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PB-284 001

Summary of Environmental Information on the Continental Slope Canadian/United States Border to Cape Hatteras, N.C. Chapters 1 through 6

Research Institute of the Gulf of Maine, Portland

Prepared for

Bureau of Land Management, New York

May 76

50272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO. BLM-ST-78-36
2.
3. Recipient's Accession No. PB28[illegible]-001
4. Title and Subtitle Summary of Environmental Information on the Continental Slope Canadian/United States Border to Cape Hatteras, N.C.: Chapters 1 through 6.
5. Report Date May, 1976
6.
7. Author(s) The Research Institute of the Gulf of Maine
8. Performing Organization Rept. No. NYOCS-01A
9. Performing Organization Name and Address

The Research Institute of the Gulf of Maine
21 Vocational Drive
South Portland, Maine 04106

10. Project/Task/Work Unit No.
11. Contract(C) or Grant(G) No.
(C) 08850-CT5-47
(G)
12. Sponsoring Organization Name and Address

U.S. Department of the Interior
Bureau of Land Management
Washington, D.C. 20240

13. Type of Report & Period Covered Final Report
14.
15. Supplementary Notes This volume contains Chapters 1 to 6, inclusive. These chapters consist of: Introduction, Overview, Meteorology, Physical Oceanography, Geological Oceanography and Chemical Oceanography.

16. Abstract (Limit: 200 words)

The results of an environmental survey of the Mid-Atlantic and North Atlantic Regions of the Outer Continental Slope are described. This region is the area extending from Cape Hatteras, N.C. to the U.S./Canadian border and from the 200 to 2000 meter depth contour; however, many topic areas include information from the continental shelf break to the Gulf Stream. The continental slope is a complexed feature representing the transition between two principal levels of the earth's surface, the low density rocks of the continent and the high density rocks of the ocean floor. In the northwest Atlantic, the slope width averages 100 km(62 mi). This relatively narrow band of ocean is a region of change. The geologic structure is a transitional one. The physical and chemical characteristics of the water are highly variable, reflecting the mixing between several major water masses; the coastal waters, Gulf Stream, Labrador Current and western boundary undercurrent. The flora and fauna of the study region are highly diverse, representing a change between the shallow boreal shelf biota and the tropical and warm, temperate oceanic biota in the pelagic realm; and between the abundant, adaptive fauna of the shelf floor and the sparse, conservative fauna of the deep ocean floor in the benthic realm.

17. Document Analysis a. Descriptors

Meteorology, Winds, Cyclones, Oceanography, Circulation, Geological Oceanography, Sediments Bathymetry, Nutrients, Hydrocarbons, Trace Elements

b. Identifiers/Open-Ended Terms

North Atlantic Region, Mid-Atlantic Region, Outer Continental Slope, Physical Oceanography, Chemical Oceanography

c. COSATI Field/Group 4B, 8C, 8D, 8J

18. Availability Statement Release Unlimited
19. Security Class (This Report) Unclassified
20. Security Class (This Page) Unclassified
21. No. of Pages 353
22. Price PC A16
MF A01

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

A Summary of Environmental Information on the Continental Slope

Canadian/U.S. Border to Cape Hatteras, N.C.

PB 284 001

TRIGOM

The Research Institute of the Gulf of Maine

SUMMARY OF ENVIRONMENTAL INFORMATION

ON THE

CONTINENTAL SLOPE

Canadian/United States Border to Cape Hatteras, N.C.

Submitted to Bureau of Land Management, Marine Minerals Division

in fulfillment of Contract 08550-CT5-47

May, 1976

The Research Institute of the Gulf of Maine
21 Vocational Drive
South Portland, Maine

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ABSTRACT

A six month study by The Research Institute of the Gulf of Maine was conducted to summarize existing environmental information pertinent to the continental slope of the northeast United States. The reason for the study was the requirement for impact assessments prior to oil, gas and mineral explorations and production on the outer continental shelf. The specified boundaries of the study were Cape Hatteras to the U.S./Canadian border and from the 200 to the 2000 meter depth contour; however, many topic areas include information from the continental shelf break to the Gulf Stream. The following list shows the major topic areas presented in the report:

- Environmental Features
  - Meteorology
  - Physical Oceanography
  - Geological Oceanography
  - Chemical Oceanography
  - Biological Oceanography
    - Phytoplankton
    - Zooplankton
    - Benthos
    - Nekton
    - Offshore Birds
  - Submarine Canyons
- Human Impact
  - Environmental Quality
  - Fisheries
  - Ocean Transport and Hazards
  - Archaeological and Historical Sites

The report, constituting over 1700 pages and over 400 tables and figures, includes a summary of environmental topics, data on past, current and future research in the study area, a master bibliography of over 1400 citations and an index. The report was the result of a literature review and personal contacts with over 200 people involved in the study of the offshore environment.

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CHAPTER 1.0

INTRODUCTION

1.0 BACKGROUND

The obvious need for additional petroleum reservoirs has precipitated interest in potential oil reserves along the continental margin off the New England and the mid-Atlantic regions. Prior to petroleum development, an evaluation of environmental impacts is required by the National Environmental Policy Act (NEPA) of 1969. As a prerequisite, the Bureau of Land Management (BLM), sponsored an inventory and summary of existing knowledge pertinent to the marine environment of the North Atlantic region.

