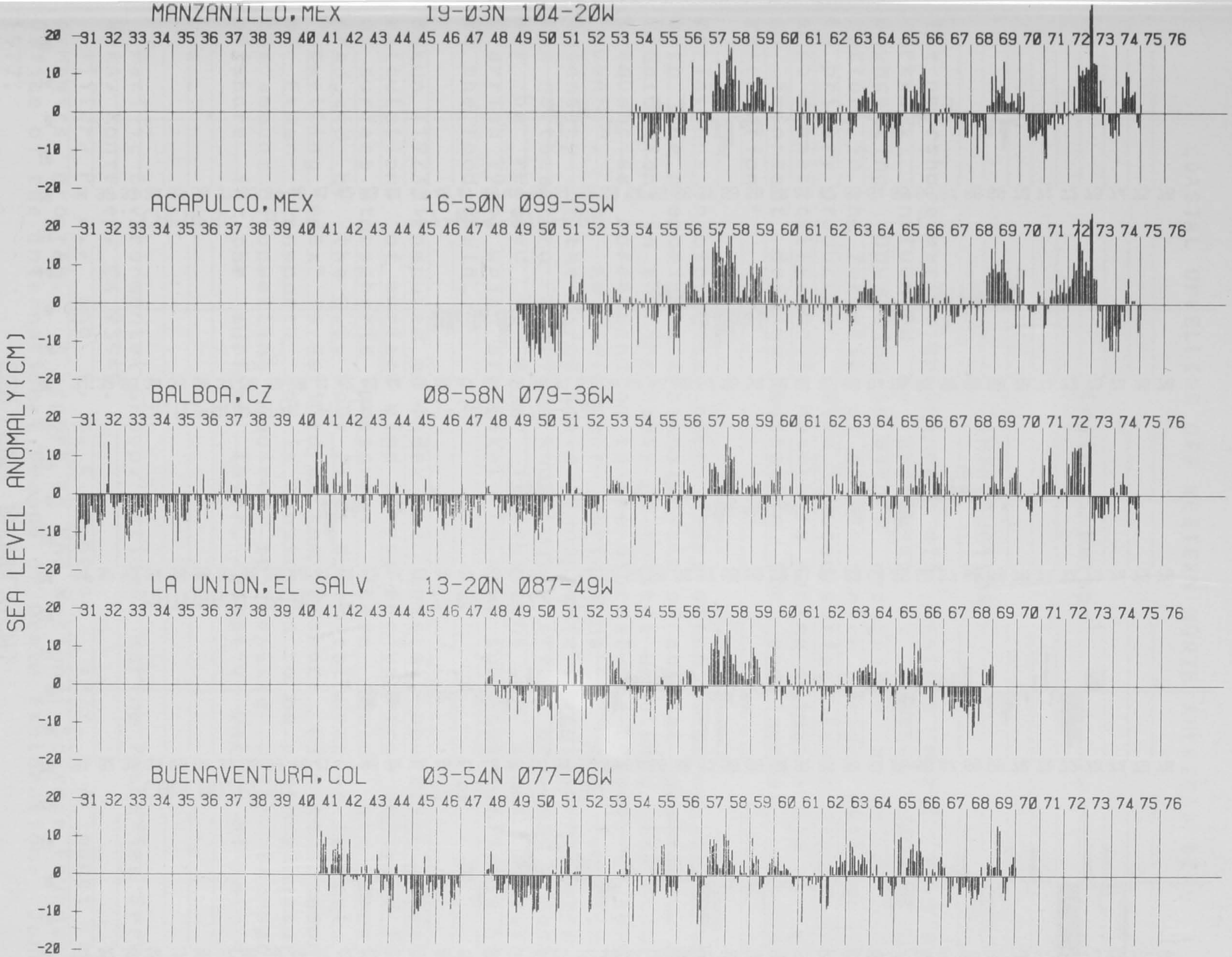
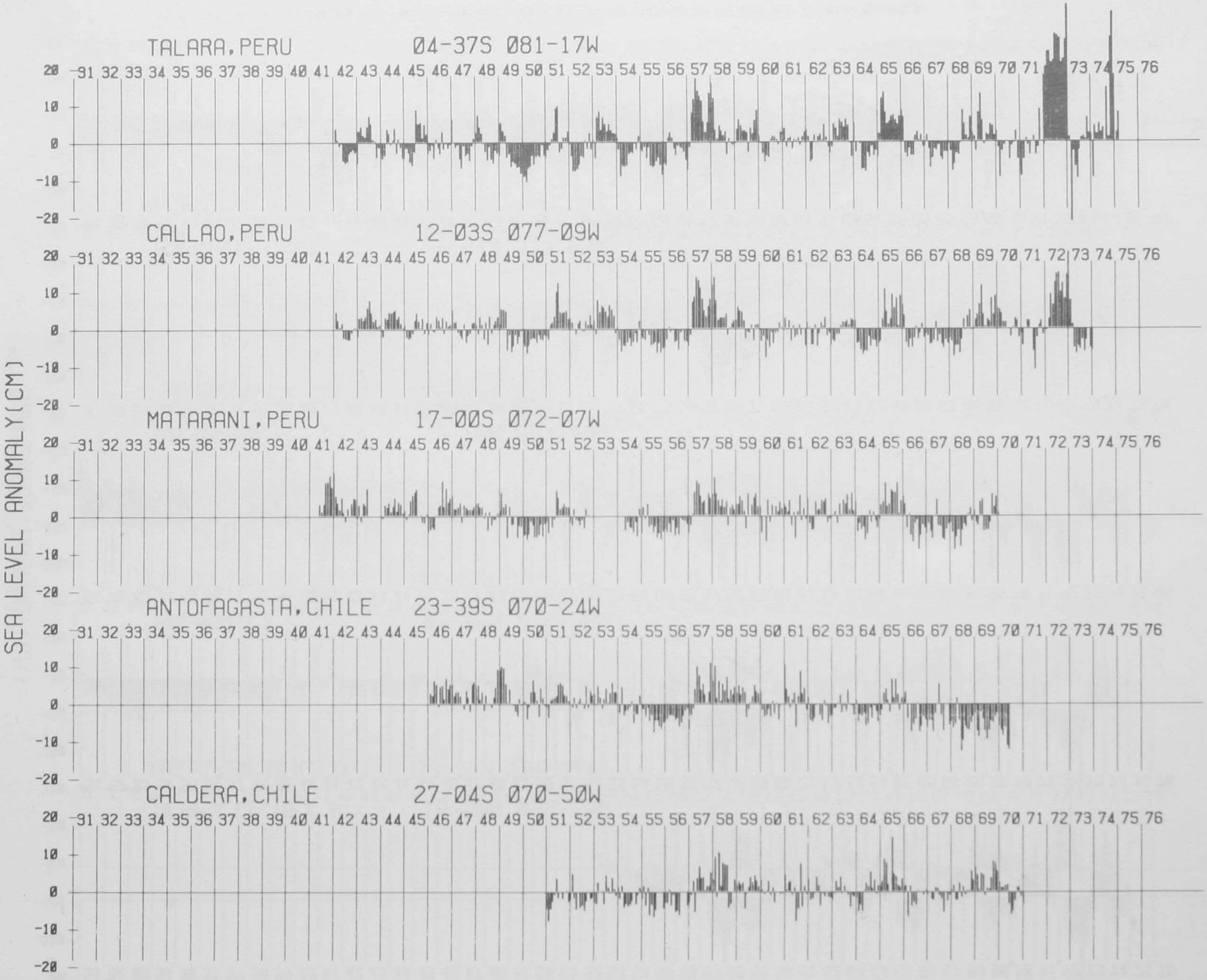


Figure 5.5.—Anomalies of mean sea level for stations in Mexico and Central America.


TALARA, PERU 04-37S 081-17W
CALLAO, PERU 12-03S 077-09W
MATARANI, PERU 17-00S 072-07W
ANTOFAGASTA, CHILE 23-39S 070-24W
CALDERA, CHILE 27-04S 070-50W
SEA LEVEL ANOMALY (CM)
20
10
0
-10
-20
31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76

Paper 6

COASTAL UPWELLING OFF WESTERN NORTH AMERICA, 1976

Craig S. Nelson[1]

INTRODUCTION

The nearshore marine environment off western North America is markedly influenced by processes of coastal upwelling and downwelling. Upwelling is widely recognized as a fundamental factor in the formation of nutrient rich surface water favorable to primary production. Wind induced surface layer divergence may also dramatically modify nearshore marine climate, and may act as an important driving mechanism for continental shelf/slope circulation.[2]

Variations in biological communities often occur nearly in phase with the predominant seasonal cycle of coastal upwelling. Major fluctuations in the intensity of coastal upwelling also occur at frequencies corresponding to the diurnal sea breeze, to synoptic "events", and to interyear variations in the location and intensity of the large scale atmospheric circulation system over the northeastern Pacific. Anomalously strong or weak upwelling may be related to major fluctuations in stock recruitment (Parrish 1976) which are likely to have subsequent effects higher in the food chain.

Bakun (1973) computed an index of coastal upwelling based on calculations of surface wind stress derived from analyzed fields of surface atmospheric pressure. These fields are routinely produced by the U.S. Navy Fleet Numerical Weather Central. The "upwelling index" is defined as the offshore directed component of Ekman transport, and is considered to be a gross measure of the amount of upwelling required to replace water transported offshore in the surface layer. Negative values of this index

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[1] Pacific Environmental Group, National Marine Fisheries Service, NOAA, Monterey, CA 93940.

[2] Niiler, P. P., and C. N. K. Mooers. 1977. A model shelf dynamics program. A report to the National Science Foundation, Office of the International Decade of Ocean Exploration, January 1977.

indicate onshore surface transport and downwelling at the coast Monthly mean upwelling index values for the period 1946-71 wer presented for the 15 locations shown in Figure 6.1. These tim series have been updated for 1972-74 and 1975 (Bakun 1976, 1978)

Monthly upwelling indices for 1976 are given in Table 6.1 Anomalies from the 20-yr (1946-67) mean monthly values ar presented in Table 6.2. Upwelling indices are displayed i percentiles in Figure 6.2. Percentile values were based on th rank of the upwelling index for each month and location withi the 31-yr (1946-76) time series.

THE GULF OF ALASKA

wind driven surface transport in the Gulf of Alaska (60N, 149W t 51N, 171W) tends to be divergent in the interior and convergen at the coast.[3] The annual cycle of coastal convergence i dominated by vigorous downwelling during the winter season, whe intense cyclonic storm activity characterizes the atmospheri circulation in the region. During 1976 monthly upwelling indice were negative along both northern and eastern boundaries, excep in June and July when small positive values were evident.

In January more intense than normal downwelling was indicate along the eastern boundary, while positive anomalies occurred i the northern Gulf of Alaska. This pattern of anomalies reverse the trends for these two areas begun during the last quarter o 1975 (Bakun 1978). The remainder of the first quarter of 197 was marked by less intense than normal winter downwelling Reduced levels of coastal convergence may be associated with les intense than normal surface divergence offshore. A decrease i the strength of the coupled "pumping" between the central Gulf o Alaska and the coast would tend to reduce the baroclinicit established during the previous three months.

More intense than normal coastal convergence was evident durin the remaining months of 1976. A general pattern of upwellin indices below the median (Fig. 6.2) was interrupted in June, whe small positive values occurred, and in October, when an irregula transition to vigorous winter downwelling was apparent Anomalies from the long-term monthly means (Table 6.2) wer negative from April through September, except during June, a

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[3] Ingraham, W. J., Jr., A. Bakun, and F. Favorite. 1976. Physical Oceanography of the Gulf of Alaska. U.S. Dep. Commer. NOAA, NMFS, Northwest Fish. Cen., Processed Rep., 132 p.

these five locations. Upwelling indices at 54N, 134W and 51N, 131W for May and July were the lowest (largest negative values) calculated in the 31-yr time series. Coastal convergence continued through the summer at approximately one-half the intensity of the preceding winter's downwelling. Under these conditions, the existing baroclinic structure would tend to be maintained. This situation contrasts with more typical relaxed summer conditions, in which the baroclinicity established during a previous winter is dissipated.

A smooth transition to vigorous winter downwelling was replaced by less intense than normal downwelling in October. This period of positive anomalies immediately followed and preceded several months of large negative anomalies. An examination of the monthly mean surface atmospheric pressure field for October (not shown) indicated a westward shift, relative to the long-term mean position, of the center of the low pressure system and a much reduced pressure gradient near the coast. A return to near normal (50th percentile) winter downwelling occurred in December.

VANCOUVER ISLAND TO POINT CONCEPTION

The stretch of coast from Vancouver Island (48N) to Point Conception (36N) is a transition zone, in which wind driven surface transport changes from predominantly onshore to predominantly offshore. During 1976 this entire coastal region was characterized by a pattern of three periods of more positive than normal upwelling indices separated by two short intervals of more negative than normal indices. These features repeat the general pattern noted in the previous section, and indicate a degree of coherence in the large scale atmospheric circulation on space scales approaching 1,200 km and on time scales of two to four months.

Neah Bay to Central Oregon (48N, 125W to 45N, 125W). Large positive anomalies in January extended a period of relaxed coastal convergence first noted in December 1975 (Bakun 1978). This trend did not continue; near normal downwelling was indicated from February through April along the coasts of Washington and northern Oregon. A prolonged period of relaxed coastal upwelling from May to September was interrupted in June by a return to near normal index values. However, this feature appeared as an anomaly in a pattern of upwelling indices below the median, in a region stretching from the northern Gulf of Alaska to Oregon. Upwelling peaked in June, somewhat earlier than the long-term mean values would indicate (Bakun 1973). Fall and early winter were characterized by a return to negative mean values (coastal convergence), although positive anomalies indicated less intense than normal downwelling.

Cape Blanco to Point Conception (42N, 125W to 36N, 122W). The patterns of positive anomalies during winter and negative anomalies during summer noted above were not repeated exactly along the coasts of southern Oregon and northern California. This stretch of coast encompasses the core of the California Current upwelling region, which is characterized, in the mean, by a maximum in the alongshore component of surface wind stress during July (Nelson in press). In 1976 the timing, duration, and intensity of the indicated upwelling at Cape Blanco (42N), Cape Mendocino (39N), and to a lesser extent Point Conception (36N), were markedly different than the 1946-67 long-term mean conditions.

Positive anomalies occurred in January and February, during a part of the year ordinarily characterized by coastal convergence. Although onshore transport was indicated at 42N, upwelling indices for 39N were positive and were clearly above the 50th percentile. This feature continued a long trend of positive anomalies which began in April 1975 (Bakun 1978).

The onset of anomalous upwelling appeared to occur rather abruptly in March. The timing of this event was coherent at three locations along the coast (Fig. 6.2). Near Cape Mendocino (39N), the March index was nearly a factor of three greater than the long-term mean value for this month and location. A return to near normal conditions occurred in April.

Conditions favorable to strong coastal upwelling reappeared in May, June, and July. Monthly mean indices exceeded the 80th percentile at both 42N and 39N. The values computed for Cape Mendocino (39N) were the second highest in May, and the third largest in June within the 31-yr series. This recurrence of unusually large positive anomalies marked the fourth consecutive year in which stronger than normal coastal divergence has been indicated. Such long-term persistence possibly suggests either a shift in, or intensification of, the large-scale atmospheric circulation influencing the west coast of North America. The timing of the summer upwelling season was also somewhat unusual. Index values peaked in May, two months earlier than the peaks in the long-term mean cycles for these locations.

A rapid transition to below normal upwelling (i.e., negative anomalies) during August was immediately followed by a return to large positive anomalies in September. The period of relaxed upwelling in August was notable, since negative anomalies during this month were evident along the entire stretch of coast from the northern Gulf of Alaska to the Southern California Bight.

The pattern of positive anomalies persisted through the last quarter of 1976. While the upwelling indices at 42N approached the 20-yr mean values (i.e., downwelling), indices exceeding the

80th percentile occurred in September and October at Cape Mendocino. The indices for November and December showed a gradual return to median values; however, upwelling was still indicated for 39N. As Bakun (1978) has already noted, such a prolonged period of upwelling would appear to be favorable for those fish stocks dependent upon upwelling based primary production.

POINT CONCEPTION TO BAJA CALIFORNIA

A secondary California Current upwelling regime along this coast (33N, 119W to 21N, 107W) is characterized by positive values of offshore transport throughout the year (Bakun and Nelson in press). Maximum upwelling index values occur from March to May and coincide, in time, with major peaks in spawning.

Although the upwelling index remained positive during 1976, the most prominent features were the extended periods of large negative anomalies in January and February, and again from August to December. This pattern marked an almost complete reversal of the conditions which prevailed in 1975. During the previous year, below median values occurred in summer, while above median indices were evident in spring and fall.

Positive monthly mean anomalies were evident from March to August (Table 6.2). Much more intense than normal upwelling at locations from Punta Eugenia (27N) to Cabo San Lucas (21N) extended the upwelling season to late summer. This period was immediately followed by a decline to large negative anomalies. This pattern of negative anomalies during fall and early winter encompassed the entire region from Point Conception (36N) to Cabo San Lazaro (24N). Upwelling indices were consistently below the 30th percentile, which suggested extremely relaxed upwelling for this time of year.

The pattern of negative anomalies corresponded in time and in location with a rapid warming of surface water during fall and winter. The intensity of warming was indicated by December sea surface temperature anomalies 2C warmer than the 1946-67 mean, and more than 3C warmer than the temperatures during the 1975 winter season.[4] Relaxed upwelling (i.e., small values of offshore transport) is correlated with northward surface flow

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[4] _Fishing Information_, No. 12, December 1976. Southeast Fisheries Center, NMFS, NOAA, La Jolla, CA 92038.

near the coast.[5] The upwelling conditions during fall and winter 1976 indicated the possibility of a major intrusion of warm southern water which could have extended beyond Point Conception.

RELATION TO FISHERIES

Within the coastal region from Point Conception (33N) to Cabo San Lucas (21N), upwelling and upwelling related processes may be important transport mechanisms for fish stocks which spawn in the area.[6] The five months of below normal indices in this region followed a period of moderate upwelling at 30N, 119W. On the basis of above normal upwelling at this location during peak spawning, recruitment models predicted better than average reproductive success for Pacific mackerel in 1976.[7] Relaxed upwelling during the fall and increased northward flow near the coast would tend to favor northward transport of the southern stock of Pacific mackerel, *Scomber japonicus*, which would increase the estimates of the 1976 year class above those predicted on the basis of spring upwelling alone. Current market evidence indicates that, indeed, the 1976 year class is much stronger than had been anticipated.[8]

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[6] Parrish, R. H., and C. S. Nelson. Fish stocks and the California Current. Paper presented at the Calif. Coop. Oceanic Fish. Invest. Conference, November 16-18, 1976, Palm Springs, CA. Unpubl. manuscr.

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Table 6.1 - Monthly coastal upwelling indices for 1976. Units are cubic meters per second per 100m length of coast. Negative values indicate onshore transport of surface waters and resultant downwelling.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
60N 149W	-85	-91	-10	-16	-2	4	2	-1	-17	-12	-68	-94
60N 146W	-113	-104	-13	-26	-4	8	2	-2	-33	-22	-123	-146
57N 137W	-201	-50	-35	-54	-35	6	-6	-8	-81	-58	-237	-132
54N 134W	-159	-18	-40	-55	-55	5	-26	-7	-56	-39	-163	-86
51N 131W	-81	1	-16	-33	-21	20	-23	4	-12	-6	-68	-48
48N 125W	-63	-35	-24	-3	6	31	5	9	1	-6	-37	-53
45N 125W	-41	-30	-10	-0	21	56	23	17	14	-0	-31	-47
42N 125W	-10	-4	20	15	132	166	95	44	52	7	-23	-27
39N 125W	9	9	101	59	331	304	249	111	134	79	2	3
36N 122W	22	20	124	115	259	196	224	109	80	49	4	1
33N 119W	-1	34	120	198	304	262	277	212	88	50	4	-6
30N 119W	44	64	139	160	231	199	160	145	70	80	54	28
27N 116W	27	51	127	158	215	214	142	170	57	58	28	17
24N 113W	24	50	127	153	191	172	107	86	57	72	34	32
21N 107W	21	33	122	125	119	36	30	4	1	16	18	35

Table 6.2 - Monthly coastal upwelling index anomalies for 1976 relative to the 20-year (1948-67) mean value for each month and location. Units are cubic meters per second per 100 m length of coast.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
60N 149W	54	-5	36	-5	-2	-2	-4	-6	-14	14	5	14
60N 146W	67	-2	35	-14	-2	1	-3	-5	-24	12	-29	-17
57N 137W	11	67	16	-30	-25	6	-8	-2	-52	29	-96	31
54N 134W	-63	49	-12	-35	-46	5	-29	-7	-33	43	-65	5
51N 131W	-17	37	-4	-27	-25	5	-39	-9	-9	34	-10	9
48N 125W	27	12	-3	-3	-11	5	-29	-13	-3	33	51	47
45N 125W	53	18	5	-9	-13	8	-51	-34	-3	20	42	46
42N 125W	57	24	16	-18	53	63	-36	-47	16	7	19	31
39N 125W	21	0	65	-10	207	136	68	-28	71	59	8	16
36N 122W	12	-15	44	-5	56	-43	25	-73	-14	0	-8	-6
33N 119W	-20	-14	-0	20	21	-50	46	-0	-49	-26	-18	-16
30N 119W	-12	-14	23	19	31	-0	17	3	-59	-23	-11	-26
27N 116W	-45	-43	8	10	13	19	28	65	-54	-48	-46	-46
24N 113W	-26	-24	34	36	49	44	59	42	8	3	-19	-8
21N 107W	3	-7	25	25	32	-3	27	-2	15	31	10	26

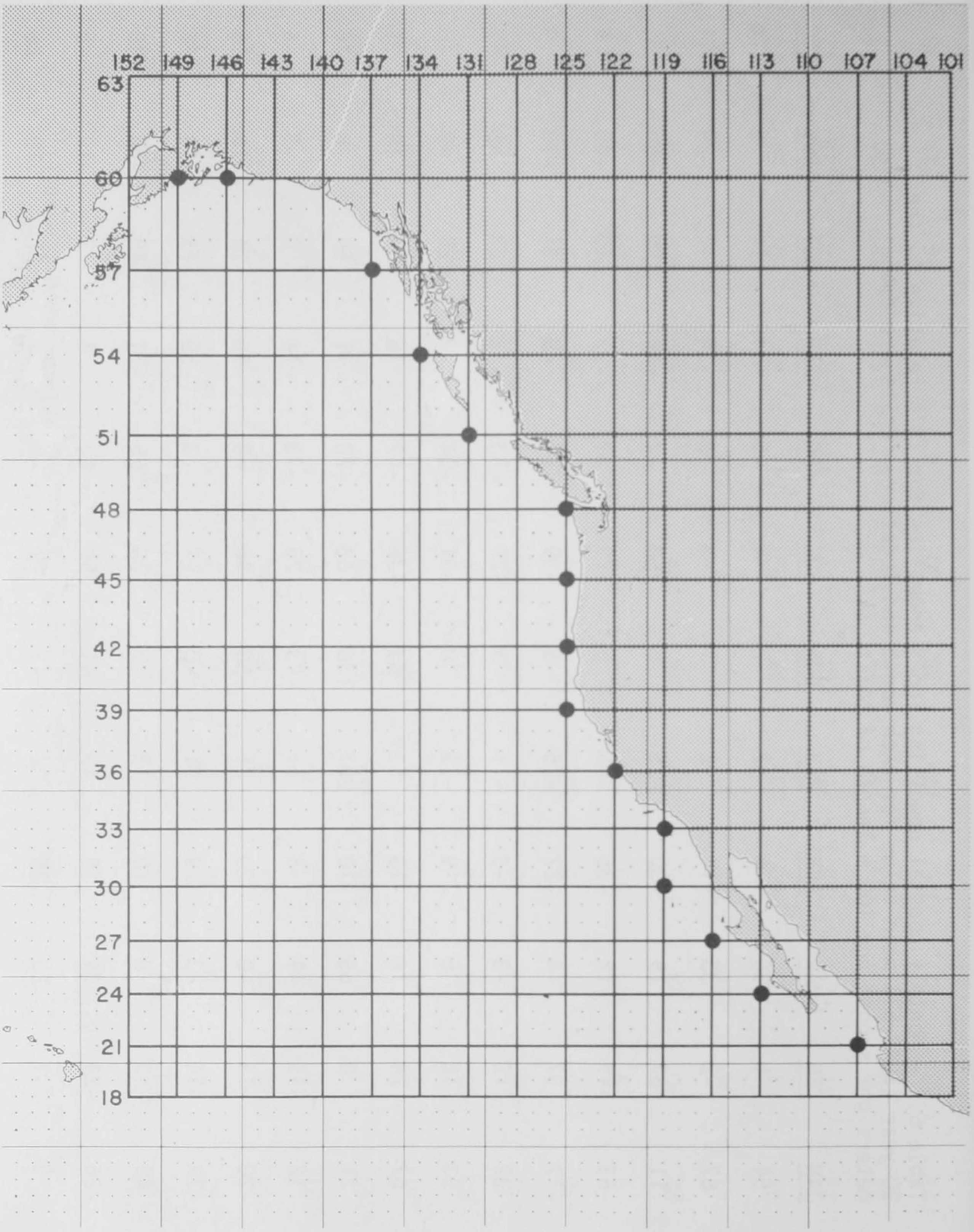
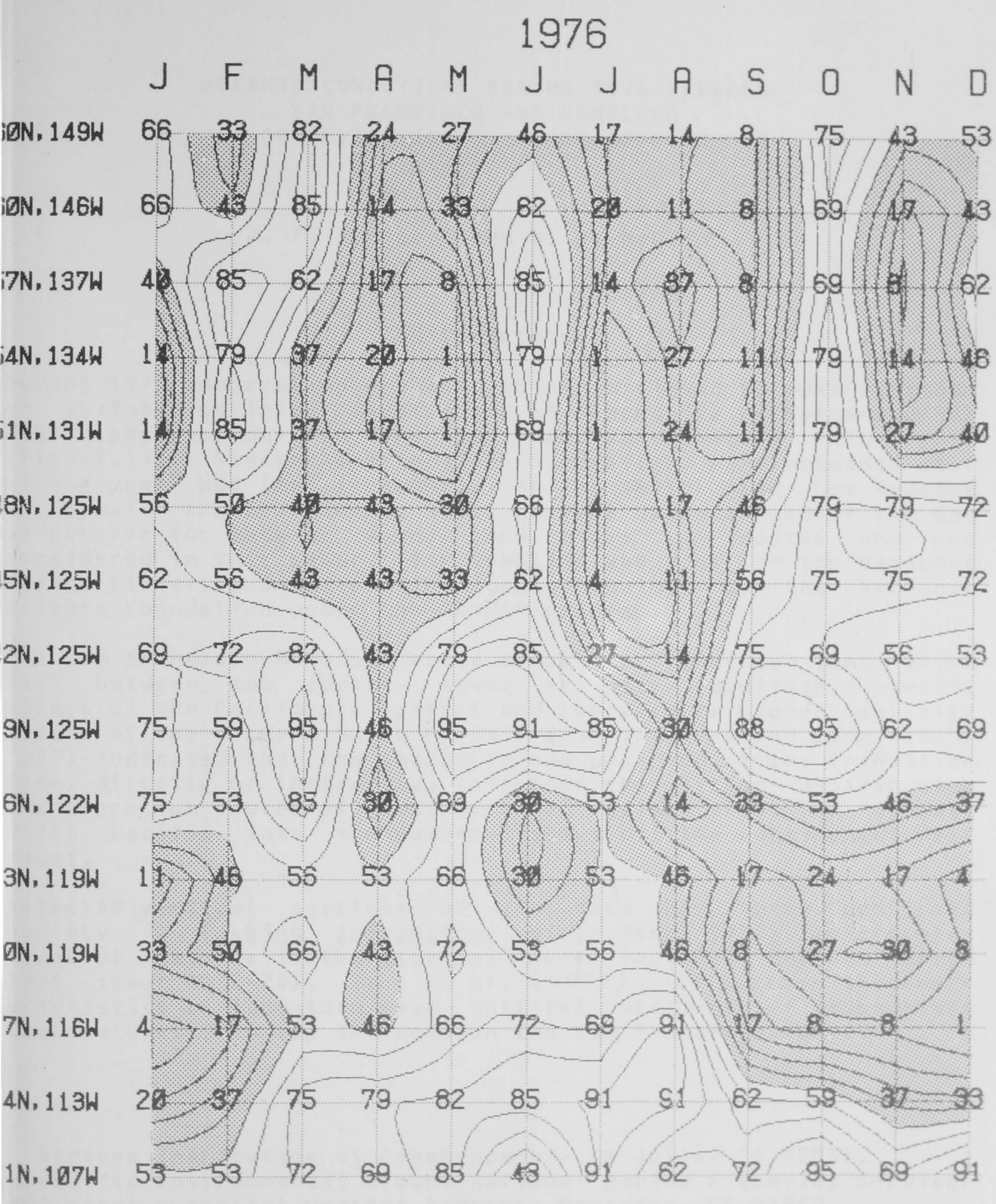


Figure 6.1.—Computation grid. Intersections at which upwelling indices are computed are marked with large dots.

ERCENTILIZED MONTHLY MEAN UPWELLING INDICES



1976	J	F	M	A	M	J	J	A	S	O	N	D
0N,149W	66	33	82	24	27	46	17	14	8	75	43	53
0N,146W	66	43	85	14	33	62	20	11	8	69	17	43
7N,137W	40	85	62	17	8	85	14	37	8	69	8	62
4N,134W	14	79	37	20	1	79	1	27	11	79	14	46
1N,131W	14	85	37	17	1	69	1	24	11	79	27	40
8N,125W	56	50	40	43	30	66	4	17	46	79	79	72
5N,125W	62	56	43	43	33	62	4	11	56	75	75	72
2N,125W	69	72	82	43	79	85	27	14	75	69	56	53
9N,125W	75	59	95	46	95	91	85	30	88	95	62	69
6N,122W	75	53	85	30	69	30	53	14	33	53	46	37
3N,119W	11	46	56	53	66	30	53	46	17	24	17	4
0N,119W	33	50	66	43	72	53	56	46	8	27	30	8
7N,116W	4	17	53	46	66	72	69	91	17	8	8	1
4N,113W	20	37	75	79	82	85	91	91	62	59	37	33
1N,107W	53	53	72	69	85	43	91	62	72	95	69	91

igure 6.2.—Percentalized upwelling index values for 1976. Percentiles indicate relative ranking within the 31-yr data set for each month and location. The contour interval is 10 percentile units. Values below the median (50th percentile) are shaded.

Paper 7

OCEANIC CONDITIONS DURING 1976 BETWEEN SAN FRANCISCO AND HONOLULU AS OBSERVED FROM SHIPS OF OPPORTUNITY

J. F. T. Saur[1] and D. R. McLain[2]

INTRODUCTION

During 1976 cooperating merchant ships continued to make sections of surface salinity samples and of expendable bathythermograph (XBT) observations on the San Francisco-Honolulu ship route (Fig. 7.1). Similar sections of observations were obtained most of the year, but less frequently, on the Seattle and Los Angeles to Hawaii routes. These, however, were discontinued at the end of October for lack of funds, and these two routes are not considered in this paper. The sampling was done for the National Marine Fisheries Service using funds provided by the National Science Foundation under the NORPAX program.

The San Francisco-Honolulu route crosses a Transition Zone which lies between the cooler, lower salinity, modified subarctic waters of the California Current and the warmer, higher salinity waters of the Eastern North Pacific (ENP). Laurs and Lynn (1975, 1977) indicated that the character and position of the Transition Zone, directly or indirectly, influence the offshore distribution and migration routes of albacore tuna moving from the central North Pacific into the summer fishery off the continental west coast.

Selected vertical sections of the data have been published monthly in <u>Fishing Information</u>[3] since March 1972. Interpretations of features in the sections were included through March 1975 (Saur 1972-75). Saur et al. (1979) discussed the characteristics of long-term mean vertical sections of subsurface temperatures from the XBT data on the San Francisco route.

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[1] Scripps Institution of Oceanography, La Jolla, CA 92037.

[2] Pacific Environmental Group, National Marine Fisheries Service, c/o Fleet Numerical Weather Central, Monterey, CA 93940.

[3] Southwest Fisheries Center, NMFS, NOAA, La Jolla, CA 92037.

In this report we present distributions of surface salinity, sea surface temperature (SST), and heat storage (surface to 100-m layer) during 1976, and have extended the previously published 1972-75 time series of their anomalies through 1976. We discuss the 1976 distributions and differences in anomalies from the preceding years. An apparently atypical relation of positive temperature anomalies occurring with negative salinity anomalies off the Pacific coast during October-December 1976 is attributed, at least partially, to a decrease in evaporation and weak vertical mixing by winds.

OBSERVATIONS

Observational programs and procedures for making XBT observations aboard cooperating merchant ships have been described by Saur and Stevens (1972). The "surface" salinities are determined from water samples drawn at around 7 m below the surface. "Surface" temperatures from the XBT observations are representative of temperatures at about 5 m. Heat storage is presented as average temperature from the surface to 100 m as determined from the XBT observations. These observations were normally scheduled at 4-h intervals.

For 1976 the number of ship of opportunity transits, number of observations, and range of observed values are shown in Table 7.1.

Table 7.1

	Number of Transits	Obs.	Minimum	Maximum	Range
Surface salinity (o/oo)	27	814	32.37	35.59	3.22
Surface temp. (C)	31	926	10.0	25.9	15.9
Heat storage (C, 0-100 m)	30	868	10.0	25.2	15.2

The locations of the observations are shown in Figures 7.2-7.4. In these, and other figures, the location of an observation is given by its great circle distance from a reference point, 21N12', 157W42', which is in the ocean channel near Honolulu, south of Makapuu Point, Oahu.

DISTRIBUTION OF VARIABLES DURING 1976

The time-space distributions of salinity, temperature, and heat storage (0-100 m) are shown in Figures 7.2, 7.3, and 7.4, respectively. The irregularly located observations were first analyzed by the NORPAX/SURFACE II computer program to a time-space grid of 24 intervals per year by 92.6 km (50 n mi). The distributions were then computer contoured from the unsmoothed grid fields using double linear interpolation with five subintervals within each standard grid interval.

The surface salinities (Fig. 7.2) showed the underlying mean pattern (Saur 1978) of a low salinity minimum (below 33.0 o/oo) a short distance offshore in the California Current; a region where salinity increased toward Hawaii and had maximum gradients located between 2,000 km and 3,000 km along the route from Hawaii; a region of maximum salinites (above 35.0 o/oo) located between 500 km and 1,750 km from Hawaii; and somewhat lower salinities (below 35.0 o/oo) most of the year near Hawaii. The high salinities occurred where the vessel track crossed the eastern end of the high salinity Eastern North Pacific Central Waters, located between 25N and 30N (Sverdrup et al. 1942).

The surface temperatures (Fig. 7.3) showed the typical annual cooling and warming cycle with minimum temperatures in late March or early April and maximum temperatures in September superimposed on the latitudinal decrease in temperature along the route from Hawaii to San Francisco. The most rapid warming normally occurs from mid-May to mid-July, but in 1976 the warming was delayed until mid-June and was greatest in July. This was followed by a broad maximum through October and slowly decreasing temperatures in November-December.

The annual cycle of temperature is much more prominent than the annual cycle of salinity. Minimum and maximum values and total range for each gridded field are shown in Table 7.1. The greatest range of salinty at a given position was about 0.5 o/oo or only 15% of the total observed range. On the other hand, near the California coast the temperature range was 6.0C, and near 3,000 km along the route (in the Transition Zone) the annual range was 5.1C, which were 39% and 32%, respectively, of the total observed range.

The heat storage (expressed by the average temperature in the upper 100 m of water, Fig. 7.4) had a pattern similar to that of surface temperature. However, at a fixed location it did not have as large an annual range; this was only about 2C over most of the route but reached about 4C near the California coast. The smaller annual range of heat storage occurred because the effects of the seasonal warming and cooling cycle decrease with depth.

ANOMALIES DURING 1976

The time series since 1972 of anomalies of salinity, temperature, and heat storage given by Saur (1978) are extended to include 1976 anomalies (Fig. 7.5). The mean data from which the anomalies were computed did not include the 1976 data, but were for the same 8-yr period (June 1966-December 1970, January 1972-June 1975) used previously. The grid fields for the anomalies were numerically smoothed by a 5 x 3 point (60 days by 100 n mi) before being contoured.

The anomalies of surface salinity were generally small, but dominantly positive, throughout the first nine months of 1976. Two exceptions are noticeable. Along the California coast there was a pulse of below normal salinity water in January-February and another in May-July. Nearer midsection the negative anomaly (-0.2 o/oo) which had appeared near 2,700 km in late summer 1975 migrated westward along the track, decreased to near normal in winter, but then increased in intensity to -0.2 o/oo around 2,000 km in May and June 1976. This propagation speed along the route was about 3.3 cm/s as compared with observed values of 2.5 cm/s in 1972-75 and speeds of 2.9 cm/s for temperature anomalies at 170 m (generally in the thermocline) found by Dorman and Saur (1978).

The outstanding feature of surface salinity anomalies in 1976 was the appearance of significant negative anomalies (below -0.2 o/oo) at the California coast and also near the outer edge of the California Current (near 2,800 km) in October. In mid-November there was a band of negative anomalies (below -0.3 o/oo) from near the California coast to midsection. Further, anomalies below -0.4 o/oo occurred in the Transition Zone and extended toward Hawaii somewhat into the ENP region. These strong negative anomalies appeared to be returning to near normal at the end of the year.

The SST anomalies in 1976 exhibited the earlier observed coherence with distance along the track and low persistence in time. From January through April temperature anomalies were positive over most of the route except that they were negative within about the last 600 km approaching the California coast. A change to significantly negative anomalies occurred in May over the entire route because of the previously mentioned delayed onset of seasonal warming. Warming in July briefly returned the anomalies to near zero over most of the route. A narrow band of positive anomalies appeared near the California coast at that time. The anomalies over the rest of the route returned, however, to significantly negative values during August through October.

During the last quarter, positive temperature anomalies appeared progressively farther westward along the route towards Hawaii at a very rapid rate. Significant positive anomalies (above 0.5C) appeared during November over the entire eastern half of the section and persisted through the remainder of the year. The pattern of these positive anomalies was quite similar to that of the negative salinity anomalies that were previously noted.

The pattern of anomalies of heat storage in the upper 100 m differed considerably from that of surface temperature anomalies. Only during the first quarter of the year was there some correspondence of positive anomalies of heat storage and surface temperature over most of the route along with negative anomalies near the California coast. During May-July over the central portion of the route, the positive anomalies of heat storage persisted while the anomalies of SST changed to negative, indicating that the warm waters remained at depth but were covered with anomalously cool waters at the surface.

Toward the last half of the year negative heat storage anomalies progressively appeared over a larger portion of the route at the Hawaiian end of the section. Otherwise, the patterns of significant heat storage anomalies were very spotty.

DISCUSSION

The oceanic conditions in 1976 on the San Francisco-Honolulu route began with the relation between surface salinity and surface temperature anomalies which has been typical for at least the period 1972-75. This historical relation had banded and westward-migrating positive (or negative) salinity anomalies over the eastern half of the route accompanied by positive (or negative) surface temperature anomalies over most of the route. This relation continued in the first quarter of 1976 when positive salinity anomalies were associated with positive temperature anomalies.

During midyear the relation broke down and 1976 ended with a strongly atypical relation between salinity and temperature anomalies. Negative salinity anomalies occurred simultaneously for 1,500 km along the eastern part of the route with positive temperature anomalies--a reversal from the previous relation.

For the years 1972-75 an heuristic model with anomalies dominated by advective processes could explain the association of positive salinity anomalies in the outer California Current region with wider spread positive temperature anomalies. The California Current is the fastest portion of the eastern limb of the major (clockwise) gyre of the central North Pacific. Along the

San Francisco-Honolulu route the average current flows from northwest to southeast, essentially normal to the route. An increase in speed of the North Pacific Gyre would bring in more cool, low salinity, modified Subarctic Water which, on the route, would appear first in the California Current region and later in the Transition Zone. This would result in more negative salinity and temperature anomalies in these areas. Over the western half of the route, an increase in speed of the gyre would also result in increasingly negative temperature anomalies (due to meridional gradients of temperature) but would not result in significant negative salinity anomalies because meridional salinity gradients are weak or nonexistent in that area (Reid 1969). The increase (or decrease) in speed of the gyre could result from long-term forcing by winds. This simple model assumes that the variability from heat exchange and vertical mixing is negligible.

The patterns of salinity and temperature diverged greatly from this model in the last three months of 1976. Dickson and Namias (Paper 2) noted that during 1976 the upper air (700 mb) patterns also changed noticeably. During the first three seasons the anomalous circulation was strongly zonal across the central North Pacific. But during the last three months, a high pressure ridge established itself over the eastern North Pacific and west coast of North America. The ensuing fair weather and 1976-77 winter drought over the western United States were documented in the Monthly Weather Review.[4]

The breakdown in October through December 1976 of the earlier relation between salinity and temperature anomalies indicated a change in balance of oceanic processes. If we consider tha surface salinity is a quasi-conservative property and the lo anomalies were due to increased advection to the south, we mus look for processes that would change a negative temperatur anomaly to positive. The possibility that increased anomalou heat exchange and less vertical mixing by weaker winds contributed to positive anomalies was explored using monthly mean dat compiled by 5-deg quadrangles at the Southwest Fisheries Center. Anomalies were computed for two quadrangles for the last thre months of 1974, 1975, and 1976 (Table 7.2). One of th quadrangles (35N-40N, 125W-130W) lies over the California Current west of San Francisco and is crossed by the ship route. The other (40N-45N, 125N-130W) is the adjacent quadrangle to the north, through which waters normally flow before crossing the route. Heat exchange anomalies were computed from the 1961-71 means given by Clark et al. (1974). Wind speed anomalies were computed from the 1961-76 monthly means published in 1976 issues

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[4] Professional journal of the American Meteorological Society, Vol. 105, Nos. 2-5, February-May 1977.

of *Fishing Information*.

The anomalies showed that wind speeds were lower and heat gained by the ocean was much higher in 1976 than in the previous two years. The decreased wind speeds along with occurrence of warm, moist air resulted in less evaporation and sensible heat loss and, consequently, more heat retention by the ocean (Table 7.2). Decreased wind speeds also permitted more stratification in the ocean and thus a greater positive surface temperature anomaly from the excess heat gain.

The major characteristics of anomalies which stand out in Table 7.2 are:

1) In both quadrangles there was a month to month consistency of heat exchange anomalies in 1976, particularly as compared with 1974. The same consistency occurred in the anomalies of wind speed.

2) Above normal retention of heat by the ocean because of reduced evaporation was the major component in 1976. Above normal incoming radiation and lower flux of sensible heat were secondary terms. Year to year changes of effective back radiation were relatively small.

3) The total heat flux anomaly in 1976, the anomaly from decreased evaporation, and the wind speed anomaly were larger in magnitude in the area to the north of the route (upcurrent) than in the immediate area of the XBT observations.

The data presented in Table 7.2 indicated that processes (heat exchange and vertical mixing) previously considered small as compared with advective processes were, at least partially, responsible for the late 1976 reversal of the relation of salinity anomalies to temperature anomalies observed in 1972-75. We are mindful that this argument is based on the assumption that the salinity anomalies resulted from advection and that the temperature anomalies were atypical. It is not immediately apparent how one could interpret the data if the temperature anomalies were assumed to be advective and it were necesssary to explain the salinity anomalies as atypical.

ACKNOWLEDGMENTS

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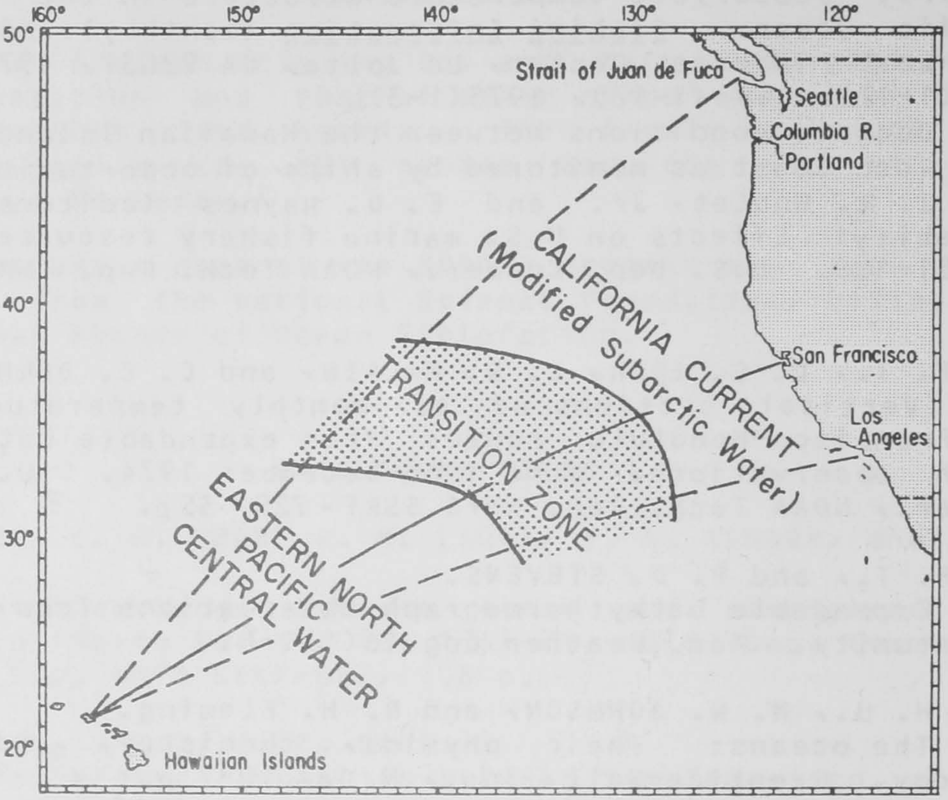


Figure 7.1.—Three oceanic domains (schematic) in the eastern North Pacific Ocean crossed by cooperating merchant ships taking surface salinity and expendable bathythermograph observations during 1976. Observations reported herein were taken on the San Francisco to Honolulu route (solid line).

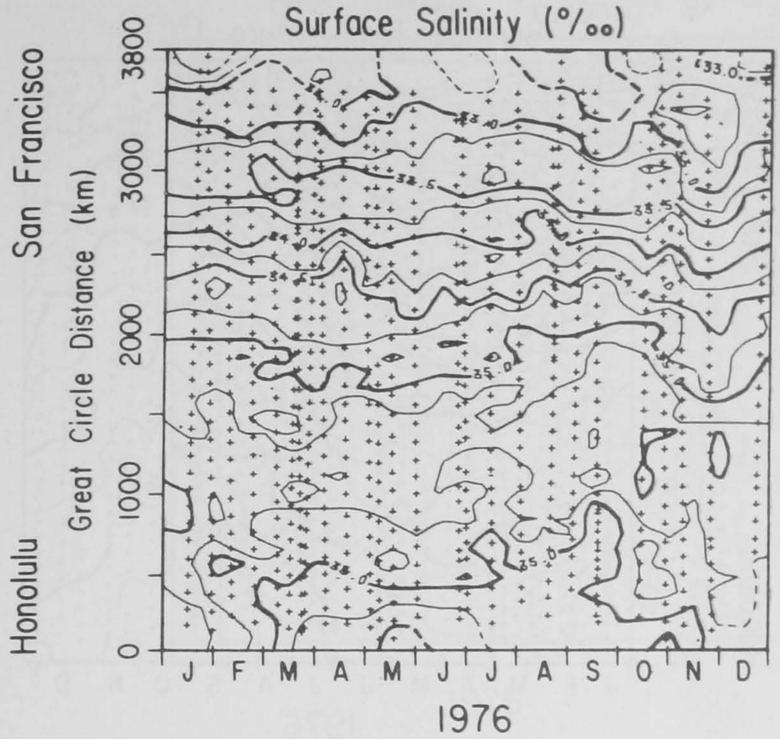
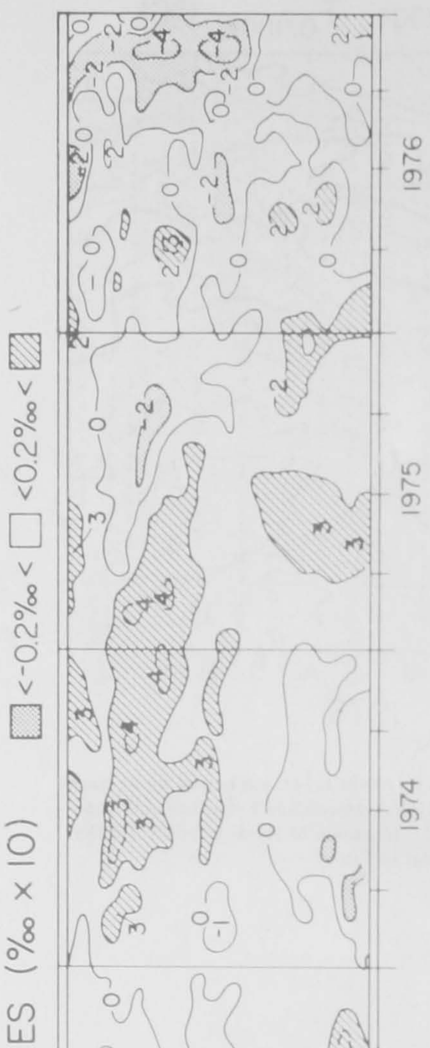


Figure 7.2.—Surface salinity in parts per thousand (‰) between San Francisco and Honolulu during 1976. Symbols (+) indicate the locations of observations in time and distance. Contour interval is 0.25‰.


SURFACE SALINITY ANOMALIES (‰ × 10)
▨ < -0.2‰ < ☐ < 0.2‰ < ▨
San Francisco
Honolulu
Great Circle Distance (km)
0
1000
2000
3000
3800
1972
1973
1974
1975
1976


SURFACE TEMPERATURE ANOMALIES (°C)
▨ < -0.5°C < ☐ < 0.5°C < ▨
San Francisco
Honolulu
Great Circle Distance (km)
0
1000
2000
3000
3800
1972
1973
1974
1975
1976

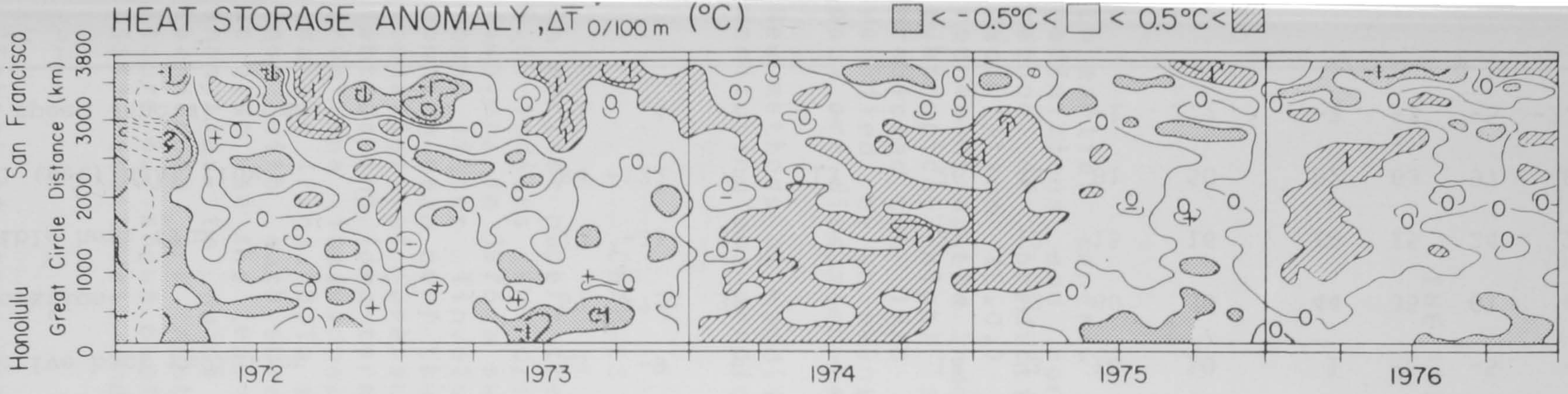


Figure 7.5.—Anomalies on the San Francisco-Honolulu route, January 1972-December 1976. Analyses in all three panels were smoothed before contouring (see text). Upper: Salinity anomalies; labels on contours are the anomaly multiplied by 10. Center: Sea surface temperature anomalies; contour interval is 0.5C. Lower: Heat storage anomalies for the surface to 100-m layer, expressed as departure from the mean of average temperature (T) 0-100 m in degrees Celsius.

TABLE 7.2. Anomalies of heat exchange (cal cm^{-2} d^{-1}) and of wind speed (knots) at two 5-degree quadrangles in the California Current Region. Quadrangles lie a) on San Francisco to Honolulu ship route and b) upcurrent from route. Positive (negative) values indicate anomalous heat gain (loss) by the ocean.

	1974			3-mo	1975			3-mo	1976			3-mo
	Oct	Nov	Dec	mean	Oct	Nov	Dec	mean	Oct	Nov	Dec	mean
On route (lat. 35°-40°N, long. 125°-130°W):												
Incoming radiation	19	-4	9	8	-12	3	-18	-9	7	3	23	11
Effective back radiation	-10	-6	1	-5	7	-7	19	6	-3	-6	-10	-6
Evaporation	-3	-58	26	-12	-18	-40	54	-1	13	19	17	16
Sensible heat flux	-4	-16	13	-2	10	-4	14	7	1	-3	11	3
Total (net) heat flux	2	-84	49	-11	-13	-48	69	3	18	13	39	23
Wind speed (knots) anomaly	-1	-2	0	-1	1	1	-1	0.3	-3	-3	-2	-2.7
Upcurrent from route (lat. 40°-45°N, long. 125°-130°W):												
Incoming radiation	-3	-10	4	-3	-20	11	-10	-6	20	15	17	17
Effective back radiation	13	-9	6	3	18	-3	16	10	1	-2	-5	-2
Evaporation	57	-73	39	8	8	22	60	30	44	35	61	47
Sensible heat flux	17	-31	26	4	21	12	15	16	18	15	24	19
Total (net) heat flux	84	-122	76	13	26	43	81	50	82	63	97	80
Wind speed (knots) anomaly	-1	4	-1	0.7	4	2	-1	1.7	-2	-3	-5	-3.3

Paper 8

THE 1976 EL NINO AND RECENT PROGRESS IN MONITORING AND PREDICTION

William H. Quinn[1]

INTRODUCTION

In earlier papers, the author (Quinn 1974, 1976) presented definitions and concepts regarding the El Nino phenomenon and a method of predicting its occurrence utilizing Southern Oscillation (S.O.) indices (pressure differences between sites representing the Indonesian equatorial low and South Pacific subtropical high) and other variables. In 1975, Quinn (1978) predicted the 1976 El Nino type event. The prediction was verified by an event of moderate intensity, and indications from data are discussed here.

New methods of handling pressure indices and other variables for monitoring and predicting El Nino are presented in this paper.

CHANGES IN FILTER AND DATA APPLICATIONS

In earlier papers the 12-mo running mean filter was applied to S.O. indices in order to bring out interannual fluctuations. However, in 1976 a switch was made to the triple 6-mo running mean filter (involving three successive passes of the 6-mo running mean over the involved data); and this was applied to anomalies of pressure difference (with anomalies obtained by subtracting long-term monthly mean values of pressure difference from the individual monthly values) to show the interannual changes (Figs. 8.1a and 8.1b). Since three months of time are lost with each successive application of the 6-mo running mean, we also use the less-smooth 3-mo running mean plot of index anomalies to guide our assessments and outlooks. The same techniques are applicable to data for other variables. Figure 8.2 shows plots of pressure index, sea surface temperature (SST), sea level, and rainfall anomalies for near equatorial

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[1] School of Oceanography, Oregon State University, Corvallis, OR 97331.

sites that reflect the interannual changes discussed in this paper. Due to the large month to month variations in pressure and rainfall, a higher degree of smoothing was applied to their anomalies in this illustration.

The El Nino (EN) type activity sets in prior to and/or in conjunction with the relaxation troughs following anti-El Nino peaks in the anomalies. The intensity of such events depends not only on the degree of relaxation but also on the time of year that it occurs. The stronger cases [denoted by EN(S) and EN(M) in Figs. 8.1a and 8.1b for strong and moderate, respectively, El Ninos] occurred when the interannual relaxation was large and indices continued to fall rapidly through the early months of the year so as to reinforce the regular seasonal relaxation of the southeast trade system (Southern Hemisphere summer season). Cases where the interannual relaxation was too small, or it occurred too early or too late to follow through the seasonal relaxation period, resulted in weaker El Nino events.

The studies of Berlage (1957, 1966) and Troup (1965) indicated that the S.O. affected not only the South Pacific subtropical high but also the North Pacific subtropical high region. This relationship was explored superficially in Quinn and Zopf (1975); however, in that case the Easter Island component was compared to the former Ship N location component using the 12-mo running mean filter. Here we consider Rapa, Austral Islands, in relation to the old Ship N position, because it is much nearer the same longitude, and use the smoother triple 6-mo running mean filter on the index anomalies. A maximum correlation of 0.59 at no lag was obtained in this case. (This is well within the 1% confidence level.) Figure 8.3 compares the Rapa-Darwin index to the Ship N-Darwin index. (The plots are correlated at 0.80.) From visual inspection one can see there is no consistent lead-lag relationship between the two index trends; in one case the change in trend will show up first south of the equator and in another it will show up first north of the equator; nevertheless, it is evident that the two high pressure areas are being similarly affected by the S.O. In the future, indications from the Ship N-Darwin index will also be actively considered for outlooks on El Nino and equatorial Pacific activity.

USE OF SEA SURFACE TEMPERATURE TRENDS

A close relationship of fluctuations in north equatorial countercurrent transport and resulting sea surface temperature (SST) anomalies off the coast of Central America (illustrated in fig. 2 of Wyrtki 1973) to the interannual variations in southeast trade strength (as reflected in the 12-mo running mean trend of the S.O. index), was noted in Quinn (1974). In a recent climatological investigation of the southeast part of the North Pacific, time series plots of SST were studied for several Marsden Square (MS) quadrants in order to find particularly suitable areas for diagnosing changes associated with the El Nino type developments. Figure 8.4 shows two of the quadrants selected; MS 10(1) reflects changes taking place along the equator, and MS 10(3) reflects changes in an area affected by the north equatorial countercurrent. Figure 8.5 shows how the Easter-Darwin index anomaly trend relates to SST anomaly trends for MS 10(1) and MS 10(3) when the data are subjected to the triple 6-mo running mean filter. MS 10(1) is next to the equator, and when the circulation is relatively strong (S.O. index is high) it shows lower SST's due to the advection of cooler Peru current water into the area and/or equatorial upwelling; when the circulation is weak (index is low), SST's rise. MS 10(3) SST's reflect changes in the north equatorial countercurrent transport discussed early in the section. Table 8.1 shows lag correlation coefficients between index and SST anomalies. Changes show up about a month earlier in the index than in the MS 10(1) SST trend and about three months earlier than in the MS 10(3) SST trend. Events of significant magnitude are reflected in both the index and SST trends of Fig. 8.5. The value of the corroborative SST evidence is shown in 1961, when the indication of a fairly deep Easter-Darwin index trough was not substantiated in the SST trend. Since this trough was of much less significance in the other index trends of Fig. 8.1a, an unrepresentatively low Easter input was the misleading factor in this case. As an interesting sidelight, Berlage in 1960 put out a widely publicized forecast for an El Nino in 1961 (Schweigger 1961). However, there was no significant El Nino development in 1961. A comparison of the Easter-Darwin index anomalies with anomalies of the other indices and the MS 10(1) SST anomalies would have precluded the forecast.

Three-month running mean plots of the index anomalies and the SST anomalies for MS 10(1) (Fig. 8.6) become particularly useful to the forecast process between 18 and 3 months prior to the onset of El Nino. However, they should also be followed closely during the course of an event to determine whether a subsequent secondary trough in the index is likely or a persistent recovery from the initial event is probable.

THE 1976 EL NINO EVENT

In summer 1975 an outlook for El Nino type activity in 1976 was prepared. The outlook was given at the October 1975 Eastern Pacific Oceanic Conference and at several subsequent meetings, workshops, and seminars. The 12-mo running mean of the Easter-Darwin index was predicted to rise from the shallow early 1975 trough to a small peak by the middle to latter part of 1975 and then to fall off to a deeper trough in 1976. The analog selected for this development was the 1964-65 situation. (There was a rise from a shallow index trough in late 1963 to a small peak in mid-1964, then a fall to a deep trough in 1965 when an El Nino occurred.) Heavy western equatorial Pacific precipitation was called for in the latter half of 1976-early 1977.

The expected small peak in the interannual index trends occurred in late 1975 and there has been a falling trend since then (Fig. 8.1b). Figure 8.5 shows the corroborative rise in SST anomalies as the index fell. Figure 8.6 shows the deep 3-mo running mean trough in index anomaly and the associated large peak in SST anomaly for MS 10(1). Figure 8.7 shows the positive SST anomalies off the coast of Peru and southern Ecuador extending westward over the equatorial Pacific. Table 8.2 shows the SST and SST anomalies for two stations along the coast of Peru during 1975-76, and Table 8.3 shows precipitation at Guayaquil, Ecuador, during the last three El Nino events. (The 1972-73 case is considered to be strong, 1975 very weak, and 1976 moderate in intensity.) Tarawa, Gilbert Islands, data have been used to represent the western equatorial Pacific rainfall; and the triple 6-mo running mean trend of the rainfall anomalies clearly shows the rainfall peak (Fig. 8.2). For the period April-December 1976 the rainfall was 1,130 mm above normal and it is expected that a few more months of this heavy rainfall will occur in early 1977. El Nino evidence indicated that the forecast for the 1976 event was accurate as to time of occurrence and intensity (similar to the selected 1965 analog). Figure 8.2 shows how trends of variables at various locations were affected by this recent El Nino.

FURTHER OUTLOOK

In the summer of 1976, the further outlook to the Coastal Upwelling Ecosystem Analysis (CUEA) Peru project called for a hold-over of the 1976 positive SST anomalies through February 1977 along the Peruvian coast, with a return to near normal coastal SST's by March or April 1977. The analog given for the 1976-77 holdover effect was the 1965-66 situation; however, the 1976 onset was a month or two later (than in 1965) and the lag effect in 1977 was also expected to be a month or two later (than in 1966).

In retrospect, Wyrtki et al. (1976) reported that a patch of the warm water that crossed the equator in the southward transgression of early 1975 had been cut off and remained south of the equator. Monthly SST analyses[2] showed this warm body of

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[2] *Fishing Information*, 1975 and 1976, Southwest Fisheries Center, NMFS, NOAA, La Jolla, CA 92038.

water to remain west of Peru through the rest of 1975 and on into 1976. This residual effect along with the event triggered by large-scale relaxation in the southeast trade system between late 1975 and mid-1976 [as characterized by the falling indices following the late 1975 peaks (Fig. 8.1b)] most likely caused the 1976 El Nino to appear as it did.

CONCLUDING REMARKS

Large-scale climatic patterns, as well as fluctuations in oceanographic conditions in the eastern tropical Pacific and particularly in the Peru fishery region, appear to be closely associated with the S.O. We have found that to a large extent we can use trends in S.O. indices to anticipate extremes in the fluctuations and provide outlooks for environmental change. We hope in the future to substantially improve our ability to predict climatic changes and to be able to roughly assess their environmental impact so that plans can be set in motion to minimize effects on the fishery. However, fishery management must be capable of using monitoring and prediction data to establish suitable fishing practices. So far this has not been the case. In both 1972 and 1976 the main fishing season (March-May) proceeded without considering an El Nino that was already underway; and in both cases it could be argued that the reproductive stock should have been conserved so as to minimize the recruitment failures in 1973 and 1977.

ACKNOWLEDGMENTS

I thank the Director of the Civil Aviation Service and the Chief of the Meteorological Service of Polynesie, Francaise; the President of the Instituto del Mar del Peru; the Director of the Australian Bureau of Meteorology; the Director of the Hydrographic Institute and Chief of the Naval Weather Service of the Armada de Chile; the National Climatic Center, Environmental Data Service, NOAA; the Pacific Environmental Group, National Marine Fisheries Service (NMFS), NOAA; and the Southwest Fisheries Center, NMFS, NOAA for their invaluable support to this study. I am greatly indebted to Forrest R. Miller of the Inter-American Tropical Tuna Commission and Richard Evans of the Southwest Fisheries Center for timely information on sea temperatures and weather conditions over the eastern tropical Pacific and to Jose M. Diaz-Andrade, Universidad, Costa Rica for the Quepos sea level data. I also thank Kent Short, now with the Western Region (Seattle), National Weather Service, NOAA, and Clayton Creech and David Zopf of the School of Oceanography, Oregon State University, for their active participation in this project. Support by the National Science Foundation under the North Pacific Experiment of the International Decade of Ocean Exploration through NSF Grant No. OCE 75-21907 A01 and under the Climate Dynamics Program of the Division of Atmospheric Sciences through NSF Grant No. ATM 77-00870 is gratefully acknowledged.

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Table 8.1.--Lag correlation coefficients between Easter-Darwin (E-D) index anomalies and sea surface temperature (SST) anomalies for Marsden Square (MS) 10(1) and Marsden Square 10(3). See Table 8.4.

Lag in Months	E-D index and SST for MS 10(1)	E-D index and SST for MS 10(3)
-2	-0.693	
-1 (index lags SST)	-0.732	-0.588
0 (no lag)	-0.755	-0.636
1 (index leads SST)	-0.761	-0.672
2	-0.748	-0.694
3	-0.717	-0.702
4	-0.668	-0.693
5		-0.668
Period of record	1948-76	1949-76

Table 8.2.--Monthly mean sea surface temperatures and anomalies of temperatures (degrees C) for Talara and Chimbote, Peru, 1975-1976. See Table 8.4.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Talara												
1975	16.3	18.6	22.4	21.5	19.8	17.8	18.0	17.7	18.1	18.1	16.2	17.7
	-4.2	-3.2	+1.0	+1.3	+0.6	-0.5	+0.2	+0.1	+0.7	+0.4	-1.8	-0.6
1976	20.5	24.4	23.6	21.4	21.7	21.2	21.2	19.0	18.9	19.5	20.1	20.3
	+0.0	+2.6	+2.2	+1.2	+2.5	+2.9	+3.4	+1.4	+1.5	+1.8	+2.1	+2.0
Chimbote												
1975	20.5	21.0	24.2	21.2	21.1	18.7	17.6	17.0	16.6	17.0	17.3	18.0
	-0.2	-0.8	+2.0	+0.3	+1.4	+0.1	-0.2	-0.6	-0.6	-1.0	-1.4	-1.6
1976	18.5	21.8	23.5	21.4	21.1	21.1	20.3	20.0	19.2	19.5	20.1	21.6
	-2.2	+0.0	+1.3	+0.5	+1.4	+2.5	+2.5	+2.4	+2.0	+1.5	+1.4	+2.0

Table 8.3.--Rainfall (mm) at Guayaquil, Ecuador for the indicated months. See Table 8.4.

	1972		1973		1975		1976	
Months	Total	Departure	Total	Departure	Total	Departure	Total	Departure
January	220	+9	701	+490	221	+10	417	+206
February	330	+45	210	-75	487	+202	586	+301
March	407	+115	492	+200	607	+315	450	+158
April	143	-62	181	-24	202	-3	182	-23
May	35	-19	136	+82	2	-52	144	+90
June	152	+141	3	-8	4	-7	10	-1

Table 8.4.--Location of stations used in the several indices.

Chimbote, Peru	9S10'	78W31'
Darwin, Australia	12S28'	130E51'
Easter Island	27S10'	109W26'
Guayaquil, Ecuador	2S10'	79W50'
Juan Fernandez Island	33S37'	78W50'
Marsden Square 10(1)	0-5N	90-95W
Marsden Square 10(3)	5-10N	90-95W
Quepos, Costa Rica	9N25'	84W10'
Rapa, Austral Islands	27S37'	144W20'
Ship N	30N	140W
Tahiti, Society Islands	17S33'	149W37'
Talara, Peru	4S34'	81W15'
Tarawa, Gilbert Islands	1N22'	172E58'
Totegegie, Gambier Island	23S06'	134W25'

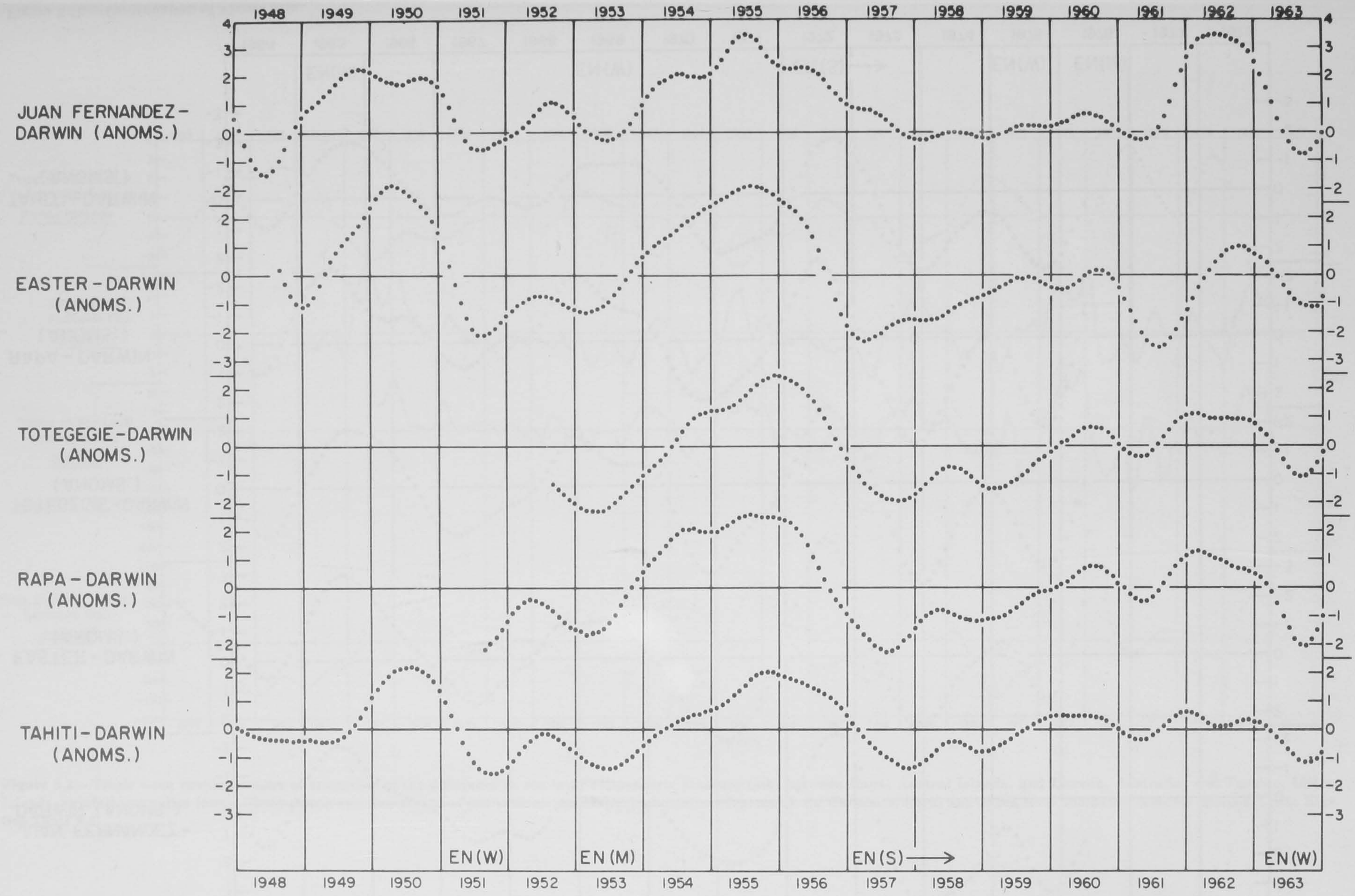

Figure 8.1a.—Triple 6-mo running means of anomalies of the difference in sea level atmospheric pressure (mb) between Darwin and Juan Fernandez, Easter, Totegegie, Rapa, and Tahiti. El Nino type events (EN) are indicated as strong (S), moderate (M), and weak or very weak (W). See Table 8.4.

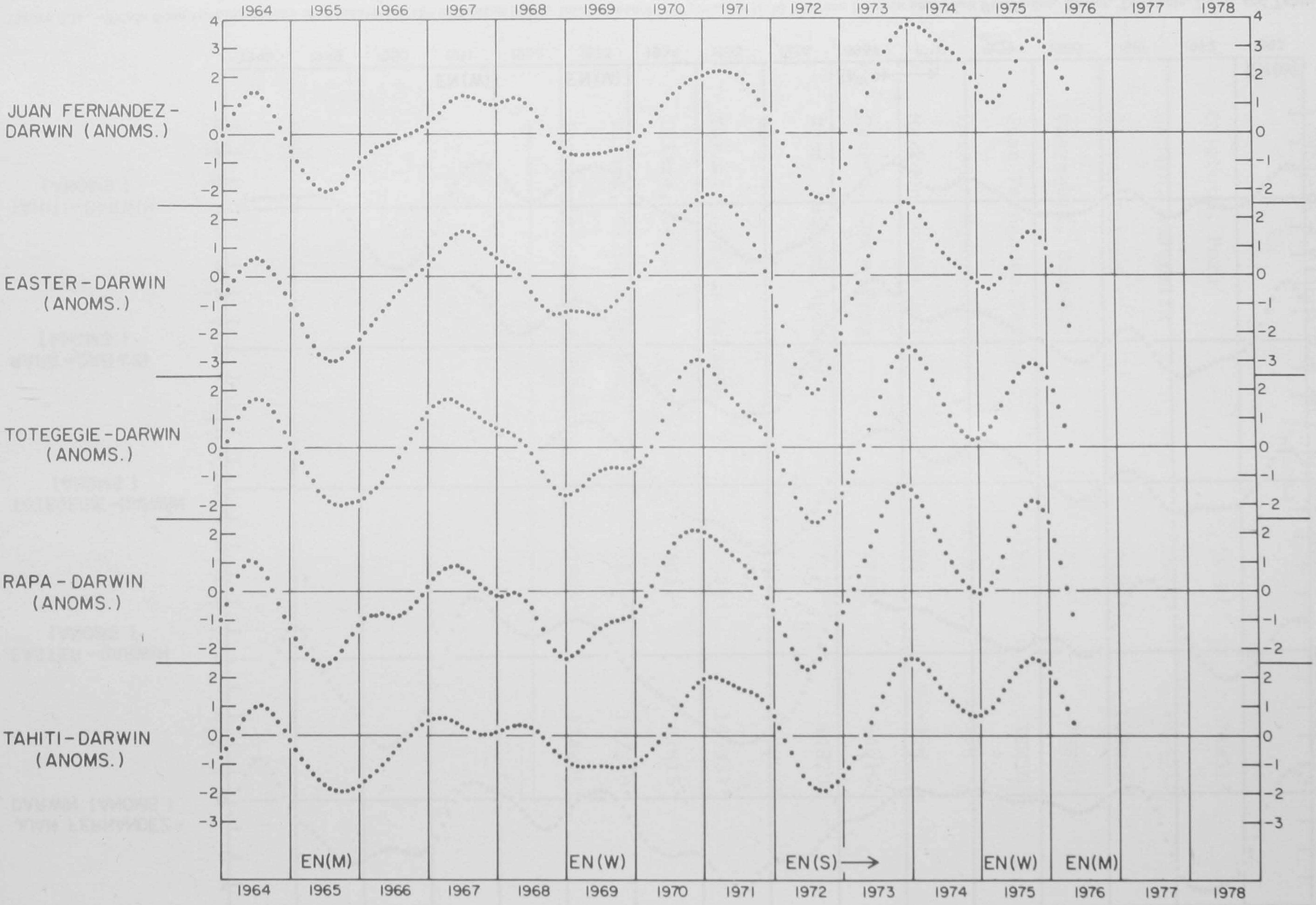

Figure 8.1b.—Continuation of Figure 8.1a.

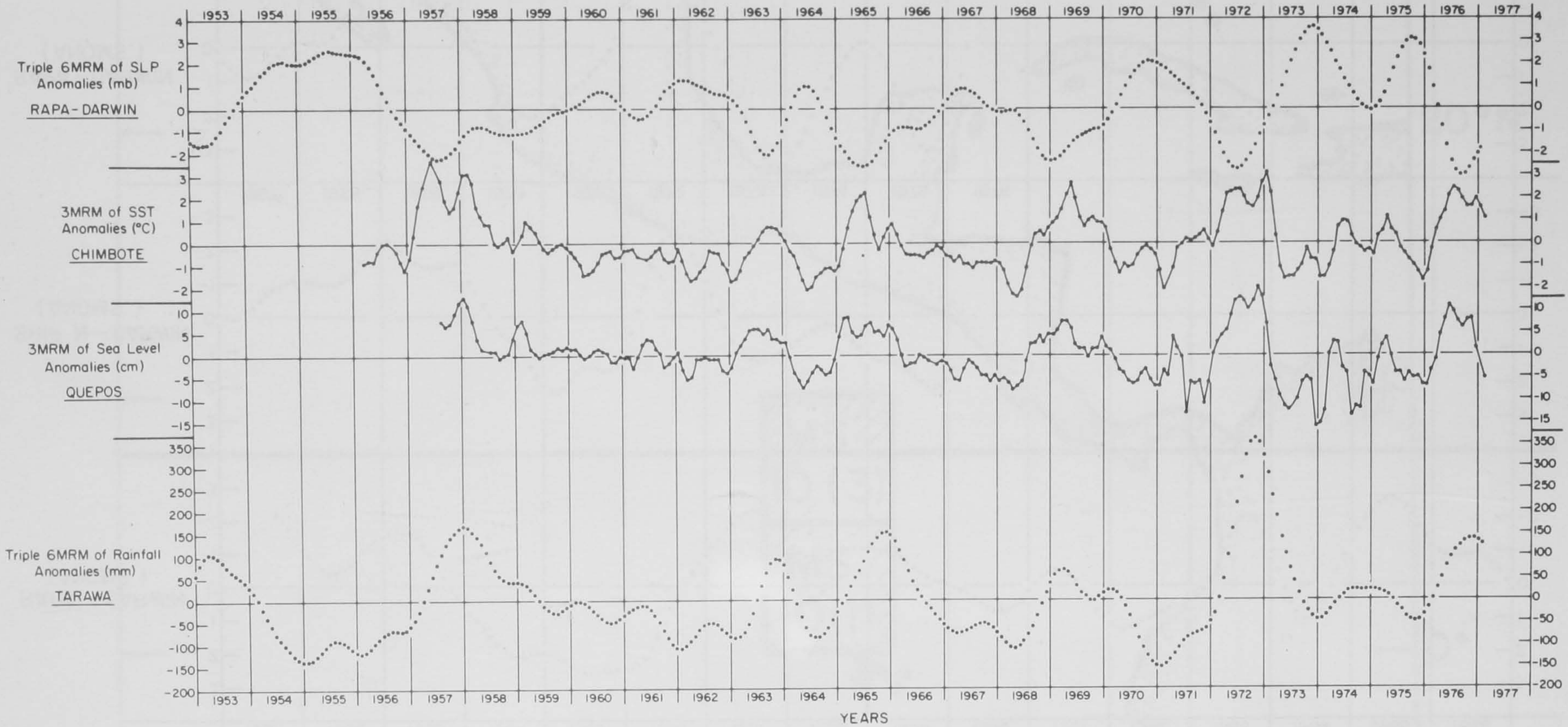

Figure 8.2.—Triple 6-mo running means of anomalies of the difference in sea level atmospheric pressure (mb) between Rapa, Austral Islands, and Darwin, Australia, and Tarawa, Gilbert Islands, rainfall anomalies (mm). Three-month running means of sea surface temperature anomalies (degrees C) for Chimbote, Peru, and of sea level anomalies (cm) for Quepos, Costa Rica. See Table 8.4.

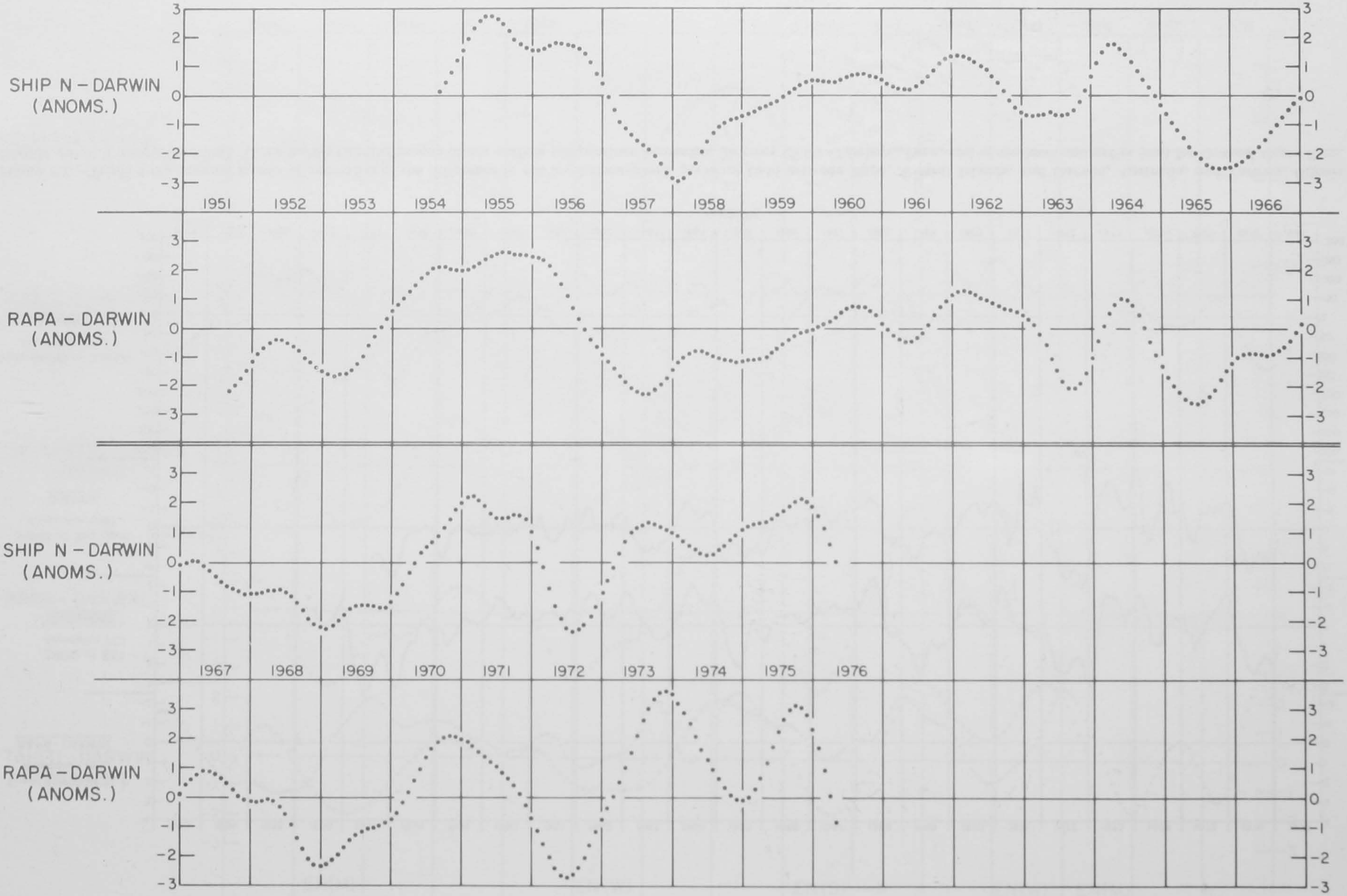

Figure 8.3.—Triple 6-mo running means of the difference in sea level atmospheric pressure (mb) between Ship N and Darwin, Australia, and between Rapa, Austral Islands, and Darwin. See Table 8.4.

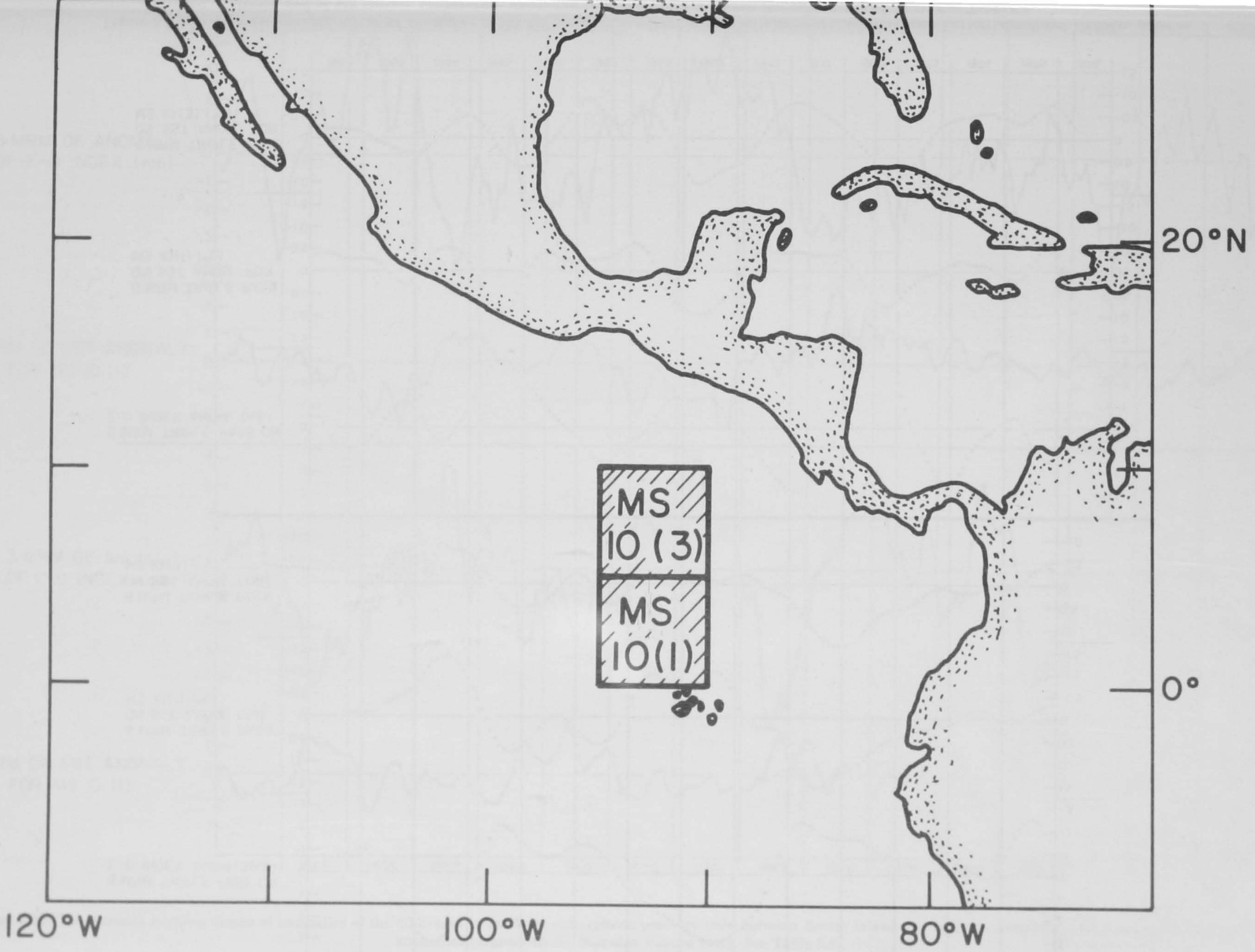

Figure 8.4.—Locations of Marsden Square quadrants 10(1) and 10(3). See Table 8.4.

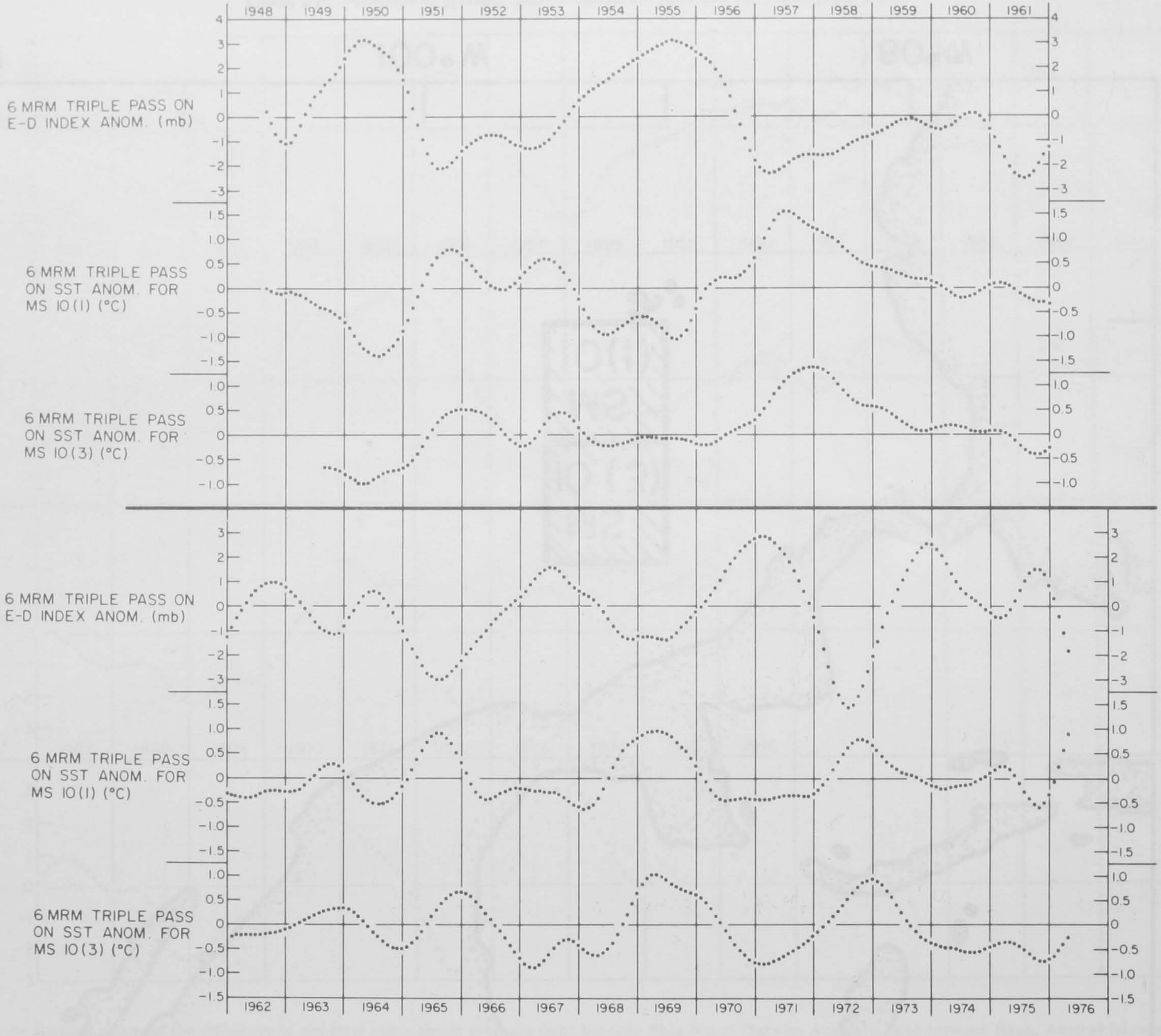

Figure 8.5.—Triple 6-mo running means of anomalies of the difference in sea level atmospheric pressure (mb) between Easter Island and Darwin, Australia, and of sea surface temperature anomalies (degrees C) for Marsden Squares 10(1) and 10(3). See Table 8.4.

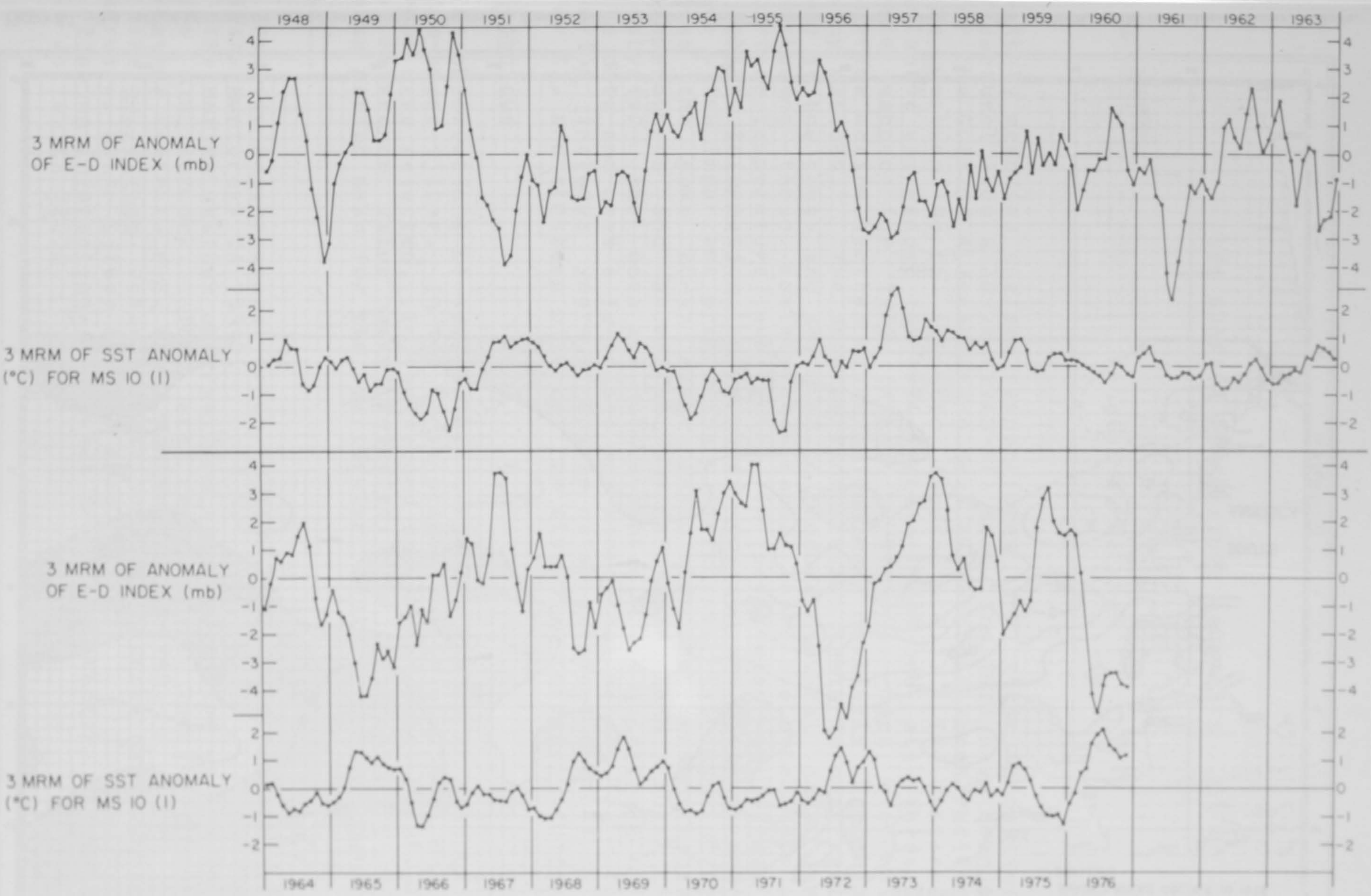

Figure 8.6.—Three-month running means of anomalies of the difference in sea level atmospheric pressure (mb) between Easter Island and Darwin, Australia, and of sea surface temperature anomalies (degrees C) for Marsden Square 10(1). See Table 8.4.

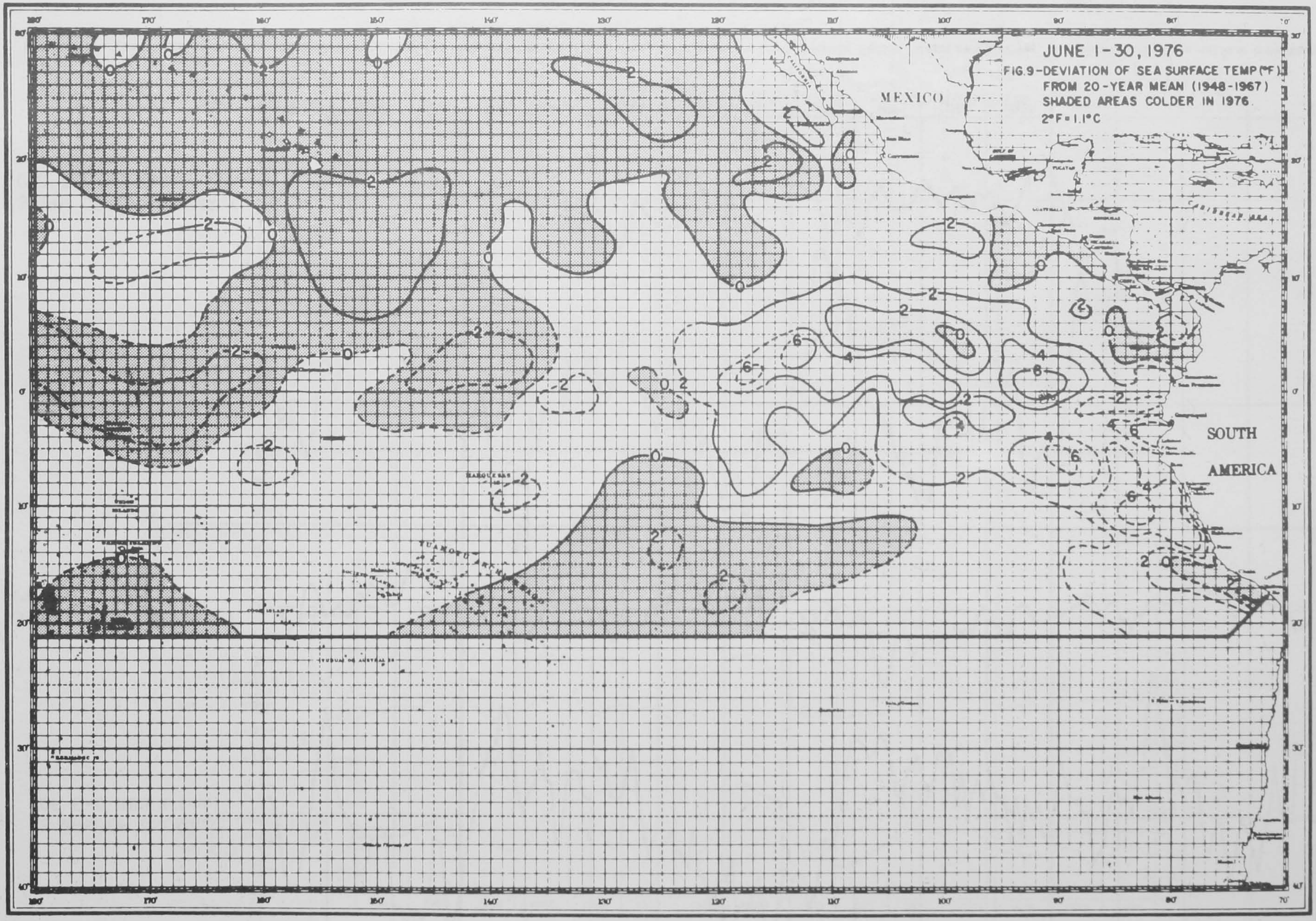

Figure 8.7.—Sea surface temperature anomalies (deviations, degrees F, from 1948-67 mean) for June 1976 (from *Fishing Information*, 1976, No. 6, NMFS, Southwest Fisheries Center, La Jolla, CA 92038)

Paper 9

SEA SURFACE TEMPERATURE ANOMALIES

Douglas R. McLain[1]

Monthly mean sea surface temperatures and their anomalies, or departures from a 20-yr (1948-67) mean, for 1976 have been mapped for the Gulf of Alaska-Bering Sea, the eastern North Pacific, and the western North Atlantic (Appendix 9.1). The western North Atlantic was mapped for 1974 (McLain 1976) and all three areas were mapped for 1975 (McLain 1978). The maps are based on surface marine weather observations made routinely by ships of many nations.[2] The observations are available in near real-time and at low cost, and are used to produce several data products including these monthly mean maps. There are other maps of sea surface temperature available, in particular *gulfstream*[3] and *Fishing Information*.[4] The areas covered are distinct and there are a few important processing differences. *Fishing Information* uses the same 20-yr base period as the present maps. The temperatures and anomalies are contoured and thus reflect analysis; the data are not presented. The *gulfstream* presents the data and uses a full data set historical mean. The reference period includes years of sparse data, particularly before World War II, and clusters of data from classical research cruises.

Technique

The observations of sea surface temperature were edited through a two-stage filter. In the first stage, all observations <-2.0C or >40C were rejected. In the second stage, observations >8.0C from a reference value were rejected. The reference value was the base period mean for the particular month and the particular

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[1] Pacific Environmental Group, National Marine Fisheries Service, NOAA, Monterey, CA 93940.

[2] The marine weather observations are transmitted worldwide over the GTS network. They are received at the Fleet Numerical Weather Central, U.S. Navy, Monterey, CA 93940.

[3] The *gulfstream*, Oceanographic Services Branch, National Weather Service, NOAA, Silver Spring, MD 20910.

[4] *Fishing Information*, Southwest Fisheries Center, NMFS, NOAA, La Jolla, CA 92038.

1-deg square for the first two observations of that month; for later observations the reference value was the current mean for the particular month and 1-deg square.

Saur (1963) and McLain (1976, 1978) discussed sources of error in the observations and in the maps.

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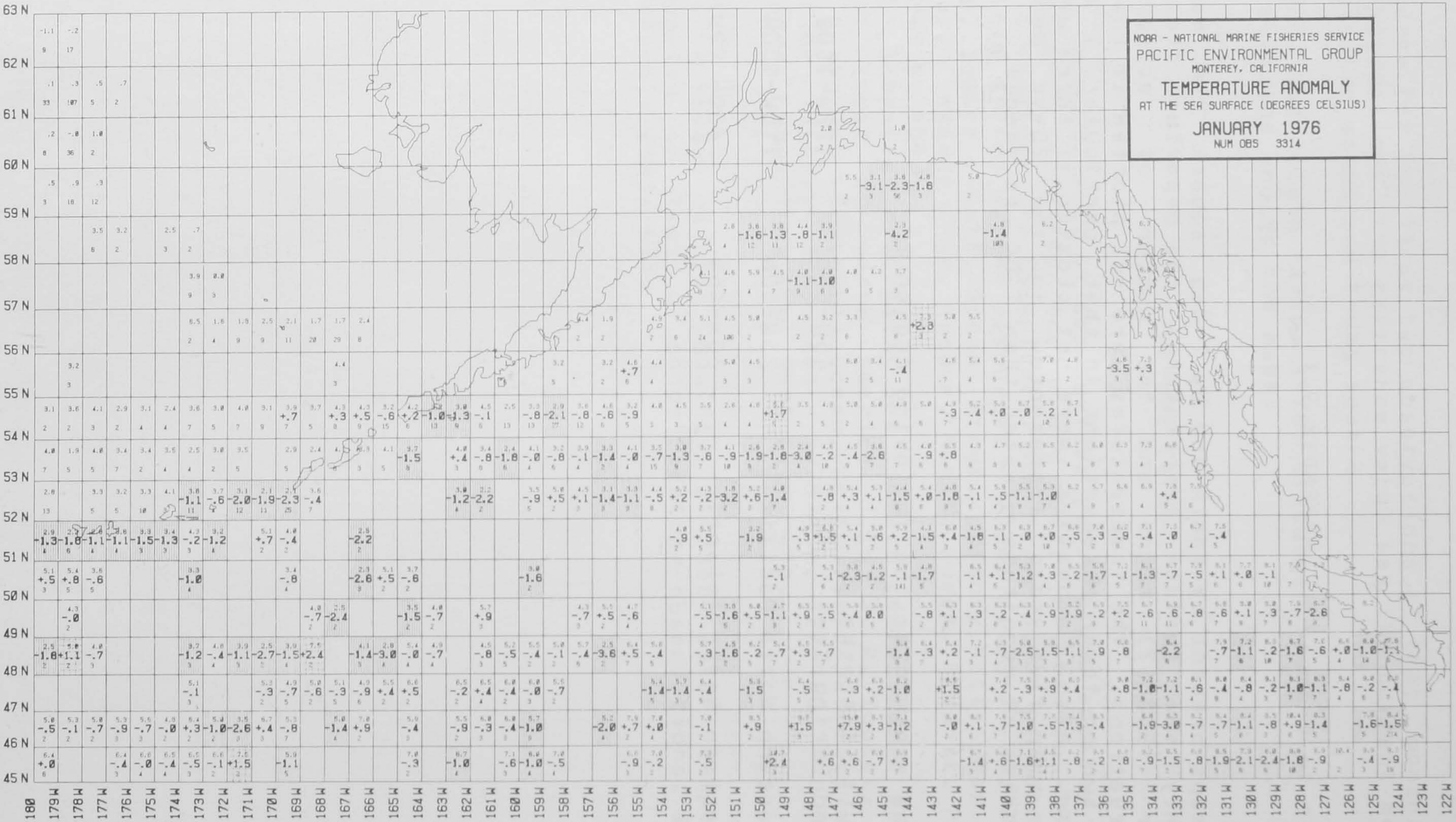
APPENDIX 9.1

The maps present by month and by 1-deg square the mean monthly sea surface temperature, the departure from a 20-yr (1948-67) mean, and the number of accepted observations. The temperatures were not plotted if there were two or fewer observations in that particular 1-deg square. Also, anomalies were not plotted if there were fewer than five years represented in the 20-yr mean. Anomalies of magnitude greater than 1.0C are shaded.