The staff at The Research Institute of the Gulf of Maine (TRIGOM), under BLM Contract 08550-CT3-8 from June 29, 1973 to July 29, 1974 completed a study entitled A Socio-Economic and Environmental Inventory of the North Atlantic Coast and Continental Shelf from The Bay of Fundy to Sandy Hook, New Jersey (TRIGOM, 1974). The outer limit of this study was set at the 200 m isobath (the edge of the continental shelf) and, therefore, only scattered reference was made to the ocean regions beyond. It was apparent, however, that many environmental features of the continental slope are closely related to the continental shelf and are, therefore, potentially within the zone of influence of oil development activities. Because of this, and the possibility of the presence of oil reserves on the slope itself, a subsequent study was initiated by TRIGOM, again under BLM contract, to inventory the existing data pertinent to the continental slope.

This report represents the final results of the six-month study entitled A Summary of Environmental Information on the Continental Slope: Canadian/United States Border to Ca. Hatteras. The primary purpose of the study has been to gather and summarize available data that describes the continental slope environment. The study was conducted by the staff of TRIGOM and their outside consultants for the United States Department of the Interior, Marine Minerals Division under Contract 08550-CT5-47 during the period July 1, 1975 to December 31, 1975.

1.1 PURPOSE AND OBJECTIVES

The purpose of this study was to summarize and synthesize environmental information pertinent to the designated study area on the continental slope, the results to be used by BLM as a data base from which to prepare environmental impact statements and study plans, make management decisions, and to determine where gaps and deficiencies exist and where further research is required.

The specific objectives were to:

- Collect and compile environmental data pertinent to the designated study region and topic areas from diverse information sources.

- Synthesize and reduce this information into a usable data base.
- Prepare a bibliographic listing of all published and unpublished reports concerning the study region.

1.2 SCOPE OF WORK

1.2.1 AUTHORIZATION

The scope of this study was originally defined in a Request for Proposals (RFP-BLM 75-9) and subsequently by Contract 08550-CT5-47.

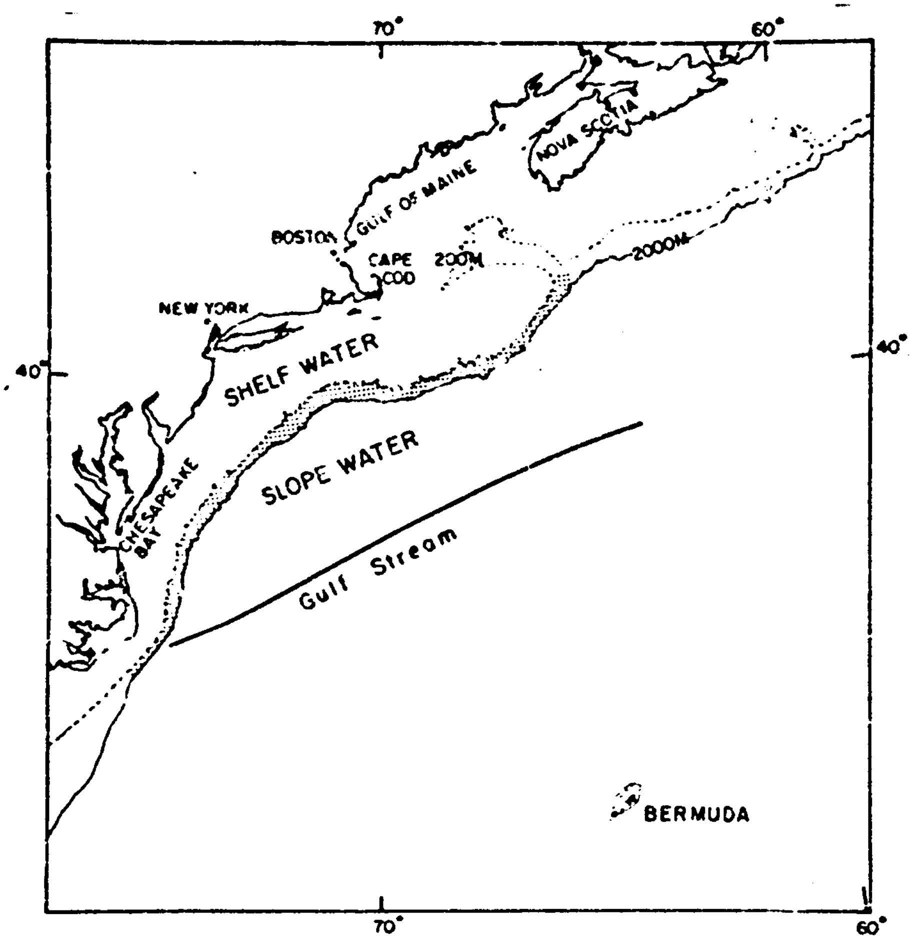
1.2.2 GEOGRAPHICAL AREA

The study region, as specified in Contract 08550-CT5-47, is bounded by the Canadian/United States border on the north, Cape Hatteras on the south, and includes the area from the 200 m isobath seaward to the 2000 m isobath. This is the area of primary concern relative to environmental impacts from oil activities (Figure 1-1).

It should be recognized that any comprehensive physical or biological consideration of the slope environment cannot be restricted to the area between 200 m and 2000 m, because the region enclosed by these boundaries is not isolated, in any strict sense, from adjacent regions.

This is particularly true of the water column. The closest thing to a physical and biological entity in this region is the "slope water" which encompasses the area between the continental shelf water and the Gulf Stream. Dissection of data from this region into the water column between 200 and 2000 m would be both impractical and unrealistic. Therefore, in matters concerning the water column, we have generally considered the "slope water" as a whole.

The consideration of the geology and biology of the slope surface itself is more easily definable within the 200 m to 2000 m depth contour. The 200 m contour approximates the break between the gradually deepening surface of the continental shelf and the steeper gradient of the slope. The 2000 m contour represents, approximately, the depth at which the relatively steep gradient of the slope changes to the more gradual gradient of the continental rise. Even here, however, the physical and biological relationships between the slope and adjacent regions cannot be ignored. Structurally, this region is related to the continental shelf and deep ocean basin. Physical events, such as sedimentation, slumping, and turbidity currents are ultimately transient processes between the shelf above and the ocean basin beneath. Biologically, the zonation of benthic organisms overlaps the adjacent regions and for certain benthic fishes of the shelf, the upper slope has particular significance. Therefore, the slope surface has to be considered in



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 1-1 Study Area

relation to the adjoining regions.

1.2.3 TOPICAL COVERAGE

The subject areas can be broadly divided into two categories: the slope environment and the effects of man's influence upon it. The major topics within these two categories are treated by discipline as follows:

- Environmental Features
    - Meteorology
    - Physical Oceanography
    - Geological Oceanography
    - Chemical Oceanography
    - Biological Oceanography
        - Phytoplankton
        - Zooplankton
        - Benthos
        - Nekton
        - Offshore Birds
    - Submarine Canyons
- Human Impact
    - Environmental Quality and Pollutants
    - Fisheries
    - Threatened and Endangered Species
    - Ocean Transport and Hazards
    - Archaeological and Historical Sites

Because they are such a significant feature of the continental slope, the submarine canyons have been treated separately in an attempt to integrate information from the various disciplines into a type of habitat summary. The appendices have been reserved for a descriptive account of the current and future research effort on the slope.

1.2.4 INFORMATION SOURCES

The textual summary of this report is comprised of information from the following sources:

- Published data - the main source of information was from the review of over 1000 published articles that appear in the bibliography.
- Unpublished data - another major source was the body of information that results in unpublished reports, data banks, and the personal observations of the scientists who have first-hand knowledge of the study area.
- Current research - The preliminary results of current research projects made this report as timely as possible.

1.3 METHOD AND APPROACH

Our approach to the study was to carry out three somewhat overlapping tasks:

Data collection
Data reduction
Data synthesis

The collection of data was accomplished by two teams, a northern team consisting of the TRIGOM staff and a consultant from the Woods Hole Oceanographic Institution, and a southern team consisting of consultants at the Marine Division of Westinghouse Corporation. The work was accomplished by reviewing publisjed literature and conducting telephone and field interviews. A limited mailing questionnaire was also sent. An effort was made to contact people at all institutions from the Canadian Maritimes to North Carolina who were even remotely involved in the outer continental shelf and slope. From all these contacts, however, it soon became evident that relatively few people were actually involved in work within the study region.

The reduction of information, which involved extracting slope information, analyzing data, and developing graphic formats and report outlines was accomplished primarily by the TRIGOM staff. Although the scope of the study prevented extensive analysis of some data, a number of important data banks and summaries were drawn on and analyzed in a limited way. We felt in some cases this was necessary because of the lack of substantial published information for the continental slope region.

The synthesis of data into chapter form was accomplished largely by the staff at TRIGOM. However, in the case of several of the chapters, the bulk of information and its highly technical nature made it advisable to enlist consultants who were specialists in those particular fields. The authors of all chapters are, therefore, duly noted in the report.

The report is contained in four volumes:

Volume I
Chapters 1 to 6

Volume II
Chapter 7

Volume III
Chapters 8 to 12

Volume
Appendices A to C

Within this framework, the chapters are presented according to the several disciplines and topics. The sources cited in the text are listed at the end of each chapter and in the master bibliography. The master bibliography also contains references that are pertinent to the subject, but not directly cited in the text of the report. Past, current and proposed future studies are described in the appendix.

1.4 LIMITATIONS

We have attempted, in a relatively short time, to survey, collect, analyze and summarize information from widely scattered sources. Studies that are specific to the continental slope are not abundant. In most cases, small bits of information are contained in sources that refer to larger regions, requiring that the slope data be extracted and collected into this report. Also, many recent environmental measurements taken on the continental slope are in the form of raw data. In cases where the information was particularly desirable and where it was practical, we have attempted to reduce and present this data; however, in most cases it was beyond the scope of this report to more than mention the existence of the information.

We have attempted, through rigorous editing, to make the report as free of errors as possible. All data from published and unpublished sources have been cited and checked for error in transfer. However, recognizing that a very large amount of information has been condensed in a relatively short period of time, and that perfection is rarely achieved even in the best of circumstances, we expect there will be errors in this report. We hope any errors or suggestions for changes and additions will be brought to our attention.

1.5 ACKNOWLEDGEMENTS

This report is the result of the efforts of a great number of people. To all of them we wish to express our thanks.

We are particularly grateful to those individuals working in the continental slope region who provided information from their own knowledge, much of it unpublished and very current. Many of the scientists at the Woods Hole Oceanographic Institution, the National Marine Fisheries Service at Woods Hole, and the Virginia Institute of Marine Science, were particularly helpful.