The maps cover the following regions:

Gulf of Alaska and Bering Sea	45N-63N	122W-180W
Eastern North Pacific	25N-50N	110W-150W
Western North Atlantic	20N-46N	60W- 99W



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

JANUARY 1976

NUM OBS 3314

NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

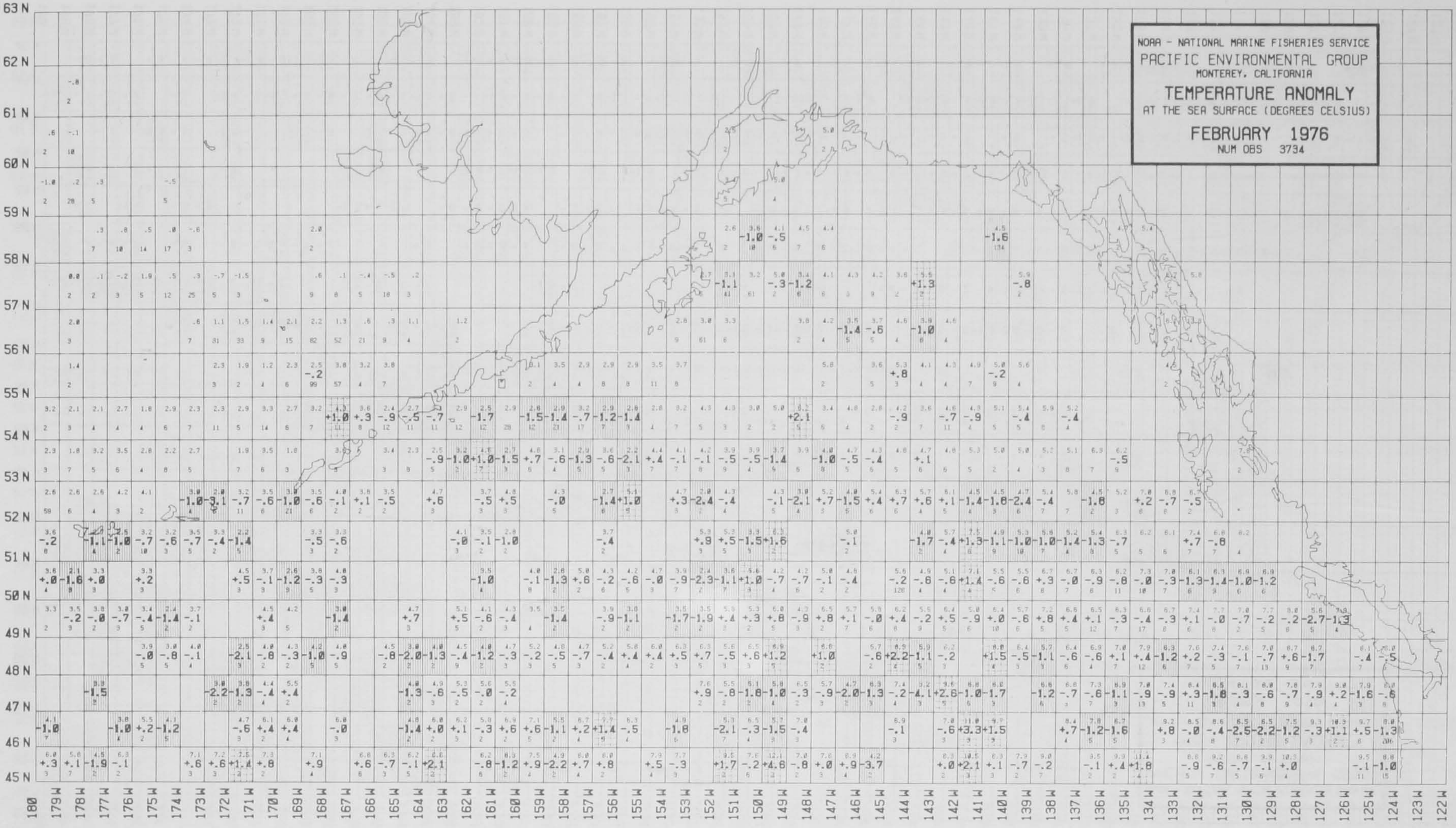
MONTEREY, CALIFORNIA

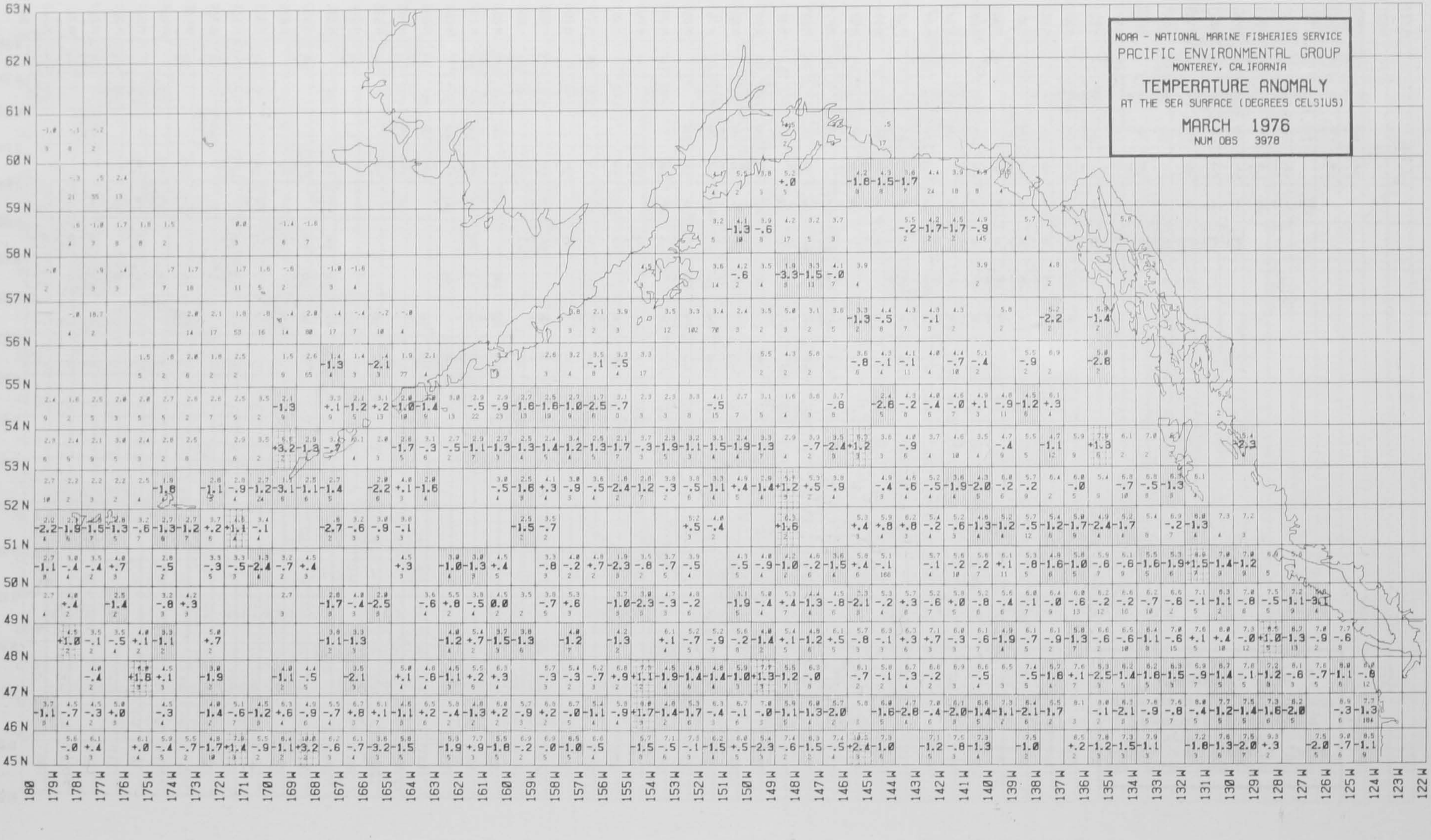
TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

FEBRUARY 1976

NUM OBS 3734





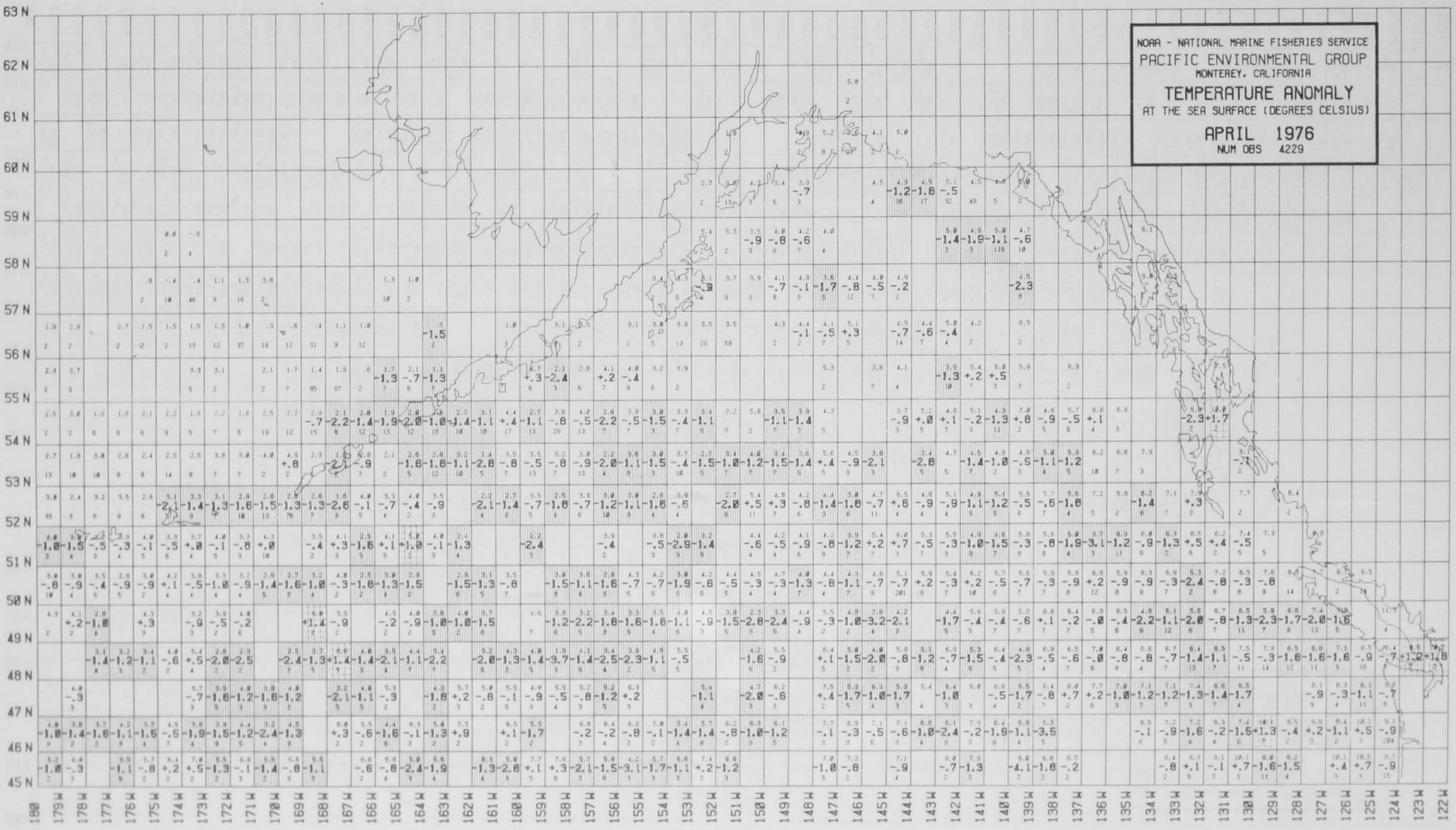
NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

MARCH 1976

NUM OBS 3978



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

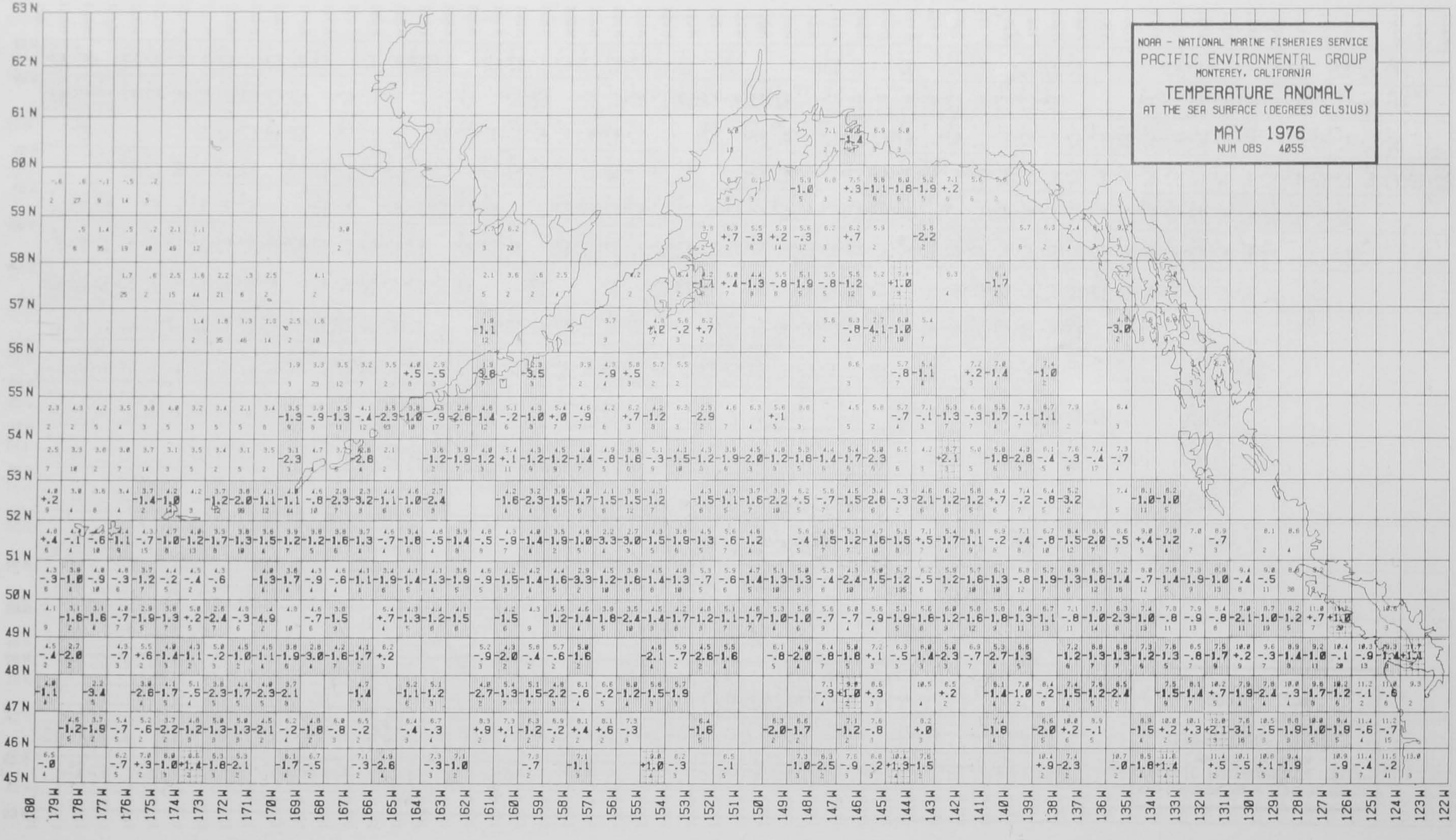
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

APRIL 1976

NUM OBS 4229



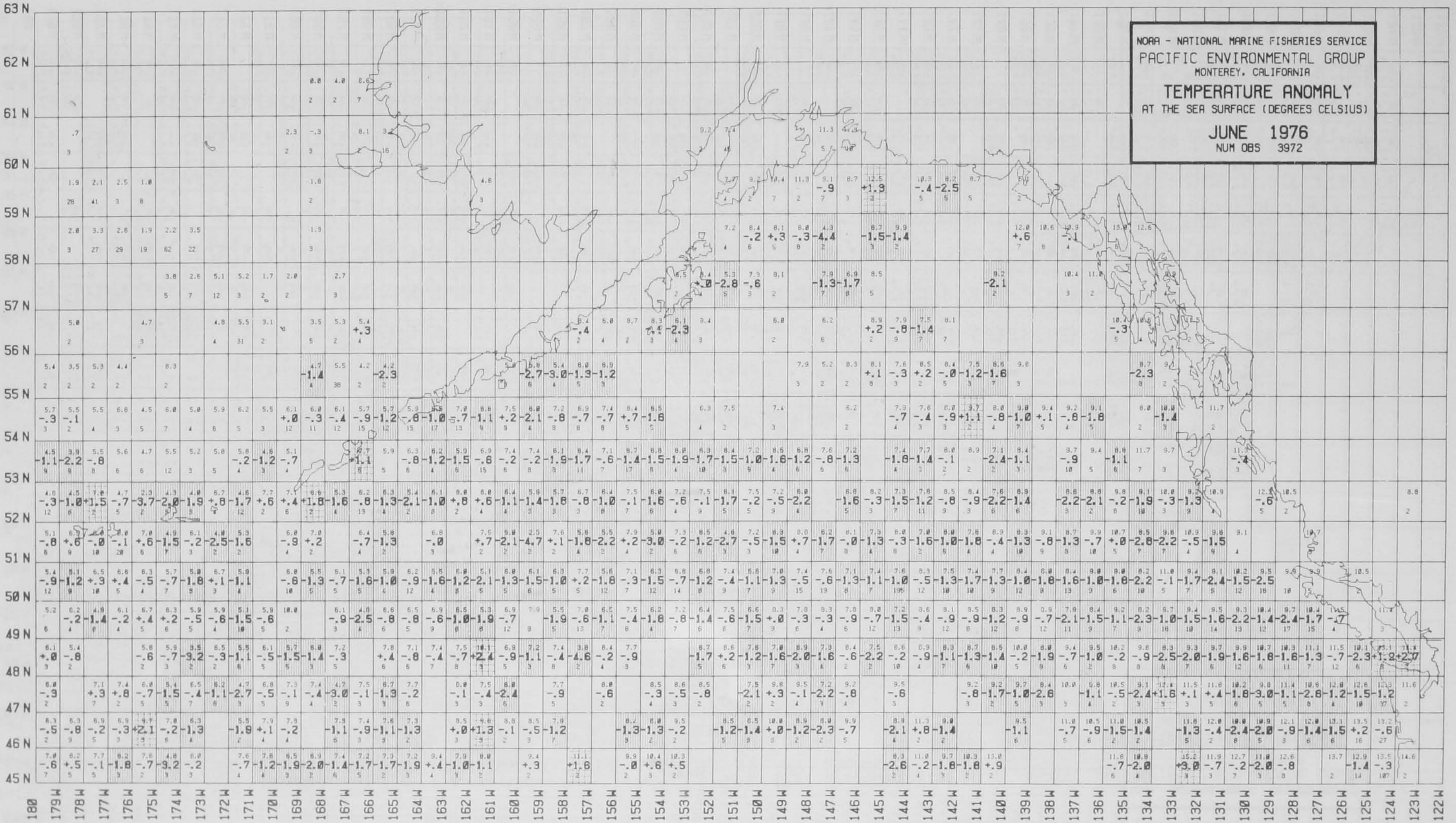
NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

MAY 1976

NUM OBS 4055



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

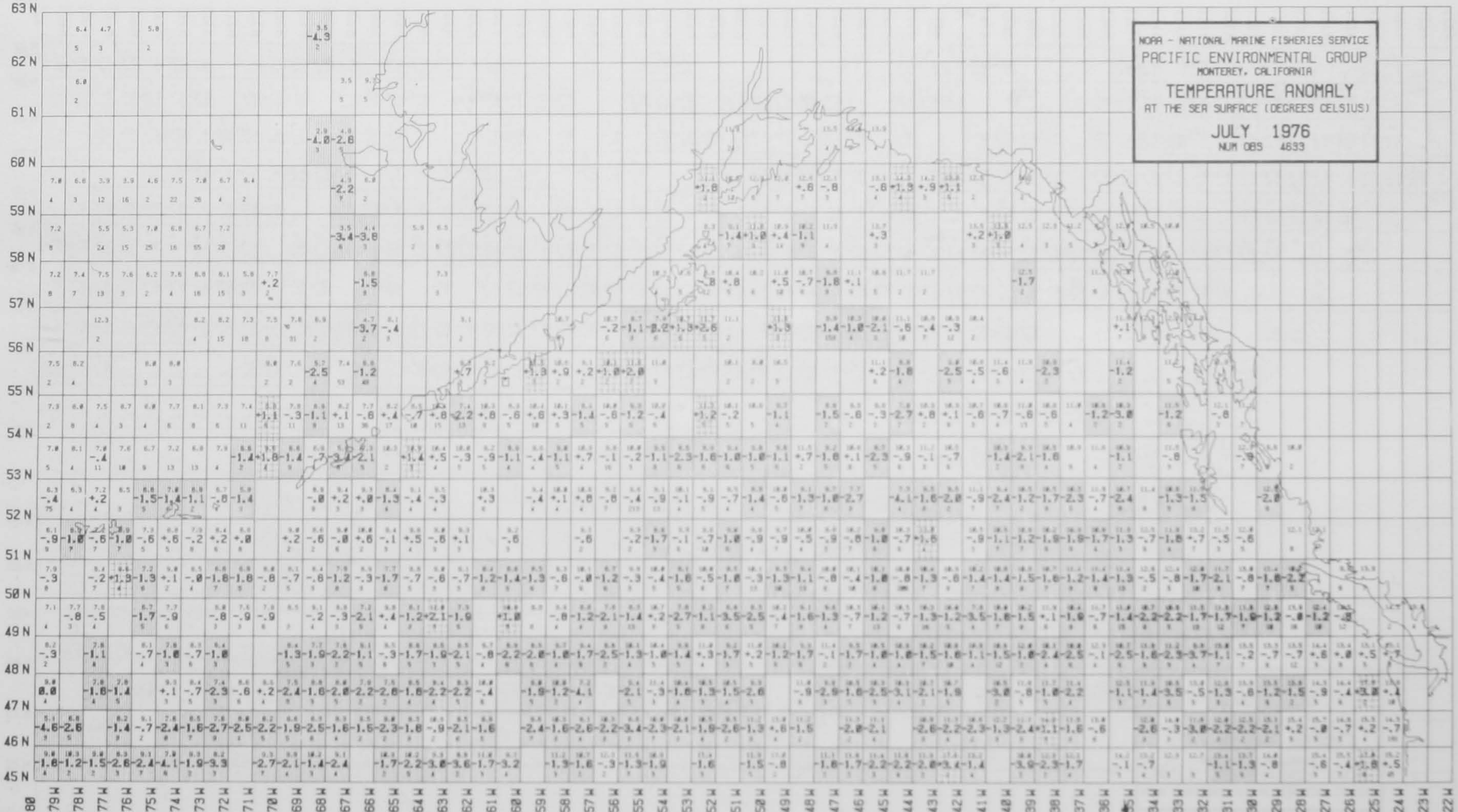
MONTEREY, CALIFORNIA

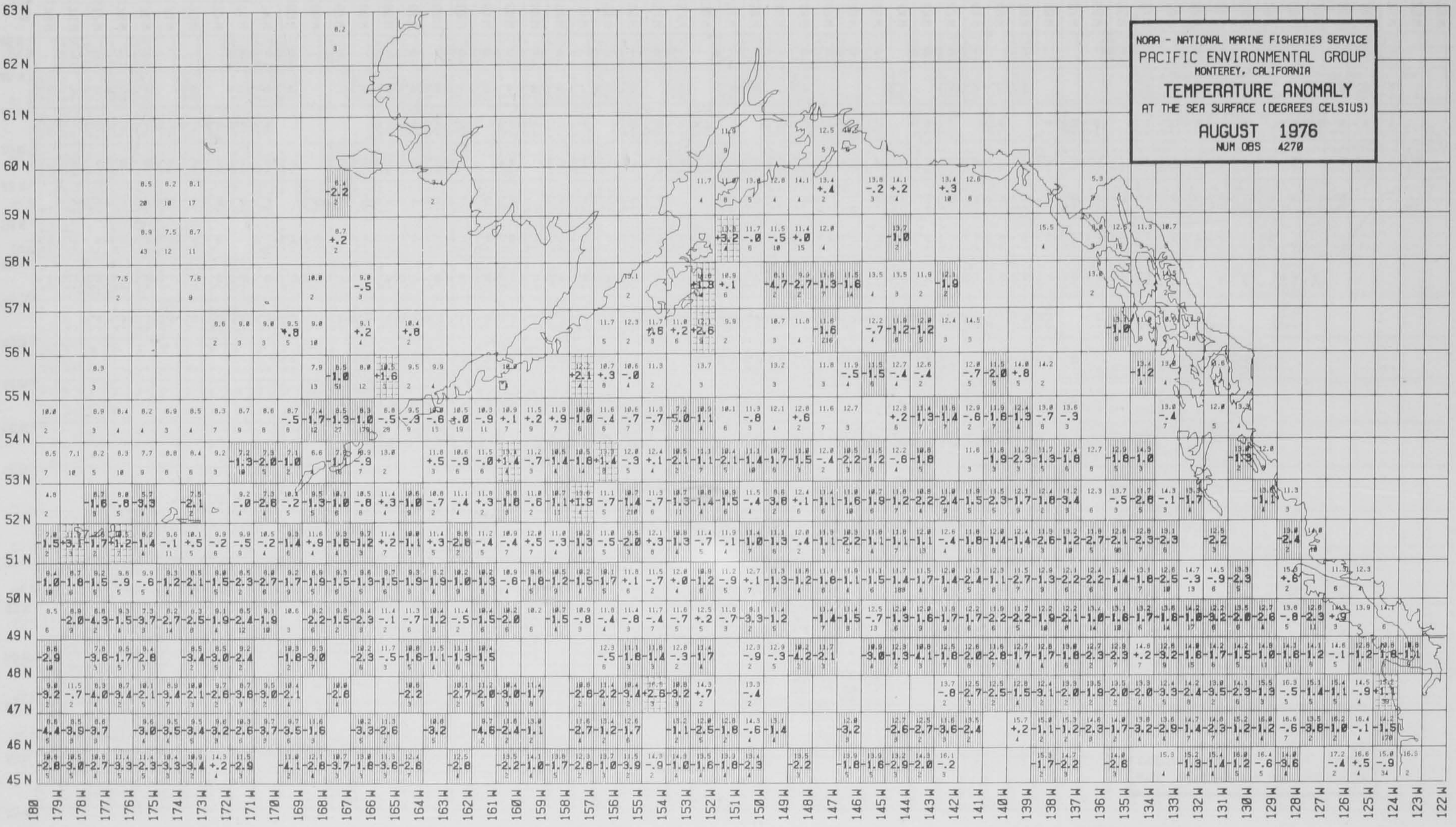
TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

JUNE 1976

NUM OBS 3972


NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA
TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)
JULY 1976
NUM OBS 4833
63 N
62 N
61 N
60 N
59 N
58 N
57 N
56 N
55 N
54 N
53 N
52 N
51 N
50 N
49 N
48 N
47 N
46 N
45 N
180
179 W
178 W
177 W
176 W
175 W
174 W
173 W
172 W
171 W
170 W
169 W
168 W
167 W
166 W
165 W
164 W
163 W
162 W
161 W
160 W
159 W
158 W
157 W
156 W
155 W
154 W
153 W
152 W
151 W
150 W
149 W
148 W
147 W
146 W
145 W
144 W
143 W
142 W
141 W
140 W
139 W
138 W
137 W
136 W
135 W
134 W
133 W
132 W
131 W
130 W
129 W
128 W
127 W
126 W
125 W
124 W
123 W
122 W


NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA
TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)
AUGUST 1976
NUM OBS 4270
63 N
62 N
61 N
60 N
59 N
58 N
57 N
56 N
55 N
54 N
53 N
52 N
51 N
50 N
49 N
48 N
47 N
46 N
45 N
180
179 W
178 W
177 W
176 W
175 W
174 W
173 W
172 W
171 W
170 W
169 W
168 W
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166 W
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148 W
147 W
146 W
145 W
144 W
143 W
142 W
141 W
140 W
139 W
138 W
137 W
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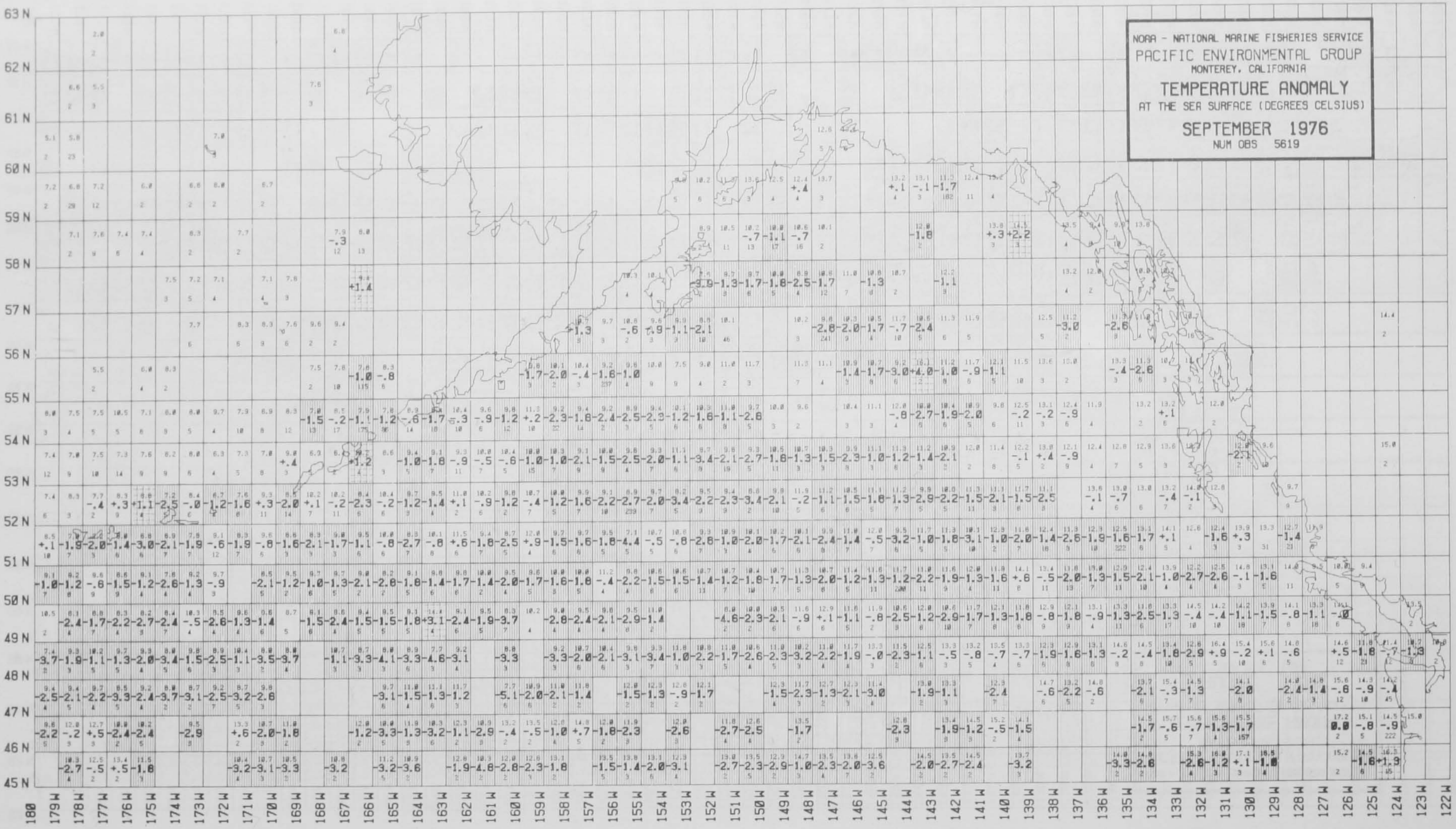
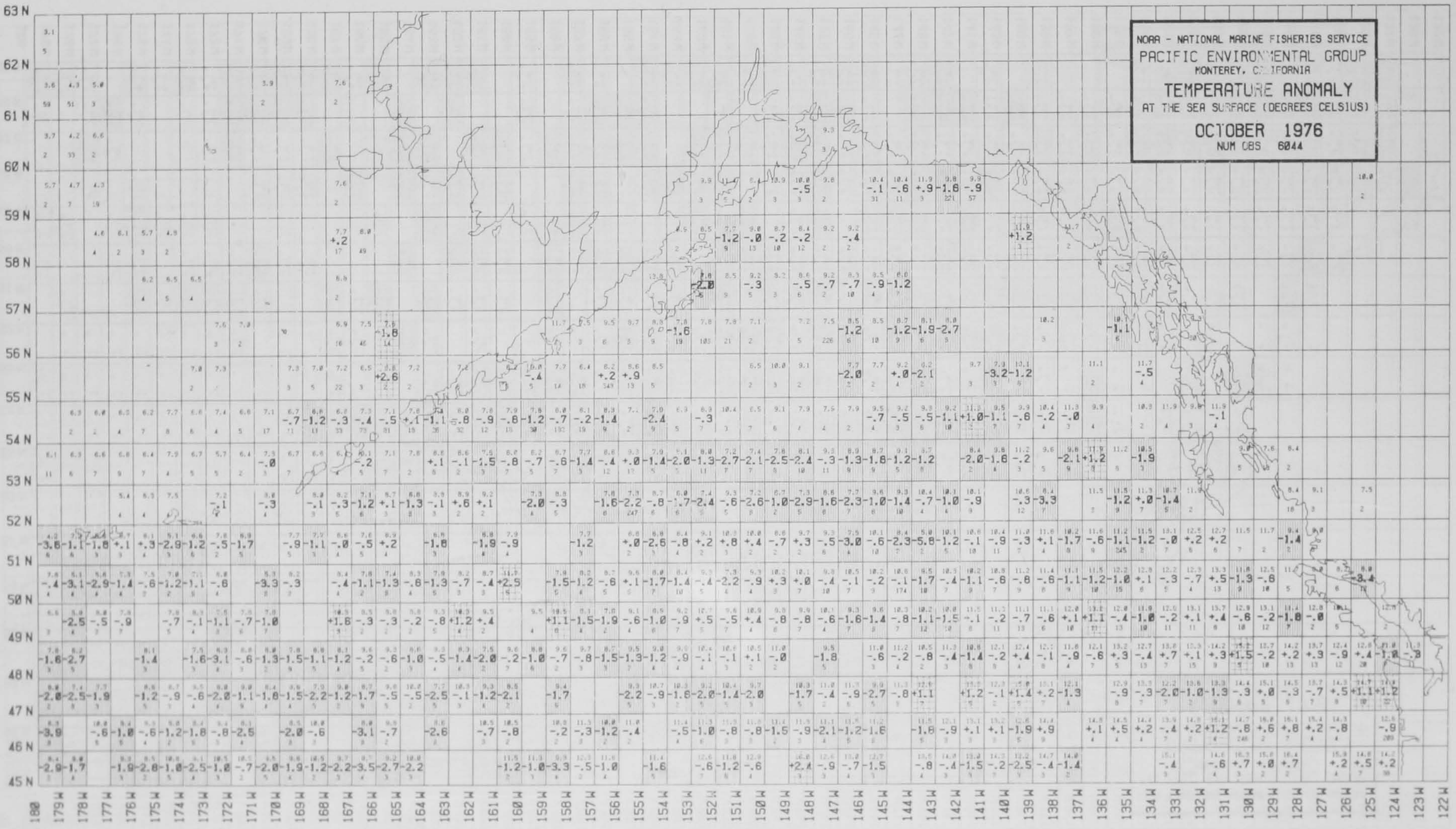
126 W
125 W
124 W
123 W
122 W


NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)

SEPTEMBER 1976
NUM OBS 5619


NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA
TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)
OCTOBER 1976
NUM OBS 6044
63 N
62 N
61 N
60 N
59 N
58 N
57 N
56 N
55 N
54 N
53 N
52 N
51 N
50 N
49 N
48 N
47 N
46 N
45 N
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179 W
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142 W
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138 W
137 W
136 W
135 W
134 W
133 W
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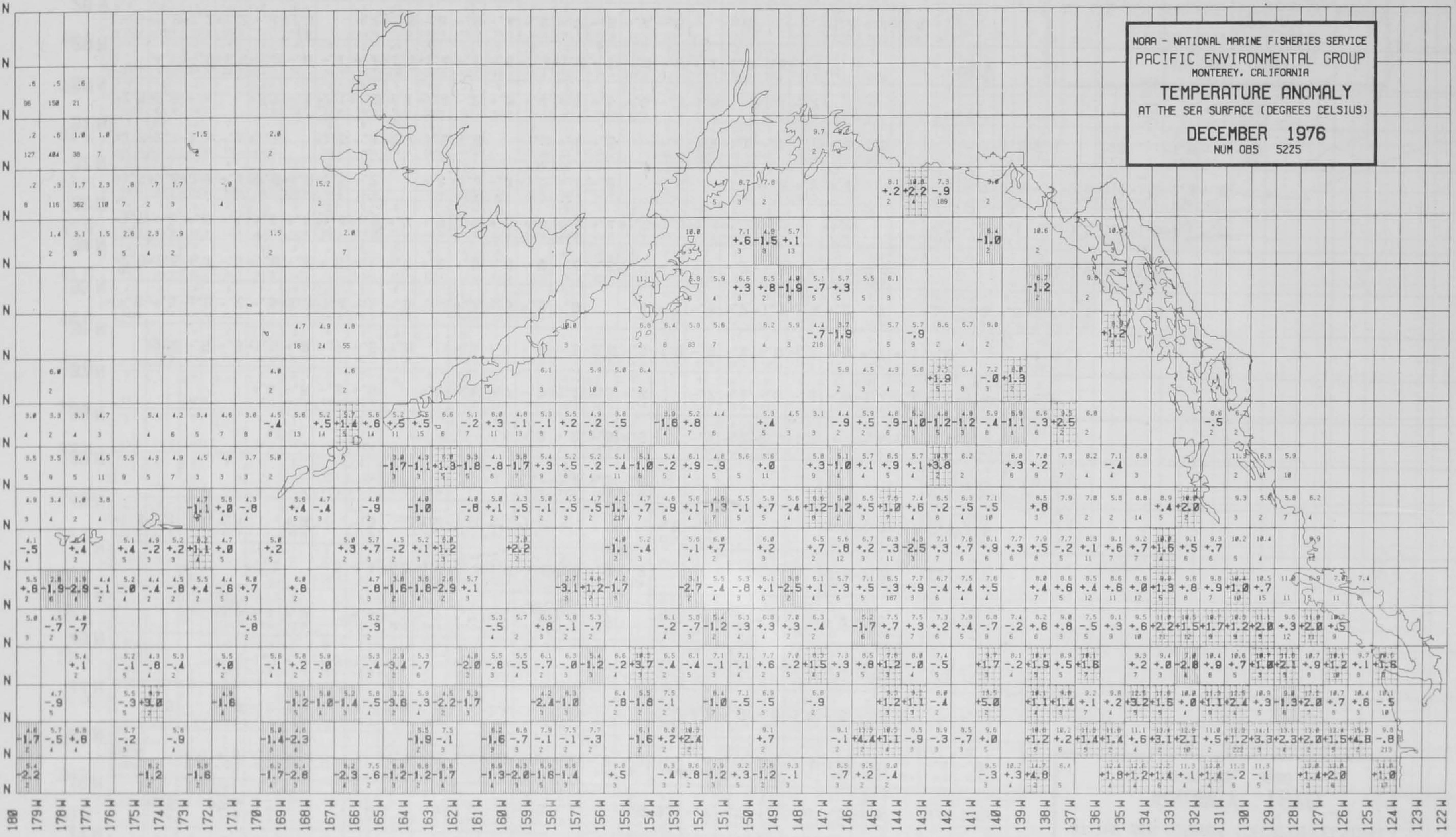
129 W
128 W
127 W
126 W
125 W
124 W
123 W
122 W


NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA
TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)
NOVEMBER 1976
NUM OBS 5014



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

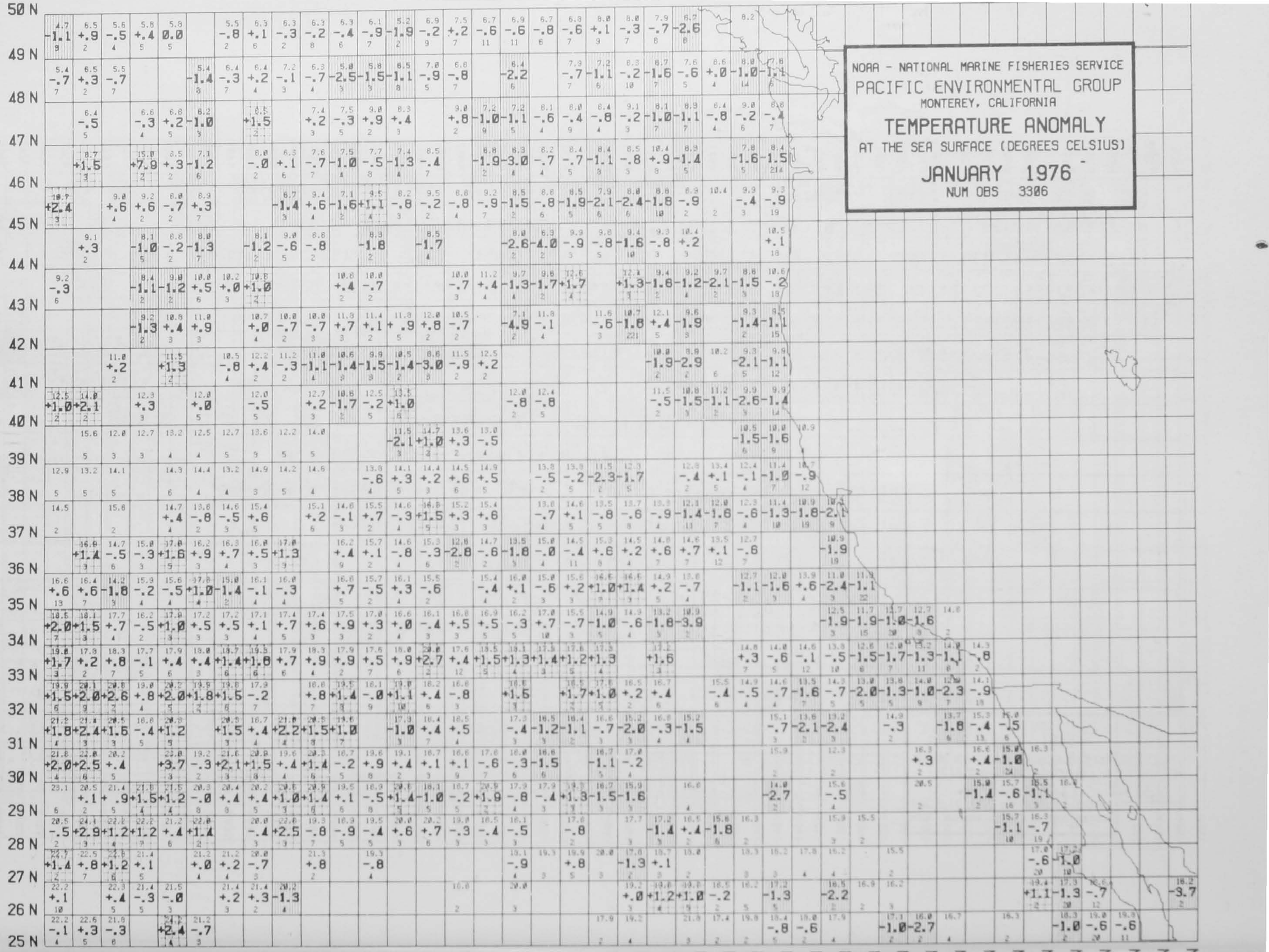
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

DECEMBER 1976

NUM OBS 5225



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

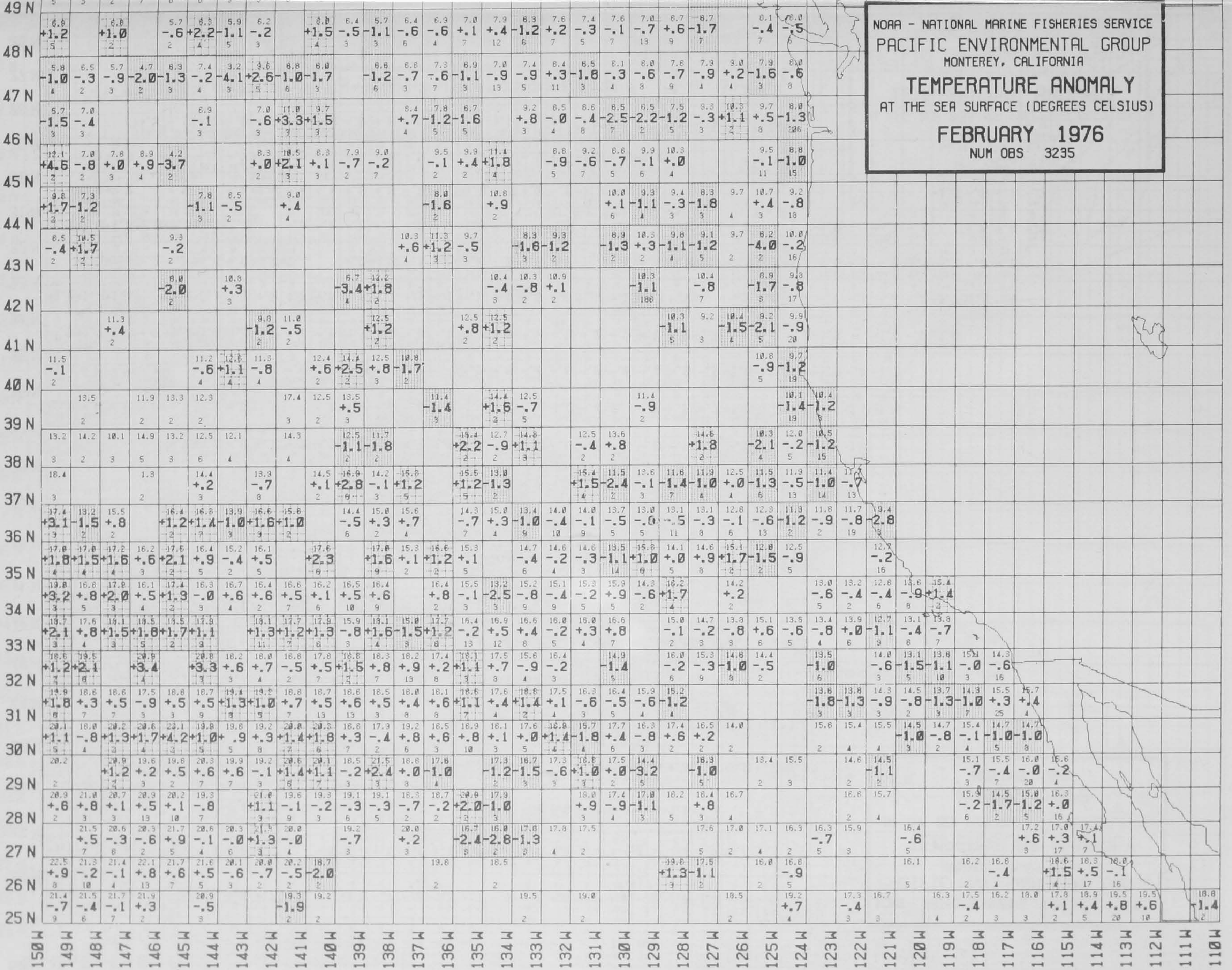
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

JANUARY 1976

NUM OBS 3306



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

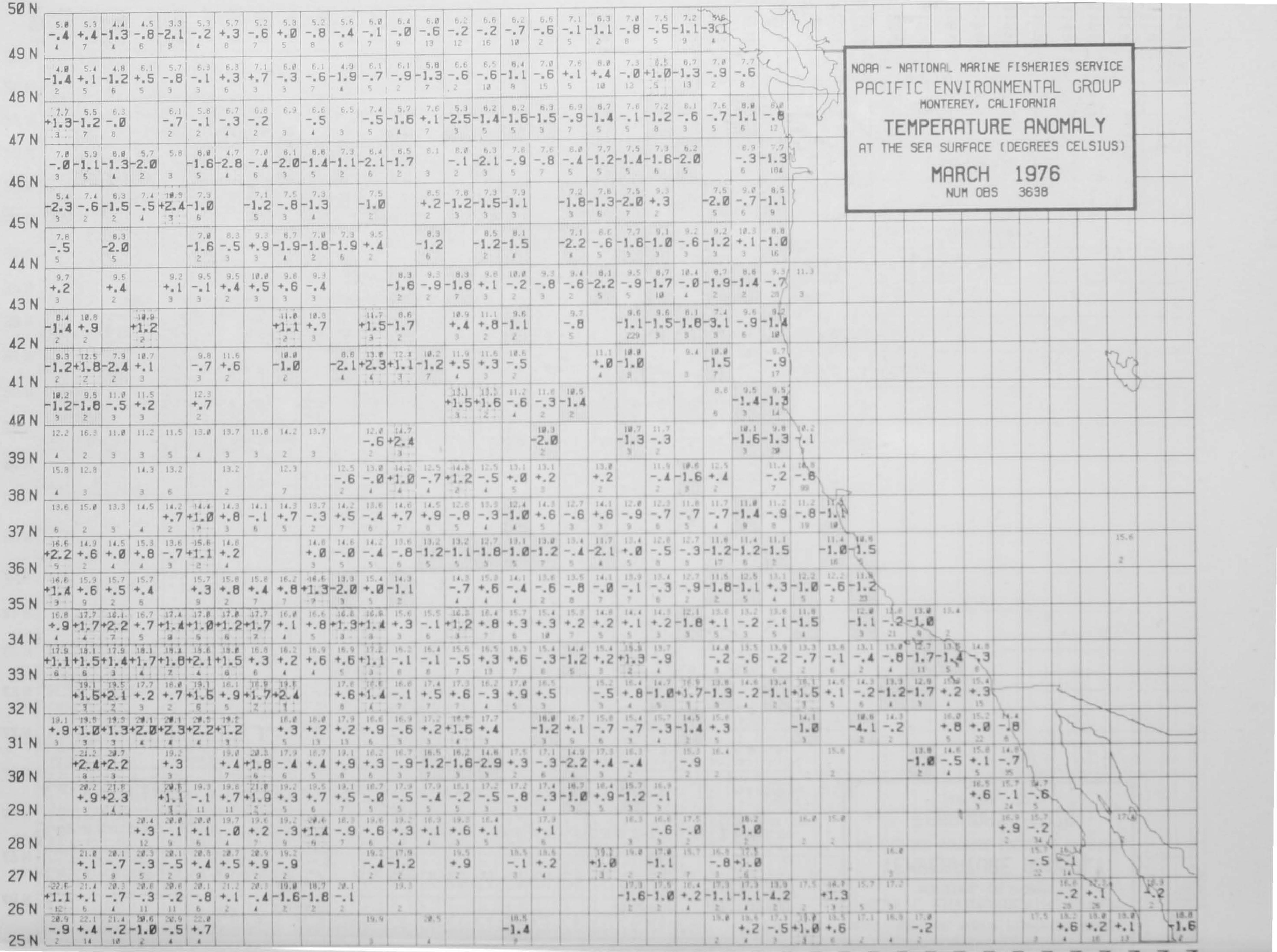
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

FEBRUARY 1976

NUM OBS 3235



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

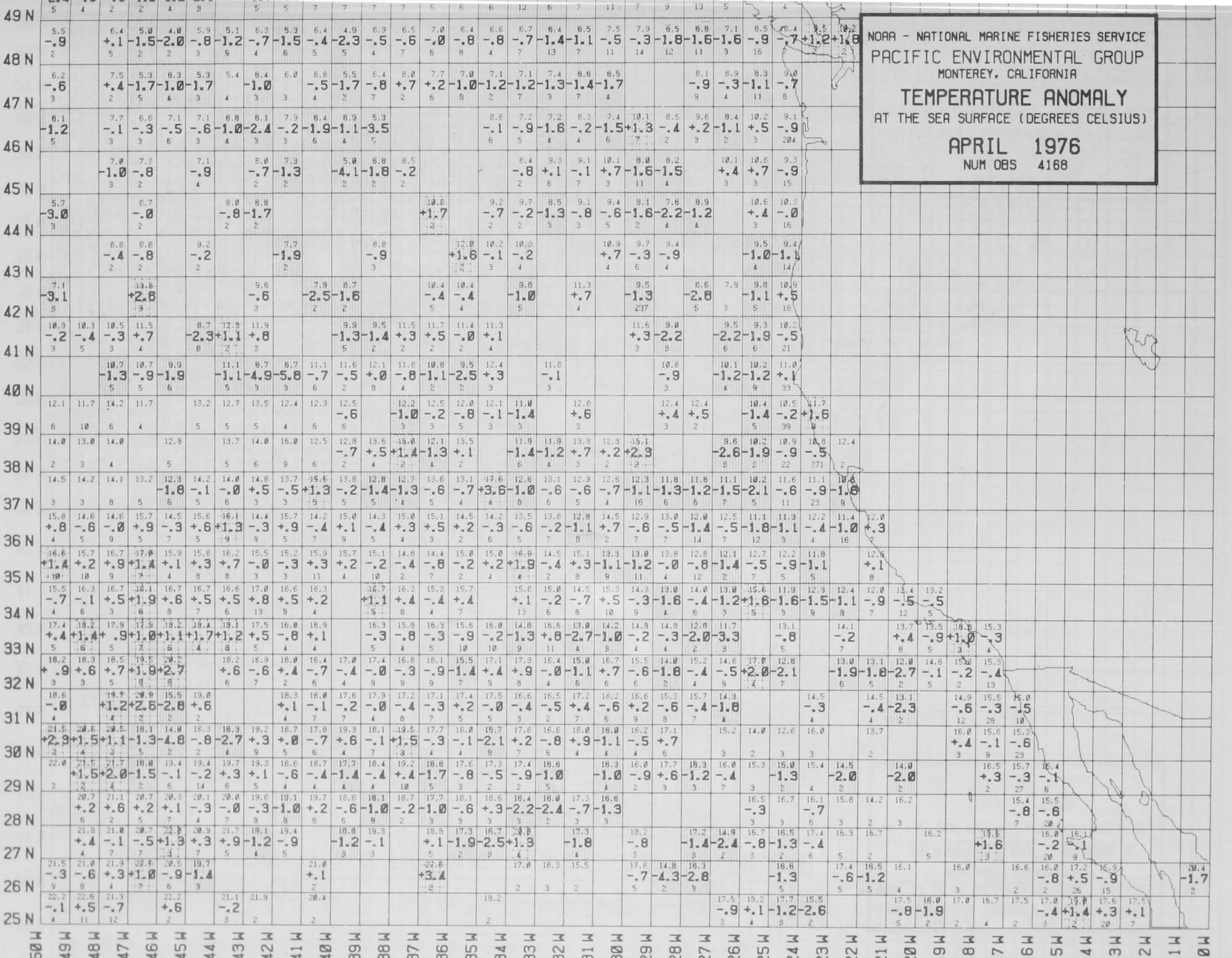
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

MARCH 1976

NUM OBS 3638



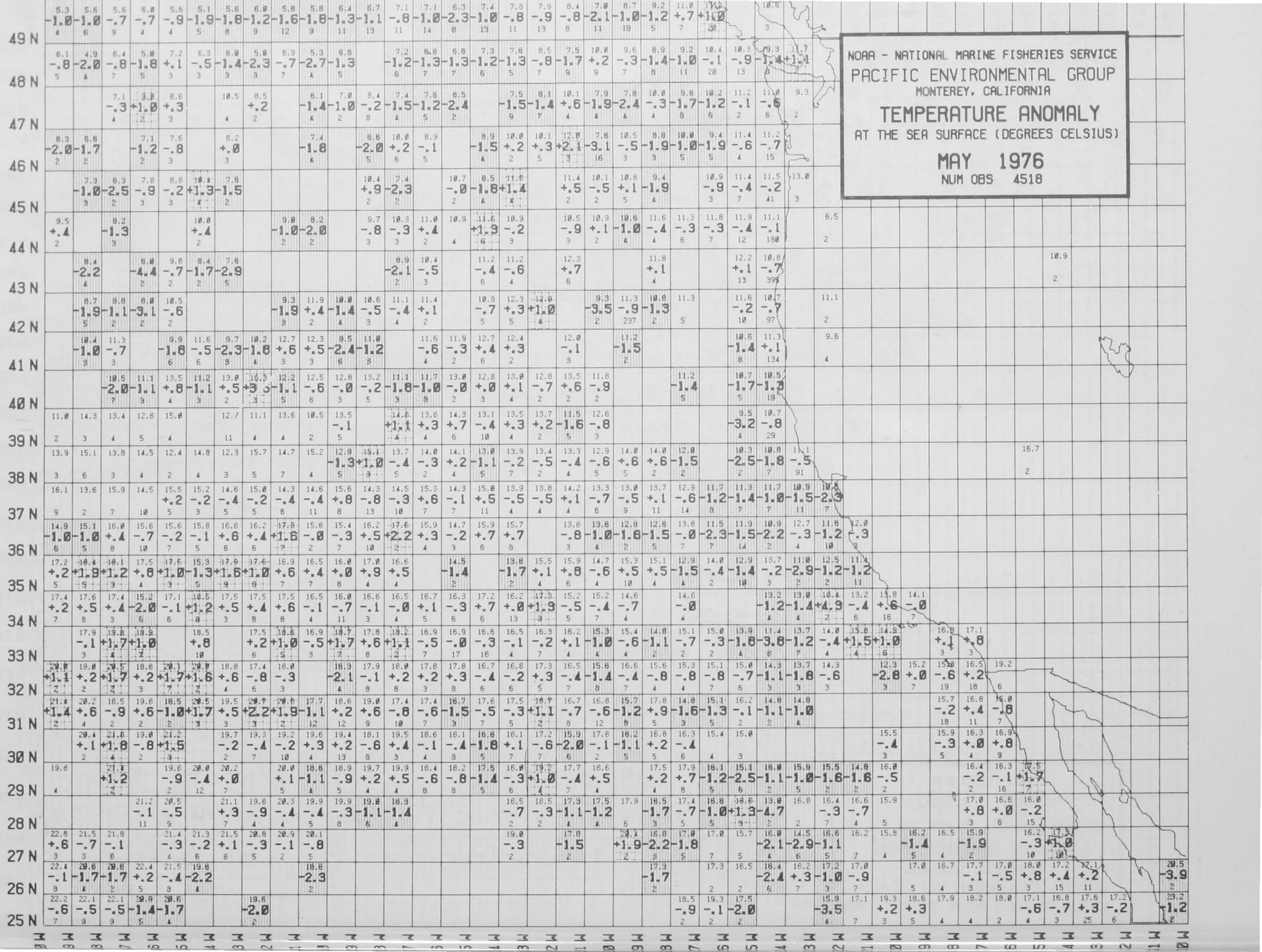
NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

APRIL 1976

NUM OBS 4168



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

MAY 1976

NUM OBS 4518

NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

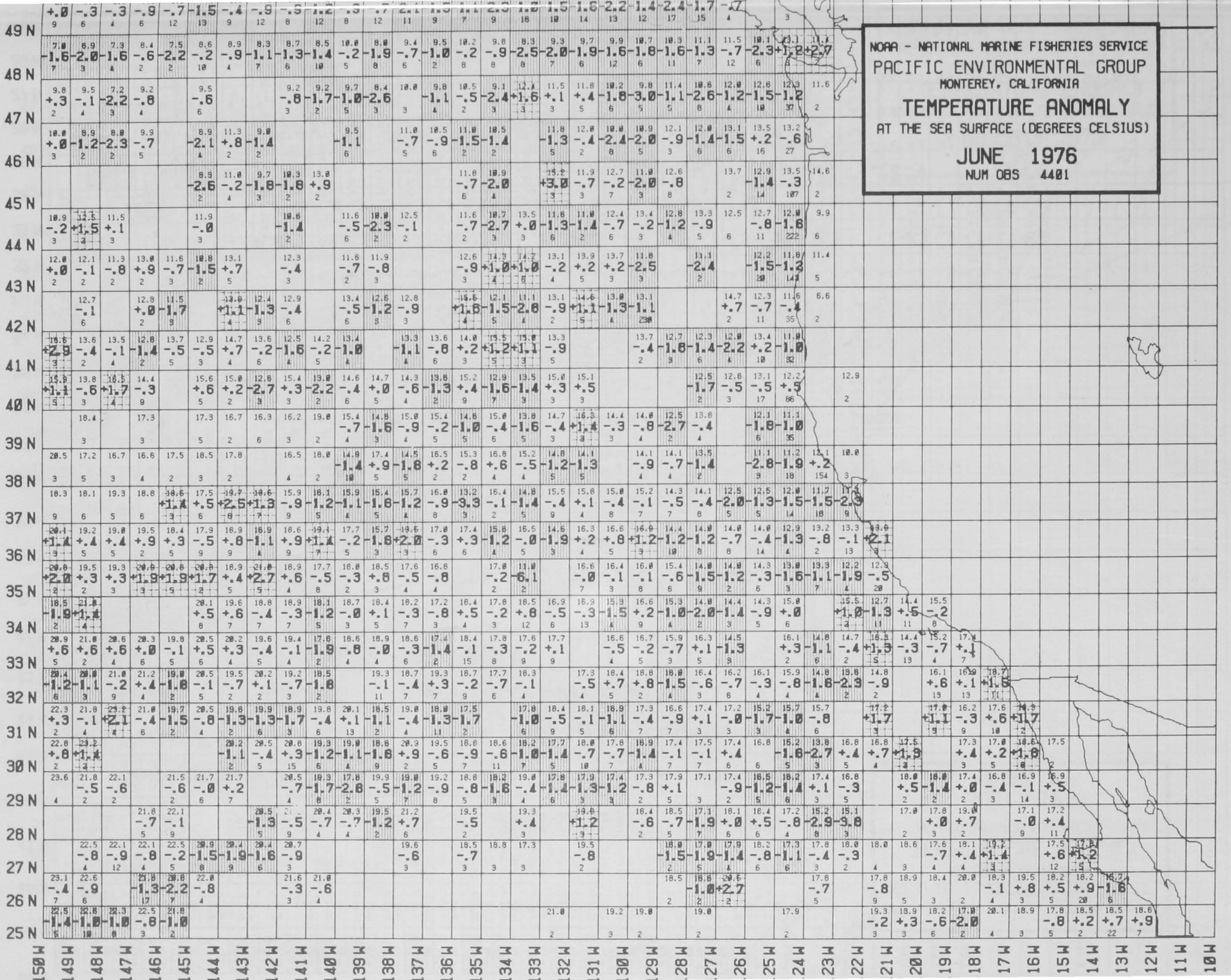
MONTEREY, CALIFORNIA

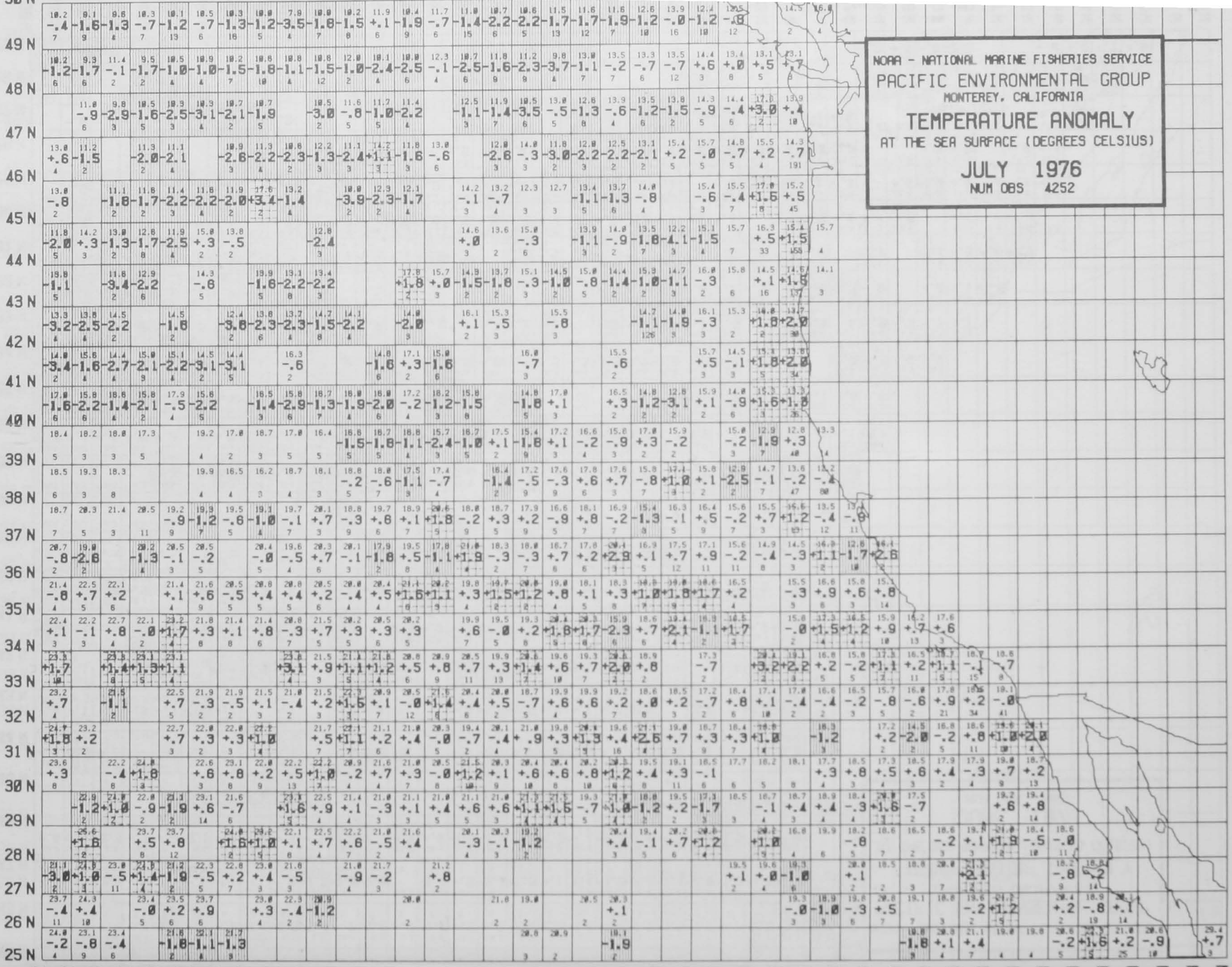
TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

JUNE 1976

NUM OBS 4401





NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

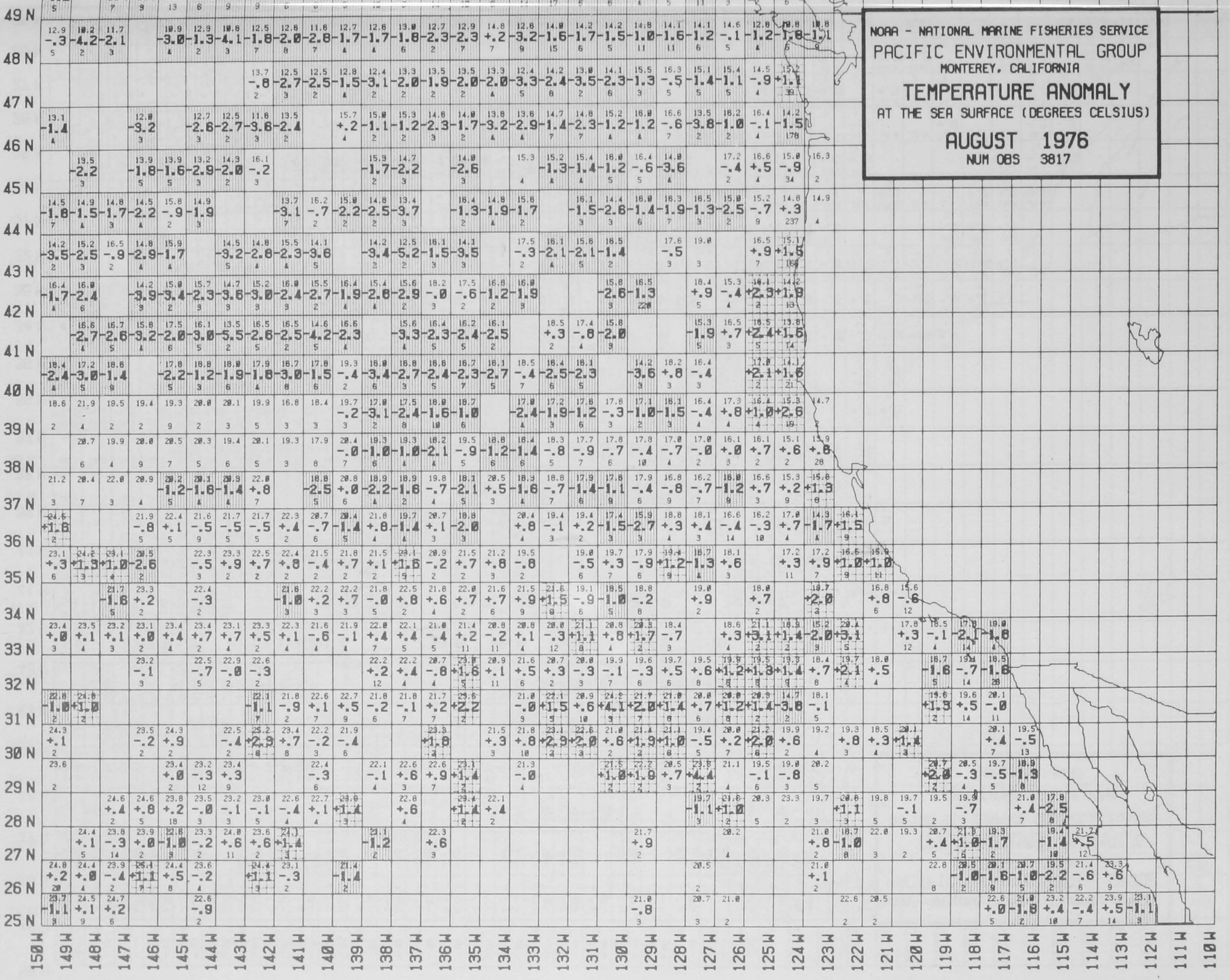
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

JULY 1976

NUM OBS 4252


NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA
TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)
AUGUST 1976
NUM OBS 3817
49 N
48 N
47 N
46 N
45 N
44 N
43 N
42 N
41 N
40 N
39 N
38 N
37 N
36 N
35 N
34 N
33 N
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31 N
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26 N
25 N
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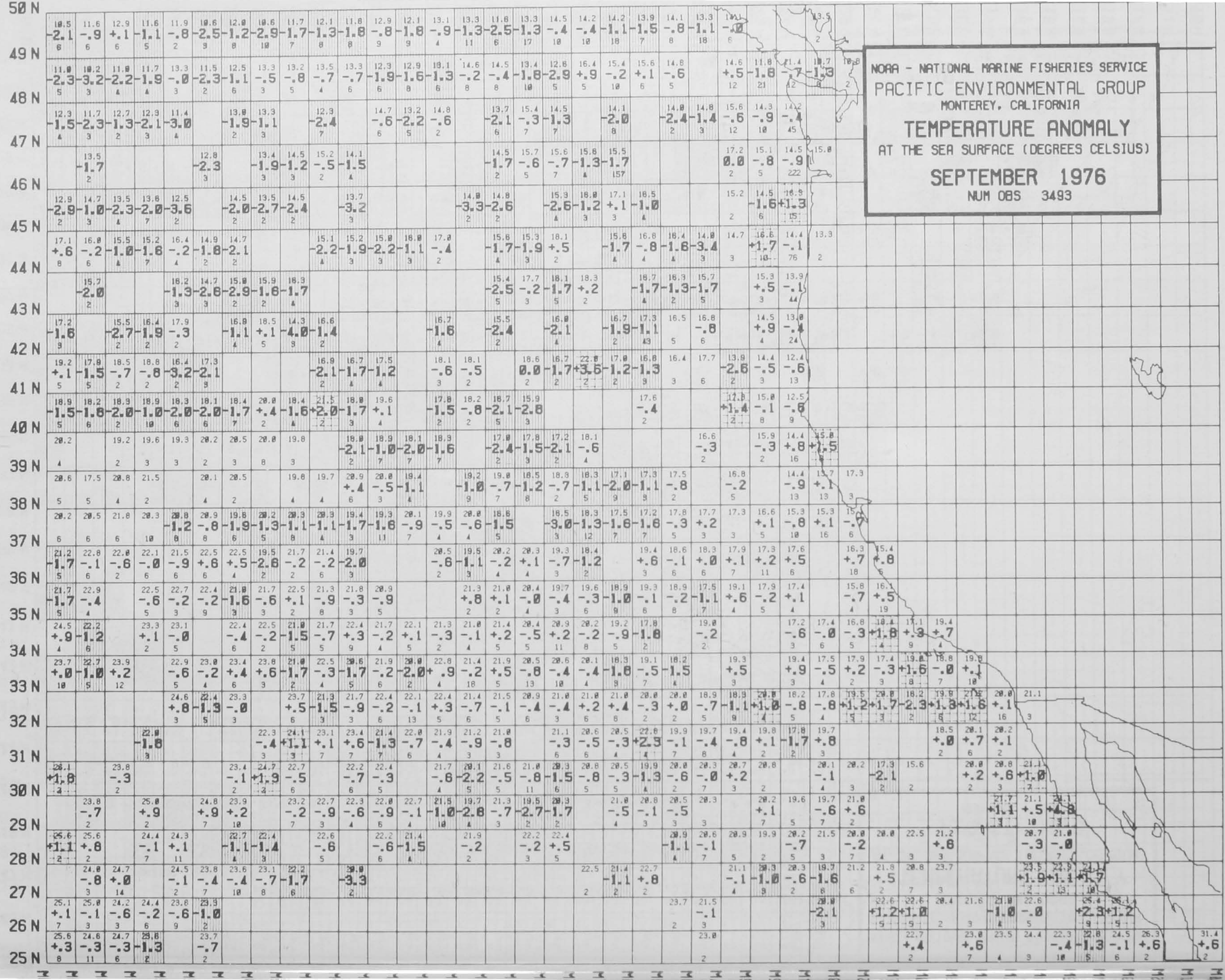


NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

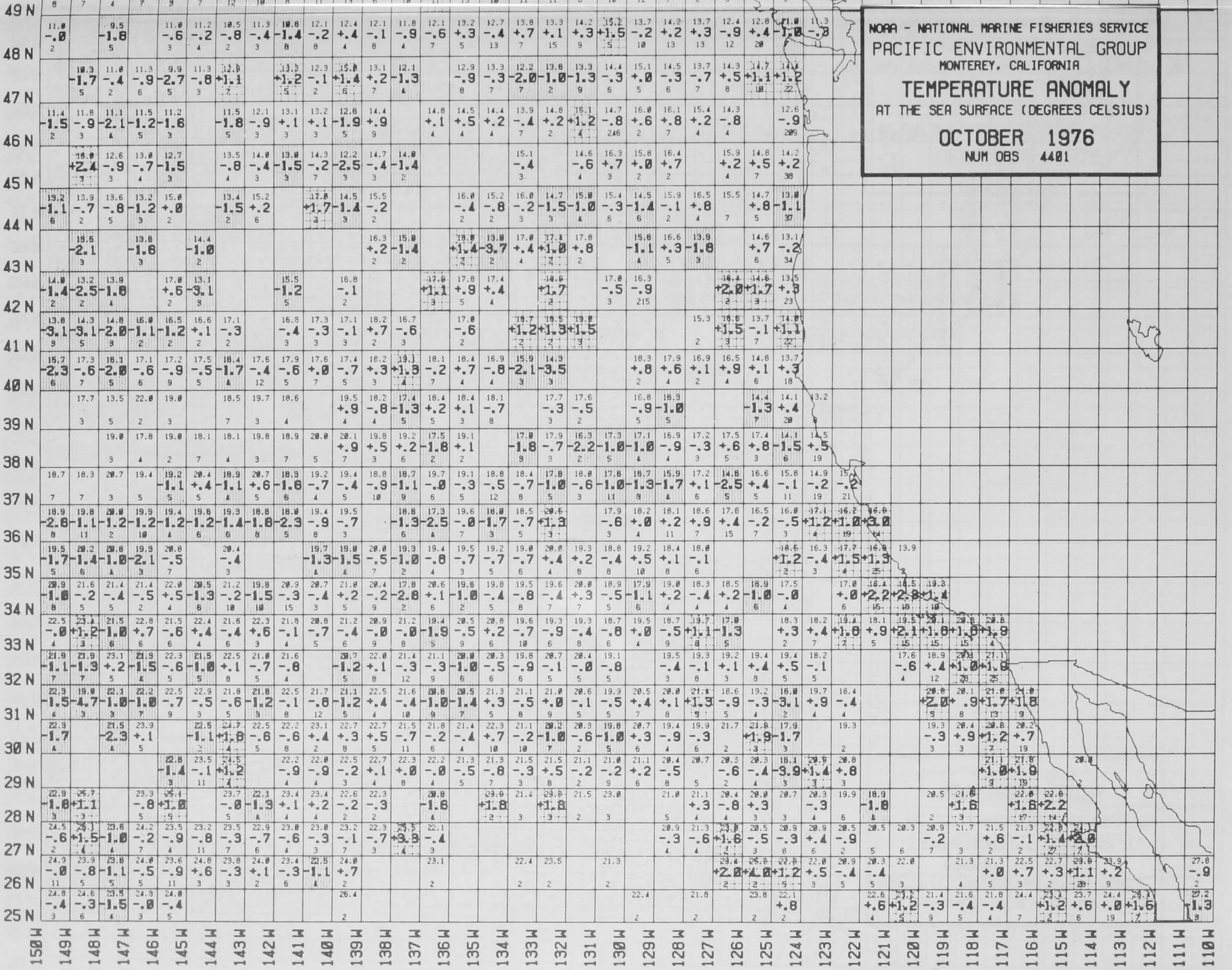
TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)

SEPTEMBER 1976
NUM OBS 3493

NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)

OCTOBER 1976
NUM OBS 4401



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

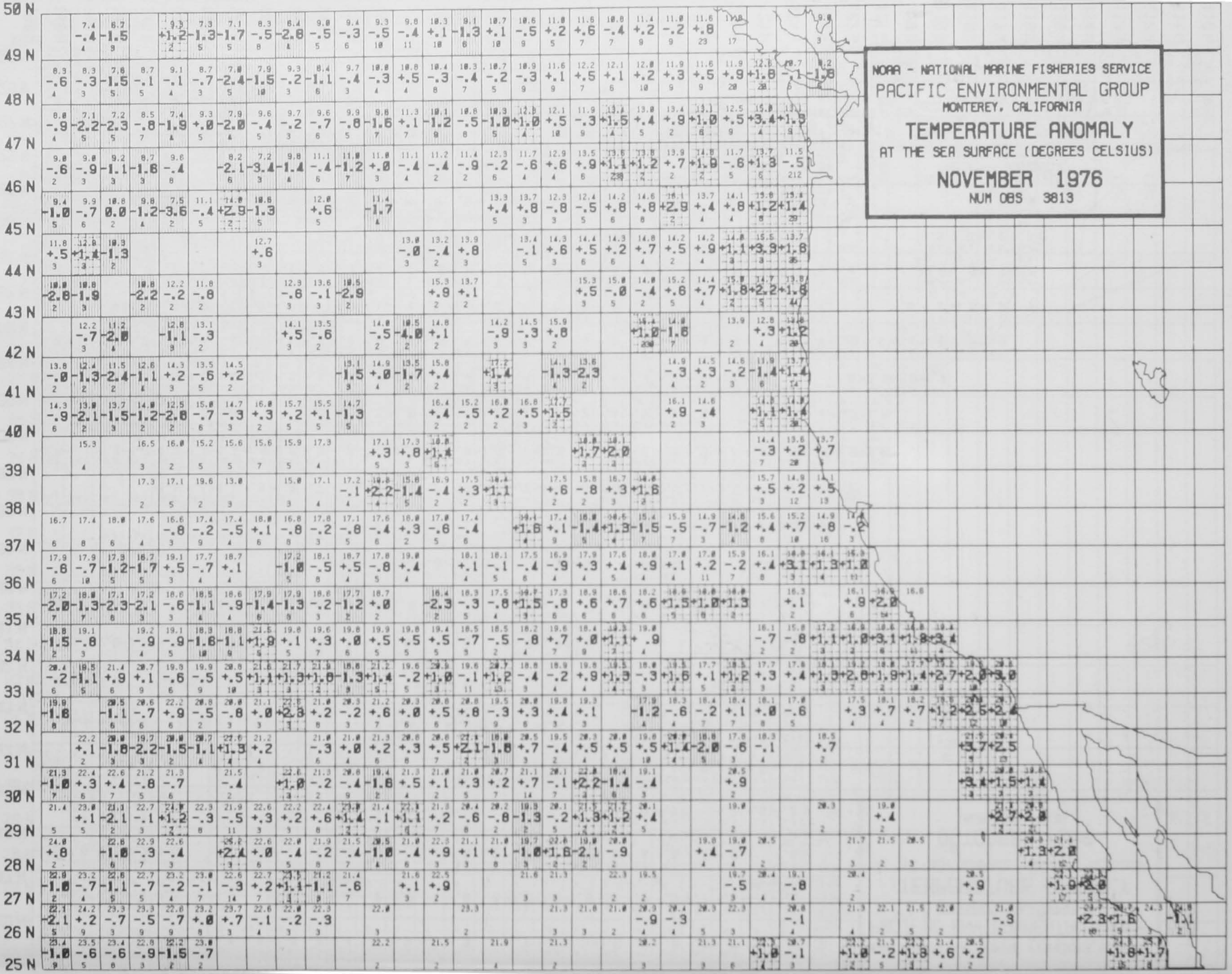
MONTEREY, CALIFORNIA

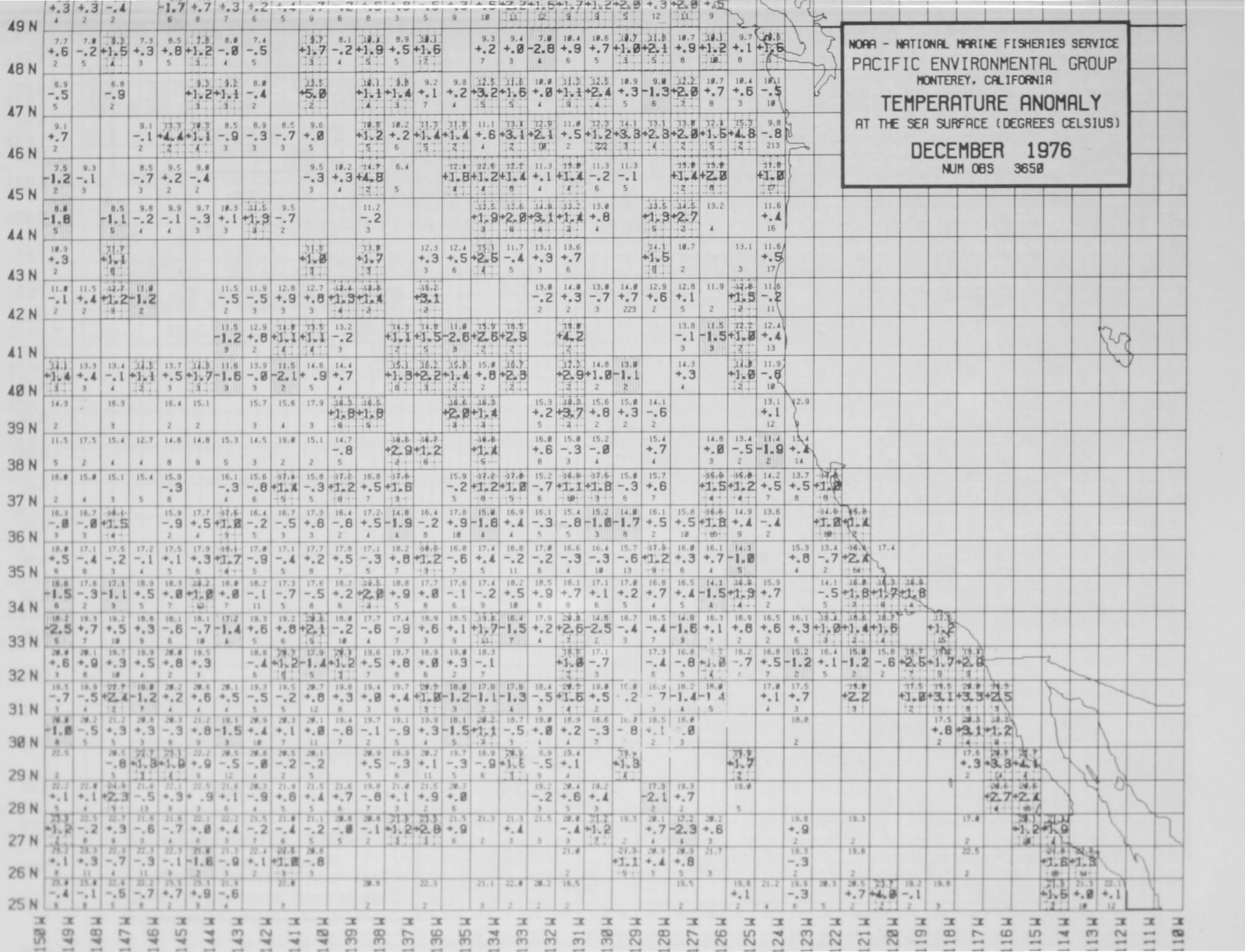
TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

NOVEMBER 1976

NUM OBS 3813

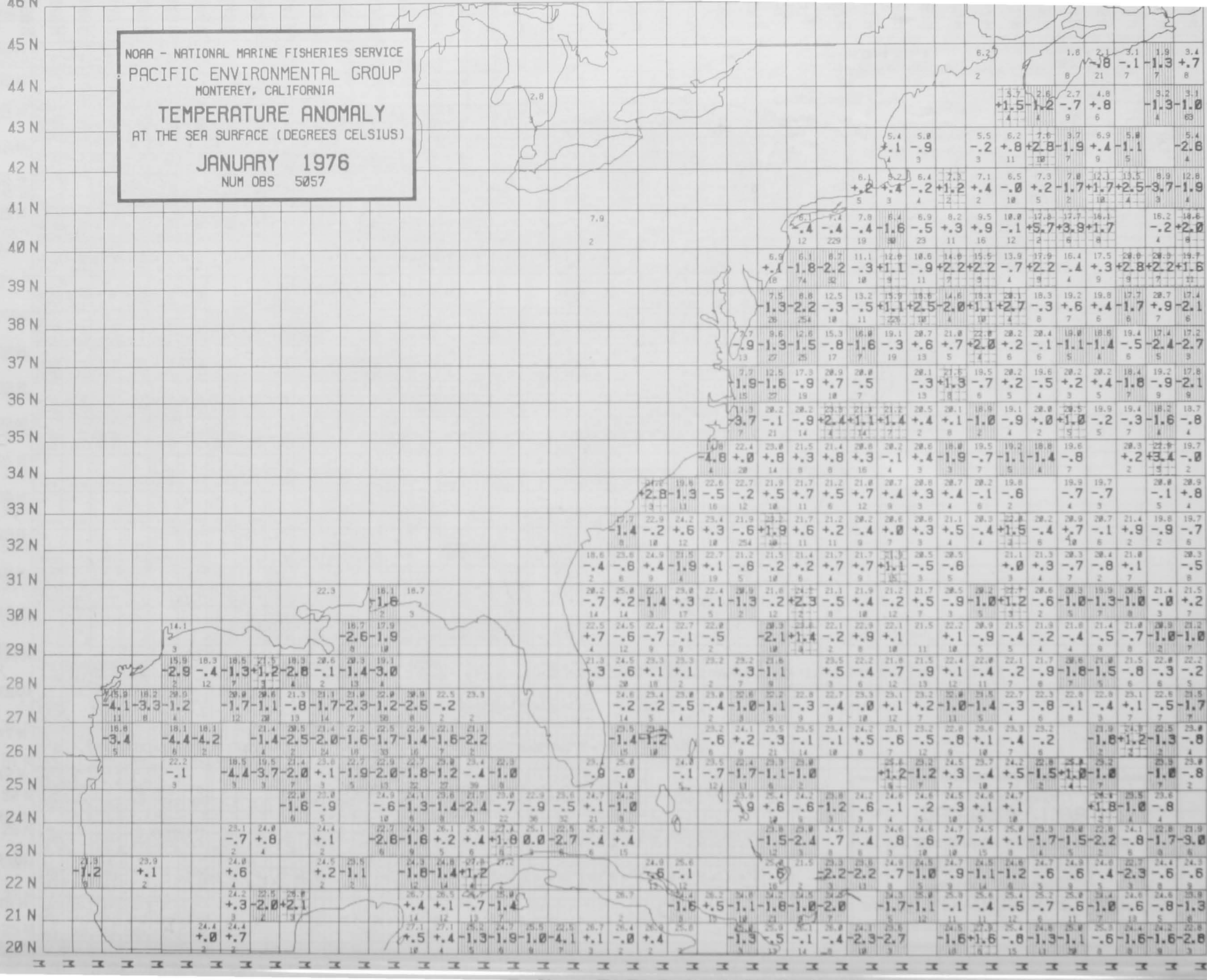




NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)

DECEMBER 1976
NUM OBS 3650



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

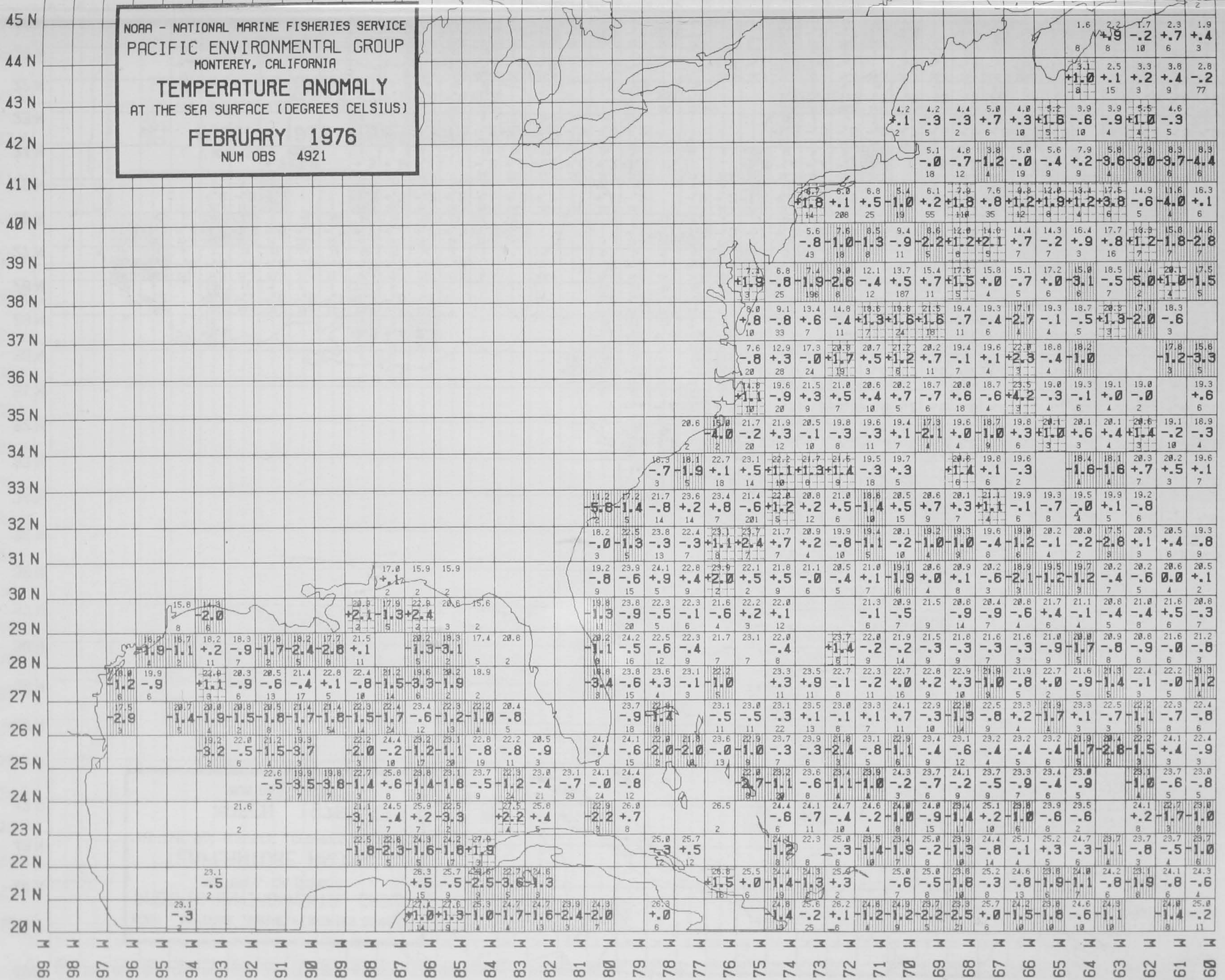
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

JANUARY 1976

NUM OBS 5057



NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)

FEBRUARY 1976
NUM OBS 4921

NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

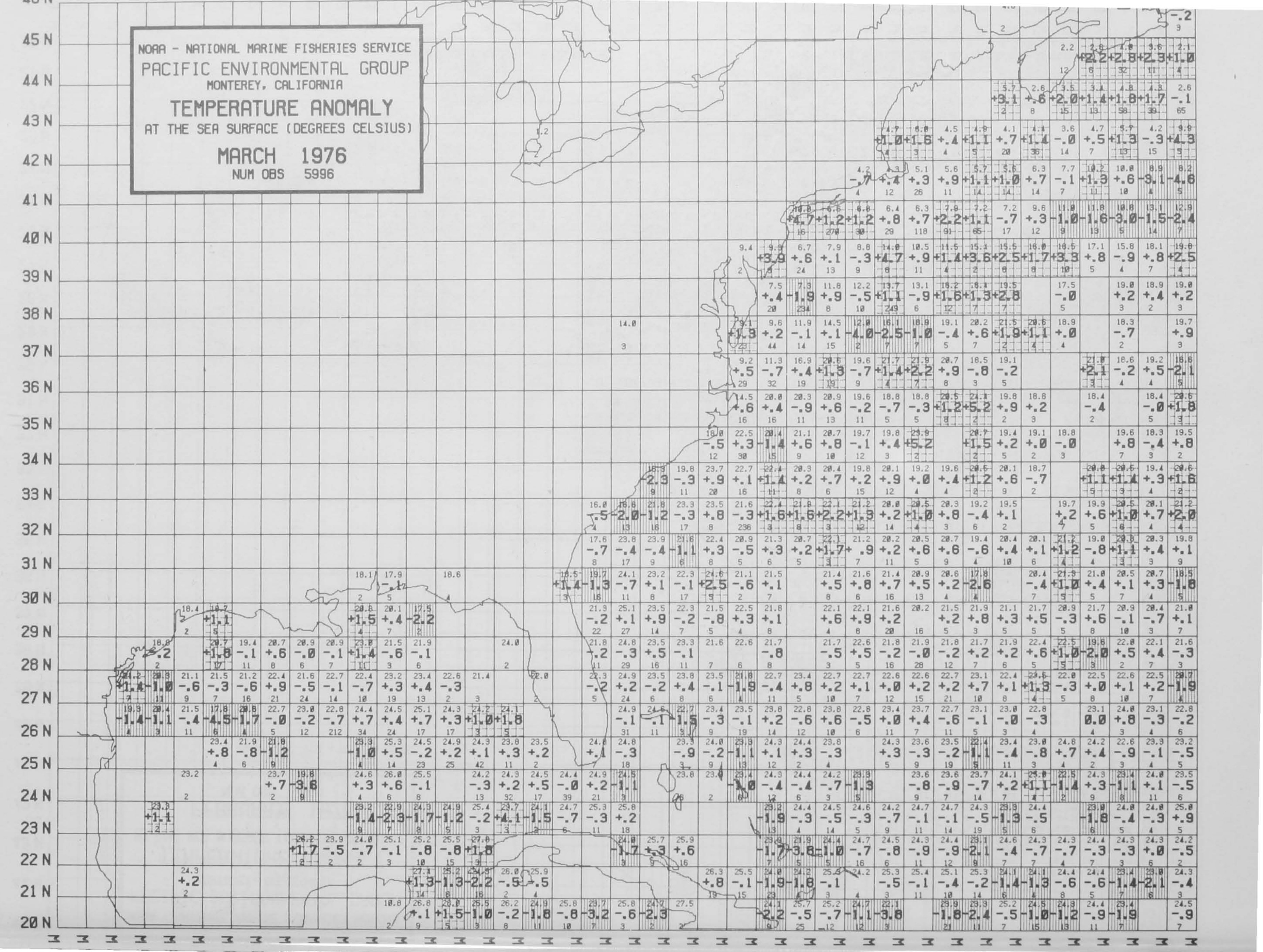
MONTEREY, CALIFORNIA

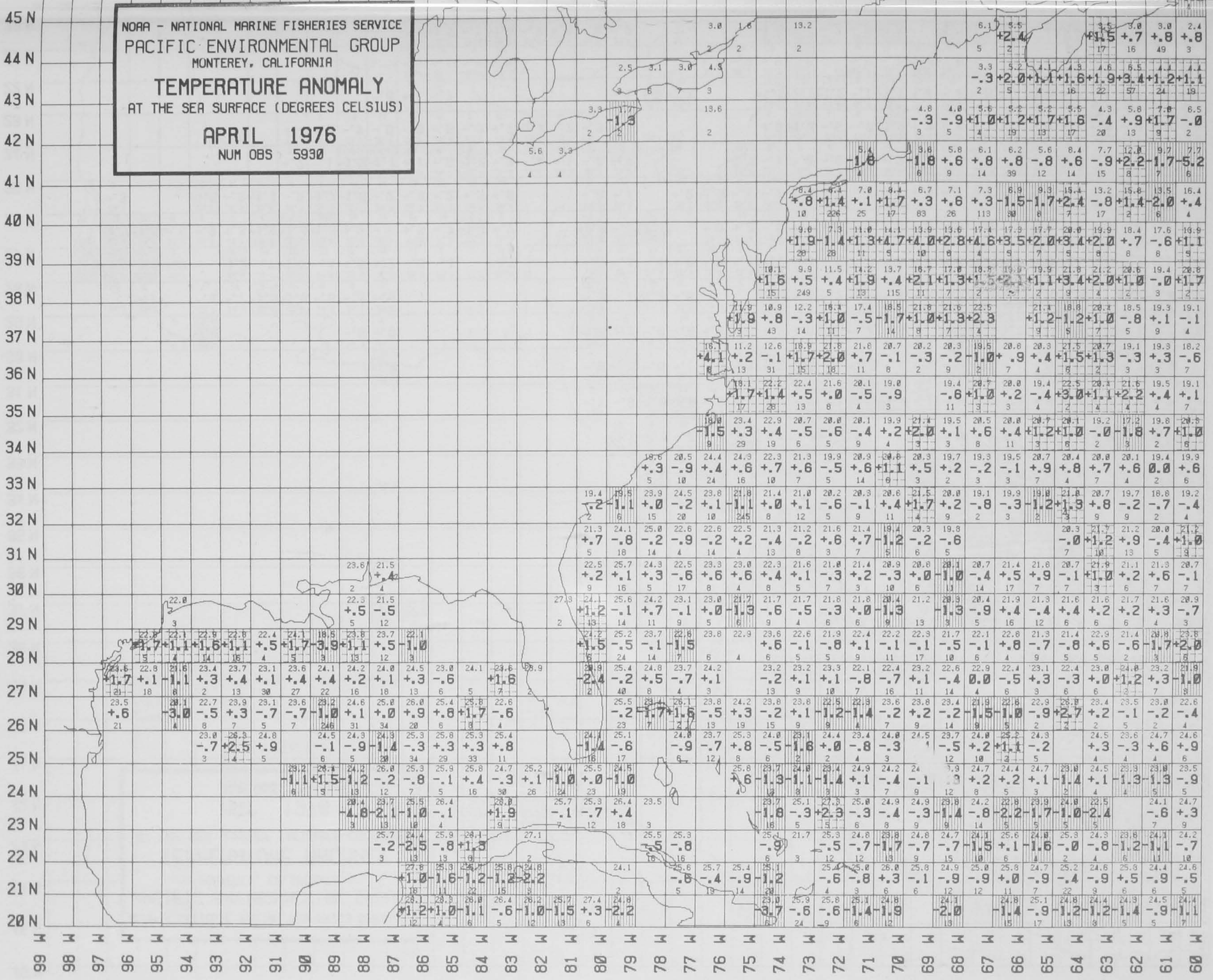
TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

MARCH 1976

NUM OBS 5996





NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

APRIL 1976

NUM OBS 5930

NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

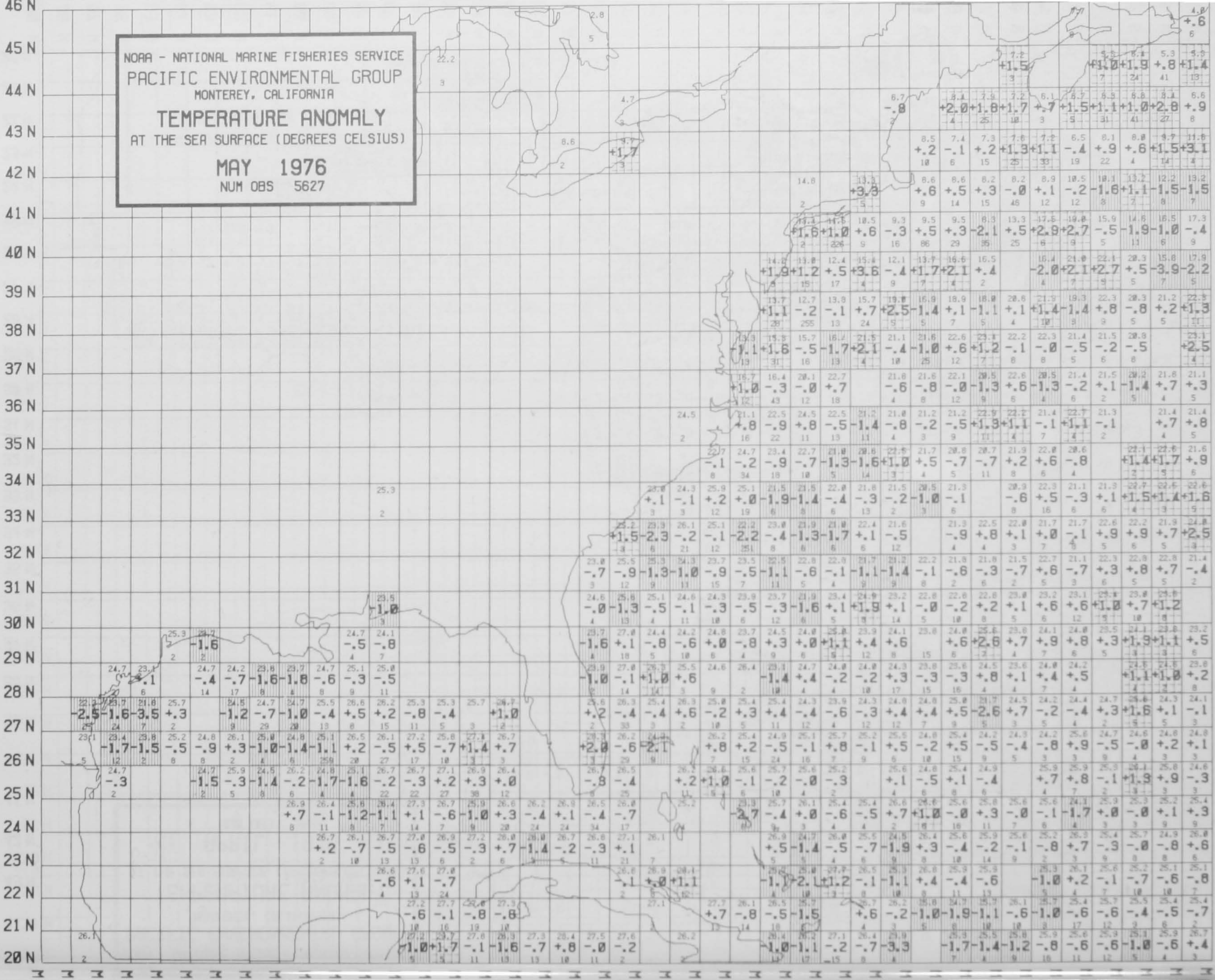
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

MAY 1976

NUM OBS 5627



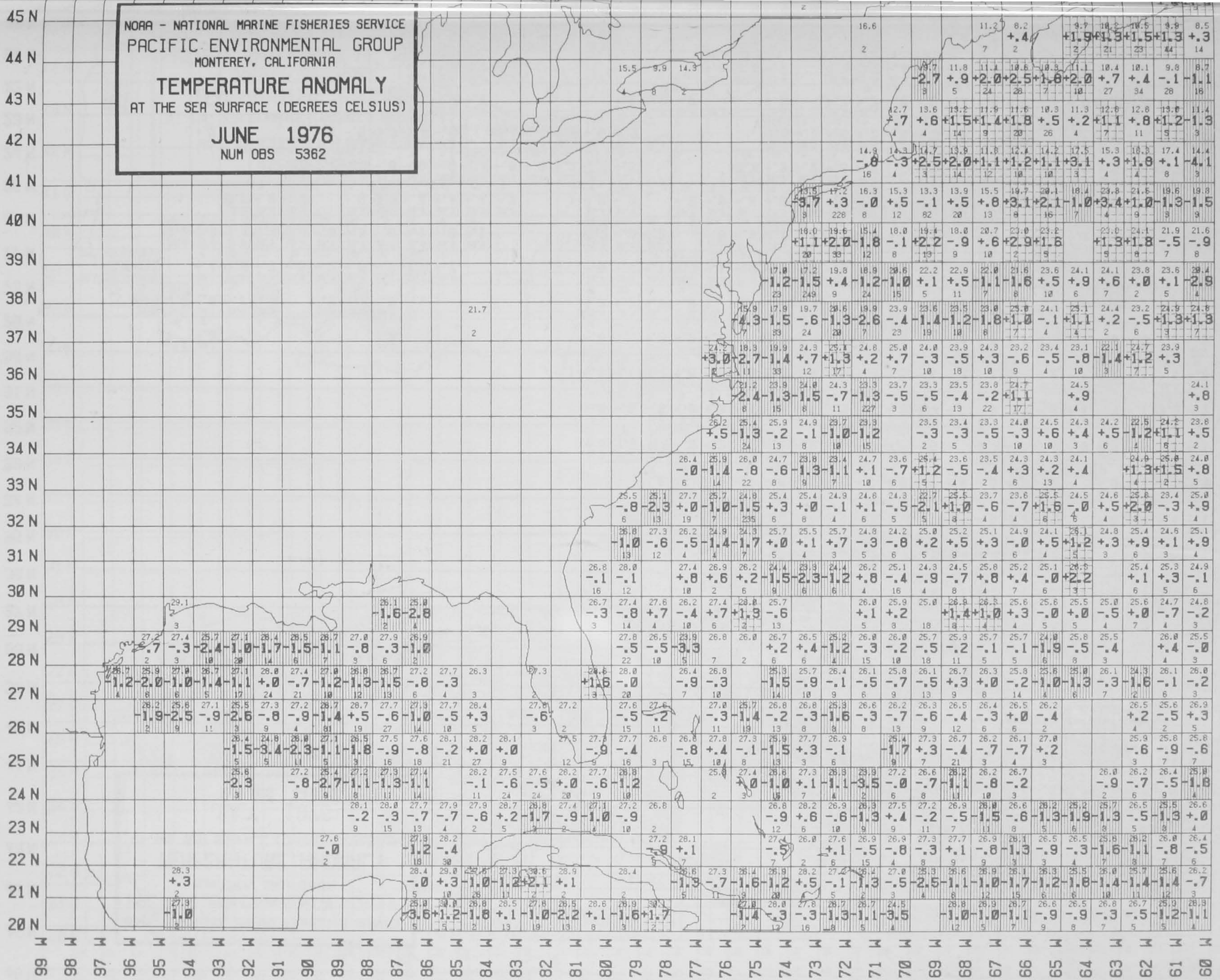
NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

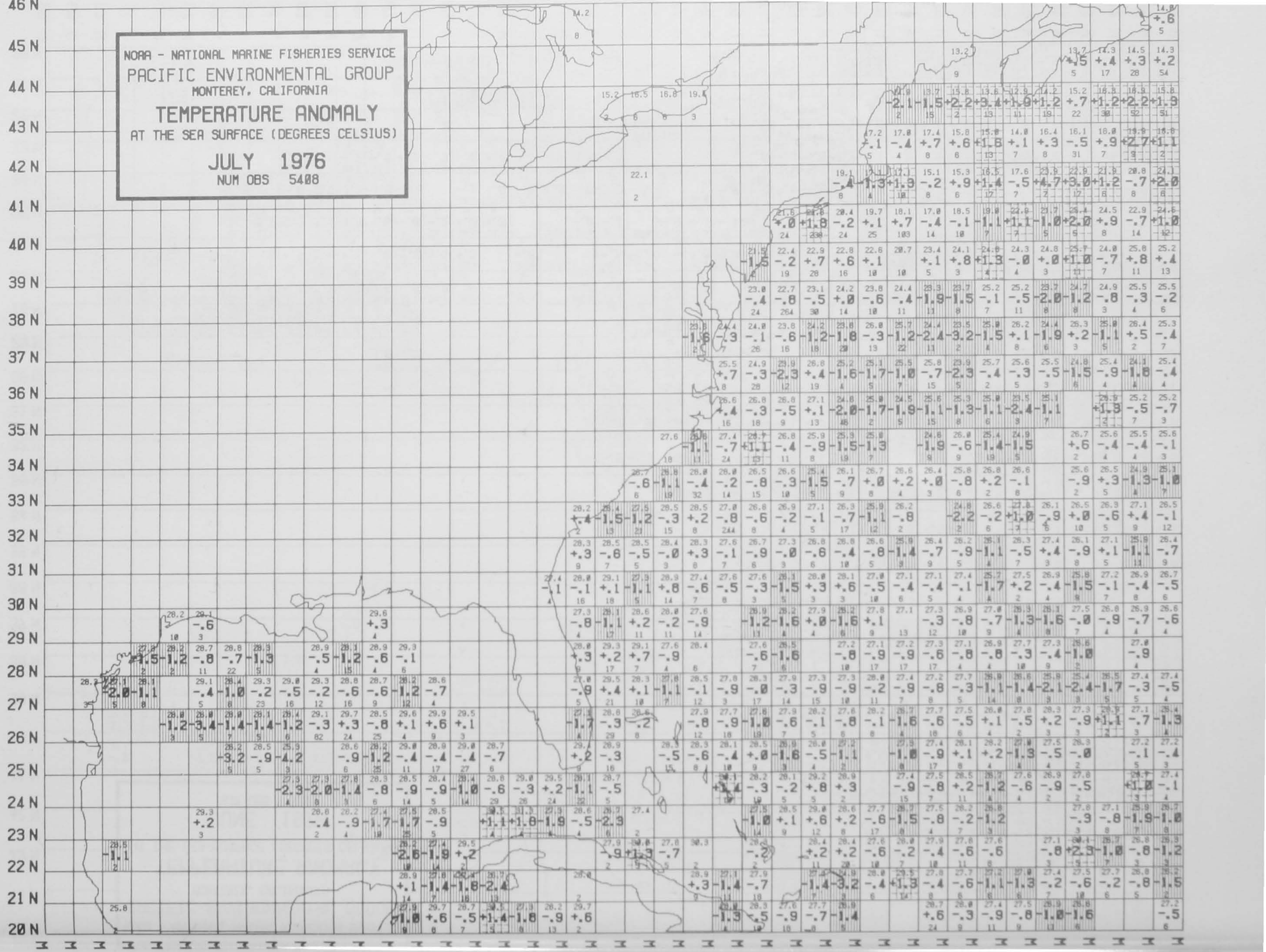
TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

JUNE 1976

NUM OBS 5362





NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

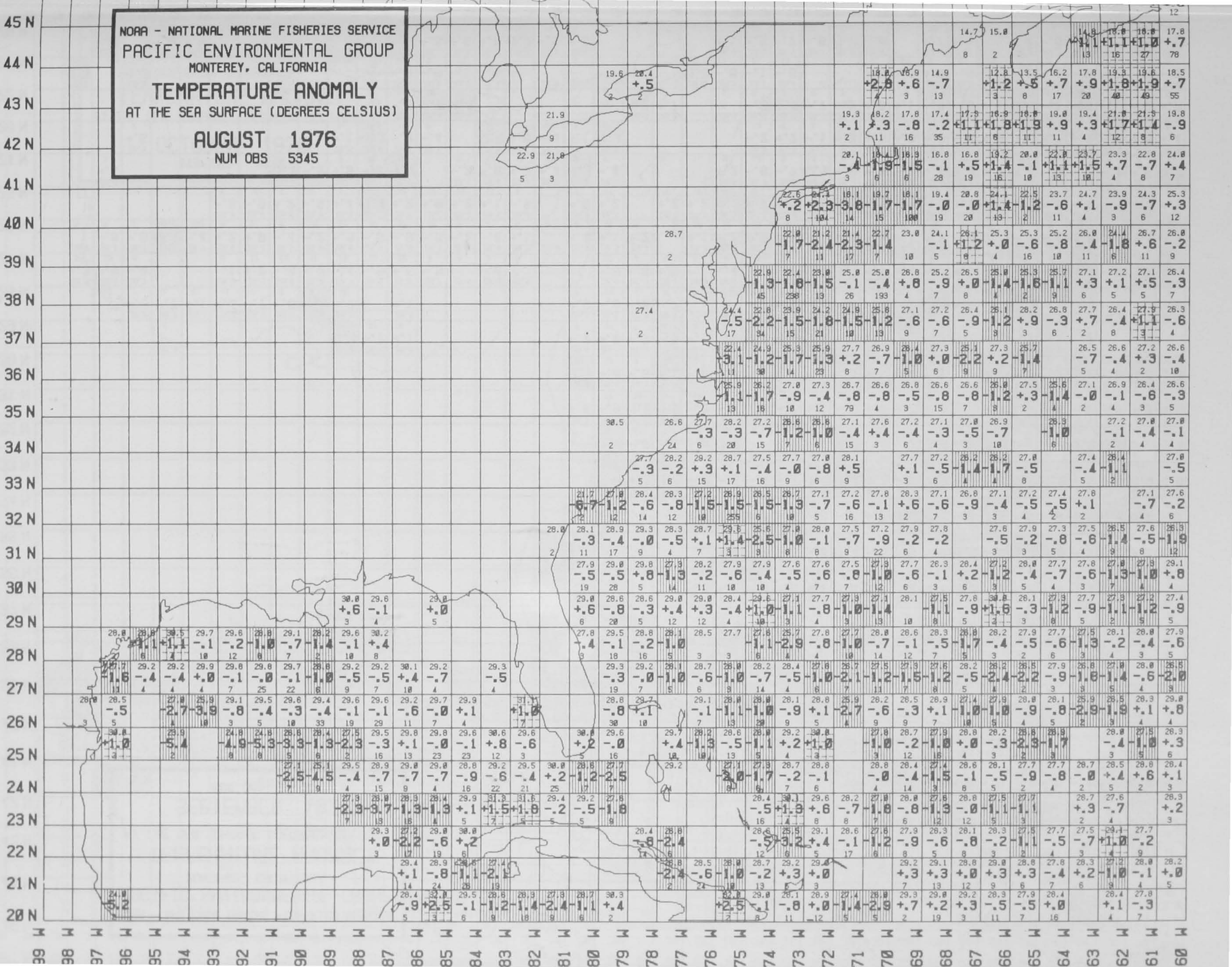
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

JULY 1976

NUM OBS 5408


NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

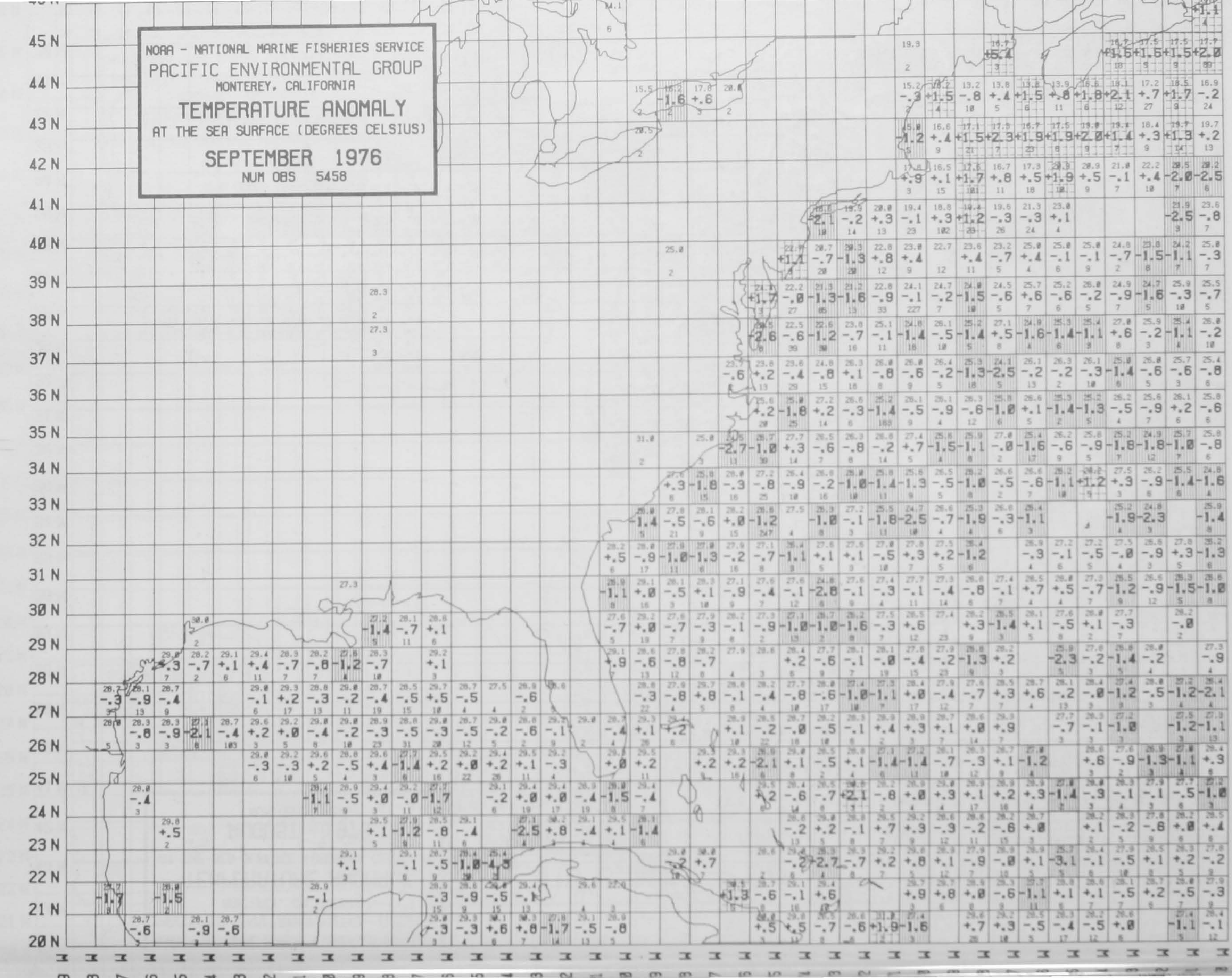
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

AUGUST 1976

NUM OBS 5345



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

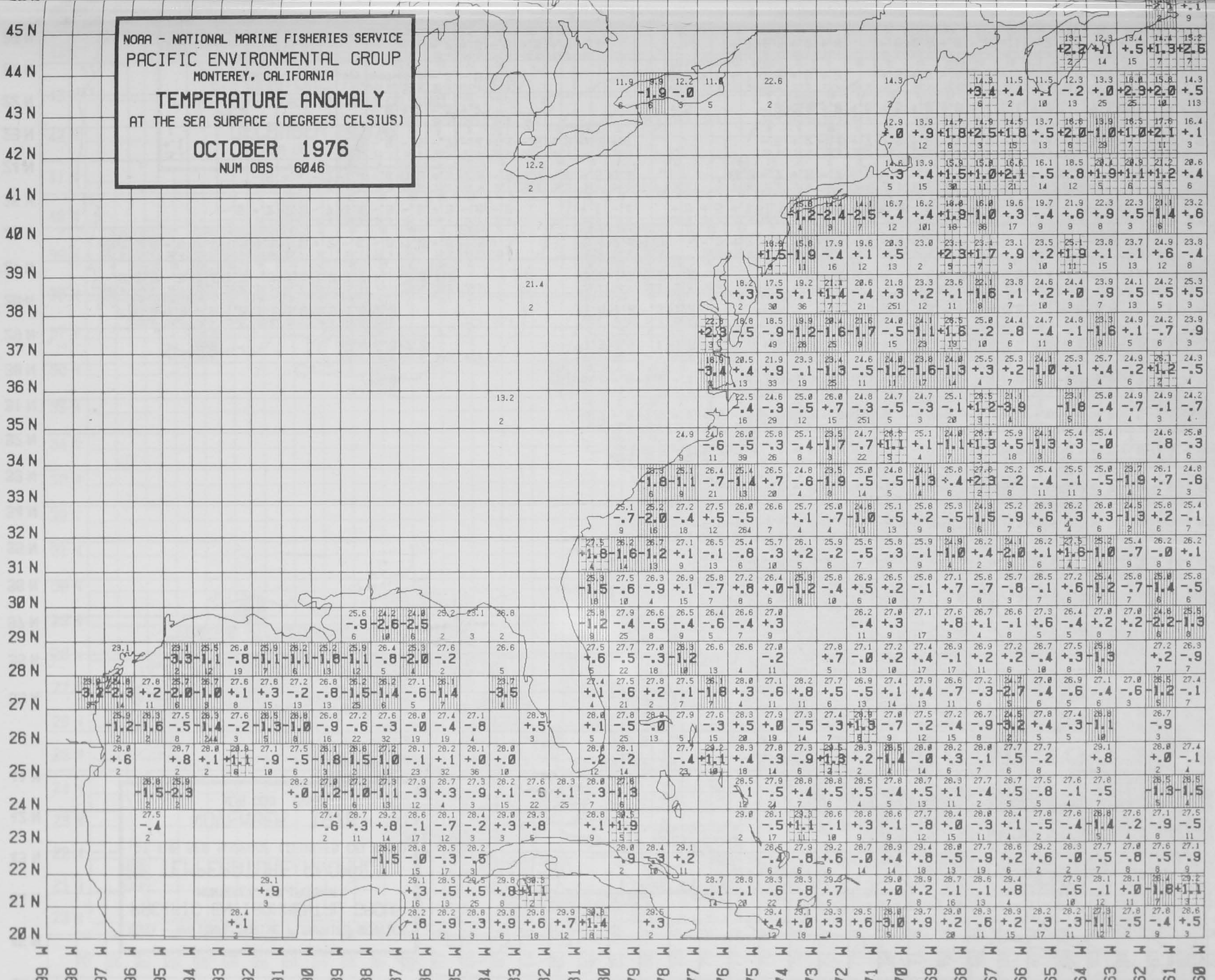
SEPTEMBER 1976

NUM OBS 5458

NOAA - NATIONAL MARINE FISHERIES SERVICE
PACIFIC ENVIRONMENTAL GROUP
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY
AT THE SEA SURFACE (DEGREES CELSIUS)

OCTOBER 1976
NUM OBS 6046



NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

NOVEMBER 1976

NUM OBS 5382

NOAA - NATIONAL MARINE FISHERIES SERVICE

PACIFIC ENVIRONMENTAL GROUP

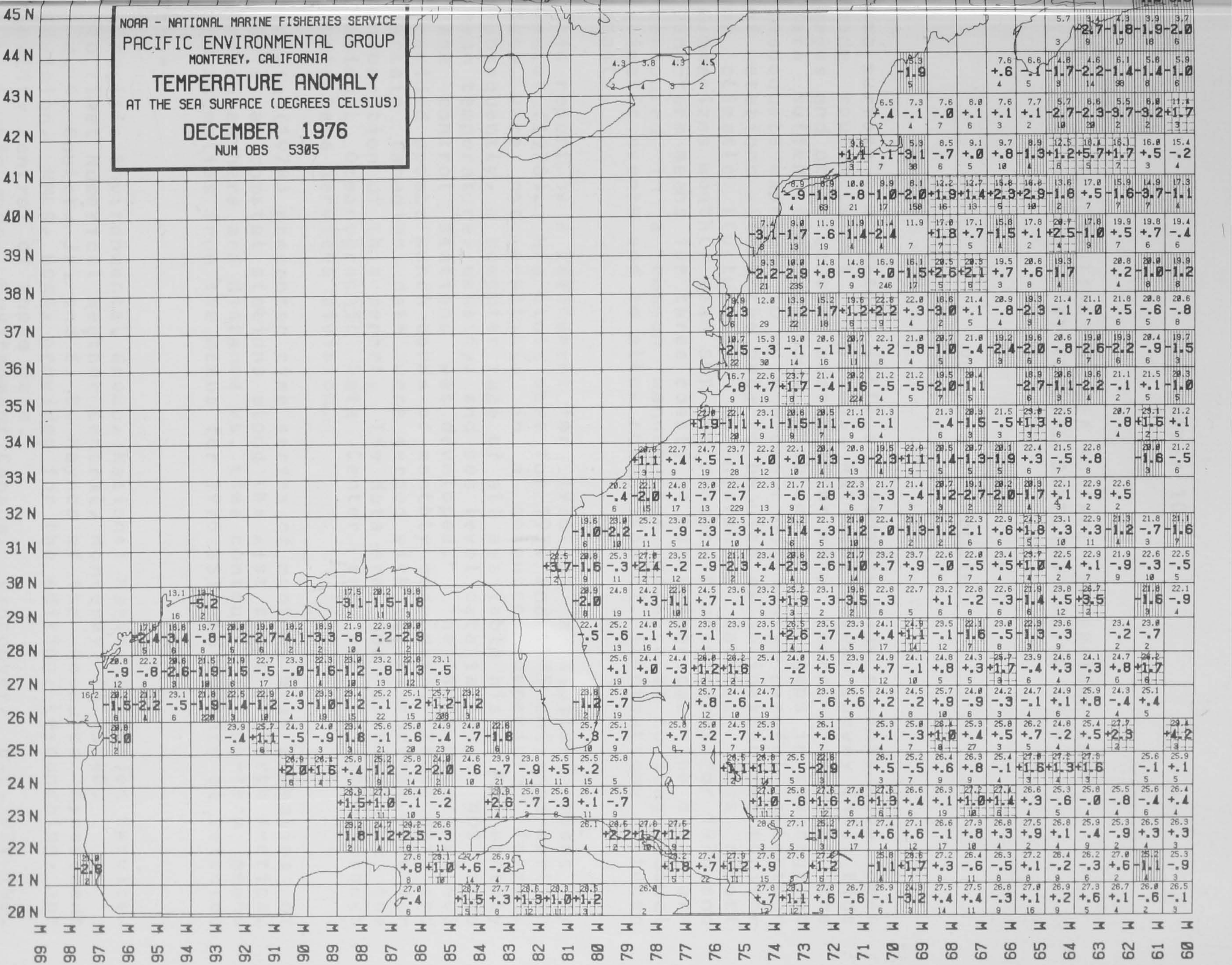
MONTEREY, CALIFORNIA

TEMPERATURE ANOMALY

AT THE SEA SURFACE (DEGREES CELSIUS)

DECEMBER 1976

NUM OBS 5305



Paper 10

FLUCTUATIONS OF SEA SURFACE TEMPERATURE AND DENSITY AT COASTAL STATIONS DURING 1976

Douglas R. McLain[1]

Sea surface temperature (SST) and density measurements have been made routinely at many U.S. National Ocean Survey (NOS) tide gages and other coastal stations for many years. Although the data suffer from various problems such as gaps in coverage or inadequate exposure to open ocean conditions, careful selection of stations allows the data to be used as an inexpensive monitor of climatic fluctuations in nearshore waters. This report summarizes monthly mean SST and density fluctuations for 1976 and long-term means for three coasts of North America. The data are contoured in a common manner for each coast to flag unusual climatic events and to allow comparison of fluctuations between coasts.