We would also thank our chapter authors who contributed their talents, time and effort toward this report. The people responsible for the

various chapters are listed below:

Meteorology	Mr. Peter Beves	Portland, Me.
Physical Oceanography	Dr. Redwood Wright	Woods Hole, Mass.
Geological Oceanography	Mr. Edward H. Shenton	Boothbay Harbor, Me.
Chemical Oceanography	Dr. Guy McLeod	New England Aquarium
	Mr. T.R. Gilbert	New England Aquarium
Biological Oceanography	Dr. Peter Larsen	Bigelow Laboratory
	Mr. Stanley Chenoweth	Boothbay Harbor, Me.
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Stanley Chenoweth
Project Manager

CHAPTER 2.0

OVERVIEW

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Chapter 2.0 Overview

2.0 OVERVIEW

2.1 INTRODUCTION

The continental slope is a complexed feature representing the transition between two principal levels of the earth's surface, the low density rocks of the continent and the high density rocks of the ocean floor. In the northwest Atlantic, the slope angle generally varies between 3° and 6° and the width averages 100 km. This relatively narrow band of ocean is a region of change. The geologic structure is a transitional one and the slope gradient creates a dynamic sedimentary environment. The physical and chemical characteristics of the water are highly variable, reflecting the mixing between several major water masses; the coastal waters, Gulf Stream, Labrador Current and western boundary undercurrent. The flora and fauna of the study region are highly diverse, representing a change between the shallow boreal shelf biota and the tropical and warm, temperate oceanic biota in the pelagic realm; and between the abundant, adaptive fauna of the shelf floor and the sparse, conservative fauna of the deep ocean floor in the benthic realm. Thus, the transition from coastal to oceanic conditions, in terms of both the water mass and its biological components and the bottom and its biological components, is an extreme one and results in a wide diversity of environments, and organisms that have adapted to them.

For the purpose of setting realistic boundaries to the area of study, the slope region between Cape Hatteras and Georges Bank will be considered in terms of two major environments - pelagic and benthic.

The pelagic environment exists as a physical entity between the shelf/slope front that roughly parallels the edge of the continental shelf, and the "cold wall", or the front that borders the western edge of the Gulf Stream. It begins to the south at Cape Hatteras where the Gulf Stream veers seaward from the shelf and gradually broadens as one moves into the boreal North Atlantic. The area encompassed by this water mass is called the "slope water" and, although comprised of highly variable components, is considered a distinct oceanographic regime. The principal dynamic force in this system is the Gulf Stream which, as it meanders in its northward flow, creates a contributing force at the eastern boundary of the slope water. The movement of shelf water and the western boundary undercurrent also contribute dynamic qualities to the slope water.

The benthic environment can be more easily treated within the original defined boundaries of the study. The limits of the continental slope, roughly the edge of the continental shelf at depths of 200 m and the beginning of the continental rise at 2,000 m, are boundaries that encompass an area with distinct geological and biological characteristics. Even here, however, the boundaries do not isolate the benthic environment of the slope from the adjacent regions. The upper slope environments are in many ways more akin to the outer shelf and the lower slope to the ocean basin. The various environmental elements of the study region: physical, chemical, geological, and biological, are to be considered in context of the pelagic and benthic environments.

2.2 METEOROLOGY

The study region is influenced by the general weather systems in the northwest Atlantic. It lies in an area of prevailing westerly winds between two semi-permanent pressure centers - the Iceland low and the Bermuda/Azores high. Prevailing southwesterly winds during the summer result from the strengthened Bermuda/Azores high, while the prevailing northwesterly winds in the winter result from the strengthened Icelandic low. Locally, the microclimate of the slope waters results from the interaction of the atmosphere and hydrosphere and will vary widely both between adjacent regions and within the slope water itself. A lack of fixed monitoring stations in the slope water means one can either make broad generalizations about meteorological conditions based on weather patterns off the northeast coast, or present recorded meteorological data from one or two fixed stations and consider it representative of the study area. Neither of these are completely satisfactory for defining the local meteorological conditions of the slope water.

2.3 PHYSICAL OCEANOGRAPHY

The western slope water is a complex and variable feature lying between the edge of the continental shelf and the Gulf Stream in a landward-seaward direction, and between Cape Hatteras and an arbitrary boundary (for the purpose of this study) of 66° W. It includes an area about equal to that of the shelf water but has a volume of water 20-25 times greater. Horizontally, it is affected by inputs from the Gulf Stream, shelf water, Labrador Current, and the western boundary undercurrent, and vertically, it is layered by a surface zone, a permanent thermocline region and a deep water zone. The physical features of these several water masses and their interrelationships have been the subject of much recent research and have resulted in a fairly good knowledge of the hydrography of this oceanic regime.

2.4 GEOLOGICAL OCEANOGRAPHY

The slope is an area of geological transition between the rock of the continent and the ocean floor. The point of contact itself is obscure, however, because of the deep burial of its crystalline basement by sediments and from topographic irregularities such as submarine canyons, rock masses, and fault blocks. The upper margin of the slope is fairly easily defined between 100 and 200 m, but the lower margin, at the juncture with the continental rise, is more variable and can range between

500 and 5,000 m.

The slope between Georges Bank and Cape Hatteras is the classic example of a continental slope. It has an average gradient of 3 to 6 degrees with a steep, irregular upper slope and a smooth lower slope resulting from an eroded upper surface and a slumped and debris-covered lower region. The textures of the sediments range from silty sand to silt and clay with grain size increasing with distance away from the shelf break. Also, the lower reaches of the slope consist to a large extent of foraminiferal and pteropod sand and ooze.

The continental slope of this region is probably most notable for its numerous submarine canyons that bisect the shelf and slope from the northeast of Georges Bank to just above Cape Hatteras. These canyons add a dynamic quality to the geological environment by accentuating the mechanisms of sediment transport downslope through slumping, down current, movement, and turbidity currents.

2.5 CHEMICAL OCEANOGRAPHY

There is a general lack of data concerning the chemical oceanography of the study area. However, there are a number of current programs that, when completed, should contribute much additional information. Of particular concern are the identification and quantification of various chemical constituents on the continental slope and the establishment of baseline levels that result from natural geochemical and biological processes and the levels that result from industrial pollution. The particular chemical constituents are: 1) organic matter and nutrients involved in the biochemical cycle; 2) the heavy metals and their relation to natural geochemical processes and industrial pollution; and 3) the petroleum and chlorinated hydrocarbons.

The continental slope, as an intermediate zone between areas of high natural and man-made production of these materials on the continental shelf and areas of low production with open ocean, is of particular interest as a region of transport. The slope water and sediments appear to be intermediate in concentration of nutrients, certain heavy metals and hydrocarbons, between the adjacent continental shelf and the Gulf Stream, Sargasso Sea and North Atlantic abyssal plain. Other compounds such as PCB's are widely dispersed and do not show a decrease from the coast. The transporting mechanisms by which organic and inorganic constituents arrive in the slope region have not yet been fully established. Submarine canyons are potential pathways for the movement of the pollutants to the lower levels of the slope and rise. The validity of the theory that industrial pollutants are transported to the deep ocean via the continental slope is currently being investigated.

2.6 BIOLOGICAL OCEANOGRAPHY

The flora and fauna of the continental slope are varied because of the environmental extremes encountered. The slope region probably does not have a distinct biota, but rather a mixture of animal and plant assemblages that have affinities to either the shallow shelf or to the deep ocean regions. Thus, the floral and faunal assemblages include very few endemic "slope species". In general, the characteristic of the slope biota is a function of its distance from the edge of the continental shelf; the closer to the shelf the more abundant, less diverse, and adaptable are its plant and animal communities.

The phytoplankton of the slope region is a mixture of neritic (primarily boreal diatoms) and oceanic (primarily oceanic coccolithophores) forms, which can become seasonally very productive, especially near the edge of the shelf. The loss of nutrients from the euphotic zone (upper 100 m) results in relatively low levels there and requires some mechanism for nutrient renewal to maintain the phytoplankton populations. A number of mechanisms, particularly upwelling, are the possible means by which nutrient concentrations are renewed in the surface layer.

The zooplankton components of the slope water are a mix of boreal shelf species and warm-temperate and tropical species from the Gulf Stream and Sargasso Sea. The dominant fauna throughout are copepods, with chaetognaths, euphausids, and foraminifera also well represented. The zooplankton too can be quite productive at the inner slope waters. Mixing of faunal groups from the Gulf Stream rings, shelf water and deeper bottom waters (below 200 m) makes for a complex situation that has not yet been fully described.

The nekton of the slope water is represented by a diverse assemblage of pelagic animals which exhibit a highly seasonal occurrence. Fishes and invertebrates (squid) common to the shelf waters are found in the slope region seasonally, as are the large, wide ranging, oceanic fishes. In the deeper waters, the mesopelagic and bathypelagic fishes are wide spread. The marine mammals from the study region are represented solely by the cetaceans that number roughly 14 species. The slope water may be a significant one for the cetaceans as a migratory pathway paralleling the productive shelf waters, which they may use as feeding grounds.

The benthic fauna (invertebrates and fish) of the continental slope is a highly diverse one appropriate to a transitional environment that includes shallow and deep water conditions. The benthic invertebrates are represented by an immense number of separate species belonging to important groups such as polychaetes, peracarid crustaceans, bivalve molluscs, sipunculids and echinoderms. The benthic fishes are dominated in the upper levels by seasonally abundant shelf oriented species, principally the members of the cod family, and at the lower slope levels by a diverse group of deep water fishes that include deepwater hakes, grenadiers, and eels. The benthic populations are characteristically zonated, conforming to the boundaries represented by the limits of their particular tolerances. Patterns and zonations of species are found in both a latitudinal plane along slope and a vertical plane down slope. Biomass also varies down slope, with each area supporting a characteristic number of animals. The deep sea benthic ecosystem appears to be quite different from that of the shallow areas. The harsh conditions imposed by increasing depth, temperature, pressure, and lack of sunlight, result in low food levels, low rates of metabolic activity and organic recycling, sparse populations, and in general, leads to a conservative environment.

The sampling difficulty normally encountered in benthic studies is compounded in the deep sea, thus the number of benthic samples from any particular area of the deep sea environment is relatively small. Scientific effort has concentrated on surveying and identifying the benthic components of the study area and in defining their zonation patterns. While there still remains much to be done in this area, very recently interest has turned toward questions concerning the benthic ecosystem and how it functions. New programs are being designed to examine the organic cycling, metabolism, and relation of the benthic communities in the environment at deep water locations on the slope.

2.7 HUMAN INFLUENCE

The continental slope has received less impact from human activities than the more coastal areas. Its distance from shore creates a buffer zone that prevents direct contamination by pollutant materials from the outflow of the land mass. Its distance has also made ocean dumping less attractive economically, which has limited the amount of contaminating materials transported to the slope water. Shipping carried out beyond the confines of the U.S. East Coast passes through the slope water at some point. The volume, however, is less than that of the nearshore waters where coastal routes add to the total shipping, and it is unlikely, barring catastrophic oil spills, that shipping has much impact on the slope environment. Also, the fishing industry, up until the mid-1960's, was almost exclusively limited to the shelf area. The dramatic increase in offshore fishing with the advent of the foreign fishing fleets is still limited to areas not much beyond the shelf break.

The exploration of new resources on or near the continental slope would increase human impacts in that region. Bottom trawling, dredging, and oil drilling are potential activities that could increase in the slope region in the near future. The consequences of these activities are not easily predictable with present knowledge, however, it is reasonable to say that the continental slope environment is somewhat different from that of the shelf in that it presents a continuous gradient seaward and, at least at deeper depths, it is a conservative and sensitive environment.

CHAPTER 3.0

METEOROLOGY

PETER BEVES

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Chapter 3.0 Meteorology

3.1 INTRODUCTION

The continental slope water lies in a zone of prevailing westerly winds that dominate the region of the northeastern United States. The weather patterns of the slope water are influenced by several major atmospheric features, by major oceanographic features, and on a local level, by the interaction between the atmosphere and the hydrosphere.