This report is a refinement for 1976 of a similar report by Goulet (1978). His plots were for 1974 and 1975 only, as earlier data were not available in a computer compatible format. Subsequently, a computer tape of all available historical monthly mean temperature, density, and sea level data taken at NOS tide gage control stations was developed.[2] The Tides Branch of NOS provided update punch cards of monthly mean data. These data and certain Canadian data[3] were merged with the historical tape for preparation of this report. The data are now archived by the National Oceanographic Data Center and are available through their Data Services Division.

McLain (1978) presented time series of monthly mean anomalies of SST's at coastal stations along the west coast of North America. Presented here are distance vs. time contours of long-term means and anomalies from the means for 1976 SST and density at selected

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[1] Pacific Environmental Group, National Marine Fisheries Service, c/o Fleet Numerical Weather Central, Monterey, CA 93940.

[2] J. R. Goulet, Jr. and E. D. Haynes of the Resource Assessment Division, NMFS, NOAA, provided for the editing, keypunching, and quality control of these data.

[3] L. F. Giovando, Environment Canada, Vancouver, B.C. V7V 1N6. Pers. commun.

stations along the coasts of North America (Appendix 10.1).

The 1976 data are presented as anomalies from a long-term mean for the period 1948-75. This reference period differs from the 1948-67 period used for other data sets such as maps of SST anomaly (McLain, Paper 9). The change was necessary to develop means for certain stations which were established in the last decade.

The stations used in this report are shown in Figure 10.1. The stations chosen were those which had the best combination of desirable characteristics: exposure to open ocean conditions, long data records, minimum gaps in data records, and equidistance between stations. The ideal combination seldom existed and consequently many of the sations used were in estuaries, had gaps in coverage, or were at varying intervals along the coast. For example, data coverage is poor in Oregon and Washington as all stations are in estuaries or are subject to river runoff (as at Neah Bay near the mouth of the Strait of Juan de Fuca). Good coverage was available from British Columbia lighthouses which have long complete data records from open, exposed locations.

The data are plotted as contoured isopleths of the long-term mean and anomaly by month and station position along the coast. Temperature data are in degrees Celsius while density data are in sigma-t units [(density-1) x 1000]. Density values are computed for a standard water temperature of 15.0C. All monthly means represent at least 12 daily observations.

WEST COAST SEA SURFACE TEMPERATURES

The long-term monthly mean (1948-75) SST's at stations along the west coast of North America (Fig. 10.2) had minimum values in January and February and maximum values in July or August. Minimum winter temperature occurred at Kodiak, AK, while maximum summer temperature occurred at Los Angeles, CA. The winter minima occurred earlier (in January) at the southern stations (California to southern British Columbia) than at the northern stations, where minimum values occurred in February. Summer maxima occurred in August at all stations along the coast except at Neah Bay, WA, where the maximum occurred in July.

Bakun et al. (1974) described the long-term mean distribution of SST from ships in 1-deg squares of longitude and latitude adjacent to the west coast of the United States. Their data show that offshore SST minima and maxima occur about one month later than at the shore stations. This may result from more rapid warming in spring and cooling in fall in shallower coastal waters. The summer maximum temperatures reported by Bakun et al. (1974) are similar to those at the coastal stations but winter minimum temperatures are about 1C lower at the coastal stations. This depression of coastal coastal temperatures may result from the lower heat capacity of the shallower water column at the coastal stations as compared to the offshore areas.

Both Figure 10.2 and the figure of Bakun et al. (1974) show a horizontal trend to the isotherms near Point Conception, CA, between Port San Luis and Los Angeles. This "flattening" of the isotherms is an indication of change of ocean water masses at Point Conception between the cold California Current water to the north and the warmer water of the Los Angeles Bight to the south.

During 1976 the anomalies of SST's at coastal stations were rather noisy and the only major trend was the presence of cooler than normal water along the coast during spring and summer from Sitka, AK, south to California. During summer, first in southeastern Alaska and later farther south, the anomalously cool water was replaced by warmer than normal water which reached maximum anomalies of +2.5C at Yakutat, AK, and off southern California in November and December.

The SST charts presented monthly in Fishing Information showed general negative anomalies of SST along the coast during 1976 until July when positive anomalies first impinged against the Oregon and southern California coasts. Positive anomalies spread during summer and fall and occurred along the entire coast in November and December, in agreement with the coastal station data.

WEST COAST DENSITIES

The long-term mean distribution of density along the west coast of North America (Fig. 10.3) showed that minimum densities occurred off California in February, probably in response to winter rains. In Alaska, however, minimum densities occurred in June or July due to snow and glacial melt.

During 1976, observations of density were spotty but showed positive anomalies off most of the coast most of the year. Large positive anomalies of density off San Francisco and Crescent City were associated with drought conditions existing over California most of the year. The low densities at Kodiak, AK, in August and September were apparently in response to local precipitation.

EAST COAST SEA SURFACE TEMPERATURES

The long-term mean SST's at stations along the east coast (Fig. 10.4) showed minimum temperatures at all stations January-March, and maximum temperatures July-September. As for the west coast, the peaks were earlier (January and July-August) at the southern stations and later (February-March and August-September) at the northern stations. Minimum winter temperatures of 0.6C occurred in February at Portland, ME, and maximum summer temperatures of 30.7C occurred in August at Key West, FL.

Two regions of rapid change of SST with distance can be seen (Fig. 10.4). These regions are between Kiptopeke Beach, VA, and Myrtle Beach, SC, and between Mayport and Miami Beach, FL. As at Point Conception on the west coast, these regions are associated with changes in ocean circulation and occur at Cape Hatteras and Cape Canaveral, respectively. Unlike Point Conception, however, where the greatest SST change between adjacent stations occurred in summer (4.0C change in August), the greatest changes in SST between stations on the east coast occurred in winter or spring (8.2C change in January at Cape Canaveral and 5.7C in April at Cape Hatteras).

During 1976, sampling at the stations was incomplete and many values were missing. In January anomalies of SST were negative along the entire coast as were air temperatures over most of the eastern United States (Wagner 1976). Anomalous warming occurred in February, and by March SST's were above normal along the coast (up to 2.6C above normal at Charleston, SC). This warming also was mentioned by Taubensee (1976a). During the summer months anomalies were positive at Montauk Point, NY, and to the north but were negative to the south. SST's were generally below normal during the fall, and became extremely cold in November as the unusually cold winter of 1976-77 began. An extreme negative anomaly of -5.5C was observed at Sandy Hook, NJ, in November.

Chamberlin and Armstrong (Paper 5) summarized air temperature data along the east coast to show the development of the winter of 1976-77 when strong northerly winds occurred over much of the eastern United States. Their data, from National Weather Service weather stations for the period July 1976-January 1977, indicated that anomalies of air temperatures in fall 1976 were most negative during November over most of the coast. This is in agreement with the SST data. In neither the air temperature nor the SST data did large negative anomalies occur as far south as Miami or Key West, FL. Dickson (1977) also showed that southern Florida air temperatures were not unusually cold in November. The strong negative anomalies of SST in November were a response to the extremely southern location of the jet stream and the consequent cold, dry winds from the north and northwest. These atmospheric conditions enhanced heat loss from the water, strengthened southward-flowing coastal currents, and increased vertical mixing. Evidently these processes were not fully effective at Miami and Key West where SST's are more closely associated with Gulf Stream advective processes.

EAST COAST DENSITIES

The long-term mean density data on the east coast (Fig. 10.5) show that many of the stations are affected by land runoff. Such runoff is particularly evident in the figure at Boston, MA, Sandy Hook, NJ, Kiptopeake Beach, VA, and Charleston, SC, where closed contours enclose regions of minimum water density. Minimum density water occurred at the northern stations March-May, while at the southern stations it occurred January-April. This delay in the time of minimum density at the northern stations resulted from retarded snowmelt and river discharge in spring in the north relative to winter precipitation in the south. The timing of maximum water density similarly is delayed to the north as maximum density generally occurred May-September at the southern stations and during September or October at the northern stations.

During 1976 density observations were frequently missing, and the available observations did not have much coherence from station to station or month to month. A region of coherent positive anomalies occurred from Montauk Point, NY, and north over most of the year, with the obvious exception of Boston, MA, and Portland, ME, during January-March. Positive density anomalies at Woods Hole, MA, and Montauk Point increased rather steadily during the year.

Large and variable anomalies occurred at Charleston, SC, and Mayport, FL, and resulted from fluctuations of river discharge near these stations. For example, the positive anomalies of density at these stations February-May were associated with drought during February and March (Dickson 1976a; Taubensee 1976a). Similarly the negative density anomalies at these stations in June were associated with higher than normal precipitation in the area (Dickson 1976b; Taubensee 1976b).

GULF OF MEXICO COAST SEA SURFACE TEMPERATURES

The long-term means of SST's at all stations along the U.S. coast of the Gulf of Mexico (Fig. 10.6) showed minimum values in January and maximum values in July or August. Minimum winter temperatures occurred at the most northern, estuarine station, Dauphin Island, AL, and maximum summer temperatures occurred at the most southern, open ocean station, Key West, FL.

During 1976, observations of SST's at Gulf coast stations were fairly complete and showed good coherence in space and time. A pattern of SST anomalies similar to that observed at east coast stations from New Jersey to Florida occurred. SST's were anomalously cold at all Gulf coast stations during December 1975 and January 1976 with the greatest anomalies in Florida. Anomalous warming began in February in Texas, and SST anomalies peaked in March at Cedar Key, FL. Anomalous cooling then occurred over most of the area for the remainder of the year, peaking in the large negative anomalies of November over most of the coast. The negative anomalies in November were <1C in magnitude only at Key West, FL. The greatest negative anomaly (-5.1C) was at Galveston, TX, in November. Chamberlin and Armstrong (Paper 11) in their summary of Gulf coast air temperatures during late 1976 also found greatest negative anomalies at Galveston during November. The anomalies of air temperature were caused by strong northerly winds, whereas the SST anomalies were caused by heat losses to the cold, dry air.

GULF OF MEXICO COAST DENSITIES

Long-term mean water density (Fig. 10.7) ranged from almost fresh in January at Dauphin Island, AL (in Mobile Bay), to open ocean conditions at Key West, FL. The months of minimum and maximum densities varied and reflected variations in timing of local river discharge. Minimum densities occurred January-June and maximum densities occurred June-November.

Anomalies of density in 1976 were variable, and apparently were related to local fluctuations of precipitation and runoff. Negative anomalies of density were observed almost all year at south Texas stations. Positive anomalies occurred during August-October from Dauphin Island to Key West, and into December at stations in southern Florida.

SUMMARY

Although coastal station data are noisy and have frequent gaps in coverage, they do show large-scale coherences among stations. These coherences are in general caused by climatic fluctuations that affect long stretches of coastline. An extreme example of such a climatic change is the strong northerly winds over much of the eastern United States during November 1976. These winds created negative anomalies of SST at coastal stations of at least

1C in magnitude from Portland ME, to Mayport, FL, and from t. Petersburg, FL, to Padre Island, TX. Extreme anomalies of -5.5C were observed at Sandy Hook, NJ, and -5.1C at Galveston, X, in November.

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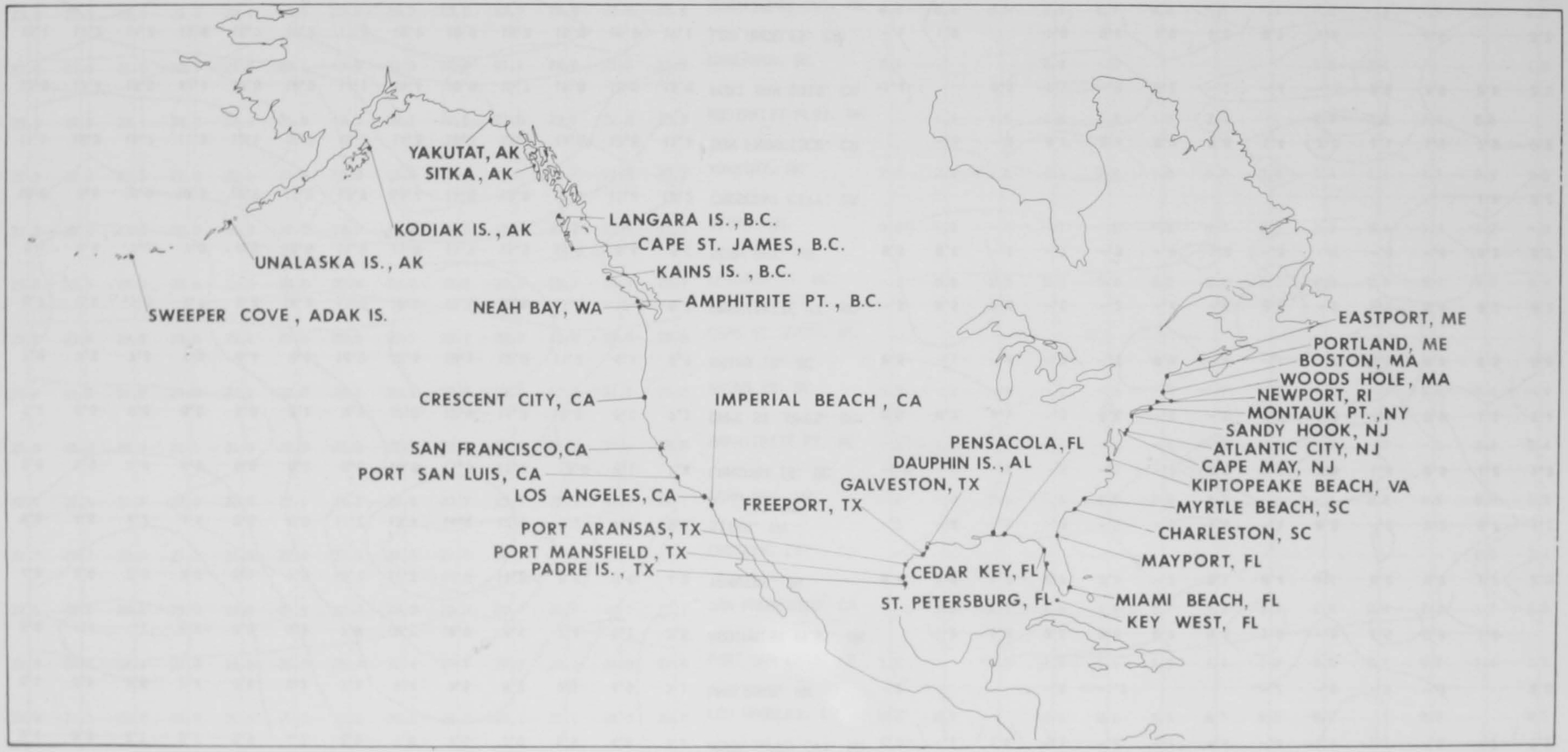
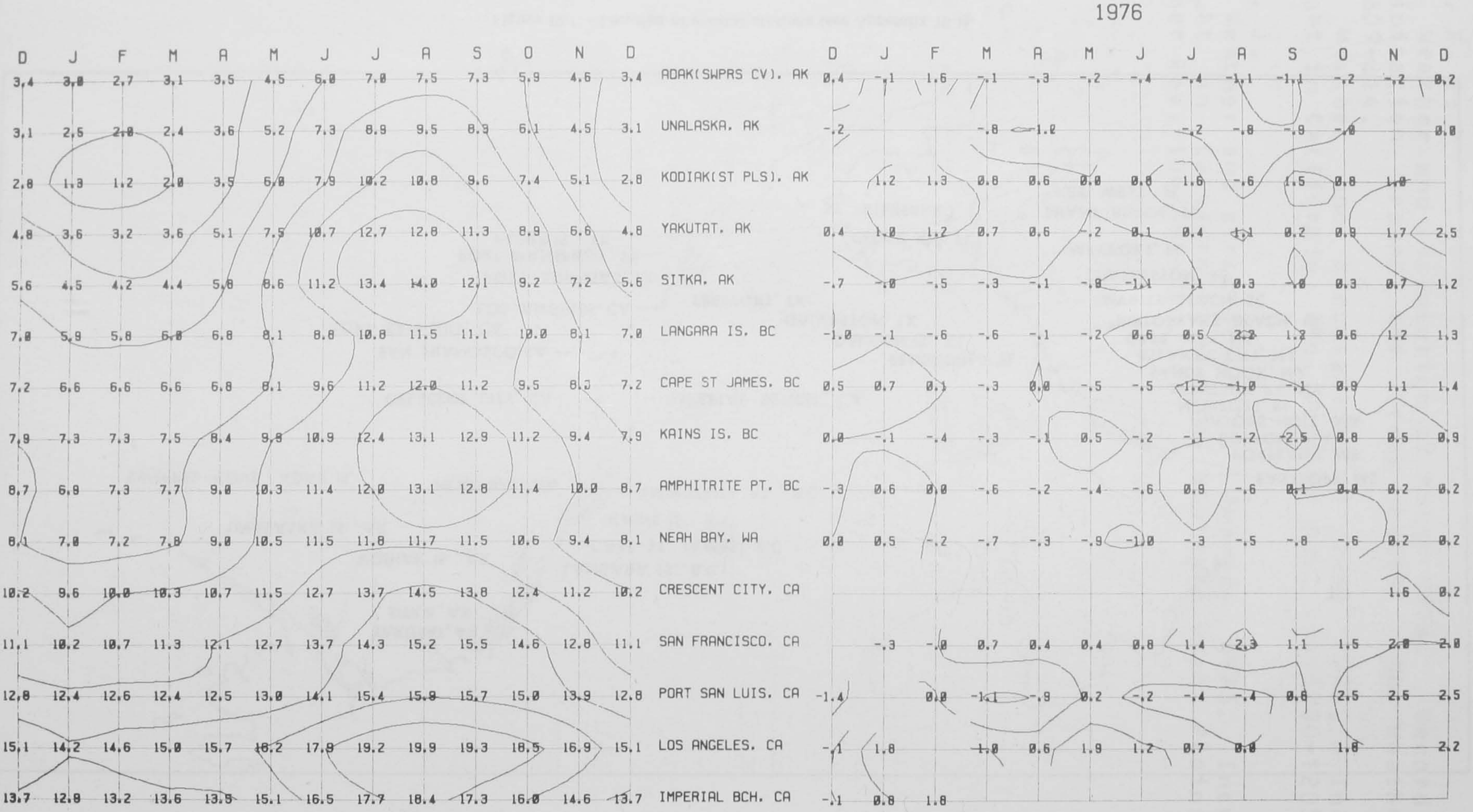


Figure 10.1.—Location of coastal stations (see Appendix 10.1).

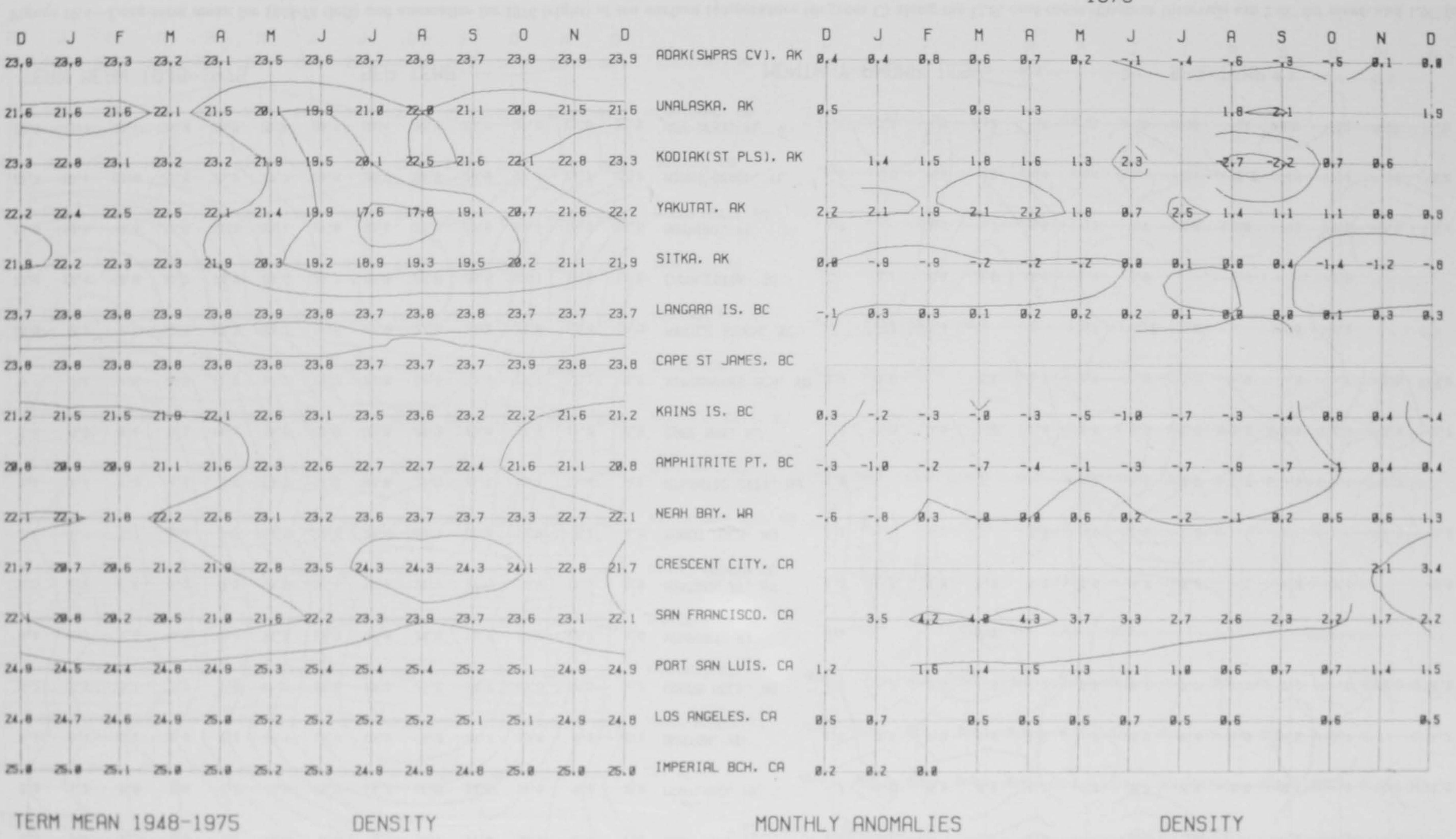


	D	J	F	M	A	M	J	J	A	S	O	N	D
ADAK(SWPRS CV). AK	3.4	3.0	2.7	3.1	3.5	4.5	6.0	7.0	7.5	7.3	5.9	4.6	3.4
UNALASKA. AK	3.1	2.5	2.0	2.4	3.6	5.2	7.3	8.9	9.5	8.9	6.1	4.5	3.1
KODIAK(ST PLS). AK	2.8	1.3	1.2	2.0	3.5	6.0	7.9	10.2	10.8	9.6	7.4	5.1	2.8
YAKUTAT. AK	4.8	3.6	3.2	3.6	5.1	7.5	10.7	12.7	12.8	11.3	8.9	6.6	4.8
SITKA. AK	5.6	4.5	4.2	4.4	5.8	8.6	11.2	13.4	14.0	12.1	9.2	7.2	5.6
LANGARA IS. BC	7.0	5.9	5.8	6.0	6.8	8.1	8.8	10.8	11.5	11.1	10.0	8.1	7.0
CAPE ST JAMES. BC	7.2	6.6	6.6	6.6	6.8	8.1	9.6	11.2	12.0	11.2	9.5	8.3	7.2
KAINS IS. BC	7.9	7.3	7.3	7.5	8.4	9.8	10.9	12.4	13.1	12.9	11.2	9.4	7.9
AMPHITRITE PT. BC	8.7	6.9	7.3	7.7	9.0	10.3	11.4	12.0	13.1	12.8	11.4	10.0	8.7
NEAH BAY. WA	8.1	7.0	7.2	7.8	9.0	10.5	11.5	11.8	11.7	11.5	10.6	9.4	8.1
CRESCENT CITY. CA	10.2	9.6	10.0	10.3	10.7	11.5	12.7	13.7	14.5	13.8	12.4	11.2	10.2
SAN FRANCISCO. CA	11.1	10.2	10.7	11.3	12.1	12.7	13.7	14.3	15.2	15.5	14.6	12.8	11.1
PORT SAN LUIS. CA	12.8	12.4	12.6	12.4	12.5	13.0	14.1	15.4	15.8	15.7	15.0	13.9	12.8
LOS ANGELES. CA	15.1	14.2	14.6	15.0	15.7	16.2	17.9	19.2	19.9	19.3	18.5	16.9	15.1
IMPERIAL BCH. CA	13.7	12.8	13.2	13.6	13.5	15.1	16.5	17.7	18.4	17.3	16.0	14.6	13.7

1976

	D	J	F	M	A	M	J	J	A	S	O	N	D
ADAK(SWPRS CV). AK	0.4	-.1	1.6	-.1	-.3	-.2	-.4	-.4	-1.1	-1.1	-.2	-.2	0.2
UNALASKA. AK	-.2			-.8	-1.0			-.2	-.8	-.9	-.0		0.0
KODIAK(ST PLS). AK		1.2	1.3	0.8	0.6	0.0	0.0	1.6	-.6	1.5	0.8	1.0	
YAKUTAT. AK	0.4	1.0	1.2	0.7	0.6	-.2	0.1	0.4	1.1	0.2	0.9	1.7	2.5
SITKA. AK	-.7	-.0	-.5	-.3	-.1	-.8	-1.1	-.1	0.3	-.0	0.3	0.7	1.2
LANGARA IS. BC	-1.0	-.1	-.6	-.6	-.1	-.2	0.6	0.5	2.2	1.2	0.6	1.2	1.3
CAPE ST JAMES. BC	0.5	0.7	0.1	-.3	0.0	-.5	-.5	-1.2	-1.0	-.1	0.9	1.1	1.4
KAINS IS. BC	0.0	-.1	-.4	-.3	-.1	0.5	-.2	-.1	-.2	-2.5	0.8	0.5	0.9
AMPHITRITE PT. BC	-.3	0.6	0.0	-.6	-.2	-.4	-.6	0.9	-.6	0.1	0.0	0.2	0.2
NEAH BAY. WA	0.0	0.5	-.2	-.7	-.3	-.9	-1.0	-.3	-.5	-.8	-.6	0.2	0.2
CRESCENT CITY. CA												1.6	0.2
SAN FRANCISCO. CA		-.3	-.0	0.7	0.4	0.4	0.8	1.4	2.3	1.1	1.5	2.0	2.0
PORT SAN LUIS. CA	-1.4		0.0	-1.1	-.9	0.2	-.2	-.4	-.4	0.6	2.5	2.5	2.5
LOS ANGELES. CA	-.1	1.8		1.0	0.6	1.9	1.2	0.7	0.0		1.0		2.2
IMPERIAL BCH. CA	-.1	0.8	1.8										

Figure 10.2.—Long-term mean for 1948-75 (left) and anomalies for 1976 (right) of sea surface temperature (degrees C) along the U.S. west coast. Contour intervals are 2.0C for mean and 1.0C for anomalies.



	D	J	F	M	A	M	J	J	A	S	O	N	D
ADAK(SWPRS CV). AK	23.9	23.8	23.3	23.2	23.1	23.5	23.6	23.7	23.9	23.7	23.9	23.9	23.9
UNALASKA. AK	21.6	21.6	21.6	22.1	21.5	20.1	19.9	21.0	22.0	21.1	20.8	21.5	21.6
KODIAK(ST PLS). AK	23.3	22.8	23.1	23.2	23.2	21.9	19.5	20.1	22.5	21.6	22.1	22.8	23.3
YAKUTAT. AK	22.2	22.4	22.5	22.5	22.1	21.4	19.9	17.6	17.8	19.1	20.7	21.6	22.2
SITKA. AK	21.9	22.2	22.3	22.3	21.9	20.3	19.2	18.9	19.3	19.5	20.2	21.1	21.9
LANGARA IS. BC	23.7	23.8	23.8	23.9	23.8	23.9	23.8	23.7	23.8	23.8	23.7	23.7	23.7
CAPE ST JAMES. BC	23.8	23.8	23.8	23.8	23.8	23.8	23.8	23.7	23.7	23.7	23.9	23.8	23.8
KAINS IS. BC	21.2	21.5	21.5	21.9	22.1	22.6	23.1	23.5	23.6	23.2	22.2	21.6	21.2
AMPHITRITE PT. BC	20.8	20.9	20.9	21.1	21.6	22.3	22.6	22.7	22.7	22.4	21.6	21.1	20.8
NEAH BAY. WA	22.1	22.1	21.8	22.2	22.6	23.1	23.2	23.6	23.7	23.7	23.3	22.7	22.1
CRESCENT CITY. CA	21.7	20.7	20.6	21.2	21.9	22.8	23.5	24.3	24.3	24.3	24.1	22.8	21.7
SAN FRANCISCO. CA	22.1	20.8	20.2	20.5	21.0	21.6	22.2	23.3	23.9	23.7	23.6	23.1	22.1
PORT SAN LUIS. CA	24.9	24.5	24.4	24.8	24.9	25.3	25.4	25.4	25.4	25.2	25.1	24.9	24.9
LOS ANGELES. CA	24.8	24.7	24.6	24.9	25.0	25.2	25.2	25.2	25.2	25.1	25.1	24.9	24.8
IMPERIAL BCH. CA	25.0	25.0	25.1	25.0	25.0	25.2	25.3	24.9	24.9	24.8	25.0	25.0	25.0

1976	D	J	F	M	A	M	J	J	A	S	O	N	D
ADAK(SWPRS CV). AK	0.4	0.4	0.8	0.6	0.7	0.2	-.1	-.4	-.6	-.3	-.5	0.1	0.0
UNALASKA. AK	0.5			0.9	1.3				1.8	2.1			1.9
KODIAK(ST PLS). AK		1.4	1.5	1.8	1.6	1.3	2.3		-2.7	-2.2	0.7	0.6	
YAKUTAT. AK	2.2	2.1	1.9	2.1	2.2	1.8	0.7	2.5	1.4	1.1	1.1	0.8	0.9
SITKA. AK	0.0	-.9	-.9	-.2	-.2	-.2	0.0	0.1	0.0	0.4	-1.4	-1.2	-.8
LANGARA IS. BC	-.1	0.3	0.3	0.1	0.2	0.2	0.2	0.1	0.0	0.0	0.1	0.3	0.3
CAPE ST JAMES. BC													
KAINS IS. BC	0.3	-.2	-.3	-.0	-.3	-.5	-1.0	-.7	-.3	-.4	0.8	0.4	-.4
AMPHITRITE PT. BC	-.3	-1.0	-.2	-.7	-.4	-.1	-.3	-.7	-.8	-.7	-.1	0.4	0.4
NEAH BAY. WA	-.6	-.8	0.3	-.0	0.0	0.6	0.2	-.2	-.1	0.2	0.5	0.6	1.3
CRESCENT CITY. CA												2.1	3.4
SAN FRANCISCO. CA		3.5	4.2	4.0	4.3	3.7	3.3	2.7	2.6	2.3	2.2	1.7	2.2
PORT SAN LUIS. CA	1.2		1.6	1.4	1.5	1.3	1.1	1.0	0.6	0.7	0.7	1.4	1.5
LOS ANGELES. CA	0.5	0.7		0.5	0.5	0.5	0.7	0.5	0.6		0.6		0.5
IMPERIAL BCH. CA	0.2	0.2	0.0										

Figure 10.3.—Long-term mean for 1948-75 (left) and anomalies for 1976 (right) of density (sigma-t) along the U.S. west coast. Contour interval is 2 units.

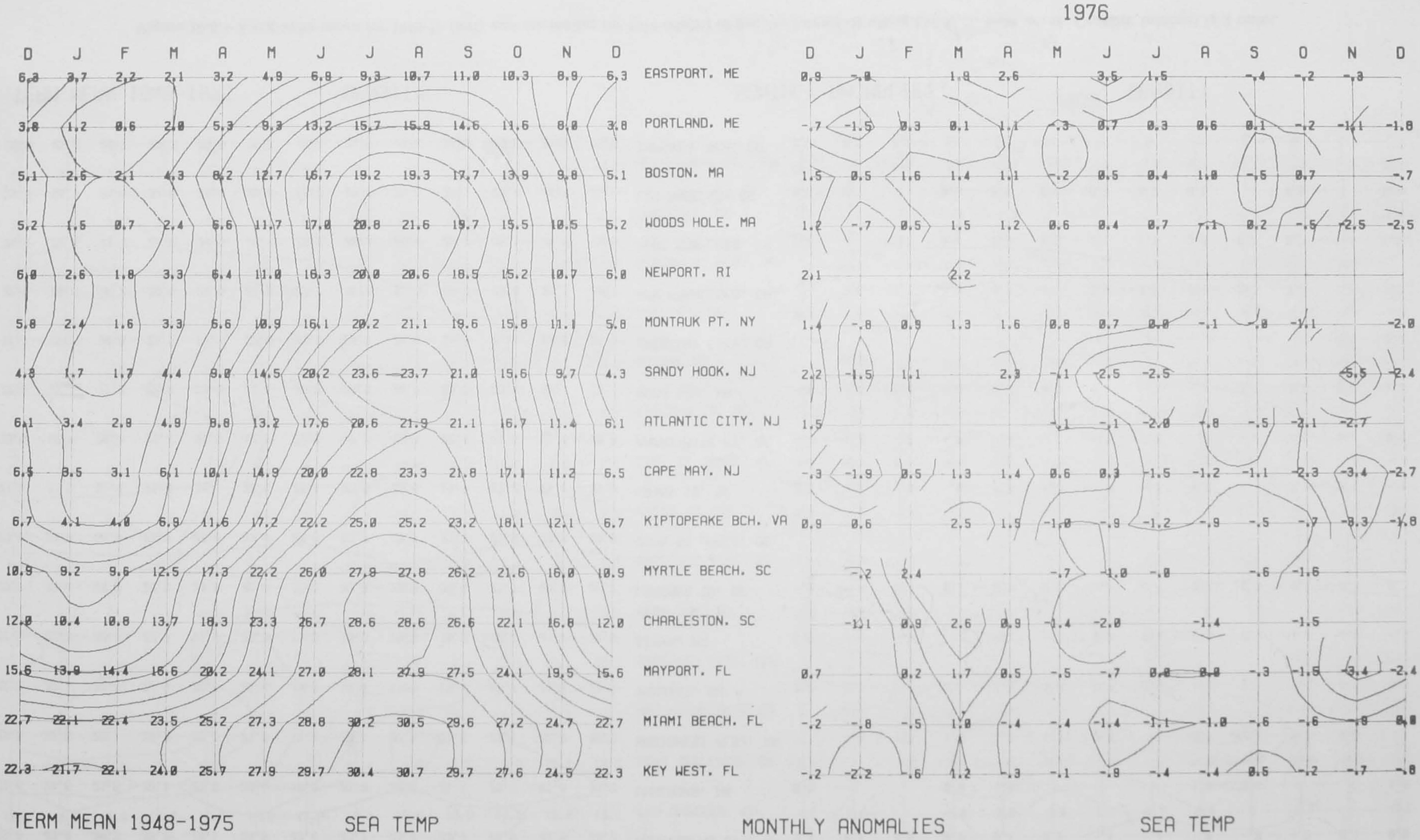


Figure 10.4—Long-term mean for 1948-75 (left) and anomalies for 1976 (right) of sea surface temperature (degrees C) along the U.S. east coast. Contour intervals are 2.0C for mean and 1.0C for anomalies.

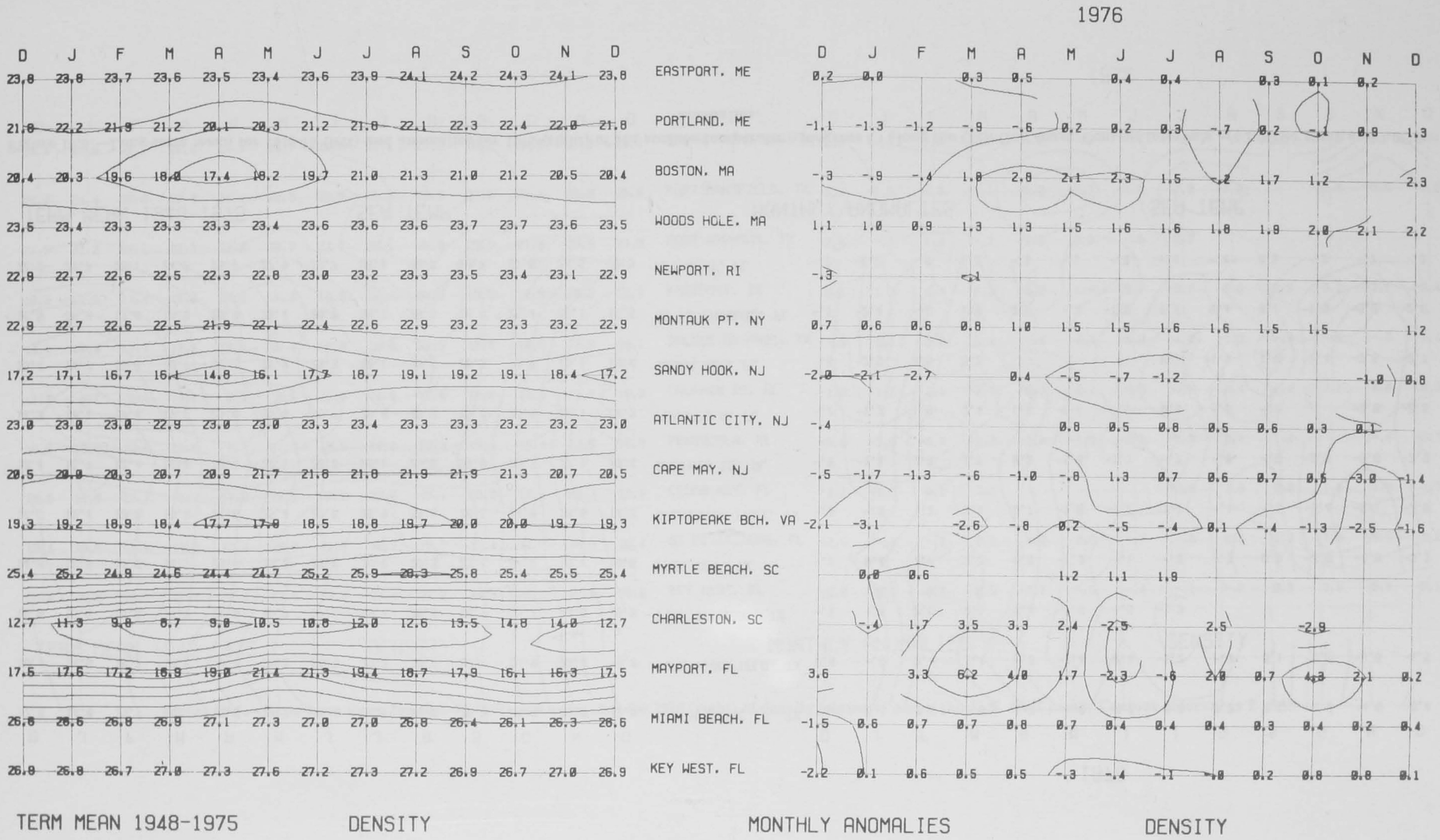
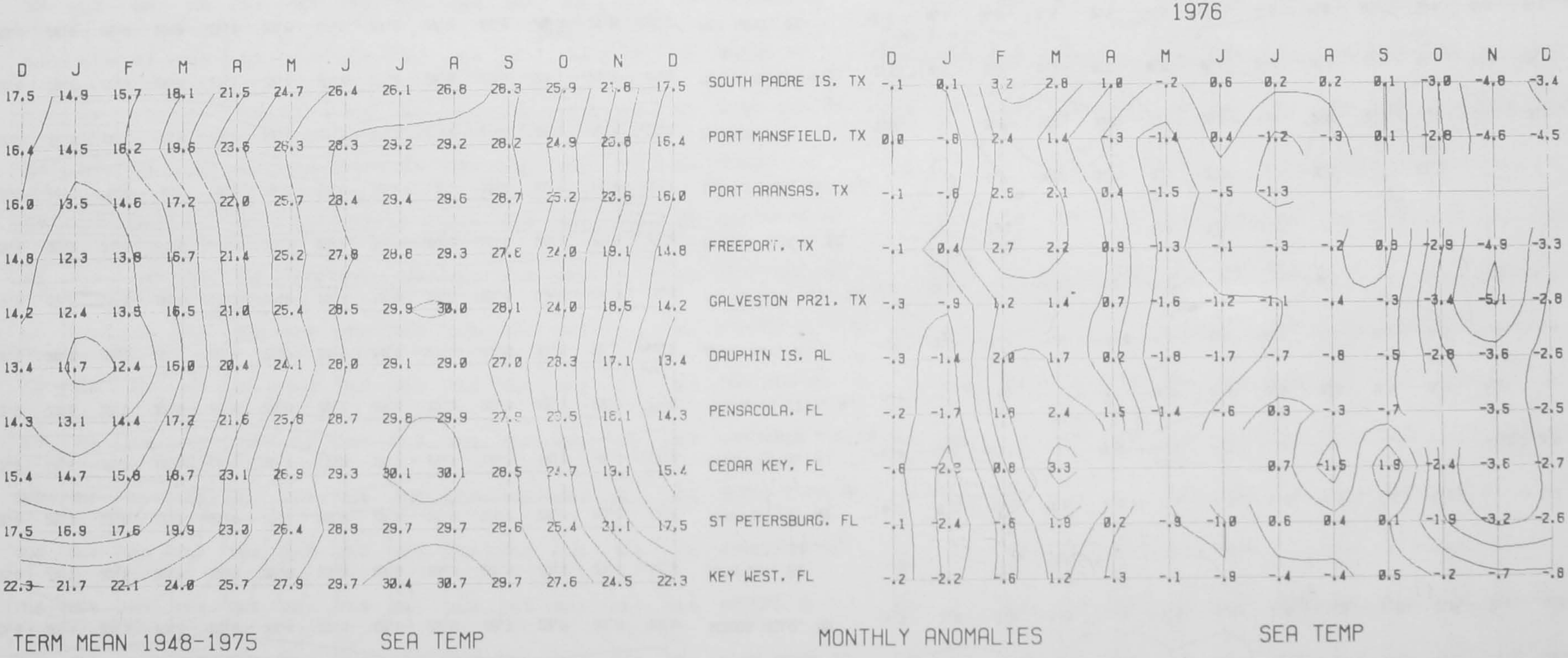


Figure 10.5.—Long-term mean for 1948-75 (left) and anomalies for 1976 (right) of density (sigma-t) along the U.S. east coast. Contour interval is 2 units.



D	J	F	M	A	M	J	J	A	S	O	N	D
17.5	14.9	15.7	18.1	21.5	24.7	26.4	26.1	26.8	28.3	25.9	21.8	17.5
16.4	14.5	16.2	19.6	23.6	26.3	28.3	29.2	29.2	28.2	24.9	20.8	16.4
16.0	13.5	14.6	17.2	22.0	25.7	28.4	29.4	29.6	28.7	25.2	20.6	16.0
14.8	12.3	13.8	16.7	21.4	25.2	27.8	28.8	29.3	27.8	24.0	19.1	14.8
14.2	12.4	13.5	16.5	21.0	25.4	28.5	29.9	30.0	28.1	24.0	18.5	14.2
13.4	10.7	12.4	16.0	20.4	24.1	28.0	29.1	29.0	27.0	23.3	17.1	13.4
14.3	13.1	14.4	17.2	21.6	25.8	28.7	29.8	29.9	27.9	23.5	16.1	14.3
15.4	14.7	15.8	18.7	23.1	26.9	29.3	30.1	30.1	28.5	24.7	19.1	15.4
17.5	16.9	17.6	19.9	23.0	26.4	28.9	29.7	29.7	28.6	25.4	21.1	17.5
22.3	21.7	22.1	24.0	25.7	27.9	29.7	30.4	30.7	29.7	27.6	24.5	22.3

	D	J	F	M	A	M	J	J	A	S	O	N	D
SOUTH PADRE IS. TX	-.1	0.1	3.2	2.8	1.0	-.2	0.6	0.2	0.2	0.1	-3.0	-4.8	-3.4
PORT MANSFIELD. TX	0.0	-.8	2.4	1.4	-.3	-1.4	0.4	-1.2	-.3	0.1	-2.8	-4.6	-4.5
PORT ARANSAS. TX	-.1	-.6	2.5	2.1	0.4	-1.5	-.5	-1.3					
FREEPORT. TX	-.1	0.4	2.7	2.2	0.9	-1.3	-.1	-.3	-.2	0.3	-2.9	-4.9	-3.3
GALVESTON PR21. TX	-.3	-.9	1.2	1.4	0.7	-1.6	-1.2	-1.1	-.4	-.3	-3.4	-5.1	-2.8
DAUPHIN IS. AL	-.3	-1.4	2.0	1.7	0.2	-1.8	-1.7	-.7	-.8	-.5	-2.8	-3.6	-2.6
PENSACOLA. FL	-.2	-1.7	1.8	2.4	1.5	-1.4	-.6	0.3	-.3	-.7		-3.5	-2.5
CEDAR KEY. FL	-.6	-2.2	0.8	3.3				0.7	-1.5	1.9	-2.4	-3.6	-2.7
ST PETERSBURG. FL	-.1	-2.4	-.6	1.9	0.2	-.9	-1.0	0.6	0.4	0.1	-1.9	-3.2	-2.6
KEY WEST. FL	-.2	-2.2	-.6	1.2	-.3	-.1	-.9	-.4	-.4	0.5	-.2	-.7	-.8

Figure 10.6.—Long-term mean for 1948-75 (left) and anomalies for 1976 (right) of sea surface temperature (degrees C) along the U.S. Gulf coast. Contour intervals are 2.0C for mean and 1.0C for anomalies.

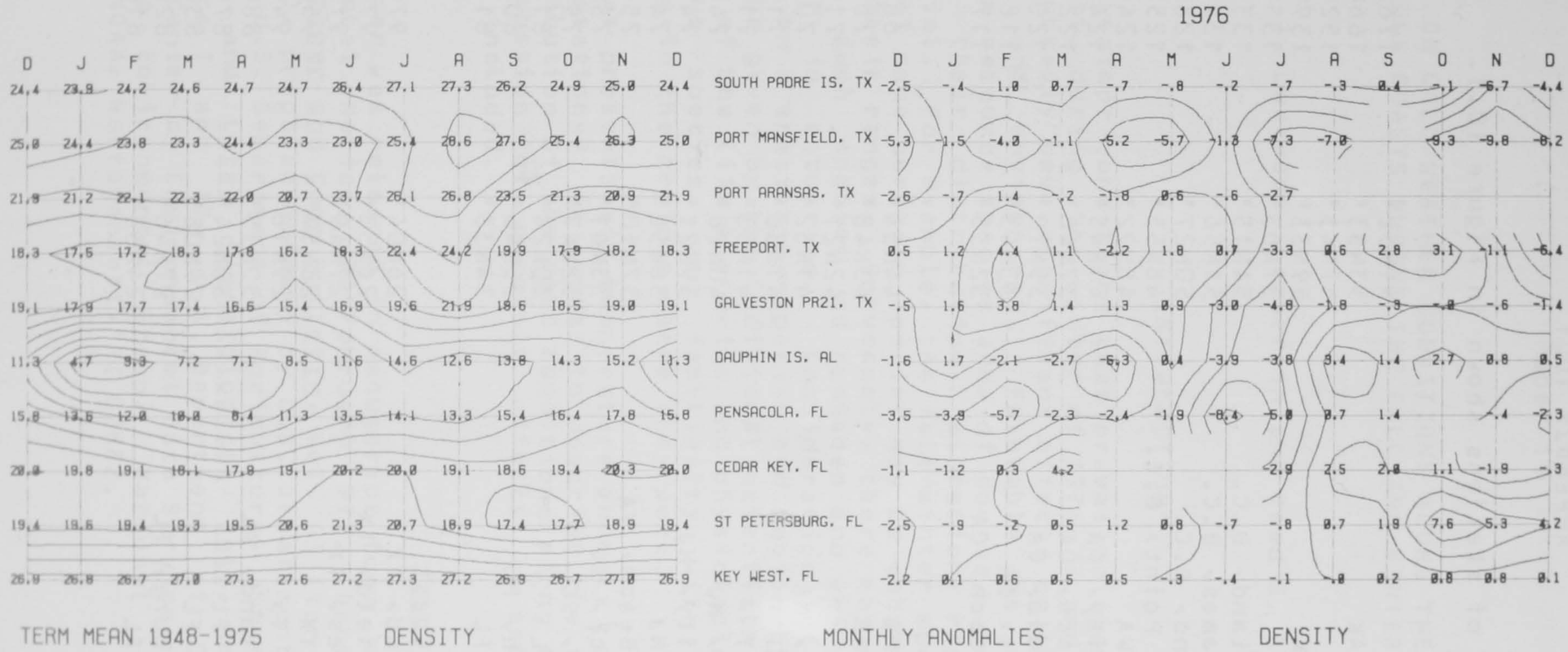


Figure 10.7.—Long-term mean for 1948-75 (left) and anomalies for 1976 (right) of density (sigma-t) along the U.S. Gulf coast. Contour interval is 2 units.

APPENDIX 10.1

Locations of stations shown in Figure 10.1.

West coast		
Adak, AK	51N52'	176W39'
UnaLaska, AK	53N53'	166W33'
Kodiak, AK	57N45'	152W29'
Yakutat, AK	59N33'	139W44'
Sitka, AK	57N03'	135W21'
Langara Island, B.C.	54N15'	133W04'
Cape St. James, B.C.	51N56'	131W01'
Kains Island, B.C.	50N27'	128W02'
Amphitrite Point, B.C.	48N55'	125W32'
Neah Bay, WA	48N22'	124W37'
Crescent City, CA	41N45'	124W12'
San Francisco, CA	37N48'	122W28'
Port San Luis, CA	35N10'	120W45'
Los Angeles, CA	33N43'	118W16'
Imperial Beach, CA	32N35'	117W08'
East Coast		
Eastport, ME	44N54'	66W59'
Portland, ME	43N40'	70W15'
Boston, MA	42N21'	71W03'
Woods Hole, MA	41N32'	70N40'
Newport, RI	41N30'	71W20'
Montauk, NY	41N03'	71W58'
Sandy Hook, NJ	40N28'	74W01'
Atlantic City, NJ	39N21'	74W25'
Cape May, NJ	38N58'	74W58'
Kiptopeke Beach, VA	37N10'	75W59'
Myrtle Beach, SC	33N41'	78W53'
Charleston, SC	32N47'	79W56'
Mayport, FL	30N24'	81W26'
Miami Beach, FL	25N46'	80W08'
Key West, FL	34N33'	81W49'
Gulf of Mexico Coast		
Padre Island, TX	26N04'	97W09'
Port Mansfield, TX	26N33'	97W26'
Port Aransas, TX	27N49'	97W04'
Freeport, TX	28N57'	95W19'
Galveston, TX	29N18'	94W47'
Dauphin Island, AL	30N15'	88W05'
Pensacola, FL	30N24'	87W13'
Cedar Key, FL	29N08'	83W02'
St. Petersburg, FL	27N46'	82W37'
Key West, FL	24N33'	81W49'

Paper 11

DATA ON COLD WEATHER CONDITIONS ALONG THE ATLANTIC AND GULF COASTS DURING THE FALL AND WINTER OF 1976-77[1]

J. Lockwood Chamberlin and Reed S. Armstrong[2]

INTRODUCTION

The cold weather conditions that prevailed along the Atlantic and Gulf Coast during the winter of 1976-77 and the preceding fall will undoubtedly have significant effects on the marine fishery resources and environment. Favorable as well as unfavorable effects on resource species are, of course, readily conceivable regarding their distribution, migration, reproduction, growth, and survival. For example, the fall-winter spawning and larval survival of some northern species may be enhanced in the southern parts of their ranges. Conversely, there may be damage to the young of such species as menhaden and white shrimp where they overwinter in estuaries. Consideration of possible effects should be on a species-by-species and region-by-region basis, and can best be given by the individual scientists who have special knowledge of the life histories and physiological requirements of the various species, and familiarity with the environmental conditions in the regions where they work.

This report presents air temperature anomaly data for selected weather stations, in order to describe the severity, duration, and distribution of the cold conditions along the entire coast. Some discussion of possible effects on estuarine and coastal waters is included.

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[1] This paper was released in manuscript form as a NMFS Marine Environmental Notice, 22 February 1977. Data were derived from Weekly Weather and Crop Bulletin, Vol. 63 (for 1976) and Vol. 64 (for 1977), prepared jointly by U.S. Department of Commerce, NWS, NOAA, and U.S. Department of Agriculture, Statistical Reporting Service; and Local Climatological Data, Annual Summaries for 1975, Parts I and II, U.S. Department of Commerce, National Climatic Center of Environmental Data Service, NOAA.

[2] Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

Paper 11

ENTIRE COAST COLDER THAN IN PREVIOUS 40 YEARS

Anomalies of monthly mean air temperatures for July 1976 January 1977 appear in Figure 11.1 for 12 coastal stations. T anomalies are based on long-term monthly means for the 40- period, 1936-75. For comparison with these anomalie Figure 11.1 also includes the extremes and standard deviations the monthly means for the 40-yr period.

The anomaly data in Figure 11.1 show colder than avera temperatures every month from October to January along the enti coast except in southern Florida. Furthermore, the record co anomalies of the past 40 years are equalled or exceeded in one more months at every station except Key West. At both Savann and Jacksonville the negative anomalies equalled or exceeded t 40-yr record in three of the four months--all but Decembe Record breaking anomalies are notable at Atlantic City January, Jacksonville in November, and Galveston in October. December, the negative anomalies were relatively moderate alo the entire coast.

Some apparent regional patterns are:

- -- North of Cape Hatteras, negative anomalies in all mont from July to January.
- -- Hatteras to Jacksonville, negative anomalies in a months from August to January.
- -- Gulf of Mexico, negative anomalies in all months fr October to January.

To permit interyear comparisons of entire cold seasons, averag of the monthly mean air temperature anomalies have be calculated for the five months, September-January, at six of t stations: Portland, Atlantic City, Savannah, Key Wes Tallahassee, and Galveston. These averages appear in Table 11 for the 1976-77 fall-winter period. Also listed in Table 11 are comparable values for each station for the four colde September-January periods of the previous 40 years.

The data in Table 11.1 clearly show: 1) that record co weather conditions prevailed in the fall and winter of 1976- along the entire coast, with the exception of southern Florid and 2) that unusually cold conditions in earlier years we more localized--not extending along the entire coast.

Longer records from a few stations (Providence, 1905-197 Hatteras, 1875-1977; Jacksonville, 1871-1977; and Galvesto 1905-1977) indicate that the 1976-77 cold season was unrival during the years of record, except at Providence in 1917-18.

NOTES ON INDIVIDUAL STATIONS

Portland, ME

1) All 5 months below normal (2nd time in last 41 years; also in 1964-65).

2) All 5 months 1 standard deviation below normal (only time in last 41 years with monthly means that low for more than 2 months).

3) Record low of 41 years in October.

4) Average anomalies for 5-mo period, -4.6F (-2.6C), which is 1.9 times the previous coldest (1958-59).

5) December monthly mean colder than normal January value.

Atlantic City, NJ

1) All 5 months below normal (5th time in last 41 years; also in 1969-70, 1968-69, 1967-68, 1962-63).

2) All 5 months 1 standard deviation below normal (only time in last 41 years with monthly means that low for more than 4 months; 4 months in 1967-68).

3) Record lows of 41 years in October, November, and January.

4) Average of anomalies for 5-mo period, -7.6F (-4.2C), which is 1.3 times the previous coldest (1967-68).

5) December monthly mean colder than normal January value.

Savannah, GA

1) All 5 months below normal (4th time in last 41 years; also in 1965-66, 1963-64, 1955-56).

2) Four of the 5 months 1 standard deviation below normal (only time in last 41 years with monthly means that low for more than 3 months; 3 in 1967-68).

3) Record lows of 41 years in October, November, and January.

4) Average of anomalies for 5-mo period, -5.3F (-2.3C), which is 1.6 times the previous coldest (1969-70).

5) November monthly mean equivalent to normal December value, and December mean below normal January value.

Key West, FL

1) Three months below normal, September above normal, and December normal.

2) Only 1 month 1 standard deviation below normal (January).

3) No record lows established in 1976-77.

4) Average of anomalies for 5-mo period, -1.2F (-0.7C), which is 0.6 times the coldest of the 41-yr record (1939-40).

Tallahassee, FL

1) All 5 months below normal (only time in last 41 years).

2) Four of the 5 months 1 standard deviation below normal (only time in last 41 years with monthly means that low for more than 3 months; 3 in 1969-70).

3) Record low of 41 years in October.

4) Average of anomalies for 5-mo period, -5.2F (-2.9C), which is 1.6 times the previous coldest (1963-64).

5) November monthly mean equivalent to normal January value, and December mean below normal January value; January was second coldest of 41-yr record.

Galveston, TX

1) Four months below normal (October-January) occurred 7 times in previous 40 years; only in 1943-44 were temperatures below normal for all 5 months.

2) Four of the 5 months 1 standard deviation below normal (only time in last 41 years with monthly means that low for more than 3 months; 3 in 1943-44).

3) Record lows of 41 years in October and November.

4) Average of anomalies for 5-mo period, -5.4F (-3.0C), which is 2.3 times the previous coldest (1943-44).

5) October monthly mean about equivalent to normal November value, November mean below normal December value, and December mean below normal January; January mean was second coldest in 41-yr record.

EFFECTS ON ESTUARINE AND COASTAL WATERS

Increased vertical mixing: The increased density of chilled water will accelerate vertical mixing and alter normal circulation patterns in inshore waters.

Ice cover: Because the onset of ice cover causes abrupt cessation of wind driven vertical mixing, the salinity in some estuaries may be above normal near bottom and below normal near the surface.

Decreased runoff: Decreased coastal runoff resulting from frozen streams and snowfall, instead of rain, results in general elevation of estuarine salinities, although the opposite effect can be looked for in the upper parts of mixed estuaries where the penetration of saline water along the bottom is driven by surface flow toward the ocean.

Ice cover effects in coastal zone: Ice cover and near freezing temperatures in estuaries and lagoons along the southeast Atlantic coast, where such conditions are a rarity, may severely affect some resident marine species. Along the northeast coast such conditions, although normal in the winter, may be having marked effects on the marine life because of their unusual duration, offshore extension, and depth penetration.

Strong spring runoff: Wherever there are above normal accumulations of snow and ice in the drainage basins, the possibility exists of strong spring runoff. In the estuaries, this would result in an abrupt reversal of the salinity and circulation conditions that now prevail. On the inner continental shelf, strong runoff could lead to early stratification of the water column with the possibility of anoxia developing next summer, as occurred last summer off New Jersey. Despite the accumulation of snow and ice in the drainage basins, however, strong runoff will still depend on the volume of precipitation during the spring and timing of the thaw.

Shelf Water temperatures: Not only should water temperatures be expected to equal or go below record low values, but the normal spring and summer warming cycle may be delayed. Persistence of the cold water can be expected, particularly in bottom waters over the outer continental shelf, where the cold water becomes insulated from seasonal warming by formation of a warm surface layer. The vertical stratification may also be stronger than usual because of cold dense water persisting at the bottom.

The Atlantic Environmental Group, NMFS, is attempting to determine whether the warm Slope Water that contacts bottom on the outer continental shelf in the Middle Atlantic Bight could be displaced in 1977 by abnormally chilled Shelf Water. Such displacement might increase mortality of tilefish and other bottom dwelling animals whose distribution is apparently limited to the Slope Water zone, where the temperature regime is normally quite stable throughout the year. (The well-known mass mortality of tilefish off the Middle Atlantic in March-May 1882 was not preceded by a cold winter.)

RECENT REPORTS OF COLD WEATHER EFFECTS ON FISHERY RESOURCES

The following information has come to our attention on the apparent influence of the cold weather on the fishery resources:

White shrimp in South Carolina: A newspaper article from the United Press International dated February 19, 1977 reports that "Charles H. Farmer, head of the [South Carolina] Department of Wildlife and Marine Resources' crustacean management program, said a week-long survey showed the cold weather has virtually wiped out the white shrimp that spend the winter along the South Carolina coast."

Snook and other tropical fish in Florida: Thomas H. Fraser, Environmental Quality Laoratory, Inc., Port Charlotte, FL, has informed us by telephone that unusually widespread kills of snook were reported in Florida during and following the extremely cold weather in the third week of January. Other species for which kills were reported or observed by Fraser during the same period of January include mojarra, ladyfish, crevalle, and tarpon. Fraser advised that cold weather kills have been reported in Florida for each of these tropical species in earlier years.

ACKNOWLEDGMENTS

We appreciate the cooperation of Lyle M. Denny, Agriculture Weather Support Service, NWS, NOAA, Washington, DC, who supplied us with the Weekly Weather and Crop Bulletin for 1976 and early 1977, and Robert G. Quayle, National Climatic Center, EDS, NOAA, Asheville, NC, who supplied the historical air temperature data. Donald L. Gilman, National Meteorological Center, NWS, NOAA, Washington, DC, gave advice on sources of data. John A. Holston, Sandy Hook Laboratory, Northeast Fisheries Center, first told us of the snook kill in Florida, and Alexander Dragovich, Miami Laboratory, Southeast Fisheries Center, referred us to additional sources of information on Florida fish kills. In the Atlantic Environmental Group of NMFS, David A. Mizenko and Robert W. Christ made the statistical calculations and helped prepare the figures.

Table 11.1.--Averages of monthly mean air temperature anomalies (degrees F) for September-January at selected Atlantic and Gulf coast weather stations. The averages for 1976-77 are listed for each station. Only the four coldest averages from the previous 40 years are listed.

	Portland	Atlantic City	Savannah	Key West	Tallahassee	Galveston
1976-77	-4.6	-7.6	-5.3	-1.2	-5.2	-5.4
1970-71	-2.2					
1969-70			-3.8	-3.3		-2.5
1968-69		-3.3			-1.9	
1967-68		-5.9	-2.9			
1963-64			-3.1	-1.6	-3.3	
1961-62						-1.4
1960-61	-2.2					
1958-59	-2.4	-2.9				-1.5
1956-57	-2.4					
1955-56			-2.4			
1954-55				-1.7		
1943-44					-2.7	-2.3
1939-40				-1.9		-1.8
1937-38				-1.6		

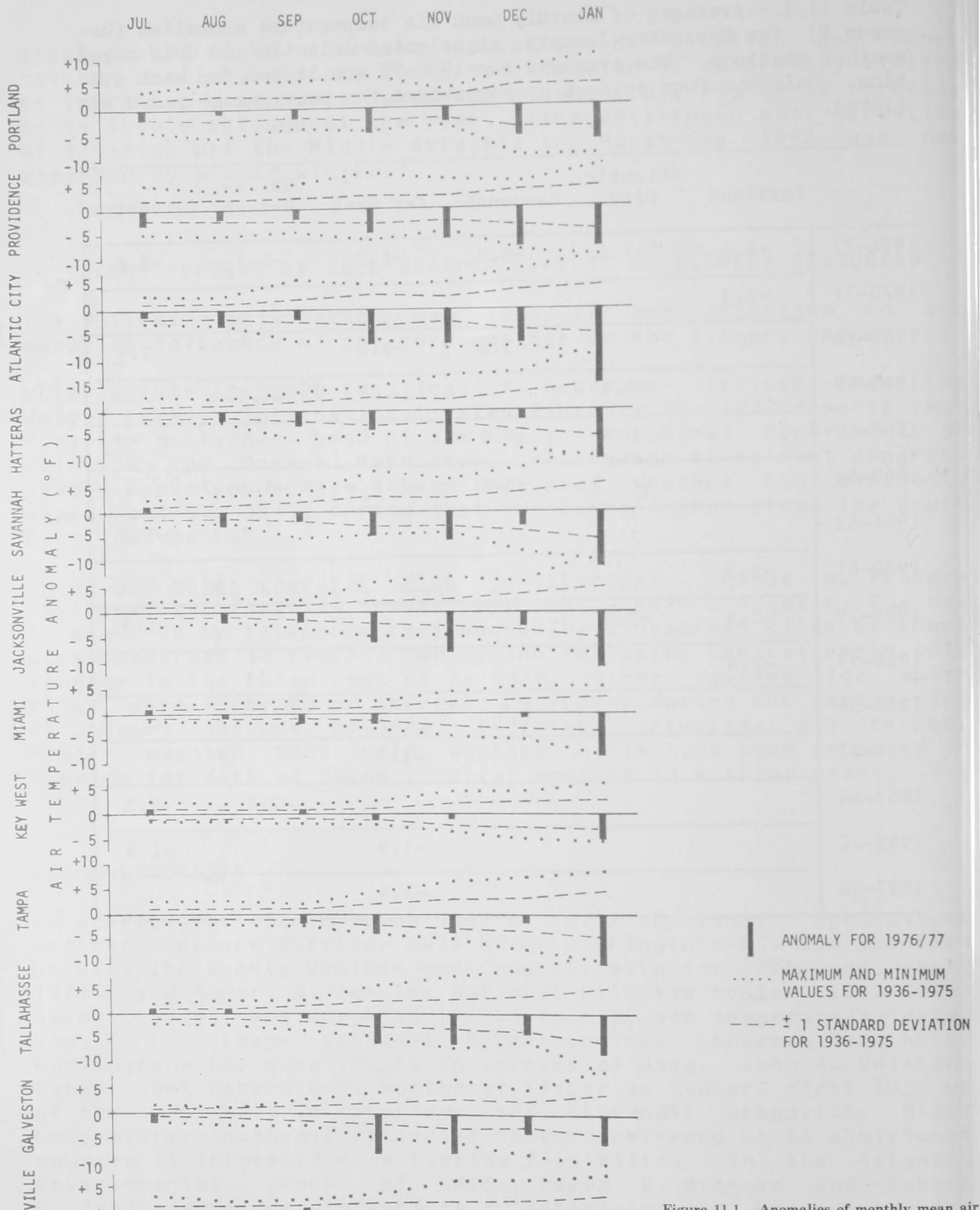

Figure 11.1.—Anomalies of monthly mean air temperatures at selected Atlantic and Gulf coast weather stations, July 1976-January 1977, based on long-term monthly means for the 40 years, 1936-75. Shown for comparison are the maxima and minima and standard deviations of the anomalies for the same period.

Paper 12

WIND DRIVEN TRANSPORT ATLANTIC COAST AND GULF OF MEXICO

Merton C. Ingham[1]

INTRODUCTION

ariations in surface currents and transports resulting from hanges in the overlying wind field are significant factors in he survival and development of the early stages of several esource species and the strength of year classes of their opulations. This is especially true for species whose larvae pend a relatively long period of time as plankton in the surface ayer.

n example of the influence of wind driven transport on larval urvival, recruitment, and year class strength can be found in he Atlantic menhaden. Winter spawning of this species takes lace south of Cape Hatteras at some distance offshore, near the dge of the Gulf Stream. Eggs and larvae from this spawning ctivity are transported toward estuarine nursery grounds, under avorable conditions, by wind driven currents in the surface ayer. Studies of monthly Ekman (wind-driven) transport and ecruitment for the years 1955-70 have revealed a strong link etween years of high or low recruitment and years of strong or eak westward Ekman transport during January-March. A model elating these factors shows that variations in January-March onal Ekman transport at a point south of Cape Hatteras accounts or about 60% of the variation between actual and expected density-dependent) recruitment (Nelson et al. 1977).

n addition to the effect of wind driven transports on larval drift, there are other reasons for scientific interest in the variations of Ekman transport:

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[1] Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragnasett, RI 02882.

1. Coastal upwelling, which is quite pronounced along the Pacific coast, is a consequence of offshore transports of this type and can occur along any coastline, given the appropriate wind stress.

2. Coastal circulation patterns, such as those described by Armstrong[2] for the western Gulf of Mexico, are strongly influenced by variations in Ekman transport.

3. The position of water masses and their boundaries, such as the Shelf Water/Slope Water front along the Atlantic coast, are influenced by wind driven transports. As a consequence, the distribution of pelagic fishes also may be influenced because many of them tend to associate with particular water masses, especially in frontal areas.

4. The efficiency of productivity cycles and their timing in a particular location may depend a great deal on the presence or absence of specific water masses, whose movement may depend largely on wind driven transport.

The data portrayals presented here are drawn from among the suite of parameters computed from monthly average pressure distributions.[3] Figures 12.1-12.4 graphically display mean monthly Ekman transport values for 1976 and for a 10-yr base period, taken from an alternate 5-deg grid for the Atlantic and a 3-deg grid for the Gulf of Mexico. Table 12.1 contains the corresponding zonal and meridional transport values.

In order to provide a more complete set of data for studies in areas not well represented by the locations selected for Figures 12.1-12.4, the 1976 mean monthly and 10-yr monthly mean zonal and meridional transport values for all points on the 3-deg grid in the mapped areas are portrayed in Appendix 12.1.

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[2] Armstrong, R. S. 1976. Seasonal cycle of temperature, salinity and circulation. In Environmental Studies of the South Texas Outer Continental Shelf, 1975, Vol. II, Physical Oceanography, p. 43-51. Gulf Fisheries Center, NMFS, NOAA, Galveston, TX 77550.

[3] Data provided by Pacific Environmental Group, National Marine Fisheries Service, NOAA, Monterey, CA 93940.

DISCUSSION OF 1976 CONDITIONS

Atlantic (Figs. 12.1 and 12.2)

Significant anomalous conditions are revealed in the 1976 record of mean monthly Ekman transport for both 35N, 75W and 40N, 70W during the early months (February-March) and the late months (November-December). During February and March the transports were to the southeast instead of to the southwest, produced by winds from the southwest instead of the northwest. The eastward component of Ekman transport was larger than for any other February in the 31 years of record. Only one other February in that period (1971) showed eastward transports, and it was about one-half that shown in 1976. These anomalously persistent winds from the southwest, especially in February, brought with them much warmer and more humid air than usual and very few storms offshore. This condition yielded unseasonably mild weather and high river runoff along the coast and apparently led to unusually early stratification over the shelf (Armstrong, Paper 17).

Another possible impact of the unusual southeastward transports in February and March is the loss of larvae of several commercial species from Georges Bank, located immediately northeast of 40N, 70W. Once transported off the Bank to the southeast the larvae would be in a more hostile, deep-water, pelagic environment and probably would be permanently lost from the year class.

During November and December at these two points the transports were toward the southwest, in agreement with the 10-yr average conditions, but their magnitudes were unusually large. The persistent, strong northwesterly winds which produced these unusually large transports brought with them the cold temperatures of the continental air mass, yielding the record breaking severe winter experienced by the east coast (Chamberlin and Armstrong, Paper 11). Here again, as was the case in February and March, the unusual transports shown at 40N, 70W reflect conditions which could have caused significant transport of planktonic organisms away from Georges Bank. Fish larvae from the year class developing on the Bank at that time and still in the planktonic stages would suffer losses.

The anomalous transports which occurred in the vicinity of 35N, 75W in February and March should have had an impact on the transport of menhaden larvae spawned offshore south of Cape Hatteras in the January-March period. The eastward components of the transports would tend to transport the larvae offshore, away from the estuarine nursery areas they require for development. That portion of the spawning and larval transport which occurred in January, when there was a westward component in the Ekman transport, should have been more successful.

In the vicinity of 30N, 80W, an area of considerably smaller Ekman transports, the most unusual condition in 1976 was the relatively strong northeastward transport in June. Such transport should have resulted in some upwelling along the Florida shelf. During July the transport shifted to southeastward and was stronger farther north, at 35N, 75W, which could have produced upwelling on the shelf off Georgia and the Carolinas.

Gulf of Mexico (Figs. 12.3 and 12.4)

The most apparent departure in 1976 from the 10-yr mean conditions in the Gulf of Mexico was the strong northwestward transports during the October-December period. These transports, which were more westward than normal at all three of the positions portrayed, are the consequence of unusually strong or persistent northeasterly winds during the early part of the severe winter of 1976-77. These conditions should have produced unusually strong onshore and counterclockwise alongshore flow.

During January the difference between the transport vectors at 27N, 96W and 27N, 90W, which usually produces counterclockwise nearshore circulation in the western Gulf (see footnote 2), was greater than normal. This condition should have led to more intense nearshore flow to the west and south (counterclockwise). In February and March the difference in transport values between the two positions reversed, with the stronger value at 27N, 96W, including a strong eastward component. This may have caused a reversal in nearshore circulation, to clockwise, during February, a month earlier than normal.

LITERATURE CITED

NELSON, W. R., M. C. INGHAM, and W. E. SCHAAF.
1977. Larval transport and year class strength of Atlantic menhaden, Brevoortia tyrannis. Fish. Bull. U.S. 75:23-41.

Table 12.1.--Monthly average Ekman transports for selected points off the U.S. east coast and in the Gulf of Mexico for 1976. Units are t/s-km. Positive is eastward or northward.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
40°N, 70°W												
Zonal	-70	170	30	-90	240	180	110	20	20	-20	-200	-130
Meridional	-220	-700	-190	-270	-290	-260	-250	-70	-90	-40	-760	-470
35°N, 75°W												
Zonal	-60	130	80	-50	180	170	100	10	0	-50	-190	-100
Meridional	-170	-440	-140	-80	-90	-30	-290	30	0	30	-310	-180
30°N, 80°W												
Zonal	-60	10	100	-10	190	180	80	40	10	-150	-180	-120
Meridional	20	-20	30	20	20	140	-110	160	80	210	60	60
27°N, 84°W												
Zonal	-270	-30	220	-30	220	100	20	-10	10	-380	-480	-260
Meridional	500	170	430	190	70	260	10	160	110	650	720	570
27°N, 90°W												
Zonal	-340	-10	520	80	30	100	10	-130	-60	-520	-740	-450
Meridional	780	260	960	630	230	550	160	210	230	770	1020	720
27°N, 69°W												
Zonal	20	410	530	1000	210	500	790	190	120	-240	-680	-480
Meridional	450	330	1110	1140	510	790	890	320	470	620	880	520

In the vicinity of 30N, 80W, an area of considerably smaller Ekman transports, the most unusual condition in 1976 was the relatively strong northeastward transport in June. Such transport should have resulted in some upwelling along the Florida shelf. During July the transport shifted to southeastward and was stronger farther north, at 35N, 75W, which could have produced upwelling on the shelf off Georgia and the Carolinas.

Gulf of Mexico (Figs. 12.3 and 12.4)

The most apparent departure in 1976 from the 10-yr mean conditions in the Gulf of Mexico was the strong northwestward transports during the October-December period. These transports, which were more westward than normal at all three of the positions portrayed, are the consequence of unusually strong or persistent northeasterly winds during the early part of the severe winter of 1976-77. These conditions should have produced unusually strong onshore and counterclockwise alongshore flow.

During January the difference between the transport vectors at 27N, 96W and 27N, 90W, which usually produces counterclockwise nearshore circulation in the western Gulf (see footnote 2), was greater than normal. This condition should have led to more intense nearshore flow to the west and south (counterclockwise). In February and March the difference in transport values between the two positions reversed, with the stronger value at 27N, 96W, including a strong eastward component. This may have caused a reversal in nearshore circulation, to clockwise, during February, a month earlier than normal.

LITERATURE CITED

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Table 12.1.--Monthly average Ekman transports for selected points off the U.S. east coast and in the Gulf of Mexico for 1976. Units are t/s-km. Positive is eastward or northward.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
40°N, 70°W												
Zonal	-70	170	30	-90	240	180	110	20	20	-20	-200	-130
Meridional	-220	-700	-190	-270	-290	-260	-250	-70	-90	-40	-760	-470
35°N, 75°W												
Zonal	-60	130	80	-50	180	170	100	10	0	-50	-190	-100
Meridional	-170	-440	-140	-80	-90	-30	-290	30	0	30	-310	-180
30°N, 80°W												
Zonal	-60	10	100	-10	190	180	80	40	10	-150	-180	-120
Meridional	20	-20	30	20	20	140	-110	160	80	210	60	60
27°N, 84°W												
Zonal	-270	-30	220	-30	220	100	20	-10	10	-380	-480	-260
Meridional	500	170	430	190	70	260	10	160	110	650	720	570
27°N, 90°W												
Zonal	-340	-10	520	80	30	100	10	-130	-60	-520	-740	-450
Meridional	780	260	960	630	230	550	160	210	230	770	1020	720
27°N, 69°W												
Zonal	20	410	530	1000	210	500	790	190	120	-240	-680	-480
Meridional	450	330	1110	1140	510	790	890	320	470	620	880	520

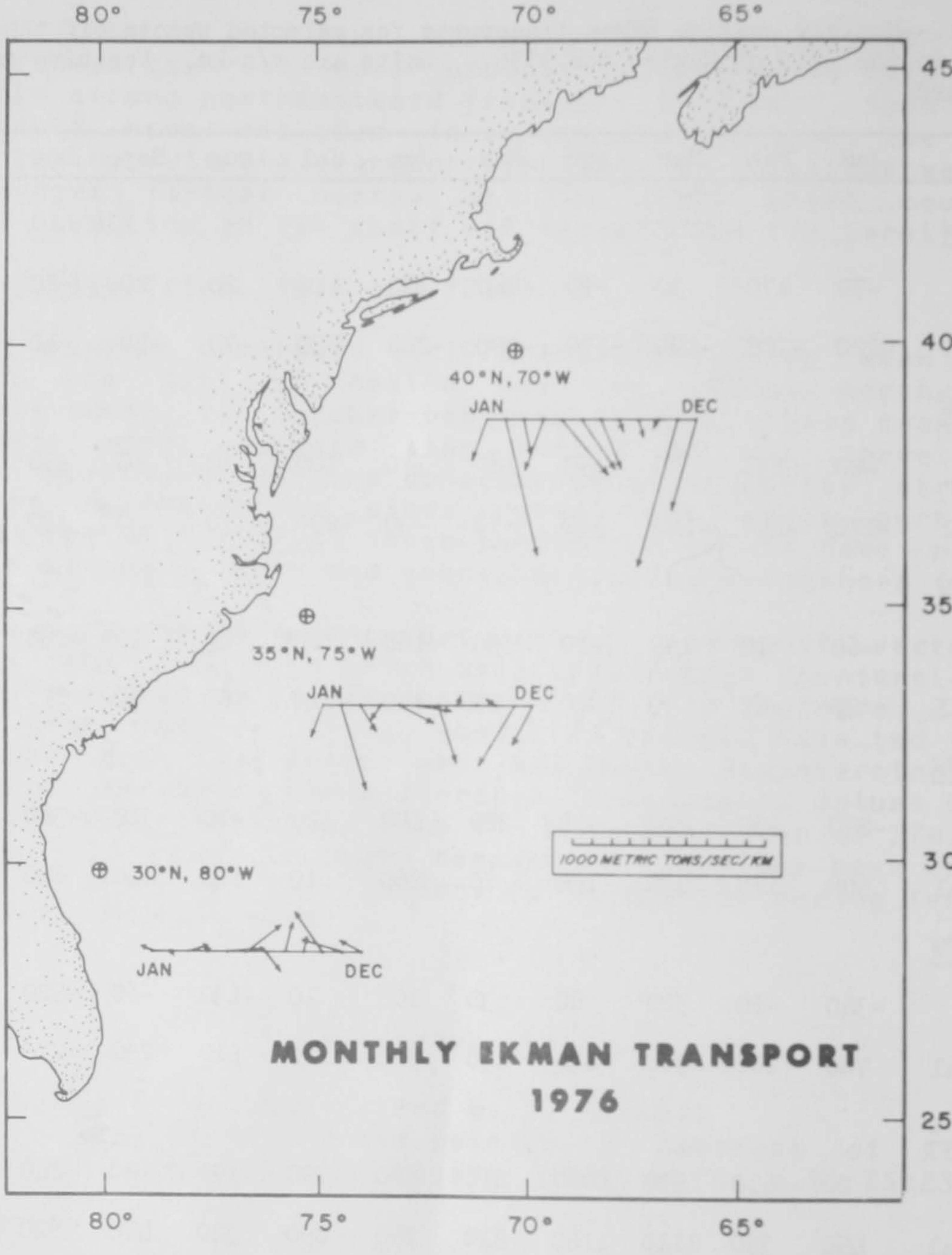


Figure 12.1.—Mean monthly Ekman transports for three representative points off the U.S. Atlantic coast for 1976.

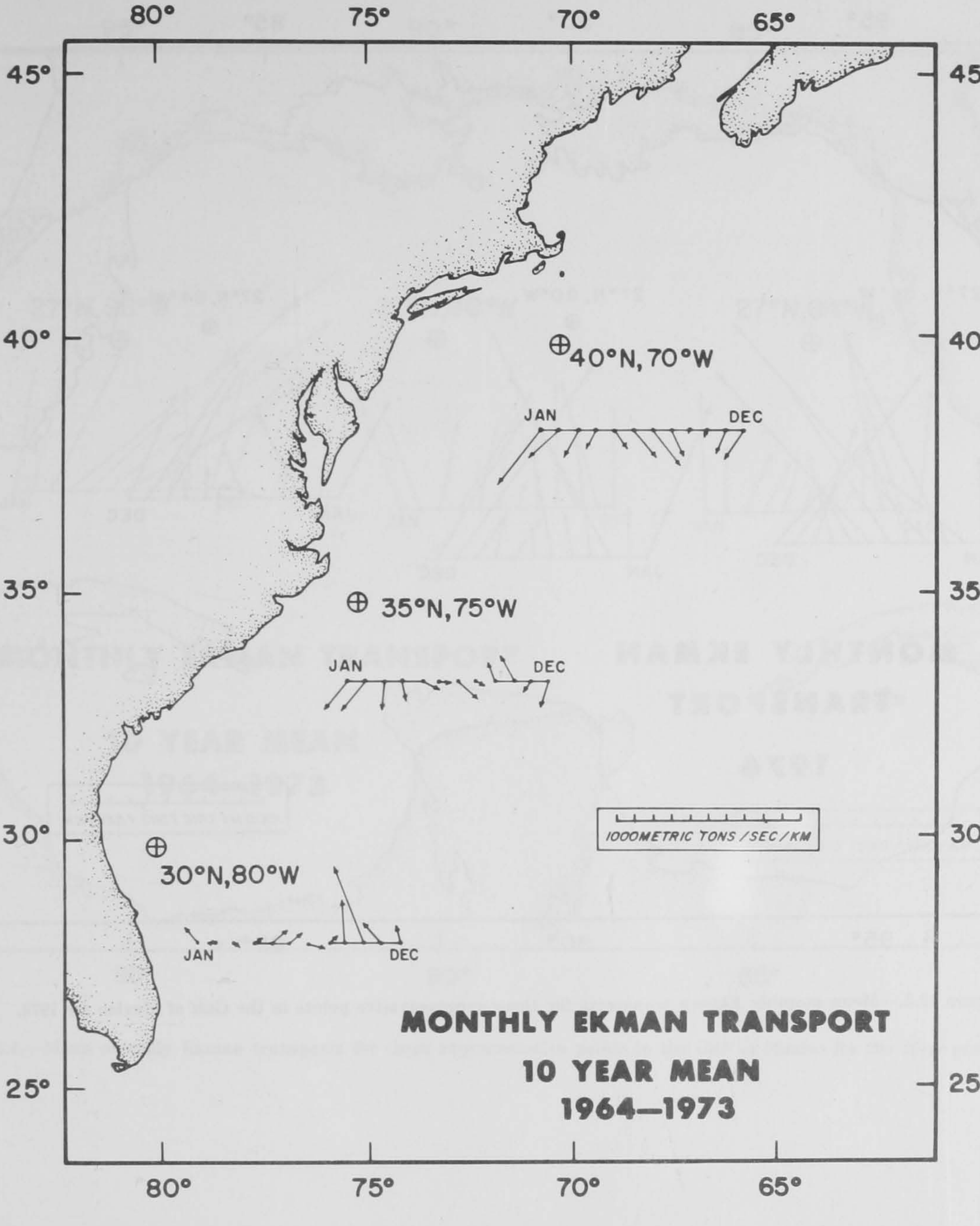


Figure 12.2.—Mean monthly Ekman transports for three representative points off the U.S. Atlantic coast for the 10-yr period 1964-73.

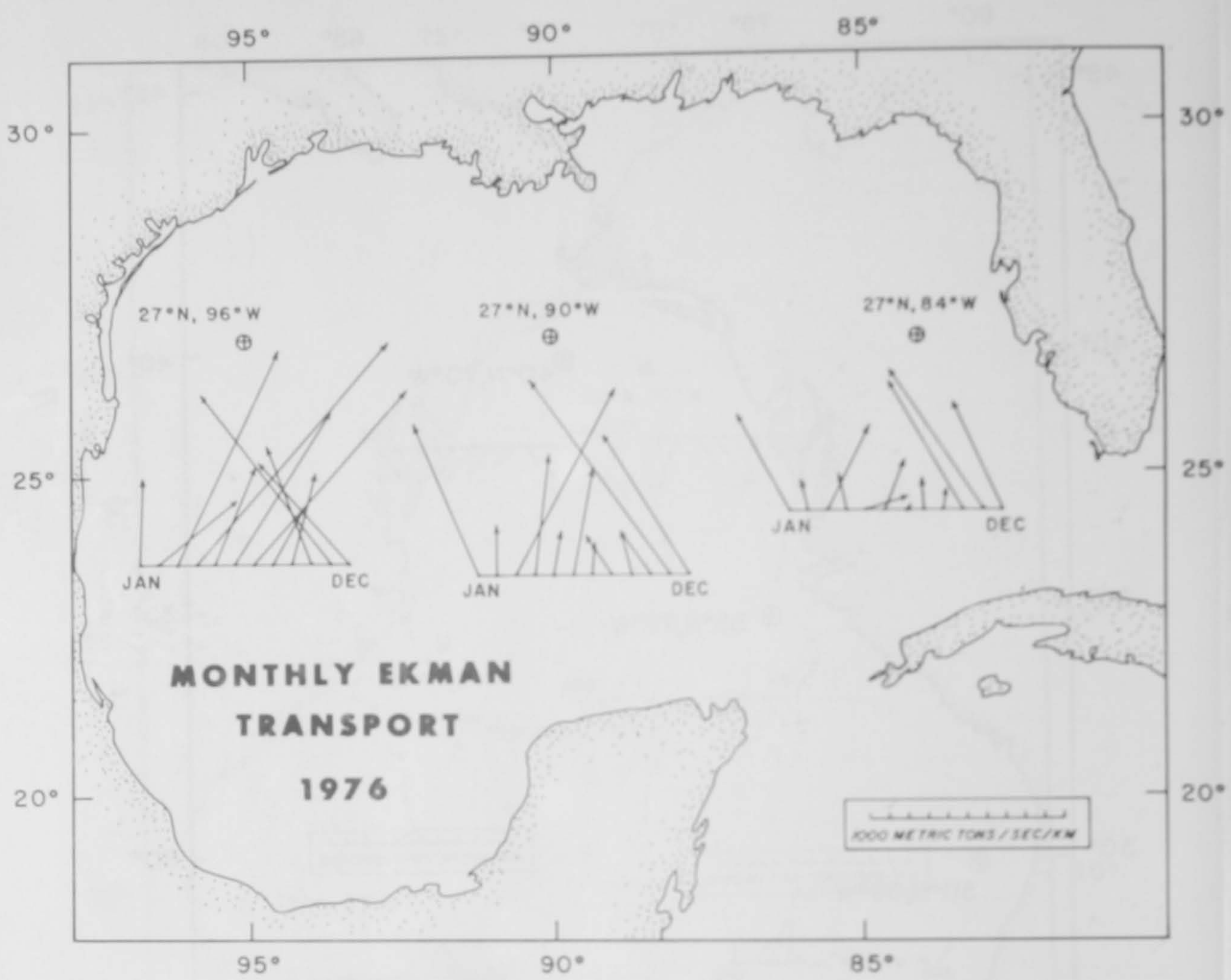


Figure 12.3.—Mean monthly Ekman transports for three representative points in the Gulf of Mexico for 1976.

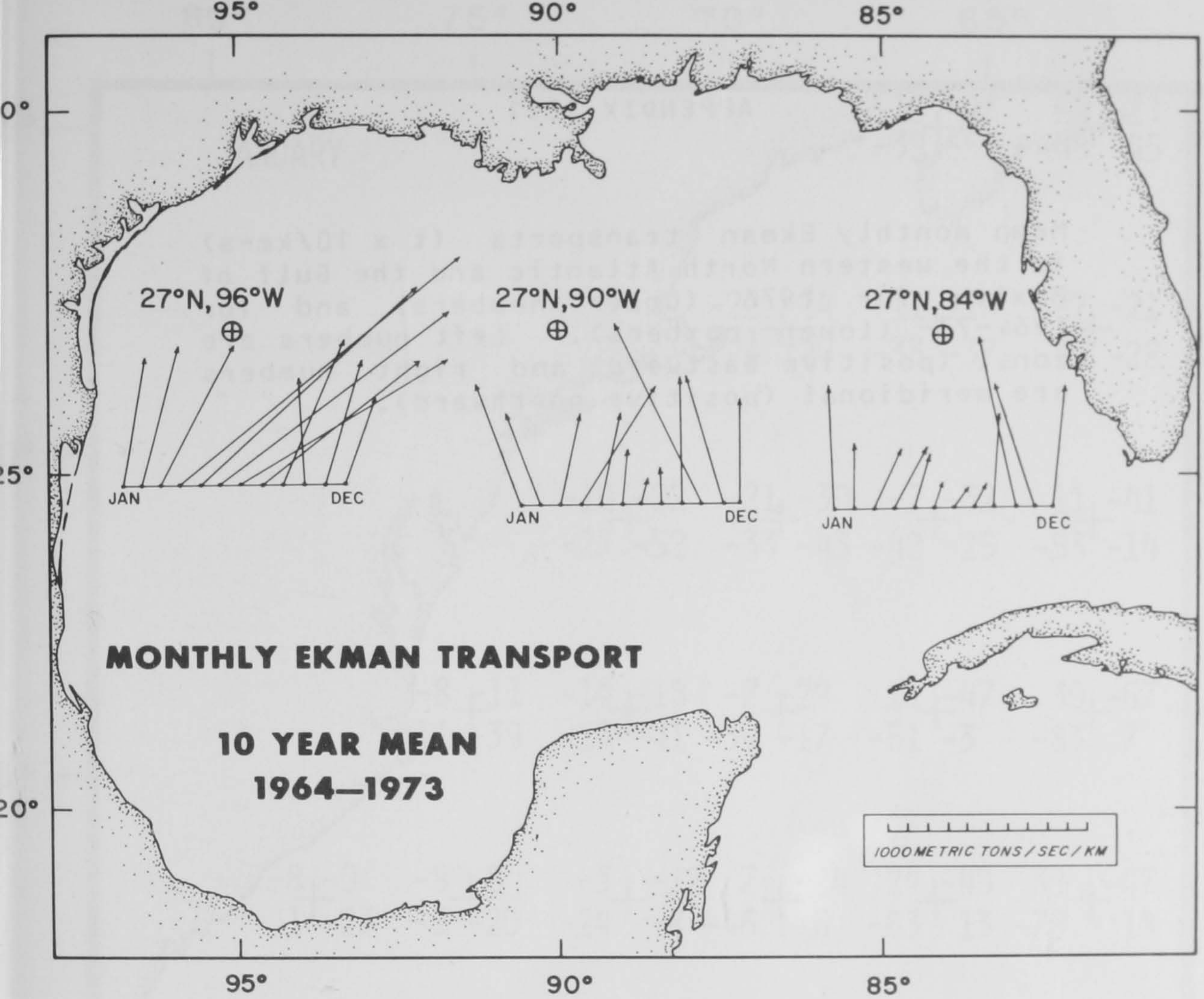
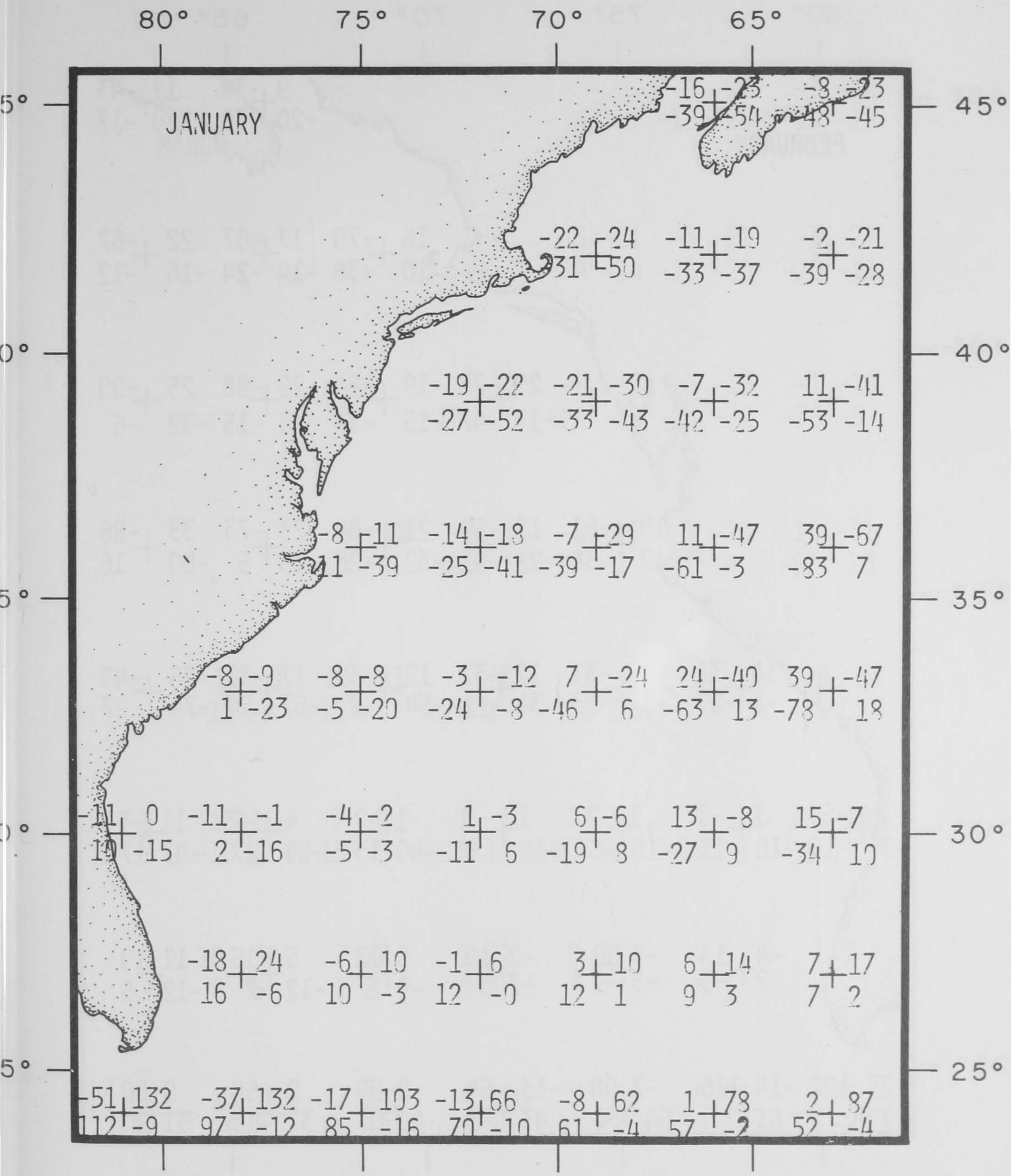


Figure 12.4.—Mean monthly Ekman transports for three representative points in the Gulf of Mexico for the 10-yr period 1964-73.