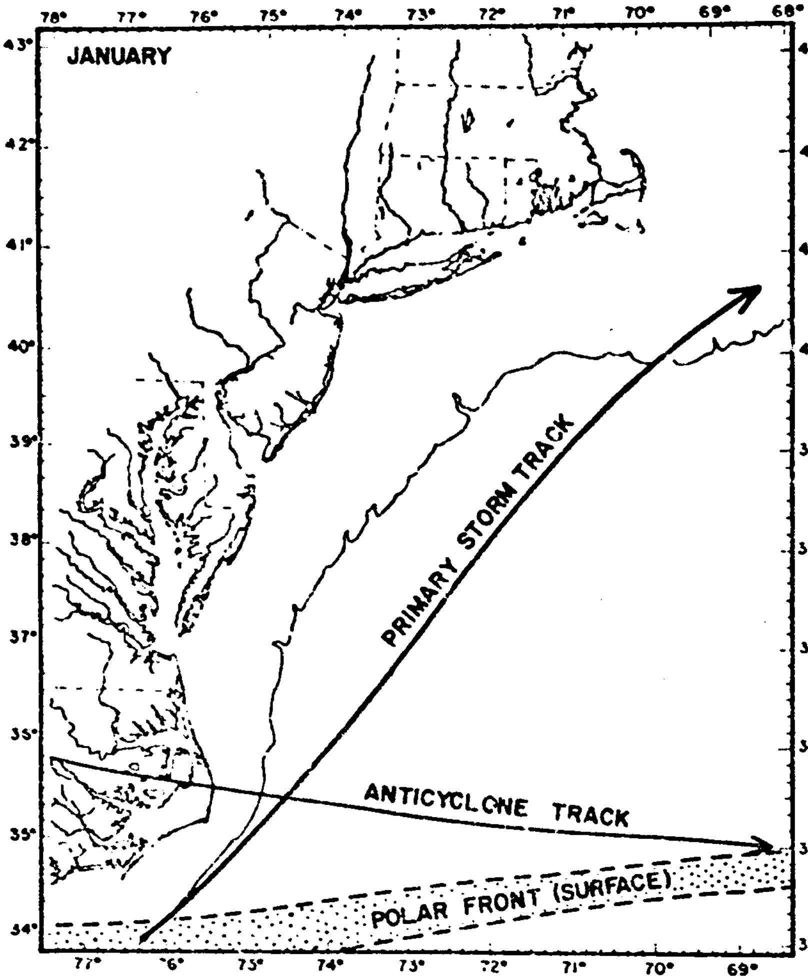
The two semi-permanent pressure centers that alternately dominate the region, the Icelandic Low (approximately 63°N) and the Bermuda-Azores High (approximately 31°N), affect the pressure pattern and therefore the general air circulation (Chase, 1975). The alternating dominance of the Icelandic Low in the winter and the Bermuda-Azores High in the summer contributes to the varying weather patterns and storm tracks in the slope region. As the Icelandic Low develops during the winter, prevailing winds shift to northwest and the eastern offshore region becomes one of the hemisphere's major areas of cyclooenesis (Havens, Shaw, and Levine, 1973), hurricanes being prevalent in late summer and early autumn. During the summer months as the Bermuda-Azores High gains strength, the prevailing winds offshore of the U.S. East Coast move in a southwesterly direction. The prevailing pressure patterns in the northwest Atlantic are illustrated in Figures 3-22 to 3-34.

An upper level long wave trough, another feature of the atmosphere that influences the weather in the slope region, lies between 70° and 80° longitude. Extra-tropical storms transverse the region in response to the position of this trough (Havens, et al., 1973).

A third feature is the polar front jet stream, an upper level thermal gradient separating air masses of polar and tropical origin. The front has a generally southwest to northeast orientation and provides for storm development and maintenance (Havens, et al., 1973). The seasonal extremes of the upper level wave trough and the polar front are illustrated in Figures 3-1 and 3-2.