APPENDIX 12.1

Mean monthly Ekman transports (t x 10/km-s) in the western North Atlantic and the Gulf of Mexico for 1976 (upper numbers) and for 1964-73 (lower numbers). Left numbers are zonal (positive eastward) and right numbers are meridional (positive northward).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7 -24 -46 6
24 -40 -63 13
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-11 -1 2 -16
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6 -6 -19 8
13 -8 -27 9
15 -7 -34 10
-18 24 16 -6
-6 10 10 -3
-1 6 12 -0
3 10 12 1
6 14 9 3
7 17 7 2
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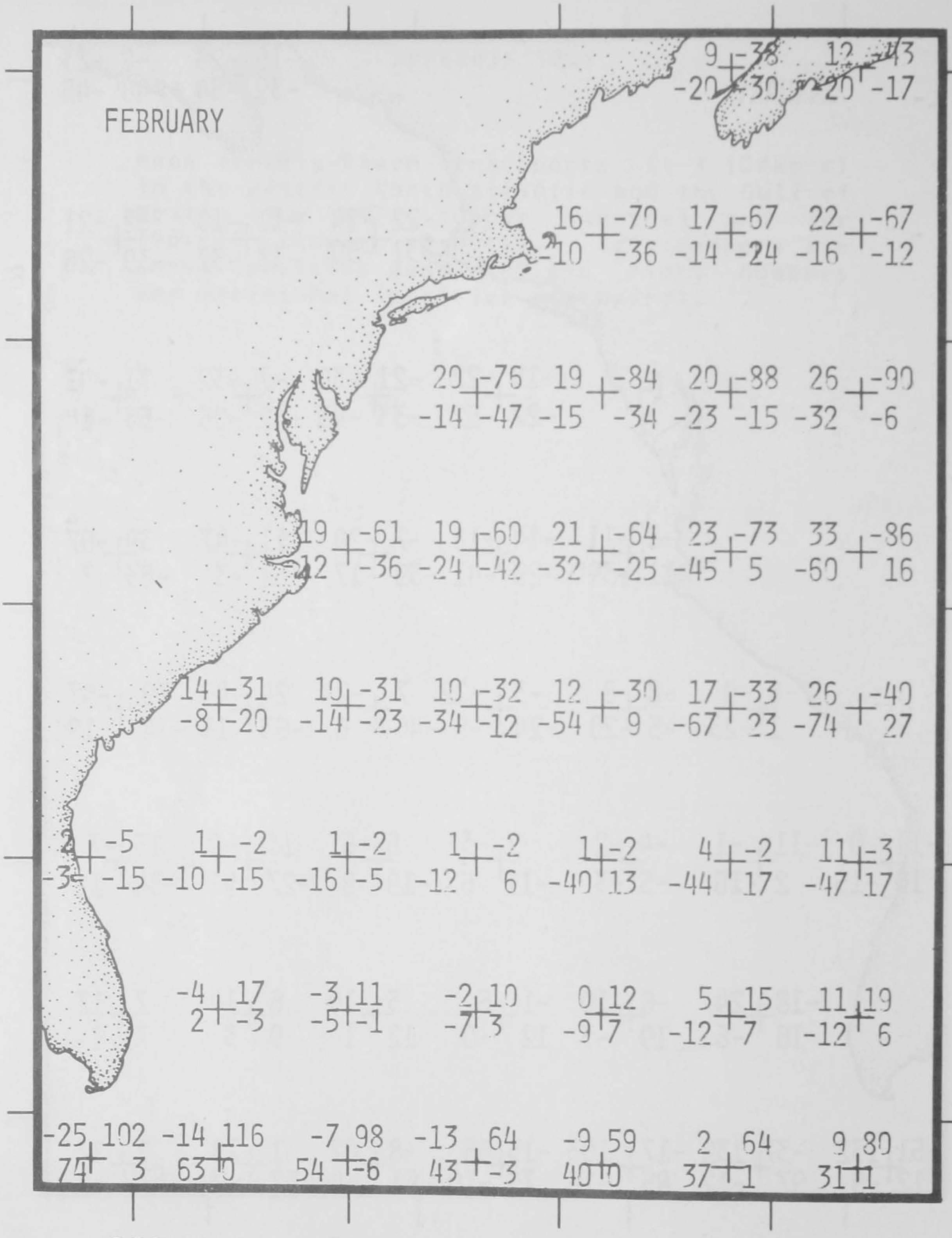
65°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1 -2 -12 6
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-3 11 -5 -1
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0 12 -9 7
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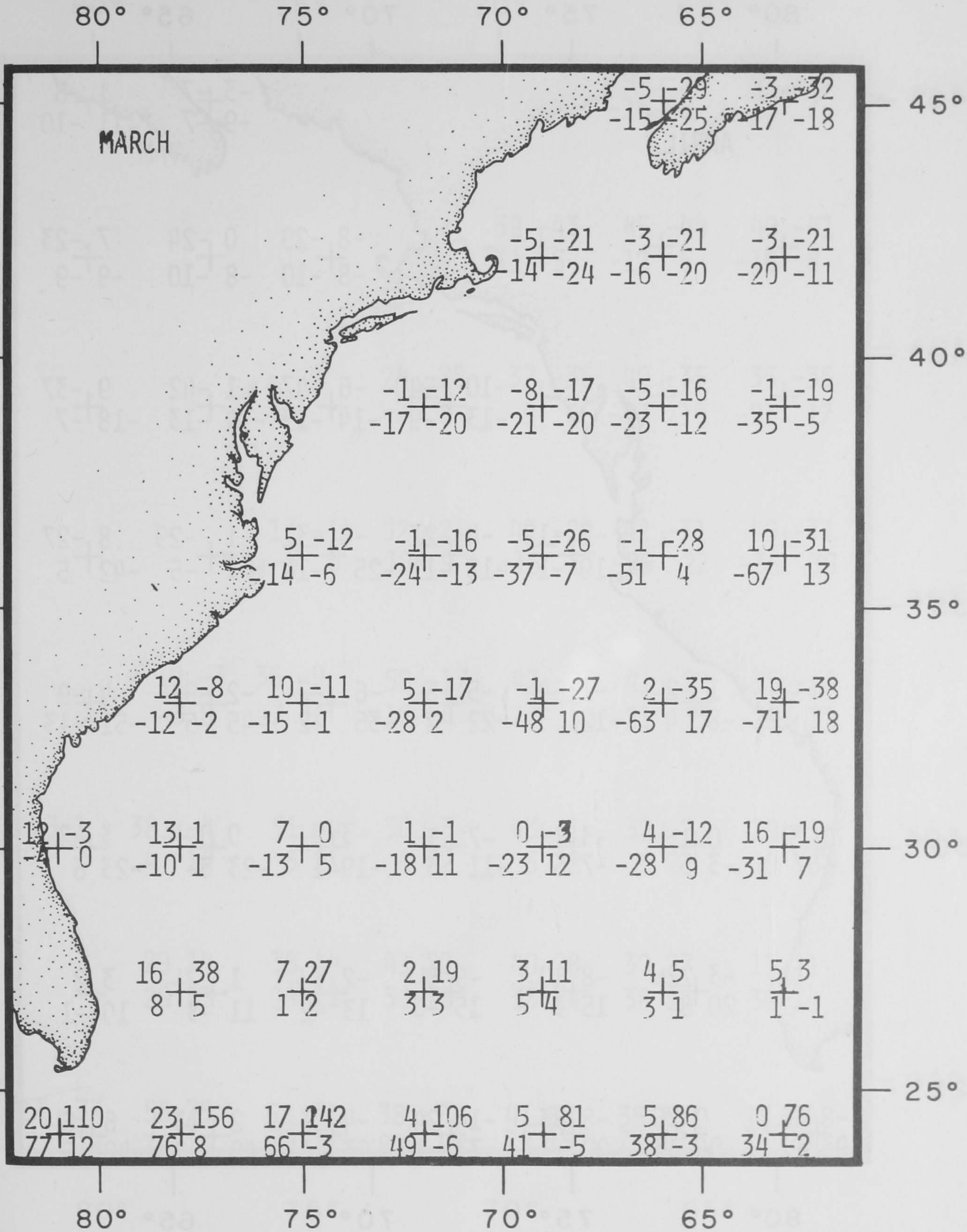
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2 19
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3 11
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4 5
3 1
5 3
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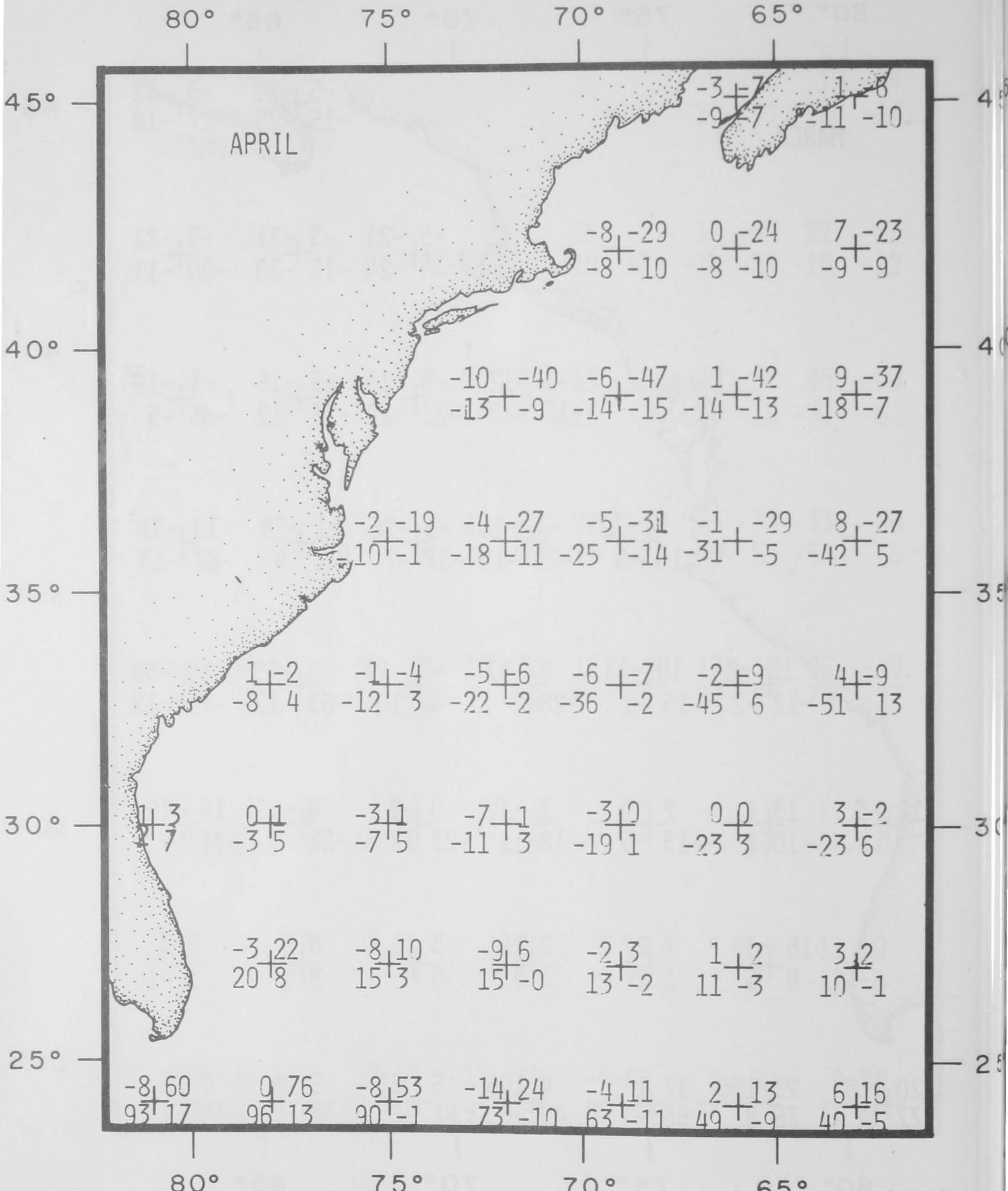
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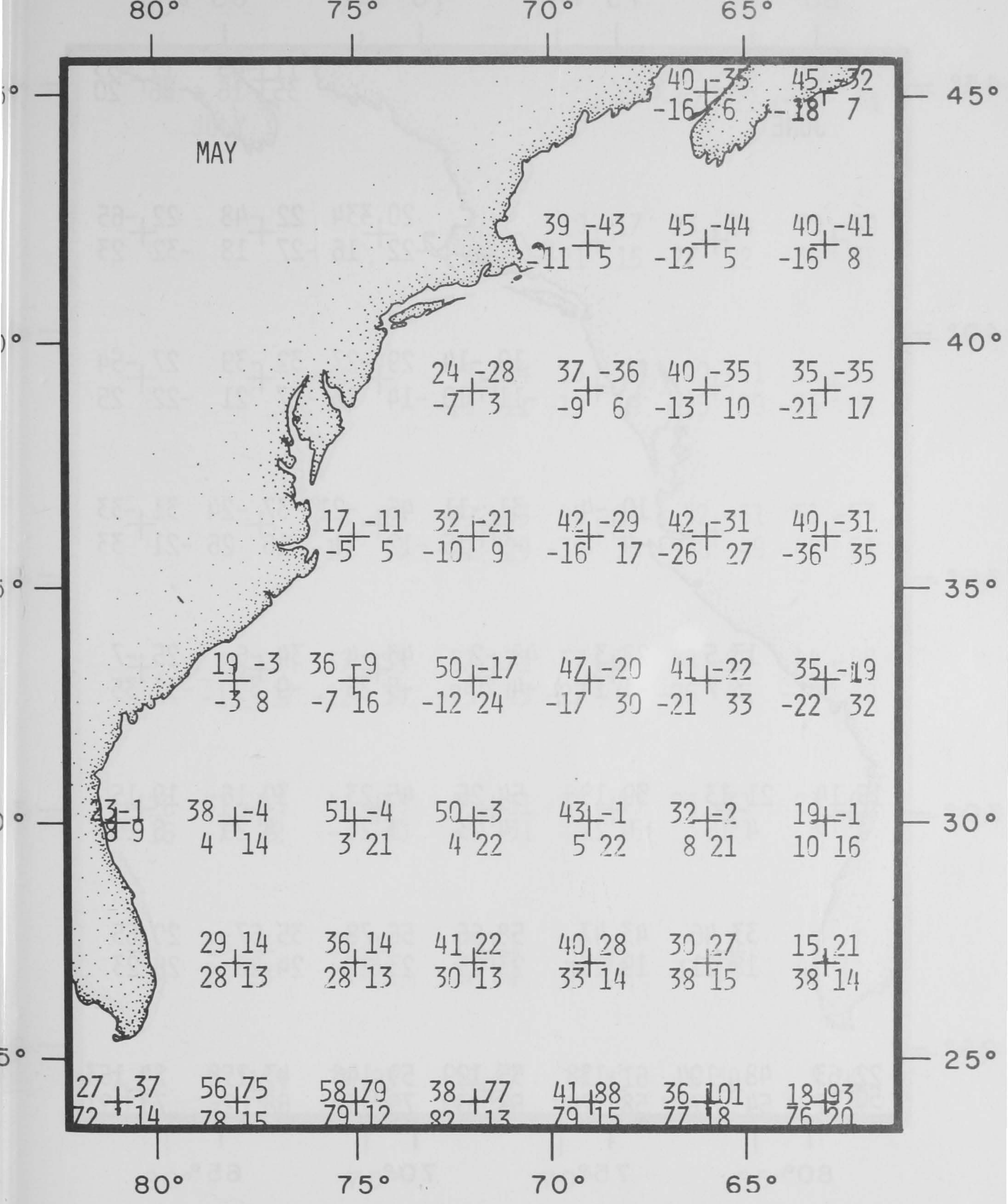
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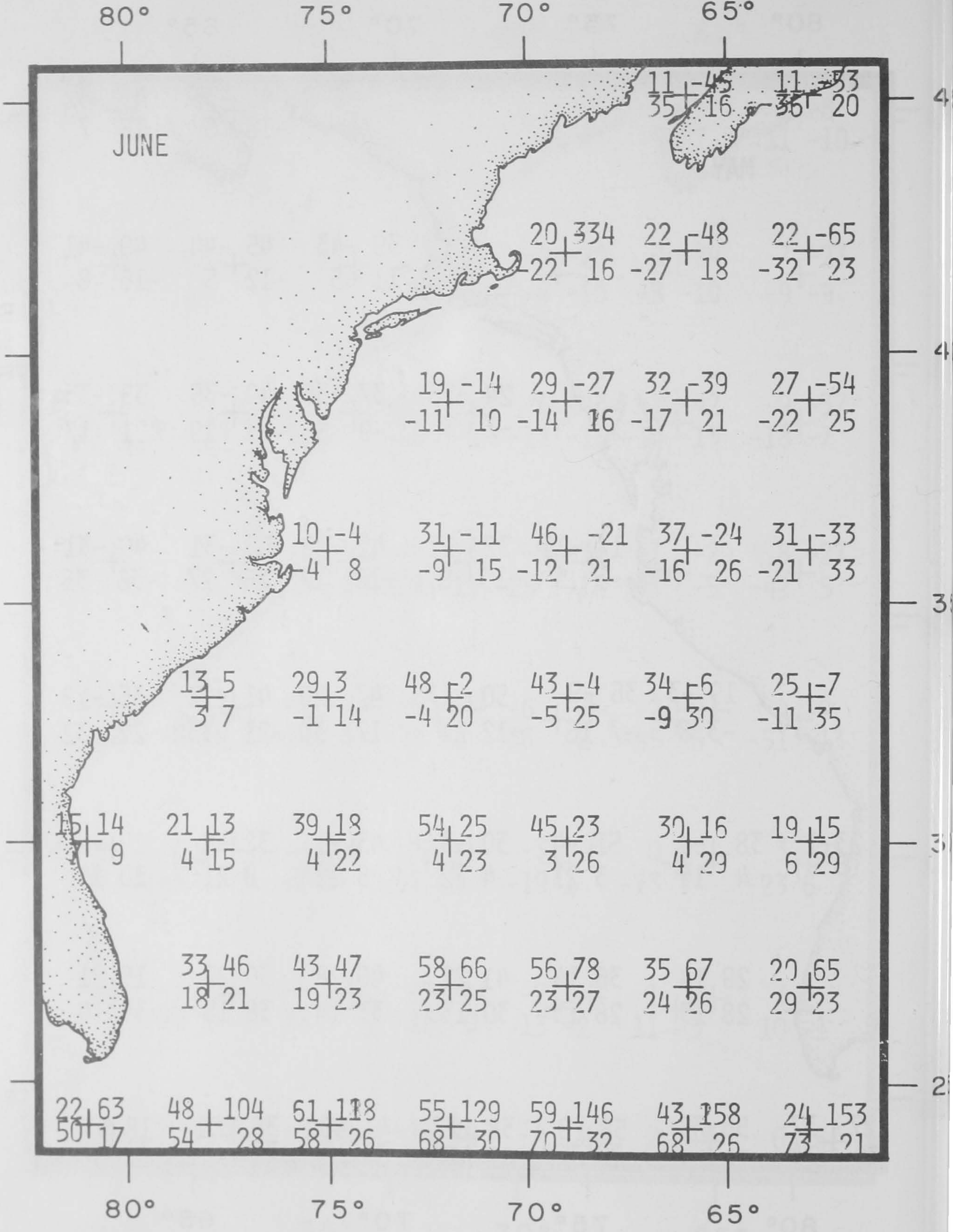
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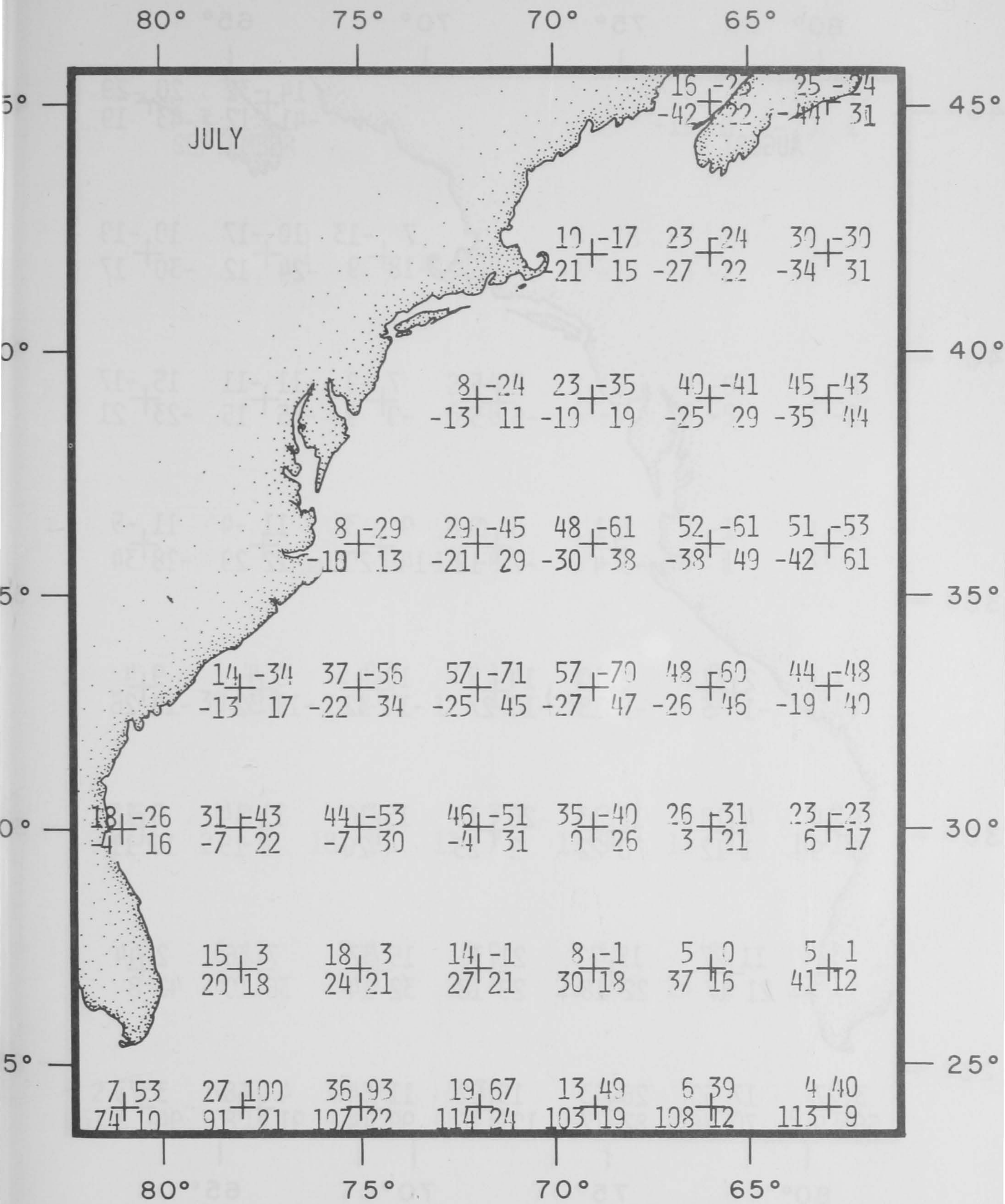
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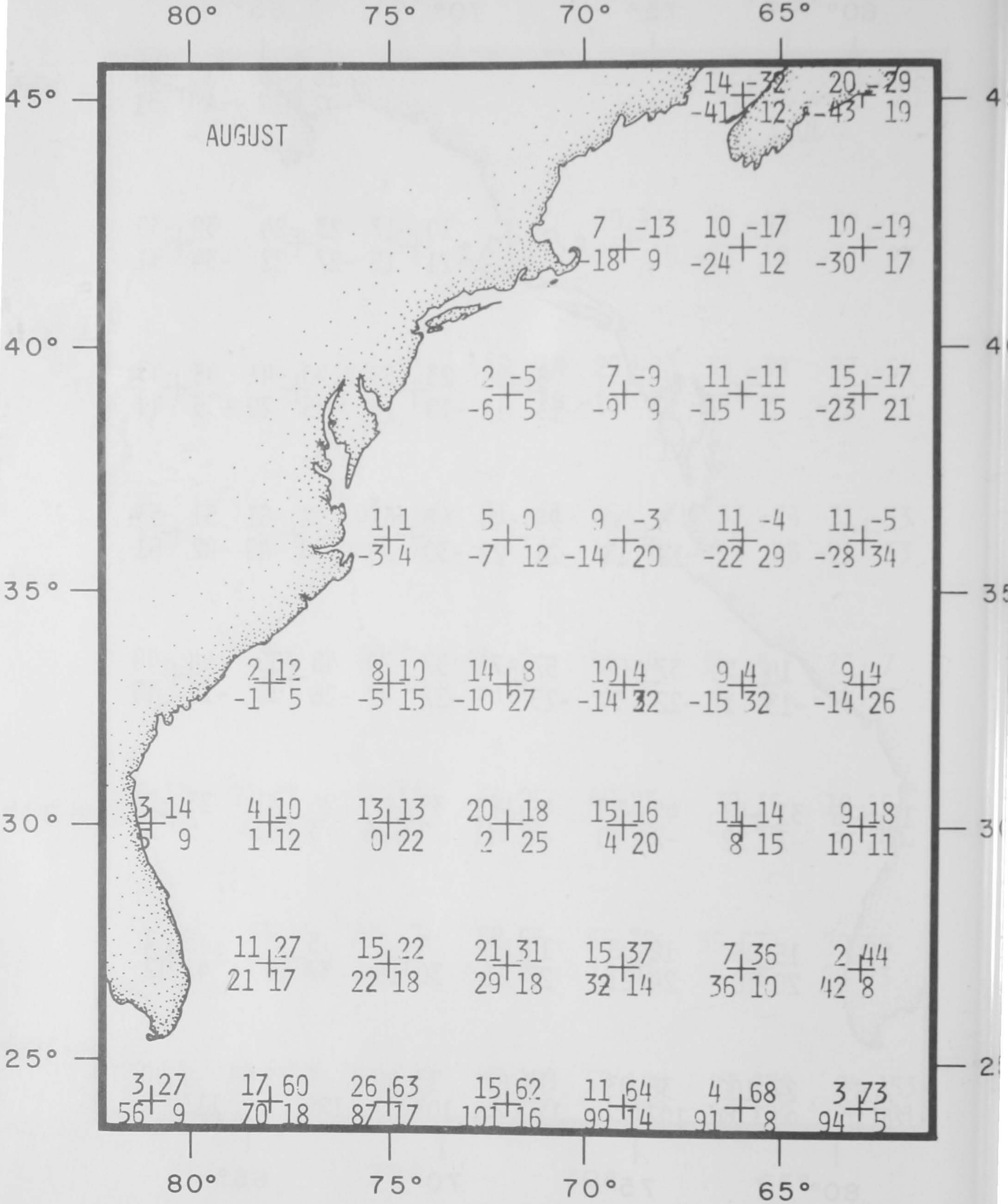
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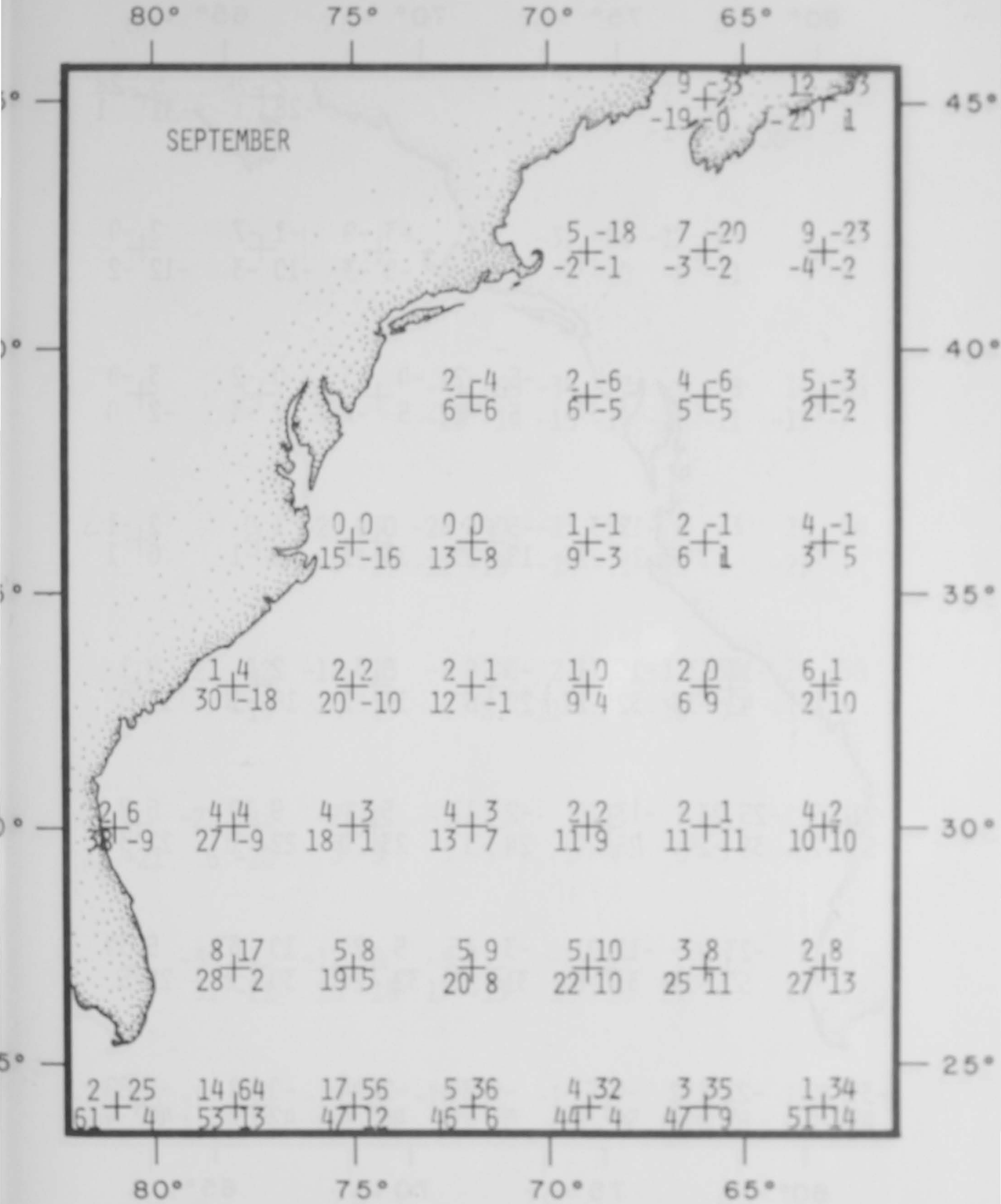
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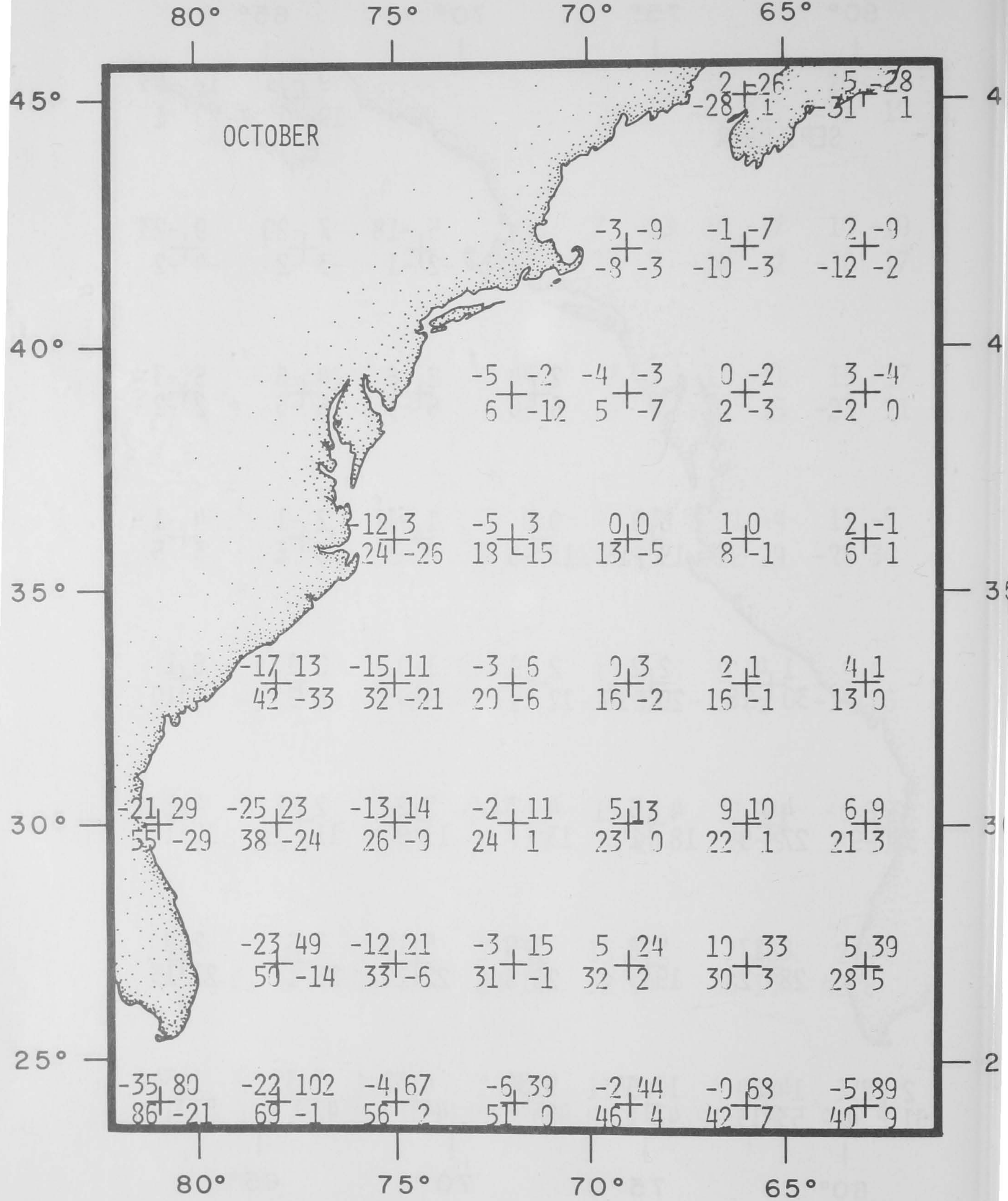
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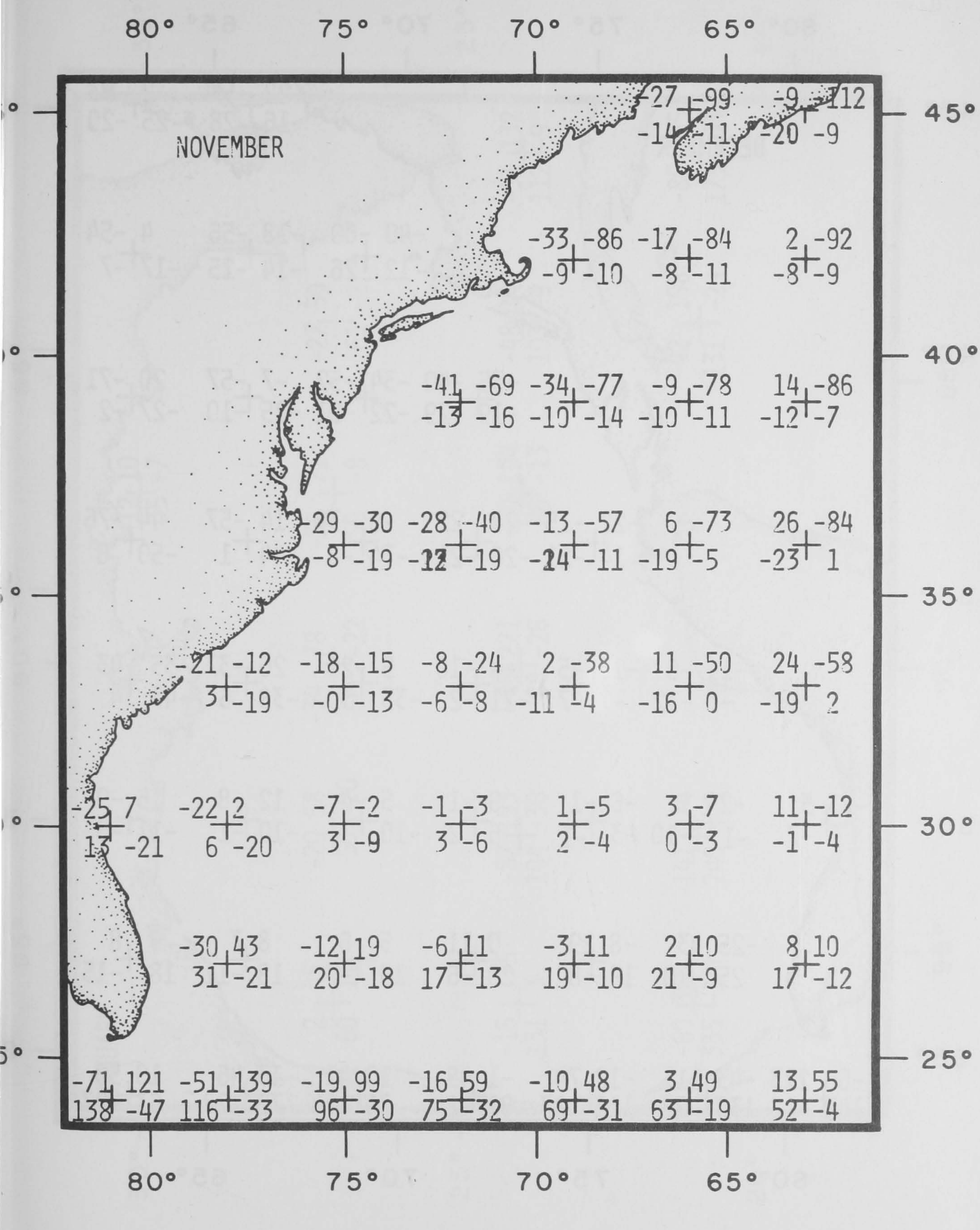
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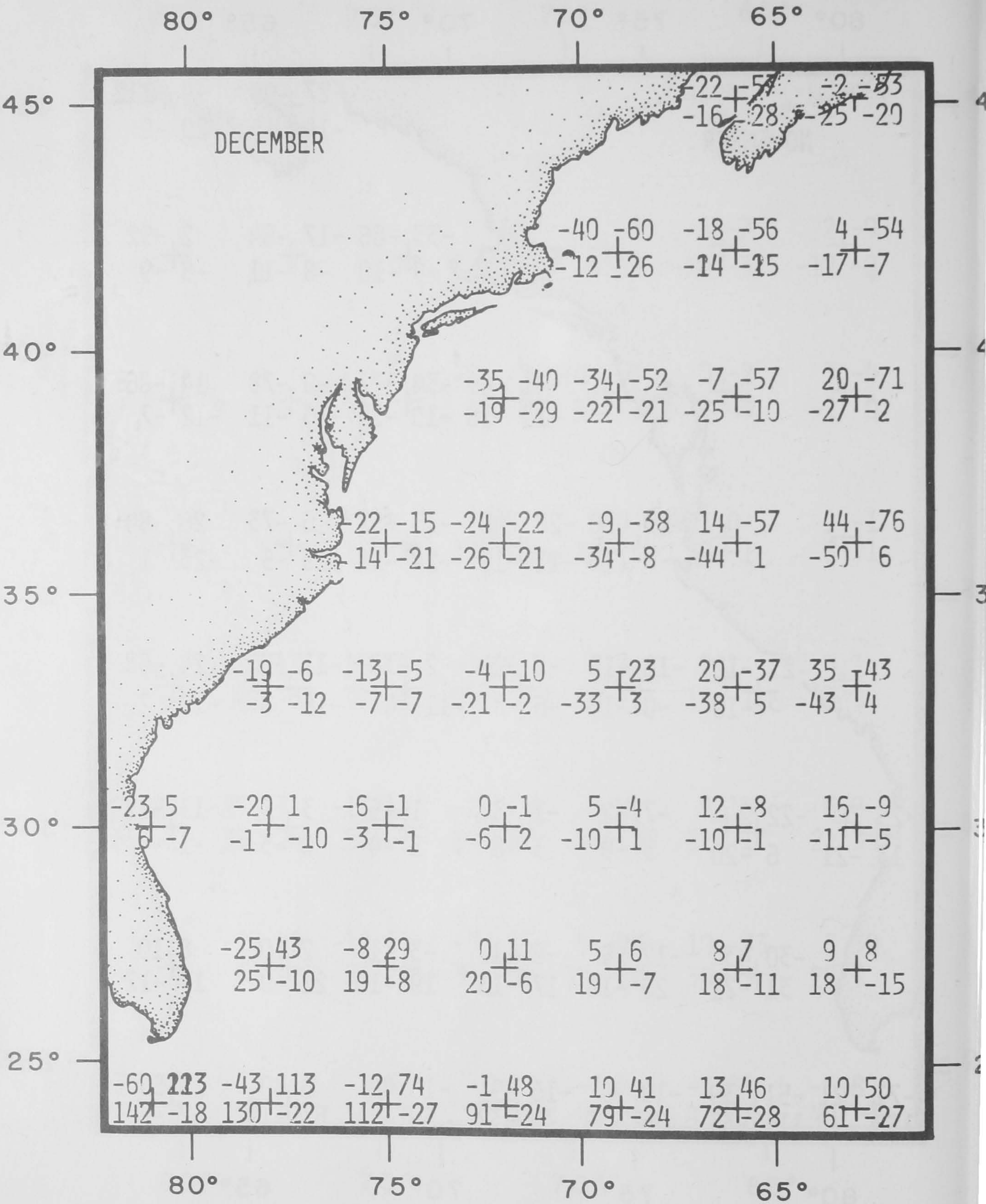
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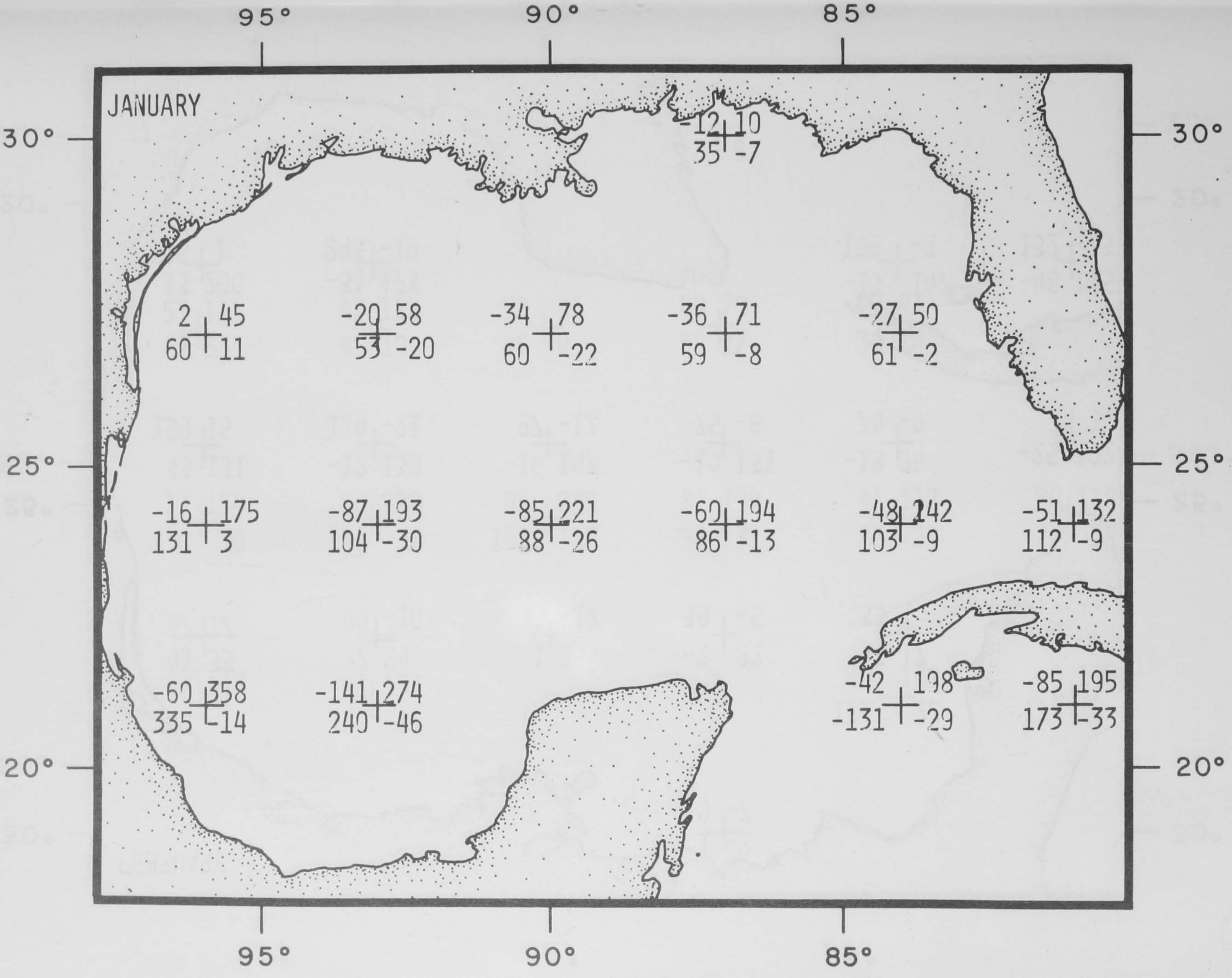95°
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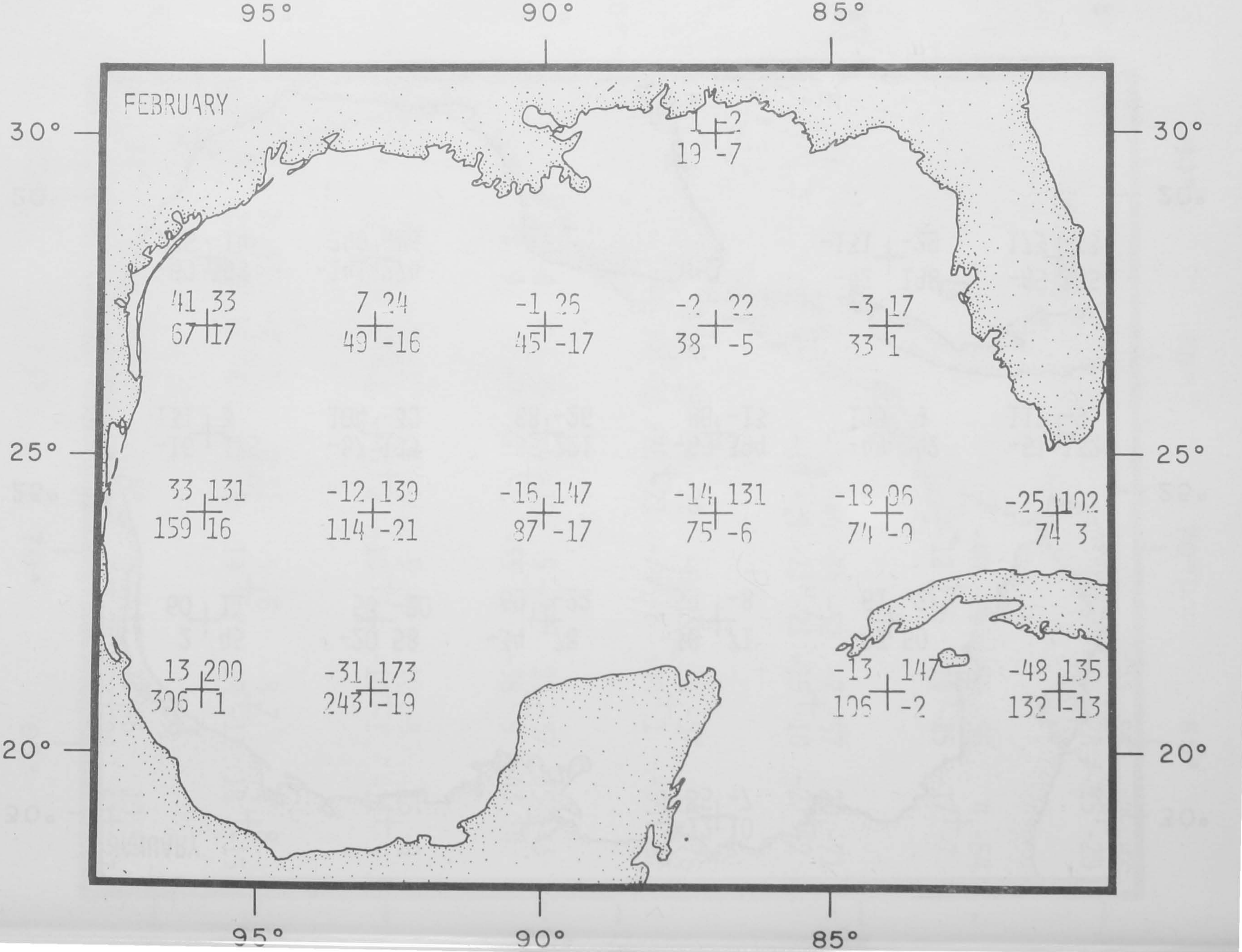
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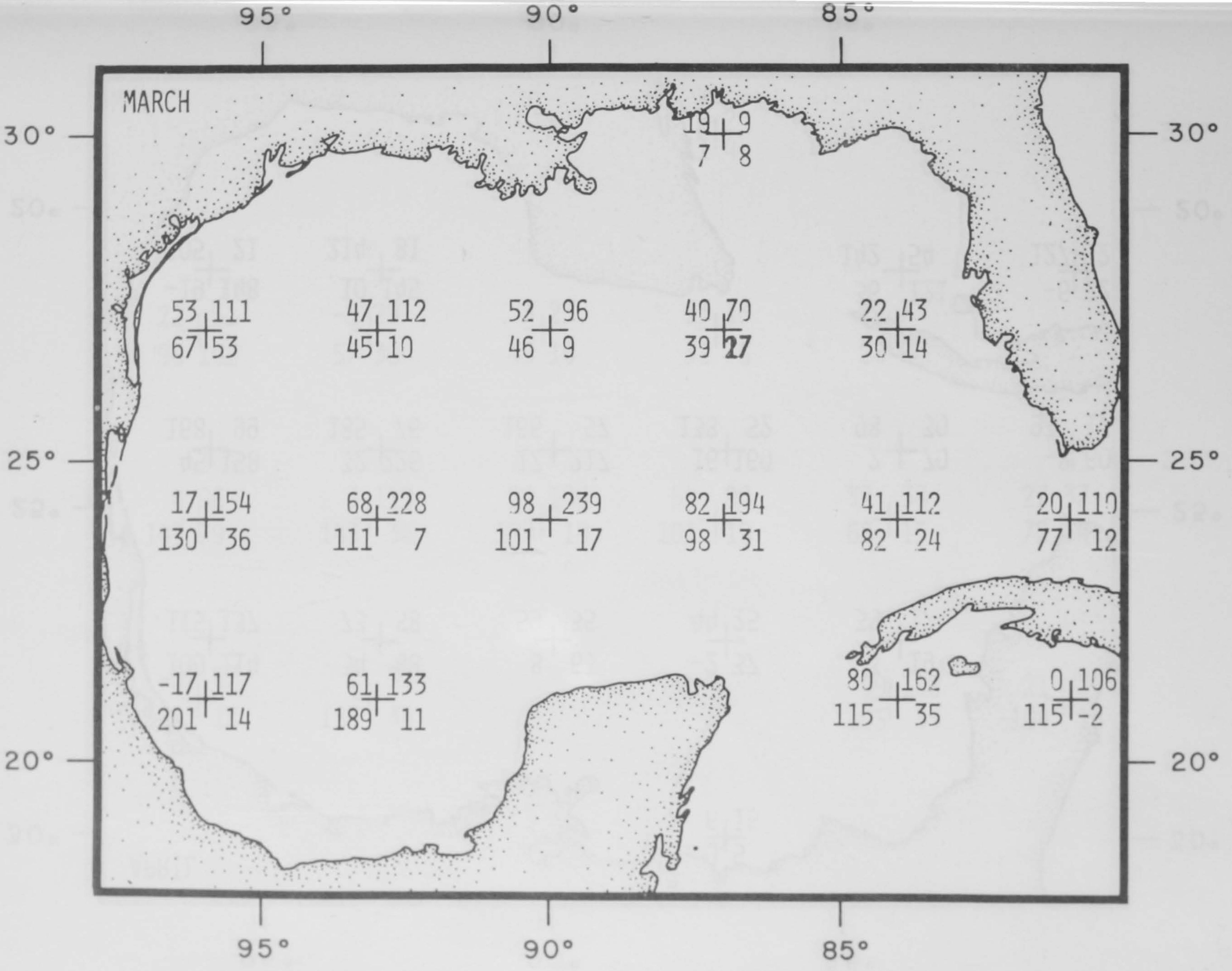
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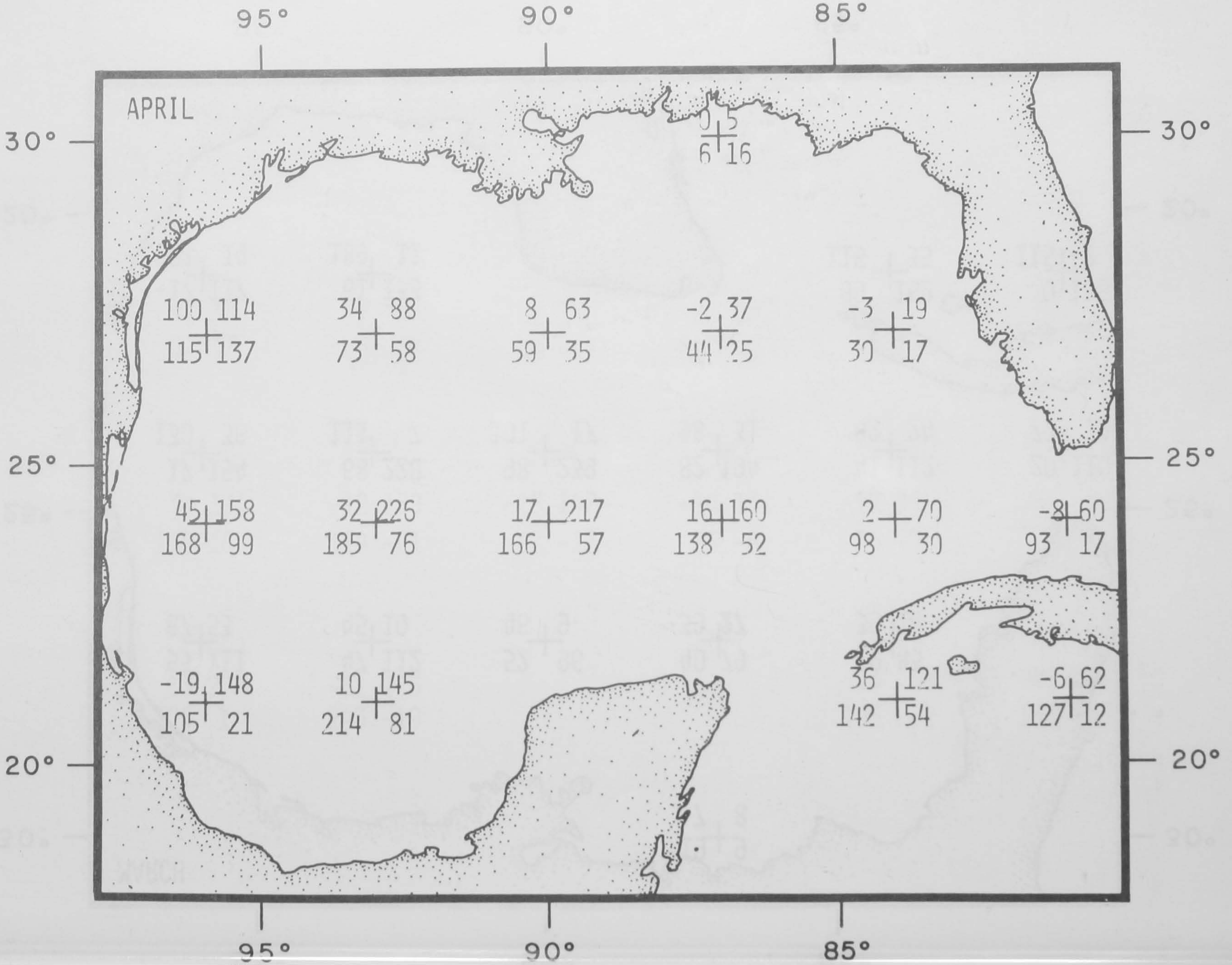
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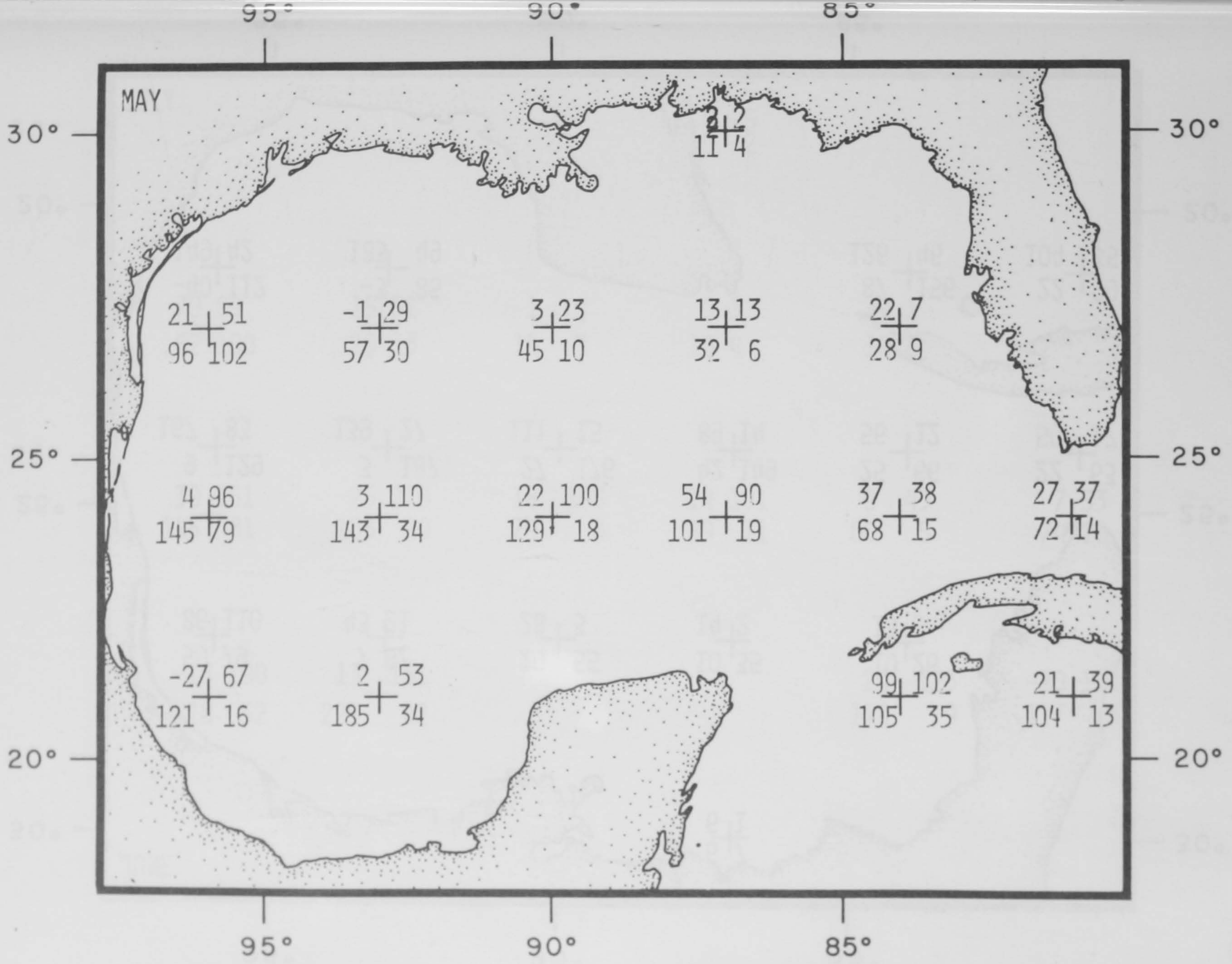
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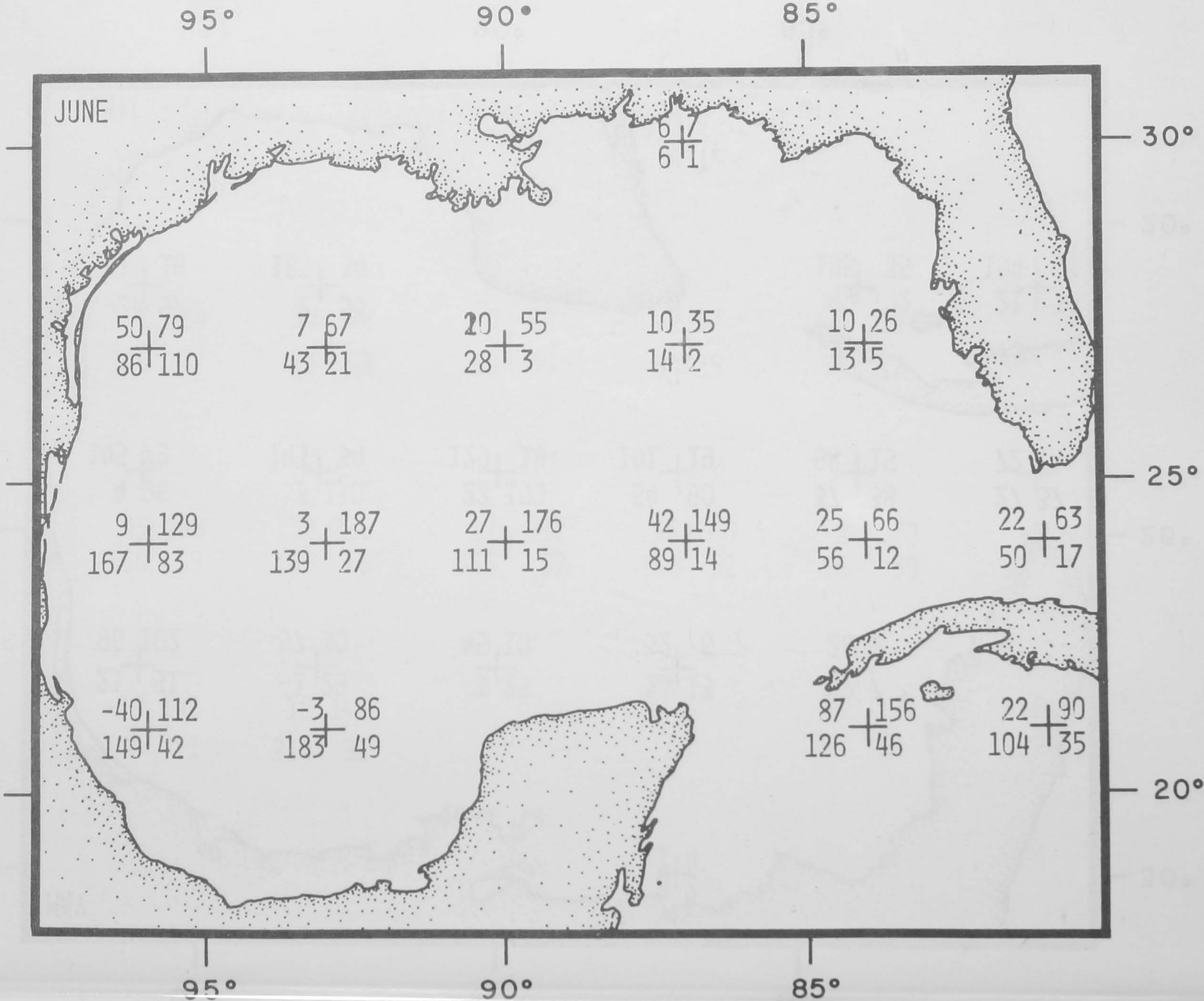
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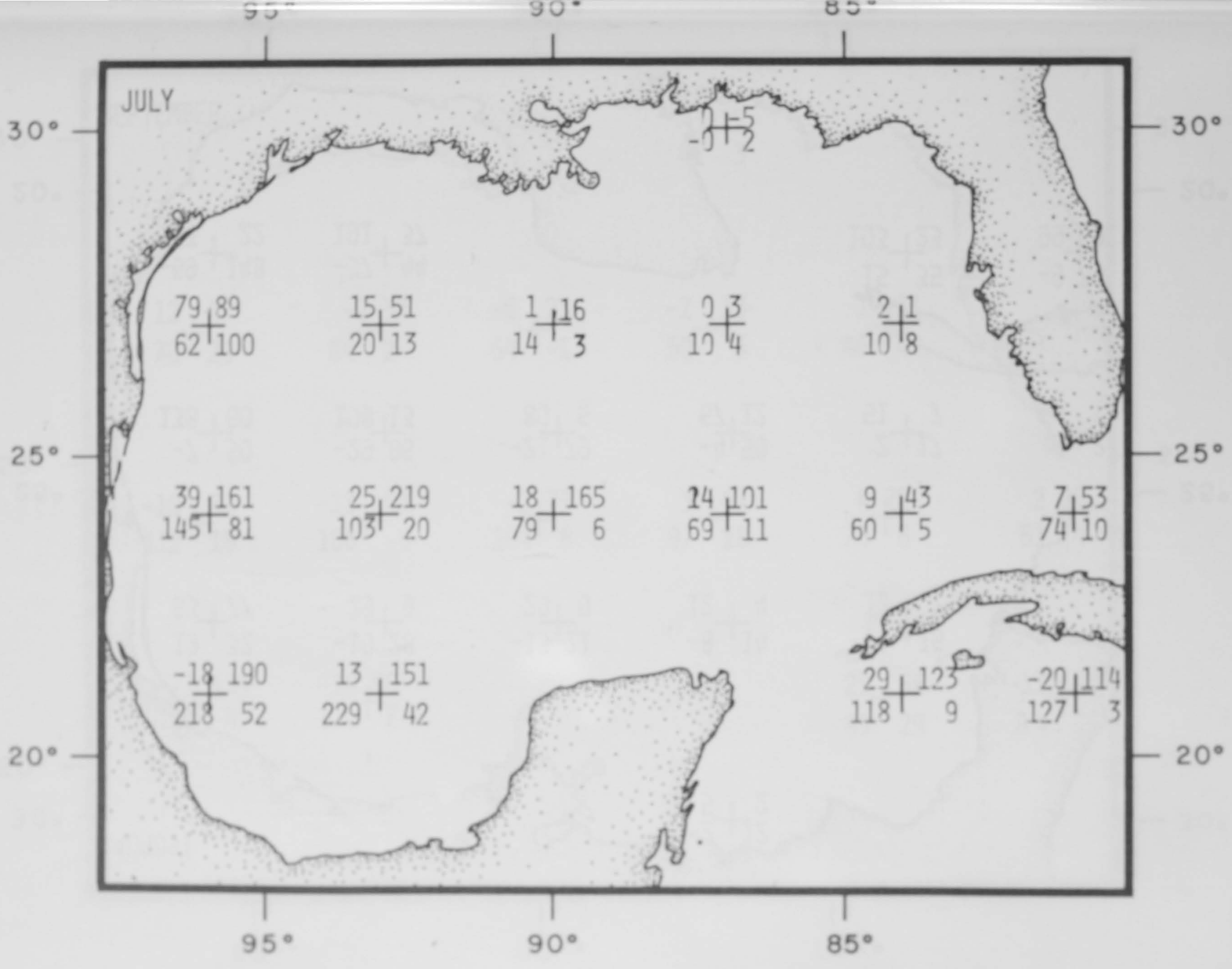
90°
85°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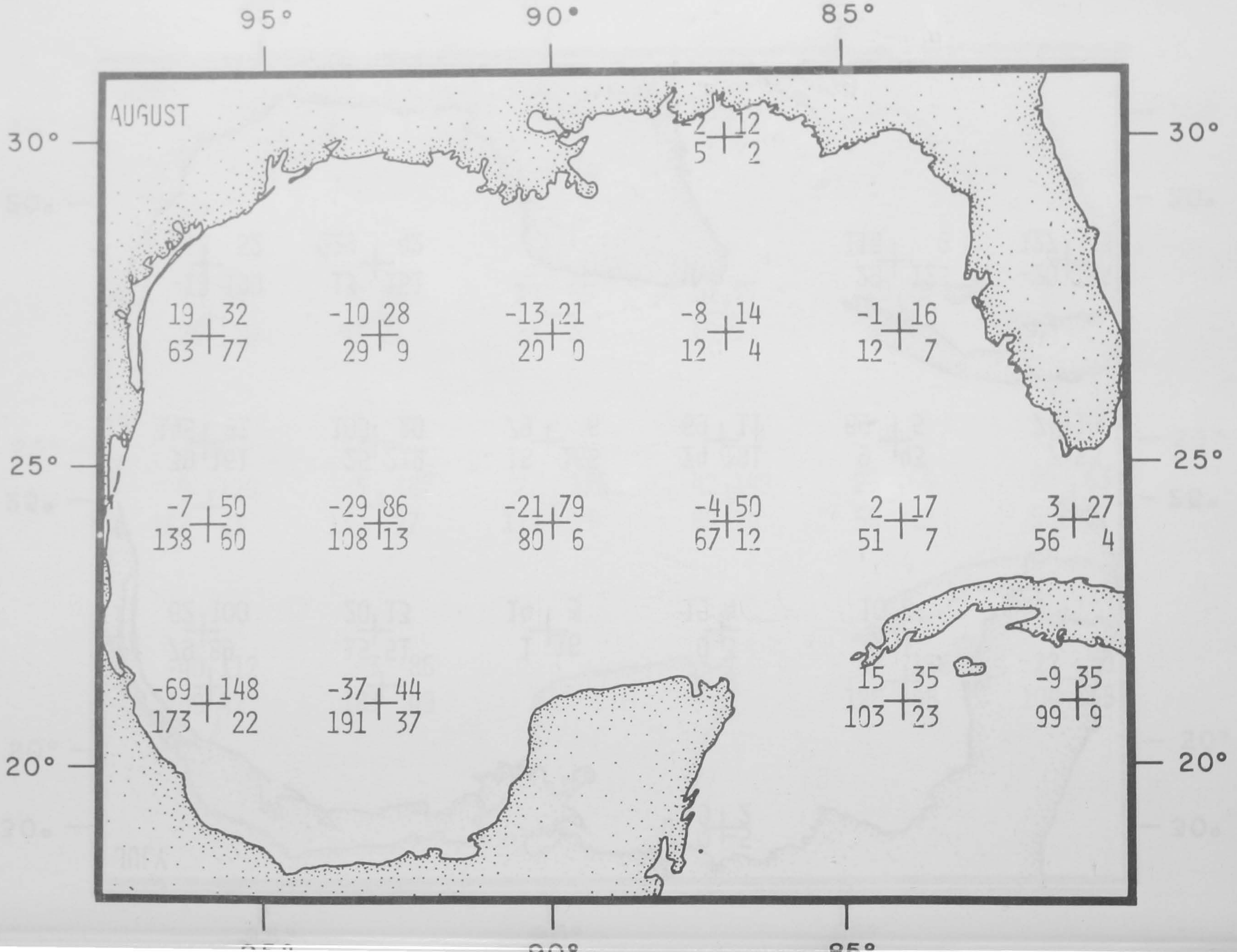
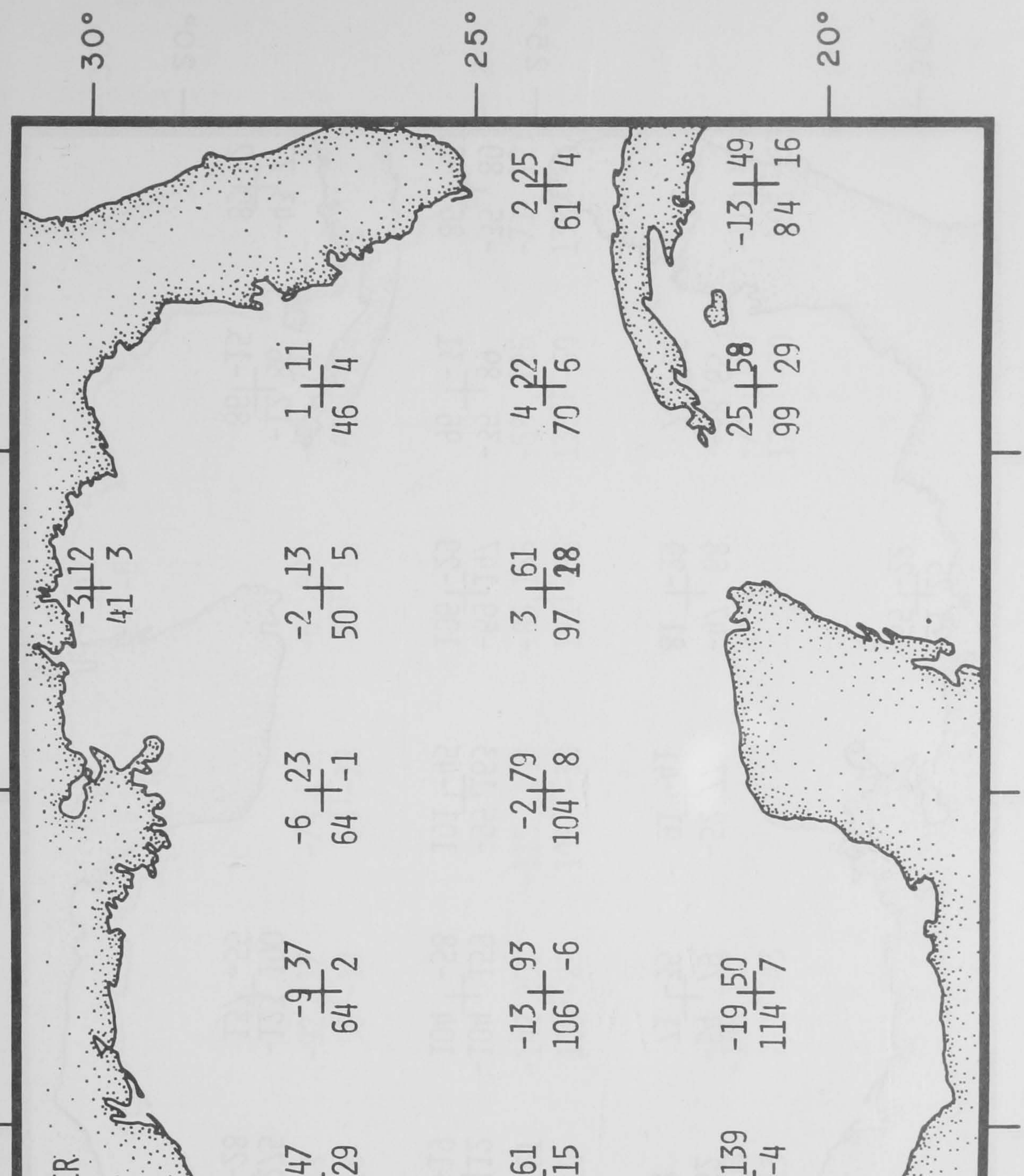
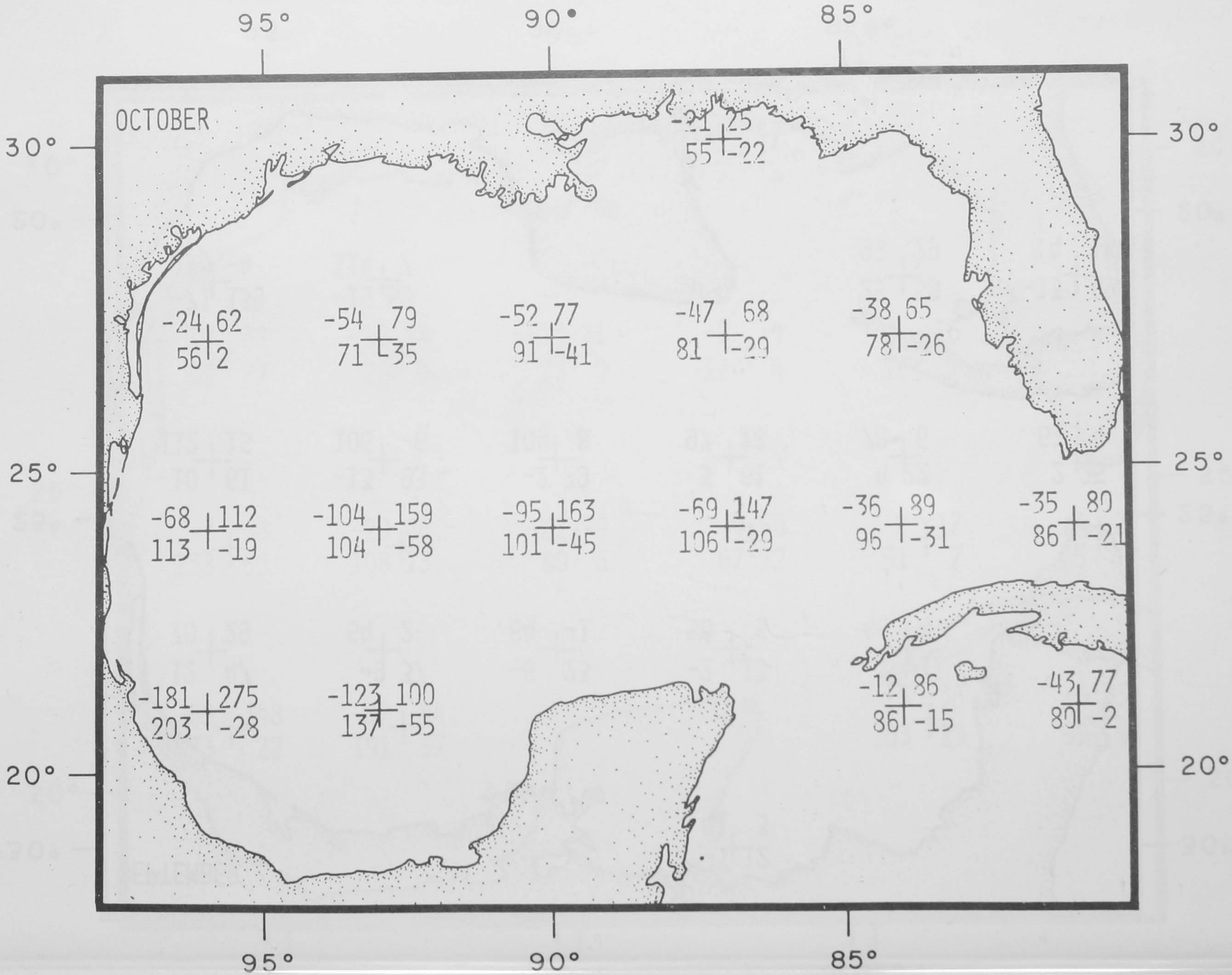
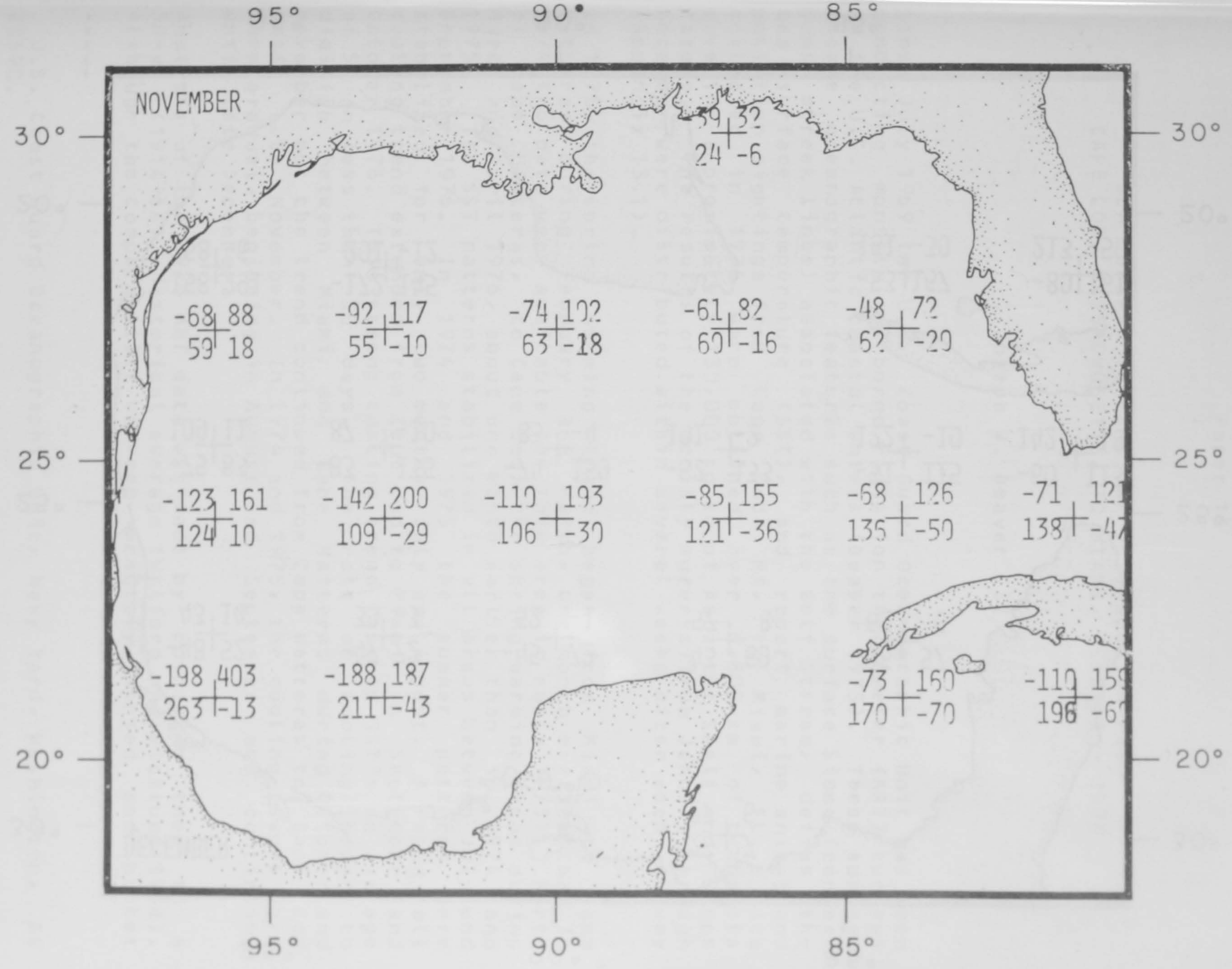
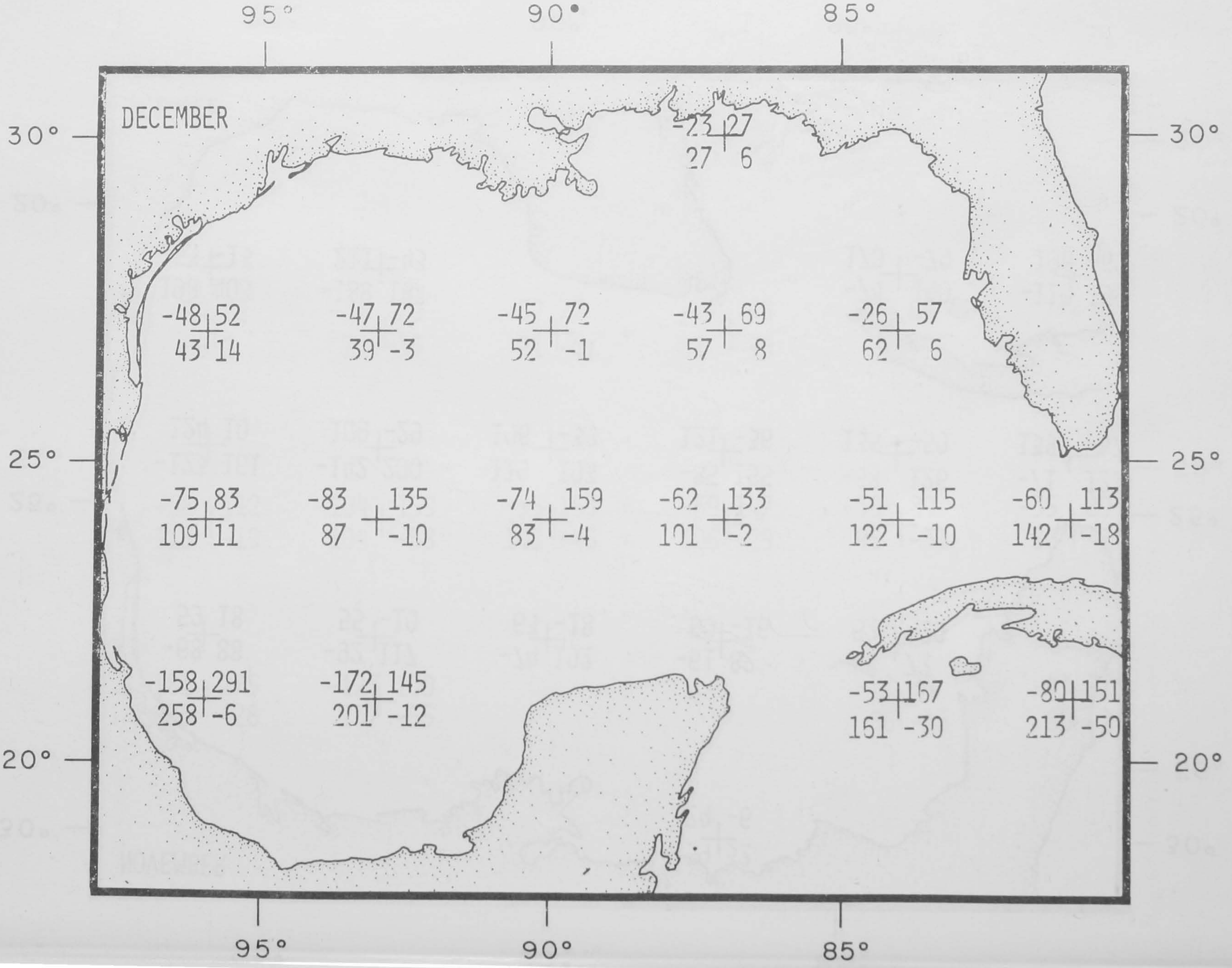
0 -5
-0 2
79 89
62 100
15 51
20 13
1 16
14 3
0 3
10 4
2 1
10 8
39 161
145 81
25 219
103 20
18 165
79 6
24 101
69 11
9 43
60 5
7 53
74 10
-18 190
218 52
13 151
229 42
29 123
118 9
-20 114
127 3
30°
25°
20°
95°
90°
85°


AUGUST
95°
90°
85°
30°
25°
20°
2 12
5 2
19 32
63 77
-10 28
29 9
-13 21
20 0
-8 14
12 4
-1 16
12 7
-7 50
138 60
-29 86
108 13
-21 79
80 6
-4 50
67 12
2 17
51 7
3 27
56 4
-69 148
173 22
-37 44
191 37
15 35
103 23
-9 35
99 9


SEPTEMBER
30°
25°
20°
95°
90°
85°
-3 12 41 3
12 47 70 29
-9 37 64 2
-6 23 64 -1
-2 13 50 5
1 11 46 4
-10 61 112 15
-13 93 106 -6
-2 79 104 8
3 61 97 18
4 22 70 6
2 25 61 4
-71 139 120 -4
-19 50 114 7
25 58 99 29
-13 49 84 16


95°
90°
85°
30°
25°
20°
OCTOBER
-21 25
55 -22
-24 62
56 2
-54 79
71 35
-52 77
91 -41
-47 68
81 -29
-38 65
78 -26
-68 112
113 -19
-104 159
104 -58
-95 163
101 -45
-69 147
106 -29
-36 89
96 -31
-35 80
86 -21
-181 275
203 -28
-123 100
137 -55
-12 86
86 -15
-43 77
80 -2


95°
90°
85°
30°
25°
20°
NOVEMBER
39 32
24 -6
-68 88
59 18
-92 117
55 -10
-74 102
63 -18
-61 82
60 -16
-48 72
62 -20
-123 161
124 10
-142 200
109 -29
-110 193
106 -30
-85 155
121 -36
-68 126
135 -50
-71 121
138 -47
-198 403
263 -13
-188 187
211 -43
-73 160
170 -70
-110 159
196 -6



DECEMBER
95°
90°
85°
30°
25°
20°
-23 27
27 6
-48 52
43 14
-47 72
39 -3
-45 72
52 -1
-43 69
57 8
-26 57
62 6
-75 83
109 11
-83 135
87 -10
-74 159
83 -4
-62 133
101 -2
-51 115
122 -10
-60 113
142 -18
-158 291
258 -6
-172 145
201 -12
-53 167
161 -30
-80 151
213 -50

Paper 13

SEA SURFACE TEMPERATURE DISTRIBUTION FROM CAPE COD, MASSACHUSETTS, TO MIAMI, FLORIDA - 1976

Joseph W. Deaver III[1]

Since July 1969 the U.S. Coast Guard Oceanographic Unit has been conducting monthly airborne radiation thermometer (ART) surveys of the U.S. Atlantic coastal waters (Deaver 1975). These surveys locate oceanographic features such as the surface Siome (convergence streak lines) associated with the Gulf Stream, define the sea surface temperature (SST), and report marine animal and pollution sightings from Cape Cod, MA, to Miami, FL. Data collected in 1976 were obtained over 6,800 km of transects covering approximately 130,000 sq km of Atlantic Shelf and Slope Waters. The results of the monthly surveys from January through December were distributed within several weeks after each survey (Appendix 13.1).

In 1976, the spring warming trend began from Miami to Cape Hatteras during February and March, one month earlier than in 1974 (no data were available for this area in early 1975). North of Cape Hatteras, to Cape Cod, the spring warming began during March and April 1976, about one month earlier than in 1974 and 1975. The SST patterns stabilized in all areas between July and September 1976. In 1974 and 1975 the summer patterns were stabilized for only two months, July and August. A rapid fall cooling trend extended from Cape Cod to Miami in September and October 1976. This strong cooling trend lowered SST's an average of 5C in less than 30 days. The rate of cooling began to diminish between Miami and Cape Hatteras during October and November but the trend continued from Cape Hatteras to Cape Cod until late November. In 1974 and 1975, the cooling trends were more gradual, beginning in August and September and continuing until late December.

Analysis of the 1976 ART data was made by comparing them to a 50-yr (1914-64) historical average (Walford and Wicklund 1968). Although the comparability between remotely sensed and bucket

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[1] U.S. Coast Guard Oceanographic Unit, Navy Yard, Washington, DC 20590.

gathered temperatures might be questioned, it is still of interest to make such a comparison. The difference between low altitude ART and bucket temperatures is small; ART temperatures averaged 1.0C lower than bucket values, and 95% of ART values were 0.3C to 1.8C lower than bucket values. Comparisons between ART observations on Coast Guard aircraft and surface truth measurements have shown differences of less than 1C.[2]

For both the 1976 ART data and Walford and Wicklund's (1968) data, a monthly, distance weighted, mean transect SST was calculated for each of 20 equally spaced sampling transects from Cape Cod to Miami (Fig. 13.1). The sampling transects were aligned normal to the 180-m isobath and the shoreline (Fig. 13.2). The weighted means are given in Tables 13.1 and 13.2. The means from the 20 transects were averaged to give the mean east coast SST for each month (Fig. 13.3). The monthly means were than averaged to give an annual mean east coast SST.

The 1976 annual mean east coast SST averaged just 0.6C below the historical annual mean SST of 19.0C (Fig. 13.3). In 1976, January, February, and September-December SST's were below historical averages. Conversely, the remaining spring and summer months were slightly warmer than the historical average.

In addition to the comparisons for the entire east coast, the Middle Atlantic Bight winter and summer temperatures were compared. This was done by averaging the monthly distance weighted mean transect SST's for transects 14-19 (Fig. 13.2) to obtain monthly Middle Atlantic Bight SST's. The January-March and July-September monthly Middle Atlantic Bight SST's were then averaged to give seasonal winter and summer means for both the 1976 data and Walford and Wicklund's (1968) data. The winter 1976 SST in the Bight was 5.6C, which is 0.3C cooler than historical averages. Interestingly, the July-September 1976 mean east coast SST's were 0.1C warmer than the historical averages, as were the 1976 mean Middle Atlantic Bight values.

The warmest monthly distance weighted mean transect SST off the east coast in 1976 was transect 1 off Miami, FL, in August with a value of 29C; the coolest was transect 20 off Cape Cod, MA, in March with a value of 3.8C.

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[2] Picket, R. L. 1966. Accuracy of an airborne infrared radiation thermometer. U.S. Naval Oceanographic Office, Informal Manuscript Report No. 0-1-66.

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DEAVER, J. W.
1975. Aerial oceanographic observations, Cape Cod, Massachusetts to Miami, Florida, July 1969-June 1970. U.S. Coast Guard Oceanogr. Rep. CG 373-68, 27 p.

WALFORD, L. A., and R. I. WICKLUND.
1968. Monthly sea temperature structure from the Florida Keys to Cape Cod. Ser. Atlas Mar. Envir., Am. Geogr. Soc., Folio 15, 16 plates.

Table 13.1.--Distance weighted historical mean sea surface temperatures (degrees C) at 20 transects off the U.S. Atlantic coast; calculated from Walford and Wicklund (1968, see Fig. 13.1).

SECTION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	22.5	22.5	22.5	25.0	25.0	27.5	27.5	27.5	27.5	27.5	25.0	22.5
2	23.0	22.5	22.5	23.9	25.0	26.6	27.5	30.0	27.5	26.3	24.8	23.2
3	22.0	20.6	21.8	23.1	23.8	25.8	26.7	26.4	27.5	25.0	24.5	22.5
4	19.0	19.9	19.6	21.4	24.4	25.4	26.6	27.3	27.5	25.0	23.3	21.5
5	18.4	18.9	19.8	21.1	23.0	25.4	27.2	27.5	27.5	23.8	21.2	20.4
6	15.9	17.3	18.4	21.0	21.0	25.9	27.5	27.5	27.5	23.8	19.9	18.2
7	15.0	15.7	17.0	18.7	21.9	25.3	26.3	27.5	27.0	23.0	20.2	16.3
8	17.5	16.6	17.0	17.1	22.5	25.0	25.8	27.5	26.0	22.3	19.0	16.9
9	15.9	15.6	16.5	18.4	21.2	25.0	27.0	27.5	25.9	22.1	18.4	18.0
10	17.6	13.8	15.7	20.8	22.5	25.0	25.0	27.5	26.5	21.5	19.0	18.4
11	14.5	17.8	15.6	19.4	21.3	23.0	25.5	25.9	25.3	21.9	18.7	17.0
12	18.6	19.2	17.5	20.0	22.0	25.0	27.3	25.0	25.6	23.4	17.9	16.9
13	15.9	13.0	11.3	20.0	19.5	22.9	23.8	25.3	25.0	21.3	18.6	15.0
14	8.1	7.3	8.1	10.5	15.0	20.0	23.4	24.3	23.1	17.9	15.0	11.7
15	7.7	6.0	4.1	7.1	12.5	18.1	22.5	22.5	23.5	17.5	14.1	9.8
16	5.9	5.0	7.0	8.2	10.4	15.7	21.6	23.3	22.1	19.8	15.9	10.2
17	5.4	6.3	4.6	7.5	10.6	15.5	20.8	22.2	20.5	16.1	13.7	9.5
18	7.6	4.7	4.1	5.3	9.5	14.3	20.0	21.6	20.3	16.5	12.3	8.9
19	6.4	4.5	3.0	5.5	8.7	12.9	18.8	21.3	18.7	15.0	12.7	7.9
20	3.1	4.2	3.4	5.2	8.6	14.7	16.3	20.6	19.4	15.0	12.9	9.3

Table 13.2.--Distance weighted 1976 mean sea surface temperatures (degrees C) at 20 transects off U.S. Atlantic coast; calculated from monthly sea surface temperature charts (see Figure 13.1).

SECTION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	22.0	22.0	24.0	24.0	25.0	27.0	28.0	29.0	28.0	25.0	25.0	22.2
2	22.4	20.7	24.0	24.0	26.0	27.0	29.0	28.5	28.0	23.7	24.4	22.5
3	19.3	17.9	22.0	23.2	24.3	25.6	27.9	28.0	27.4	23.2	23.1	20.2
4	17.3	18.1	20.7	23.3	24.5	25.5	28.0	28.0	27.0	23.0	22.1	19.3
5	17.8	16.9	20.5	22.8	23.0	25.5	29.0	-	26.0	21.4	19.2	16.8
6	14.5	13.8	18.7	23.2	23.3	24.7	29.0	-	25.6	20.3	18.5	16.8
7	13.4	12.8	17.6	21.6	23.7	24.3	29.0	-	25.5	20.4	18.2	16.8
8	13.1	11.8	16.7	21.2	22.4	24.0	28.5	-	25.5	19.8	18.9	17.6
9	14.5	12.1	16.4	20.9	22.0	23.3	27.4	-	24.8	19.7	17.7	16.0
10	12.8	12.8	17.6	21.1	22.2	23.9	27.0	26.6	25.6	21.0	18.6	17.8
11	12.6	11.5	16.2	20.7	21.7	23.0	27.0	26.5	25.3	19.8	16.8	-
12	13.3	12.9	15.5	20.7	21.9	22.9	-	26.6	25.3	19.8	14.6	-
13	6.0	14.8	9.4	19.6	20.4	19.3	-	28.0	23.5	18.4	13.1	14.1
14	6.0	8.0	8.6	12.9	16.3	19.4	-	24.0	23.0	18.3	12.7	9.5
15	4.4	6.2	6.2	12.4	13.1	17.3	23.0	22.6	23.0	16.9	10.8	9.2
16	4.7	5.8	5.6	11.3	13.5	18.0	23.3	21.7	21.8	14.4	9.3	8.1
17	4.8	5.0	5.3	12.0	12.7	16.4	-	21.0	21.0	14.7	9.6	7.2
18	4.6	5.3	5.3	10.9	11.6	16.3	-	17.9	19.6	14.0	10.1	9.1
19	4.8	5.2	4.4	8.8	11.4	15.8	-	18.3	20.1	13.9	10.6	-
20	3.9	4.1	3.8	8.3	9.5	13.3	-	18.5	19.0	14.0	8.4	-

$$\overline{T} = \frac{\sum_{i=1,n} \ell_i T_i}{\sum_{i=1,n} \ell_i}$$

Where: T = Distance weighted mean temperature

T_i = Value of an isotherm crossing transect

ℓ_i = Distance weighting factor equal to the distances between the isotherm crossing and the midpoints between it and adjacent isotherms or it and the end point of the transect as shown in figure below

n = Number of isotherms crossing the transects.

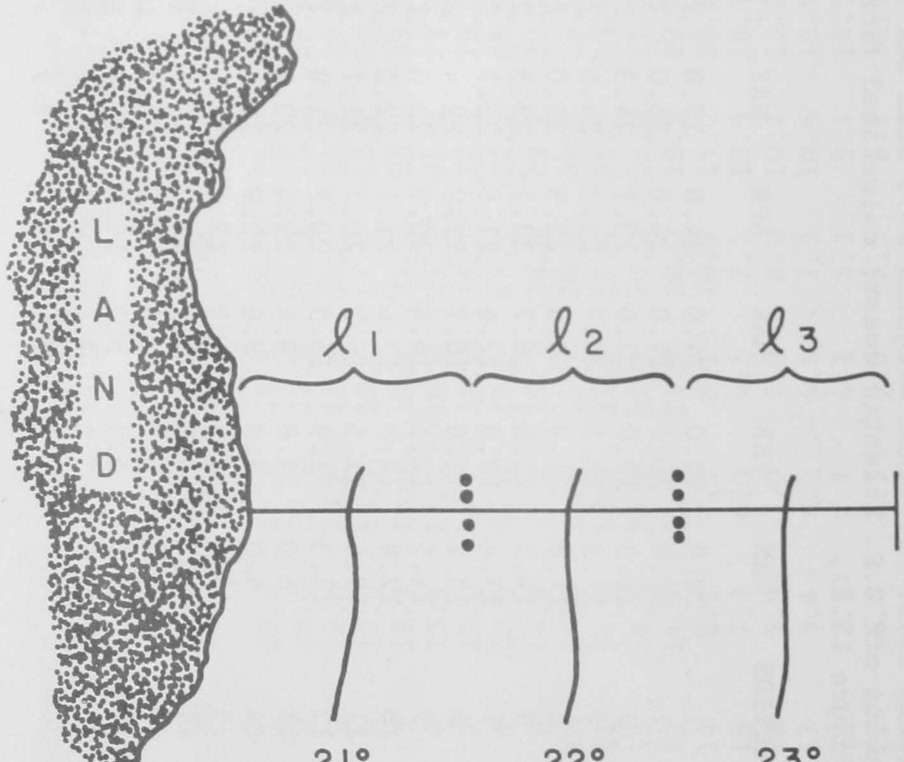


Figure 13.1.—Formula and graphic portrayal of method used to calculate distance weighted mean sea surface temperature from contoured isotherm chart.

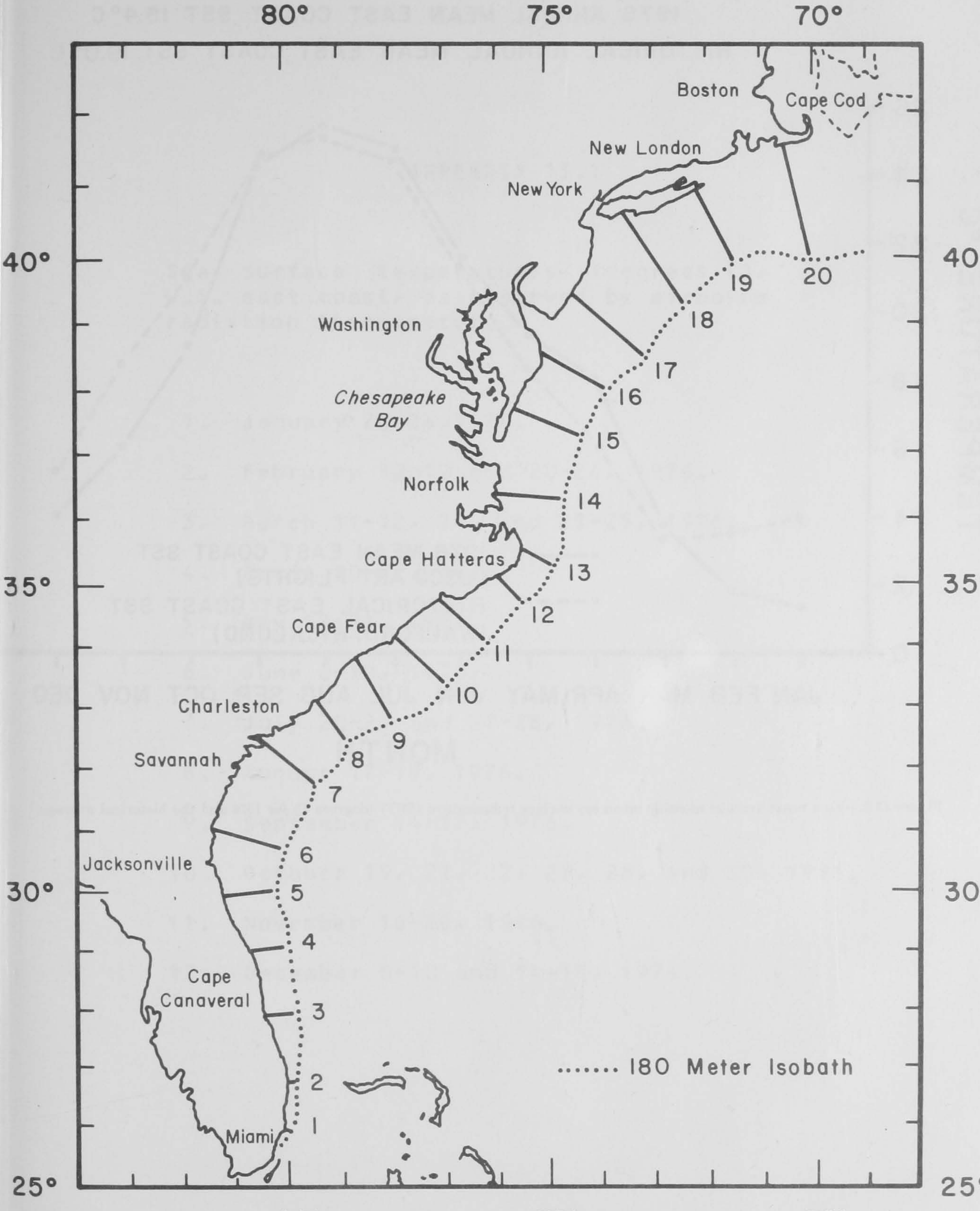


Figure 13.2.—Standard airborne radiation thermometer sampling transects from Cape Cod, MA, to Miami, FL.

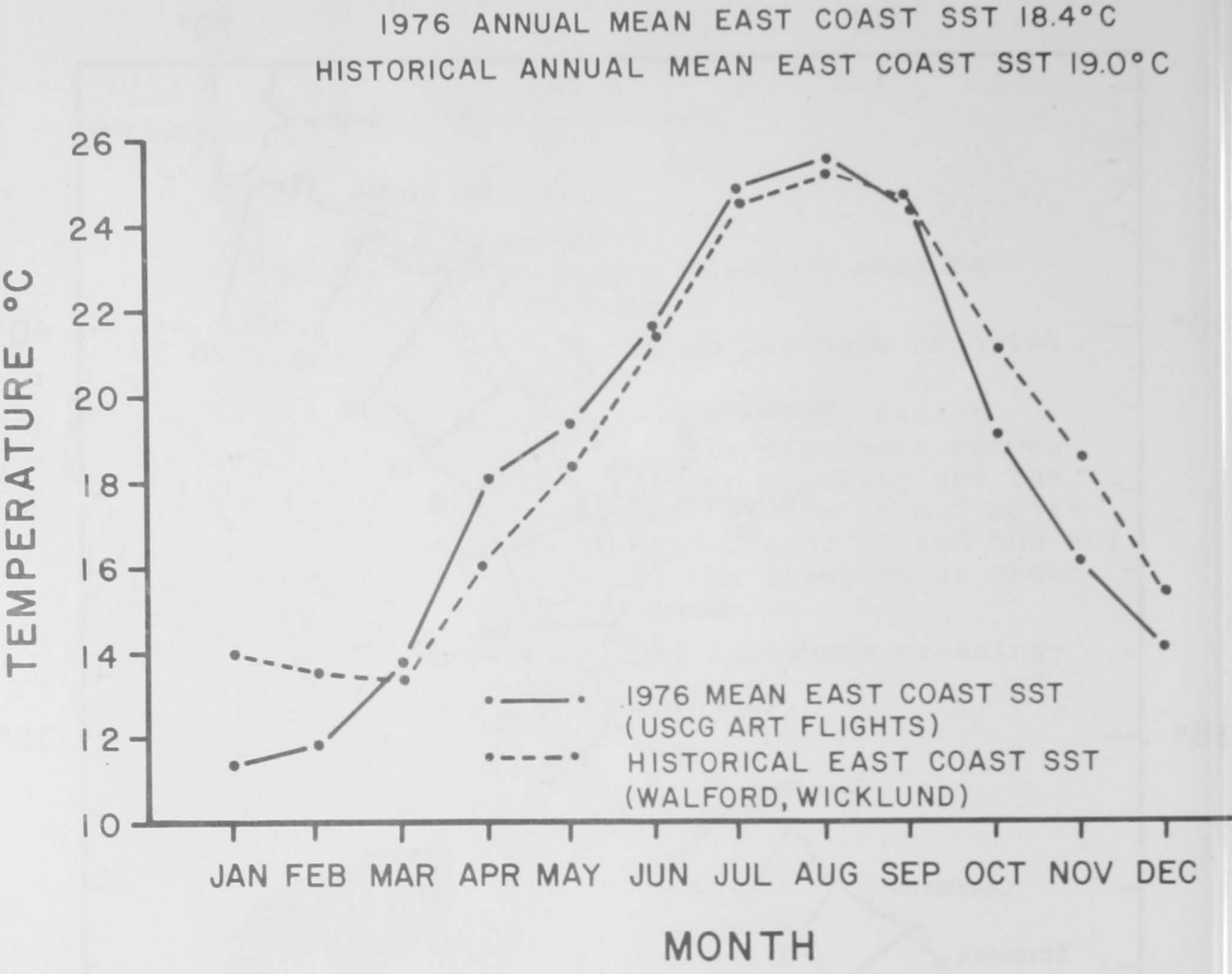
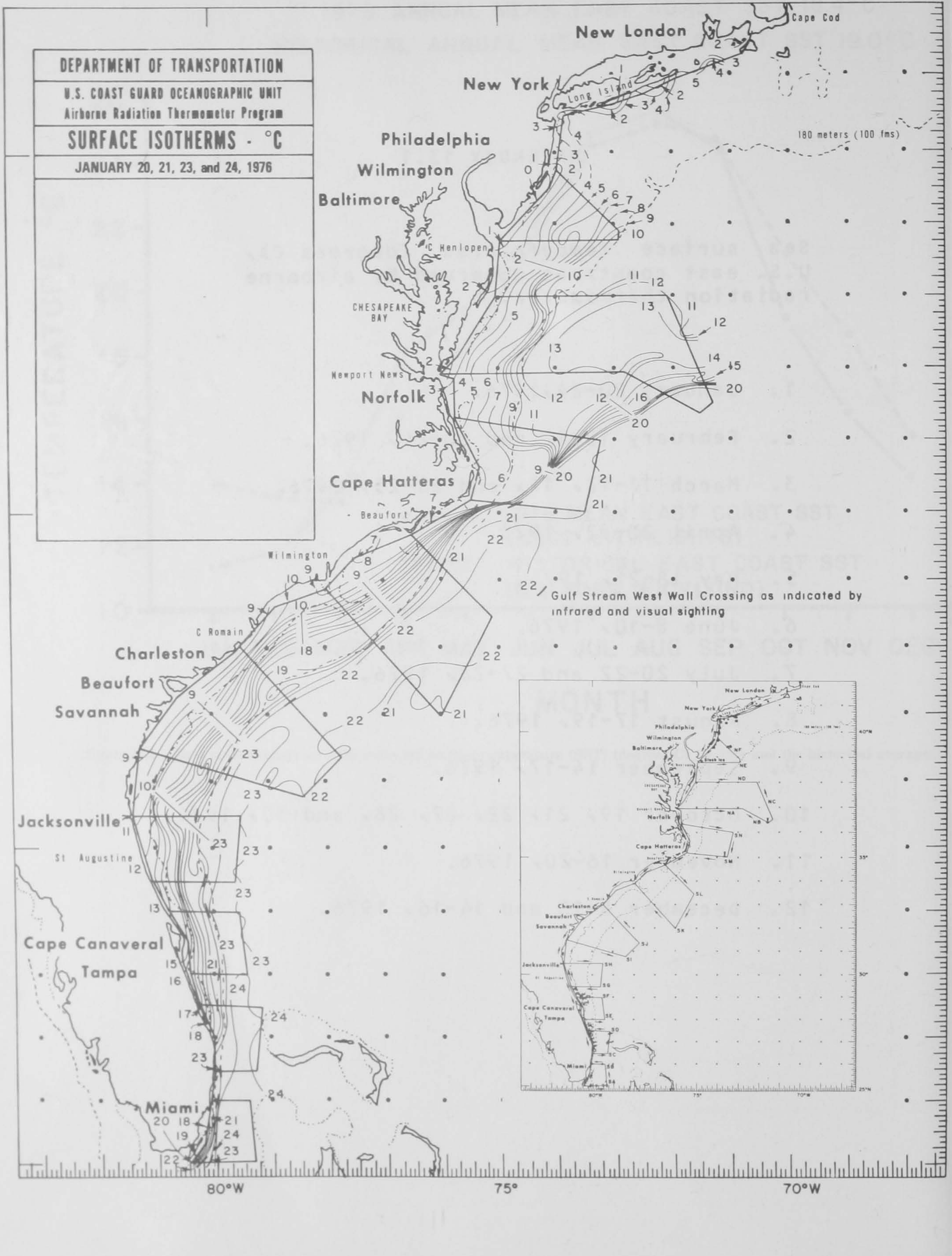


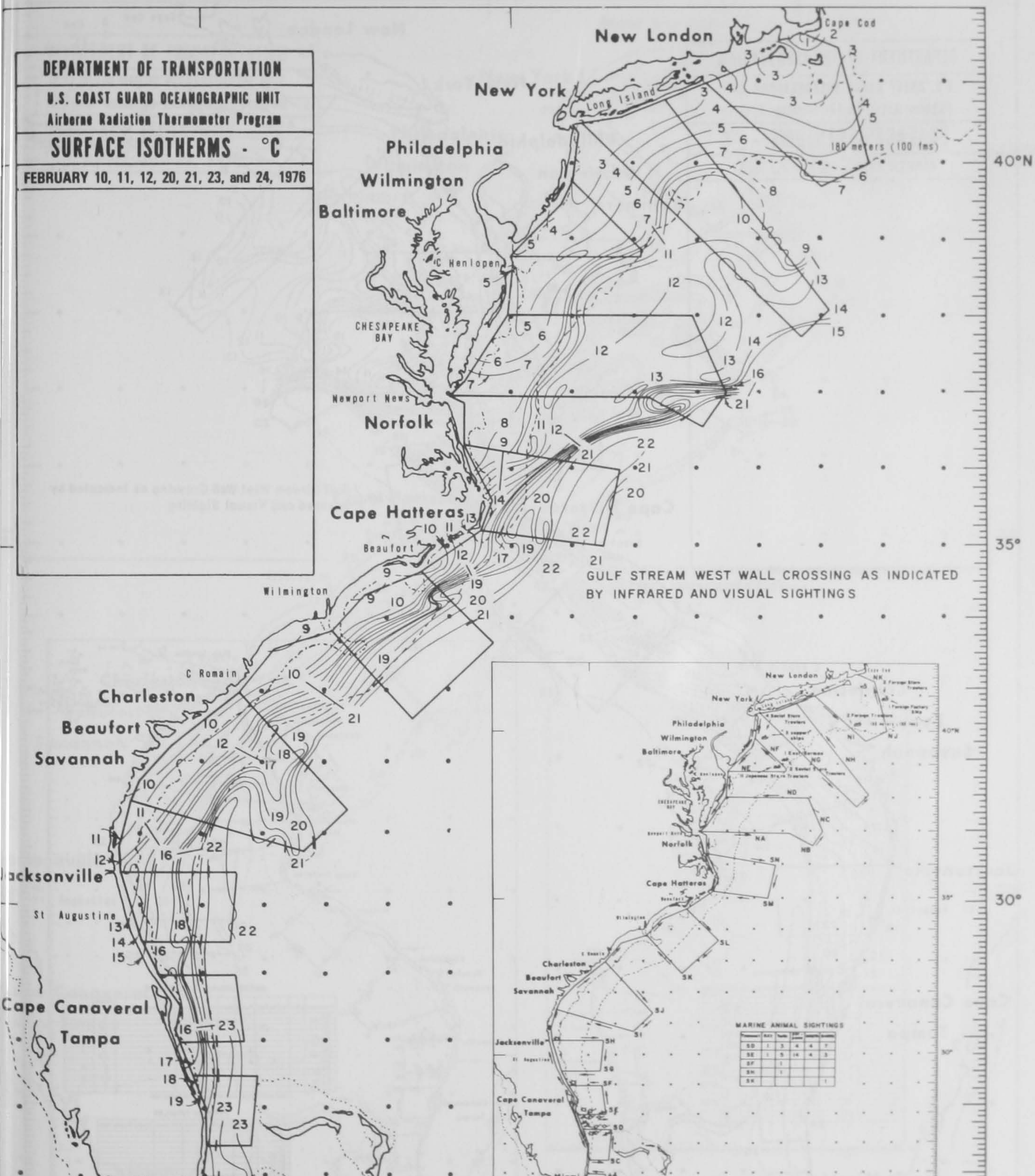
Figure 13.3.—East coast average monthly mean sea surface temperature (SST) (degrees C) for 1976 and the historical average.

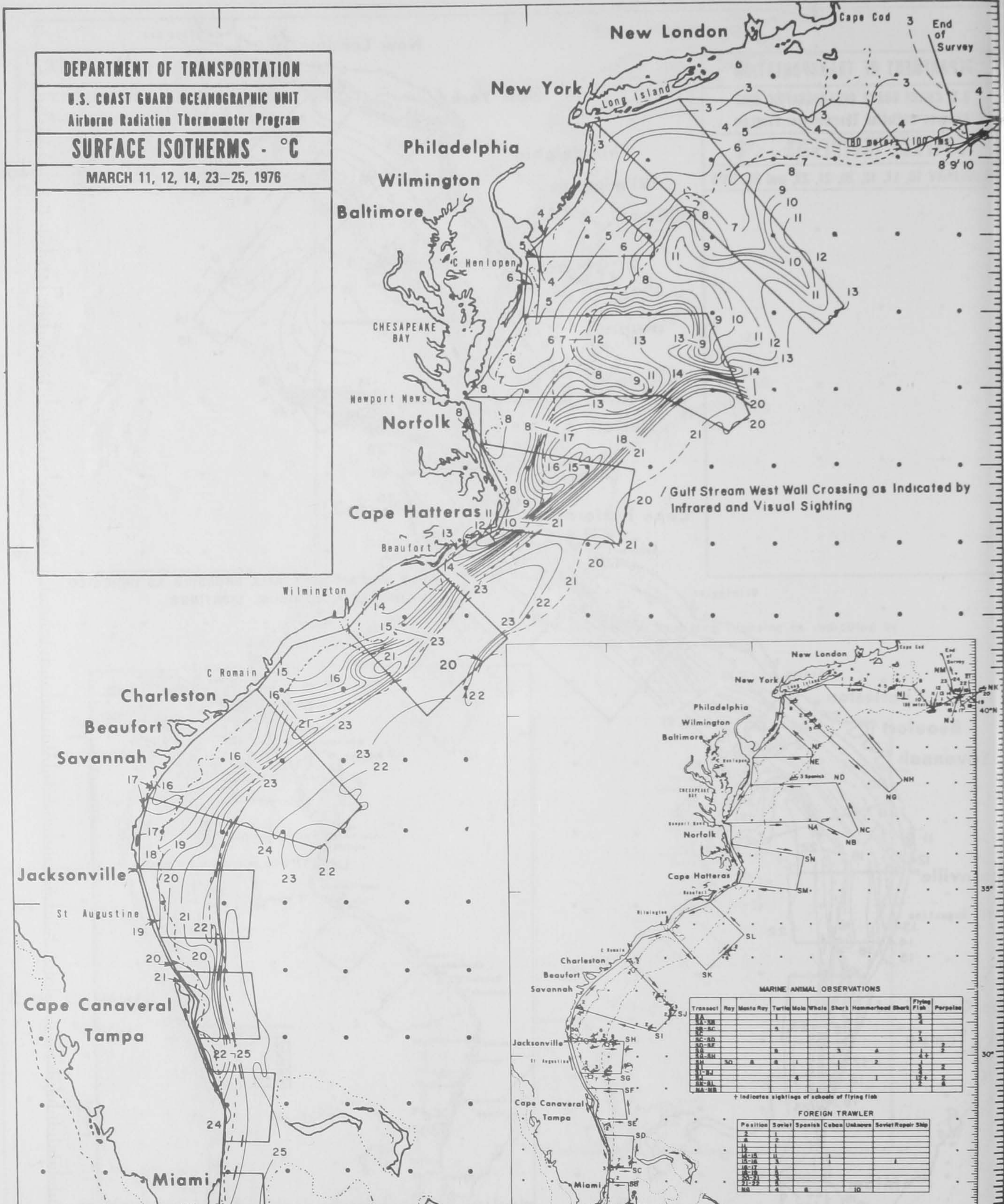
APPENDIX 13.1

Sea surface temperatures (degrees C), U.S. east coast, as observed by airborne radiation thermometer.

1. January 20-24,1976.
2. February 10-12 and 20-24, 1976.
3. March 11-12, 14, and 23-25, 1976.
4. April 20-22, 1976.
5. May 18-21, 1976.
6. June 8-10, 1976.
7. July 20-22 and 27-28, 1976.
8. August 17-19, 1976.
9. September 14-17, 1976.
10. October 19, 21, 22, 27, 28, and 30, 1976.
11. November 16-20, 1976.
12. December 8-10 and 14-16, 1976.


DEPARTMENT OF TRANSPORTATION
U.S. COAST GUARD OCEANOGRAPHIC UNIT
Airborne Radiation Thermometer Program
SURFACE ISOTHERMS - °C
JANUARY 20, 21, 23, and 24, 1976
Cape Cod
New London
New York
Long Island
Philadelphia
Wilmington
Baltimore
180 meters (100 fms)
C Henlopen
CHESAPEAKE BAY
Newport News
Norfolk
Cape Hatteras
Beaufort
Wilmington
C Romain
Charleston
Beaufort
Savannah
Jacksonville
St Augustine
Cape Canaveral
Tampa
Miami
Gulf Stream West Wall Crossing as indicated by infrared and visual sighting
80°W
75°
70°W
NF
NE
ND
NC
NB
NA
SN
SM
SL
SK
SJ
SI
SH
SG
SF
SE
SD
SC
SB
SA
40°N
35°
30°
25°N


DEPARTMENT OF TRANSPORTATION
U.S. COAST GUARD OCEANOGRAPHIC UNIT
Airborne Radiation Thermometer Program
SURFACE ISOTHERMS - °C
FEBRUARY 10, 11, 12, 20, 21, 23, and 24, 1976
Cape Cod
New London
New York
Long Island
180 meters (100 fms)
Philadelphia
Wilmington
Baltimore
C Henlopen
CHESAPEAKE BAY
Newport News
Norfolk
Cape Hatteras
Beaufort
Wilmington
C Romain
Charleston
Beaufort
Savannah
acksonville
St Augustine
Cape Canaveral
Tampa
Miami
GULF STREAM WEST WALL CROSSING AS INDICATED BY INFRARED AND VISUAL SIGHTINGS
MARINE ANIMAL SIGHTINGS
40°N
35°
30°
25°N
80°W
75°
70°W



MARINE ANIMAL OBSERVATIONS

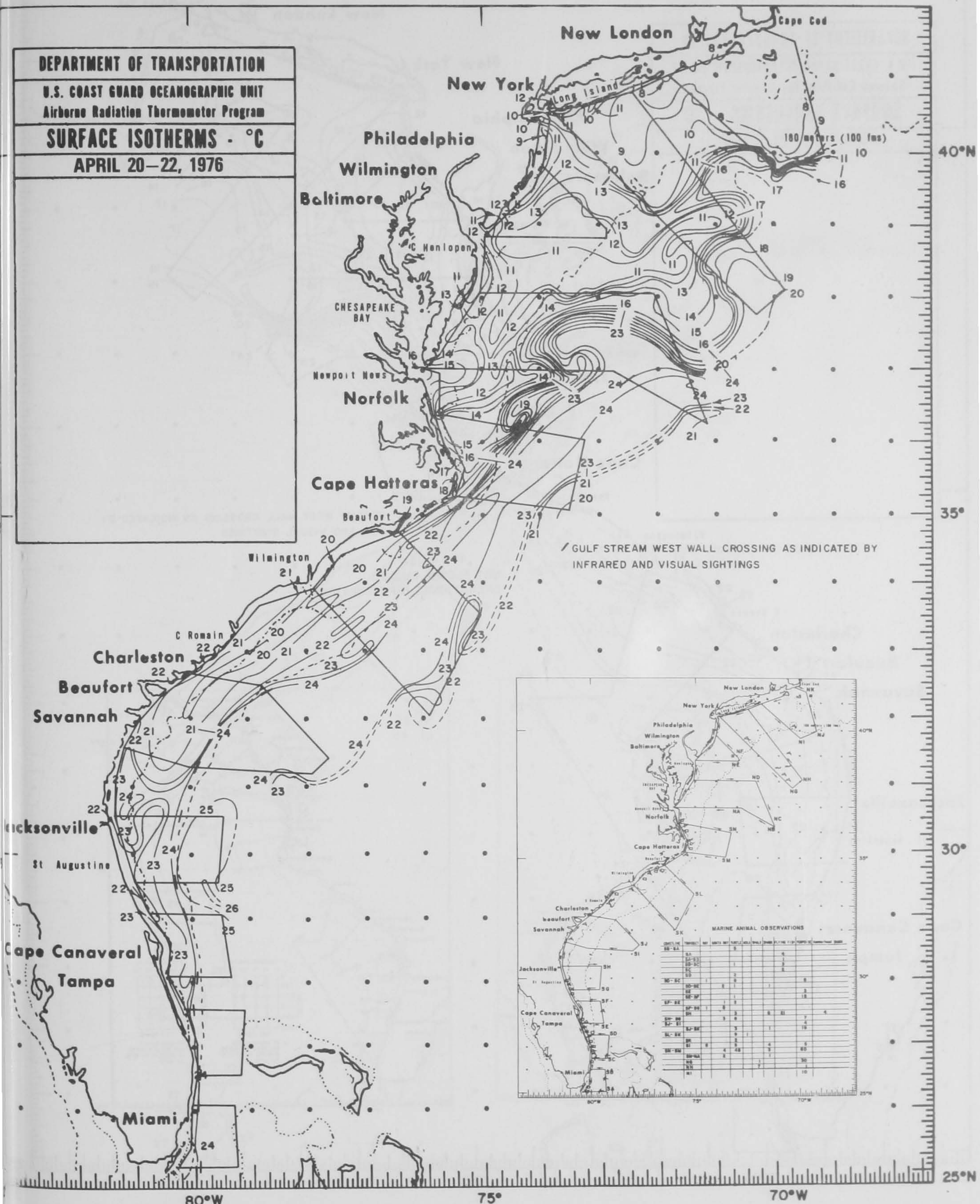
Transect	Ray	Manta Ray	Turtle	Mola	Whale	Shark	Hammerhead Shark	Flying Fish	Porpoise
SA			1					5	
SA-SB								4	
SB-SC			5						
SC								7	
SC-SD								3	
SD-SF									2
SG			8			3	4	1	2
SG-SH								4+	
SH	30	8	8	1		1	2	1	
SI						1		3	2
SI-SJ								4	
SJ				4			1	12+	2
SK-SL								2	6
NA-NB					1				

+ indicates sightings of schools of flying fish

FOREIGN TRAWLER

Position	Soviet	Spanish	Cuban	Unknown	Soviet Repair Ship
2	1				
6	2				
11	1				
12	1				
14-15	11		1		
15-16	3		1		1
16-17	1				
18-19	5				
20-21	3				
21-22	5				
NG	4	6		10	

March 11, 12, 14, 23-25, 1976

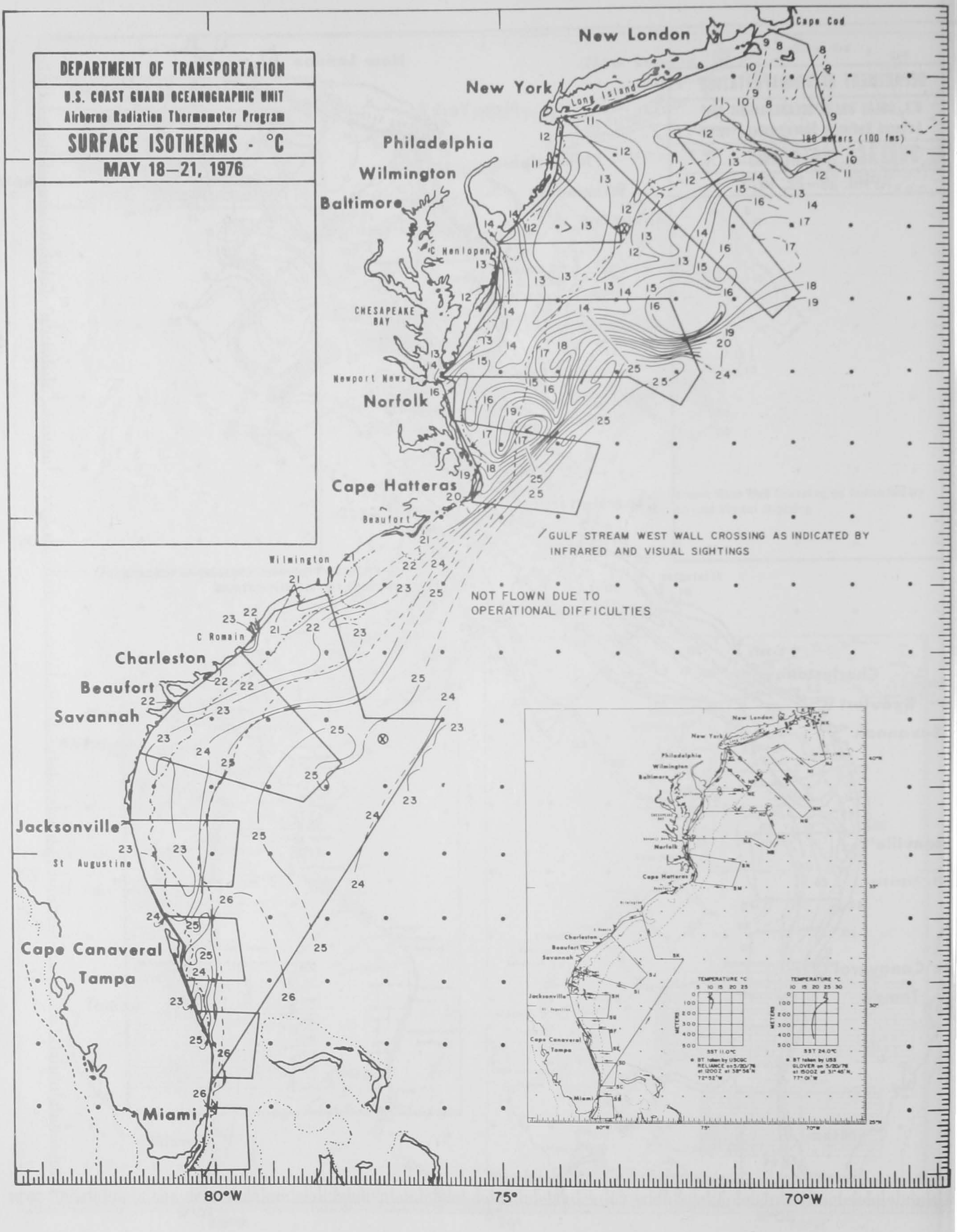


DEPARTMENT OF TRANSPORTATION

U.S. COAST GUARD OCEANOGRAPHIC UNIT
Airborne Radiation Thermometer Program

SURFACE ISOTHERMS - °C

APRIL 20—22, 1976



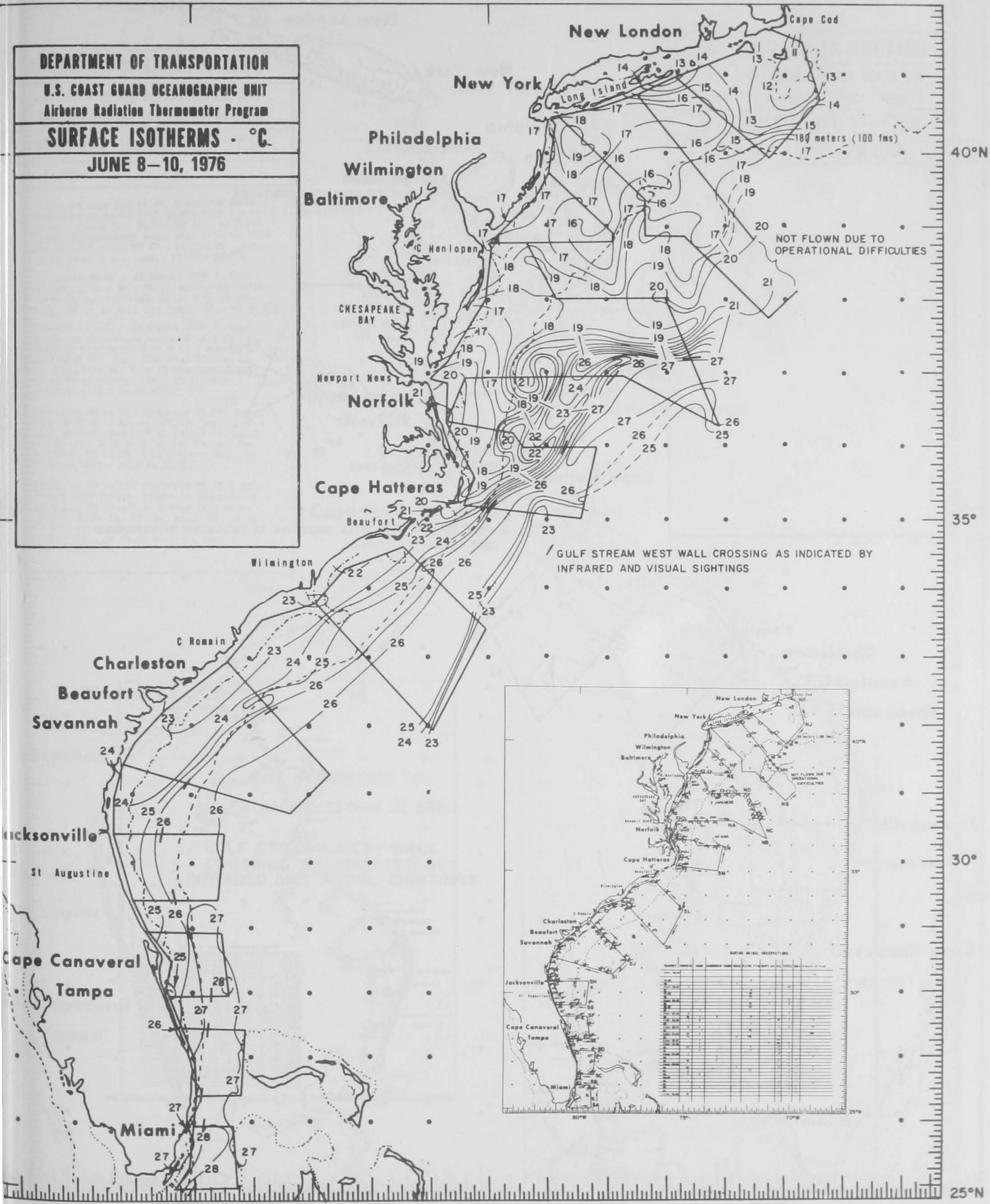
DEPARTMENT OF TRANSPORTATION

U.S. COAST GUARD OCEANOGRAPHIC UNIT

Airborne Radiation Thermometer Program

SURFACE ISOTHERMS - °C

MAY 18–21, 1976



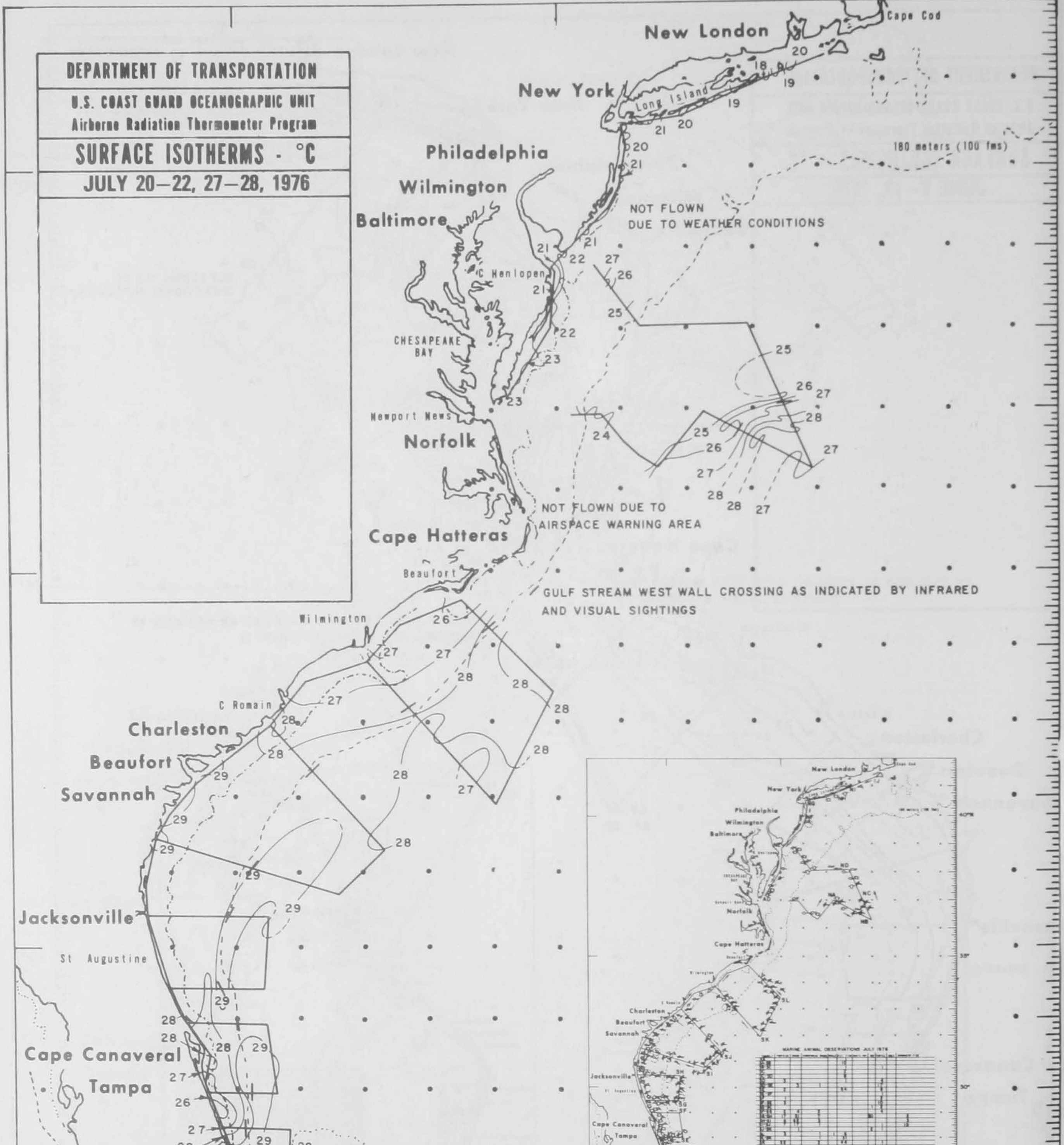
DEPARTMENT OF TRANSPORTATION

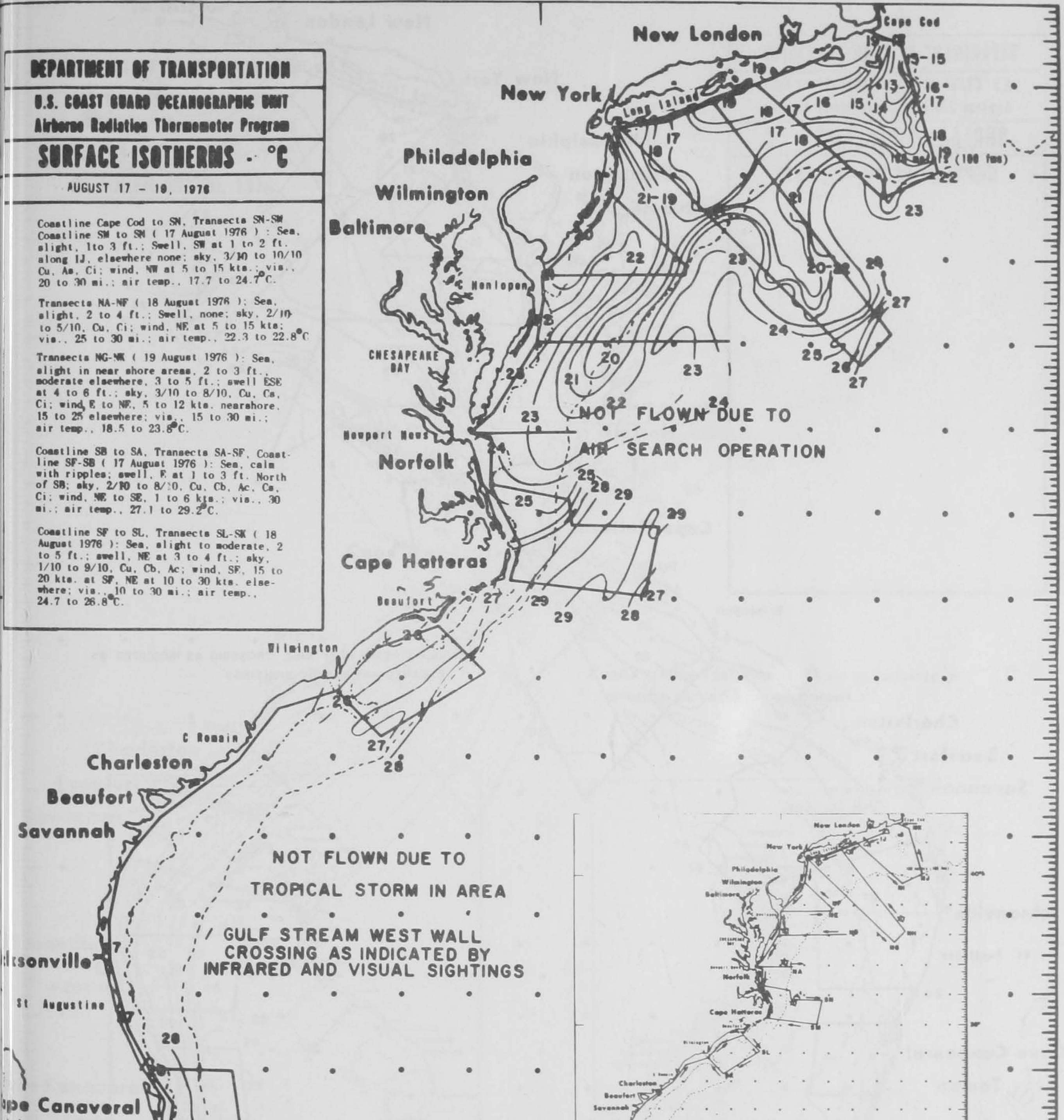
U.S. COAST GUARD OCEANOGRAPHIC UNIT

Airborne Radiation Thermometer Program

SURFACE ISOTHERMS - °C

JUNE 8–10, 1976


DEPARTMENT OF TRANSPORTATION
U.S. COAST GUARD OCEANOGRAPHIC UNIT
Airborne Radiation Thermometer Program
SURFACE ISOTHERMS - °C
JULY 20–22, 27–28, 1976
New London
Cape Cod
New York
Long Island
Philadelphia
Wilmington
Baltimore
C Henlopen
CHESAPEAKE BAY
Newport News
Norfolk
Cape Hatteras
Beaufort
Wilmington
C Romain
Charleston
Beaufort
Savannah
Jacksonville
St Augustine
Cape Canaveral
Tampa
Miami
180 meters (100 fms)
NOT FLOWN DUE TO WEATHER CONDITIONS
NOT FLOWN DUE TO AIRSPACE WARNING AREA
GULF STREAM WEST WALL CROSSING AS INDICATED BY INFRARED AND VISUAL SIGHTINGS
80°W
75°
70°W



DEPARTMENT OF TRANSPORTATION

U.S. COAST GUARD OCEANOGRAPHIC UNIT
Airborne Radiation Thermometer Program

SURFACE ISOTHERMS - °C

AUGUST 17 - 19, 1976

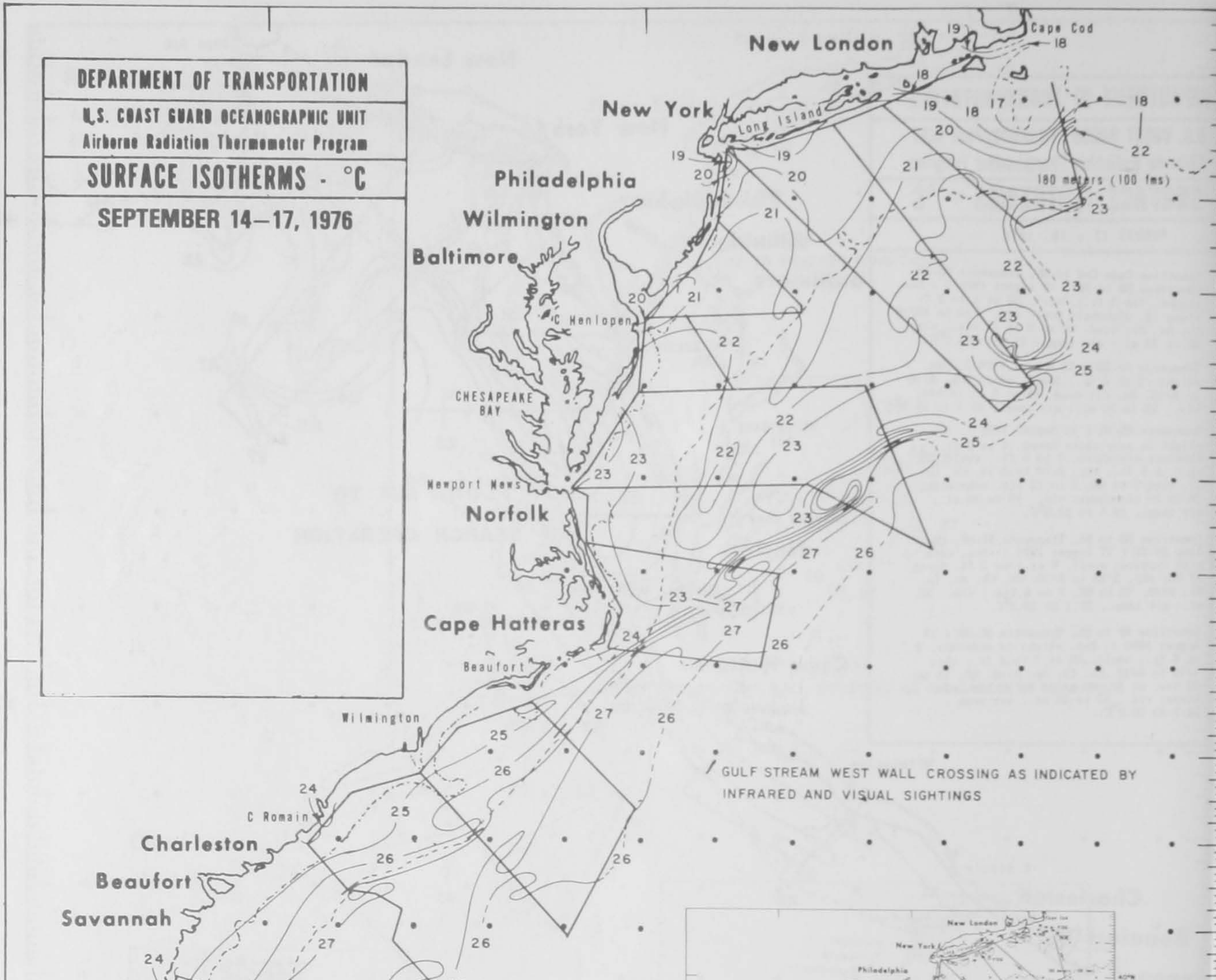
Coastline Cape Cod to SN, Transects SN-SM Coastline SM to SN (17 August 1976) : Sea, slight, 1to 3 ft.; Swell, SW at 1 to 2 ft. along IJ, elsewhere none; sky, 3/10 to 10/10 Cu, As, Ci; wind, NW at 5 to 15 kts.; vis., 20 to 30 mi.; air temp., 17.7 to 24.7°C.

Transects NA-NF (18 August 1976): Sea, slight, 2 to 4 ft.; Swell, none; sky, 2/10 to 5/10, Cu, Ci; wind, NE at 5 to 15 kts; vis., 25 to 30 mi.; air temp., 22.3 to 22.8°C

Transects NG-NK (19 August 1976): Sea, slight in near shore areas, 2 to 3 ft., moderate elsewhere, 3 to 5 ft.; swell ESE at 4 to 6 ft.; sky, 3/10 to 8/10, Cu, Cs, Ci; wind, E to NE, 5 to 12 kts. nearshore, 15 to 25 elsewhere; vis., 15 to 30 mi.; air temp., 18.5 to 23.8°C.

Coastline SB to SA, Transects SA-SF, Coastline SF-SB (17 August 1976): Sea, calm with ripples; swell, E at 1 to 3 ft. North of SB; sky, 2/10 to 8/10, Cu, Cb, Ac, Cs, Ci; wind, NE to SE, 1 to 6 kts.; vis., 30 mi.; air temp., 27.1 to 29.2°C.

Coastline SF to SL, Transects SL-SK (18 August 1976): Sea, slight to moderate, 2 to 5 ft.; swell, NE at 3 to 4 ft.; sky, 1/10 to 9/10, Cu, Cb, Ac; wind, SE, 15 to 20 kts. at SF, NE at 10 to 30 kts. elsewhere; vis., 10 to 30 mi.; air temp., 24.7 to 26.8°C.

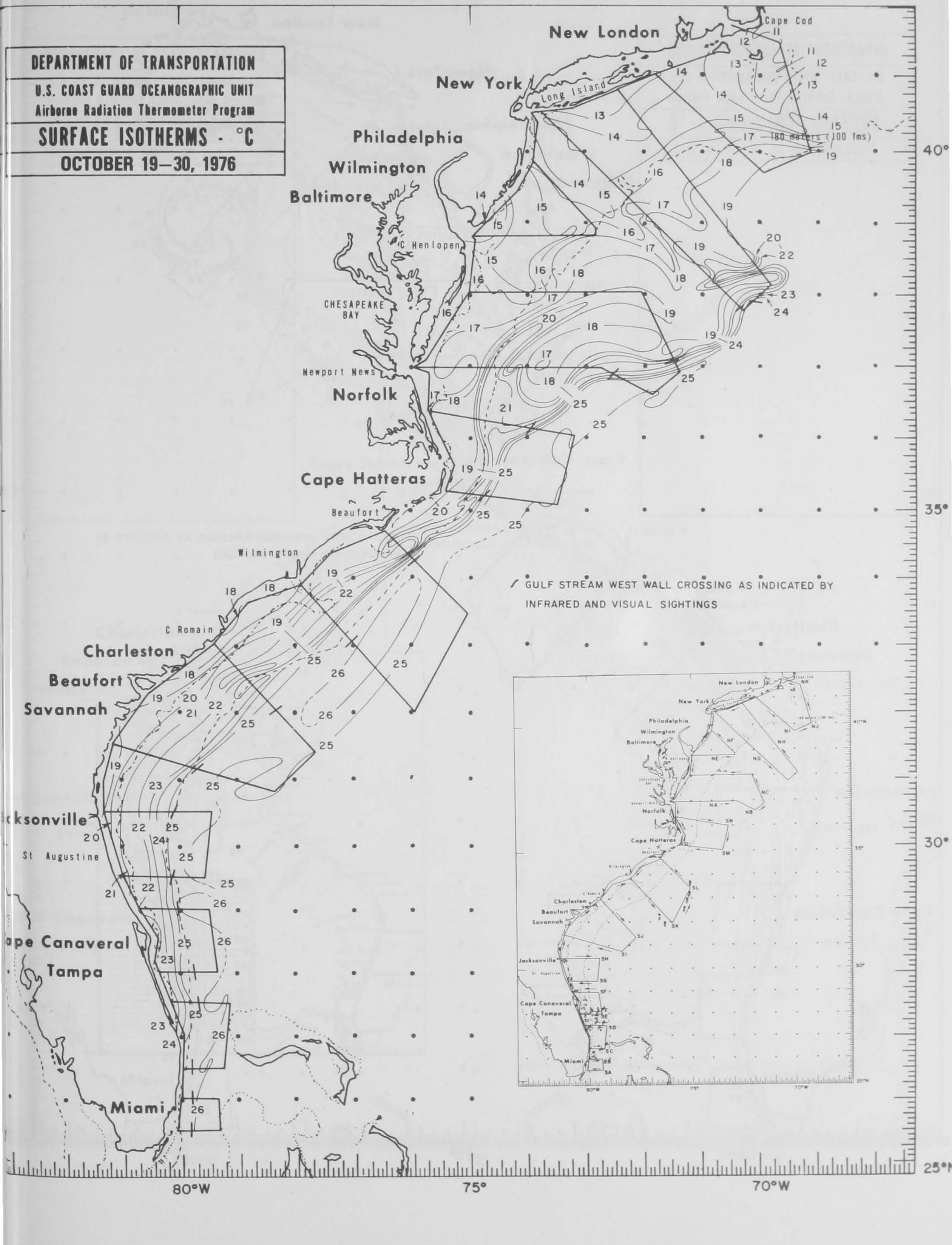


DEPARTMENT OF TRANSPORTATION

U.S. COAST GUARD OCEANOGRAPHIC UNIT
Airborne Radiation Thermometer Program

SURFACE ISOTHERMS - °C

SEPTEMBER 14–17, 1976



DEPARTMENT OF TRANSPORTATION

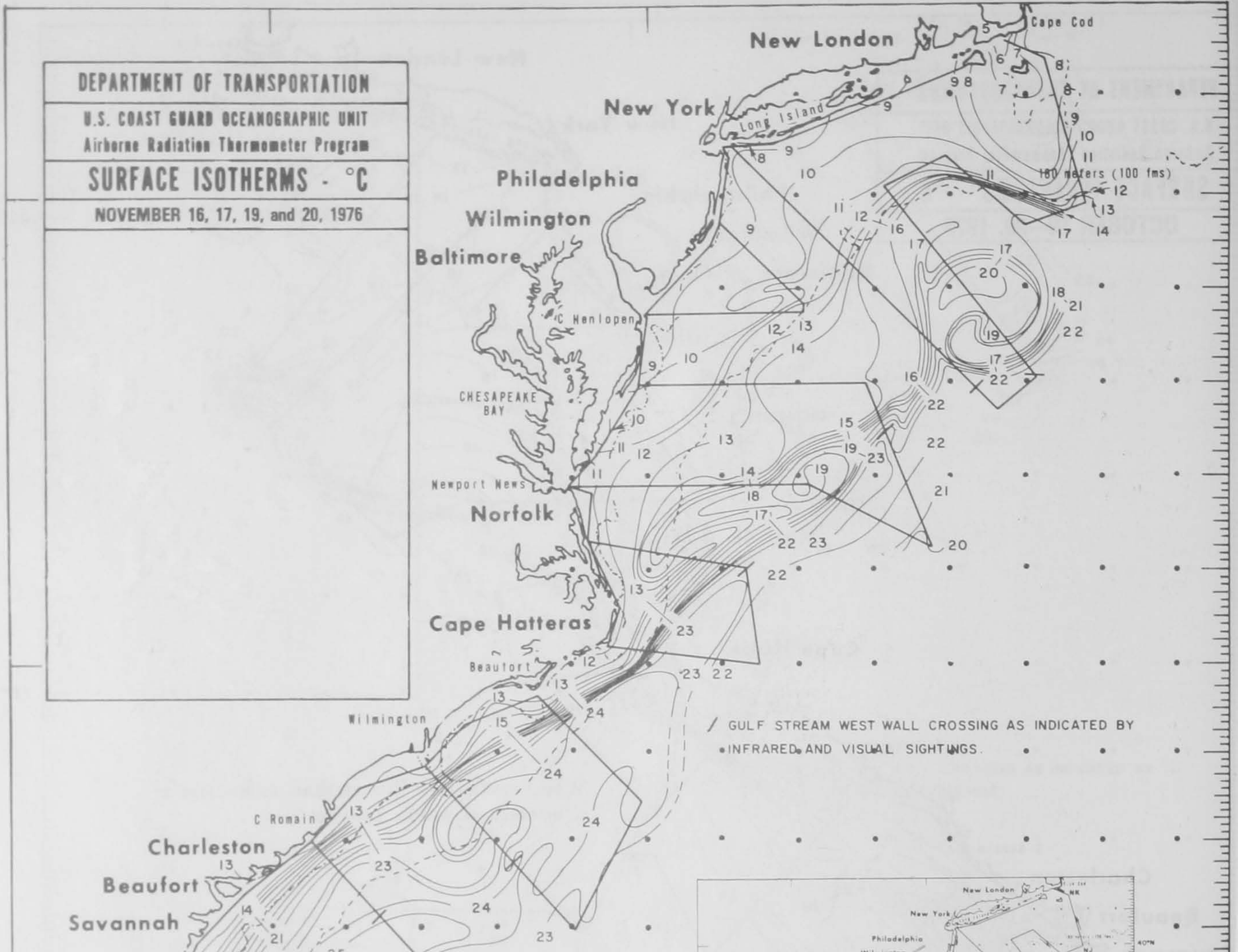
U.S. COAST GUARD OCEANOGRAPHIC UNIT

Airborne Radiation Thermometer Program

SURFACE ISOTHERMS - °C

OCTOBER 19–30, 1976

/ GULF STREAM WEST WALL CROSSING AS INDICATED BY INFRARED AND VISUAL SIGHTINGS



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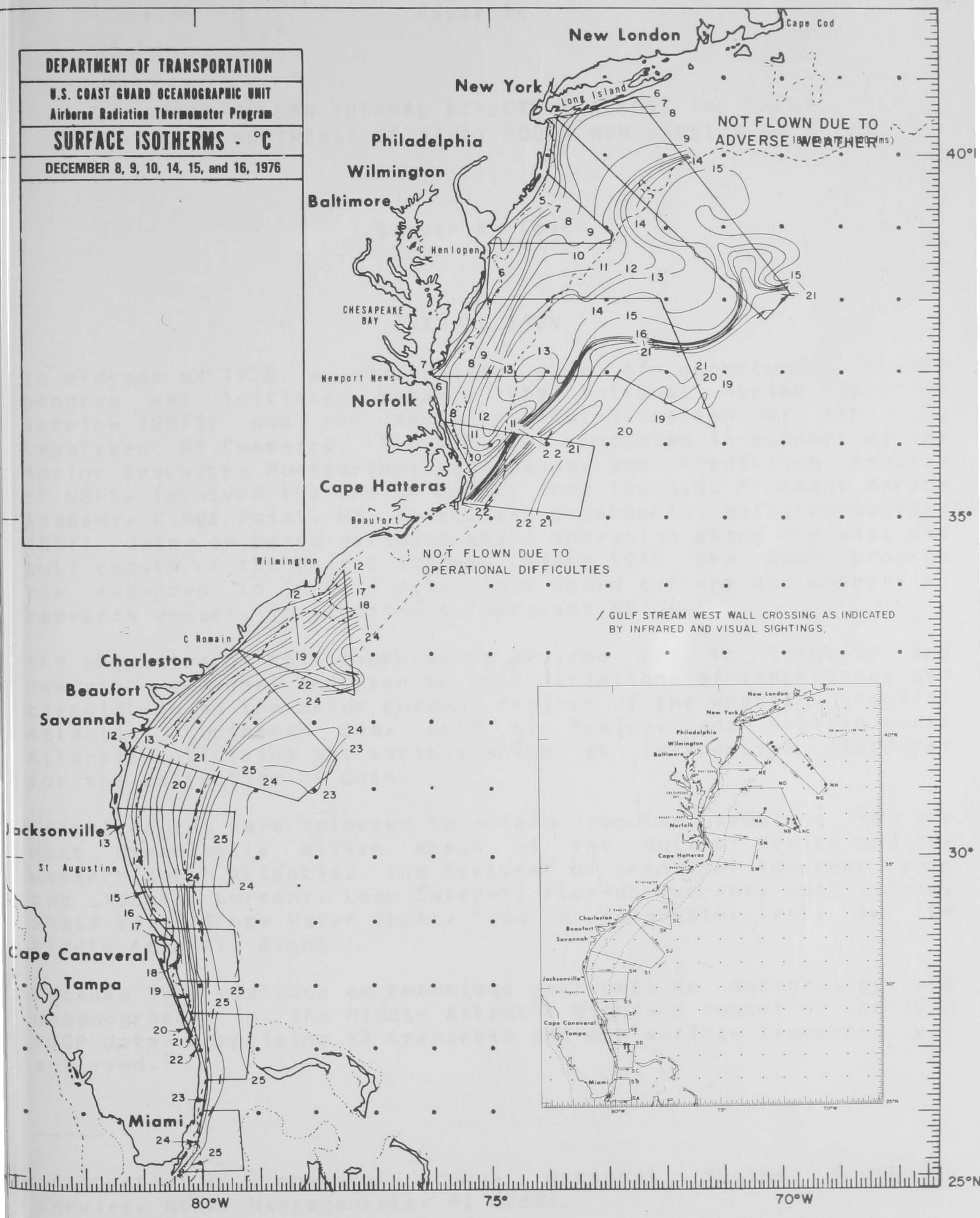
U.S. COAST GUARD OCEANOGRAPHIC UNIT
Airborne Radiation Thermometer Program

SURFACE ISOTHERMS - °C

NOVEMBER 16, 17, 19, and 20, 1976

/ GULF STREAM WEST WALL CROSSING AS INDICATED BY
• INFRARED AND VISUAL SIGHTINGS.


DEPARTMENT OF TRANSPORTATION
U.S. COAST GUARD OCEANOGRAPHIC UNIT
Airborne Radiation Thermometer Program
SURFACE ISOTHERMS - °C
DECEMBER 8, 9, 10, 14, 15, and 16, 1976
New London
Cape Cod
New York
Long Island
Philadelphia
Wilmington
Baltimore
C Henlopen
CHESAPEAKE BAY
Newport News
Norfolk
Cape Hatteras
Beaufort
Wilmington
C Romain
Charleston
Beaufort
Savannah
Jacksonville
St Augustine
Cape Canaveral
Tampa
Miami
NOT FLOWN DUE TO ADVERSE WEATHER
NOT FLOWN DUE TO OPERATIONAL DIFFICULTIES
/ GULF STREAM WEST WALL CROSSING AS INDICATED BY INFRARED AND VISUAL SIGHTINGS,
40°N
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SI
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SD
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SB
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Paper 14

WATER COLUMN THERMAL STRUCTURE ACROSS THE SHELF AND SLOPE SOUTHEAST OF SANDY HOOK, NEW JERSEY, IN 1976

Steven K. Cook[1]

INTRODUCTION

In midyear of 1970 a cooperative ship of opportunity (SOOP) program was initiated between the National Marine Fisheries Service (NMFS) and the Maritime Administration of the U.S. Department of Commerce. The program, conducted in support of the Marine Resources Monitoring, Assessment, and Prediction Program of NMFS, involved the use of cadets from the U.S. Merchant Marine Academy, Kings Point, NY, to collect expendable bathythermograph (XBT) data on board merchant ships operating along the east and gulf coasts of the United States. Since 1970 the SOOP program has expanded to include U.S. Coast Guard cutters and university research vessels in addition to merchant ships.

The objective of this cooperative program was to identify and describe seasonal and year to year variations of temperature and circulation in the major current regimes of the western tropical Atlantic, Caribbean Sea, Gulf of Mexico, and western North Atlantic, utilizing the various ships as inexpensive platforms for the collection of data.

Ships' routes were selected to obtain regular sampling in the most dynamically active areas of the Gulf of Mexico and the western North Atlantic. The features of principal interest were the Yucatan Current, Loop Current, Florida Current, Gulf Stream, Shelf Water/Slope Water front, and a cold-water cell in the Middle Atlantic Bight.

Because 1976 was such an anomalous year both in meteorology and oceanography in the Middle Atlantic Bight, a subset of the 1976 SOOP data, comprising 18 transects and one surface transect, was analyzed.

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[1] Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

The anoxic event which began early in the year off New Jersey and lasted through the spring and summer of 1976 necessitated a detailed analysis of the thermal water column structure, considering how it evolved, was maintained, and eventually declined. Oxygen depletion in the bottom waters over a large area off the coast during the summer had severe effects on the sport and commercial fisheries. The immediate impact included finfish and shellfish mortalities and unusual fish distribution patterns and concentrations. Likely causes of the oxygen depletion can be traced back to anomalous environmental conditions in January and February of 1976 in the Middle Atlantic Bight (Armstrong, Paper 17).

HISTORICAL SUMMARY

Water temperatures in the Middle Atlantic Bight range from a minimum of <3C in the New York Bight in February to >27C off Cape Hatteras in August (Bumpus et al. 1973). The annual range of surface temperature may be >15C in the Slope Water to >20C in the Shelf Water.

Minimum winter temperatures are reached in late February or early March and may be as low as 1C. During this coldest season the Shelf Water column is well mixed (isothermal) from surface to bottom and extends out to the Shelf Water/Slope Water front (at approximately the 100-m isobath) (Gunn, Paper 18). Irregular warming usually begins in late February or early March, and a thermocline develops in late April or early May.

A rather intense thermocline develops during the summer, sealing off the bottom waters and isolating a pool or cell of cold winter water that rests on the bottom surrounded shoreward, seaward, and above by warmer water. As the summer progresses into early fall, this cold cell tends to erode in extent and increase in temperature. This erosion is presumably caused by mixing from above with warmer near surface waters and from a "calving" process, described by Whitcomb (1970), where parcels of this cooler water break off and flow and mix seaward into the Slope Water.

For this report all figures have been annotated to show:

Shelf Water/Slope Water front - SSF
Shelf Water/Slope Water meander - SSFM
North wall of the Gulf Stream - GS
Anticyclonic warm core eddy - ACE
Gulf Stream meander - GSM
Flow direction - ⊗ into the page
- ⊙ out of the page

TRANSECT ANALYSIS

Locations of features are given in parentheses in kilometers from the 200-m isobath. Positive is seaward.

January. Unfortunately, the three January transects occurred in the latter part of the month, but still they are relevant in that they show the early beginning of the stratification which usually occurs in late February or early March.

The *Mormac Rigel* 76-01 (Fig. 14.1) crossed through the area during 24-25 January. This transect showed the normal isothermal water inshore with slight warming of surface waters offshore. The sea surface temperatures (SST's) ranged from <4C to >21C which were warmer than usual (on the inshore end of the transect) for that time of year. The Shelf Water/Slope Water front was crossed at station 3 (-65 km) and the north wall of the Gulf Stream was crossed between stations 4 and 5 (+160 km).

The USCGC *Dallas* 76-01 (Fig. 14.2) crossed through the area during 26-27 January (just after the *Mormac Rigel*). The *Dallas* section did not extend as far offshore as did the *Rigel* section, and therefore the SST's shown range only from <4C to >15C. Again the normal isothermal water structure was evident with a slight warming of the surface waters showing up, especially between stations 5 and 10 (-50 km to +75 km). The Shelf Water/Slope Water front was crossed between stations 6 and 7 (-15 km).

The *Lash Atlantico* 76-01 (Fig. 14.3) crossed through the area during 31 January-1 February. The SST's ranged from <5C to >14C. The nearshore water column structure was isothermal, while the offshore waters were beginning to show stratification. The subsurface warming (100 m) was probably due to Slope Water intruding up onto the shelf. The Shelf Water/Slope Water front was crossed between stations 12 and 13 (+15 km).

While it may not have been obvious from these three vertical sections, comparisons with the past eight years of Gulf Stream SST data[2] indicated that the January surface water temperatures were about 0.5C warmer than normal and that some evidence, at least in offshore waters, showed that surface stratification was beginning to develop early.

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[2] *The Gulf Stream Monthly Summary*, U.S. Naval Oceanographic Office, Vols. 4 through 9 (1969-1974); *gulfstream*, National Weather Service, Vols. I and II (1975-1976).

February. The USCGC *Bibb* 76-02 (Fig. 14.4) crossed through the area on 6 February. The SST's had increased, and ranged from <7C to >14C. Stratification had definitely set in over the shelf, with vertical temperature gradients as large as 0.4C/m at the thermocline. Patches of isothermal water extending to >100 m depth were still evident offshore. The Shelf Water/Slope Water front was crossed between stations 2 and 3 (+15 km).

The *Export Defender* 76-02 (Fig. 14.5) crossed through the area during 7-8 February. The SST's ranged from <3C to 16C. This was a rather complex section showing some return of cooling and some stratification. This on again off again cooling and warming is not uncommon for this area at this time of year. These perturbations in warming and cooling are probably caused by small-scale, short-lived forcing events, such as rapid frontal passings and reversals in wind direction that affect shallow coastal waters in a very complex fashion.

The Shelf Water/Slope Water front was crossed between stations 13 and 14 (+45 km) with a small meander (also visible in satellite imagery) in the front between stations 9 and 14 (-170 km to +45 km). The north wall of the Gulf Stream was crossed between stations 15 and 16.

The USCGC *Gallatin* 76-02 (Fig. 14.6) crossed through the area during 27-28 February. Unfortunately only surface values of temperatures and salinity were obtained, but from these data we could still determine the position of the Shelf Water/Slope Water front (between stations 7 and 8, -10 km) and an increase in SST's (<8C to >10C).

March. The *Mormac Rigel* 76-03 (Fig. 14.7) crossed through the area on 23 March. The SST's ranged from <7C to >19C. Stratification of the water column was well established, with surface to bottom temperature differences as large as 4C in <50 m depth. The Shelf Water/Slope Water front was crossed between stations 5 and 6 (-30 km).

April. The *Export Defender* 76-04 (Fig. 14.8) crossed through the area during 3-4 April. The SST's offshore had increased to >22C. The nearshore waters had warmed to greater than 7C, however, the stratification appeared weak in this transect. The Shelf Water/Slope Water front was crossed between stations 11 and 1 (+350 km). The north wall of the Gulf Stream was crossed between stations 18 and 19 (+640 km) with a Gulf Stream meander occurring between stations 13 and 16 (+420 km to +500 km). The distances indicated are so great because the ship's track ran parallel to and just offshore of the 200 m isobath. Subtracting about 330 km would give more reasonable distances.

The *Lash Atlantico* 76-04 (Fig. 14.9) crossed through the area during 24-25 April. The SST's ranged from >11C to 19C. This rather complex section showed a large cold cell of 7C water overlying a warm cell of >10C water (obviously of Slope Water origin) between stations 3 and 12 (-350 km to -85 km). The cell-like structure of the warm water was probably an artifact of the contouring in that the transect was run at an oblique angle to the Shelf Water/Slope Water front rather than perpendicularly. Thermal stratification (gradients up to 0.1C/m) was evident above the cold cell (upper 30 m). This section was further complicated by the presence of two Gulf Stream meanders (verified by satellite imagery) occurring between stations 16 and 18 (+45 km to +160 km) and 19 and 21 (+195 km to +280 km). The final crossing of the north wall must have occurred to the east of the end of this transect.

May. The *Mormac Rigel* 76-05 (Fig. 14.10) crossed through the area during 15-16 May. The SST's ranged from 11C to >19C in the Middle Atlantic Bight and increased to >25C south of Cape Hatteras. The cold cell consisted of multiple bubblelike structures that are probably an artifact of the contouring because of the highly oblique angle at which the cold cell was crossed on this transect. The Shelf Water/Slope Water front was crossed between stations 12 and 14, in about 50 m. A sharp thermal front occurred between stations 12 and 13 and a less sharp salinity front occurred between stations 13 and 14.

The *Delaware II* 76-05 (Fig. 14.11) crossed through the area during 17-24 May. The SST's ranged from slightly >12C to a little <14C across the whole section. The cold cell extended out to the shelf break and its minimum temperatures were <8C. The stratification was normal for that time of year with surface to thermocline differences as large as 4C in <100 m depth. The Shelf Water/Slope Water front was weak but discernible between stations 5 and 8 (+30 km).

June. The *Delaware II* 76-06 crossed through the area during 9-13 June. The SST's ranged from about 16C to 19C. The cold cell had moved shoreward to about the 75-m isobath with minimum temperatures still <8C. The Shelf Water/Slope Water front showed up between stations 5 and 6 (+20 km) as a weak subsurface thermal front. Stratification was fairly intense with surface to bottom temperature differences as large as 10C in <50 m depth.

July. The *Mormac Rigel* 76-05 (Fig. 14.13) crossed through the area during 6-7 July. The SST's had increased, and ranged from 22C to >27C. The cold cell was generally <8C and extended off the shelf break. The Shelf Water/Slope Water front apparently was crossed near station 41 (-95 km), well seaward of the 100-m isobath. Its location was uncertain, because no thermal structure was present to identify the front and it was arbitrarily located at the 34.5 o/oo surface isohaline. The stratification was intense, with surface to bottom temperature differences as large as 14C in <50 m depth and gradients >0.5C/m at the thermocline. The north wall of the Gulf Stream was crossed betweeen stations 36 and 37 (+240 km).

August. There was no SOOP transect during this month in the Middle Atlantic Bight.

September. The Mormac Rigel 76-09 crossed through the area during 1-2 September. The SST's had reached their peak and ranged from 20C to 28C. The cold cell was still well developed but had warmed; the volume of water <8C was much smaller than in July. The Shelf Water/Slope Water front was slightly seaward of the 200-m isobath (+5 km) and had a weak surface temperature signal. The 34.5 o/oo surface isohaline was again used to identify the front. The stratification was still strong with surface to bottom temperature differences as large as 10C in <50-m depth. The north wall of the Gulf Stream was crossed between stations 12 and 13 (+240 km).

October. The Lash Turkiye 76-10 (Fig. 14.15) crossed through the area during 7-8 October. The SST's ranged from <17C to >23C. The cold cell had a double bubble shape with the minimum temperature (<12C) occurring within the shoreward bubble and the warmer temperature (<13C) occurring within the seaward bubble. The Shelf Water/Slope Water front was crossed at station 7 (-300 km) and possibly again between stations 10 and 11 (-180 km). A Gulf Stream meander occurred at station 2 (+210 km) with the other half of the meander occurring just t the east of station 22 (+310 km).

The USCGC Gallatin 76-10 (Fig. 14.16) crossed through the are during 23-24 October. The SST's ranged from 14C to 20C. Th cold cell was quite eroded and had a double bubble shape agai with the shoreward bubble again having the lower temperatures below 11C on one station and generally <12C. The seaward bubbl was warmer, with minimum temperatures at least 1 deg higher tha those of the shoreward bubble. The Shelf Water/Slope Water fron was crossed between stations 7 and 8 (-20 km) and was shorewar of the 100 m isobath. At this time of year the thermal structur of the front was weak, and it was identified mostly by th 34.5 o/oo isohaline. Stratification had weakened considerably and the fall overturn was in progress.

November. The Lash Turkiye 76-10 (Fig. 14.17) crossed throug the area during 17-18 November. The SST's ranged from 11C t 20C. The Shelf Water/Slope Water front was crossed betwee stations 35 and 34 (-0 km), and had a weak thermal signature. A anticyclonic eddy was crossed between stations 26 and 23 (+310 k to +420 km) with the north wall of the Gulf Stream being to th east of the end of the transect. The fall overturn had mixed away all thermal stratification over the shelf. The water column was nearly isothermal, ranging from 11C on the shelf to 14C just off the shelf.

December. The USCGC *Bibb* 76-11 (Fig. 14.18) crossed through the area during 4-5 December. The SST's ranged from <9C to >20C. The cold cell had eroded away with the overturn and the Shelf Waters were isothermal, ranging from 10C on the inner shelf to 12C on the outer shelf. The Shelf Water/Slope Water front was evident between stations 29 and 28 (+55 km) with a fairly strong thermal front. The north wall of the Gulf Stream was crossed at station 15 (+450 km). This distance is overly large because the transect paralleled the continental shelf.

The USCGC *Gallatin* 76-12 (Fig. 14.19) crossed through the area on 21 December. The SST's ranged from >7C to <16C. The Shelf Waters were isothermal, ranging from 9C to 11C (onshore to offshore). The Shelf Water/Slope Water front was crossed between stations 4 and 5 (-10 km), and had a strong thermal signature.

SUMMARY

Water temperatures in the Middle Atlantic Bight in 1976 generally followed normal trends for most of the year. However, two anomalous conditions arose during late winter and early spring. During late winter the SST's averaged about 0.5C warmer than usual. During spring the nearshore surface salinities were greatly reduced. Sometimes these reduced surface salinities extended beyond the Shelf Water/Slope Water front with values of <28 o/oo.

A combination of the high river discharge in spring coupled with slightly increased surface temperatures led to earlier than usual stratification in the nearshore zone.

The offshore waters (at the shelf break and beyond) followed the normal trends of warming and cooling in both intensity and duration. Even the passage of hurricane Belle did little to interrupt the normal seasonal warming.

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WHITCOMB, V. L.
1970. Oceanography of the mid-Atlantic Bight in support of ICNAF, September-December 1967. U.S. Coast Guard Oceanogr. Rep. CG 373-35, 157 p.

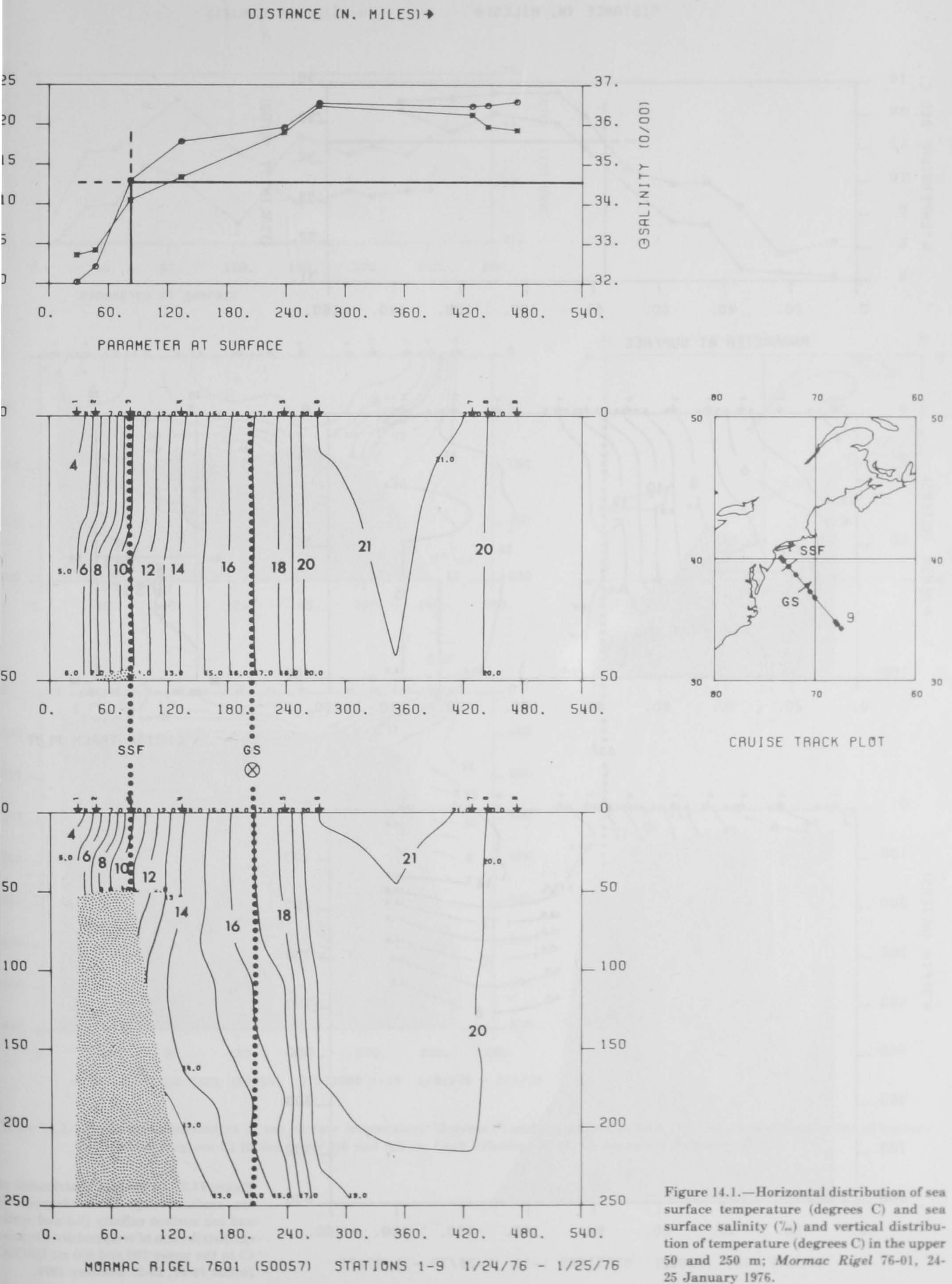


Figure 14.1.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 50 and 250 m; *Mormac Rigel* 76-01, 24-25 January 1976.

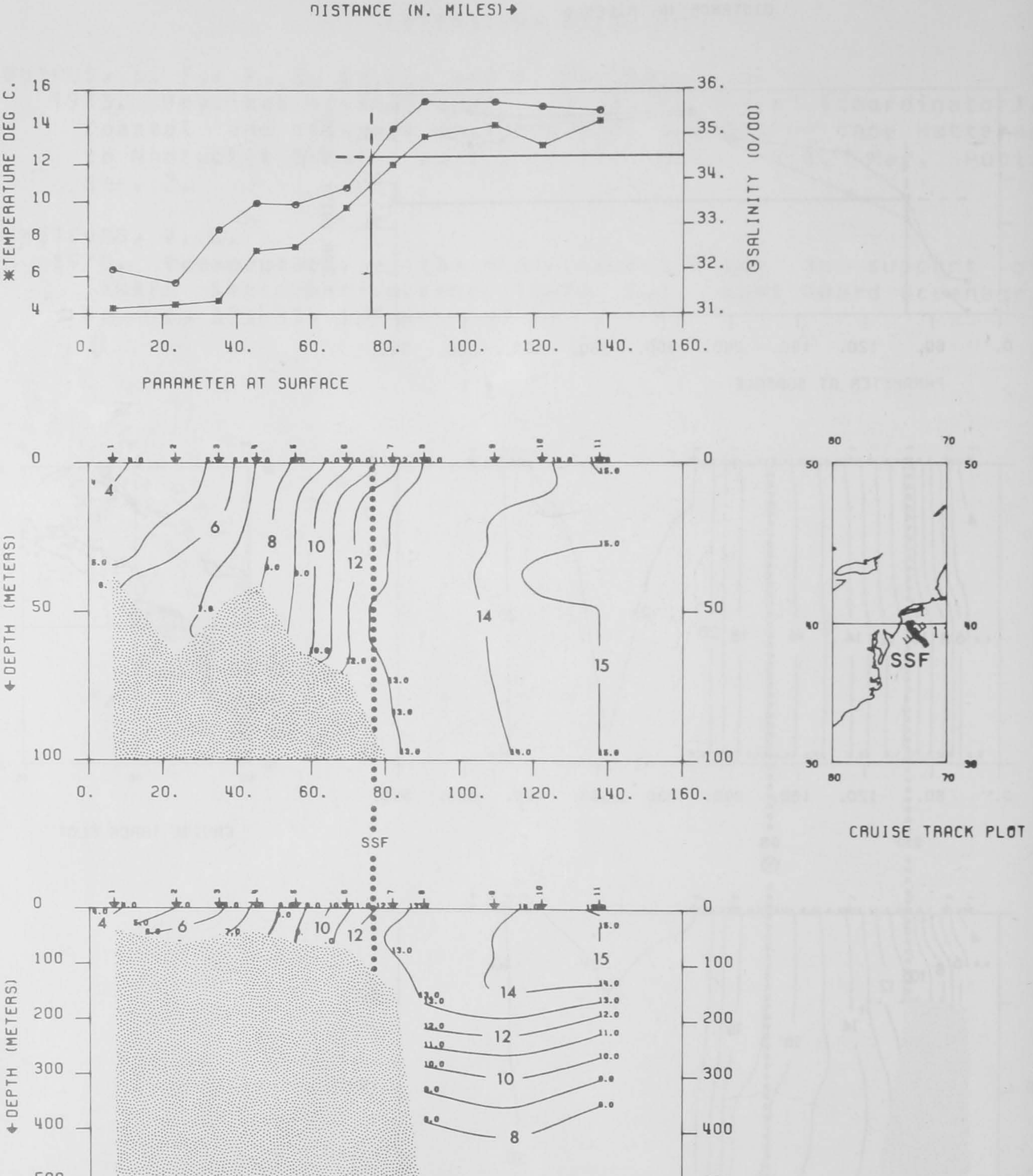
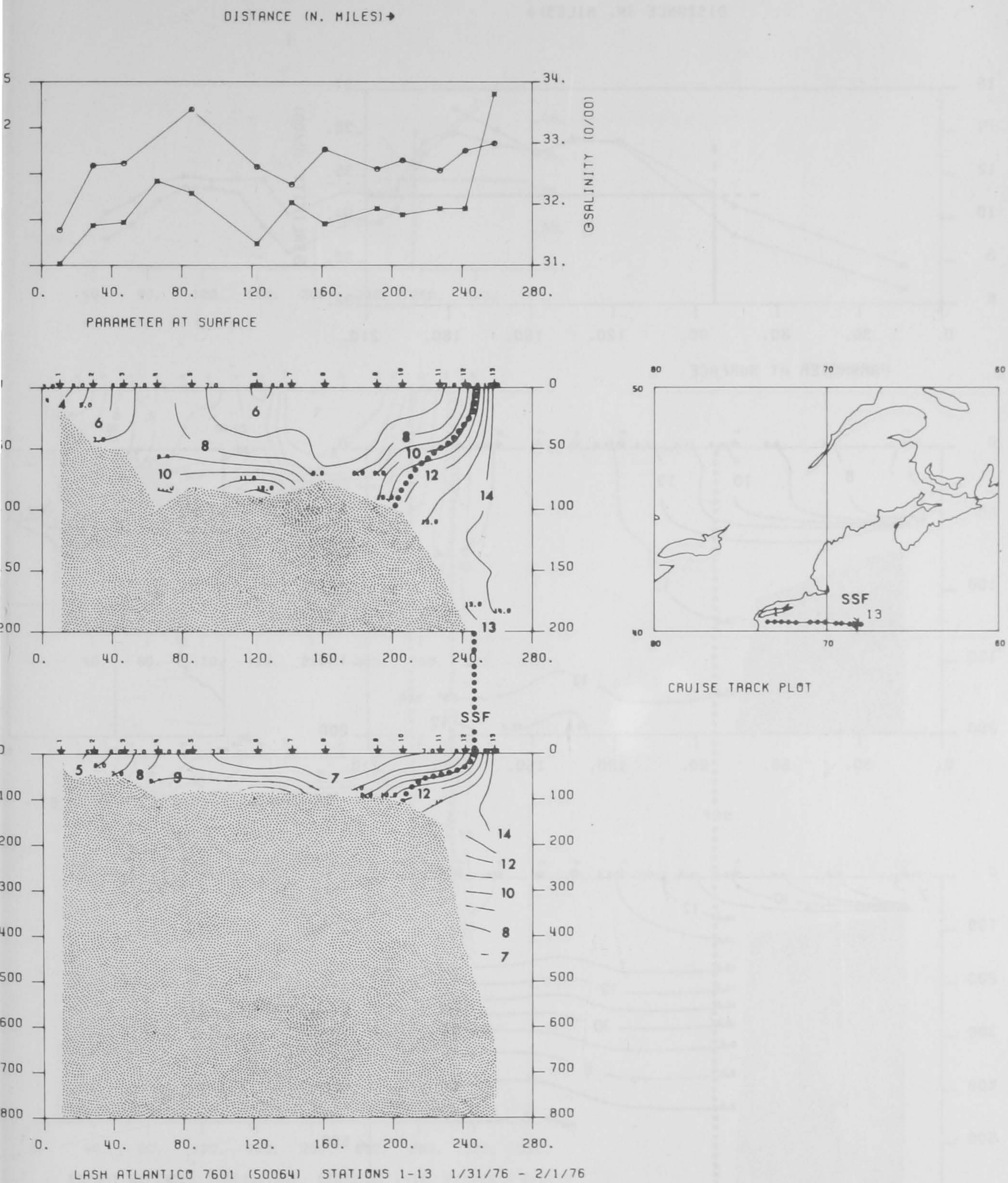


Figure 14.2.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 100 and 800 m; USCGC *Dallas* 76-01, 26-27 January 1976.



igure 14.3.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 200 and 800 m; *Lash Atlantico* 76-01, 31 January-1 February 1976.

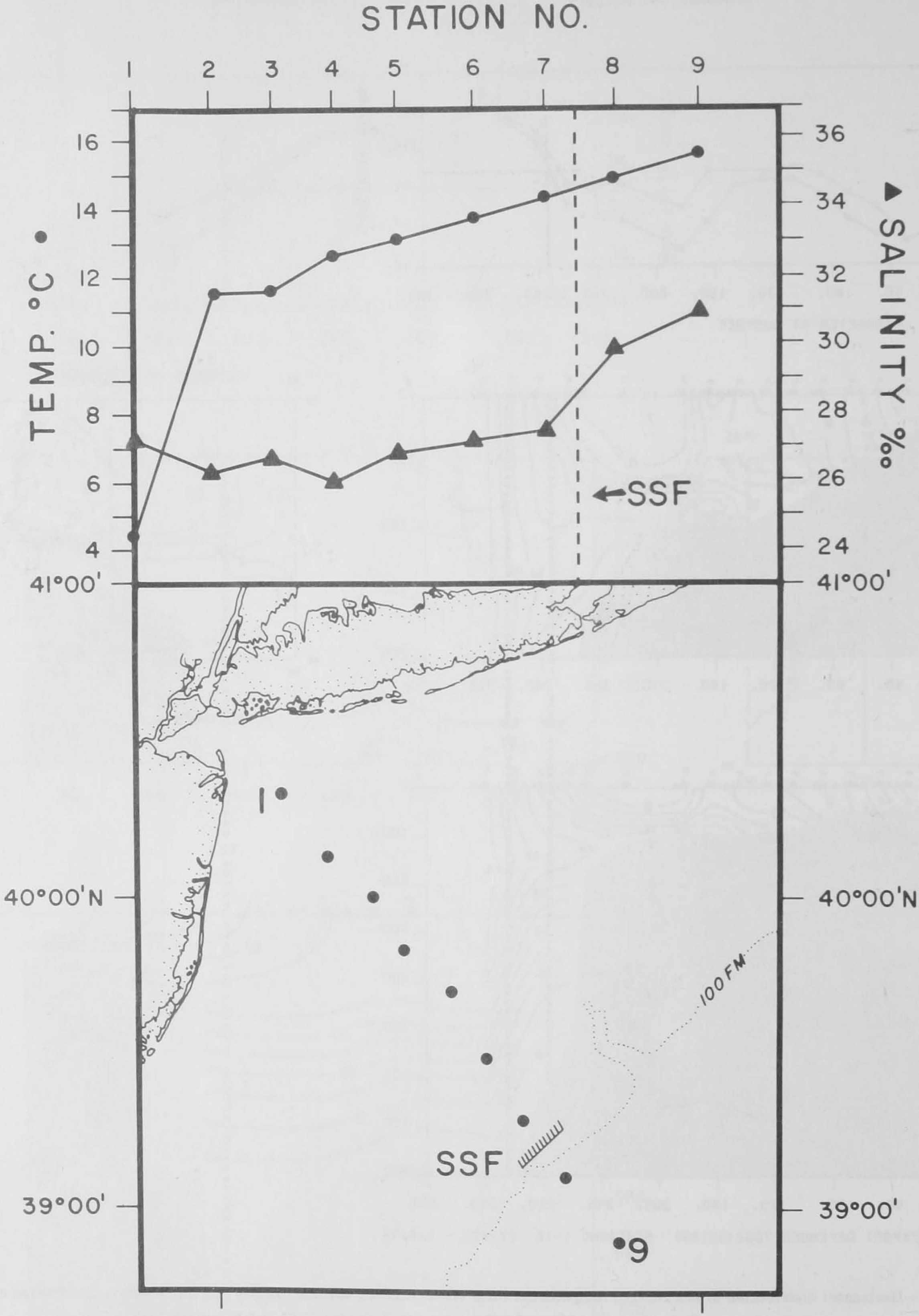
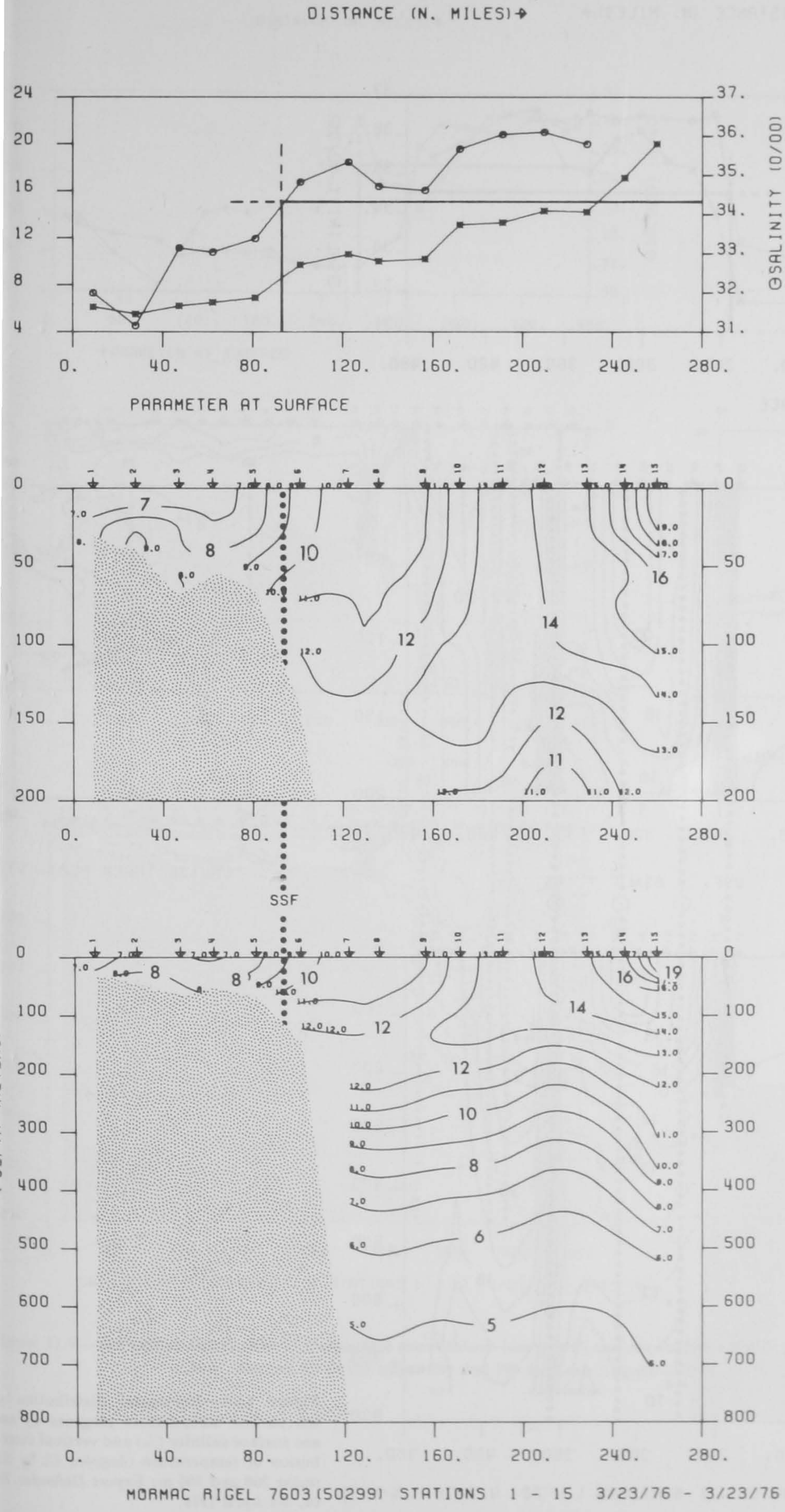


Figure 14.6.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰); USCGC *Gallatin* 76-02, 27-28 February 1976.



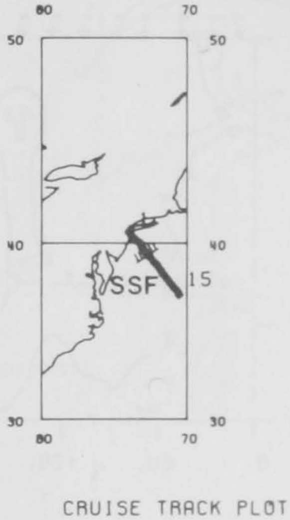


Figure 14.7.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 200 and 800 m; *Mormac Rigel* 76-03, 23 March 1976.

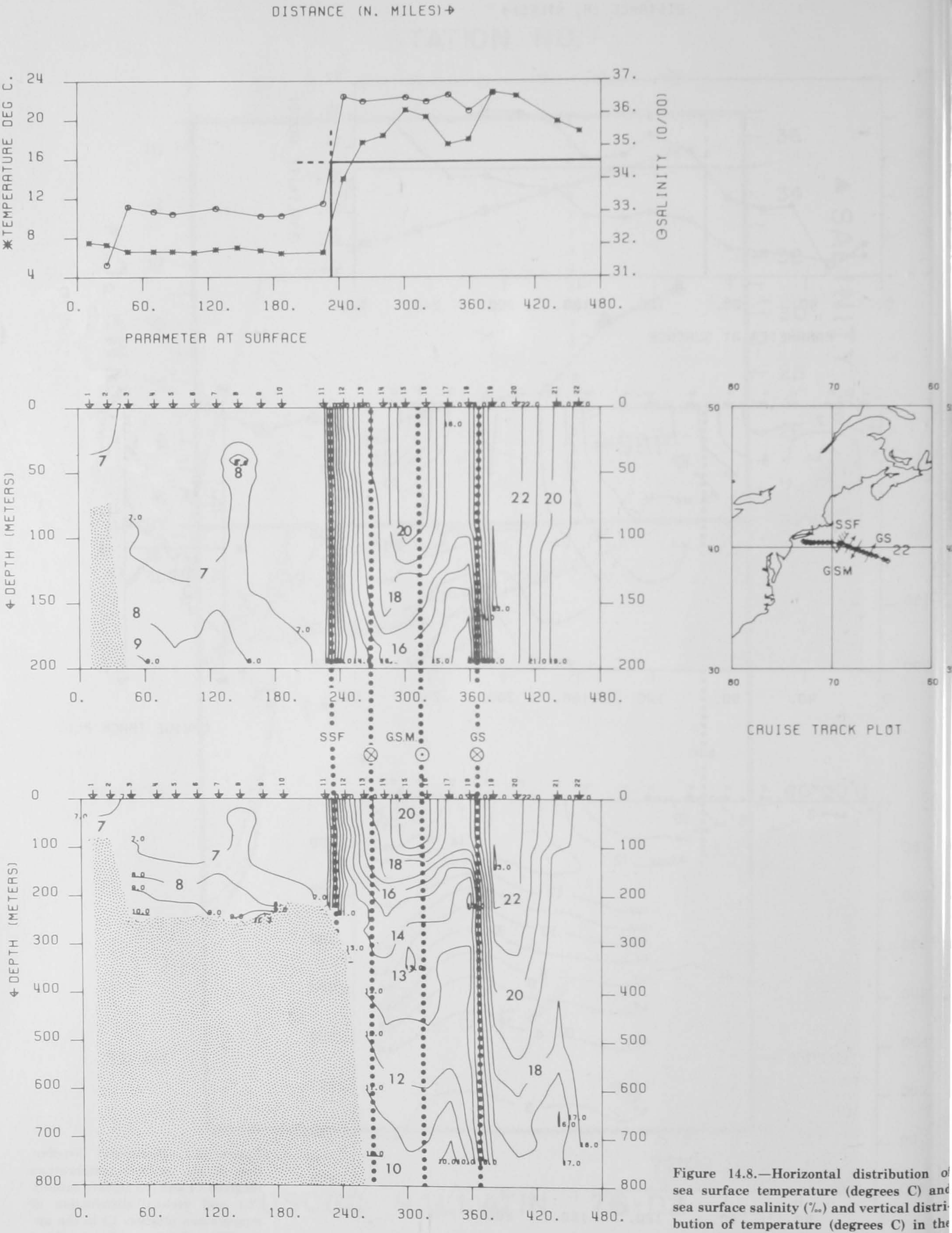


Figure 14.8.—Horizontal distribution o sea surface temperature (degrees C) an sea surface salinity (‰) and vertical distribution of temperature (degrees C) in th upper 200 and 800 m; *Export Defender* 76 04, 3-4 April 1976.

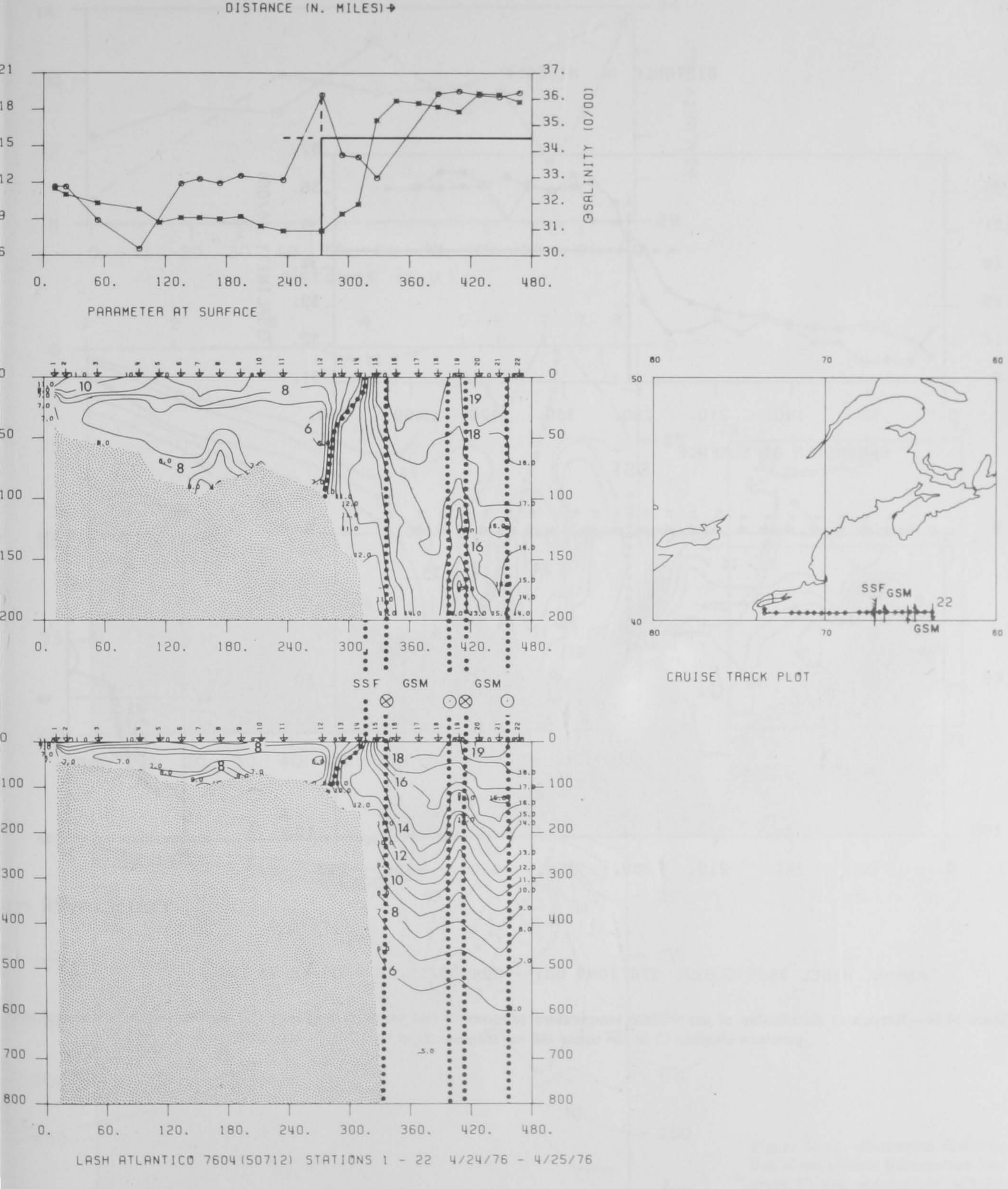


Figure 14.9.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 200 and 800 m; *Lash Atlantico* 76-04, 24-25 April 1976.

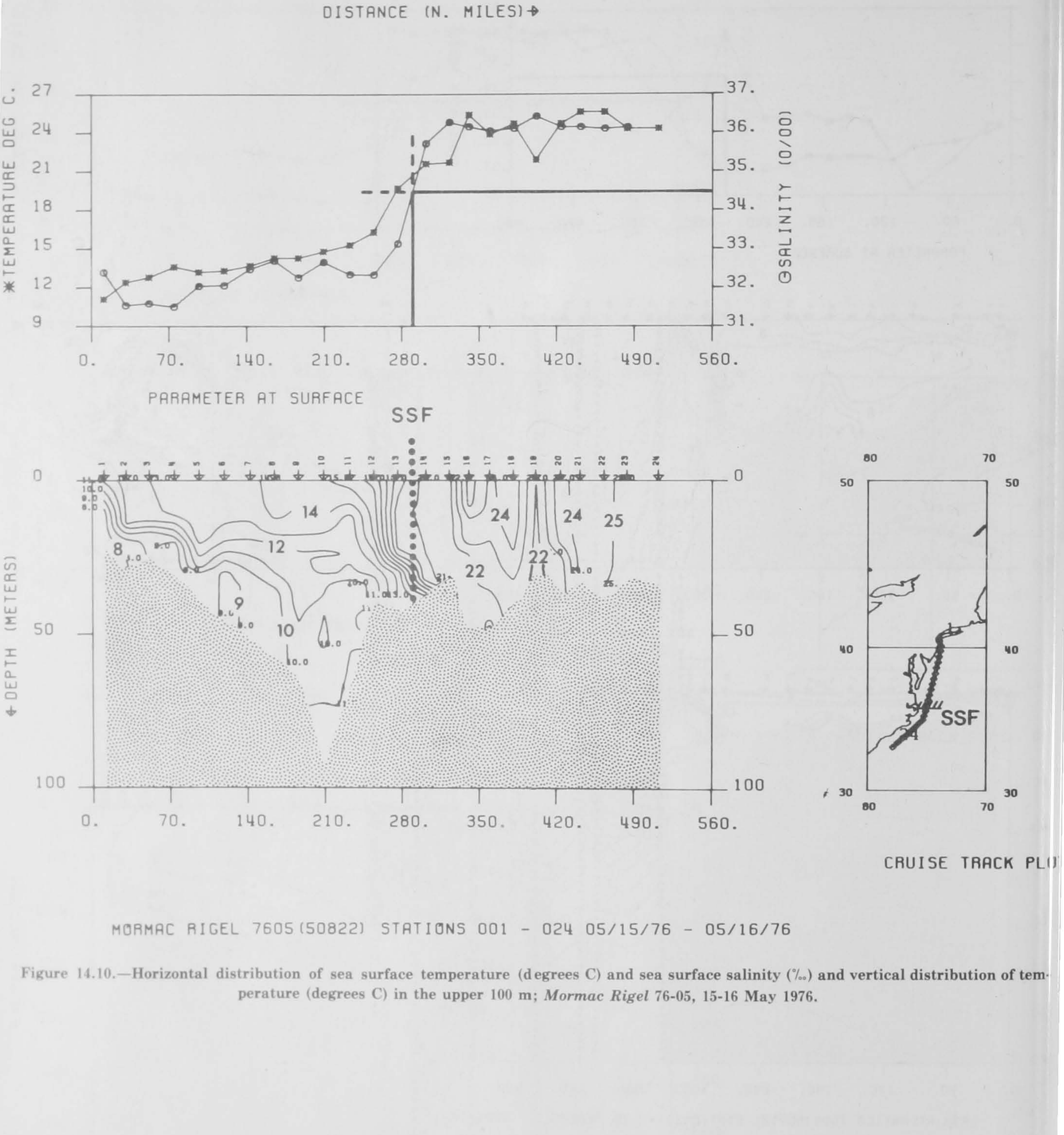


Figure 14.10.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 100 m; *Mormac Rigel* 76-05, 15-16 May 1976.

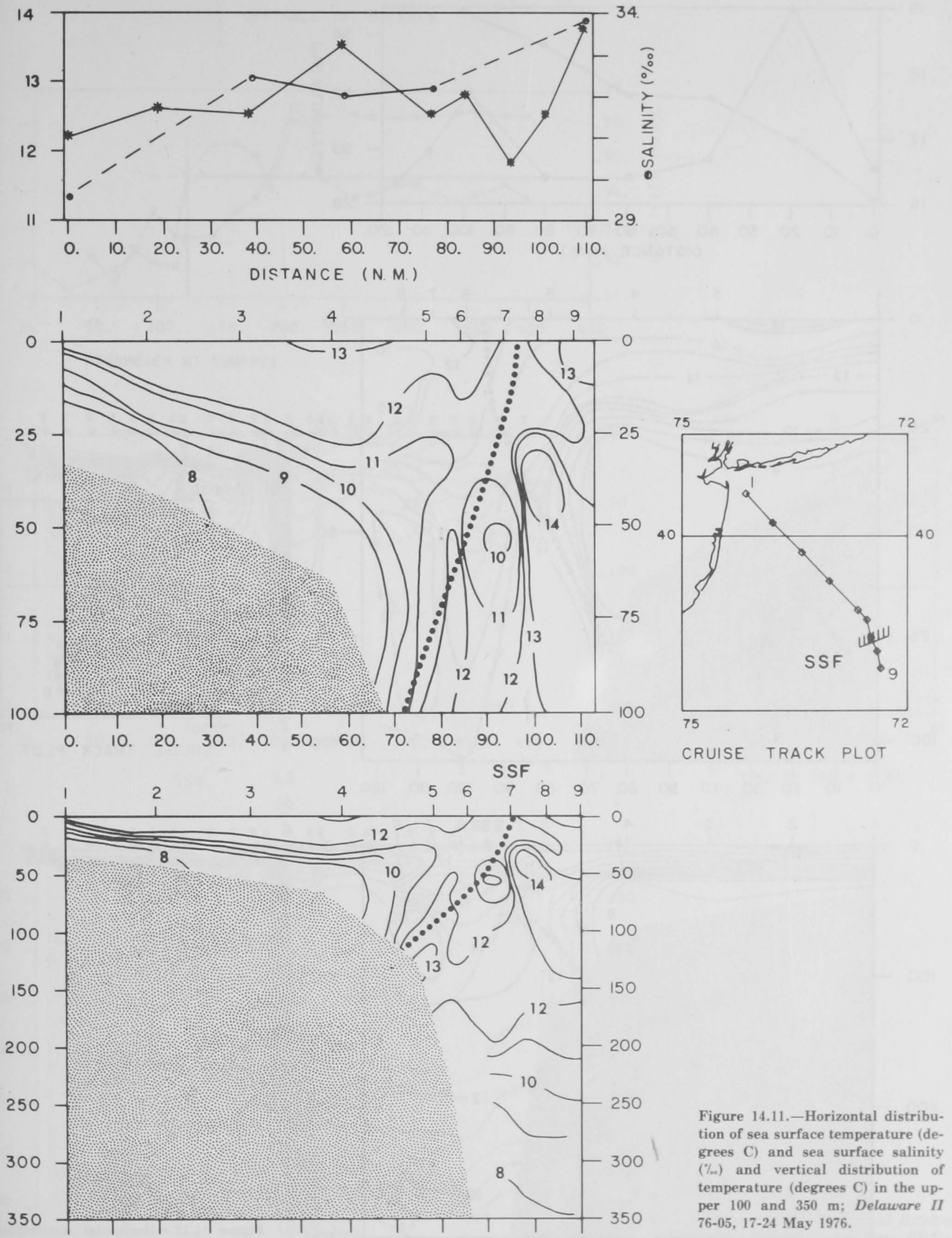


Figure 14.11.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 100 and 350 m; *Delaware II* 76-05, 17-24 May 1976.

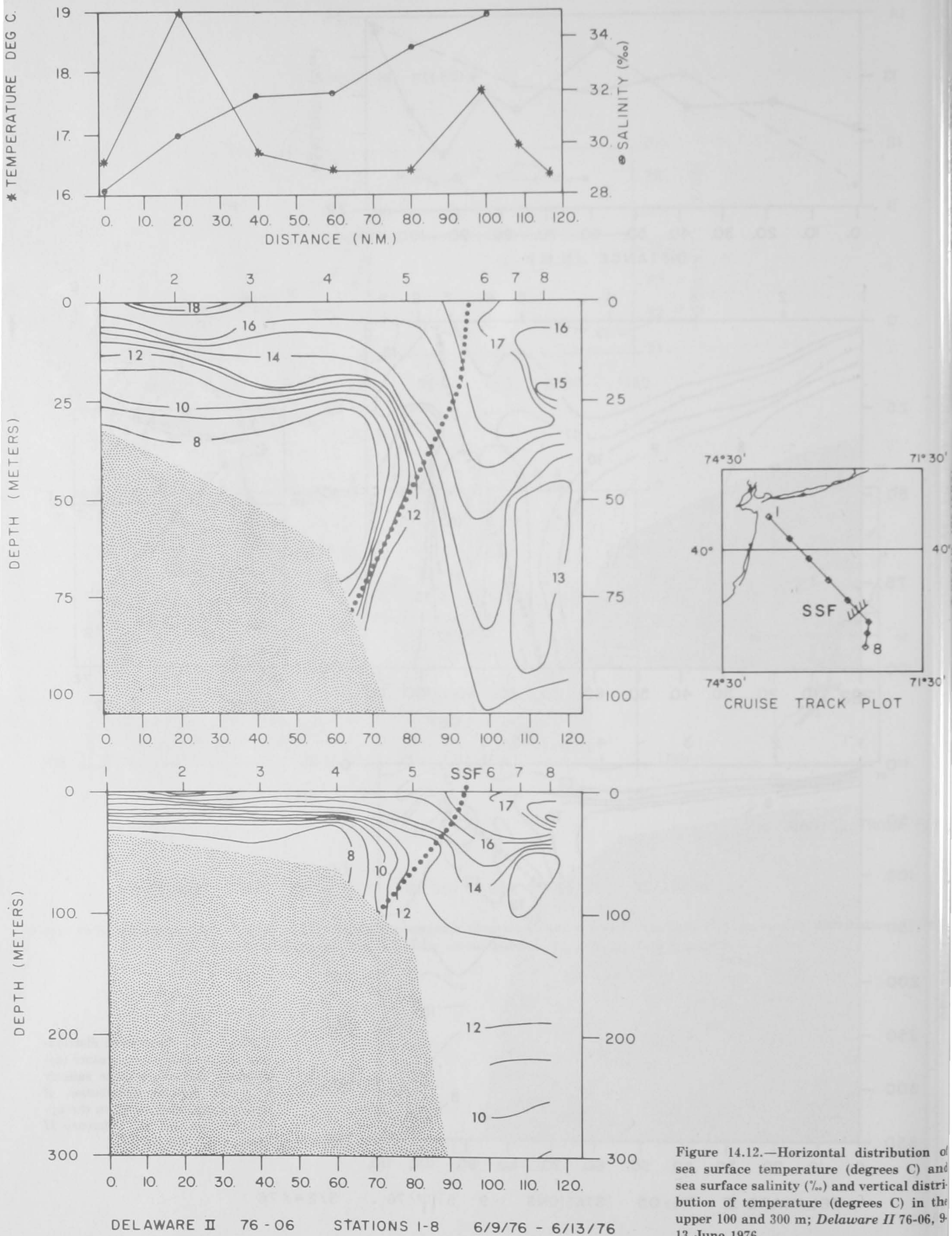


Figure 14.12.—Horizontal distribution o sea surface temperature (degrees C) an sea surface salinity (‰) and vertical distribution of temperature (degrees C) in th upper 100 and 300 m; *Delaware II* 76-06, 9-13 June 1976.