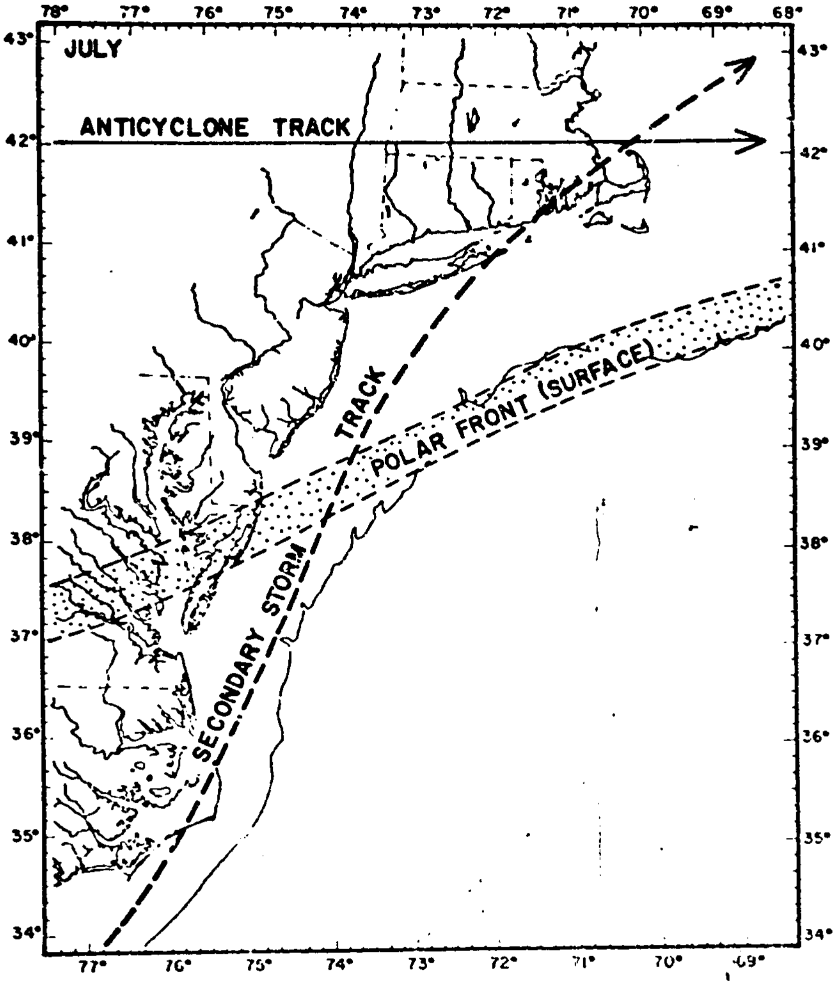
The oceanographic features that bound the slope water, relatively cold continental shelf water and the comparatively warm Gulf Stream, and various sea surface phenomena within the slope water itself have an effect on and are in turn affected by the weather on a regional scale. Local phenomena at the sea surface/atmospheric interface also influence the weather patterns on a local scale. It is quite likely that the slope water has regional meteorological characteristics that differ somewhat from adjacent regions, however, these differences cannot be clearly defined without a significant increase in the data base.

The totally inadequate data base for continental slope meteorology results from the lack of observation stations in the region. There are over 100 recording stations making observations of precipitation, temperature, and wind velocity, etc. along the coast and inland areas of the six northeastern states. There were eight recording stations identi-



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-1	Synoptic Scale Features in the Study Area During January (Havens, *et al*, 1973).



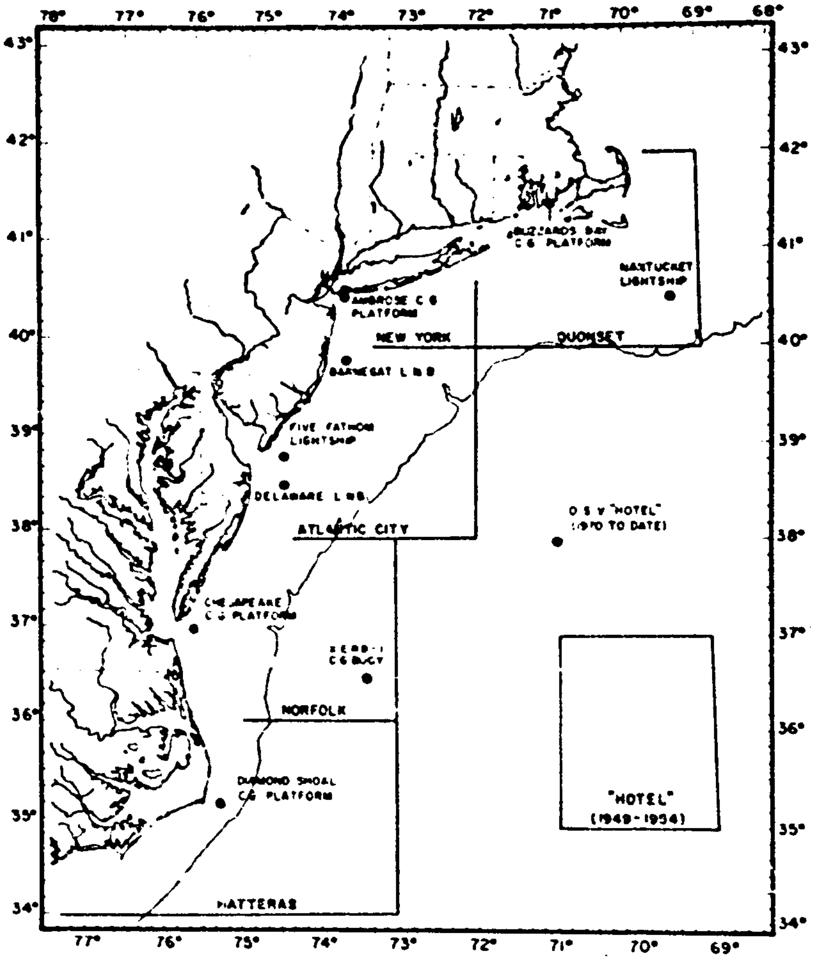
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 3-2 | Synoptic Scale Features in the Study Area During July (Havens, *et al.*, 1973) fied by Havens, et al. (1973) along the coastal shelf from Cape Cod to Cape Hatteras. There are two main sources of meteorological data in the slope water region: those data collected by U.S. Weather Service from ships in passage and those collected at weather station "Hotel", an ocean station vessel located since 1970 at 38°N, 71°W. The reports taken from ships in passage have a built-in weather bias because they tend to avoid bad weather. The data from sea station "Hotel" will be used extensively in this chapter because of its greater reliability.