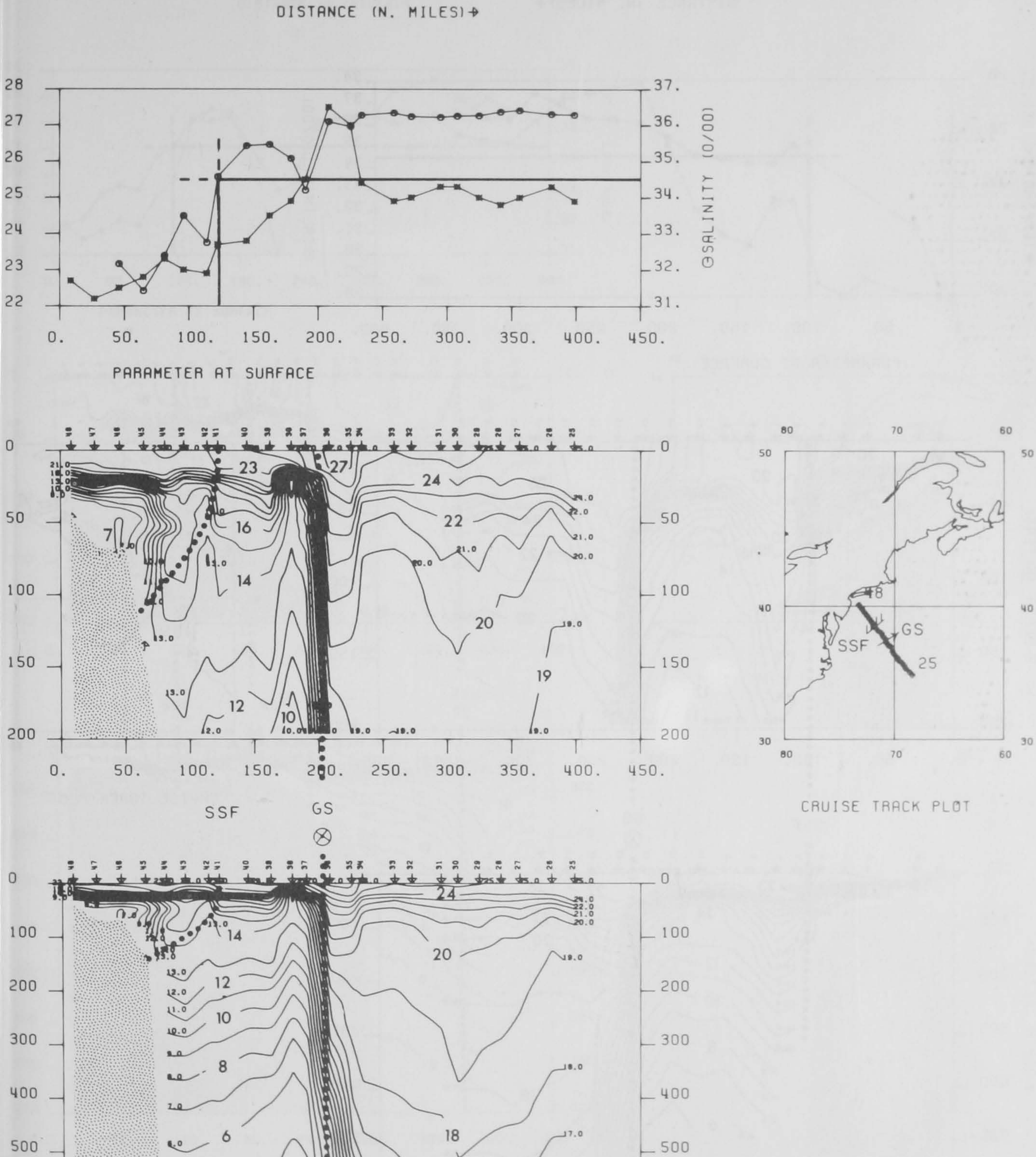
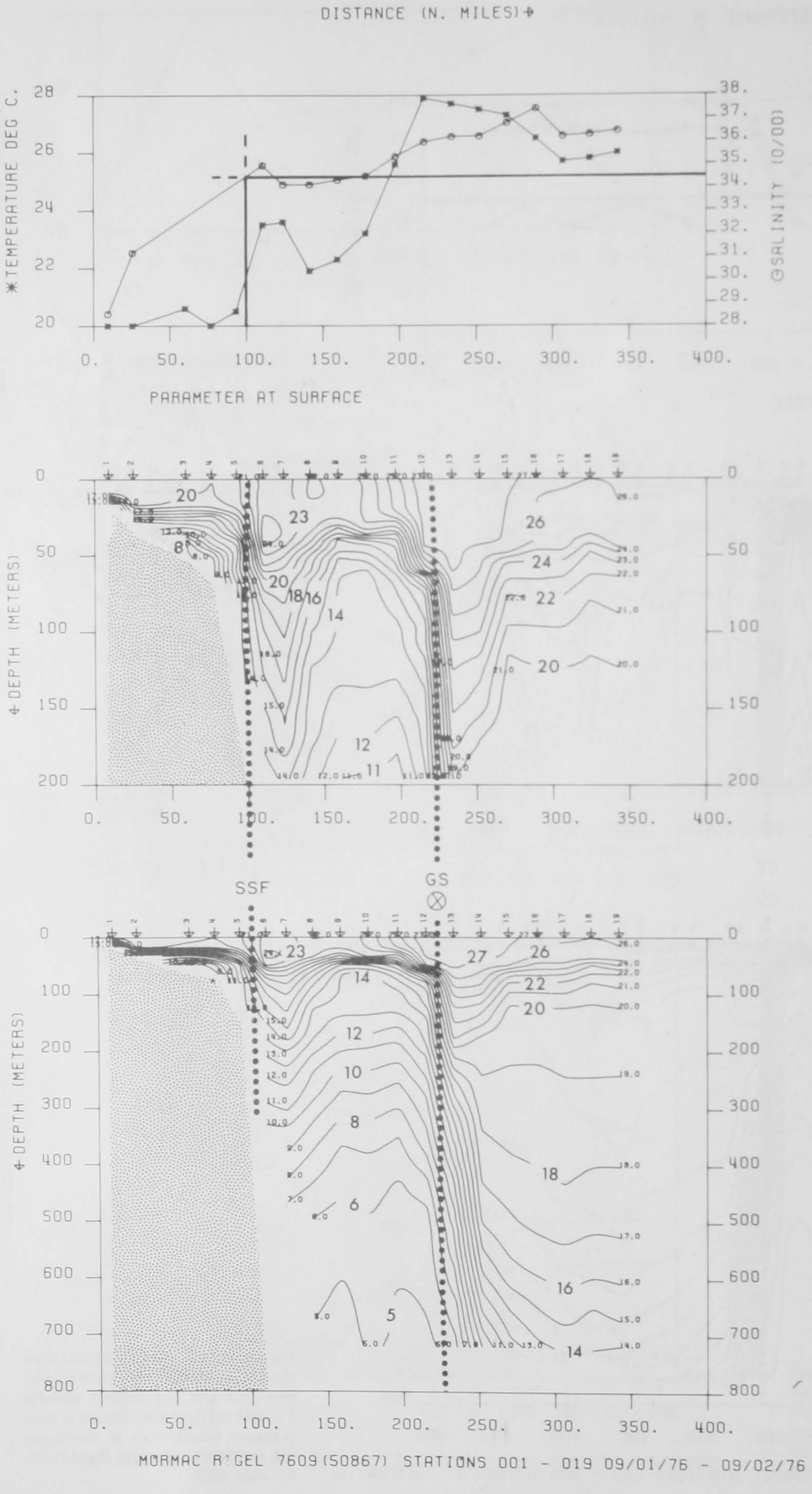


Figure 14.13.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 200 and 800 m; *Mormac Rigel* 76-05, 6-7 July 1976.



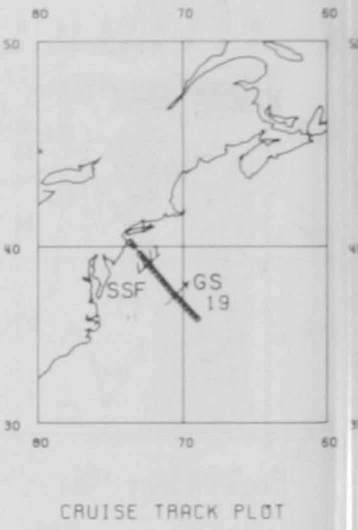


Figure 14.14.—Horizontal distrib
tion of sea surface temperature (d
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temperature (degrees C) in the u
per 200 and 800 m; *Mormac Rig*
76-09, 1-2 September 1976.

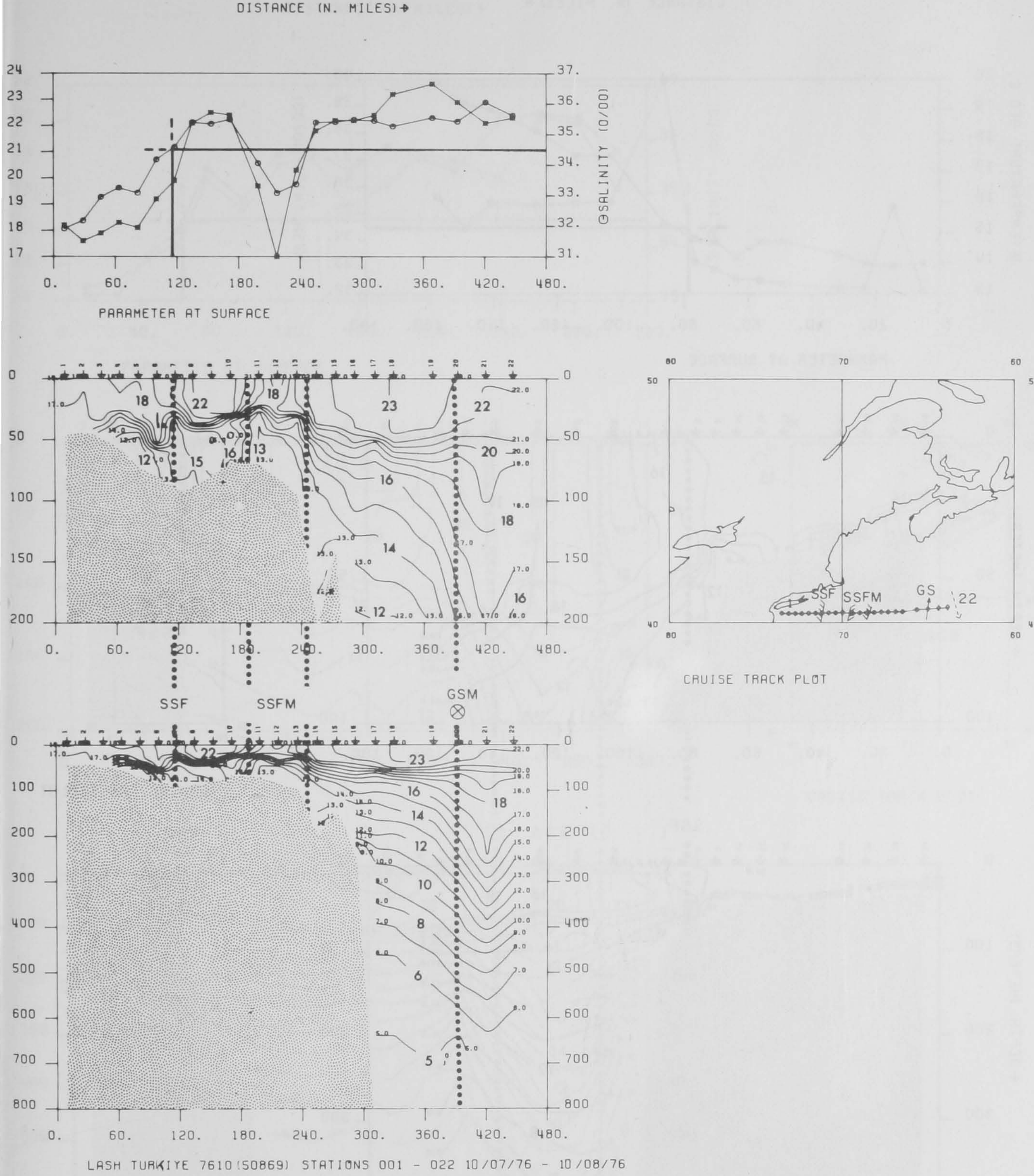

Figure 14.15.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 200 and 800 m; *Lash Turkiye* 76-10, 7-8 October 1976.

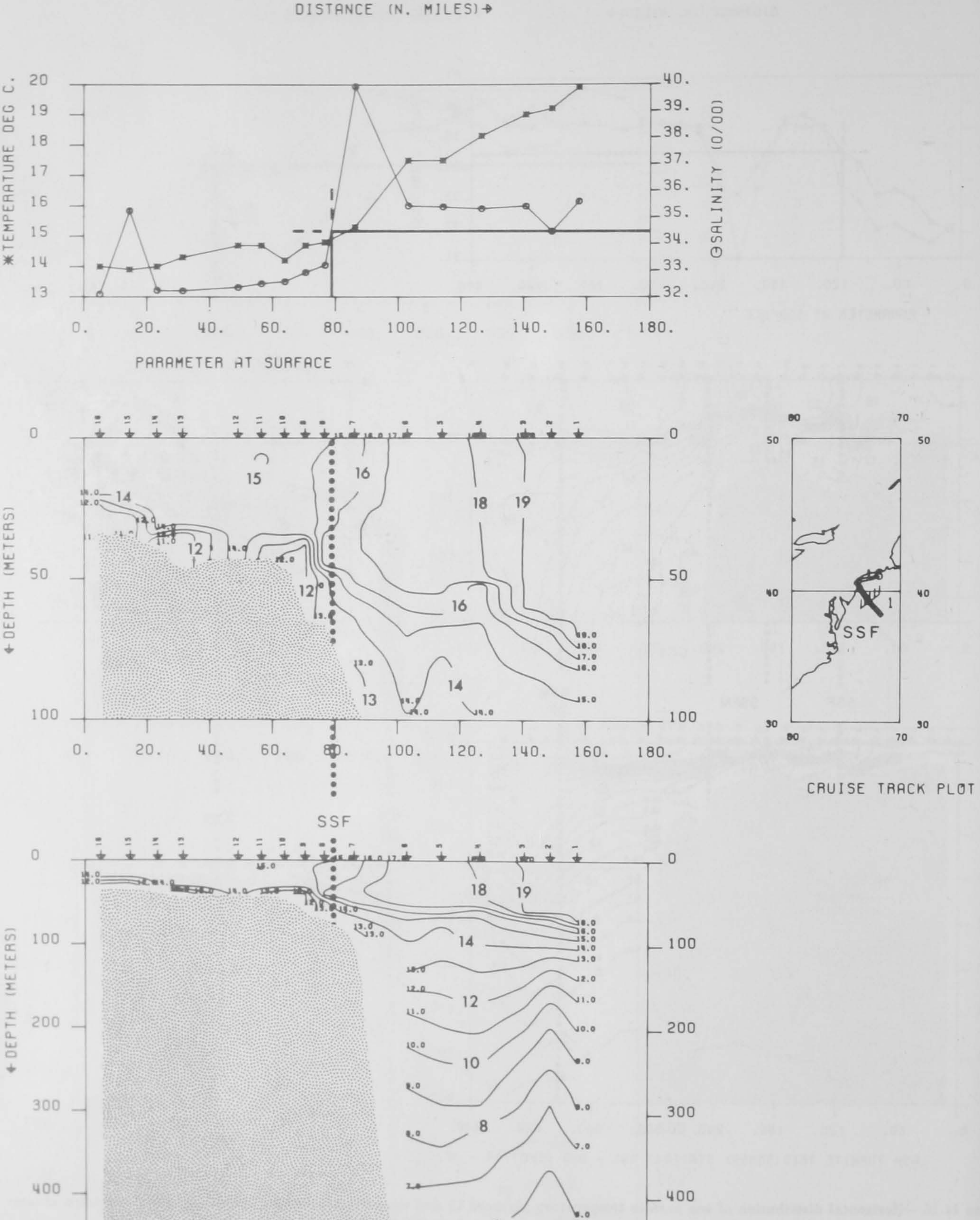

Figure 14.16.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 100 and 500 m; USCGC *Gallatin* 76-10, 23-24 October 1976.

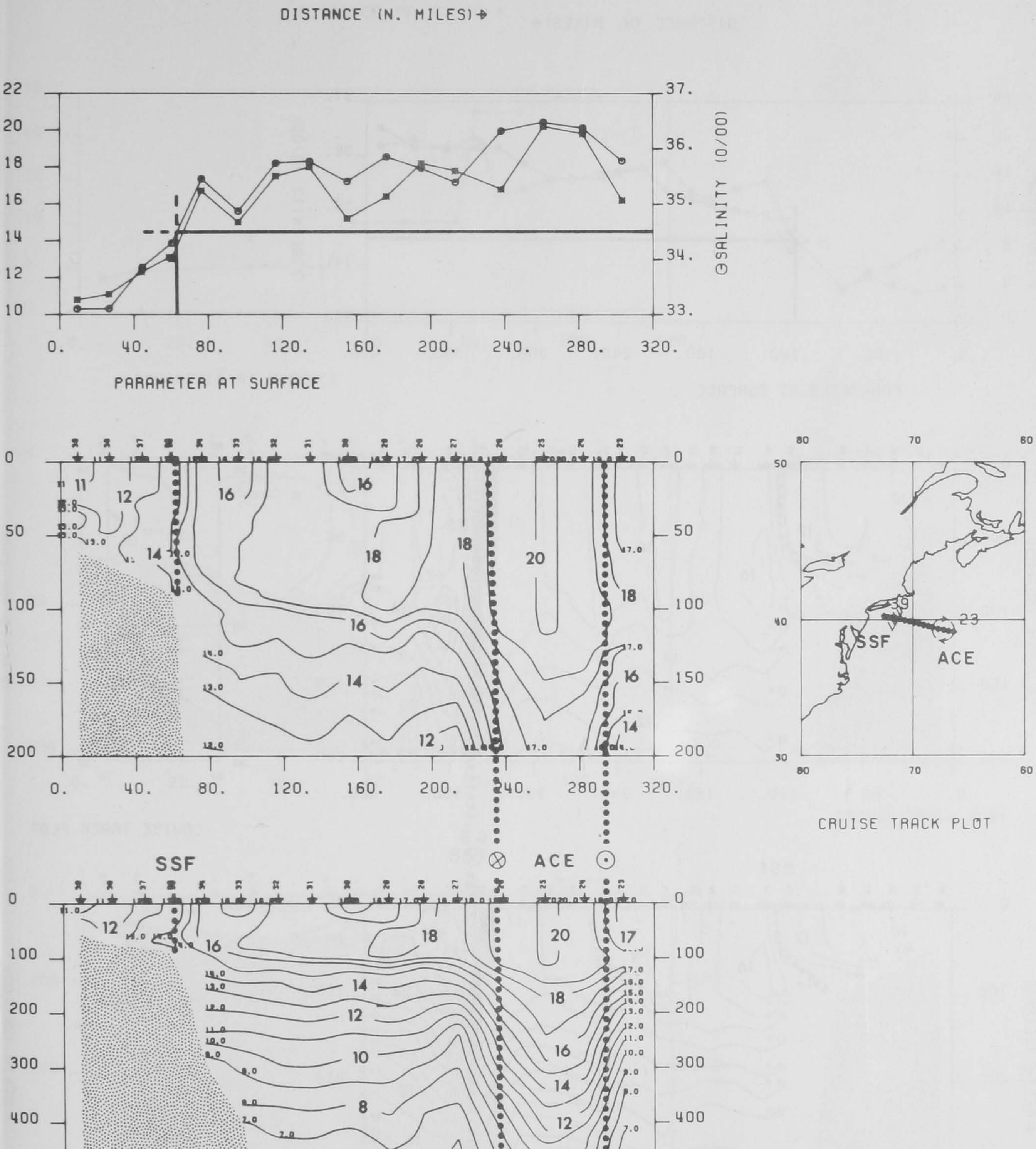

Figure 14.17.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 200 and 800 m; *Lash Turkiye* 76-10, 17-18 November 1976.

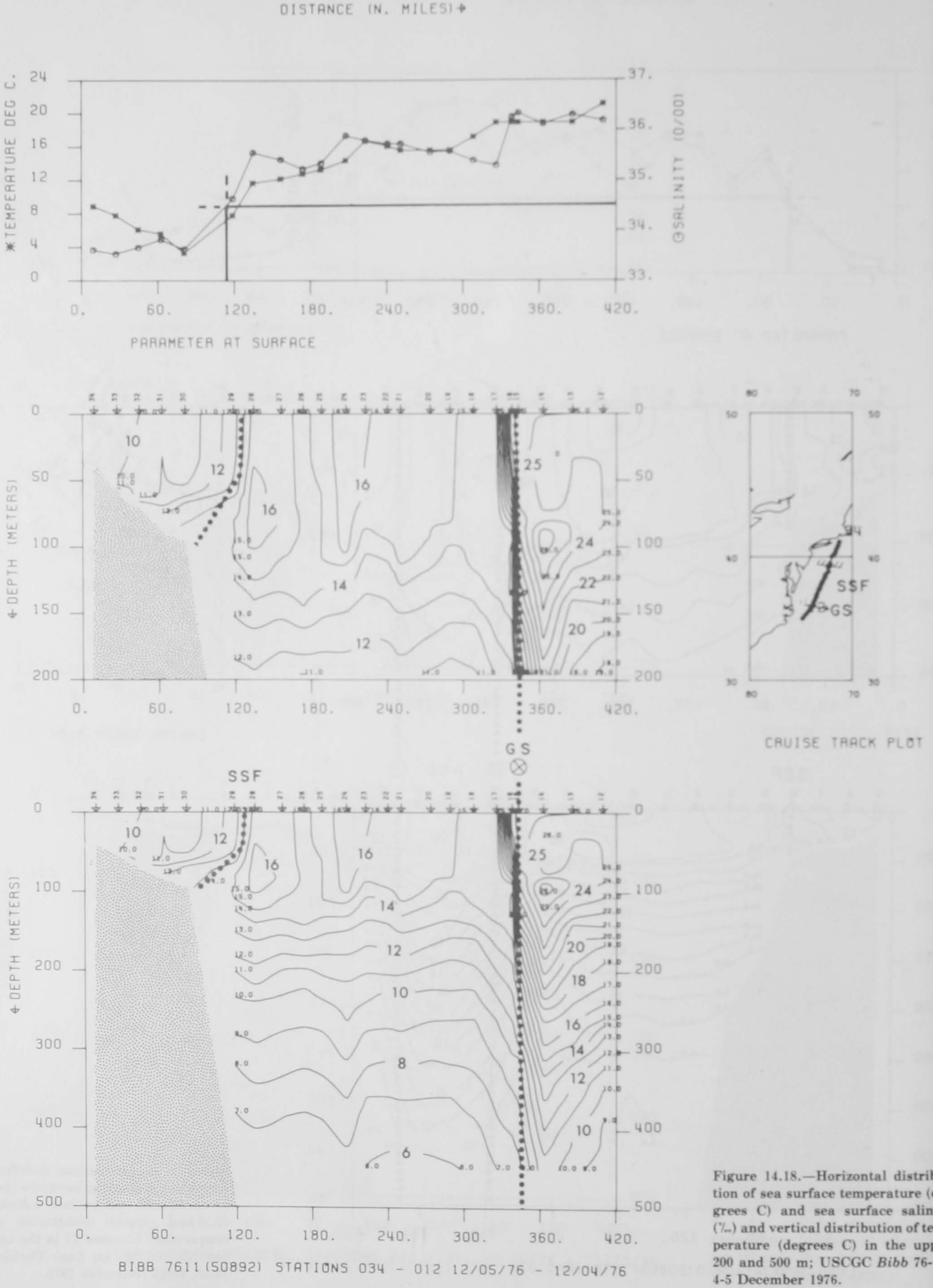

Figure 14.18.—Horizontal distribution of sea surface temperature (degrees C) and sea surface salinity (‰) and vertical distribution of temperature (degrees C) in the upper 200 and 500 m; USCGC *Bibb* 76-11, 4-5 December 1976.

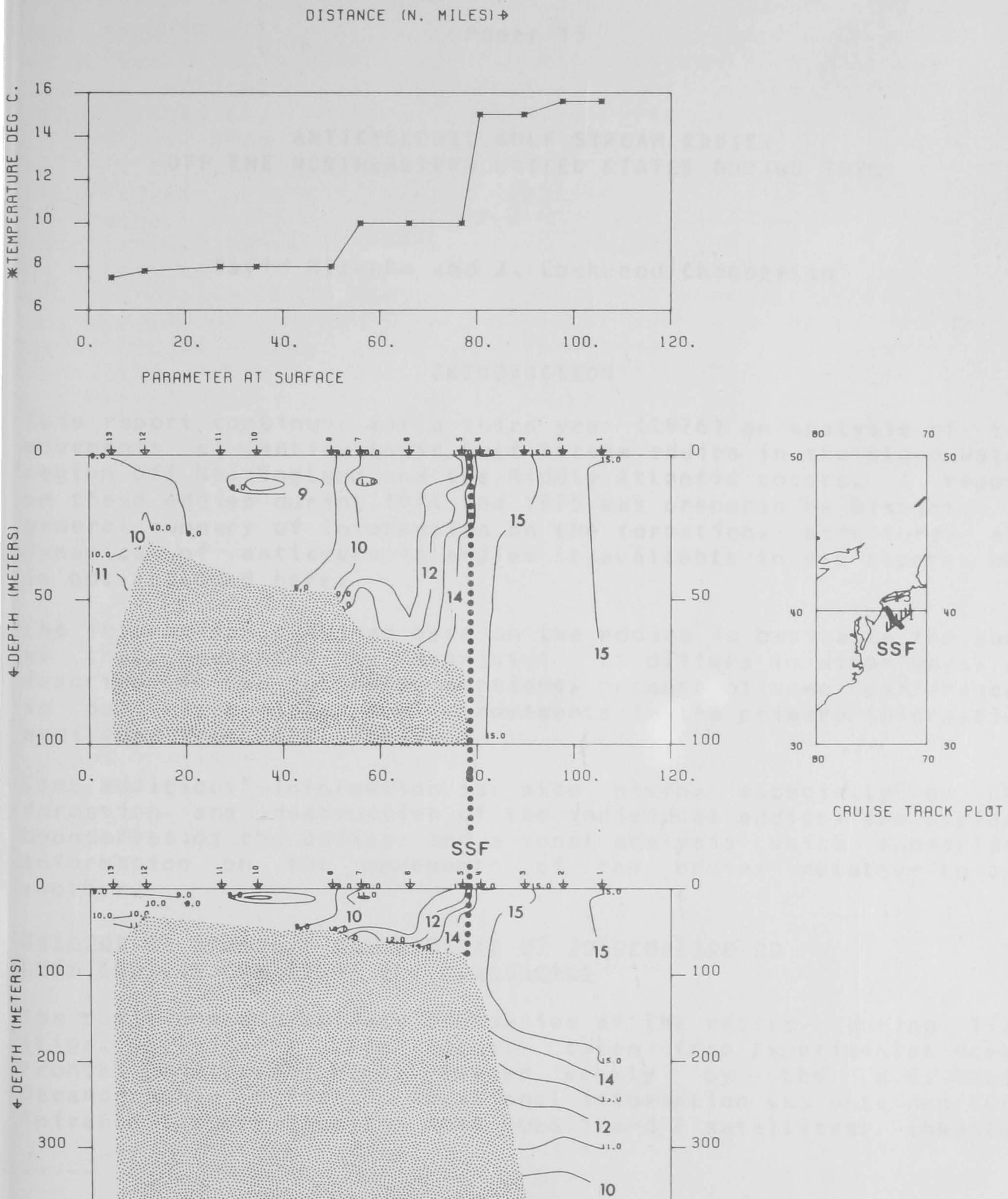

Figure 14.19.—Horizontal distribution of sea surface temperature (degrees C) and vertical distribution of temperature (degrees C) in the upper 100 and 500 m; USCGC *Gallatin* 76-12, 21 December 1976.

Paper 15

ANTICYCLONIC GULF STREAM EDDIES OFF THE NORTHEASTERN UNITED STATES DURING 1976

David Mizenko and J. Lockwood Chamberlin[1]

INTRODUCTION

This report continues for a third year (1976) an analysis of the movements of anticyclonic Gulf Stream eddies in the Slope Water region off New England and the Middle Atlantic coasts. A report on these eddies during 1974 and 1975 was prepared by Bisagni. A general summary of information on the formation, structure, and dynamics of anticyclonic eddies is available in his report, and is not included here.

The information provided here on the eddies is basically the same as that presented by Bisagni.[2] It differs in minor ways, as described in the following sections, because of some differences in our methodology and improvements in the primary information available from satellites.

Some additional information is also given, especially on the formation and destruction of the individual eddies, the surface boundaries of the eddies, and a zonal analysis which summarizes information on the movements of the eddies relative to one another.

Methods of Analysis and Sources of Information on Eddy Surface Positions and Boundaries

The positions and surface boundaries of the eddies, during 1976 (Figs. 15.1-15.7), were largely taken from Experimental Ocean Frontal Analysis charts issued weekly by the U.S. Naval Oceanographic Office. Additional information was obtained from infrared imagery from the NOAA GOES 1 and 2 satellites, enhanced

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[1] Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

[2] Bisagni, J. J. 1976. The passage of anticyclonic Gulf Stream eddies through Deepwater Dumpsite 106, 1974-1975. NOAA Dumpsite Evaluation Report 76-1, 39 p.

for sea surface temperature (about 6 to 8 images available per day), and the Experimental Gulf Stream Analysis, issued weekly by the National Environmental Satellite Service. For the special analysis of the February-April period, NOAA-4 satellite imagery was also used.

Positions based on imagery that clearly shows the surface boundaries of the eddies are drawn with solid lines; uncertain positions from unclear imagery are drawn with dashed lines. The dots (Figs. 15.1-15.7) are the centers of the eddies as estimated by eye from the surface boundaries. Surface boundaries are only shown for representative states in the lifetimes of the eddies. Both the positions and boundaries should be regarded as rough approximations, because the surface expressions of the eddies in the imagery are often distortions of the subsurface structure.[3] Potocsky (1976) has pointed out that eddies entraining Shelf Water may appear much smaller in satellite imagery than is indicated by the subsurface structure, and that this distortion is most frequent west of 70W.

Eddies that made surface contact with the Gulf Stream were still regarded as eddies, so long as it appeared from the imagery that their circulation was largely separate from that of the Stream. In the Experimental Ocean Frontal Analysis, eddies which later made such contact were labeled as meanders.

While the methods used here are basically similar to those of Bisagni (see footnote 2), there are some important differences in detail. On his "trajectory" maps, Bisagni shows all positions, sure and estimated, from several sources. We have avoided plotting estimated positions except where long time gaps exist between sure positions, and have given only one position for an eddy on any given date.

Though similar data sources were used, their quality has improved markedly since the period 1974-75 studied by Bisagni. This is especially true of the Experimental Ocean Frontal Analysis charts, which during 1974 lacked the detail, accuracy, and documentation which has since been incorporated--especially during 1976. This improvement has allowed more accurate data to be presented here than was available to Bisagni.

The dates of eddy formation and destruction were interpolated when necessary. For example, if a feature was clearly a Gulf Stream meander on 15 October and an eddy on 19 October, it is

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[3] Chamberlin, J. L. 1977. Monitoring effects of Gulf Stream meanders and warm core eddies on the continental shelf and slope. Int. Comm. Northwest Atl. Fish., Sel. Pap. 2:145-153.

assumed to have detached from the Gulf Stream as an eddy on 17 October. These interpolations are accurate to within a week or less. Bisagni used the dates an eddy was first sighted and last sighted as his formation and destruction dates, making his estimates of eddy lifetimes a little shorter (on the order of a week) than would be obtained by our method. Infrared imagery from the Geostationary Orbiting Environmental Satellites at 3-h intervals, which Bisagni did not have available, was very useful for establishing such dates.

Only eddies that were observed west of 60W are considered in this report. These are labeled by the year in which they formed plus a sequentially assigned letter. The dates of their formation and destruction, and the number of days they survived, are summarized in Table 15.1.

Table 15.1.--Summary of estimated eddy formation and destruction dates and days of survival.

Eddy	Dates	Days	Days in 1976
75E	7/23/75 - 3/27/76	248	87
75I	11/1/75 - 3/17/76	137	80
76A	2/27/76 - 3/30/76	37	32
76B	4/1/76 - ?	>90	>90
76C	4/19/76 - 10/15/76	179	179
76D	5/20/76 - 2/4/77	260	225
76E	5/28/76 - 7/24/76	57	57
76F	10/15/76 - 2/4/77	112	77
76G	10/27/76 - 5/13/77	198	65
	Total eddy-days in 1976:		>892

Date first observed (see text footnote 2).
Subject to revision.
May have survived into August.
Totals by quarter:

Jan-Mar	199
Apr-Jun	236
Jul-Sep	208
Oct-Dec	249

(See also Bisagni 1978).

EDDY HISTORIES - 1976

Two eddies survived 1975 into 1976 (75E and 75I). Eddy 75E (Fig. 15.1), first observed on 23 July 1975 (Bisagni's ACE-10), was off southern Delaware with an apparent surface diameter of about 40 nm (70 km) at the start of 1976. An expendable bathythermograph (XBT) survey on 18 February and 19 revealed a maximum core temperature of 13C extending to nearly 300 m depth (Cook et al. 1976). This eddy coalesced with the Gulf Stream about 27 March.

Eddy 75I (Fig. 15.2), which formed in early November 1975, was not apparent in satellite imagery after the latter part of that month for two months until the end of January 1976, when it was located at 66W with an apparent surface diameter of 90 nm (170 km). After moving southwest about 100 nm (190 km) to the vicinity of 68W, the eddy appeared to be largely destroyed, about 17 March, by encroachment of a Gulf Stream meander (Figs. 15.8b and 15.8c). About 1 April, part of this meander appeared to have detached from the Stream as another eddy (76B), indicated as an extensive patch of Gulf Stream water at 67W30' on 7 April (Fig. 15.8e). Another possible interpretation of the imagery is that eddy 75I was not destroyed during March and that eddies 76B and 75I are the same.

An XBT section from *Albatross IV* on 2-3 April (line AB in Fig. 15.9) in the area of the warm patch indicates anticyclonic circulation, especially in the form of the isotherms for 12C and colder, but because of the section's placement, does not determine the feature as a meander or eddy, although the thermal structure does show a surface connection with the Gulf Stream. The very steep thermal gradient at the inshore margin of the eddy (Fig. 15.9) is based on the traces from three XBT probes dropped near together in quick order. An additional XBT section along line BC in the inset map on Figure 15.9 is not reproduced in this report, but shows a similar steep thermal gradient (at position C). An eastward current can be inferred on the offshore side of the gradient.

The history of eddy 76B (Fig. 15.2) is not clearly apparent in the satellite imagery. The 24 April position is based on a warm-water patch of uncertain character. The 29 May position is based on a protrusion of Shelf Water that has the appearance of entrainment around an eddy with a surface diameter of about 50 nm (90 km). The presence of 13C water to a depth >155 m over the outer shelf south of New England (71W12'), in an XBT section from the *Eastward* on 11-12 May, provided evidence of the passage of an eddy. If the deep 13C water was from this eddy, then 76B moved westward much more quickly than was indicated by satellite imagery, and then remained in the area of 71W for about three weeks. This eddy may have been the one that appeared in the area of Deepwater Dumpsite 106 (38N40'-39N00', 72W00'-72W30') at the end of June as shown by several XBT sections.[4] After May, however, the history of the eddy was not revealed in satellite imagery.

Eddy 76A formed about 22 February from a large meander centered at 63W (Figs. 15.3, 15.8a, 15.8b). The large decrease in apparent surface diameter of this eddy from 140 nm (260 km) at the end of February to 100 nm (190 km) at the end of March was probably a result of deceptive surface expression. A hydrocast transect from the RV Ernst Haeckel made on 20 March (Fig. 15.10) showed this eddy to be a smoothly structured mass of Sargasso Water, with a sigma-t range of only 25.9 to 26.3 at stations 1 to 4 (except in a few of the deepest samples at stations 2 and 4).

A special set of diagrams (Fig. 15.8) has been prepared to illustrate major interactions between the Gulf Stream and anticyclonic eddies in the area southeast of Georges Bank from mid-February through April. Involved in these interactions were two large changes of course by the Stream and the destruction of eddies 75I and 76A, as well as the formation and destruction of a cyclonic eddy.

- On 17 February (Fig. 15.8a), eddy 75I lay south of Georges Bank, and a Gulf Stream meander was separating as eddy 76A.

- On 28 February (Fig. 15.8b), eddy 75I was entraining warm Gulf Stream water, and eddy 76A was fully formed and had moved westward.

- By 24 March (Fig. 15.8c), a developing Gulf Stream meander had encroached on eddy 75I, apparently destroying it. Eddy 76A moved westward and entrained warm Gulf Stream water.

- By 27 March (Fig. 15.8d), Gulf Stream water was separating from the meander south of Georges Bank as eddy 76B. Eddy 76A ceased entraining Gulf Stream water and was apparently losing water to the Gulf Stream. Meandering of the Stream intensified southeast of eddy 76A.

- By 7 April (Fig. 15.8e), eddy 76B had separated from the Stream south of Georges Bank and had moved westward. The Gulf Stream changed course through the northern portion of eddy 76A, forming a broad meander that incorporated this eddy. The former path of the Stream to the south became a cyclonic eddy. A hydrocast transect from the Wieczno made

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[4] J. J. Bisagni, Atlantic Environmental Group, NMFS, Narragansett, RI 02882. Pers. commun.

on 4-7 April (Fig. 15.11; station location plotted on Fig. 15.8e) showed only one crossing of the Gulf Stream axis, indicating that the Gulf Stream had assumed its directly eastward path by the time of the section. The rise in isotherms and isohalines at station 4 was due to the proximity of this station to the Gulf Stream's northern edge.

- On 14 April (Fig. 15.8f), eddy 76B, south of Georges Bank, was not visible in satellite imagery. The Gulf Stream had merged with the west margin of the cyclonic eddy.
- By 18 April (Fig. 15.8g), the cyclonic eddy was incorporated into the Gulf Stream, but the former path of the Stream was not completely abandoned. Hydrocast stations (Fig. 15.2, Belogorsk, 17-19 April) of leg AB were entirely in Slope Water, while the middle stations of leg BC were in the Gulf Stream, providing agreement with the surface pattern shown in Figure 15.8g. Because of the placement of stations, the link between the old and the new Gulf Stream paths was not recorded in Figure 15.12.
- On 24 April (Fig. 15.8h), eddy 76C formed from the remnants of the old Gulf Stream path.

The position of eddy 76C (Fig. 15.3), following its formation in April, was not clearly seen in the satellite imagery until August. The position for 15 May was based on a warm water patch, and for 28 July, a suggestive Shelf Water protrusion. The 28 July position was especially questionable, because in order to reach its fairly certain position of 18 August, the eddy would have had to travel at an average rate of at least 6 nm (11 km) per day. This speed is inconsistent with average rates of up to 4 nm (7 km) per day that we have calculated for other eddies in 1976. Evidence for the passage of this eddy south of New England was provided by 13C water to a depth of >140 m over the outer continental shelf at 71N10', in an XBT section from the Oceanus on 12-13 August. The satellite imagery provides no clear picture of this eddy's size until late August when the apparent surface diameter was 60 nm (110 km). The surface expression shrank markedly during late September and October, and the eddy coalesced with the Gulf Stream about 15 October.

Eddy 76D (Fig. 15.4) formed about 20 May from a large meander centered at 65W. Its apparent surface diameter was about 110 nm (200 km). The eddy appeared to have maintained its circulation despite contact with the Gulf Stream from July to September. The Belogorsk made an XBT temperature section through eddy 76D and the Gulf Stream on 5-6 September (Figs. 15.13, 15.14). Although there is considerable exchange between the Gulf Stream and shallow eddy water, the deeper circulation seemed to be closed. The sharp thermal front on the shoreward side of the eddy (Fig. 15.14) indicated considerable velocity shear. In mid-December, the eddy was located at 70W30' and had an apparent surface diameter of 80 nm (150 km). This eddy persisted into 1977 until captured by the Gulf Stream during February.

Eddy 76E (Fig. 15.5) formed about 28 May at 62W from an elliptical meander that looped westward from 60W. Its apparent surface diameter at this time was about 80 nm (150 km). This eddy survived at least into late July, when it became masked by a large area of warm surface water. It may have lasted through the better part of August, but the fate of eddy 76E is obscure. Presumably, it coalesced into either the Gulf Stream or eddy 76D.

Eddy 76F (Fig. 15.6) formed from a northward extending meander at 64W on 15 October. Its apparent surface diameter was about 80 nm (150 km). It survived until February 1977.

Eddy 76G (Fig. 15.7) formed about 27 October from a meander that had looped westward from 65W with an apparent surface diameter of 90 nm (170 km). After initial westward movement, the eddy remained fairly stationary during December at 67W30'. This eddy persisted until well into 1977.

ZONAL ANALYSIS OF EDDY POSITIONS AND MOVEMENTS

A zonal analysis of all the eddies in 1976 is summarized in Table 15.2 to reveal their movements relative to one another. The region studied was divided into eight zones of about equal lengths along the axis of eddy movements (Fig. 15.15). The zonal boundaries were drawn approximately normal to both the mean position of the Gulf Stream's north wall and the 100-fm (180-m) isobath. The zone in which each eddy occurred at the middle of each month is shown in Table 15.2.

Eddy positions with respect to zone were also determined for 1974 and 1975 from Bisagni (see footnote 2). The last column of Table 15.2 gives the number of occurrences at midmonth for the years 1974-76 in each zone. Thus, in zone 4, eddies were present at midmonth 15 times out of a possible 36.

Except for zones 1 and 8, overall eddy activity was fairly uniform with respect to zone for the years considered. There are relatively few occurrences in zone 8 because many eddies never get that far and those that do are soon incorporated into the Gulf Stream. The low level of activity in zone 1 seems to be real, even though partly a data artifact caused by excessive cloud interference in the satellite coverage. Occasional cloud free imagery indicates that Gulf Stream eddies are common in the Slope Water region east of zone 1. It appears, therefore, that eddies formed east of zone 1 (off the central Scotian shelf) tend not to move westward very far. No eddies observed during 1976, in the area of our analysis, originated east of zone 2.

A westward boundary to the region of eddy formation is apparent in the zonal analysis. During 1974-76, no eddies originated west of zone 5.

ENVELOPES OF EDDY CENTER POSITIONS AND BOUNDARIES

Envelopes drawn around all the observed surface center positions and surface boundary positions of eddies during 1976 appear in Figure 15.16. The narrow portion of the envelope of centers between 69W and 72W reflects the fact that few eddy observations were made in this region.

DISCUSSION

Satellite imagery has proved itself an effective means of monitoring anticyclonic eddies but does have inherent limitations:

1. Imagery reveals what is happening at the surface, but the surface is the last place to become disconnected in anticyclonic eddy formation (Gotthardt 1973), whereas the area of maximum energy may be over 100 m below the surface (Khedouri and Gemmill 1974). Thus, a feature located near the Gulf Stream may appear as a meander in satellite imagery, while the main body of water beneath the surface circulates as an eddy.

2. During the summer, surface temperatures in the Slope Water may approach that in the eddies, causing the latter to "disappear" in the imagery. This effect probably contributed to eddy 76C's not being detected until mid-August (Fig. 15.3).

3. The region of our analysis is subject to long periods of cloudiness during which eddies may be formed or destroyed. Potocsky (1976), in an evaluation of imagery over the entire western North Atlantic, found that cloud free coverage was best during April and October and worst during December.

4. Eddy surface expression can be distorted by entrained Shelf Water (Potocsky 1976). Chamberlin (see footnote 3)

suggested that distortion may also occur when wind causes overrunning of an eddy by surrounding water, or chilling of an eddy at the surface.

This report and that of Bisagni (see footnote 2) demonstrate that eddies have a variable, but major, influence on physical conditions in the Slope Water. During the three years of record, the number of eddies present at any time has ranged from a low of one (November 1974 to mid-January 1975) to as many as six (early November 1975; one of which, 75I, was not recorded by Bisagni).

SUMMARY

Two well-developed anticyclonic eddies (75I and 76A) occurred south and southeast of Georges Bank in the early months of 1976, but these were short lived. Only three eddies moved westward beyond Georges Bank during the year (76B, 76C, 76D). Although two of these, 76B and 76C, were apparently weakly developed, the former probably moved at least to the vicinity of the Hudson Canyon, and the latter to the latitude of Virginia. Eddy 76D was strongly formed. It moved to the vicinity of the Hudson Canyon by the end of the year.

ACKNOWLEDGMENTS

In the National Environmental Satellite Service, NOAA, Franklin E. Kniskern provided several prints of NOAA-4 satellite imagery and Robert L. Mairs provided 3-hourly imagery from the Geostationary Orbiting Environmental Satellite. Rudolf J. Perchal, U.S. Naval Oceanographic Office, provided up-to-the-minute satellite information at times when research vessels were making special observations in eddies. Philip L. Richardson, University of Rhode Island, provided NOAA-4 satellite pictures for the February-April period.

Henry W. Jensen provided special XBT observations south of Georges Bank from RV _Albatross IV_ on 2-3 April. Special acknowledgment is owed for data provided by the crews of cooperating foreign fishery research vessels: the German Democratic Republic's RV _Ernst Haeckel_ for Nansen bottle data on 20 March, the Polish RV _Wieczno_ for XBT data on 4-7 April and for Nansen bottle data on 7-19 April, and the U.S.S.R. RV _Belogorsk_ for Nansen bottle data on 17-19 April and for XBT data on 5-6 September. W. Redwood Wright and Patrick J. Twohig, NMFS, Woods Hole, MA, assisted in obtaining oceanographic data from the foreign vessels.

Reed S. Armstrong, National Marine Fisheries Service, gave valuable oceanographic advice.

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Table 15.2.--Eddy positions at midmonth with respect to zone during 1976. The last column gives the total number of midmonth occurrences in each zone for the years 1974-76. Zones are given in Figure 15.15. Surface boundaries, as seen on satellite imagery, are shown for some positions.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	1974-76 monthly total
1.													3
2.						76E	76E			76F	76F		11
3.	75I		76A			76D						76F	17
4.		75I	75I		76C	76C	76D	76D	76D		76G	76G	15
5.				76B	76B		76C			76D	76D		16
6.						76B		76C				76D	12
7.	75E	75E	75E						76C				11
8.										76C			3

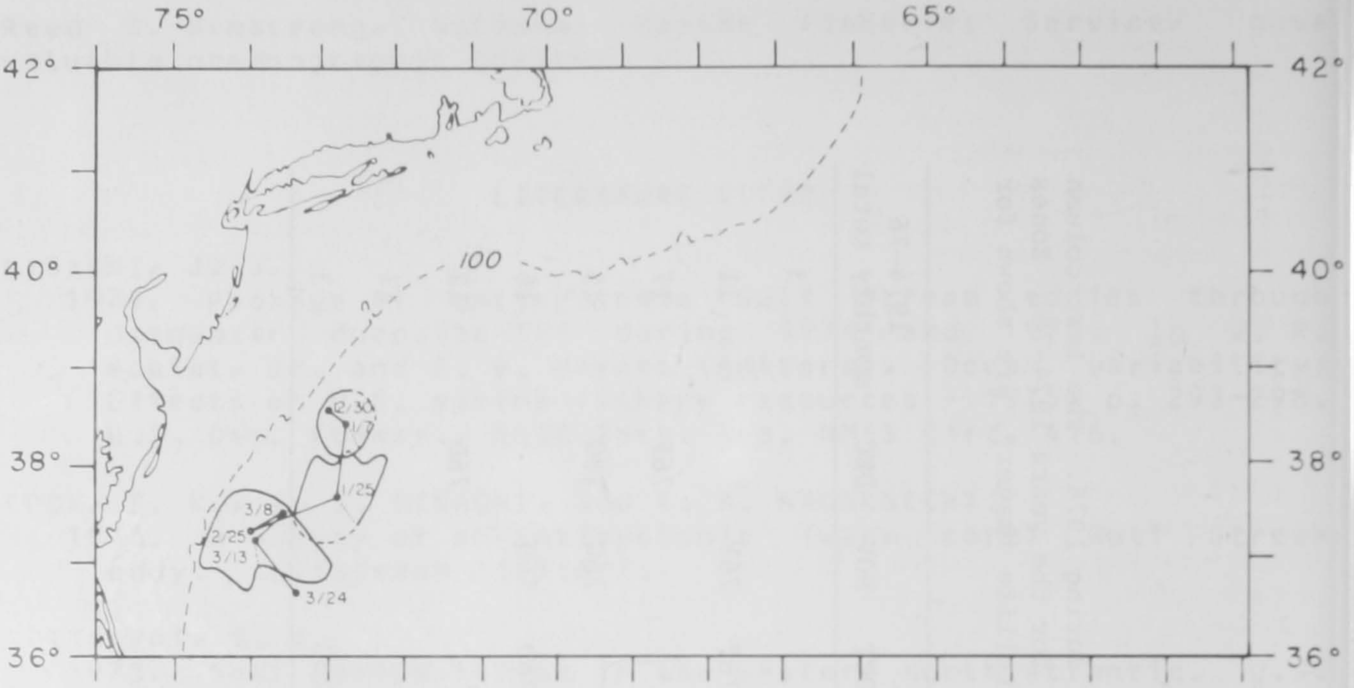

Figure 15.1.—Track line for anticyclonic eddy 75E (23 July 1975-27 March 1976). Surface boundaries, as seen on satellite imagery, are shown for some positions.

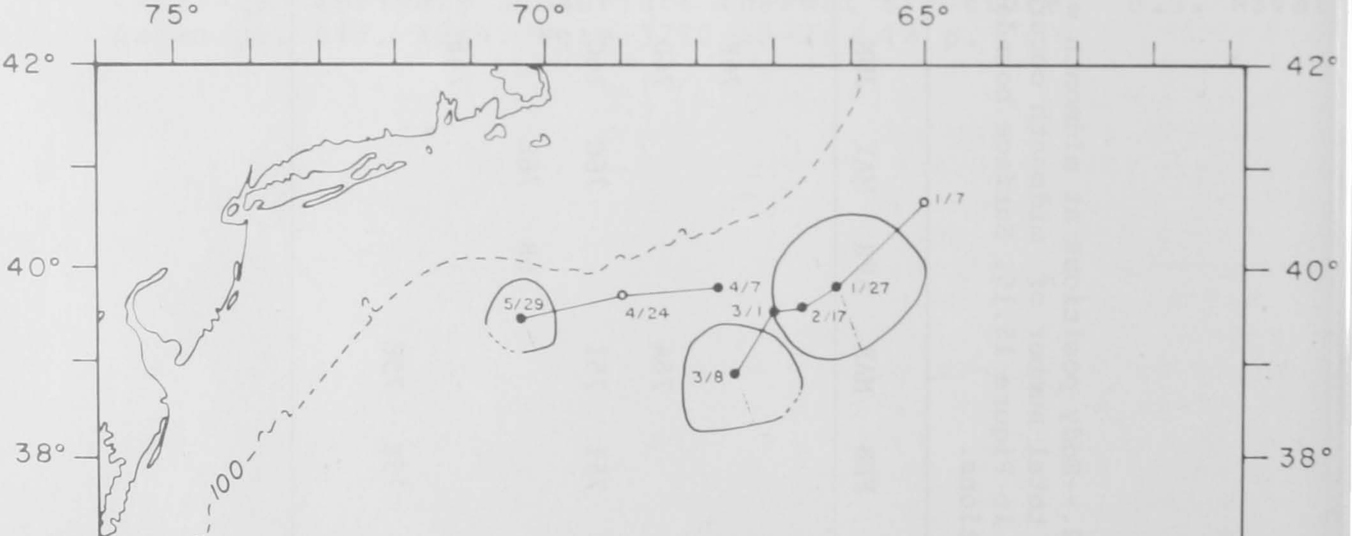

Figure 15.2.—Track lines for anticyclonic eddies 75I (1 November 1975-17 March 1976) and 76B (1 April 1976-?). Surface boundaries, as seen on satellite imagery, are shown for some positions.

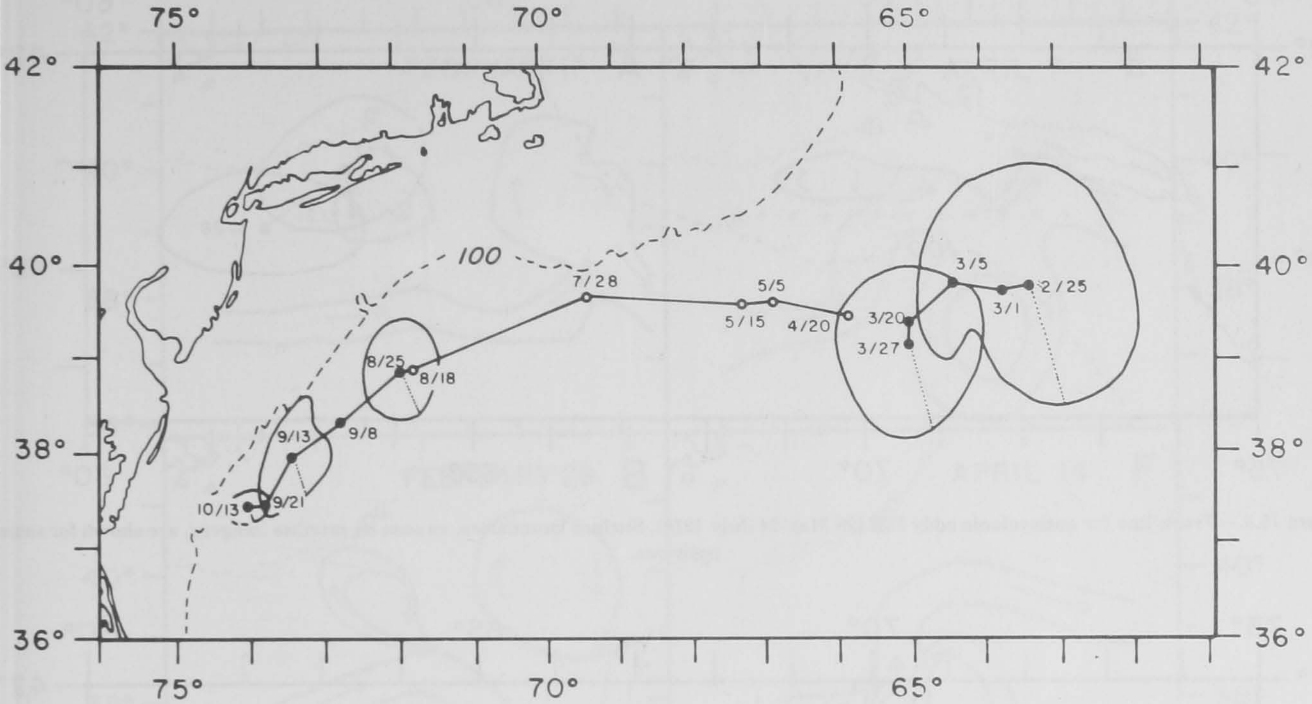

Figure 15.3.—Track lines for anticyclonic eddies 76A (22 February-30 March 1976) and 76C (19 April-15 October 1976). Surface boundaries, as seen on satellite imagery, are shown for some positions.

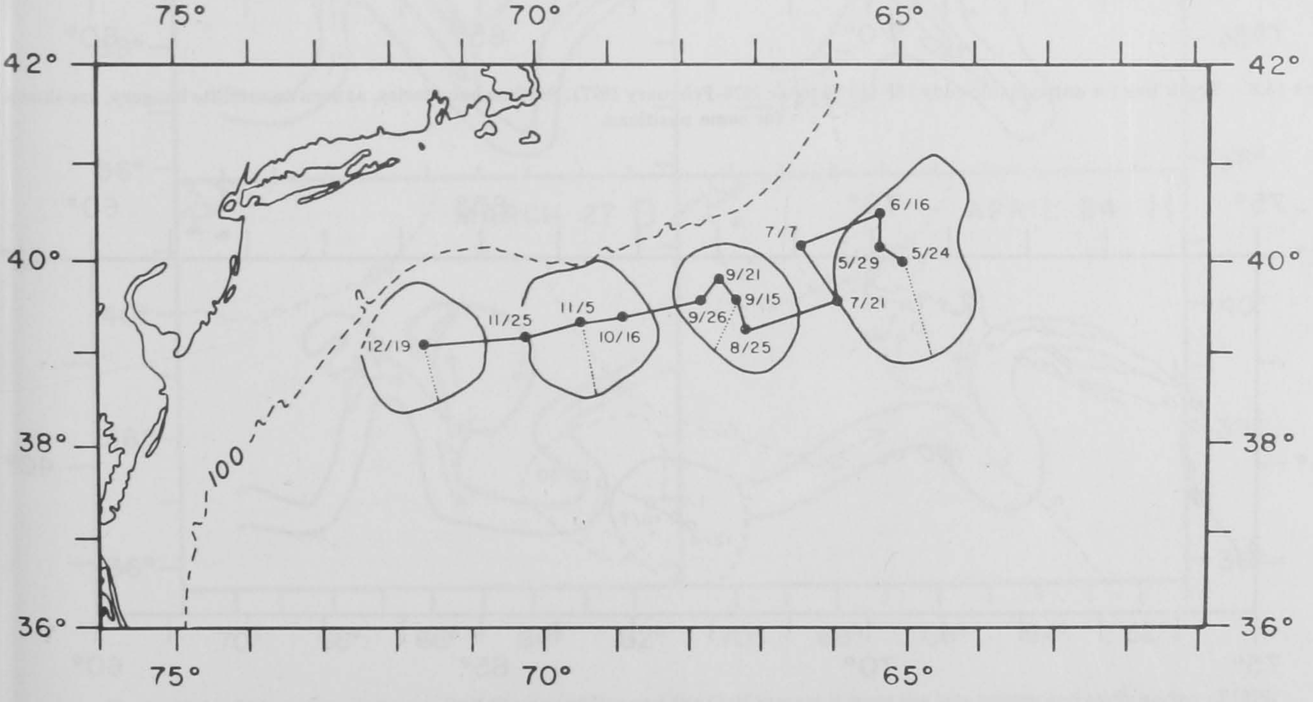

Figure 15.4.—Track line for anticyclonic eddy 76D (20 May 1976-February 1977). Surface boundaries, as seen on satellite imagery, are shown for some positions.

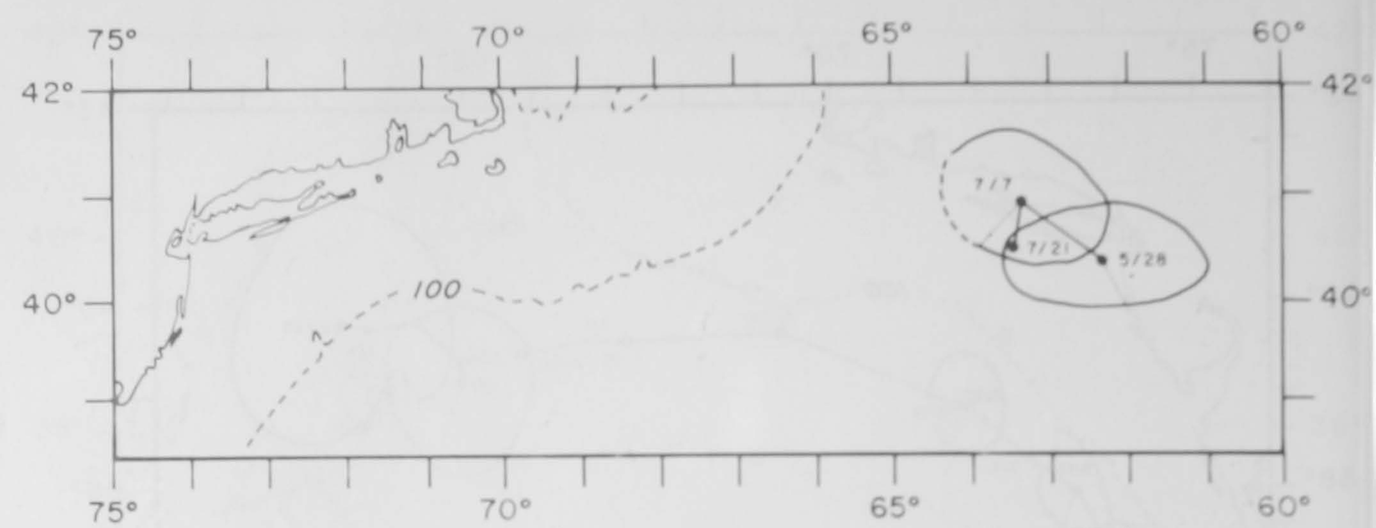

Figure 15.5.—Track line for anticyclonic eddy 76E (28 May-24 July 1976). Surface boundaries, as seen on satellite imagery, are shown for some positions.

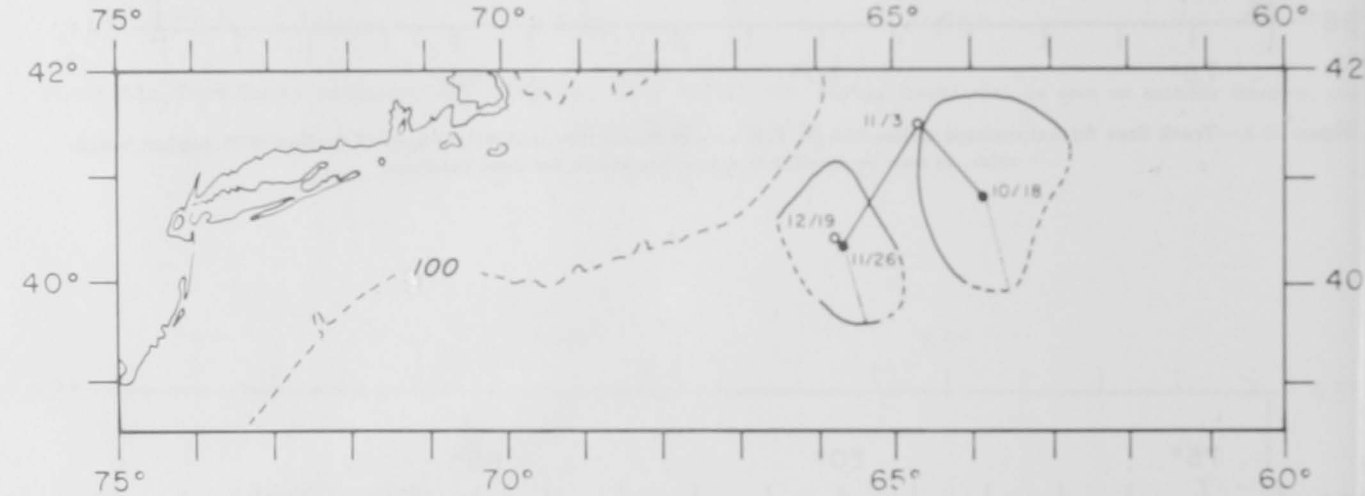

Figure 15.6.—Track line for anticyclonic eddy 76F (15 October 1976-February 1977). Surface boundaries, as seen on satellite imagery, are shown for some positions.

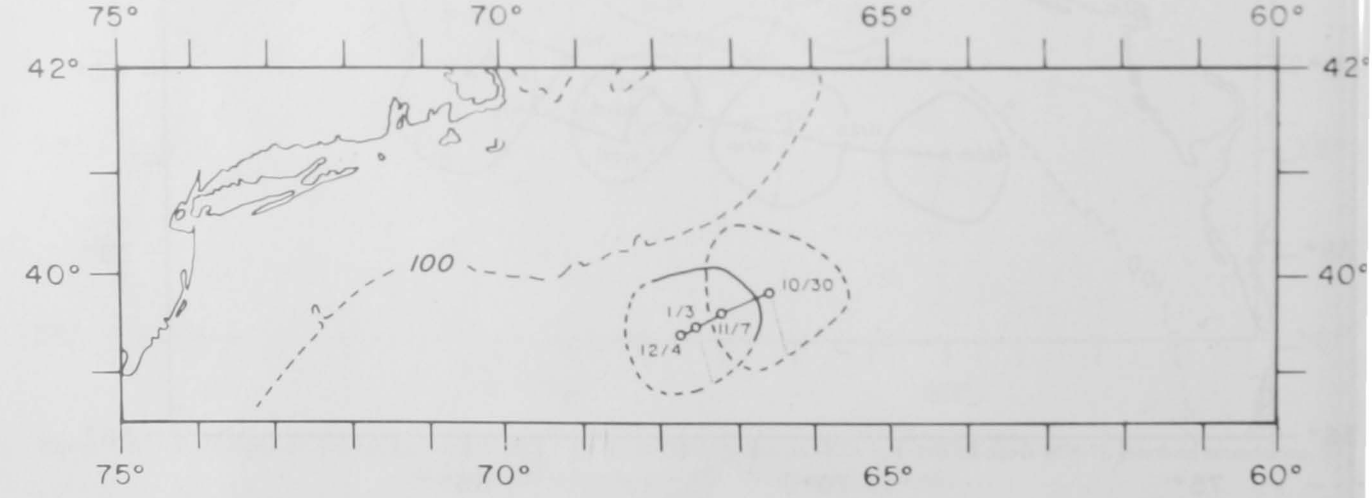

Figure 15.7.—Track line for anticyclonic eddy 76G (27 October 1976-13 May 1977). Surface boundaries, as seen on satellite imagery, are shown for some positions.

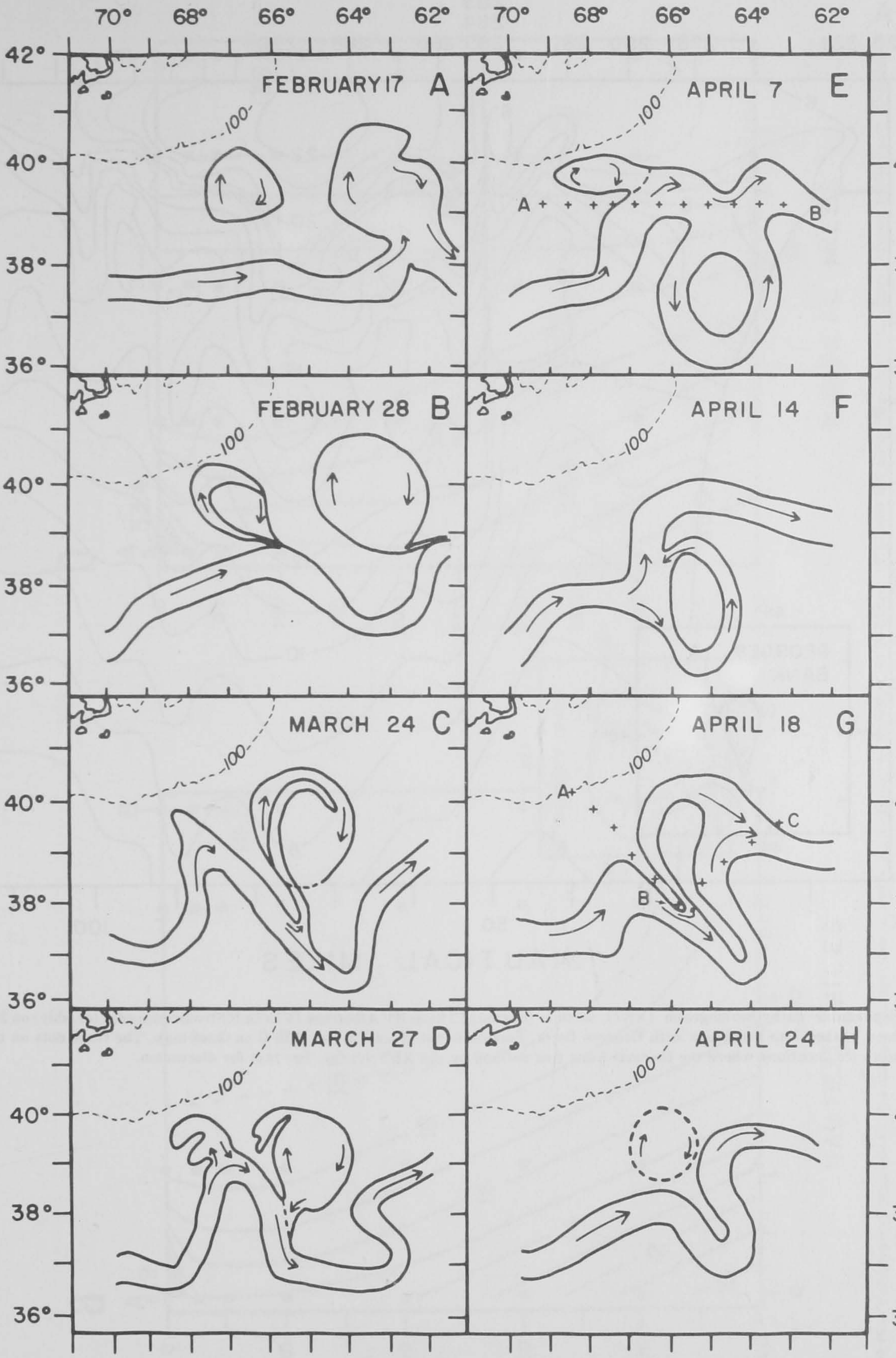

Figure 15.8.—Interactions between Gulf Stream eddies and the Gulf Stream during the late winter and early spring of 1976. See text.

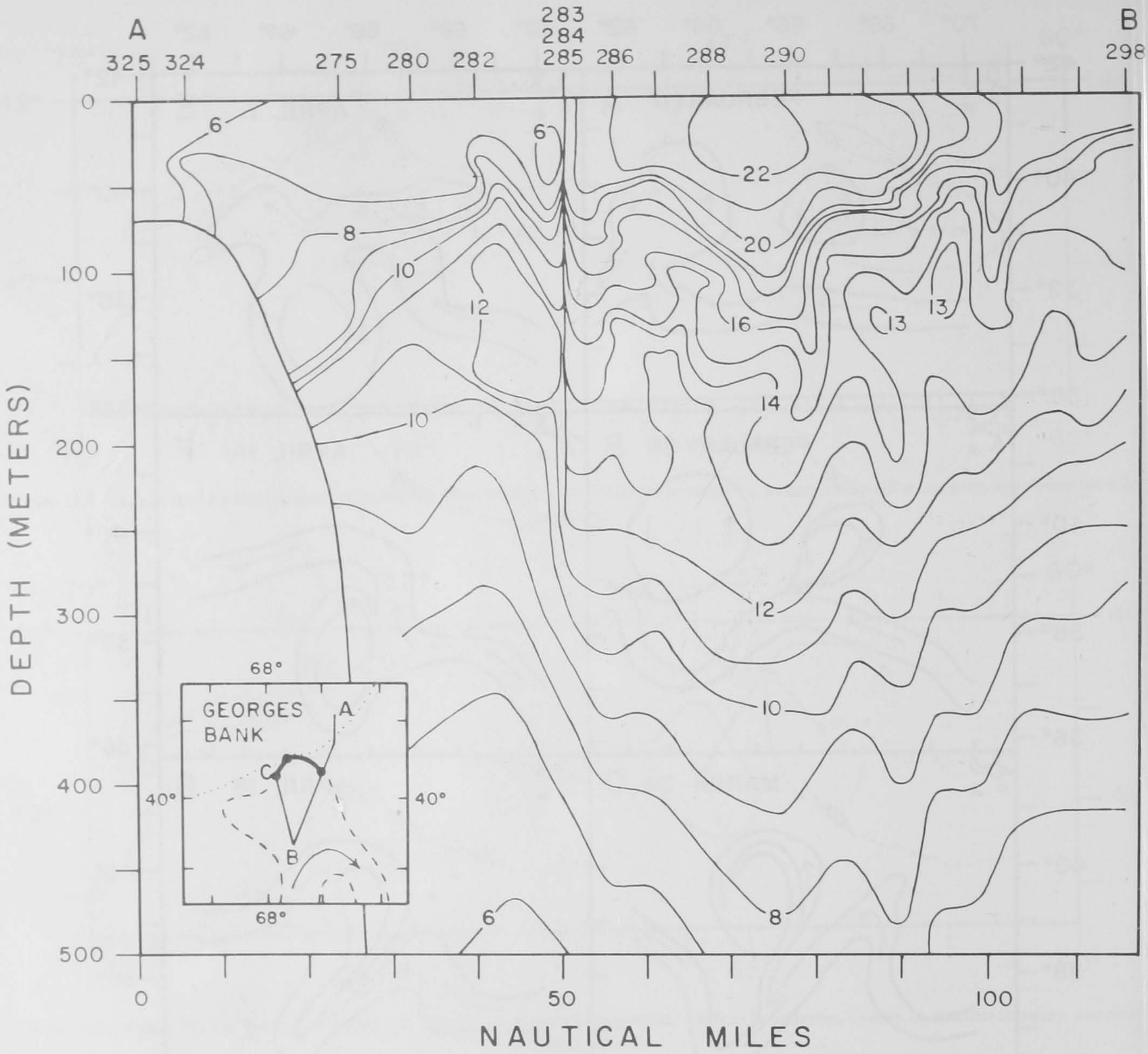

Figure 15.9.—Expendable bathythermograph (XBT) section (degrees C) from RV *Albatross IV* in Gulf Stream meander (or eddy) on 2-3 April 1976 that had been pushed into proximity with Georges Bank. Section is not given for line B to C on inset map. The three dots on the map inset correspond to the locations where the thermal front was defined by the XBT survey. See text for discussion.

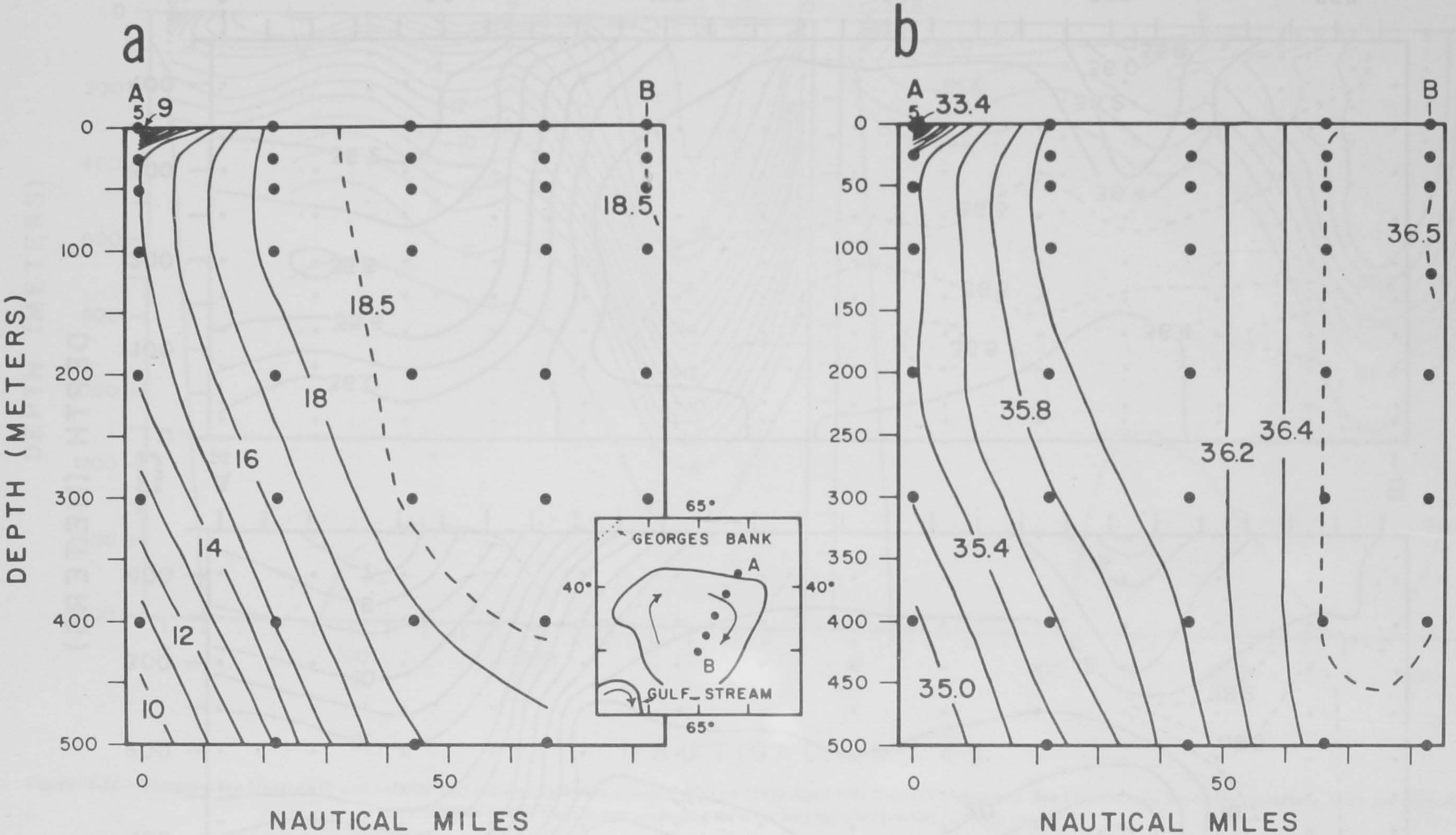

Figure 15.10.—Temperature (degrees C) and salinity (‰) sections (a and b, respectively) in eddy 76A on 20 March 1976 from RV *Ernst Haeckel*. Data from Nansen bottle casts. Depths are according to wire length, uncorrected for wire angle.

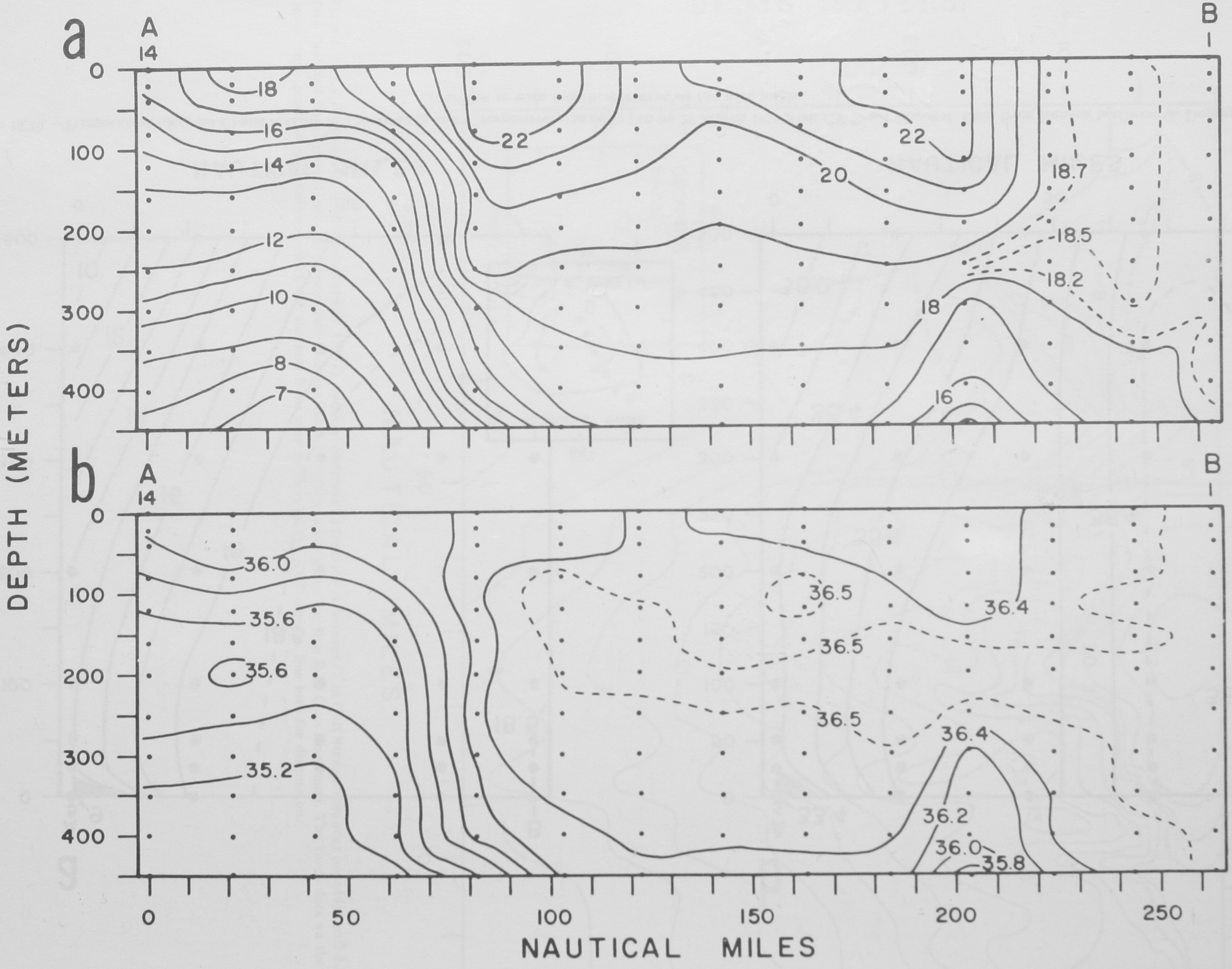

Figure 15.11.—Temperature (degrees C) and salinity (‰) sections (a and b, respectively) in the Gulf Stream on 4-7 April 1976 from RV *Wieczno*. See Figure 15.8E for station locations. Data are from Nansen bottle casts. Depths are according to wire length, uncorrected for wire angle.

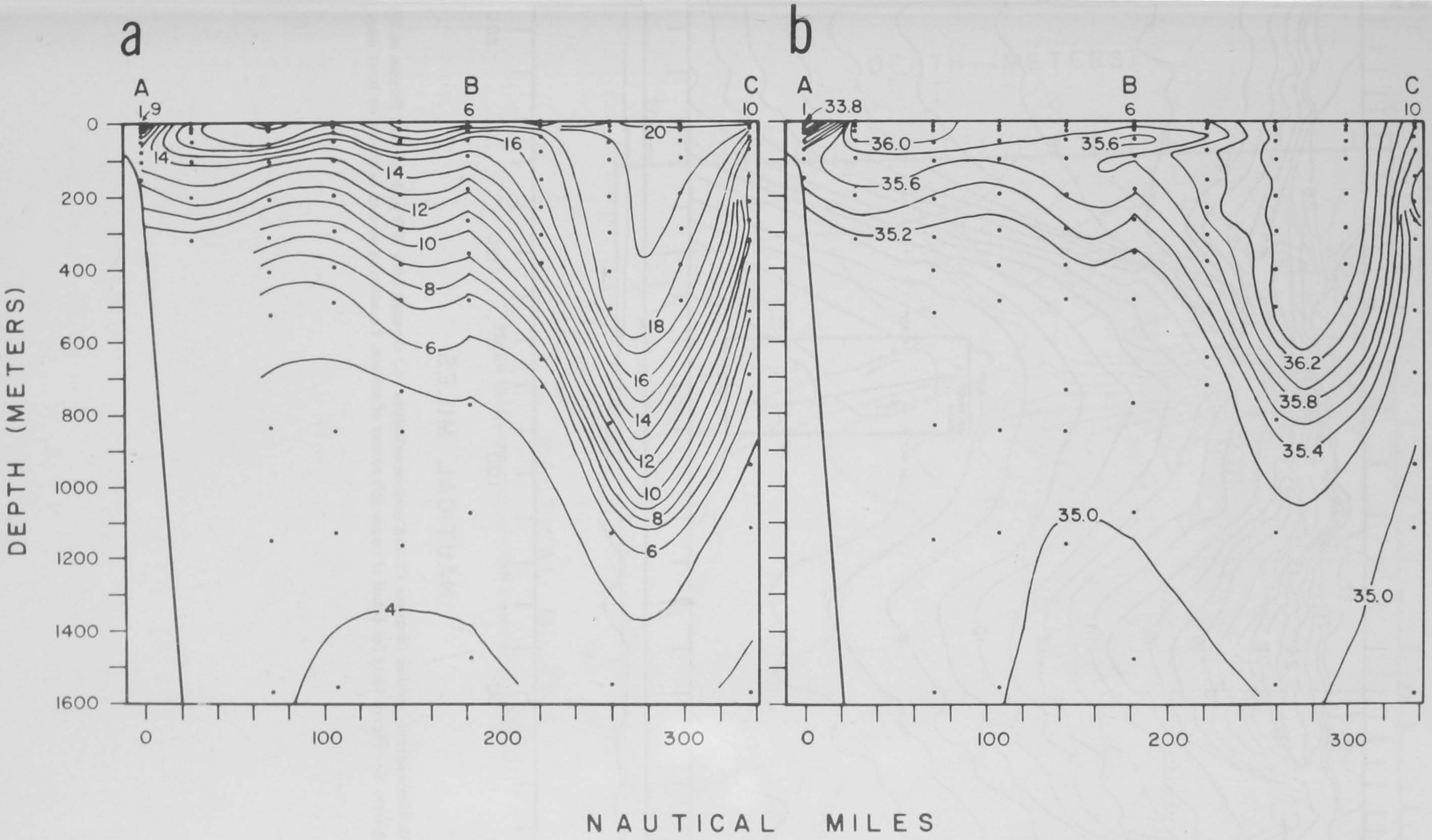

Figure 15.12.—Temperature (degrees C) and salinity (‰) sections (a and b, respectively) on 17-19 April 1976 from RV *Belogorsk*. See Figure 15.8G for station locations. Data are from Nansen bottle casts. Depths are according to wire length, uncorrected for wire angle.

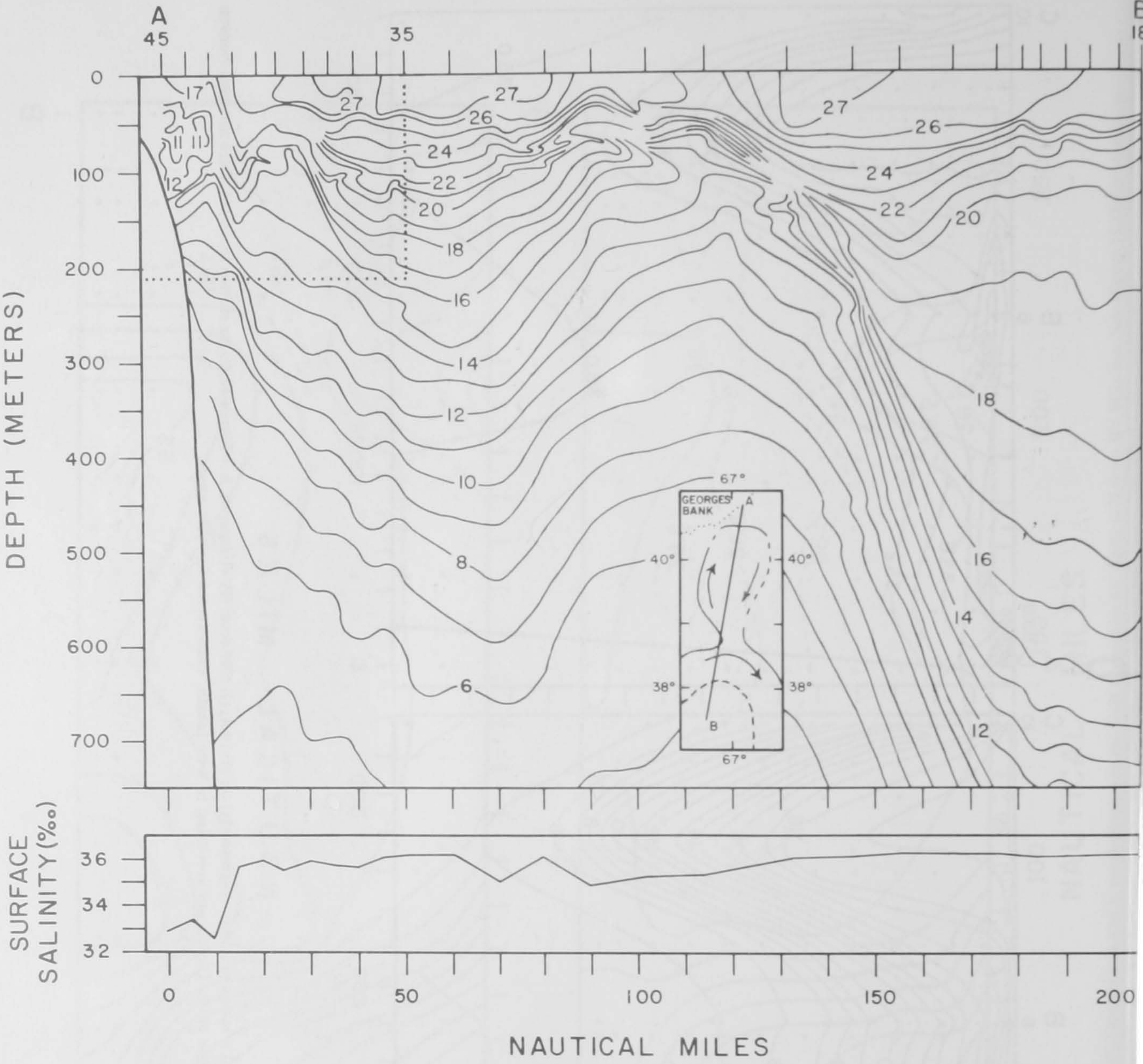

Figure 15.13.—Expendable bathythermograph section (degrees C) and surface salinities (‰) through eddy 76D and the Gulf Stream on 5- September 1976 from RV *Belogorsk*. See Figure 15.14 for detail of upper left corner of section. Location of section is shown on inset map.

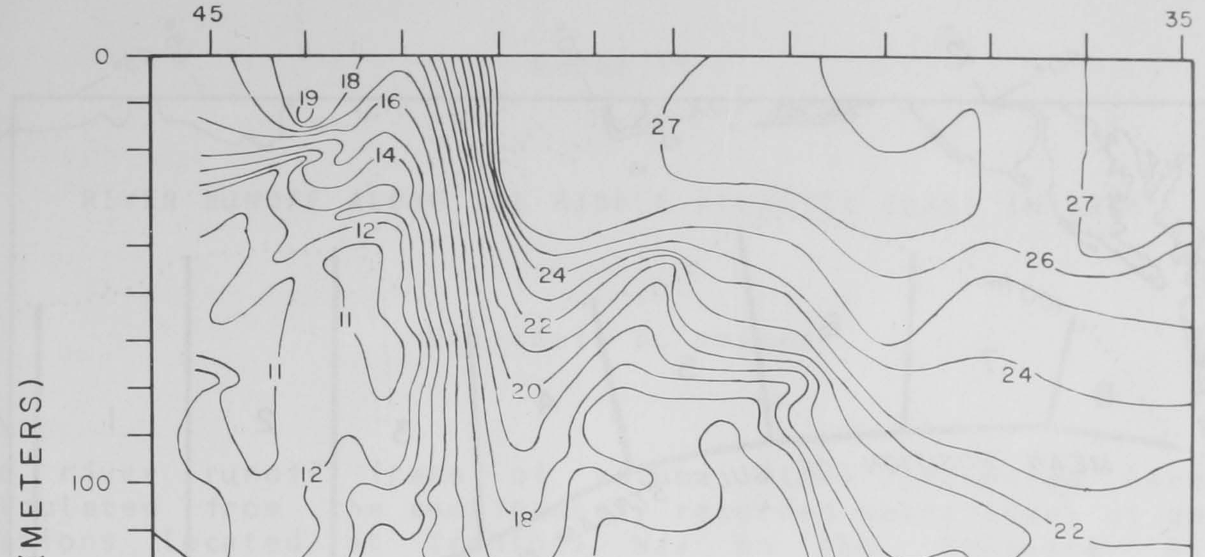

Figure 15.14.—Detail of upper left corner of Figure 15.13.

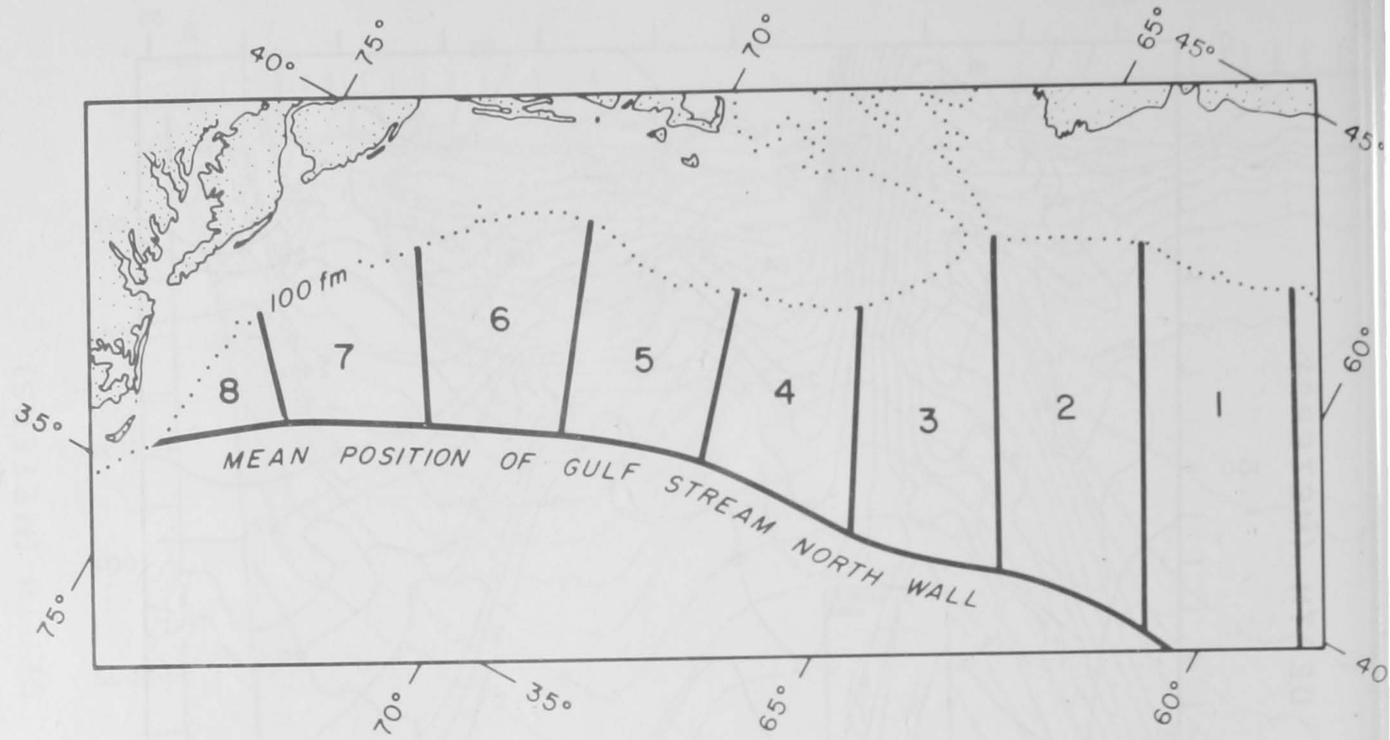

Figure 15.15.—Zones used in Table 15.2.

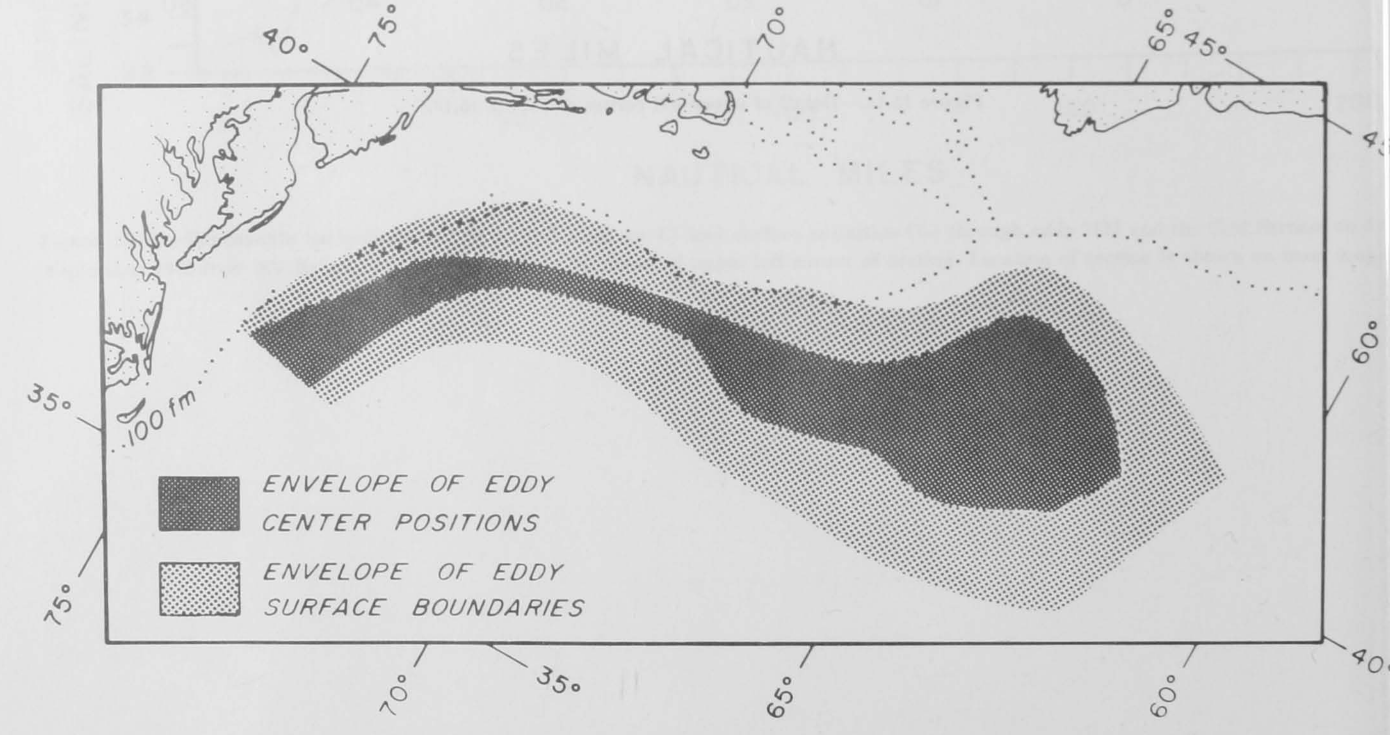

Figure 15.16.—Envelopes of surface boundaries and center positions of eddies during 1976.

Paper 16

RIVER RUNOFF ALONG THE MIDDLE ATLANTIC COAST IN 1976[1]

Elizabeth D. Haynes[2]

The river runoff (rate of volume flow) presented here is calculated from the continuously recorded water level at gaging stations located at Trenton, NJ, on the Delaware River, Poughkeepsie, NY, on the Hudson River, and along the shores of Chesapeake Bay at the sections shown in Appendix 16.1. Trenton and Poughkeepsie are upstream of any tidal influence, but the tidal flow and consequent mixing need to be accounted for in order to estimate Chesapeake Bay runoff.

The unusual warming in January and February caused higher than average runoff in February in all three estuaries. Spring runoff normally peaks at the mouth of the Chesapeake Bay in March and continues high in April as a result of snow melt in the southerly James and Potomac river basins, in contrast to Delaware Bay, in which the average runoff is greatest in April, with March a close second.

By March there was no snow nor river ice left in the drainage areas, so runoff was unusually low. April was hot and dry, with less than 50% of normal rainfall and temperatures reaching the mid-90's; runoff was low (Appendix 16.1, Fig. 16.1). Flow continued below average through May, and then was essentially average in magnitude (within 10,000 cu ft/s[3] of the long-term mean at the mouth of Chesapeake Bay) until October.

Due to a succession of frontal waves, rainfall in September exceeded 150% of normal. On one day, 5 inches of rain fell in the Chesapeake drainage basin. This weather pattern continued in October and brought three times the rainfall normal for the month.

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[1] The data used in this report were supplied by the U.S. Geological Survey District Offices in Hudson, NY, Trenton, NJ, and Towson, MD.

[2] Resource Assessment Division, National Marine Fisheries Service, NOAA, Washington, DC 20235.

[3] 1,000 cu ft/s = 28.32 m^3/s.

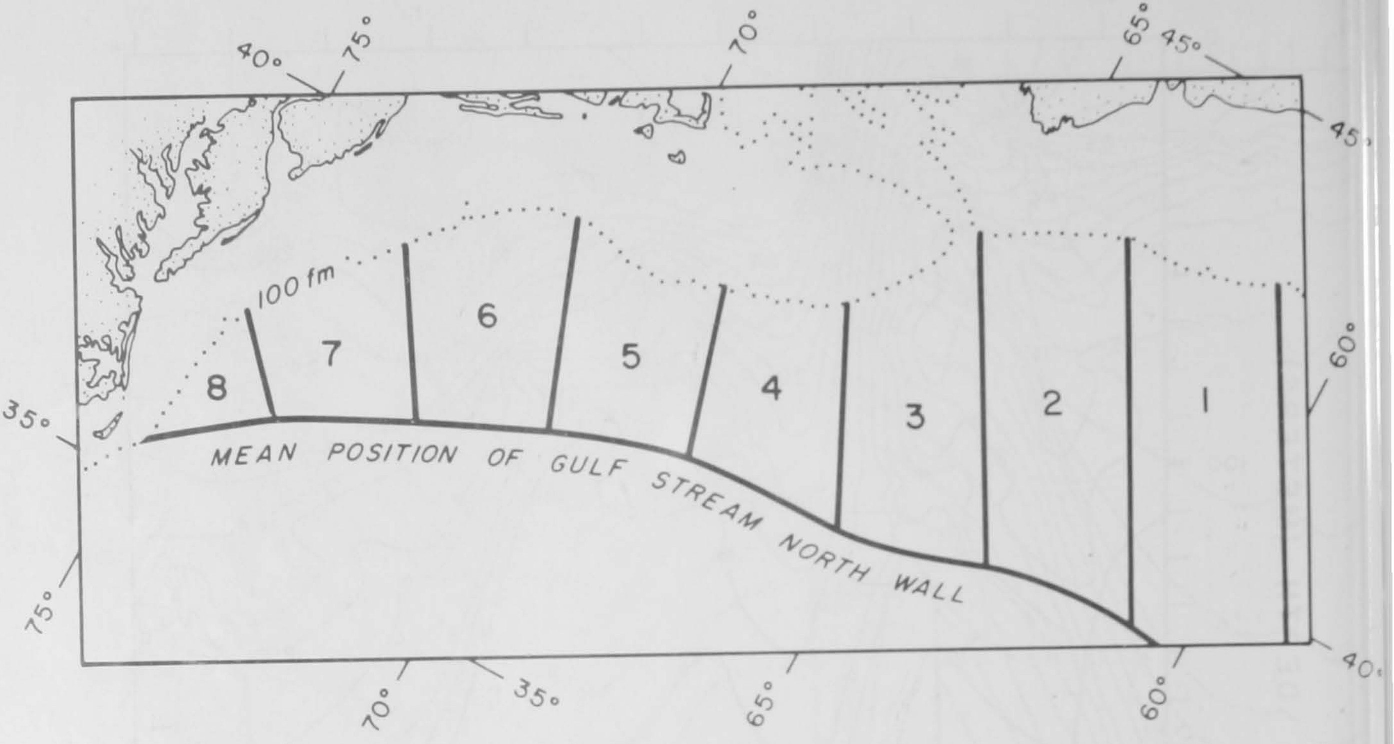
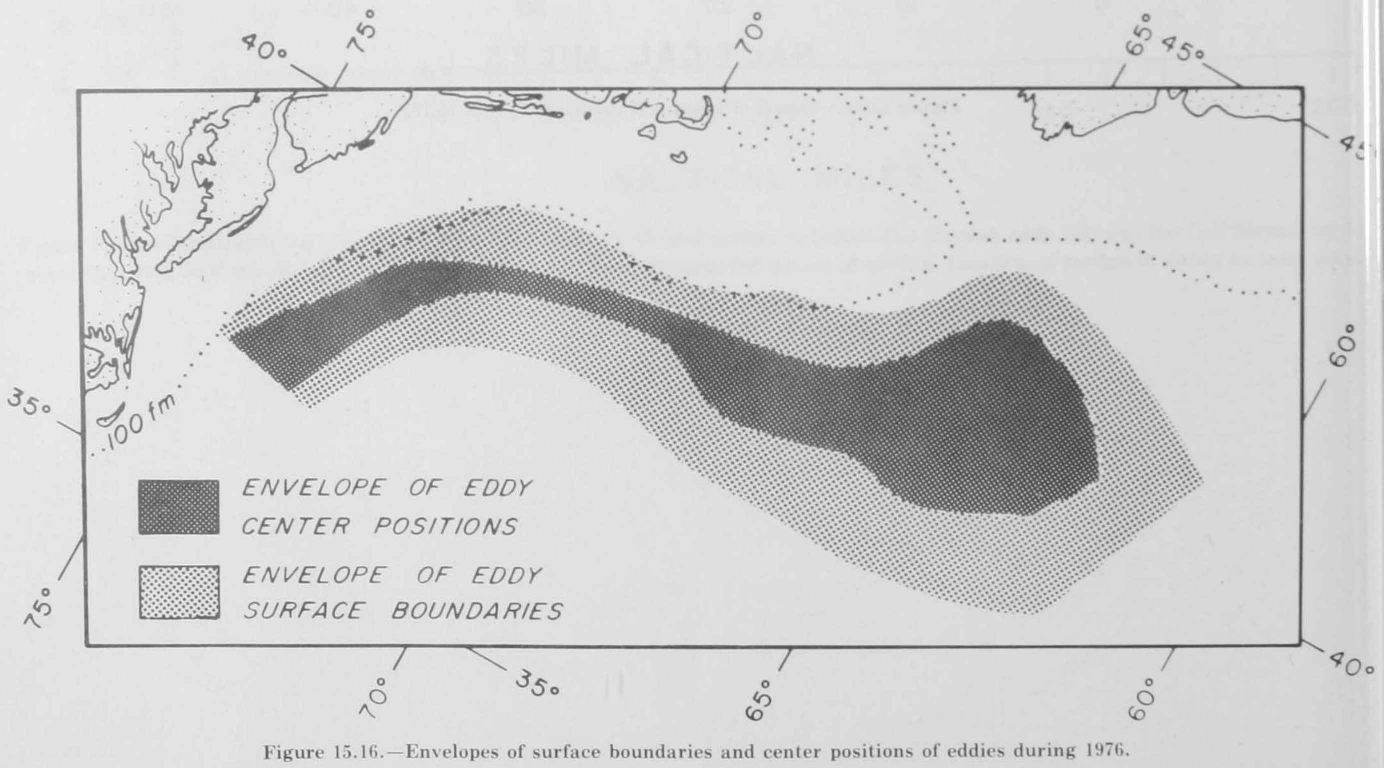


Figure 15.15.—Zones used in Table 15.2.



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Paper 16

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[2] Resource Assessment Division, National Marine Fisheries Service, NOAA, Washington, DC 20235.

[3] 1,000 cu ft/s = 28.32 m^3/s.

The highest runoff measured at the mouth of Chesapeake Bay (350,000 cu ft/sec) for any month since data were first recorded in 1950 occurred in June 1972 as a result of Hurricane Agnes, and because of it the annual mean for that year also was the highest on record (about 130,000 cu ft/sec, Appendix 16.1). The second highest annual mean (115,000 cu ft/sec), although not monthly peak, was in 1975, associated with Hurricane Eloise in September; the rest of that year was essentially normal. Mean flow in October 1976 (179,900 cu ft/sec) exceeded that of September 1975 due entirely to extratropical frontal activity. Despite the dry months of spring, the annual mean flow in 1976 (84,400 cu ft/sec) was the sixth highest of the 25 years of record. Runoff decreased in November and was average in December.

Runoff in the Delaware Bay and Hudson River (Fig. 16.1) paralleled that in the Chesapeake due to the same climatic conditions during the year. The December flow dropped in the Delaware and Hudson Rivers as the onset of the cold winter of 1976-77 locked up precipitation in snow and ice. Long-term mean monthly runoff figures were not obtained for the Hudson River, and the 1976 data are provisional. The annual average of the data set is 20,100 cu ft/sec over the period of record.

Runoff affects estuarine and offshore fishes and shellfishes by varying the salinity, turbidity, dissolved oxygen, and stratification of their environment. Early warming in the spring of 1976 was associated with high runoff very early in the year. This accentuated the early onset of stratification in the near shore waters and suppressed oxygenation two months earlier than usual. The normal summer biological depletion of dissolved oxygen led to anoxic conditions and the subsequent fish kill in July (Armstrong, Paper 17).

Table 16.1.--Mean monthly runoff in cu ft/s (0.02832 cu m/s). A - Hudson River at Poughkeepsie, NY, 1976 (provisional data); B - Delaware River at Trenton, NJ, 1976; C - Delaware River at Trenton, NJ, monthly means for 1941-70.

	A	B	C
JAN	29200	19770	11850
FEB	54800	26830	12410
MAR	42300	16450	19780
APR	46300	13420	21500
MAY	41200	12670	14390
JUN	18800	7490	8544
JUL	18200	8610	6440
AUG	20100	8007	6218
SEP	12200	4800	4995
OCT	33900	18020	5637
NOV	23600	10800	9857
DEC	19300	7476	11970

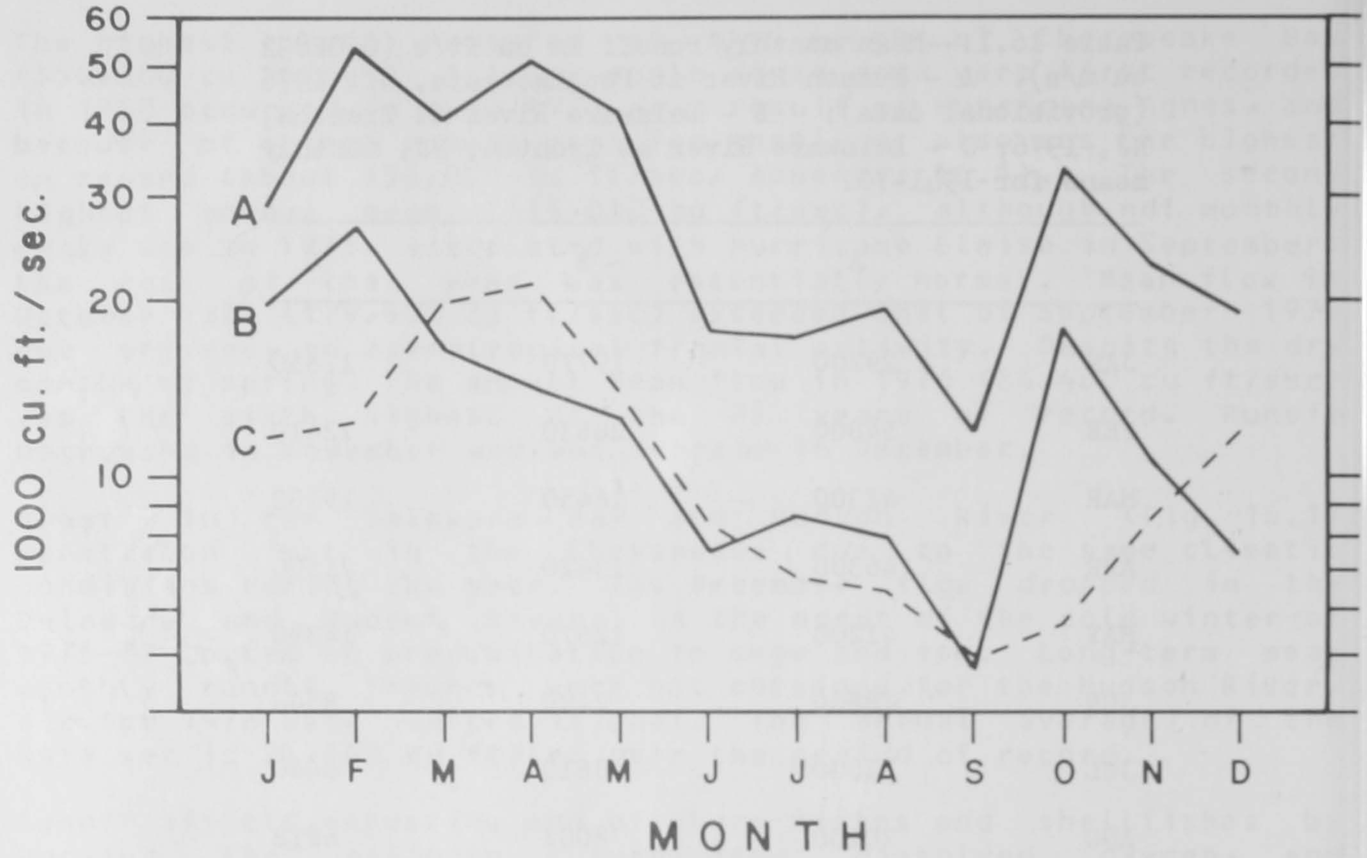


Figure 16.1.—Mean monthly runoff into the Middle Atlantic Bight. A - Hudson River at Poughkeepsie, NY, 1976 (provisional data); B - Delaware River at Trenton, NJ, 1976; C - Delaware River at Trenton, NJ, monthly means for 1941-70.

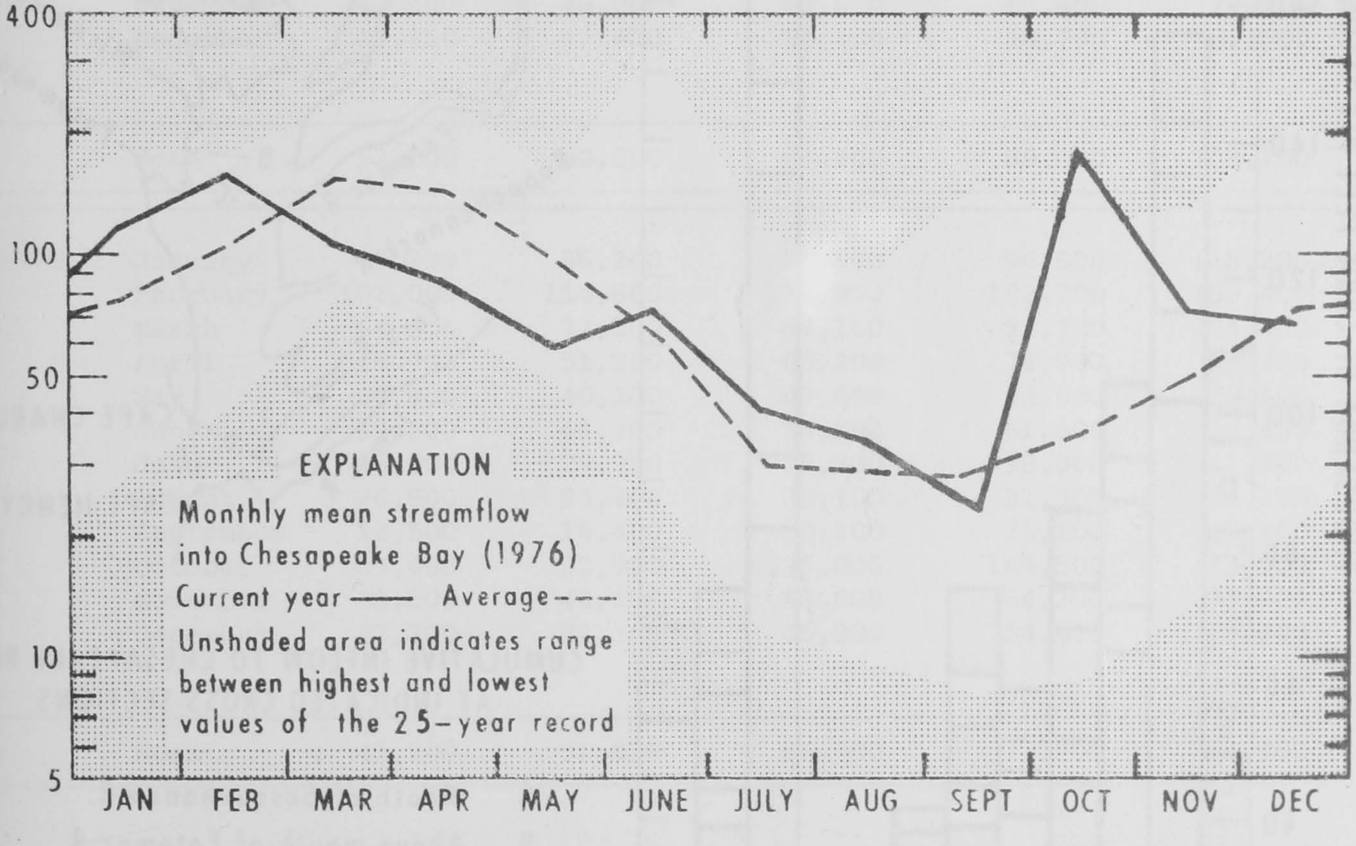
APPENDIX 16.1

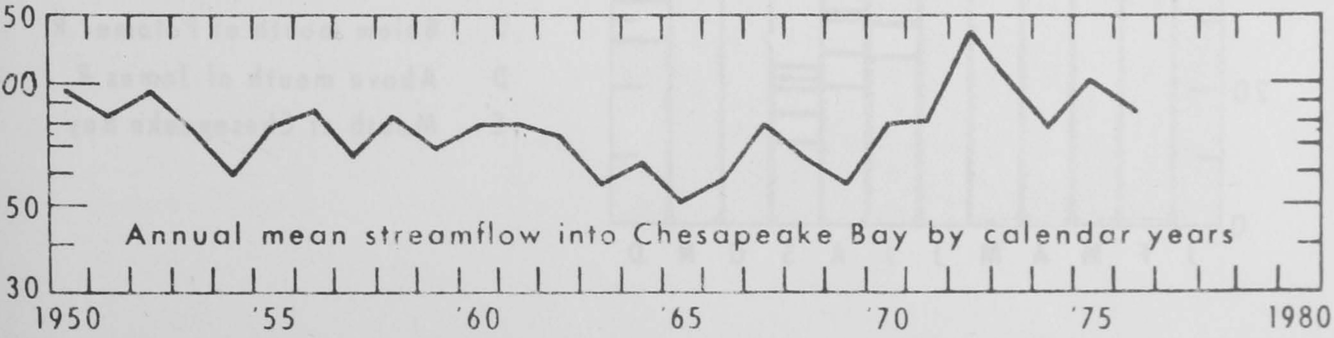
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
in Cooperation with
STATES OF MARYLAND, PENNSYLVANIA, AND VIRGINIA

ESTIMATED STREAMFLOW ENTERING CHESAPEAKE BAY

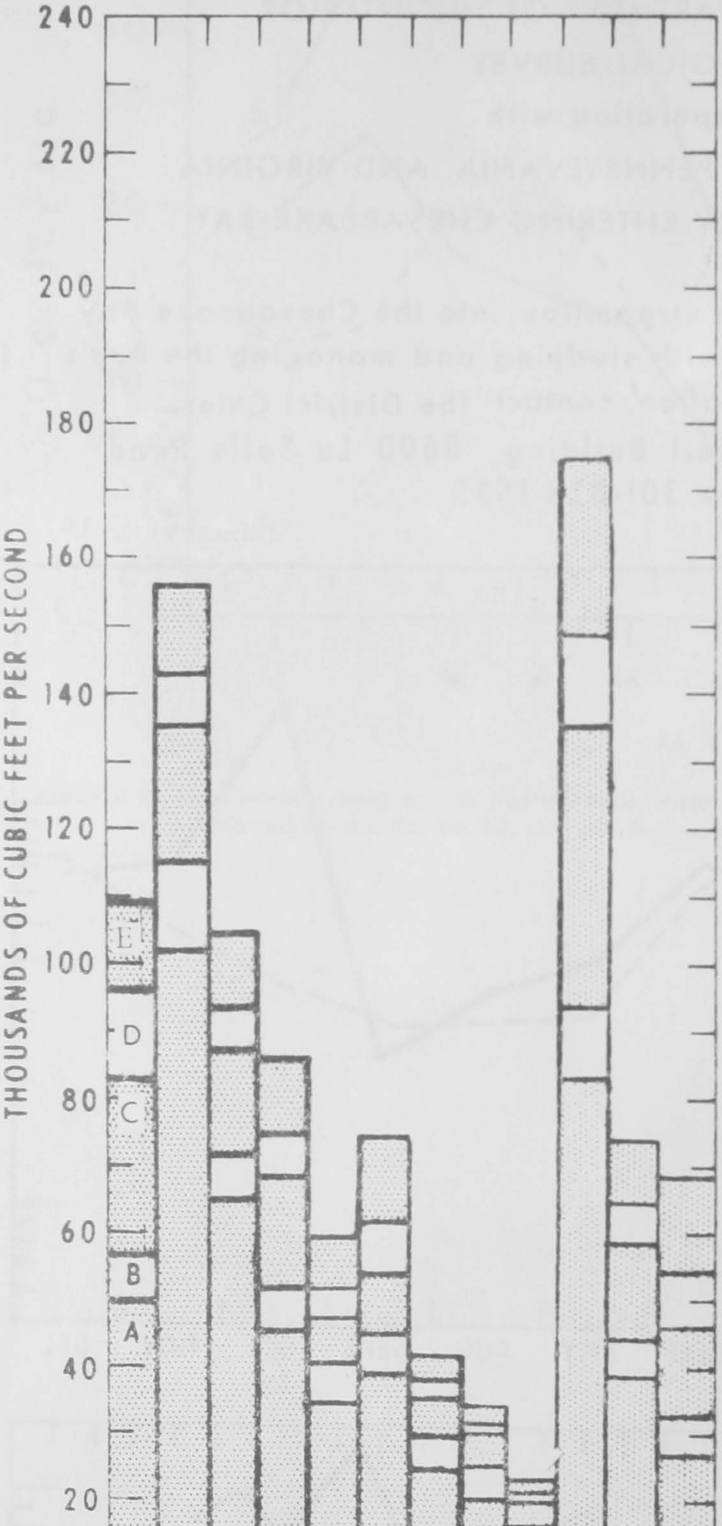
A monthly summary of cumulative streamflow into the Chesapeake Bay designed to aid those concerned with studying and managing the Bay's resources. For additional information, contact the District Chief, U.S. Geological Survey, 208 Carroll Building 8600 La Salle Road Towson, Maryland 21204 Phone 301-828-1535

January 1, 1977





ESTIMATED CUMULATIVE STREAMFLOW ENTERING CHESAPEAKE BAY ABOVE INDICATED SECTIONS BY MONTHS, DURING 1976



CUMULATIVE INFLOW TO CHESAPEAKE BA
AT INDICATED CROSS SECTIONS

A	Mouth of Susquehanna R.
B	Above mouth of Potomac R.
C	Below mouth of Potomac R.
D	Above mouth of James R.
E	Mouth of Chesapeake Bay

ESTIMATED CUMULATIVE STREAMFLOW ENTERING CHESAPEAKE BAY

		Cubic feet per second at section				
YEAR	MONTH	A	B	C	D	E
1975	January	53,000	60,600	76,400	85,000	97,600
	February	86,100	97,800	124,600	136,200	155,600
	March	83,000	94,500	132,000	151,300	185,000
	April	50,700	57,800	77,000	84,500	96,700
	May	59,000	67,800	93,500	104,100	121,800
	June	42,500	48,000	62,700	68,300	77,700
	July	19,500	24,000	36,000	43,600	56,100
	August	9,460	13,000	19,700	23,600	30,200
	September	86,100	97,800	128,600	138,600	155,100
	October	66,700	76,800	99,600	106,000	118,000
	November	42,500	48,000	63,000	68,400	77,400
	December	38,100	43,600	54,400	58,700	66,000
	Mean	53,100	60,800	80,600	89,000	103,100
1976	January	49,300	56,200	82,800	96,000	118,200
	February	102,000	114,800	134,900	142,700	155,400
	March	64,600	72,200	87,100	93,700	104,400
	April	45,700	51,800	68,200	74,900	85,900
	May	34,800	40,300	47,600	52,000	59,400
	June	39,200	44,700	53,800	61,600	74,400
	July	25,000	29,900	35,800	38,000	41,900
	August	20,900	25,400	30,100	31,300	34,300
	September	12,500	16,400	20,200	21,100	22,900
	October	82,400	93,900	135,000	148,500	173,900
	November	38,600	44,200	58,600	64,200	73,400
	December	27,200	32,300	45,900	54,400	68,300
	Mean	45,200	51,800	66,700	73,200	84,400

Paper 17

CLIMATIC CONDITIONS RELATED TO THE FISH KILL AND ANOXIA OFF NEW JERSEY DURING THE SUMMER OF 1976[1]

Reed S. Armstrong[2]

INTRODUCTION

A massive fish kill in the bottom waters over the middle continental shelf off New Jersey occurred during the summer of 1976. Beginning in late June 1976, dead or dying fish and shellfish were sighted off the northern New Jersey coast and, through the summer, the fish kill area expanded continuously southward. Low oxygen or anoxic conditions accompanied the fish kills (Bulloch 1976). By mid-September the region of extensive fish mortalities covered an area of about 2,100 square miles (5,400 km^2).[3]

Observations in August 1976 indicated that the fish kill was probably related to the presence of exceptionally low oxygen concentrations in the bottom waters on the shelf.[4] By mid-October, oxygen concentrations in the bottom waters had returned to near normal conditions. Comparison of the August 1976 data with historic August observations from the National Oceanographic Data Center (NODC) archives indicates the temperature of the waters below the thermocline and oxygen concentrations in the surface layer were not unusual in 1976

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[1] Taken from: Armstrong, R. S. 1977. "Climatic conditons related to the occurrence of anoxia in the waters off New Jersey during the summer of 1976." In Oxygen Depletion and Associated Environmental Disturbances in the Middle Atlantic Bight in 1976, p. 17-35. Tech. Ser. R. No. 3, Northeast Fisheries Center, NMFS, NOAA

[2] Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

[3] Steimle, F. 1976. A summary of the fish kill - anoxia phenomenon off New Jersey and its impact on resource species, p. 5-11. In J. H. Sharp (editor), Workshop Report, Anoxia on the Middle Atlantic Shelf during the Summer of 1976, Washington, DC, October 1976.

[4] Data provided by Northeast Fisheries Center, NMFS, NOAA, Highlands, NJ 07732.

(Fig. 17.1). Therefore, any physical phenomena related to the anoxic condition in the bottom waters must have occurred earlier.

To define environmental conditions that might have led to anoxic conditions, various sets of historical and climatological data were examined. The data used and their sources were:

Monthly mean river discharge for the Delaware River and Hudson River, and cumulative discharge into Long Island Sound, provided by the U.S. Geological Survey.

Monthly mean sea surface temperature, compiled from ship reports and published in *gulfstream* (National Weather Service, January 1975-August 1976) and in *The Gulf Stream Monthly Summary* (U.S. Naval Oceanographic Office, January 1966-December 1974).

Monthly mean shore station temperatures at tide stations (Sandy Hook, Atlantic City, and Cape May, NJ), acquired from the National Ocean Survey, NOAA.

Historical oceanographic station data, including dissolved oxygen observations, provided by the National Oceanographic Data Center, Environmental Data Service, NOAA.

In addition, data from oceanographic stations occupied in the area in 1976 were provided by the Sandy Hook Laboratory of NMFS and by the Atlantic Oceanographic and Meteorological Laboratories of NOAA'S Environmental Research Laboratories.

CLIMATOLOGICAL CONDITIONS

An examination of climatological records indicates that spring essentially began one to two months early in 1976. Comparison between the mean and 1976 annual cycles of warming and cooling in the surface waters off New Jersey (Fig. 17.2) indicates that in 1976 the waters began warming at least one month earlier than in any of the preceding 10 years (February vs. March and April). The early warming in 1976 is also indicated in shore station water temperature records, where at Sandy Hook the increase in water temperatures in February over January 1976 represented the largest warming for those months for the period of record (32 years). For the longer record of shore station temperatures at Atlantic City (1912-1920, 1923-1969, 1972-1976), the January-February 1976 warming was exceeded only once (1927). In addition, the usual spring increase in river discharge for the Delaware and Hudson Rivers (Fig. 17.3) began about two months early in 1976, which would cause an earlier than normal freshening of surface waters over the shelf. Spring increase in discharge into Long Island Sound was also two months early. These two conditions, early warming and lowering of surface salinities from early occurrence of high discharge, would establish stratification of the water column some one to two months early.

OXYGEN CYCLE AND STRATIFICATION

The annual cycle of dissolved oxygen in the subpycnocline waters is shown in Figure 17.4, which is a compilation of historic observations from the NODC archives for a 1-deg square off New Jersey (39N-40N, 73W-74W). Also included in the compilation were values collected in July 1957.[5] For this analysis oxygen measurements at the greatest sampling depth for each station with bottom depths >20 m and <60 m were plotted by month, regardless of year of observation, and a mean annual trend was derived from the plotted values. Data were available in all 12 months. They were obtained from 77 stations (28 cruises, 12 years).

During fall and winter, cooling at the surface of the Shelf Waters causes overturning, which mixes the waters from surface to bottom and raises bottom oxygen concentrations to equal surface concentrations. Surface cooling, overturning, and the resulting increase in bottom oxygen concentrations typically continue into March (Fig. 17.4), when surface warming begins. Also, surface salinities decrease as spring river discharge increases, establishing stratification. The strengthening of stratification and its persistence through spring and summer limits vertical replenishment of oxygen into the subpycnocline waters on the shelf, where dissolved oxygen is normally depleted by biological activity. The persistence of the cold core over the middle shelf through spring and summer, and the strong temperature gradient of the Shelf Water/Slope Water front over the continental slope, provide evidence of limited lateral mixing and oxygen replenishment by advection from offshore. The condition of limited vertical and horizontal exchange implies that through spring and summer the bottom water on the shelf is a somewhat stagnant water mass in which utilization of oxygen is greater than replenishment. Subpycnocline oxygen values steadily decrease (Fig. 17.4) from the onset of stratification in March until surface cooling and overturning begin breaking up the stratification in September.

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[5] Woods Hole Oceanographic Institution. 1961. Biological, chemical, and radiochemical studies of marine plankton. Reduced data report, Appendix C to Ref. No. 61-6.

APPLICATION OF OXYGEN MODEL FOR 1976

Assuming that the early warming and early spring river discharge in 1976 established stratification two months earlier than usual (January instead of March), and assuming that oxygen depletion progressed at typical rates, a trend for subpycnocline oxygen concentrations was formulated (Fig. 17.4). In this formulation the normal trend curve for the months of declining oxygen concentrations of Figure 17.4 was shifted to the left two months, adjusted downward so that the beginning point coincided with the typical January value, and extrapolated for the additional two months. This shows: 1) maximum oxygen concentration was not only achieved earlier, but also at a lower value (6.5 ml/l in January 1976 vs. 7.1 ml/l in a normal March); 2) dissolved oxygen fell to 3.0 ml/l in June, which is equivalent to the mean annual August minimum; and 3) dissolved oxygen continued to decrease to 0 ml/l in July. Subsequent to developing this oxygen trend for 1976, some actual observations of subpycnocline oxygen concentrations were received from AOML (Atlantic Oceanographic and Meteorological Laboratories) surveys as part of the MESA (Marine Ecosystems Analysis) New York Bight Project. The correspondence with the AOML observations (Fig. 17.4) seems to support the contention that anoxic conditions resulted from a lengthened period of near stagnation in the bottom waters which, in turn, was caused by the onset of stratification one to two months earlier than normal.

An additional feature during the summer of 1976 was the occurrence of a distinctly larger than normal plankton population throughout the Shelf Waters of the Mid-Atlantic Bight during spring, principally because of an unusual bloom of _Ceratium_ phytoplankton. By summer there was a large mass of dead _Ceratium_ cells on the New Jersey shelf, representing a larger than normal decaying biomass. The continued high rate of oxygen depletion of early summer and the maintenance of anoxic conditions through late summer may be attributed to the large mass of decaying _Ceratium_.

REGIONAL ASPECTS OF THE 1976 FISH KILL

Anoxic conditions and the resulting fish kill were apparently limited to the Shelf Waters off New Jersey and did not develop in waters of adjacent shelf regions. Historical oxygen observations were examined to explain the limited extent of anoxic conditions. An analysis similar to the one presented in Figure 17.4 determined the annual cycle of near bottom oxygen concentrations for a 1-deg square off Long Island (40N-41N, 72W-73W). Historic observations compiled for this analysis came from 96 stations (32 cruises, 14 years) with observations in all months except April.

Off Long Island, as off New Jersey, maximum bottom oxygen concentrations normally occur in March, decrease in spring and summer, and begin rising in September. Similar to the cycle in New Jersey Shelf Waters, the annual cycle of dissolved oxygen off Long Island reflects the seasonality of density stratification. Oxygen decrease in this 1-deg square off Long Island proceeds more rapidly during spring than off New Jersey, but less rapidly during summer (Fig. 17.5a). Sea surface temperatures and discharge rates into Long Island Sound and from the Hudson River in 1976 indicate that stratification should have been established one to two months earlier than normal off Long Island, as it was off New Jersey. Assuming that stratification became established two months earlier than normal, a trend for 1976 was developed for the waters off Long Island, beginning with the typical value for January (6.5 ml/l). This curve is shown in Figure 17.5b, along with the one formulated for New Jersey bottom waters. Given similar anomalous events for the two areas (two-month-early spring and comparable Ceratium bloom), bottom oxygen off Long Island should not have gone much below 2 ml/l in 1976.

The differences in the annual cycle of oxygen concentration between the two areas most likely are the result of bathymetric conditions. A broad bank (40-60 m depth) exists off Long Island. A similar bank is present off New Jersey, but it is about 20 m shallower. The anoxic condition in 1976 developed on the shallow bank off New Jersey, which is the region where the lowest oxygen typically occurs (Fig. 17.1). The thinner subpycnocline waters off New Jersey would have a lesser volume of water, and hence a lesser volume of oxygen, than the waters off Long Island. In August 1949, a cruise that transitted both areas found the bottom of the pycnocline at a depth of about 25 m over the banks of both New Jersey and Long Island. Thickness of the bottom water layer off New Jersey was only about 15 m, whereas it was about 30 m off Long Island. Applying the ratio of these values to oxygen concentrations, it could be argued that twice as much oxygen is typically available below the pycnocline off Long Island than off New Jersey.

Shelf Waters south of New Jersey (off the Delmarva Peninsula) also experienced early warming in 1976 and would probably be under influence of the early, high river discharge. The lack of fish kills and anoxic conditions in this area in 1976 also is attributed to bathymetric differences. Off the Delmarva Peninsula the continental shelf is only about half as wide as off New Jersey and Long Island, which allows for greater cross-shelf exchange and oxygen replenishment. Historic observations in the NODC archives for the waters off the Delmarva Peninsula were too few to develop an annual cycle of bottom oxygen.

PREVIOUS FISH KILLS

In the same area as the fish kill and anoxia development of 1976, three previous fish kills have been reported: September through early October 1968 (Ogren and Chess 1969), October 1971 (Young 1973), and August 1974.[6] Apparently none of these earlier fish kills was as extensive or enduring as the 1976 kill. Low oxygen conditions in the bottom waters accompanied all of the fish kills. Climatological records of sea surface temperature from shore station reports and discharge rates for the Hudson River for the last 30 years (1947-76) were examined for conditions similar to those of 1976. During this 30-yr period, high discharge (arbitrarily defined as >150% of the monthly mean) occurred five times in January (1949, 1950, 1952, 1973, and 1974), and three times in February (1951, 1954, and 1976). Shore station temperature records for Sandy Hook and Atlantic City indicated early warming of the water (monthly mean for February warmer than for January) occurring 12 times at Sandy Hook and 9 times at Atlantic City. No observations were made in 1970 and 1971 at Atlantic City, which were two of the years of early warming at Sandy Hook. Coincidence of early warming and high discharge occurred in 1949, 1952, 1954, 1974, and 1976. Therefore, these five years had the potential to develop low oxygen conditions as a result of early stratification. For the 30-yr record, the highest warming rates and record highest discharge in February all occurred in 1976. Included in the years of potential early stratification is 1974, one of the times of a reported fish kill, but not included are the other two instances.

A significant point here is that the fish kills of 1974 and 1976 occurred during summer, but in 1968 and 1971 they occurred during fall. The implication is that very low oxygen conditions may result from either an early spring or a late fall, either of which would lengthen the period of stratification. Only surface temperatures were examined to determine the late arrival of fall because river discharge in summer and fall is typically small (the highest discharge of the 30-yr record for August is less than the monthly means for December, January, and February, and the highest discharge for September is about the same as the means for December, January, and February). Sea surface temperature records from Atlantic City show that August was typically the warmest month and September was warmer than August only seven times from 1947 to 1976. The instances of higher September temperatures were in 1948, 1957, 1959, 1965, 1966, 1968, and 1971. Of these years the highest rate of warming

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[6] C. J. Sindermann, Northeast Fisheries Center, NMFS, Highlands, NJ 07732. Pers. commun., November 1976.

The role that plankton blooms play in the generation of anoxic conditions is not clear, but they may be a necessary ingredient.

Although the occurrence of very low oxygen concentrations is bound to have a catastrophic effect on benthic organisms and bottom fishes, perhaps an equally severe impact may develop in the recruitment of fish stocks because of the cumulative effect of frequent recurrence of low oxygen conditions. Considering the 12 instances in the last 30 years when climatic conditions may have led to very low oxygen concentrations, such conditions occurred every two to three years from 1948 through 1959, and again from 1965 to 1976 (12 years with six potential occurrences each period). During these two 12-yr periods, prospects for rebuilding abundances of bottom species might have been severely limited. During the intervening five years (1960-64), when there were no indications of either early spring or late fall kills in any of the years, maintenance of abundance might have been considerably better.

LITERATURE CITED

BULLOCH, D. K.
1976. Ocean kill in the New York Bight--summer 1976. Underwater Nat. 10(1):4-12.

OGREN, L., and J. CHESS.
1969. A marine kill on New Jersey wrecks. Underwater Nat. 6(2):4-12.

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1973. A marine kill in New Jersey coastal waters. Mar. Pollut. Bull. 4:70.

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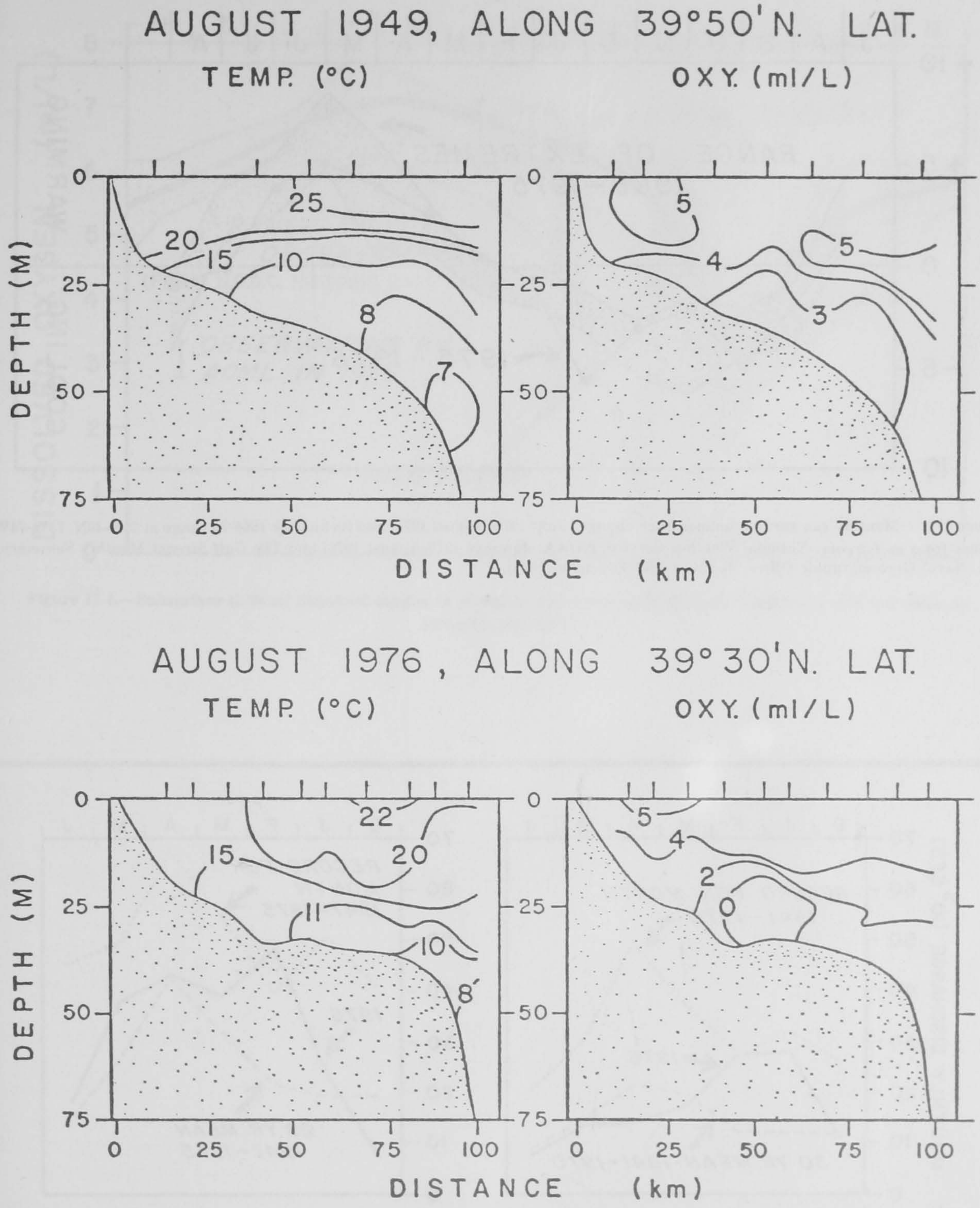

Figure 17.1.—Temperature and dissolved oxygen structure off central New Jersey (August 1949 data from National Oceanographic Data Center archives; August 1976 data from Sandy Hook Laboratory, NMFS).

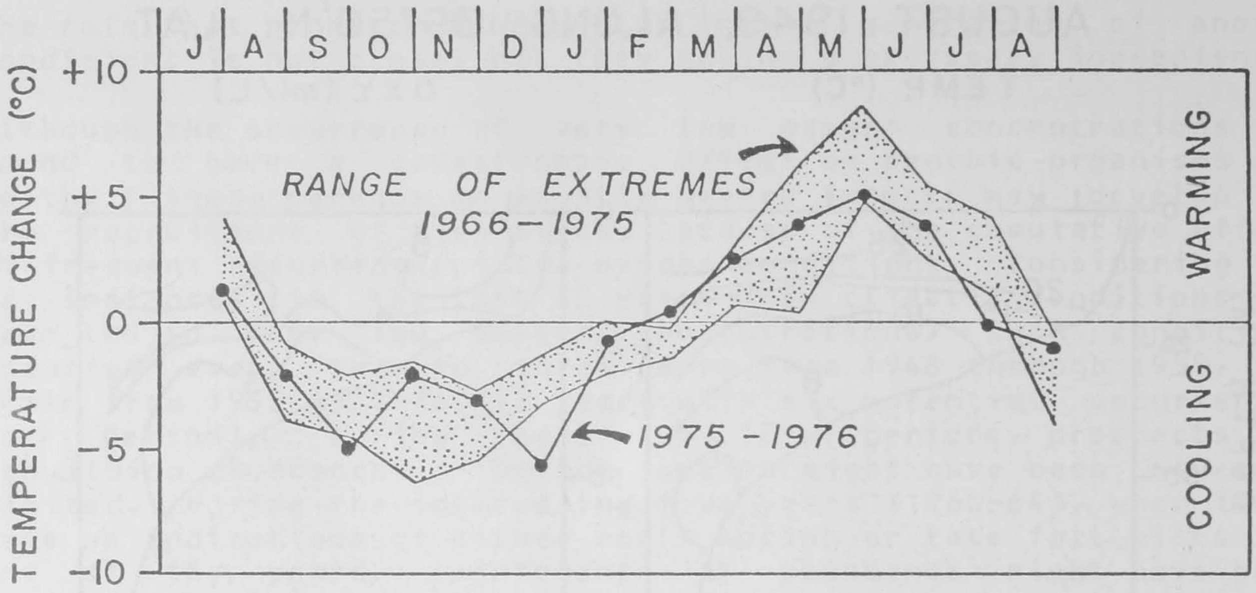

Figure 17.2.—Monthly sea surface temperature change, July 1975-August 1976, and its historic 1966-75 range at 39N-40N, 73W-74W (values from *gulfstream*, National Weather Service, NOAA, January 1975-August 1976, and *The Gulf Stream Monthly Summary*, U.S. Naval Oceanographic Office, January 1966-December 1974).

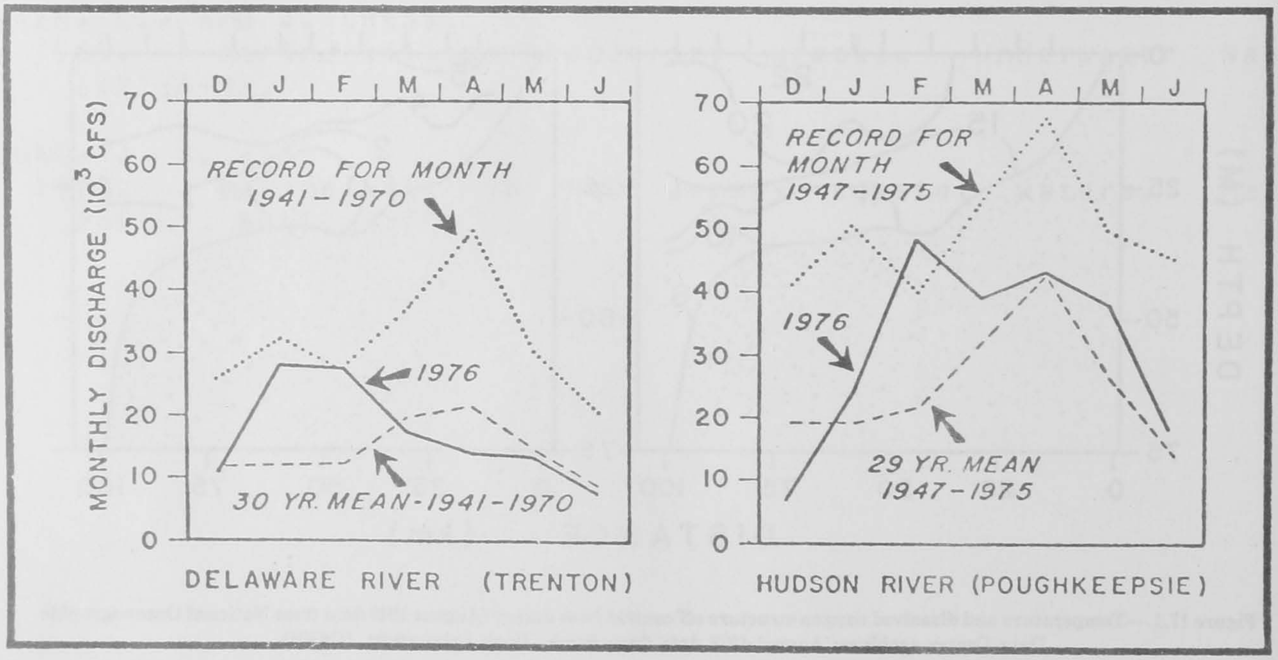

Figure 17.3.—Monthly river discharge rates for 1976 and long-term means and extremes (from U.S. Geological Survey provisional records).

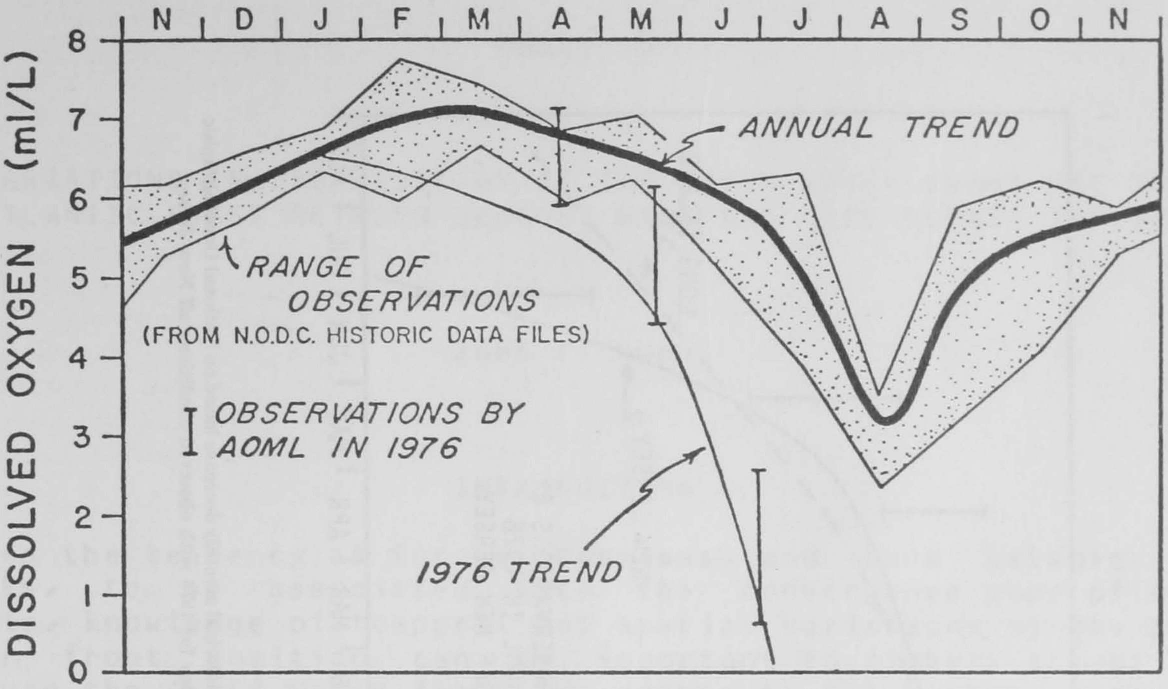

Figure 17.4.—Subsurface (>20 m) dissolved oxygen as predicted and observed in 1976 and historical range and mean at 39N-40N, 73W-74W.

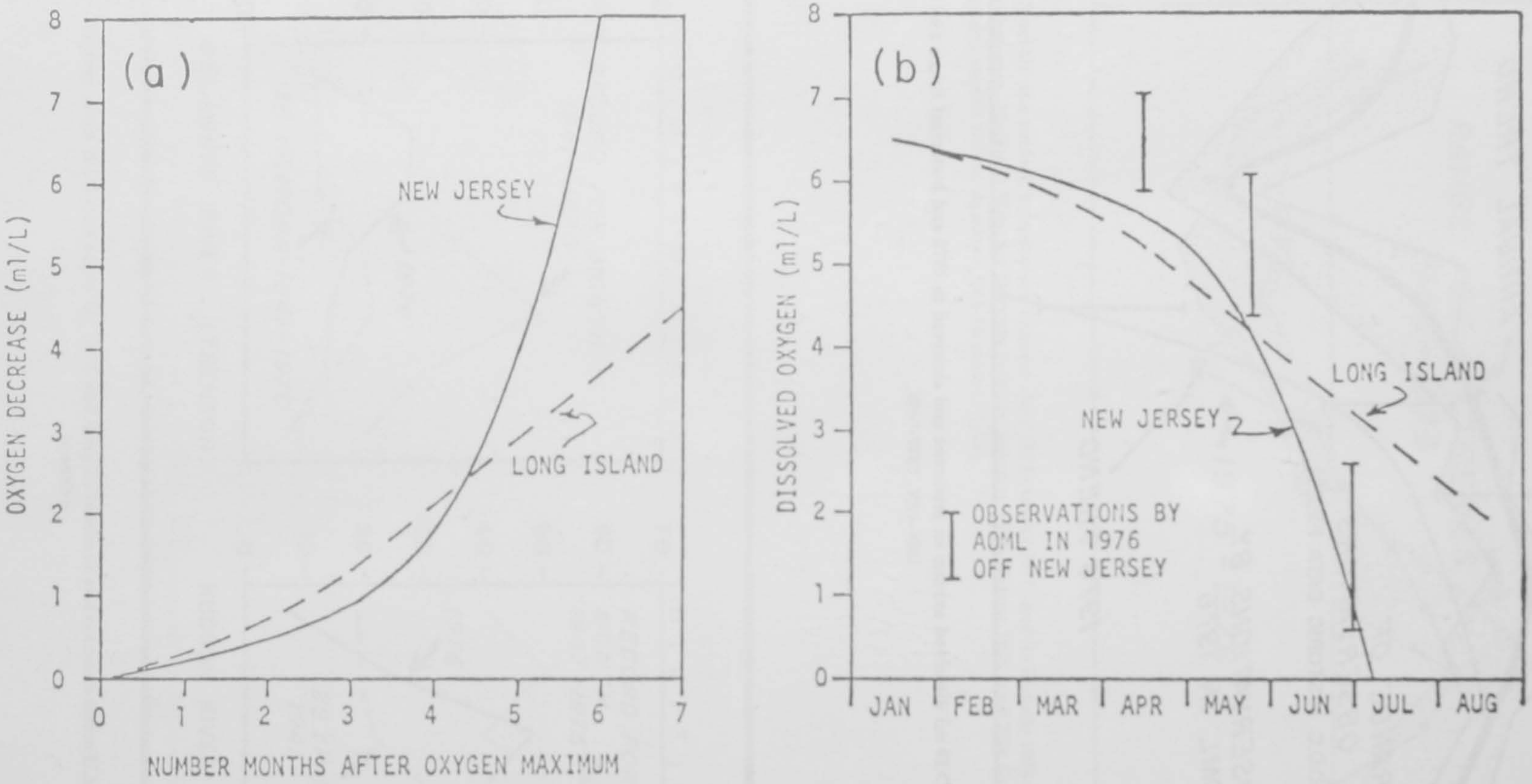

Figure 17.5.—Trends of bottom oxygen and the monthly decrease off New Jersey and off Long Island. a) Historical monthly decrease based on National Oceanographic Data Center archived data and extended for a prolonged period of stratification. b) Predicted trends for 1976 with observed conditions off New Jersey.

Paper 18

VARIATIONS IN THE POSITION OF THE SHELF WATER FRONT OFF THE ATLANTIC COAST BETWEEN GEORGES BANK AND CAPE ROMAIN IN 1976

John T. Gunn[1]

INTRODUCTION

Due to the tendency of forage organisms, and thus pelagic fish stocks, to be associated with the convergence zone of ocean fronts, knowledge of temporal and spatial variations of the Shelf Water front position can be important to fishery scientists. Because the Shelf Water front may extend to the bottom over the continental shelf, there is also the possibility of an effect on benthic and demersal species. It is anticipated that a better understanding of the interaction of different species with ocean fronts also may lead to more efficient fishing efforts.

This report is a product of a monitoring effort using infrared satellite imagery which records thermal features of the sea surface. Previous reports (Ingham 1976; Gunn 1978) have discussed front variations from June 1973, when data first became available, through 1975. This report will discuss the data for 1976 and its comparisons with previous years.

DATA

The basis of this study is the Experimental Gulf Stream Analysis Charts[2] (Fig. 18.1), drawn from the best infrared NOAA satellite image of the week or, if large gaps occur on daily charts due to clouds or observational limits, a composite of several partial images. These charts show the position of the surface thermal boundaries between the following oceanic features: Shelf Water, Slope Water, Gulf Stream, and warm and cold core Gulf Stream eddies.

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[1] Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

[2] Produced by Environmental Sciences Group, National Environmental Satellite Service, NOAA, Washington, DC 20233.

DATA ANALYSIS

To portray the variation of the Shelf Water frontal position, distances were measured to the front along 12 standard bearing lines from selected coastal points (Fig. 18.2). These bearing lines intersect the 200-m isobath at regular intervals (about 150 km) and are approximately perpendicular to it. The distances measured from each satellite chart are corrected for scale variation (+ or - 5%) from chart to chart and converted to kilometers. These distances are then reduced by the distance along each bearing line to the 200-m isobath. The resulting values represent the distance from the shelf edge, as defined by the 200-m isobath, to the front; positive values are seaward from this isobath.

Also, a measurement of the intrusion of Slope Water over Georges Bank was produced by measuring the area covered by the Slope Water on an overlay of the 200-m isobath. For this calculation, Georges Bank was defined as the area of the bottom at a depth <200 m and east of 69W in the Georges Bank region. The intrusions are expressed as a percentage of the Georges Bank area covered by Slope Water. Chart to chart scale variations are partly compensated for by using various scaled overlays.

WEEKLY FRONTAL POSITIONS

Inspection of the weekly frontal positions along a bearing line can suggest occurrences of excursions or intrusions and general spatial and temporal trends. Comparison between adjacent bearing lines allows the identification of events which affect more than one bearing line. Inspection of the individual weekly charts suggests possible causes such as Gulf Stream meandering or warm core eddies. The discussion of the different bearing lines is broken up into three regions: New England, Middle Atlantic, and Southern, in order to simplify discussion. There is some evidence in the data, however, of cohesiveness among the different groups.

New England - The three northernmost bearing lines (Fig. 18.3), originating from Casco Bay, ME, extend into the region where large amplitude Gulf Stream meandering and warm and cold core eddy production cause large fluctuations in the Shelf Water front position. Since the length scales of these phenomena are generally equal to or less than twice the separation of the bearing lines, this can lead to a biasing of the data and consequent misinterpretation. Consider, for example, the February-March period on the Casco Bay bearing lines. The graph of Casco Bay 120 indicates an intrusion which peaks at the beginning of March. The graph of Casco Bay 140 indicates an excursion that peaks at the same time, and the third graph, Casco Bay 160, shows a gradual offshore to onshore trend. The distance between the peak excursion and intrusion was approximately 50 km. Inspection of the weekly charts shows the formation of a large warm core eddy at the beginning of February. The Casco Bay 120 bearing line crossed the eddy and thus showed an intrusion of the front. The Casco Bay 140 bearing missed the eddy, but hit an area of Shelf Water entrained by a previous eddy, and thus showed an excursion of the Shelf Water front. The Casco Bay 160 bearing line measured a more realistic mean trend. Thus care must be used when interpreting short period fluctuations. Note that a similar occurrence took place in mid-July. Longer period trends are more reliable on these bearing lines, and better correlation exists from one bearing line to the next. The 2 1/2 month intrusion which showed up on the Casco Bay 120 bearing line from July to mid-September was caused by a large meander and warm core eddy formation which was also associated with a large increase in the area of Slope Water. Although the Casco Bay 140 line does not show strong evidence of this, the other two lines show definite shoreward displacements.

The Casco Bay 120 bearing line shows the greatest fluctuation of the three, with the Casco Bay 140 line showing large fluctuations only in the first three months of the year, and the Casco Bay 160 line showing only minor fluctuations during the whole year.

Middle Atlantic - This region consists of six bearing lines from Nantucket Island to Albemarle Sound (Figs. 18.3-18.5). On the first three bearing lines, Nantucket, Montauk Point, and Sandy Hook, a tongue of Slope Water moving offshore caused large fluctuations during January-March. The next event that affected a number of bearing lines was a large area of Slope Water formed in the beginning of July (also mentioned in the previous section). This resulted in a large intrusion observed on all six middle Atlantic bearing lines. Cloud cover obscured the event on the more southern bearing lines, but it was obvious that a large frontal displacement took place. On the Nantucket, Montauk Point, and Sandy Hook lines, this displacement appears to have lasted until the end of October, interrupted by a large excursion of the front in late August. The three most southern bearing lines in this region did not seem to recover as well and remained closer to their mean positions after this excursion. The excursion in late August was sudden, taking place in a week on some bearing lines.

Southern - The southern bearing lines suffer from large gaps in the data during the summer months due to cloud cover (Fig. 18.5). The number and amplitude of excursions and intrusions in this region were smaller than on the bearing lines farther north. The only well-correlated movement occurred on the Cape Fear and Cape Romain lines. A seaward excursion in late September and October changed to a significant intrusion in late November. Inspection of the weekly charts showed that during this period, the Gulf Stream had meandered offshore and a relatively large area of Slope Water forced the Shelf Water front to impinge on the coast.

MONTHLY MEAN FRONTAL POSITIONS

The monthly mean frontal positions are shown in Figure 18.6 for the three complete years of data collection. Care should be exercised in interpretation since the number of weeks averaged varies (due to lack of data because of clouds, etc.) and occasionally only one weekly value was available for the month (about 5% of the time).

Definite tendency for seasonality exists for the bearing lines from Casco Bay 120 to Sandy Hook. In all three years, these bearing lines tend to be more offshore from January to May than they are for the June to December period. There are exceptions to this, such as Casco Bay 120 in 1975, also Sandy Hook does not hold to this trend as well as the other bearing lines. However, the overall tendency was strong. The amplitude of this seasonal variation for most of the bearing lines was 30-40 km, although variations of 100-150 km exist.

Seasonal variation was not as consistent on the other bearing lines and on some, there was little indication of it. The Cape May and Cape Henry bearing lines show little seasonal variation, but seem to be affected by shorter period fluctuations and aperiodic occurrences. The Albemarle Sound bearing line showed a seasonal cycle in 1974 and 1975, being onshore the first part of the year and offshore the latter, but it did not show this cycle in 1976.

The three southern bearing lines suffer from gaps in the data, making it difficult to determine if seasonal variations do indeed exist on these bearing lines. The three bearing lines do correlate well among themselves, however, suggesting that they are affected by similar events.

YEARLY MEAN FRONTAL POSITION

The yearly mean shelf front position for 1976 agreed well with the position for the previous two years (Table 18.1; Fig 18.7a). Except for Casco Bay 120 and Sandy Hook, the 1976 positions were close to those for 1974 and 1975. The Casco Bay 120 mean position was considerably more seaward (about 40 km) and the position for Sandy Hook was slightly more shoreward (about

5 km). This was also evident in the monthly mean frontal ositions (Fig. 18.6) discussed above. It was also interesting o note that the seaward displacements of the yearly mean frontal osition from the general north-south trend, at Montauk Point and ape Henry, are evident in all three years.

he variability of the front, as reflected by the standard deviation (Table 18.1; Fig. 18.7b), increases in 1976 along the bearing lines from Nantucket to Cape Henry. Inspection of the weekly frontal position graphs seems to confirm this, with greater amplitude excursions and intrusions more prevalent in 1976.

INTRUSION OF SLOPE WATER OVER GEORGES BANK

The measurement of the area of Georges Bank covered by Slope Water confirms the seasonality of the shelf front in this region (Fig. 18.8). There are no intrusions of the Shelf Water front over Georges Bank in 1976 before the end of May and no large intrusions until July. This also agrees with previous years' data. Large intrusions occurred in the latter part of July and early part of August and September, with maximum coverages of 21%, 11%, and 16% respectively. Generally, Georges Bank was partly covered by Slope Water from July until November.

This type of seasonal coverage also occurred in the previous two years.

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INGHAM, M. C.
1976. Variations in the shelf water front off the Atlantic coast between Cape Hatteras and Georges Bank. In J. R. Goulet, Jr. (compiler), The environment of the United States living marine resources - 1974, p. 17-1--17-21. U.S. Dep. Commer., Natl. Oceanic Atmos. Admin., Natl. Mar. Fish. Serv., MARMAP (Mar. Resour. Monit. Asses. Predict. Program) Contrib. 104.

Table 18.1.--Sample size, mean separation, and standard deviation of Shelf Water front position along standard bearing lines, 1974-76.

	Sample size[2]			Mean separation[3]			Standard deviation		
Bearing line[1]	1974	1975	1976	1974	1975	1976	1974	1975	1976
Casco Bay 120°	30	38	30	45.4	72.2	119.6	70.9	59.0	76.1
Casco Bay 140°	31	38	33	35.4	0.4	39.7	64.0	22.6	46.6
Casco Bay 160°	36	41	37	6.1	-2.9	1.1	39.3	26.1	27.3
Nantucket 180°	37	35	40	0.6	-5.6	-1.1	38.5	37.8	55.6
Montauk Pt 150°	34	35	41	19.8	8.8	14.5	36.7	38.3	64.8
Sandy Hook 130°	36	35	43	1.2	-4.4	-17.0	46.8	45.0	57.8
Cape May 130°	38	34	44	4.1	-7.3	-2.5	31.8	34.8	46.4
Cape Henry 95°	40	32	41	17.4	7.3	6.6	36.4	39.5	47.1
Albemarle Sd 90°	40	31	41	-11.5	-16.7	-17.0	24.6	32.5	32.2
Cape Lookout 135°	24	31	37	-18.2	-24.5	-17.1	20.1	28.9	19.3
Cape Fear 140°	19	28	36	-20.2	-35.8	-29.6	40.5	38.4	29.2
Cape Romain 140°	21	22	32	-9.9	-40.2	-17.5	43.4	33.3	35.7

[1] See Figure 18.2.
[2] Number of weekly positions of front.
[3] Distance (km) of front from 200 m isobath; positive is seaward.

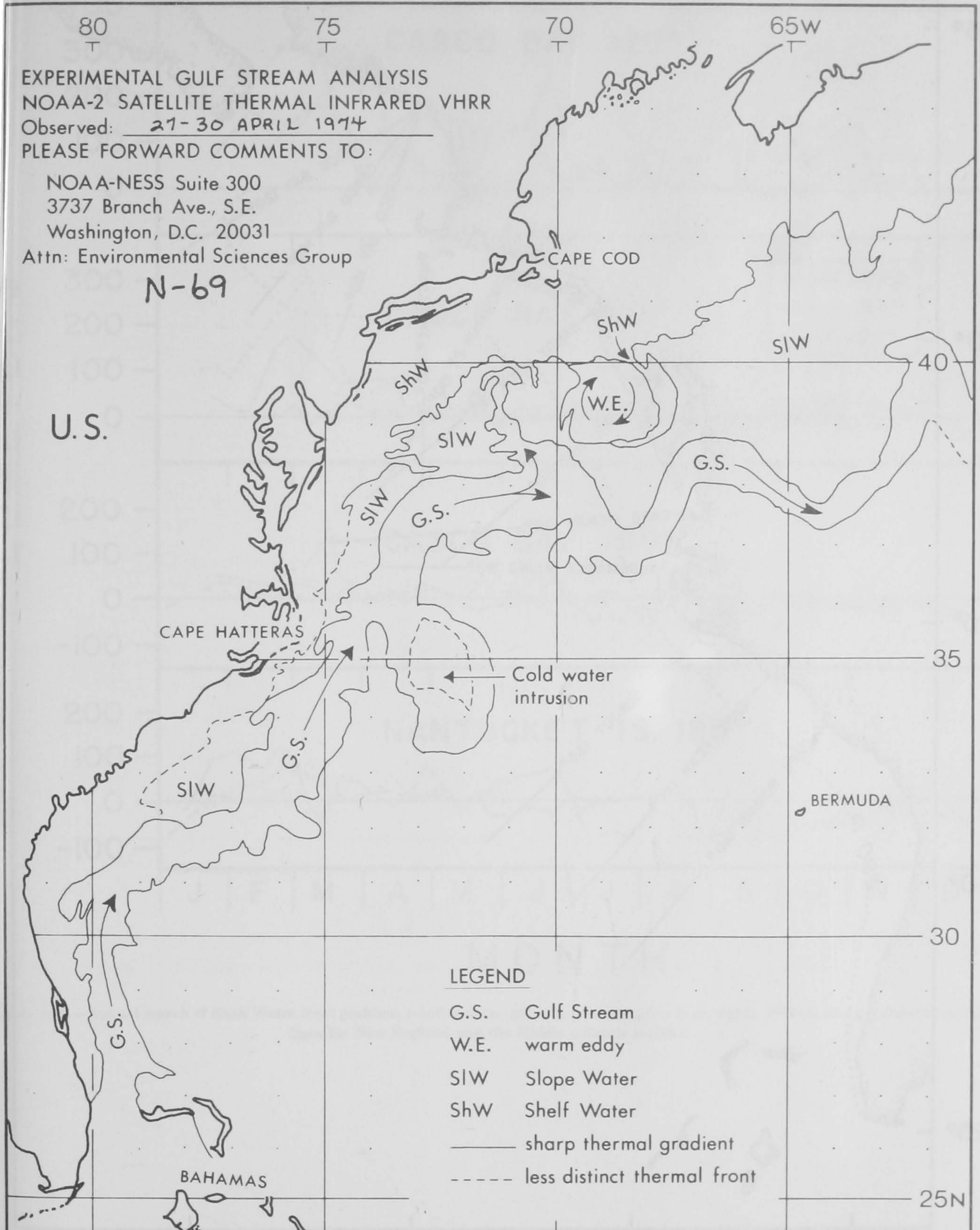


Figure 18.1.—Example of weekly Experimental Gulf Stream Analysis chart produced by Environmental Sciences Group, NESS, NOAA, Washington, DC.

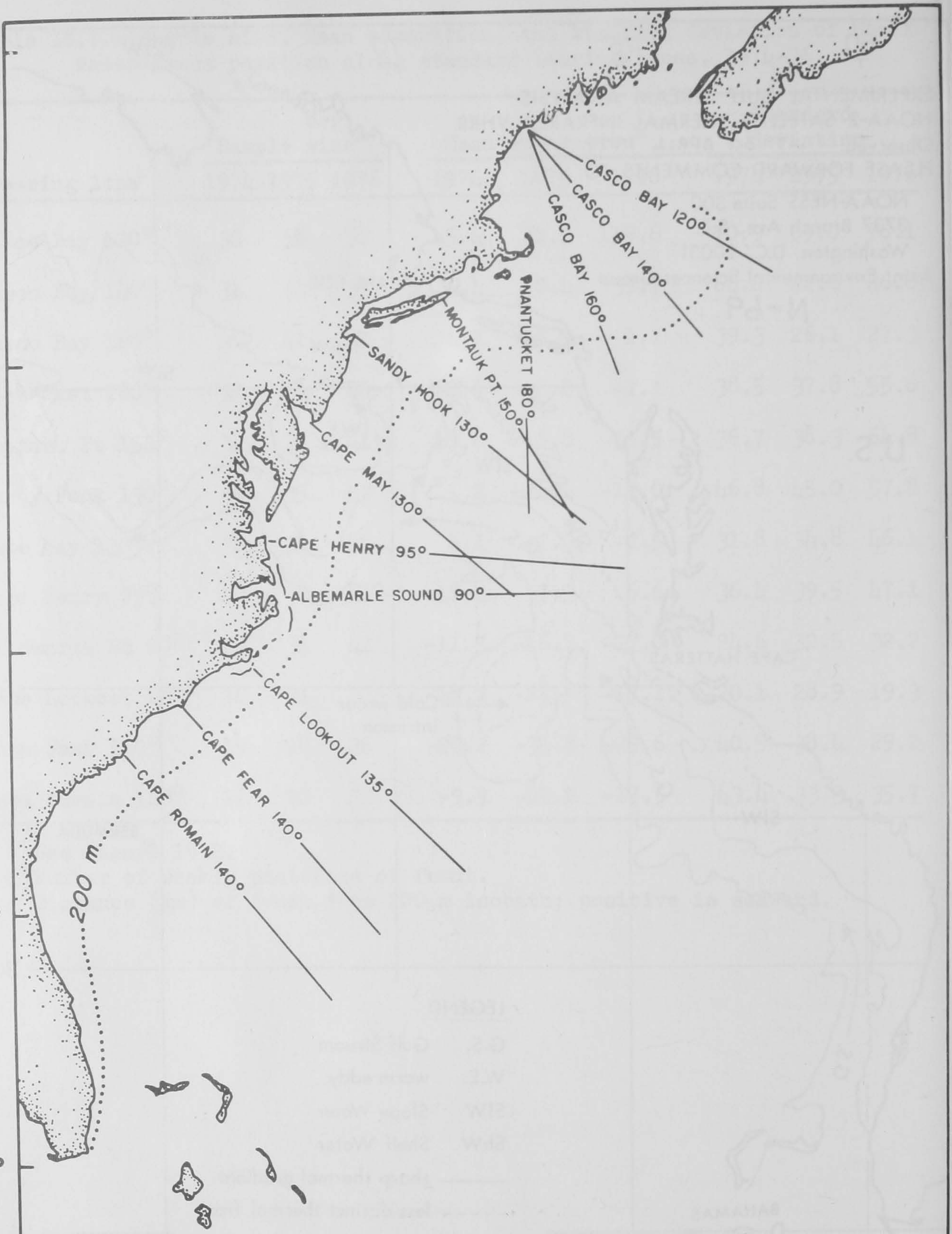


Figure 18.2.—Twelve standard bearing lines used in the portrayal of the time variations of the Shelf Water front positions relative to the 200-m isobath (dotted line).

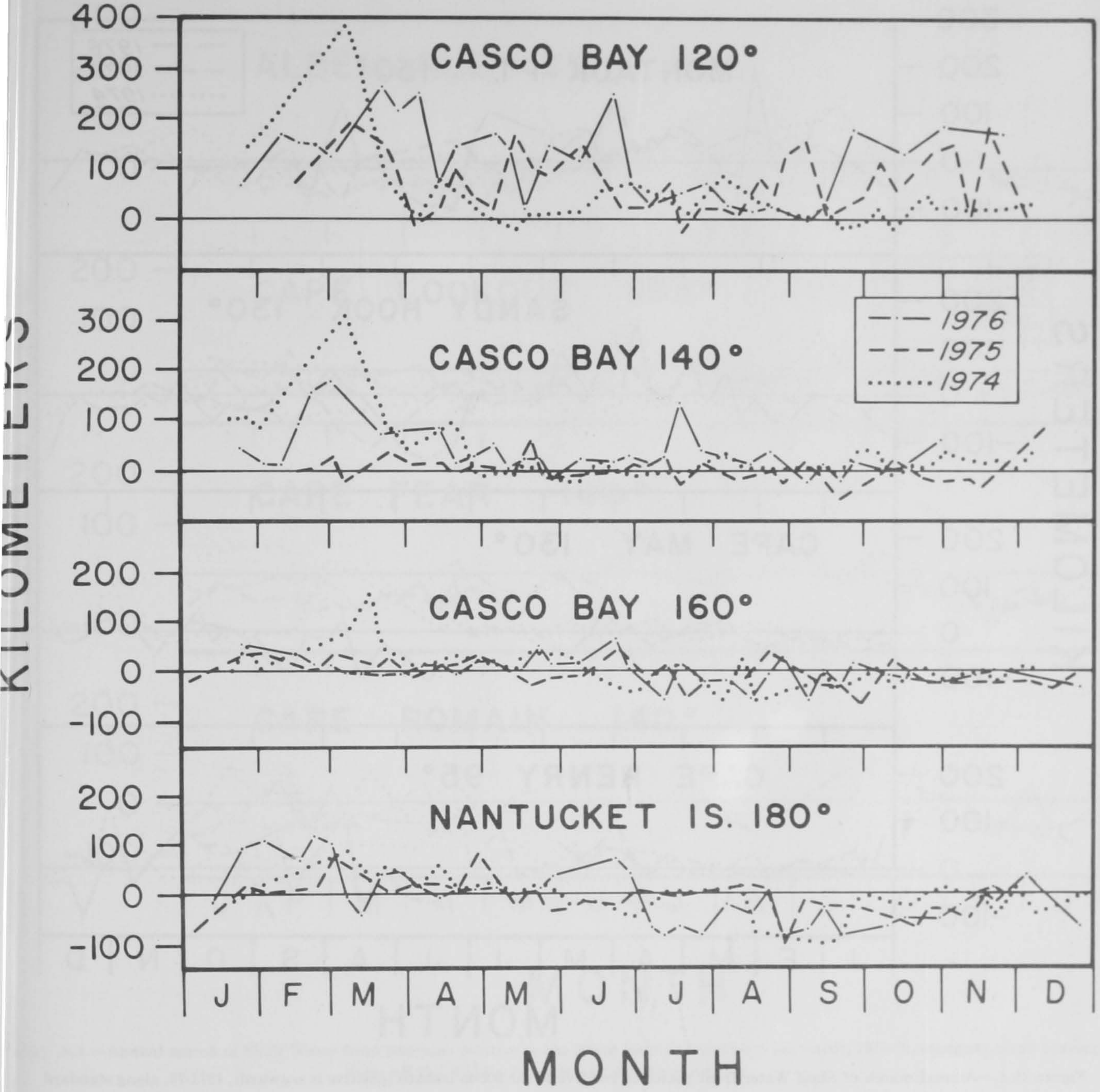


Figure 18.3.—Annual march of Shelf Water front positions relative to the 200-m isobath (positive is seaward), 1974-76, along standard bearing lines for New England and the Middle Atlantic regions.

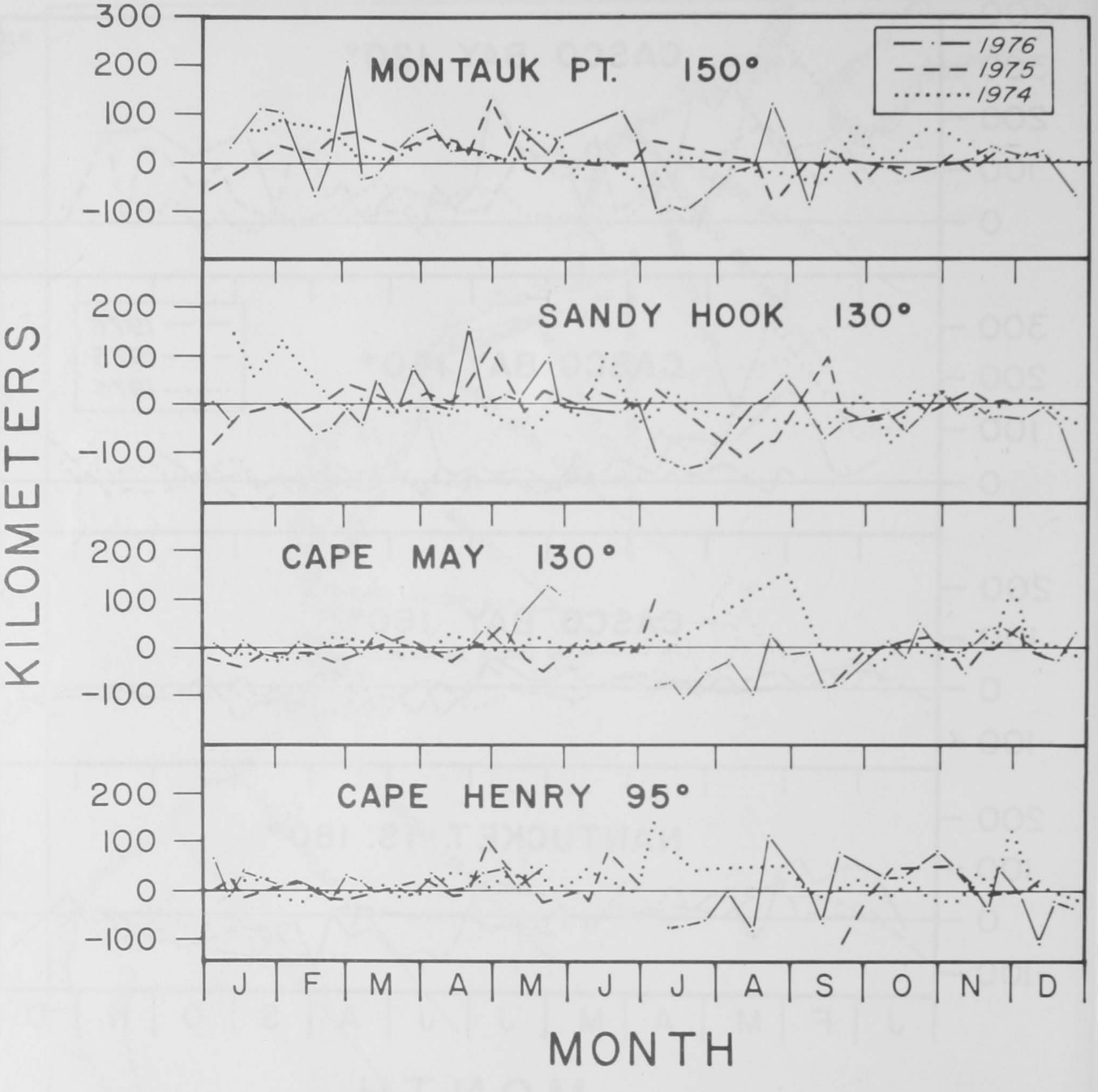
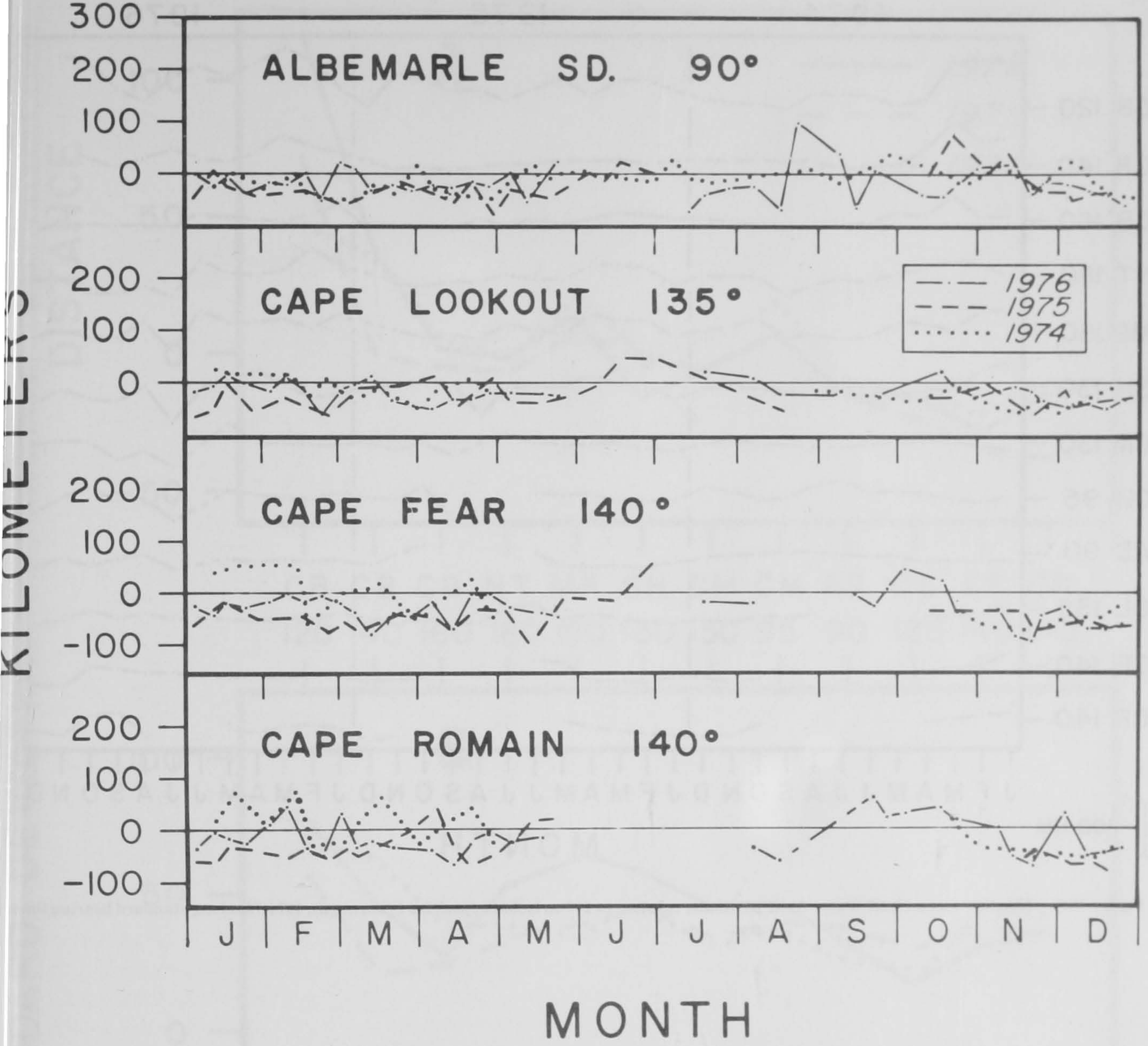


Figure 18.4.—Annual march of Shelf Water front positions relative to the 200-m isobath (positive is seaward), 1974-76, along standard bearing lines off the Middle Atlantic region.



igure 18.5.—Annual march of Shelf Water front positions relative to the 200-m isobath (positive is seaward), 1974-76, along standard bearing lines off the Middle Atlantic and southern regions.

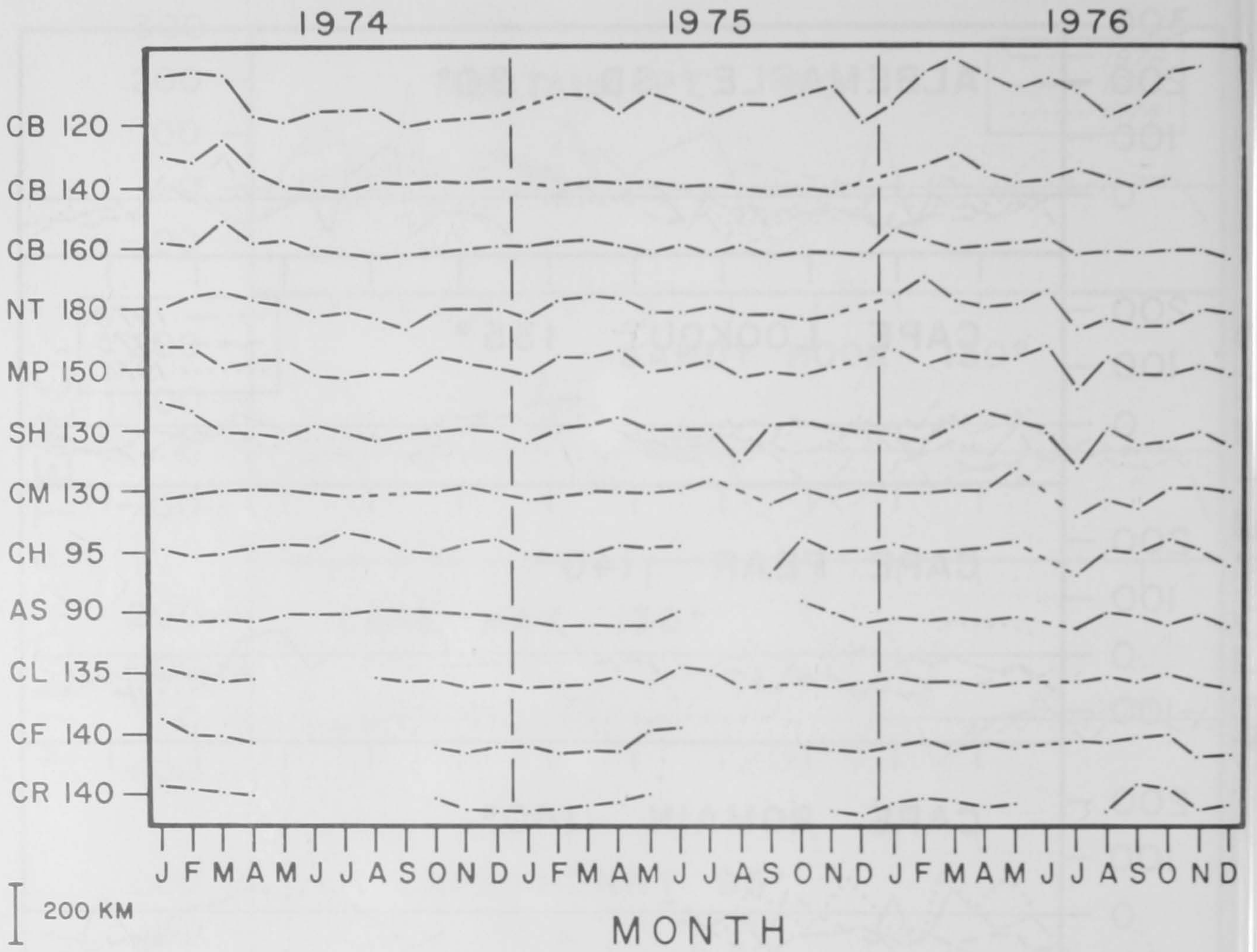


Figure 18.6.—Monthly mean Shelf Water front positions, relative to 200-m isobath (positive is seaward), 1974-76, along standard bearing line

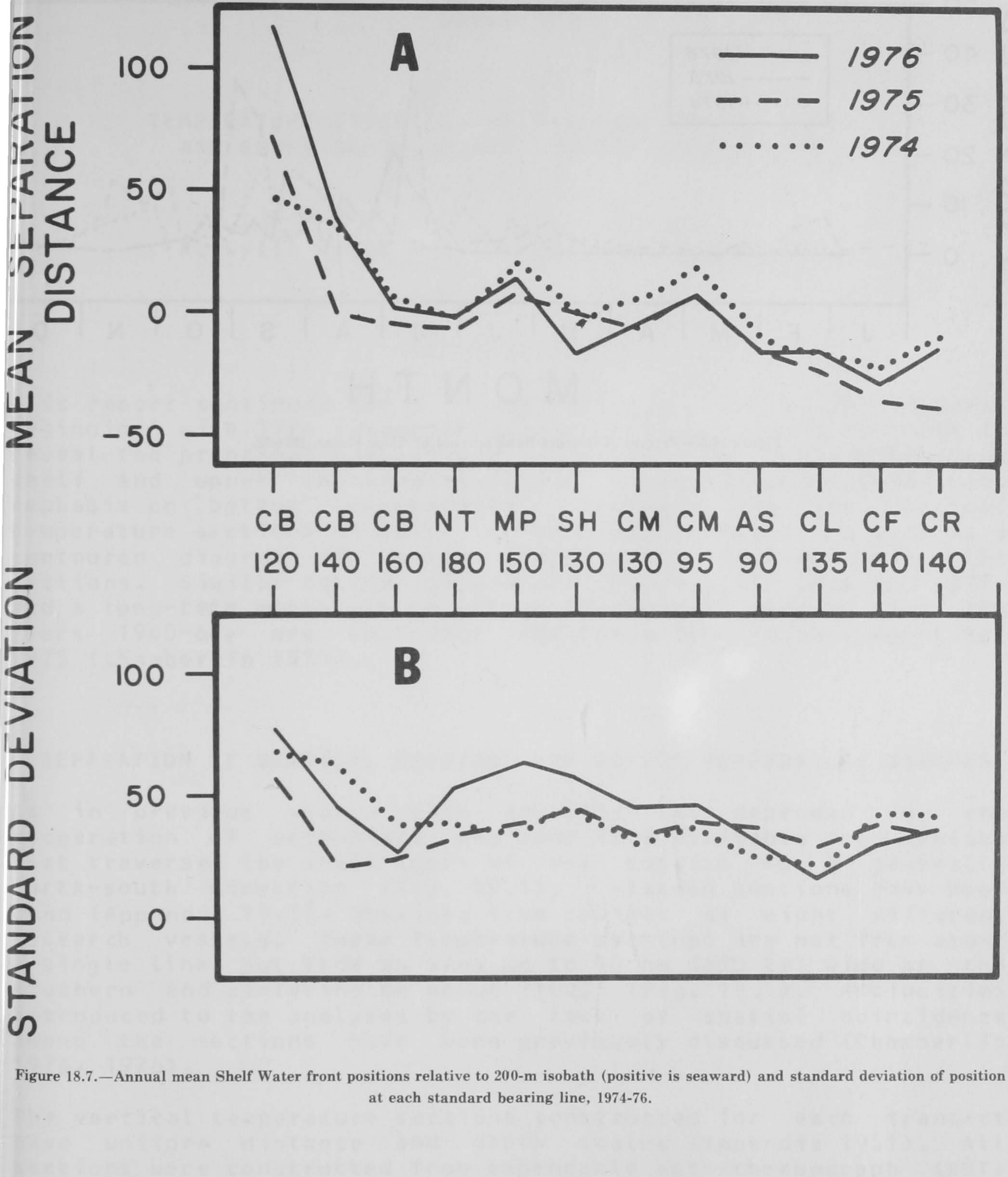


Figure 18.7.—Annual mean Shelf Water front positions relative to 200-m isobath (positive is seaward) and standard deviation of position at each standard bearing line, 1974-76.

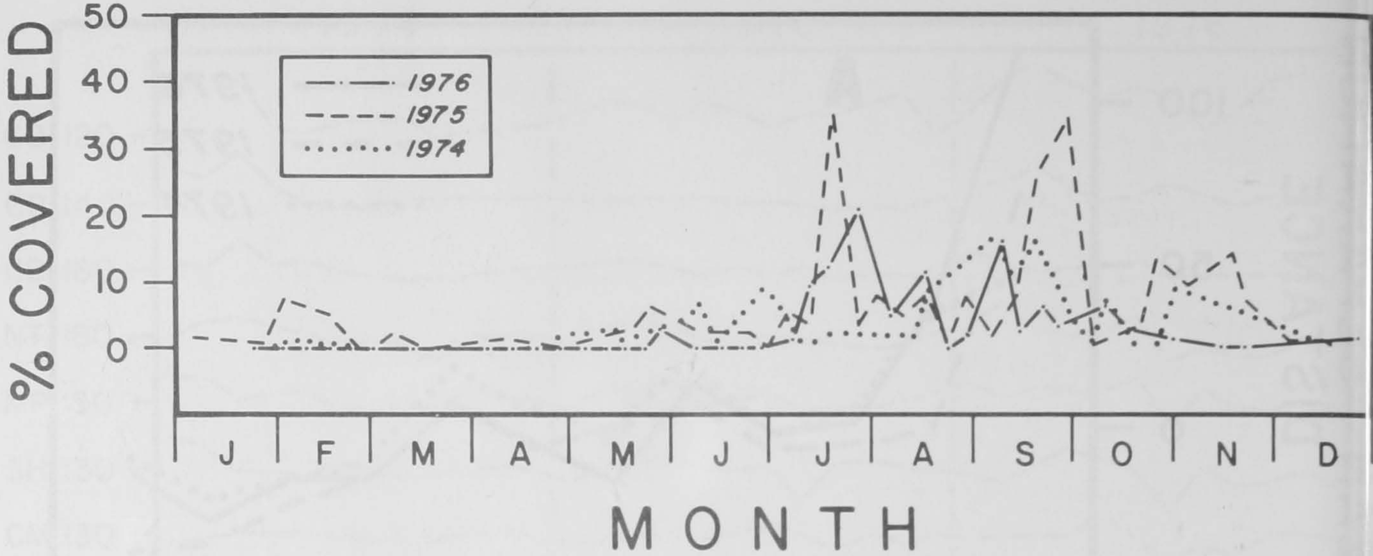


Figure 18.8.—Percent of Georges Bank covered by Slope Water, 1974-76.

Paper 19

TEMPERATURE STRUCTURE ON THE CONTINENTAL SHELF AND SLOPE SOUTH OF NEW ENGLAND DURING 1976

R. Wylie Crist and J. Lockwood Chamberlin[1]

INTRODUCTION

This report continues for a third year a series of analyses beginning with 1974 (Chamberlin 1976, 1978) that are intended to reveal the principal temperature variations on the continental shelf and upper continental slope south of New England, with emphasis on bottom temperatures. Included are the vertical temperature sections on which the analysis is based, as well as a contoured diagram of bottom temperatures derived from the sections. Similar bottom temperature diagrams for 1974 and 1975, and a long-term monthly mean bottom temperature diagram for the years 1940-66, are available for comparison in the report for 1975 (Chamberlin 1978).

PREPARATION OF VERTICAL SECTIONS AND BOTTOM TEMPERATURE DIAGRAM

As in previous years, this analysis has depended on the cooperation of scientists who made data available from cruises that traversed the shelf south of New England in a generally north-south direction (Fig. 19.1). Sixteen sections have been used (Appendix 19.1), obtained from cruises of eight different research vessels. These temperature sections are not from along a single line, but from an area up to 90 nm (170 km) wide at the southern end centering on about 71W00' (Fig. 19.1). Ambiguities introduced to the analyses by the lack of spatial coincidence among the sections have been previously discussed (Chamberlin 1976, 1978).

The vertical temperature sections constructed for each transect have uniform distance and depth scales (Appendix 19.1). All sections were constructed from expendable bathythermograph (XBT)

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[1] Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

data plotted directly from the traces, except section 7 which is based on mechanical bathythermograph data.

The bottom temperature diagram (Fig. 19.2), prepared by the same method as in previous years, is an interpretation of where isothermal surfaces intersected the bottom throughout the year (Chamberlin 1978).

The occurrence of warm core Gulf Stream eddies, numbered in accordance with Mizenko and Chamberlin (Paper 15), are indicated as duration lines at the bottom of Figure 19.2. The durations were determined from the Experimental Ocean Frontal Analysis (EOFA)[2] and from infrared imagery from NOAA environmental satellites. The duration lines are based on the same criteria used for the 1975 analysis (Chamberlin 1978), that is, the start of each line is on the approximate day when the western surface boundary of the eddy crossed 70W15' and the line ends the day the eddy completely passed south of 39N30'. Of the three eddies that apparently passed south of New England during 1976, only the last (eddy 76D) showed a clear surface temperature contrast in the satellite imagery, and thus could be tracked with assurance. The duration lines of the first two (eddies 76B and 76C) are dashed in Figure 19.2 because their times of passage are rather uncertain. Less strongly developed than eddy 76D, they showed no surface temperature contrast in the satellite imagery during their passages and were detectable only by inference on a few occasions from tongues of Shelf Water projecting into the Slope Water in the pattern generally associated with entrainment by an eddy.

HIGHLIGHTS OF TEMPERATURE SECTIONS

The following sections are illustrated in Appendix 19.1.

Section 1. NOAA RV *Kelez* Cruise 76-01, 4 February.
Temperatures in this short section from the inner shelf were 3C colder offshore to 7C colder inshore than in mid-December, seven weeks earlier (Chamberlin 1978). The water was mixed to a depth of about 20 m. The 1-2C temperature inversion in the underlying water indicated the presence of warm Slope Water near bottom on the outer shelf.

Section 2. NOAA RV *Kelez* Cruise 76-02, 9-10 February.
Thermal structure in this detailed section was unusually

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[2] Issued weekly by the U.S. Navy Oceanographic Office, Applications Research Division, Suitland, MD 20374.

complex. In the central part of the section, at depths below about 50 m, the vertically mixed Shelf Water was underlain by warm Slope Water containing an isolated 12-13C core that contacted bottom at depths around 90 m. Additional disruptions of the warm Slope Water were revealed by two much larger cells of 13C water at increasing middepths in the offshore part of the section. There was also a marked seaward excursion of the Slope Water front at the surface (10C at about 39N35'). Satellite imagery[3] revealed this excursion to have been more pronounced to the east of the section line. In addition, strong upwelling of deep Slope Water, causing marked reduction of bottom temperatures below 100-m depth, was evident in the section, as well as in Figure 19.2. The isolated body of relatively cold water (<11C) on the bottom at depths around 130 m indicated that the upwelling was subsiding at the time the section was made. Boicourt and Hacker (1976) suggested that winds may force offshore transport of surface waters, accompanied by a return flow of deep Slope Water. The isotherm pattern of section 2 was consistent with this type of event, not only in the upwelling of deep Slope Water, but also in offshore surface displacement of the slope front. Analysis of average monthly wind-driven transport off the Atlantic coast during 1976 showed an anomalously strong offshore (southward) component for February in the Slope Water area south of New England (Ingham, Paper 12). Strong westerly winds during the passage of a severe storm that moved up the Atlantic coast on 2 February may have been a factor in the offshore surface transport.

Section 3. NOAA RV Albatross IV Cruise 76-01, 23-24 February.
The mixed Shelf Water was 0.5-2C colder than in the previous section, made two weeks earlier, and was at the minimum observed during the year. The underlying intrusion of warm Slope Water on the outer shelf was of similar dimensions to that in the previous section, but lacked an isolated core of water warmer than 12C.

Section 4. NOAA RV Albatross IV Cruise 76-02, 25-26 March.
The vertically mixed Shelf Water, although little changed in temperature from a month earlier (section 3), extended to greater depth (about 60 m) where the slope front was more withdrawn. Unlike the sections from the late winter of 1975 (Chamberlin 1978), which showed temperatures of the warm Slope Water on the outer shelf to be at their annual minimum in March (maximum <12C), the 1976 sections indicated no such minimum. On the contrary, 13C water occurred near bottom, and 12C water contacted bottom in each of the February-March 1976 sections that included the Slope Water zone. This continuation of warm Slope Water temperatures may be associated with the anomalously warm air

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[3] EOFA (Experimental Ocean Frontal Analysis), 4 and 11 February.

temperatures along the Atlantic coast in February and subsequent moderate air temperatures during the spring (Dickson 1976; Taubensee 1976).

Section 5. Polish RV *Wieczno* Cruise 76-01, 10-11 April.
The first rise in Shelf Water temperatures (<1C) was evidenced in this section shoreward of the 60-m isobath. At the bottom, the slope front was withdrawn offshore to the greatest depth observed during the year. As a result, bottom temperatures were at their observed annual minimum in depths of 80-150 m.

Section 6. Duke University RV *Eastward* Cruise E2B76, 11-12 May.
Development of the seasonal thermocline had defined the underlying cold core which had a temperature minimum of about 5.5C. A "bubble" of water colder than 7C appeared to be separated from the seaward side of the cold core. The slope front, with the 10C isotherm contacting bottom at a depth of <85 m, was at a more normal shoreward position than in the previous section.

Section 7. Sea Education Association RV *Westward*, 16-17 May.
This section, constructed from mechanical bathythermograph data, resembled the previous one made five days earlier, although on the shelf the minimum temperature in the cold core was about 1C lower (4.2C) and the maximum in the warm Slope Water was 1C higher (14.6C). Detachment of water from the offshore side of the cold core appeared to be in progress. The elevation in bottom temperature to 13C at depths below about 120 m, as well as the 14.5C water, indicated the presence of Gulf Stream warm core eddy 76B beyond the offshore end of the section (Fig. 19.2).

Section 8. WHOI RV *Knorr* Cruise 58, 1-2 August.
Surface temperatures, as well as the steepness and shallowness of the thermocline, were at their observed annual maximums. Five separate bodies of minimum temperature water (colder than 9C) appeared in the cold core bottom water on the shelf, and a "bubble" of 9.5-10C water appeared to have "calved" from the offshore side of the core. The slope front lay shoreward of the 100-m isobath, as in the previous two sections, but had an unusually vertical configuration at depths below about 25 m.

Section 9. WHOI RV *Oceanus* Cruise 13-III, 12-13 August.
This section apparently showed cooling effects from hurricane Belle, which crossed the shelf in a northward direction, with its center between 70W00' and 70W30', three days before. Surface temperatures were 2-5C below those in the previous section, made a week before the hurricane; the thermocline was depressed about 10 m, and the thickness of the cold core bottom water was reduced concommitantly. Temperatures in the cold core were more homogeneous than in the previous section, and the minimum was a degree warmer, but there was a similar "calved bubble" colder

than 10C near the offshore side of the core. Warm core eddy 76C, located beyond the offshore limit of the section (Fig. 19.2) was presumed to have been the source of the isolated body of 13-14C water centered at about 90-m depth in the Slope Water zone. Inflections of isotherms were beneath this body.

Section 10. WHOI RV Knorr Cruise 58-III, 27-28 August.
Surface temperatures were warmer than in the previous section (section 9), made two weeks before, but remained about 2C cooler than in section 8, made prior to hurricane Belle. (In later sections, surface temperatures were also cooler than in section 8, except in section 12 made in early October.) The thermocline was nearer the surface than in section 9, but remained deeper than in section 8 and less sharply defined. Slow warming was apparent in the cold core water, which also had a "calving" tendency at its offshore margin.

Section 11. WHOI RV Oceanus Cruise 15, 18-19 September.
Surface temperatures were about the same as in the previous section, made a month earlier, but were 2C warmer in the cold core bottom water, which had minimum temperatures >11C and was divided into two cells. The slope front had become thermally indistinguishable near bottom, because the cold core water had warmed to about the same temperature as the adjacent warm Slope Water (see Wright 1976). The domed feature in the upper 30 m at XBT stations 5-6 may be a cyclonic eddy from the slope front.

Section 12. WHOI RV Oceanus Cruise 15, 8 October.
Surface temperatures at the shoreward end of the section were 2C colder than over the same depths of water in section 11, made 20 days earlier, and the onset of vertical mixing was apparent in the deepening of the surface layer. In contrast, surface temperatures, from about the 65- to 120-m isobaths, were warmer in section 12, with the difference increasing to about 1.7C in the offshore direction. This rise in temperature, in a season when cooling is normal and in a year when the air temperatures in October were abnormally low along the entire coast of the United States (see Chamberlin and Armstrong, Paper 11), presumably represents an influx of warm Slope Water. The prominent domed feature in the upper 150 m at XBT stations 317-318 may be a cyclonic slope front eddy. If so, warm Slope Water may have reached the shelf, near the surface, by entrainment around this feature. Influx of warm Slope Water to the shelf was also indicated below the subsurface by the rise in bottom temperatures to above 13C at depths around 70-80 m. At the bottom at 50-60 m, temperatures were about 15.5C, which was 3.5C warmer than in the previous section and was the maximum observed during the year.

Section 13. NOAA RV Albatross IV Cruise 76-09, 23-24 October.
As a result of continued autumn cooling, the Shelf Water was 4-5C colder than in section 12, made two weeks earlier, and

vertically mixed to a depth of 50 m. In the warm Slope Water at the offshore end of the section, vertical mixing was also evident to a depth of 50 m, and surface temperatures were colder by 3-5C. The few degrees rise of Slope Water temperatures in the 50- to 100-m depth range off the shelf also may have been the result of the vertical mixing. The zone of minimum temperature bottom water (colder than 13C), at depths of 80-100 m, was a degree colder than in the previous section. This temperature decline, if not a data artifact, may have resulted from advection of colder water from the east or west, or from upwelling of Slope Water, as indicated by the steep slopes of the 9-15C isotherms near bottom at depths below 120 m.

Section 14. NOAA RV <u>Albatross</u> <u>IV</u> Cruise 76-09, 9 November.
The vertically mixed Shelf Water, 2-3C cooler than in the previous section, had become colder than the underlying Slope Water, beyond the 60-m isobath. Within this underlying Slope Water, the minimum temperature water lay on the bottom (<13C at 105 m depth), as in the previous section, but was greatly diminished in cross sectional area. Temperature elevation in the warm Slope Water area beyond the shelf break and the deepening of isotherms at the bottom in depths below 120 m presumably reflected the presence of warm core eddy 76D, centered beyond the offshore end of the section (Fig. 19.2).

Section 15. NOAA RV <u>Researcher</u> Cruise 11-76, 27-28 November.
Details in this section were uncertain because of the wide spacing between XBT stations. The vertically mixed Shelf Water was about 3C colder than in the previous section made 18 days before. Temperatures in the underlying Slope Water were also cooler by about 2C, but this water penetrated farther onto the shelf, extending some unmeasured distance shoreward of the 50-m isobath. Within the warm Slope Water on the outer shelf, the core of minimum temperature that was seen at the bottom in the previous two sections apparently no longer existed. Maximum temperatures in the Slope Water, warmer than 16C to a depth of 75 m, were 2C cooler than in the previous section, but still apparently reflected the presence of eddy 76D beyond the offshore limit of the section (Fig. 19.2).

Section 16. WHOI RV <u>Knorr</u> Cruise 62, 21 December.
The Shelf Water temperatures were only 1.5-2C colder than in the previous section made three weeks before, presumably because of relatively mild air temperatures along the Atlantic coast during December (see Chamberlin and Armstrong, Paper 11). Nevertheless, these water temperatures, being colder than at the same time in December of the previous two years (Chamberlin 1978), did seem to reflect the unusually cold air temperature that prevailed along the coast during fall 1976, especially in October and November (see Chamberlin and Armstrong, Paper 11). For example, bottom temperatures shoreward of the Slope Front in

section 16 averaged about 3.5C colder than in 1974, and about 2.5C colder than in 1975. The intrusive Slope Water that occupied the bottom on the outer shelf was more withdrawn than in the previous four sections, but isolated remnants of 9C water remained, one of which contacted bottom at around 65-m depth. An apparently isolated body of 13-14C water also rested on the bottom at depths of 85-135 m, and may have been formed by counter eddying effects of warm core eddy 76D. Satellite imagery showed this eddy to have moved westward entirely beyond the section line at the time the section was made.[4] At the offshore end of the section, the steep thermal front in the upper 120 m of the water column suggested the inshore edge of a warm core eddy, but the satellite image of one day later did not show an eddy but apparently only a large patch of warm Slope Water centered beyond the offshore end of the section.

BOTTOM TEMPERATURES IN 1976

The Shelf Water Cycle

The seasonal bottom temperature cycle in the waters south of New England is most pronounced in the Shelf Water region, shoreward of the zone where Slope Water contacts bottom (Colton and Stodard 1973; Wright 1976). A general chronology and description of the seasonal Shelf Water cycle for this region is given by Bigelow (1933).

During 1976, the observed minimum bottom temperature was 2.5C, at about 30-m depth in early February. Although temperature observations from as shallow as 30 m were lacking for February 1974 and 1975, the bottom temperature diagrams for those years (Chamberlin 1978) indicated that the minimums were about the same as in February 1976. In March 1976, however, the bottom temperature at depths around 30 m rose above 4C, whereas in mid-March 1975 it was below 3C and in March 1974 was probably below 3C. The early warming in 1976 was consistent with extremely warm air temperature conditions along the Atlantic coast in February (Dickson 1976). In depths of 40-50 m, the minimum observed bottom temperature was about 4C in March. This value is within the range described by Bigelow (1933). Beyond the 50-m isobath, cooling continued at the bottom into April as isotherms moved seaward to the upper slope. The timing of this trend conformed closely to that in 1974 and 1975 (Chamberlin 1978), although the recorded minimum was somewhat warmer. The minimum at 75-m depth, for example, was about 1C warmer than in

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[4] EOFA (Experimental Ocean Frontal Analysis), 22 December.

1974, and 2C warmer than in 1975. The extent and timing of this cooling may be controlled by movement of the Slope Front. However, the fact that the deepening of the isotherms on the outer shelf had occurred in April during each of the three years, suggested the alternative explanation that the minimum Shelf Water temperatures of early spring promoted cross-frontal mixing with the warm Slope Water. Salinity data will be necessary to determine which explanation is correct.

Shoreward of the 50-m isobath, the bottom water began to warm by mid-March, rising to about 7C (warmer inshore) before thermal stratification set in by early May, and established this water as an isolated cold core. Although data were were not obtained during June and July, it appeared that summer temperatures in the cold core were similar to those in 1974, but about 1C warmer than in 1975.

The passage of hurricane Belle across the shelf on 9-10 August, with its center about 100 nm (185 km) west of where data were collected for this analysis, was apparently quite influential in cooling and deepening the surface layer south of New England (see discussion of section 9), but had no obvious effect on bottom temperatures as seen in the sections.

Cooling of the surface layer and vertical mixing broke down the cold core near the end of September, about a month earlier than in the previous two years. As a result, midshelf bottom temperatures at depths around 75 m reached the observed annual maximum (14-15C) by early October, which is also a month earlier than in 1974 and 1975. The maximum values were similar, however, in all three years.

Following an incursion of Slope Water toward the end of October, which interrupted the seasonal progression, Shelf Water cooling at the bottom was rapid to a depth of 75 m, and by the end of the year reached values, at that lower depth, about 4C lower than in 1974 and 1975. The early breakdown of stratification and strong cooling presumably resulted from unusually cold atmospheric conditions during October and November following below normal air temperatures during the summer (see Chamberlin and Armstrong, Paper 11).

Slope Water Events

The Slope Water, a band lying between the Shelf Water and the Gulf Stream and having intermediate temperature values, is separated from the Shelf Water by a thermal gradient that Wright (1976), in an analysis of historical data from 1941 to 1972, found to have an average midpoint temperature of 10C in the region south of New England, except for a brief period following the fall overturn when the minimum temperature Shelf Water is frequently warmer than 10C.

Wright also calculated an annual mean of 13.2C and a mean annual range from 12.3C to 14.6C for the maximum temperatures in the warm Slope Water that normally underlies the Shelf Water near the outer shelf. Although nonseasonal events, such as incursions of Gulf Stream Water or upwelling of deep Slope Water, may often mask` seasonal events in the Slope Water near the bottom on the outer shelf, it is apparent, nevertheless, that the warmest part of the warm Slope Water does not ordinarily contact bottom on the outer continental shelf. During 1974-76, for example, the maximum bottom temperatures were between 12.0C and 13.0C the great majority of the time (see also Chamberlin 1978). Furthermore, the maximum long-term monthly mean bottom temperatures on the outer shelf for the years 1940-66 were between 10.0C and 12C the great majority of the time (Colton and Stoddard 1973; Chamberlin 1978). Part of the reason that Colton and Stoddard's mean values are colder than the 1974-76 temperatures for the same depth zone is that they were partly based on data from years when intrusion of cold Labrador Coastal Water displaced the Slope Water from the bottom south of New England (Colton 1968). This water is not evident in any of the temperature sections from 1974 to 1976.

Wright (1976), in his analysis of historical data, also found that the slope front intersected the bottom at depths between 80 and 120 m off southern New England 84% of the time. Beardsley and Flagg (1976) suggested four possible mechanisms which might account for frontal movements: 1) propagation of barotropic waves, 2) baroclinic instabilities across the front, 3) local wind field variability, and 4) passage of Gulf Stream eddies. Frontal distortions caused by the first two mechanisms are assumed to be frequent and minor, but are not easily assessed by direct observation. The effects of wind stress transport, however, are known to be significant, although usually of brief duration (Boicourt and Hacker 1976). Passages of Gulf Stream eddies, although not frequent, may also cause significant variation in the slope front position by injection of Gulf Stream derived water, Slope Water displacement, and offshore entrainment of Shelf Water, accompanied by compensatory subsurface inshore flow of Slope Water (Chamberlin 1976; Morgan and Bishop 1977).

During 1976, the maximum observed bottom temperatures in the warm Slope Water zone ranged from slightly >12.0C to nearly 15.0C. This range is similar to that observed in 1974, but cooler than in 1975, when unusually warm, as well as moderately colder, temperatures occurred. The observed inter- section of the slope front with the bottom was generally at depths shallower than 100 m, except in April when the depth was nearly 120 m, during the time when the Shelf Water was at its annual minimum temperature in depths >70 m as described above.

During 1976, as in 1974, no data were obtained to indicate that bottom temperatures in the warm Slope Water zone fell below 12C, as they did on at least two occasions in 1975. The apparent absence of a minimum temperature interval in March is particularly interesting, because such an event occurred in 1975 and was strongly evident in long-term monthly mean bottom temperatures for the years 1940-66 (Chamberlin 1973). The apparent absence of such a minimum in March 1974 can be explained by the persistence of a warm core Gulf Stream eddy south of New England during that month (Chamberlin 1976). In 1976, however, no warm eddy was detected in that region during the entire winter and early spring. It seems possible, although questionable, that bottom temperatures at such a depth as the warm Slope Water zone remained above 12C during March 1976 because of the record warm air temperature during the preceding month (Dickson 1976).

Two strong incursions of Slope Water onto the upper slope and outer shelf are evident: the first in early February and the other in October; but only the latter appears to have caused shoreward displacement of the slope front (see discussion of sections 2 and 13).

Bottom temperature variations can be associated with each of the three Gulf Stream warm core eddies that passed south of New England during 1976 (Fig. 19.2). During May, eddy 76B presumably caused the observed elevation of bottom temperatures to above 13C in the warm Slope Water zone. During mid-August, the presence of eddy 76C was probably reflected in the deepening of isotherms (as much as 80 m) at depths below 150 m. Another effect of this eddy may have been a temporary rise in bottom temperature to above 13C in the warm zone, as suggested by dashed lines in Figure 19.2. The occurrence of such a bottom temperature rise is indicated in sections 9 and 10, although not actually shown in either of these sections. In November, eddy 76D probably caused the observed rise in bottom temperatures to above 14C (probably above 15C) in the warm zone. The deepening of isotherms at depths below 160 m may also have been caused by this eddy.

SUMMARY

Shelf Water temperatures during the spring, particularly as observed at the bottom, were about 1C warmer than in 1974 and about 2C warmer than in 1975, probably as a result of record warm air temperatures in February and moderate air temperatures in the following few months.

Marked cooling and deepening of the surface layer was recorded on the shelf following the passage of hurricane Belle in early August.

The cold core bottom water warmed to the level of the adjacent warm Slope Water by the end of September, about a month earlier than in 1974 and 1975.

At the end of the year, following record cold weather in the fall, the Shelf Water was 3-4C colder than in the previous two years.

Maximum bottom temperatures in the warm Slope Water zone on the outer shelf were not recorded below 12C nor above 14C during the year.

Three Gulf Stream warm core eddies apparently passed south of New England during 1976 (the same number as in 1974 and in 1975) but the first two, in late spring and late summer, were weakly developed and their influence on bottom temperatures moderate.

ACKNOWLEDGMENTS

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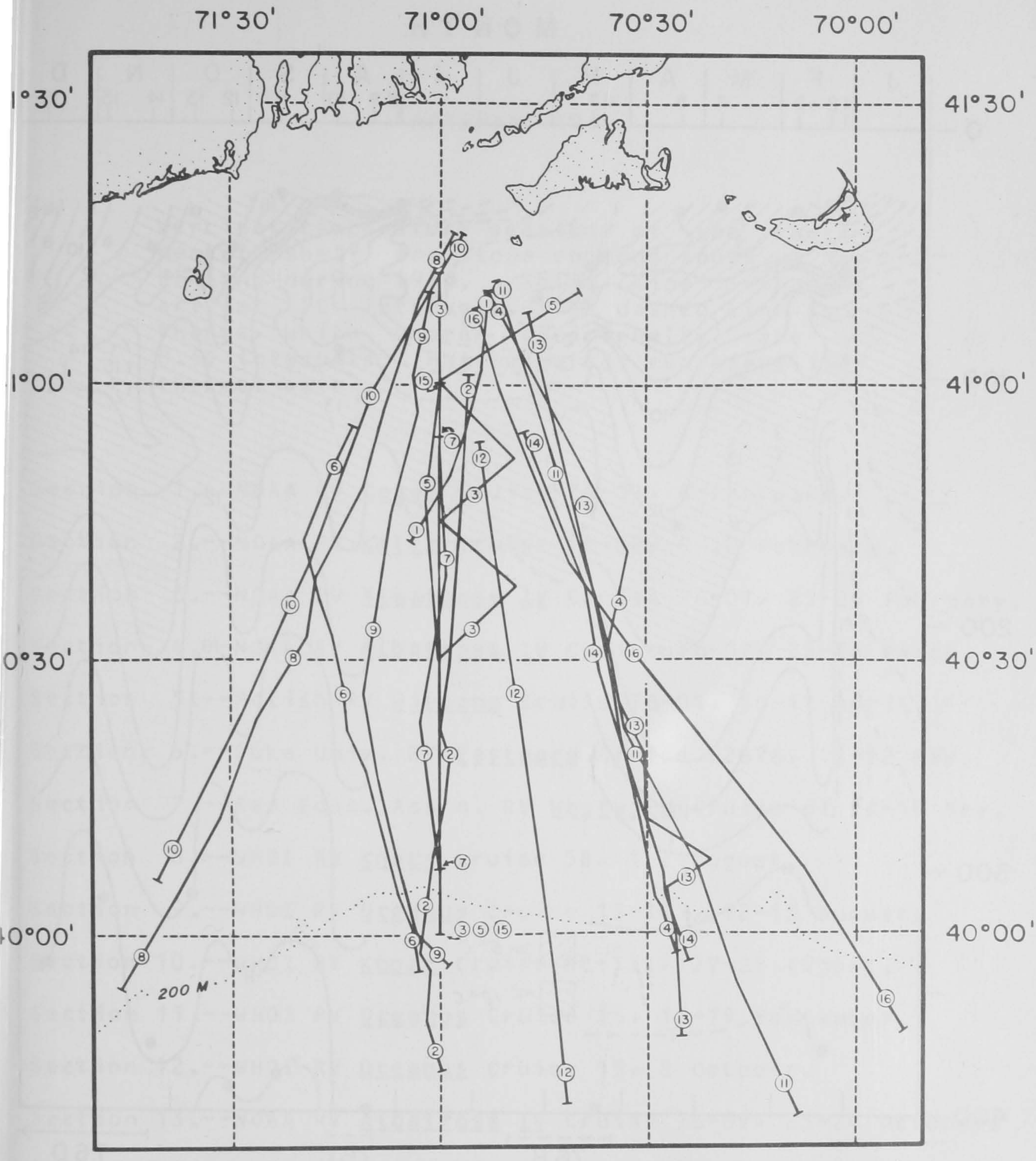


igure 19.1.—Locations of vertical temperature sections included in this report. Sections are numbered chronologically. See Appendix 19.1 for identification of sections.

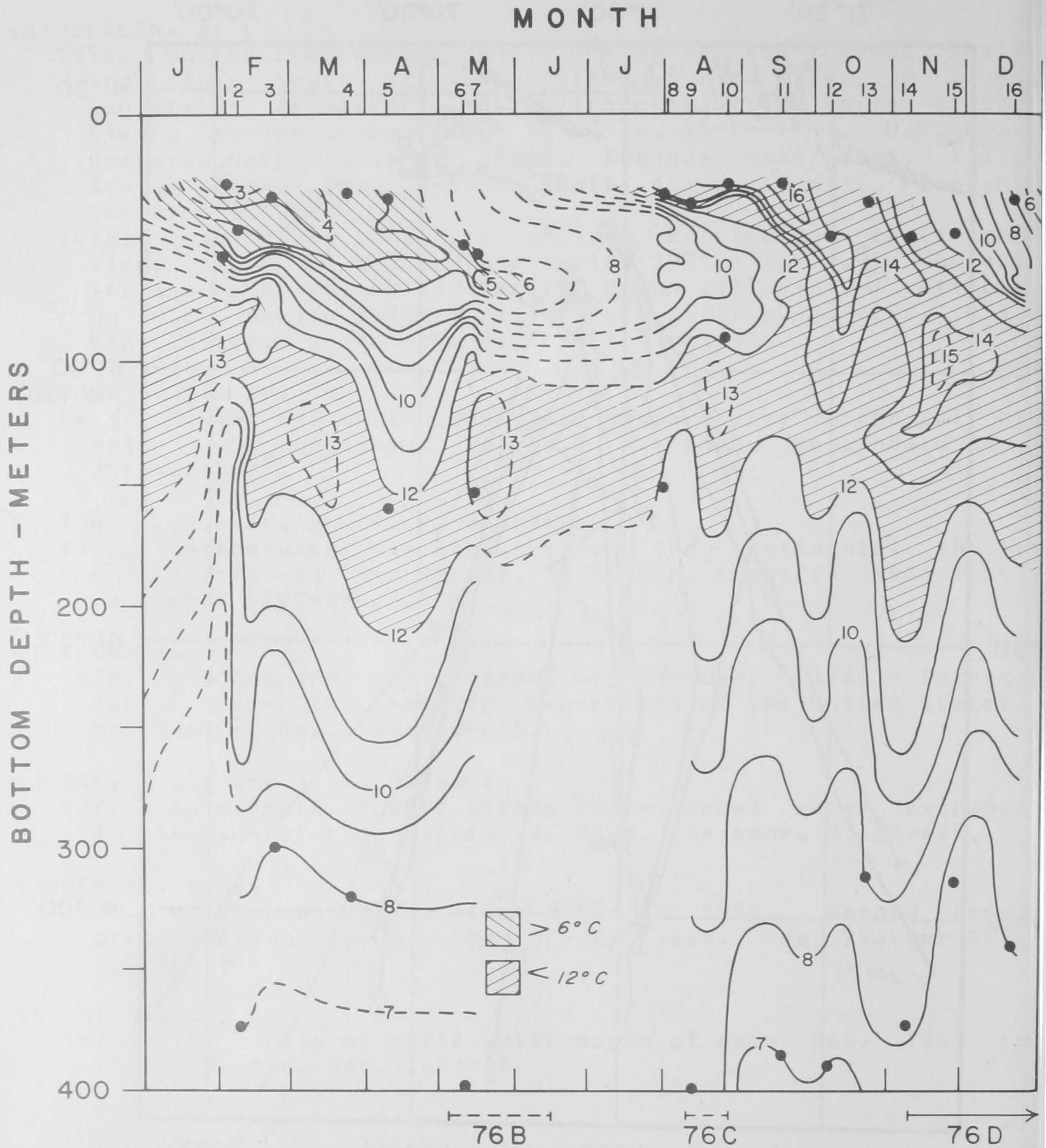


Figure 19.2.—Bottom temperatures on the continental shelf and slope south of New England during 1976. Temperature sections are numbered along the top margin (see Appendix 19.1). Dots mark the depth limits of the bottom data from each section. Horizontal lines at the bottom of the diagram indicate the times of Gulf Stream anticyclonic eddy passages south of New England.

APPENDIX 19.1

Vertical temperature sections of the continental shelf and slope regions south of New England during 1976. Solid line isotherms are at 1C intervals. The dashed line isotherms, which appear occasionally, are at 0.5C intervals. Hatched areas represent isothermal water.

Section 1.--NOAA RV *Kelez* Cruise 76-01, 4 February.

Section 2.--NOAA RV *Kelez* Cruise 76-02, 9-10 February.

Section 3.--NOAA RV *Albatross IV* Cruise 76-01, 23-24 February.

Section 4.--NOAA RV *Albatross IV* Cruise 76-02, 25-26 March.

Section 5.--Polish RV *Wieczno* Cruise 76-01, 10-11 April.

Section 6.--Duke Univ. RV *Eastward* Cruise E2B76, 11-12 May.

Section 7.--Sea Educ. Ass'n. RV *Westward* Cruise of 16-17 May.

Section 8.--WHOI RV *Knorr* Cruise 58, 1-2 August.

Section 9.--WHOI RV *Oceanus* Cruise 13-III, 12-13 August.

Section 10.--WHOI RV *Knorr* Cruise 58-III, 27-28 August.

Section 11.--WHOI RV *Oceanus* Cruise 15, 18-19 September.

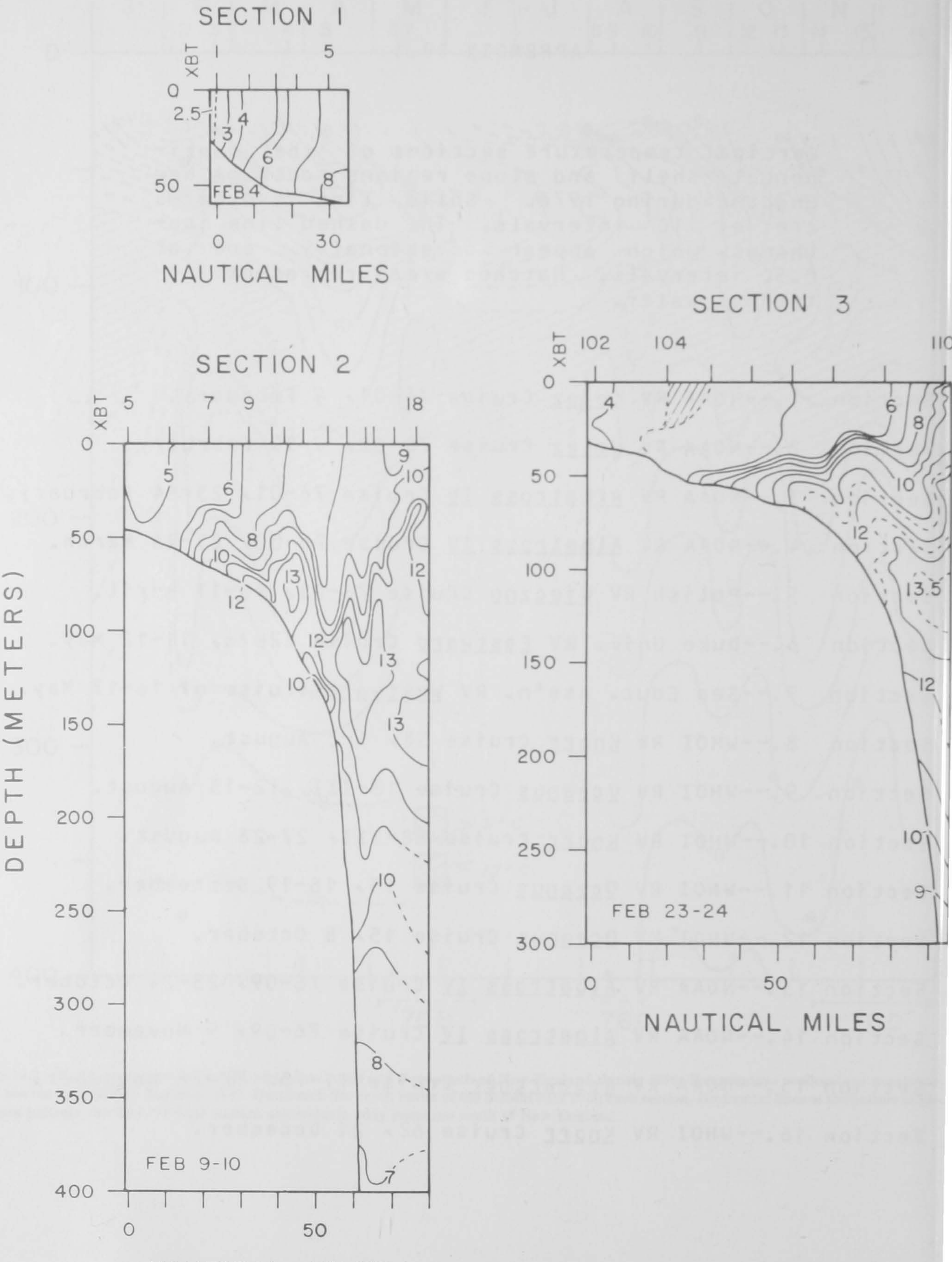
Section 12.--WHOI RV *Oceanus* Cruise 15, 8 October.

Section 13.--NOAA RV *Albatross IV* Cruise 76-09, 23-24 October.

Section 14.--NOAA RV *Albatross IV* Cruise 76-09, 9 November.

Section 15.--NOAA RV *Researcher* Cruise 11-76, 27-28 November.

Section 16.--WHOI RV *Knorr* Cruise 62, 21 December.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XBT
1
5
0
2.5
3
4
6
8
50
FEB 4
0
30
NAUTICAL MILES
SECTION 2
XBT
5
7
9
18
0
5
6
8
9
10
12
13
50
100
150
200
250
300
350
400
7
FEB 9-10
0
50
NAUTICAL MILES
DEPTH (METERS)
SECTION 3
XBT
102
104
110
0
4
6
8
10
12
13.5
9
50
100
150
200
250
300
FEB 23-24
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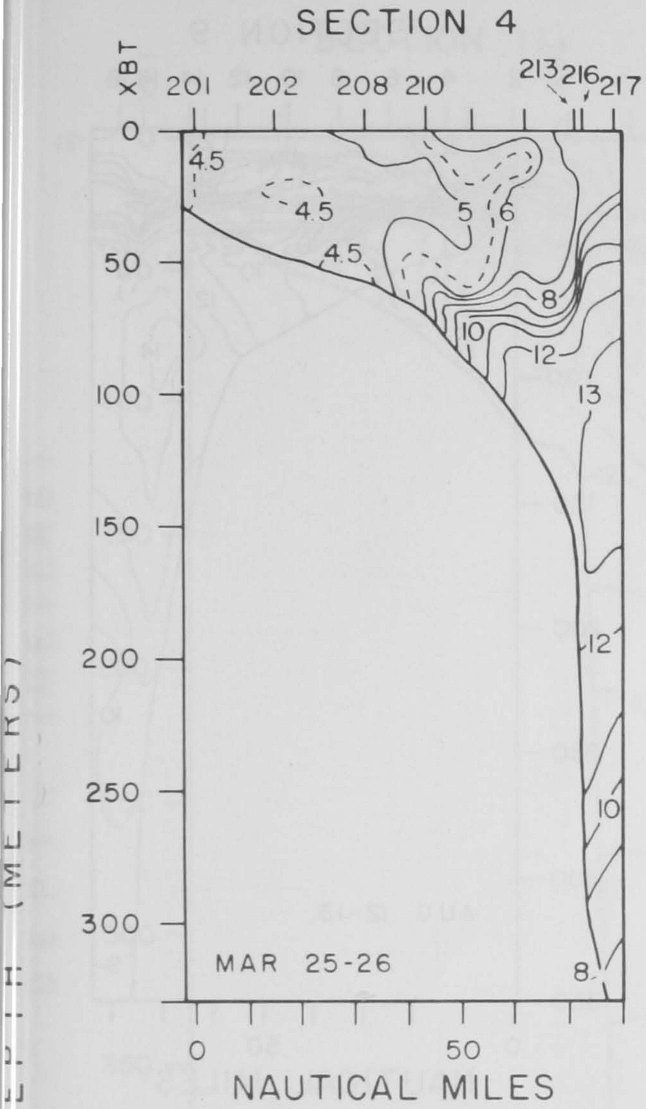
50
NAUTICAL MILES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202
208
210
213
216
217
0
50
100
150
200
250
300
DEPTH (METERS)
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4.5
4.5
5
6
8
10
12
13
12
10
8
MAR 25-26
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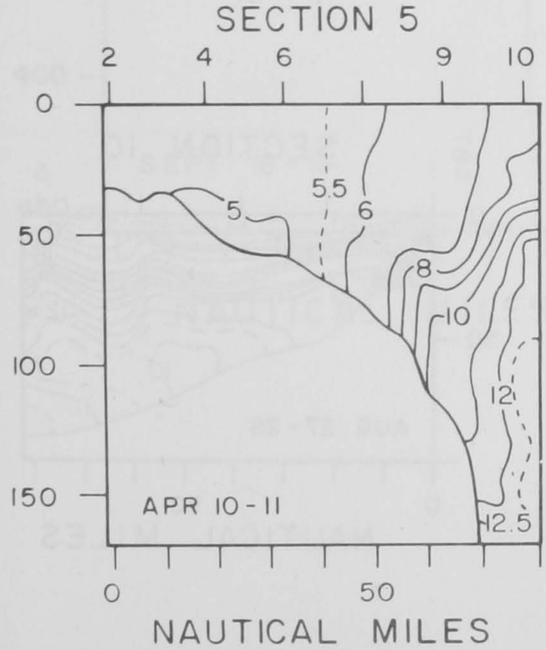
50
NAUTICAL MILES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4
6
9
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8
10
12
12.5
APR 10-11
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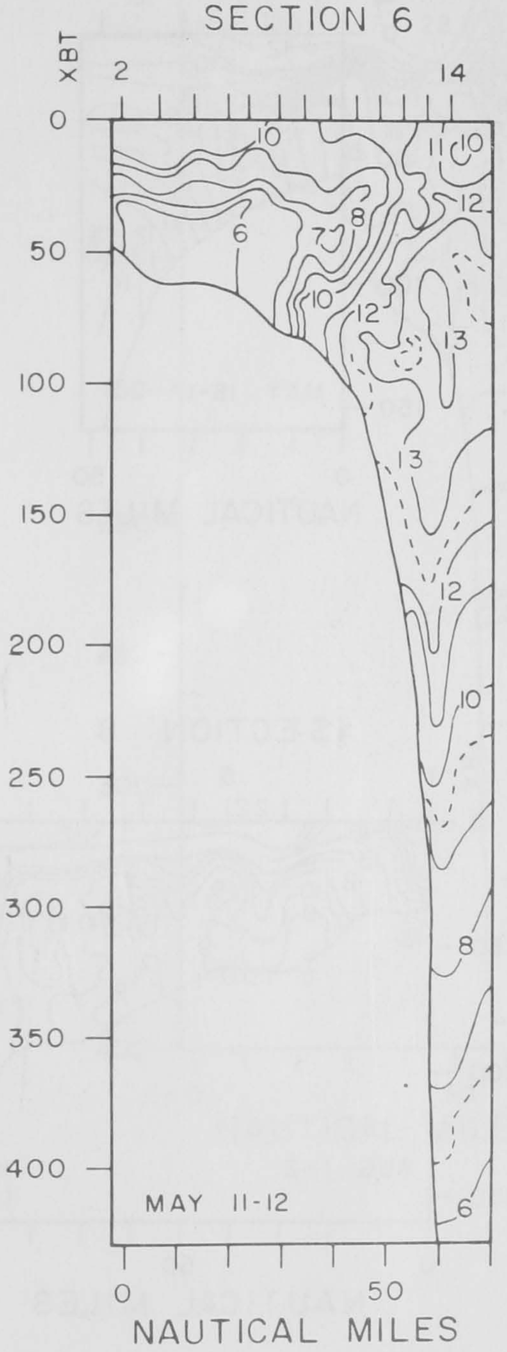
50
NAUTICAL MILES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350
400
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11
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7
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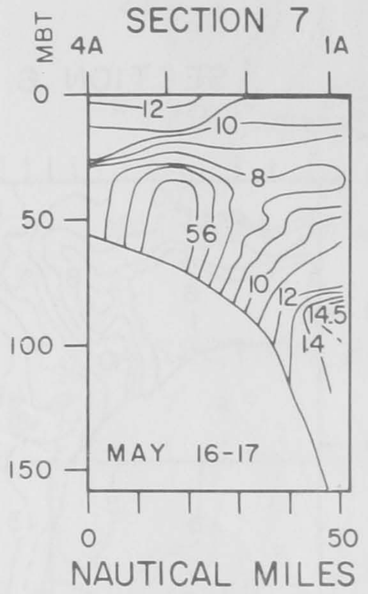
13
12
10
8
6
MAY 11-12
0
50
NAUTICAL MILES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1A
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50
100
150
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10
8
56
10
12
14.5
14
MAY 16-17
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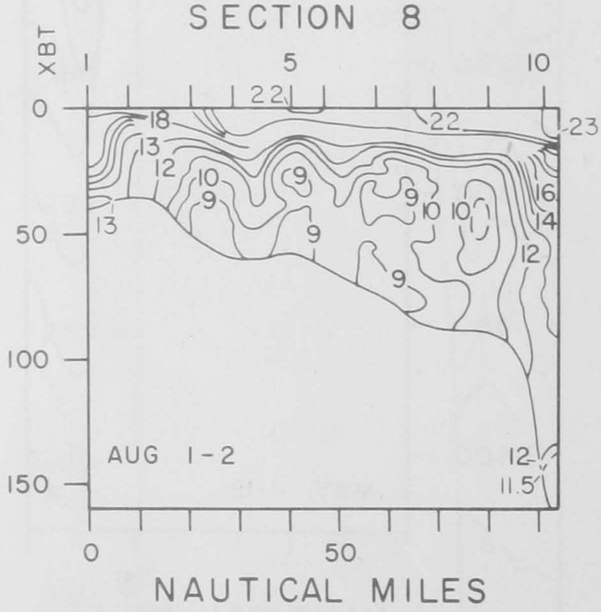
NAUTICAL MILES
DEPTH (METERS)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XBT
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5
10
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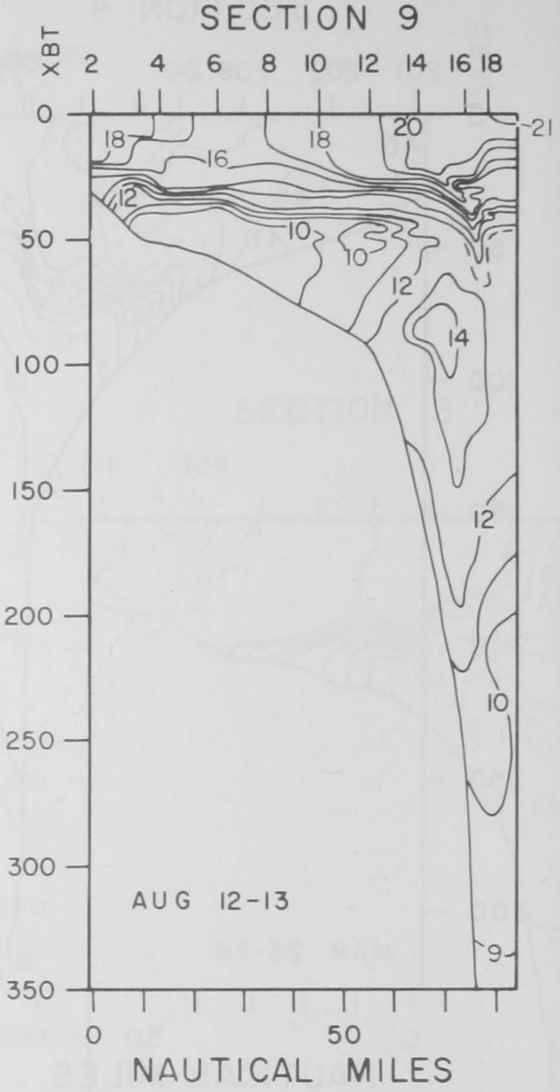
50
100
150
22
18
22
23
13
12
10
9
9
9
9
10
10
16
14
12
13
9
9
AUG 1-2
12
11.5
0
50
NAUTICAL MILES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18
16
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21
12
10
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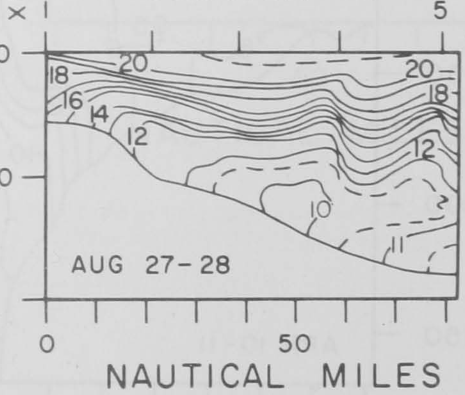
12
11
14
12
10
AUG 12-13
9
0
50
NAUTICAL MILES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20
20
16
14
12
18
12
10
11
AUG 27-28
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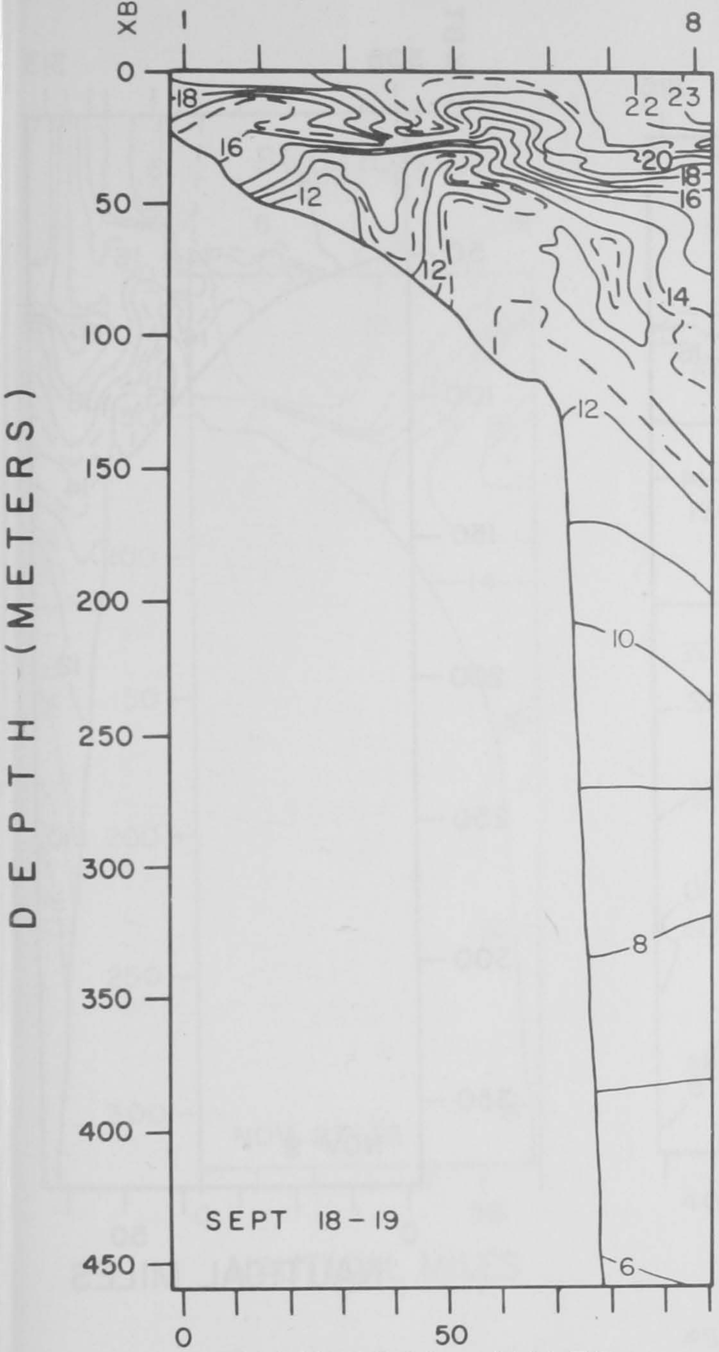
50
NAUTICAL MILES



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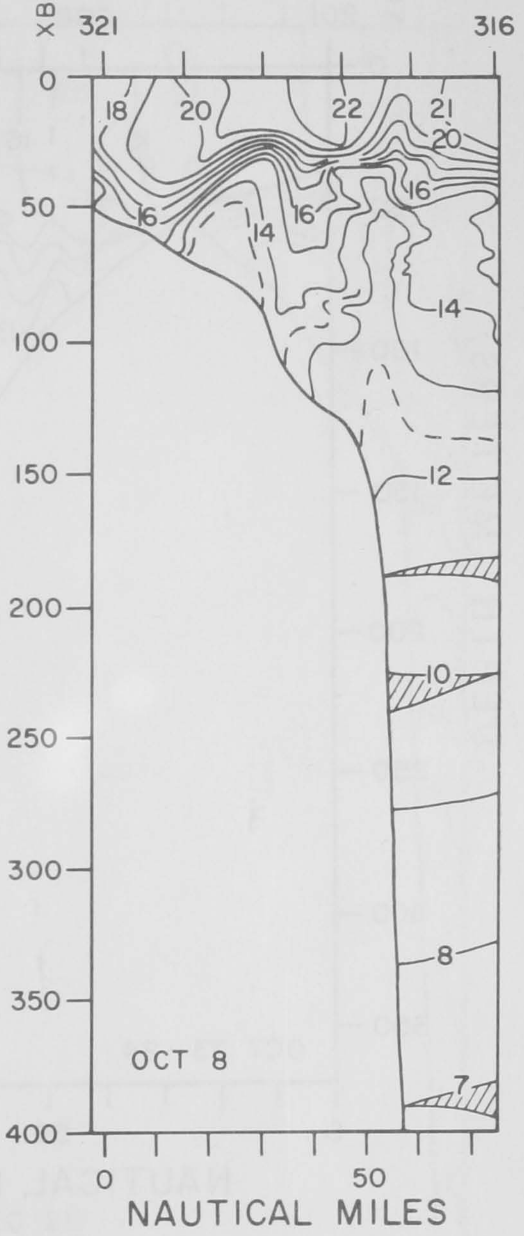
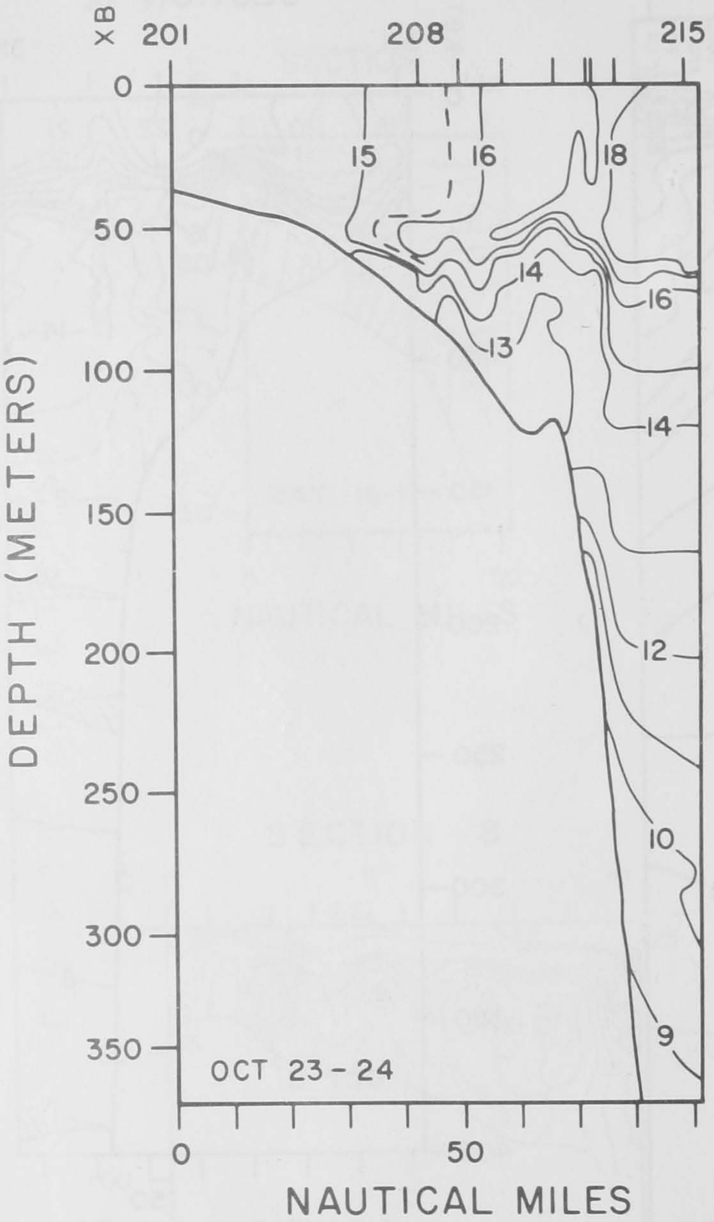


SECTION 12

SECTION 13



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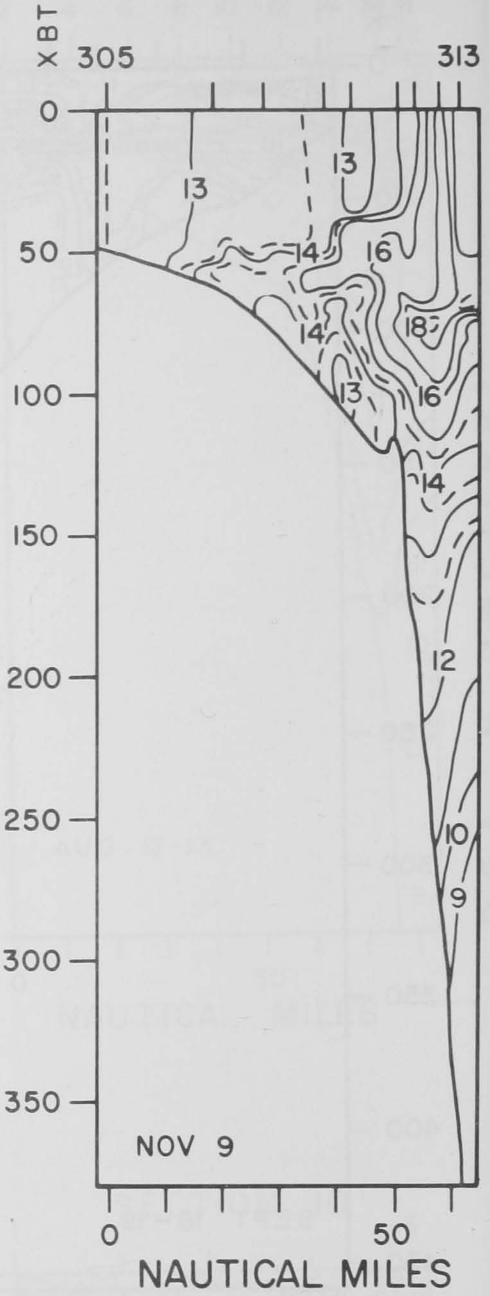

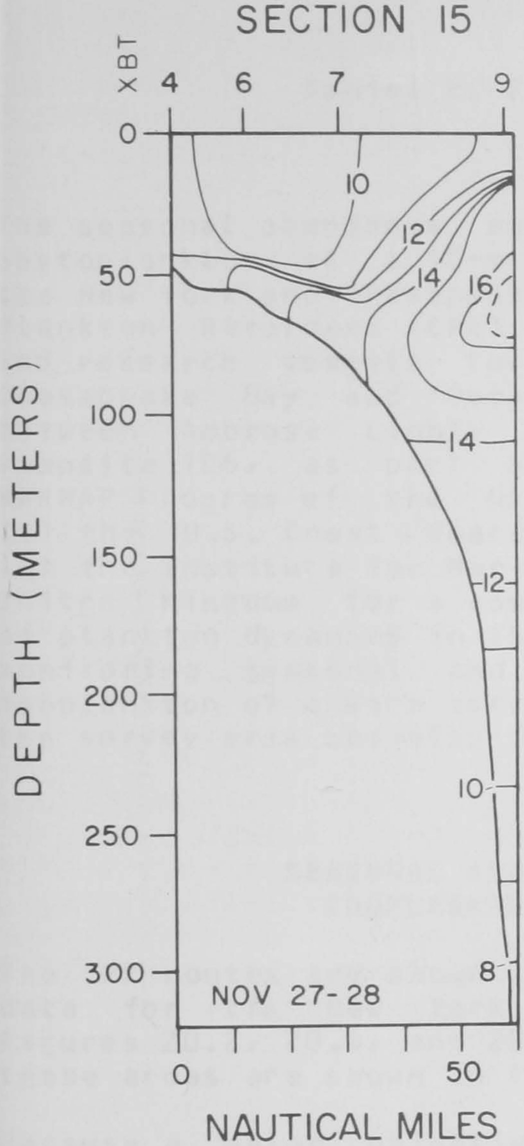
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XBT
4
6
7
9
0
50
100
150
200
250
300
DEPTH (METERS)
10
12
14
16
14
12
10
8
NOV 27-28
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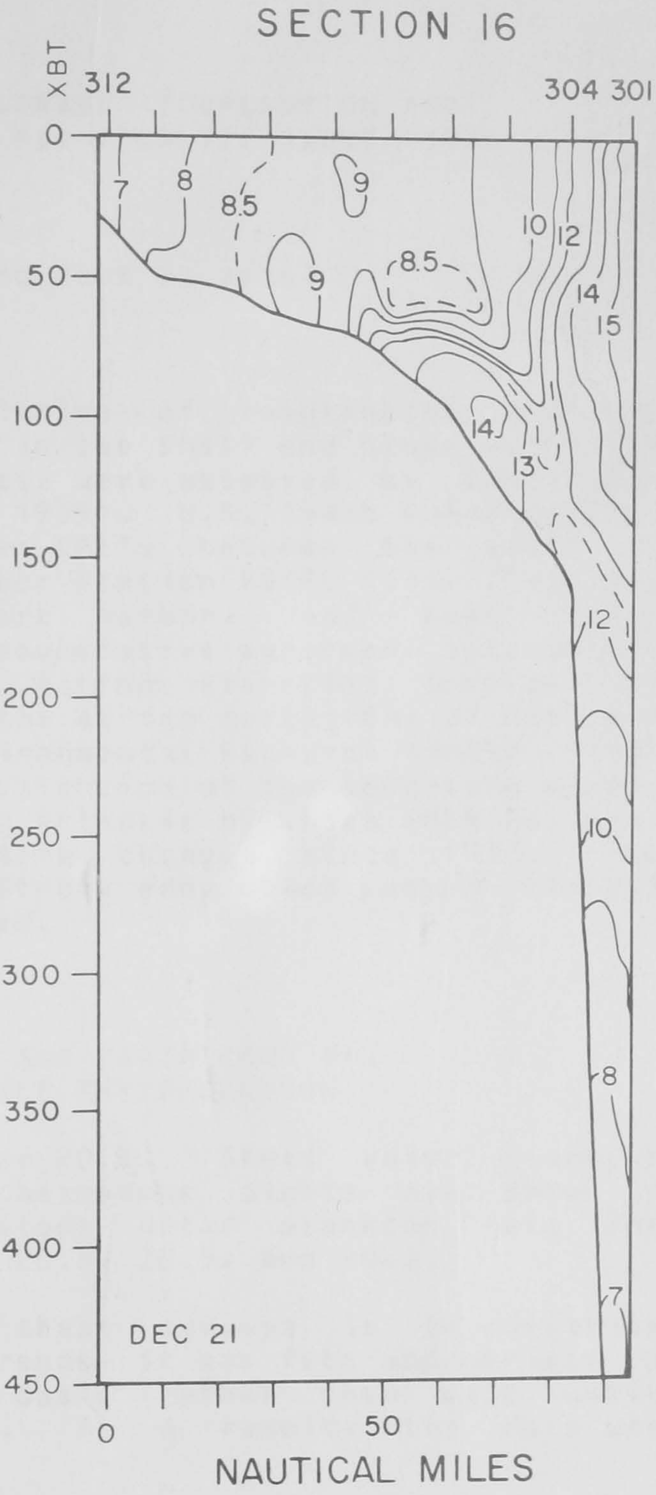
50
NAUTICAL MILES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304 301
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150
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300
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400
450
7
8
8.5
9
9
8.5
10
12
14
15
14
13
12
10
8
7
DEC 21
0
50
NAUTICAL MILES

Paper 20

CONTINUOUS PLANKTON RECORDS: ZOOPLANKTON AND NET PHYTOPLANKTON IN THE MID-ATLANTIC BIGHT, 1976

Daniel E. Smith and Jack W. Jossi[1]

The seasonal abundance and variation of zooplankton and net phytoplankton at a 10-m depth, in the Shelf and Slope Waters of the New York and Chesapeake Bights, were assessed by Continuous Plankton Recorders (CPR) (Hardy 1939). U.S. Coast Guard cutters and research vessels towed the CPR's between the mouth of Chesapeake Bay and Ocean Weather Station HOTEL (38N, 71W), and between Ambrose Light, New York Harbor, and Deep Water Dumpsite 106, as part of a cooperative agreement between the MARMAP Program of the National Marine Fisheries Service and (1) the U.S. Coast Guard for the at-sea collecting of data and (2) the Institute for Marine Environmental Research (IMER) of the United Kingdom for a southern extension of the long-term survey of plankton dynamics in the North Atlantic by which IMER has been monitoring seasonal and long-term changes since 1930. The zooplankton of a warm core Gulf Stream eddy which passed through the survey area are also described.

SEASONAL ABUNDANCE AND VARIATIONS OF ZOOPLANKTON AND NET PHYTOPLANKTON

The CPR routes are shown in Figure 20.1. Shelf Water plankton data for the New York and Chesapeake Bights are shown in Figures 20.2, 20.4, and 20.6. Slope Water plankton data for these areas are shown in Figures 20.3, 20.5, and 20.7.

Because a major objective of these surveys is to describe long-term cyces, means, and trends, it was felt appropriate to present the data on an annual basis rather than wait until detailed analysis is feasible. As a result, the data are

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[1] MARMAP Field Group, National Marine Fisheries Service, NOAA, Narragnasett, RI 02882. Present address: Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

presented with little comment. However, some explanation of the units presented and the counting system which produced them is in order. The counting system used was designed to allow for the rapid analysis of large numbers of plankton samples taken monthly from large areas of the North Atlantic Ocean.

Phytoplankton were recorded as number of occurrences per twenty 0.295-mm diameter microscopic fields taken diagonally across a section of bolting silk which had filtered $3\ m^3$ of seawater (a 10-n mi sample). The silk aperture size was 225 x 234 mm. Mean occurrences of each taxum per water mass per month are shown in Figures 20.2 and 20.3.

Zooplankton were counted by either of two methods, depending on their size. Zooplankton taxa <2 mm seen in a staggered traverse of the silk were estimated to fall within one of a set of abundance categories. An "accepted value" (weighted mean) was substituted for each category, and these accepted values were multiplied by an aliquot factor to give the number of plankton per sample (3 cu m). Finally, the numbers for all analyzed samples per water mass per month (see Fig. 20.1) were averaged together to obtain the numbers shown in Figures 20.4 and 20.5. Zooplankton >2 mm were analyzed in the same manner except that the number of all animals on a silk was recorded, thereby precluding the need for an aliquot factor. These data are shown in Figures 20.6 and 20.7. For more details concerning these methods see Colebrook (1960). Some taxa of zooplankton were present in both size categories (usually different developmental stages) and are presented separately.

Two features of the plankton dynamics which are not obvious from the figures are mentioned below. Thecosomate pteropods increased and decreased along with the *Ceratium tripos* bloom in all instances during the springtime. Compare Figures 20.2 with 20.4, and 20.3 with 20.5. The cladoceran *Pennilia* sp. dominated the plankton in October Chesapeake Bight Shelf Water samples in 1976 but were not abundant in fall samples of 1974 and 1975.[2]

ZOOPLANKTON OF A WARM CORE EDDY

A decayed warm core Gulf Stream eddy (called Eddy D by the U.S. Navy Oceanographic Office) was traversed by the CPR in February 1976 (Fig. 20.1).

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[2] Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02882. Unpubl. data.

inated the zooplankton within the eddy but also were more numerous within the eddy than without. All other taxa of plankton were more numerous in Shelf and Slope Water samples than in the eddy samples. The history of this eddy and the distribution and abundance of these copepod species show some interesting relationships.

Gotthardt (1973) showed that warm core Gulf Stream eddies form from Gulf Stream meanders, which break off into the Slope Water forming a Gulf Stream Water ring surrounding a Sargasso Sea Water core. A Gulf Stream meander was shown southeast of Georges Bank on the 25 June 1975 Experimental Ocean Frontal Analysis (EOFA)[3] chart. A week later the 30 June chart indicated a feature which was later shown to be Eddy D.

The Gulf Stream and a small area of the Sargasso Sea east of the Chesapeake Bight were sampled in June 1975. No M. lucens was found, which is consistent with the findings of other investigators in this area. It can be assumed that Eddy D formed without any M. lucens. Although P. gracilis was not found in any summertime, 10-m CPR samples of the Gulf Stream, Bowman (1971) found it abundant in all seasons in Gulf Stream samples taken between the surface and 70 m. Pleuromamma gracilis may have been present in the deep water of the eddy.

The EOFA charts showed Eddy D moving westward from southeast of of Georges Bank in late June 1975 to the New York Bight area in December 1975. It appeared from the charts to be entraining Slope and Shelf Waters as it went. Metridia lucens appeared in Chesapeake Bight Shelf Water samples in November and December 1975 and Slope Water samples in December 1975. Pleuromamma gracilis appeared in both Shelf and Slope Waters in November and December. It is likely that these two species also occurred in Slope Water in the vicinity of Eddy D. Eddy D may have been colonized by M. lucens from the Shelf and Slope Waters which it entrained to the south of New England.

During January 1976 every Slope Water sample from the New York Bight contained P. gracilis and M. lucens, while Shelf Water samples also contained M. lucens. It can be assumed that Eddy D entrained some of these as it moved through the New York Bight Slope Water.

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[3] U.S. Navy Oceanographic Office, Applications Research Division, Suitland, MD 20374.

By January and February 1976, Eddy D had moved southwestward from the New York Bight to the positions shown in Figure 20.1.

However, in the Chesapeake Bight Slope Water samples, outside the eddy, M. lucens and P. gracilis had become absent by January.

In February, when Eddy D arrived in the Chesapeake Bight, it contained more M. lucens and P. gracilis than either the Chesapeake Bight Shelf or Slope Water, and more than the New York Bight Slope Water through which it had come. However, at this time the abundance of M. lucens and P. gracilis was also increasing in Chesapeake Bight Shelf and Slope Waters.

SUMMARY

It is postulated: that Eddy D broke off from the Gulf Stream in June 1975 containing P. gracilis but no M. lucens; that Eddy D was populated with M. lucens from entrained Shelf and Slope Waters as it traveled to the west and southwest; that M. lucens and P. gracilis reproduced more and/or survived longer in the eddy than they did in the Slope or Shelf Water; and that it is unlikely that M. lucens accumulated in Eddy D by simple addition of recruits from outside the eddy, because if this were the reason for its abundance, other Shelf and Slope Water species would be expected to have accumulated in the same manner and this was not the case.

ACKNOWLEDGMENTS

We thank the staffs of the U.S. Coast Guard, Atlantic Area, Marine Services Division; the U.S. Coast Guard Oceanographic Unit; and the officers and crews of the Coast Guard cutters Alert, Dallas, Duane, Gallatin, Relieance, and Taney. We also thank the Sea Education Association, the officers and crew of their RV Westward, and the personnel of the NOAA ship Oregon II. Without the help of these groups, this survey would not have been possible.

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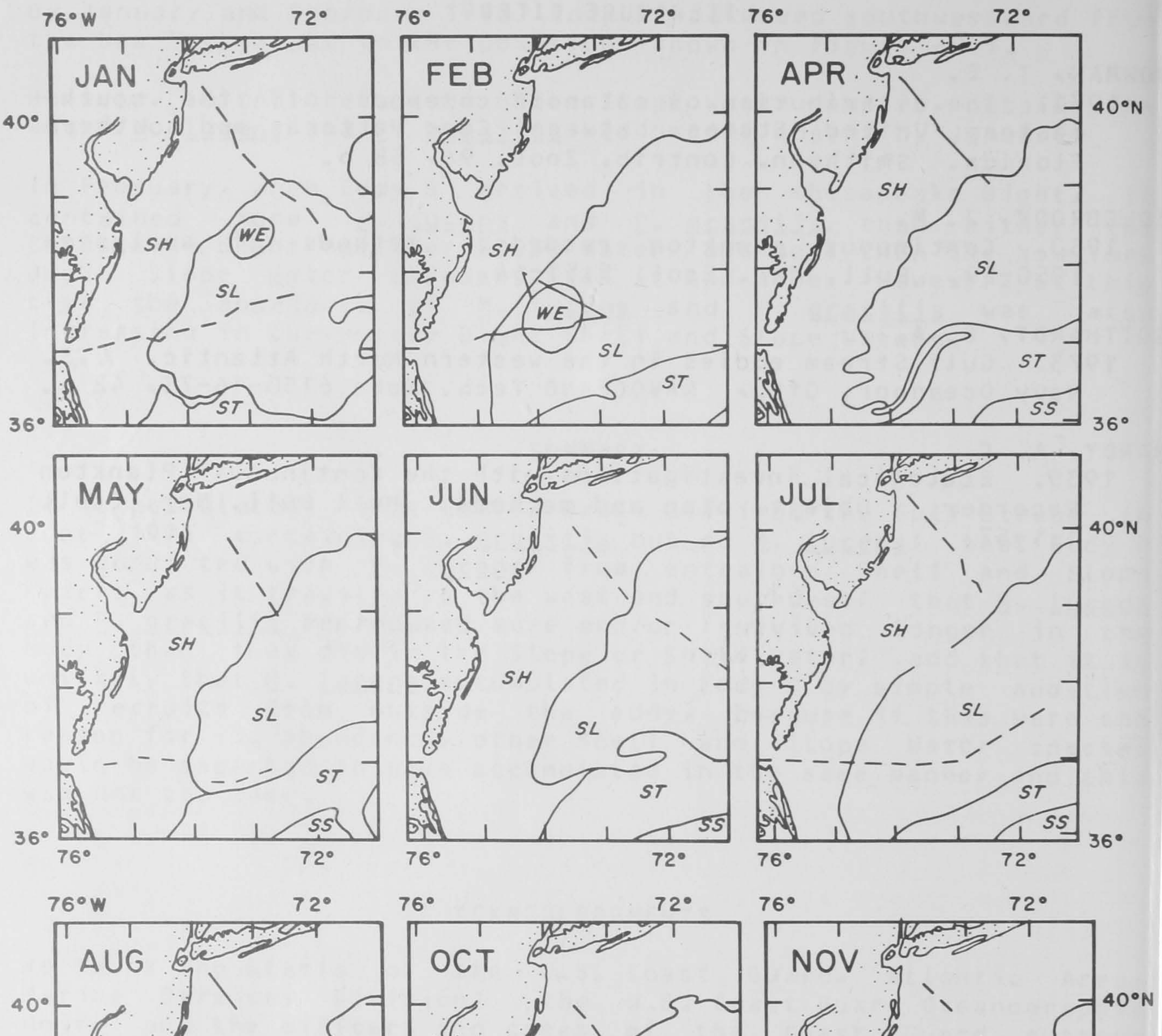

Figure 20.1.—Positions of water masses, surface fronts, and continuous plankton recorder samples during 1976. *SH* = Shelf Water, *SL* = Slope Water, *ST* = Gulf Stream Water, *SS* = Sargasso Sea Water, *WE* = warm eddy (after U.S. Navy Experimental Ocean Frontal Analysis 1976), — = 10-mi sample.

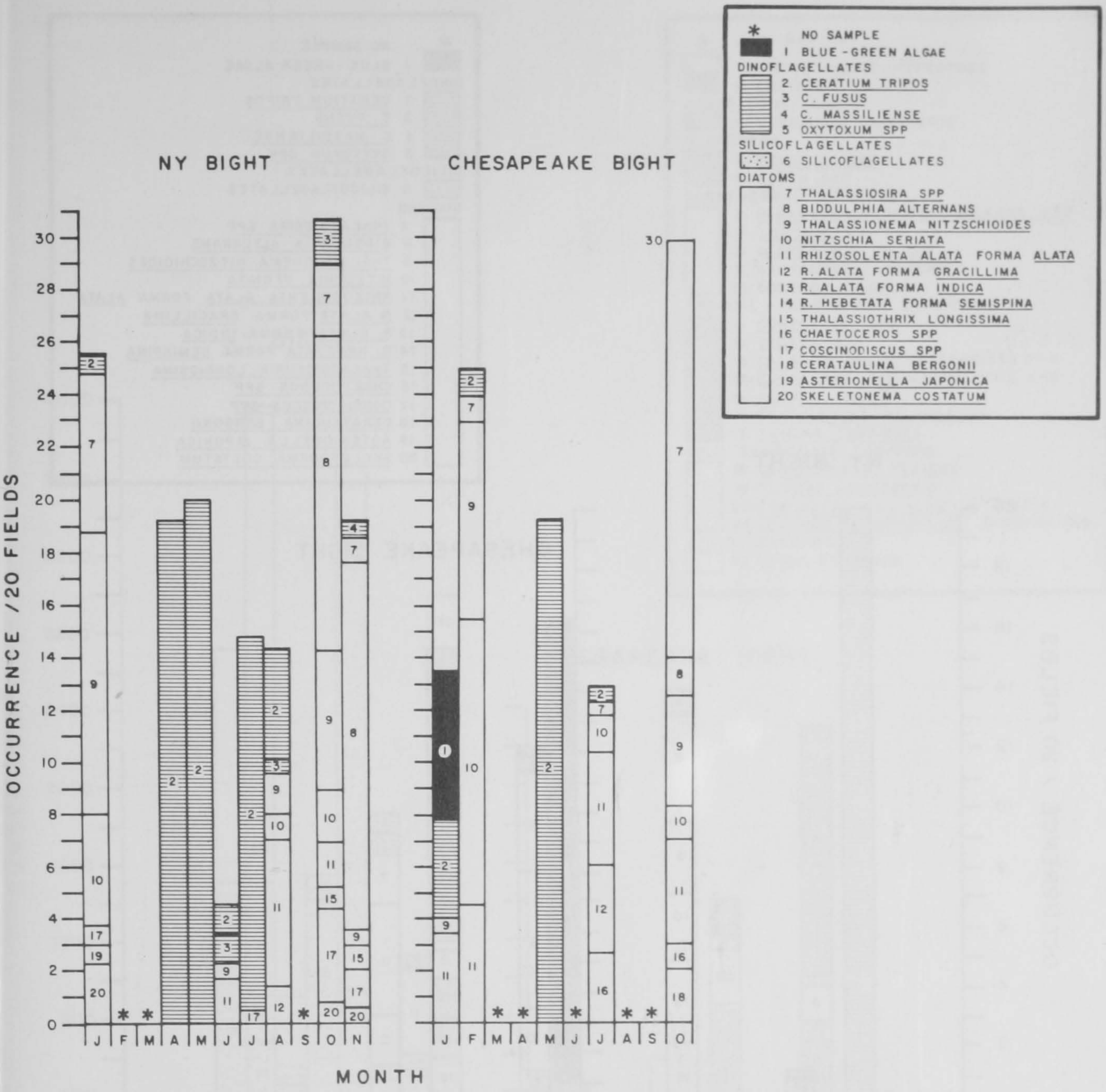

Figure 20.2.—Net phytoplankton abundance in Shelf Water of the New York and Chesapeake Bights, 1976. See text for explanation of abundance units.

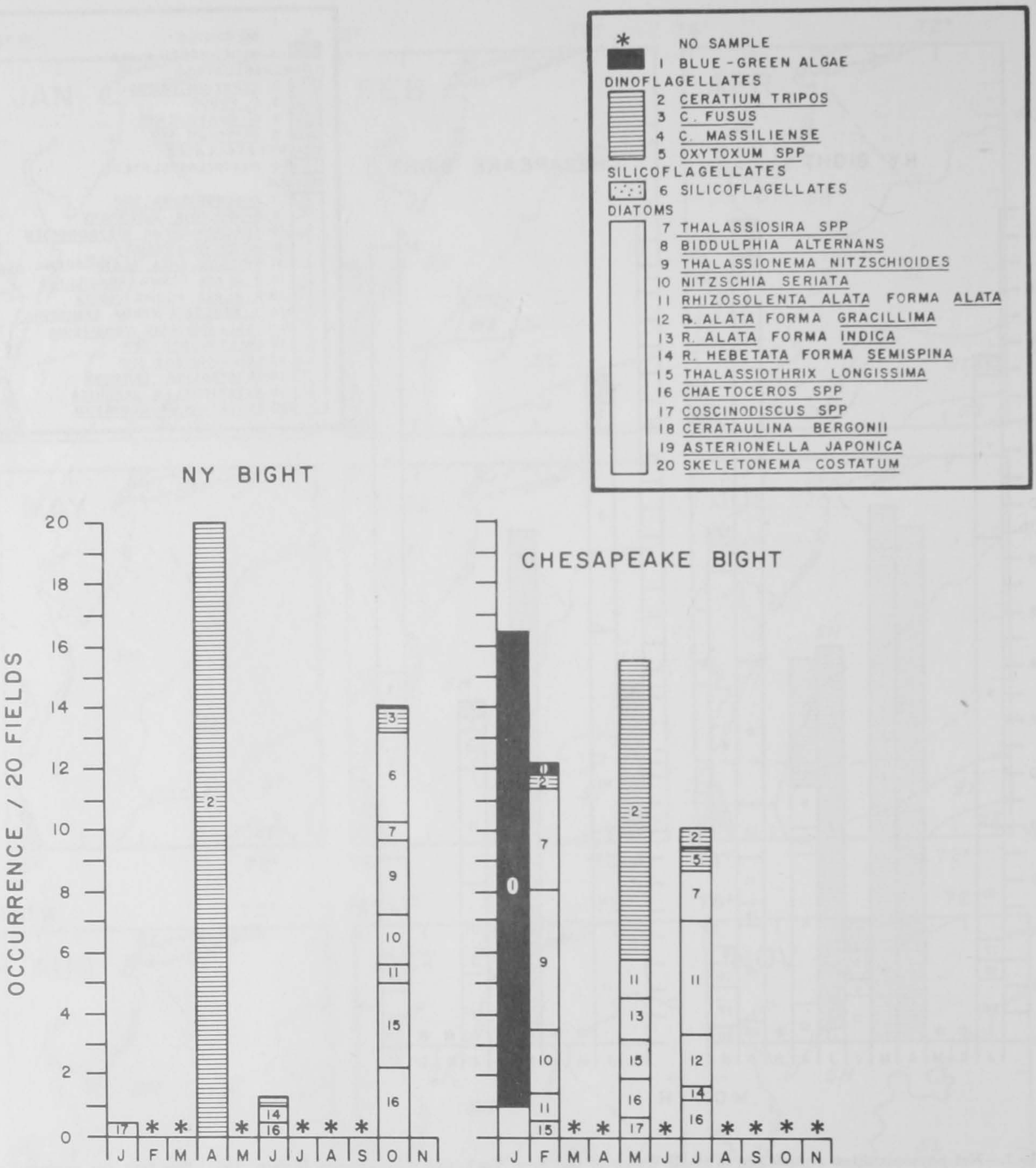

Figure 20.2.—Net phytoplankton abundance in Slope Water to the seaward of the New York and Chesapeake Bights, 1976. See text for explanation of abundance units.

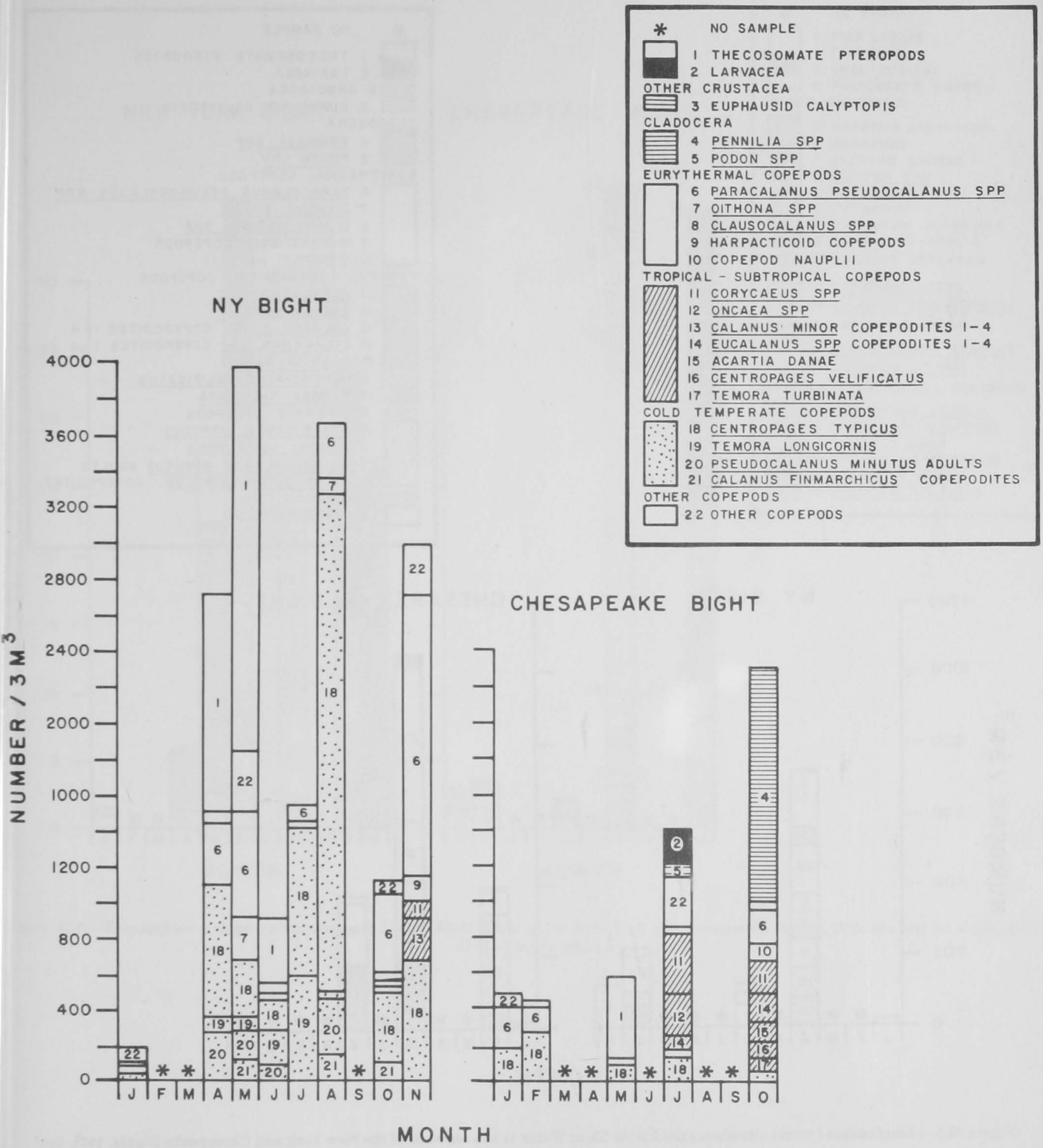

Figure 20.4.—Zooplankton (<2 mm) abundance per 3 m^3 in Shelf Water of the New York and Chesapeake Bights, 1976. See text for explanation of abundance units.

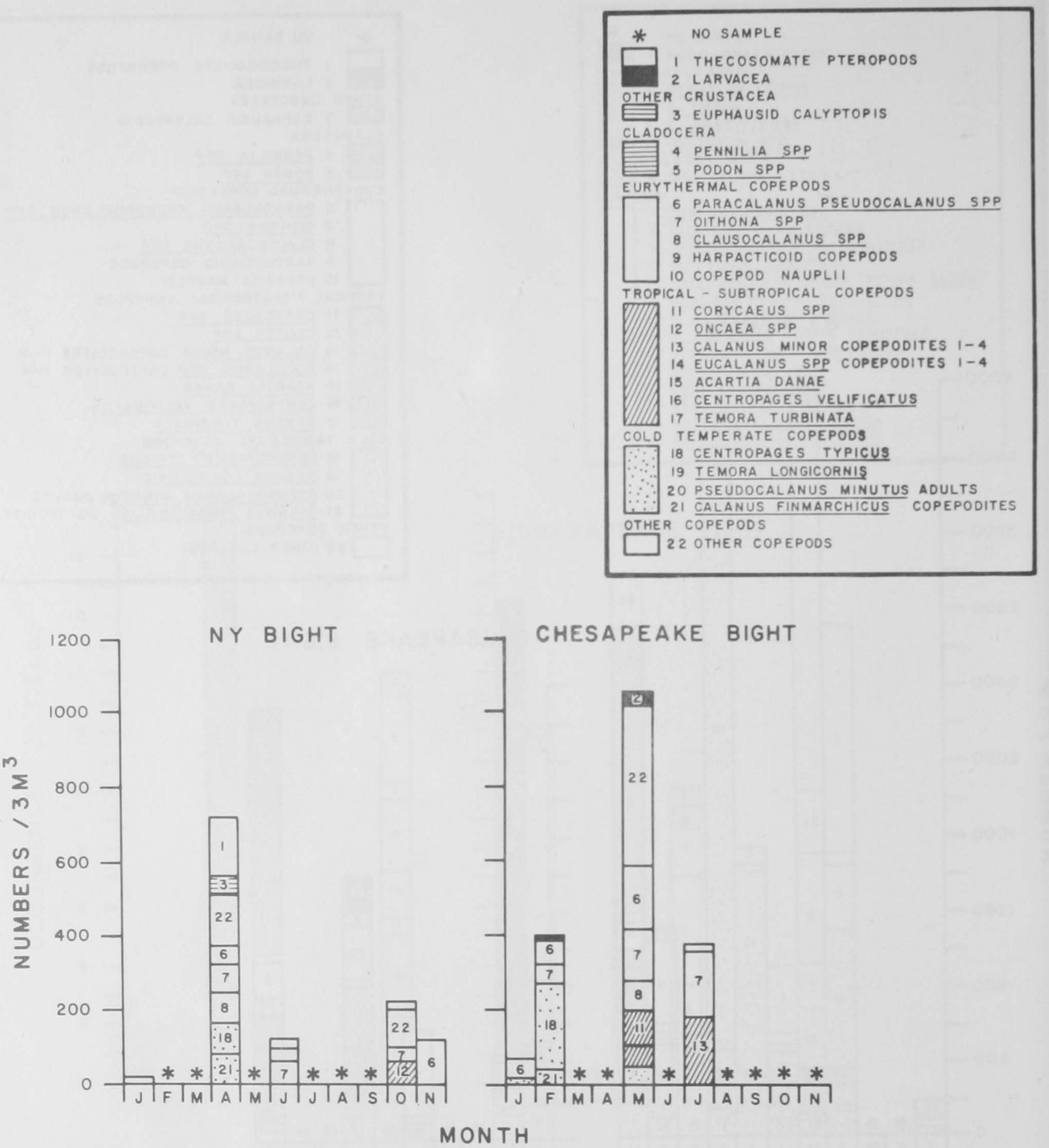

Figure 20.5.—Zooplankton (<mm) abundance per 3 m³ in Slope Water to the seaward of the New York and Chesapeake Bights, 1976. See text for explanation of abundance units.

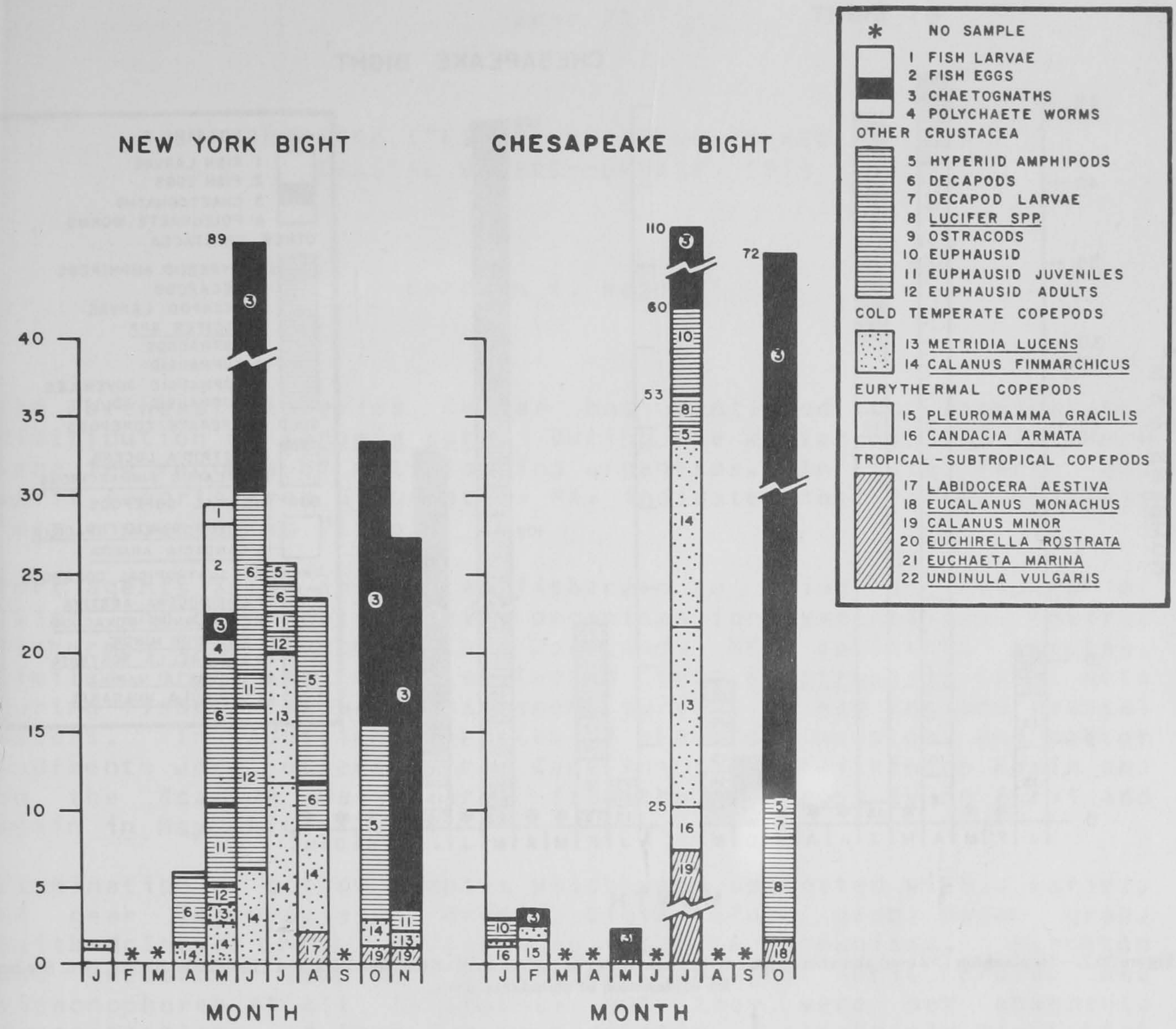

Figure 20.6.—Zooplankton (>2 mm) abundance per 3 m^3 in Shelf Water of the New York and Chesapeake Bights, 1976. See text for explanation of abundance units.

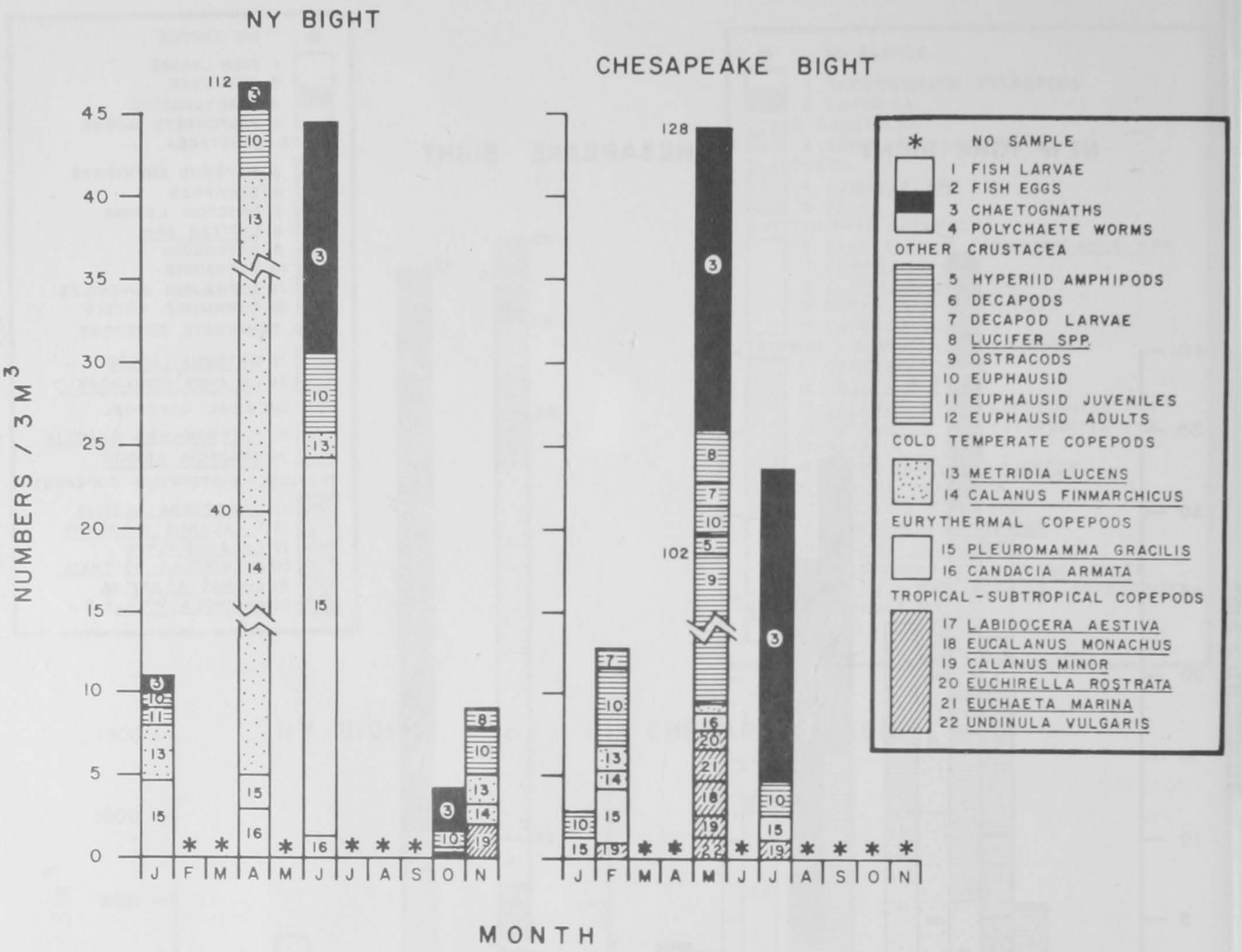

Figure 20.7.—Zooplankton (>2 mm) abundance per 3 m³ in Slope Water to the seaward of the New York and Chesapeake Bights, 1976. See text for explanation of abundance units.

Paper 21

SIPHONOPHORE ("LIPO") SWARMING IN NEW ENGLAND COASTAL WATERS--UPDATE, 1976

Carolyn A. Rogers[1]

The Northeast Fisheries Center has continued to examine the distribution of *Nanomia cara*. During the winter of 1975-76 there were few reports of net-clogging organisms. In late March and April reports from Gloucester, MA, indicated that fishermen again were encountering "lipo."

Port agents asked interested fishermen to bring in samples of "lipo" and other net-clogging organisms for examination. Several fishermen from Gloucester and Portland, ME, collected samples. Similar organisms were collected from *Albatross IV* trawl nets during fishery resource assessment surveys in New England coastal waters. In addition, samples of plankton, neuston, and bottom sediments were collected from Cape Ann to the Wilkinson Basin and in the Scantum Basin area from the *Albatross IV* in April and again in May (Fig. 21.1).

Examination of bottom samples which were collected with a variety of gear (naturalists' dredge, Dietz-Lafond grab, Ponar grab, Smith-McIntyre grab)[2] revealed no lipolike organisms. Plankton and neuston samples collected on the April cruise had siphonophores at all locations, but they were not abundant. Concentrations of *Phaeocystis pouchetii*, a planktonic alga which is enveloped in large gelatinous masses in the spring during its reproductive phase, were also found in these samples, with greatest densities in the more coastal (shallow) locations off Cape Ann and Newburyport, MA.

During May, *N. cara* was present in the plankton. However, as in April, numbers were low along the entire transect. In addition, the siphonophore colonies were smaller than those collected in autumn 1975. During our earlier studies (Rogers 1978), three

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[1] Northeast Fisheries Center, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

[2] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

categories of relative abundance were established based on the number of siphonophore remains in the plankton samples: high, moderate, and few. All samples in spring 1976 were categorized as "few" compared to the autumn 1975-winter 1976 estimates which were generally "high."

Examination of samples obtained from trawl nets during April revealed the usual invertebrates, such as brittle stars, worms and worm tubes, bryozoans, hydroids, small bivalves, urchins, and large jellyfish. The principal sources of gelatinous material in these samples, however, were Cerianthus borealis tubes. Cerianthus borealis is an anemonelike anthozoan which constructs a long, rough, thick tube of mud and various other materials cemented together by mucus. The tubes are often 2 feet in length and are buried in sandy bottoms. Cerianthus borealis is a very abundant species throughout the Gulf of Maine and especially in deep water. In addition, two samples contained Phaeocystis; one was from an inshore location and the other, which also contained siphonophores, was collected in the Fippenies area. In general all the samples examined contained the typical numbers and species of organisms which would be expected at this time of year at the locations sampled.

Conversations with port agents from Pt. Judith, RI, and New Bedford, Provincetown, and Boston, MA, indicated that there had been no significant problem with net-fouling organisms on vessels fishing from these ports during spring. Port agents Bob Morrill of Portland, ME, and Vito Giacalone of Gloucester, MA, indicated that loss of fishing time due to net-fouling organisms in spring was minimal, much reduced from autumn. They each reported the presence of a green slime high in the water column, especially in the inshore waters. From their description, and from trawl net and plankton samples, it is concluded that this slime is the alga Phaeocystis. There were also reports of small jellyfish in Ipswich Bay; this was verified by the presence of small hydromedusae in plankton and trawl net samples. Although nets occasionally get clogged with these gelatinous masses, fishermen were usually able to avoid them and they were not in sufficient quantities to reduce fishing effort. Morrill also commented that many boats were in fishing areas which had not been fished for four or five years. It is possible to conclude therefore that the populations of C. borealis had not been reduced as in areas of heavy fishing pressure, so the tubes in which these organisms live were found more frequently and in greater numbers than usual in the trawl nets.

SUMMARY OF FINDINGS

Examination of various samples and conversations with the New England port agents indicated that gelatinous organisms which could clog fishing nets were not unusually abundant in spring 1976. In fall 1975 and winter 1976 the unusually heavy swarming of one organism, the siphonophore *Nanomia cara*, was responsible for the reduction of fishing in coastal waters. In spring 1976 the occasional fouling of nets was caused by several separate organisms: the alga *Phaeocystis pouchetii*, enveloped in a gelatinous mass during its reproductive phase, resuming a motile unicellular existence as the waters warm; the siphonophore, *N. cara*, found in small numbers entangled in *Phaeocystis*; and *Cerianthus borealis* tubes, a material often brought up in small numbers in trawls. Because of increased fishing in areas where little or no fishing had occurred in recent years, the bottom population of *C. borealis* was greater than usually observed. As these areas continue to be fished, fewer and fewer tubes will become enmeshed in the nets. Small hydromedusae were also sighted. These are seasonal and their numbers should diminish as they complete their life cycles. Each organism cited is resident in New England waters and there is no indication at this time that any of these populations was abnormally abundant, nor is it likely that there will be any significant adverse impact on the fishing industry as a result of their presence if populations remain at observed levels.

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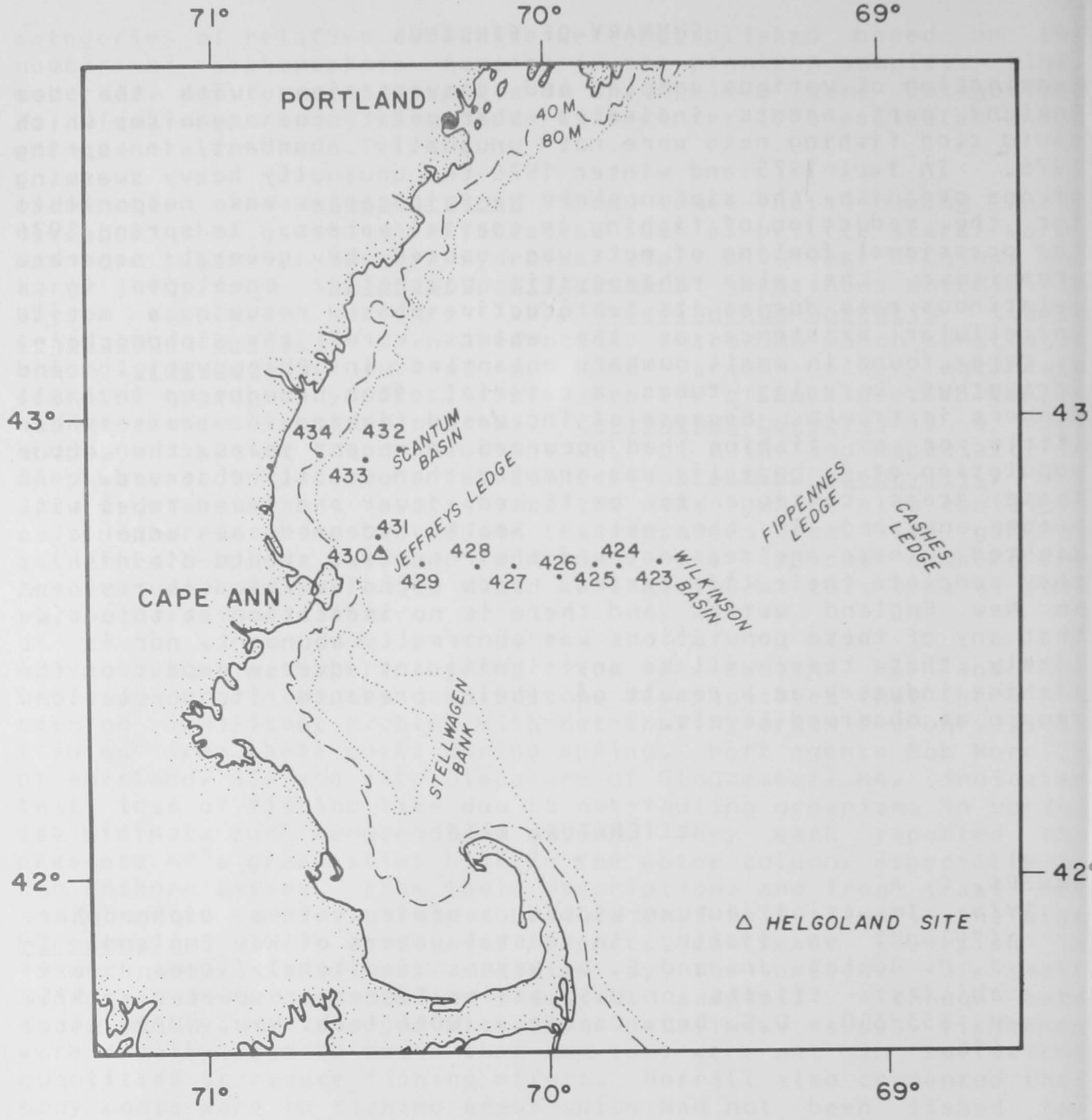

Figure 21.1.—Station locations of RV *Albatross IV* cruise 76-02-II at which plankton, neuston, and bottom samples were collected and examined for the presence of siphonophores.

Paper 22

BOTTOM-WATER TEMPERATURES IN THE GULF OF MAINE AND ON GEORGES BANK DURING SPRING AND AUTUMN, 1976

Clarence W. Davis[1]

Davis (1978) discussed observations of bottom-water temperatures in the Gulf of Maine and on Georges bank and the effects of temperature changes on fish stocks. It was generally concluded that the inflow of Slope Water through the Northeast Channel, which lies between Browns Bank and Georges Bank, was the major factor affecting changes in water temperature in this region of the Northwest Atlantic. There was a warming trend in 1968-74 in both the Gulf of Maine and on Georges Bank, but bottom-water temperatures reversed that trend in 1975. Data in this report show a resumption of the warming trend in 1976 despite record negative air temperature anomalies during the autumn along the Atlantic coast.

DATA AND METHODS

The temperature data have been obtained from approximately 150 expendable bathythermograph (XBT) casts made each spring and autumn during bottom trawl survey cruises conducted by NMFS personnel aboard _Albatross IV_. A weighted mean or index of the bottom-water temperature was obtained from the area represented by each 2C contour interval (Figs. 22.1, 22.2) by multiplying the midpoint of each interval by the percentage area within that interval and dividing the total by 100. These values were adjusted to account for differences in seasonal timing of data collection between years. Both observed and adjusted temperature indices are presented in this report; the adjusted values are more appropriate for comparing differences between years.

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[1] Northeast Fisheries Center, National Marine Fisheries Service, NOAA, Narragansett, RI 02882.

The Gulf of Maine and Georges Bank are analyzed in their entirety and by subareas of 1-deg longtitude (Table 22.1). Only those waters less than 100 m on Georges Bank and mostly deeper than 100 m in the Gulf of Maine are considered in this report.

RESULTS

Gulf of Maine

Both observed and adjusted bottom-water temperature indices reached maximum values in the Gulf of Maine in 1976 (Figs. 22.3, 22.4). The adjusted autumn index of 9.3C was 2.1C warmer than the 1963-75 mean and the adjusted spring index of 7.2C was 1.1C warmer than the 1968-75 mean. All subarea indices in the Gulf also exceeded the 1963-75 autumn and the 1968-75 spring means (Table 22.2). In the spring, subarea V had the greatest anomaly (+1.1C) while subareas II and III shared maximum of 2.2C in the autumn.

Georges Bank

Adjusted mean bottom-water temperatures on Georges Bank in 1976 were greater in both spring and autumn than the time-series means for each season and reversed the substantial drop in temperature noted in 1975 (Figs. 22.5, 22.6). All subareas of the Bank had positive anomalies in both seasons, most notable of which is the +2.3C on eastern Georges Bank in autumn (Table 22.3). This subarea is usually 2C or more colder than the remainder of the Bank in autumn, but in 1976 was only 0.7C colder than central Georges Bank and 1.0C colder than western Georges Bank.

DISCUSSION

Contrary to the occurrence of record cold weather conditions along Atlantic coast during the autumn 1976 (Chamberlin and Armstrong, Paper 11), bottom-water temperatures reached record highs in the Gulf of Maine and were higher than normal on Georges Bank. Because Georges Bank is relatively shallow and well mixed by tide and wind, it would have been reasonable to expect much colder water there in autumn 1976. The deeper waters in the Gulf of Maine would be expected to be less affected by the cold air temperatures. The reasons for the positive anomalous conditions observed in 1976 are no doubt complex, but may be explainable by a time-lag in the bottom water's response to air temperature changes or by the fact that the large amount of Slope Water that entered the Gulf in the spring, indicated by the 8C isotherm in Figure 22.1, buffered the cold air effect, especially as warmer

Gulf Water mixed with Georges Bank Water.

The record cold air temperatures of 1976, however, may have lessened the current trend, only partially reversed in 1975, to even higher temperatures than those observed.

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DAVIS, C. W.
1978. Spring and autumn bottom-water temperatures in the Gulf of Maine and Georges Bank, 1968-1975. In J. R. Goulet, Jr. and E. D. Haynes (editors), Ocean variability: Effects on U.S. marine fishery resources - 1975, p. 241-255. U.S. Dep. Commer., NOAA Tech Rep. NMFS Circ. 416.

Table 22.1.--Subarea designation and location in the Gulf of Maine and on Georges Bank.

Area	Subarea	Longitude (W)
Gulf of Maine	I	71°-70°
	II	70°-69°
	III	69°-68°
	IV	68°-67°
	V	67°-66°
Georges Bank	Western	69°-68°
	Central	68°-67°
	Eastern	67°-66°

Table 22.2.--Adjusted mean bottom-water temperatures and anomalies by subareas in the Gulf of Maine in 1976. Anomalies are based on the 1968-75 mean in the spring and the 1963-75 mean in the autumn.

Gulf of Maine subarea	Spring - 1976		Autumn - 1976	
	mean °C	anomaly °C	mean °C	anomaly °C
I	5.1	+1.0	9.0	+1.5
II	6.7	+0.9	8.8	+2.2
III	7.0	+0.9	9.1	+2.2
IV	7.7	+0.8	9.4	+1.8
V	7.2	+1.1	10.2	+2.0
Entire Gulf	7.2	+1.1	9.3	+2.1

Table 22.3.--Adjusted mean bottom-water temperatures an anomalies by subareas of Georges Bank in 1976. Anomalie are based on the 1968-76 mean in the spring and the 1963 75 mean in the autumn.

Georges Bank subarea	Spring - 1976		Autumn - 1976	
	mean °C	anomaly °C	mean °C	anomaly °
Western	5.6	+0.3	13.3	+1.0
Central	5.2	+0.1	13.0	+0.7
Eastern	5.4	+0.3	12.3	+2.3
Entire bank	5.4	+0.4	12.6	+0.9

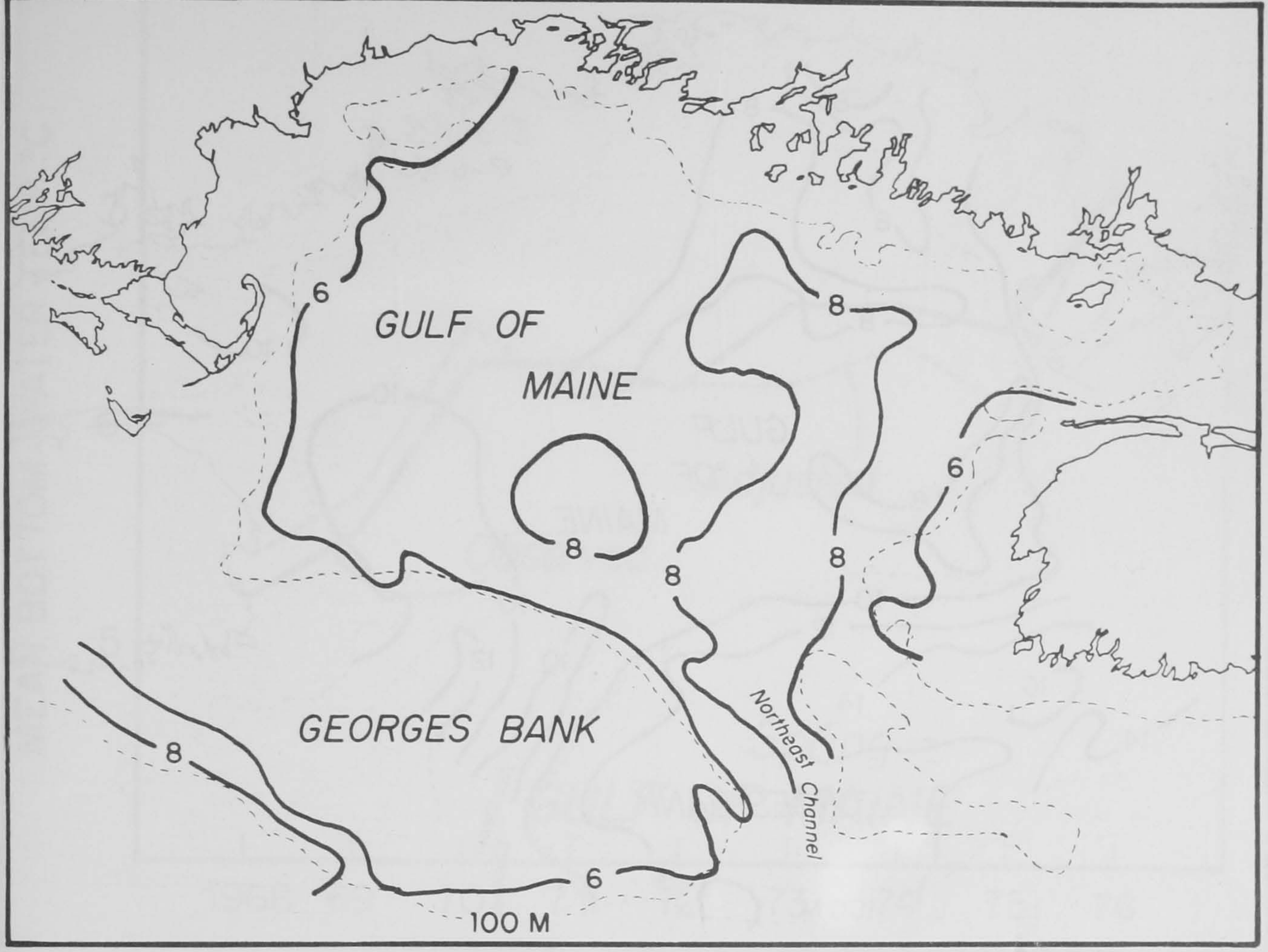

Figure 22.1.—Distribution of bottom-water temperatures in the Gulf of Maine and on Georges Bank during spring 1976; *Albatross IV* 76-02.

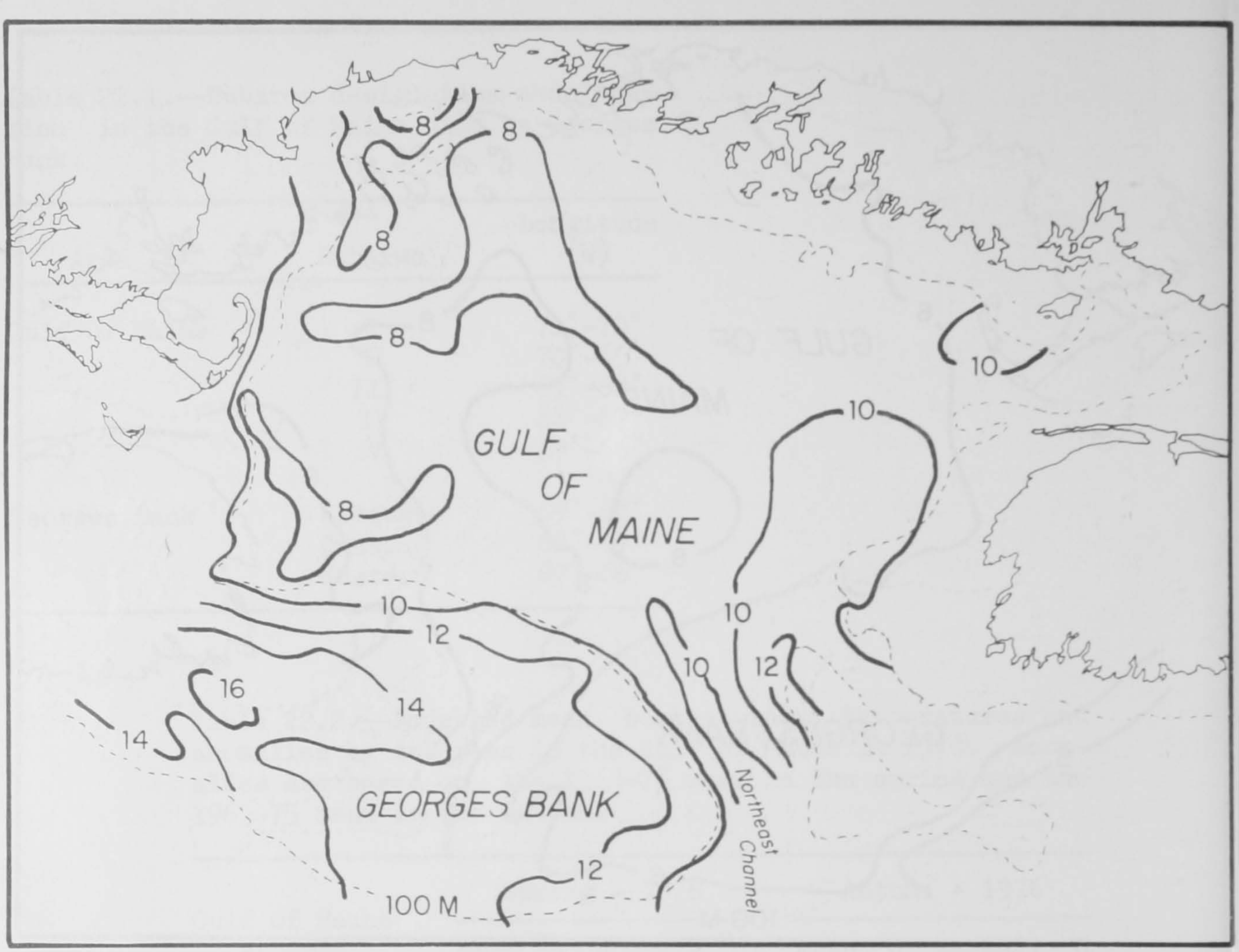

Figure 22.2.—Distribution of bottom-water temperatures in the Gulf of Maine and on Georges Bank during autumn 1976; *Albatross IV* 76-09.

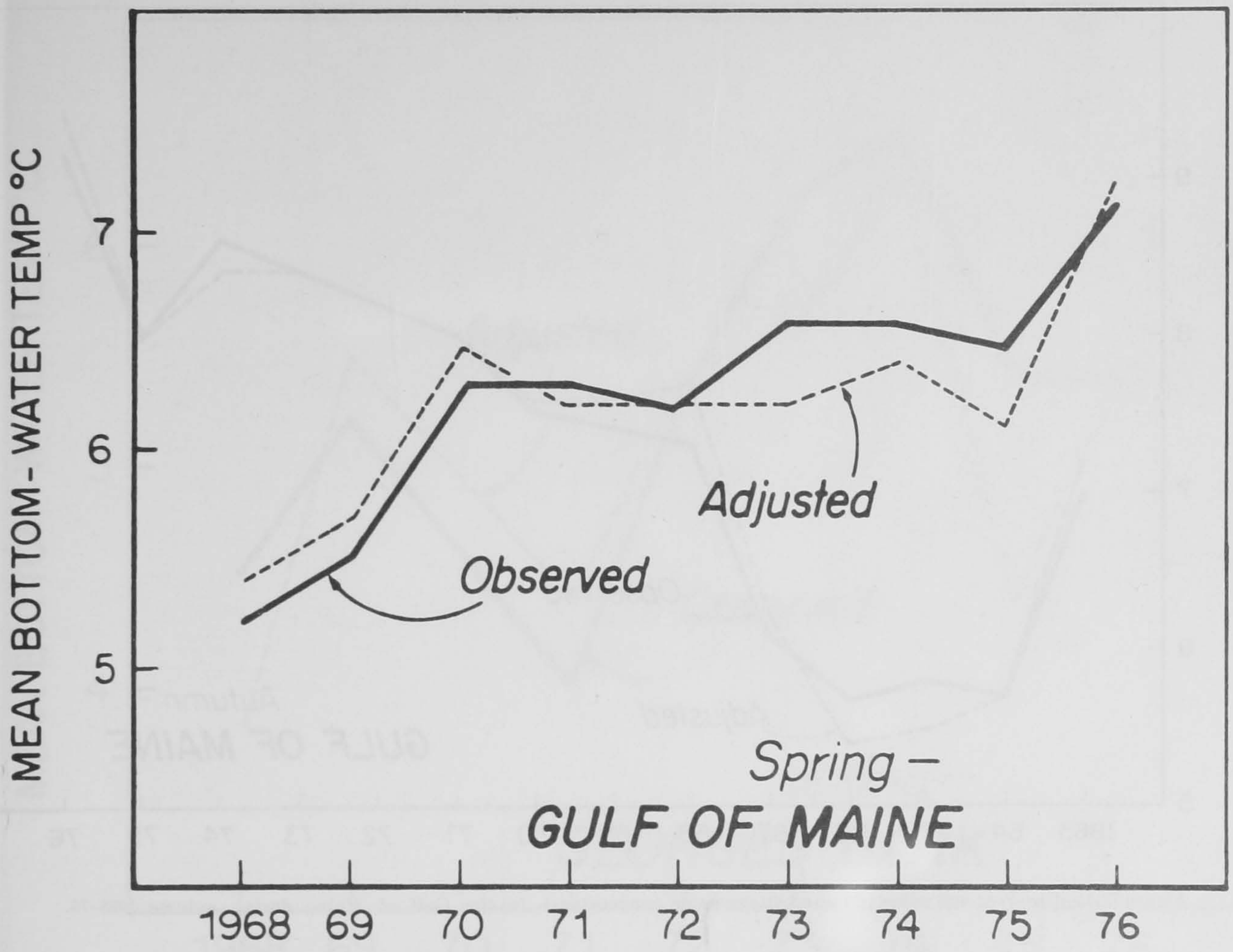

Figure 22.3.—Observed and adjusted mean bottom-water temperatures in the Gulf of Maine during spring 1968-76.

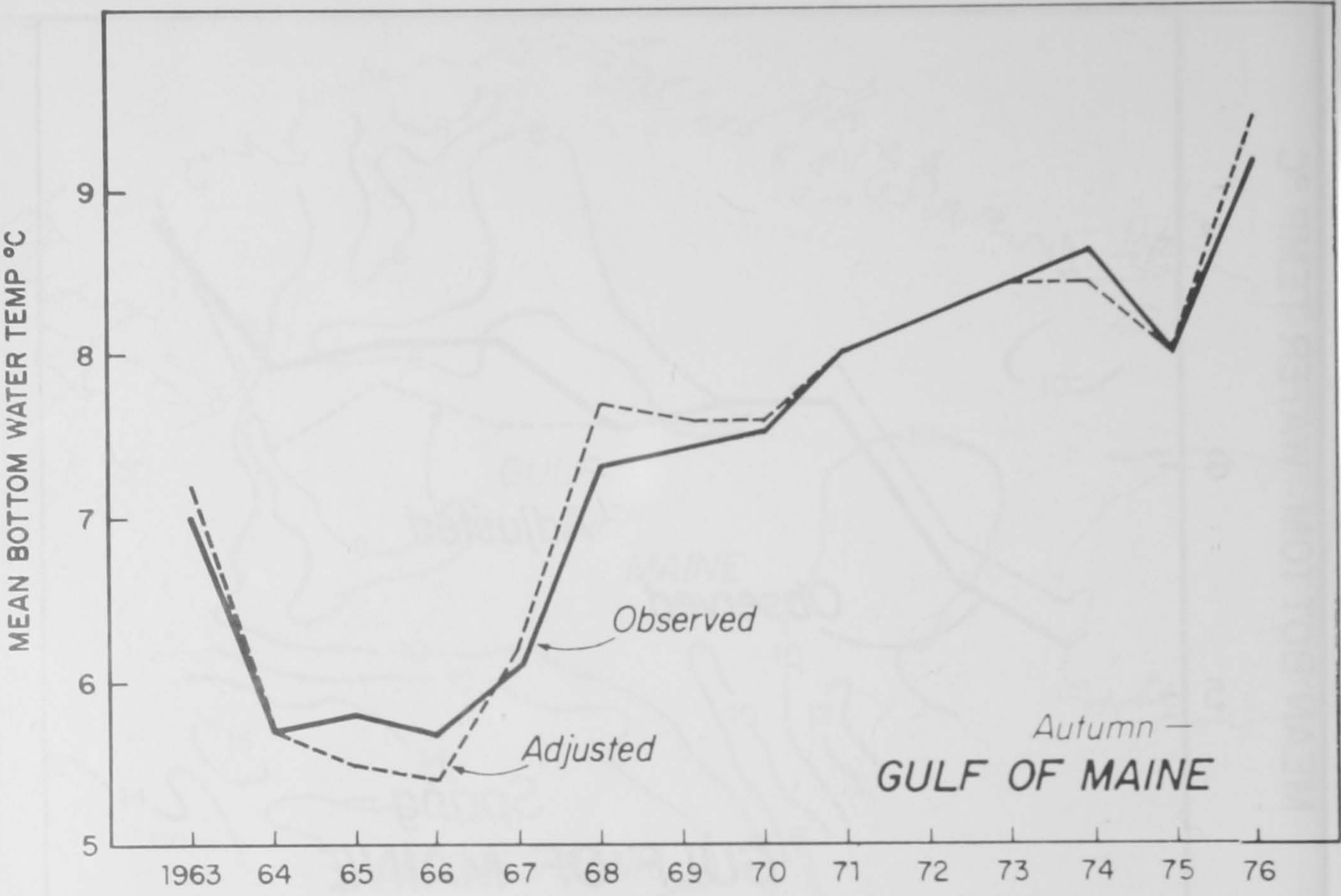

Figure 22.4.—Observed and adjusted mean bottom-water temperatures in the Gulf of Maine during autumn 1968-76.

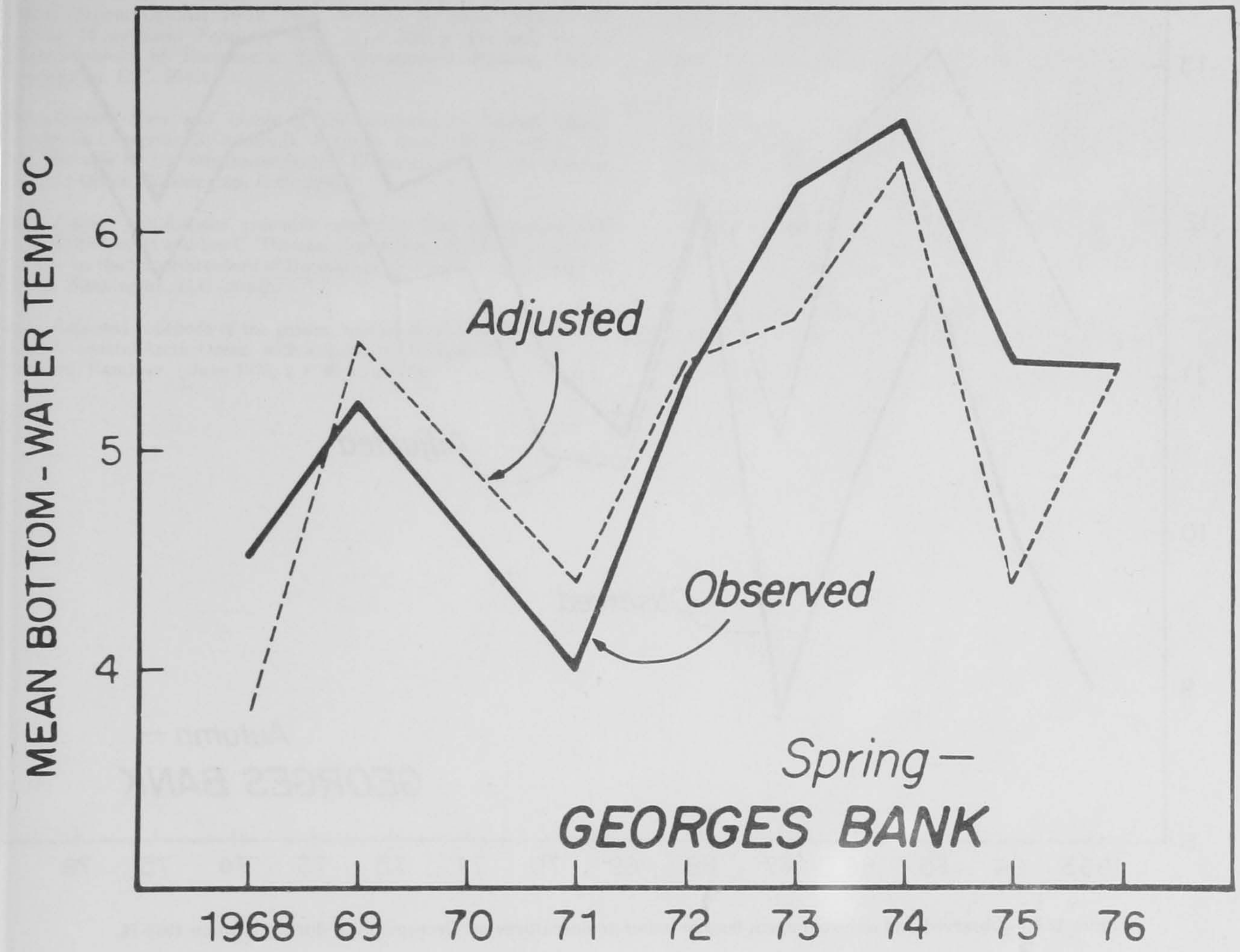

Figure 22.5.—Observed and adjusted mean bottom-water temperatures on Georges Bank during spring 1968-76.

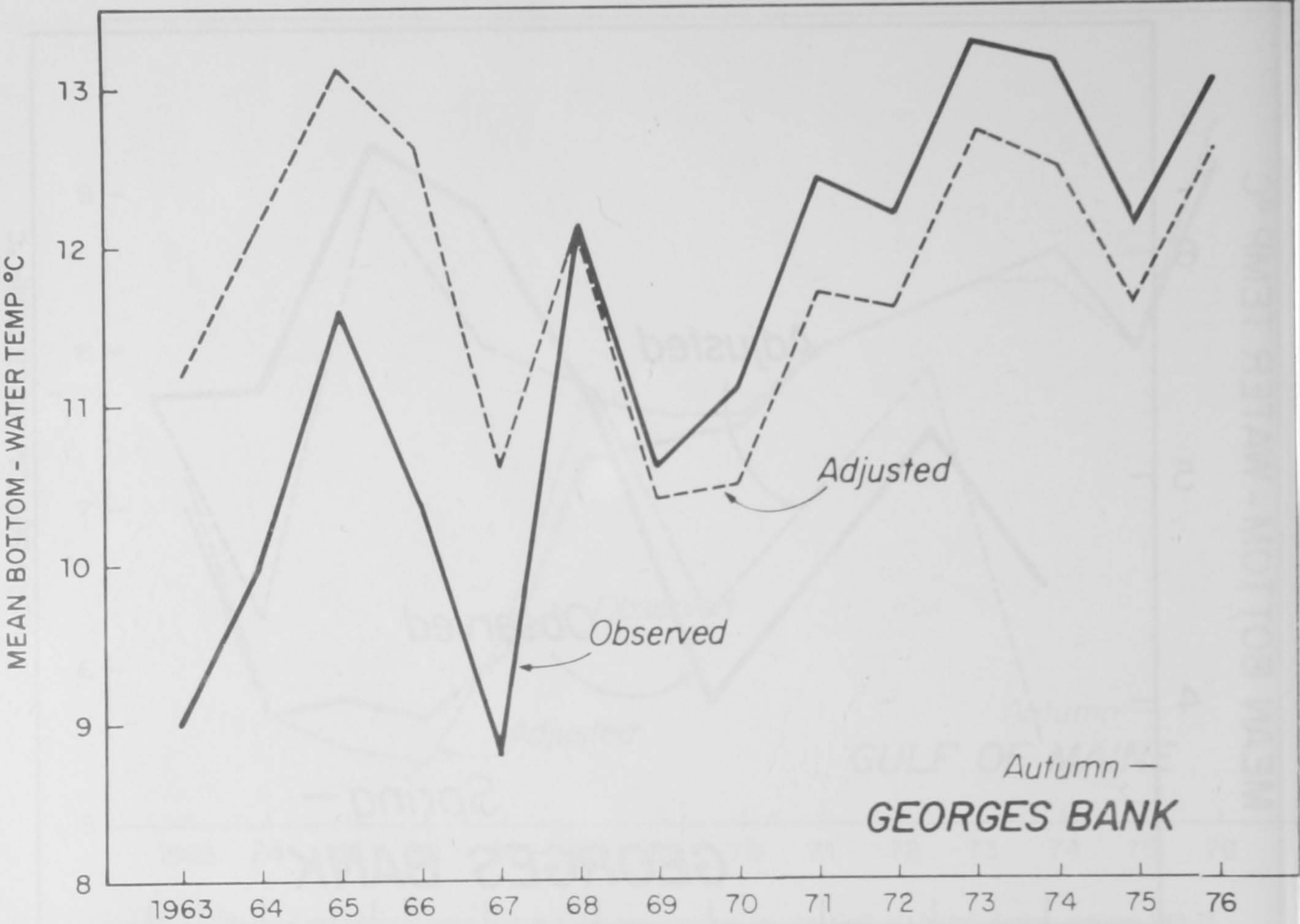

Figure 22.6.—Observed and adjusted mean bottom-water temperatures on Georges Bank during autumn 1968-76.