In their review of the meteorology of coastal and offshore waters from Cape Cod to Cape Hatteras, Havens, et al. (1973) summarized and discussed data from ocean station "Hotel" and ships in passage in the offshore area and compared it with general meteorological conditions at five coastal zones: Quonset, New York, Atlantic City, Norfolk, and Hatteras. In discussing the features of the slope meteorology, we will rely heavily on their summaries. The location of these six observational areas are presented in Figure 3-3. Data from the coastal areas consist of 80 percent of the observations between 1950 and 1958, and the remainder back 100 years. The "Hotel" data are unpublished from the National Climatic Center from 1949 to 1954. The coastal data are largely from ships in passage and therefore subject to fair weather bias. The "Hotel" data is from a stationary ocean weather vessel and therefore more reliable. Havens, et al. attempted to point out some significant weather features between the "Hotel" and the coastal observations. While these observations give some indication of the general features of the offshore climate, these data were collected during a period when ocean station "Hotel" was located somewhat beyond the study region (approximately 35° to 37°N by 69° to 71°W) and therefore cannot be considered as strictly applying to the continental slope region. Further, the lack of several observationstations within the slope region makes it impossible to discuss the variability of conditions within the study area.

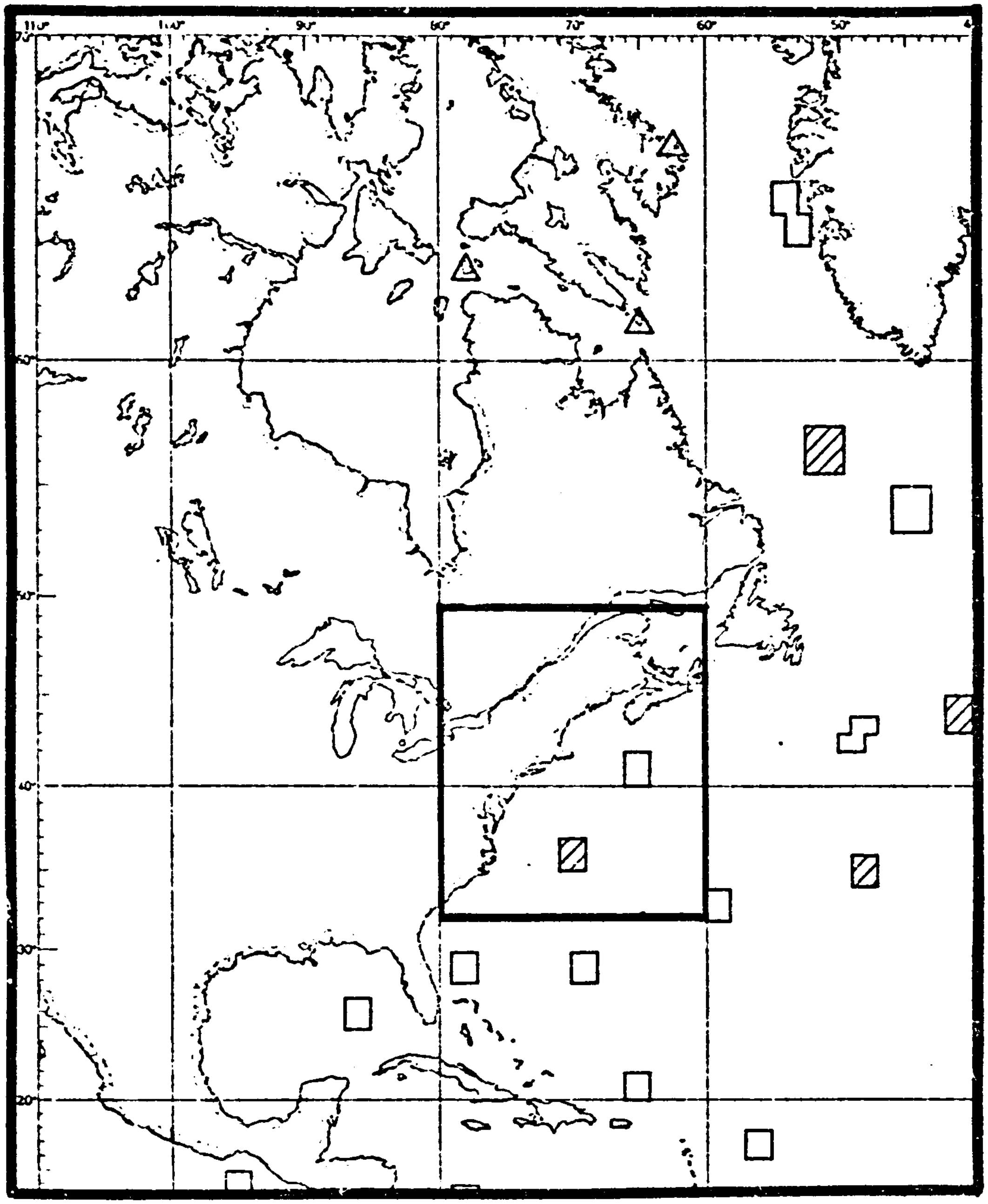
We also have relied heavily on average conditions of temperature, winds, pressure fields, visibility, dew point, precipitation, storm and sea state recorded at ocean station "Hotel" and other open ocean locations in the northwest Atlantic. The primary source for this information was from U.S. Navy and U.S. Weather Bureau (1959), U.S. Dept. of Commerce (1973) and Crutcher and Quayle (1974). U.S. Navy and U.S. Weather Bureau (1959) is undergoing a process of update and revision to incorporate more recent observations and should be re-issued fairly soon. Observation stations from the U.S. Navy and U.S. Weather Bureau (1959) are shown in Figure 3-4. Observations utilized from these three sources are from as early as 1800 up to as recently as 1970.

A discussion of meteorological data in the study area as it applies to ocean surface effects, i.e. hurricanes, sea state, heat exchange, etc., will be found in Chapter 4.0, Physical Oceanography, Section 4.6.



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-3	Locations of Observation Areas of Havens, <u>et al</u>. (1973)



Cross-hatched location is ocean station "Hotel"; open location represents ships in passage data.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

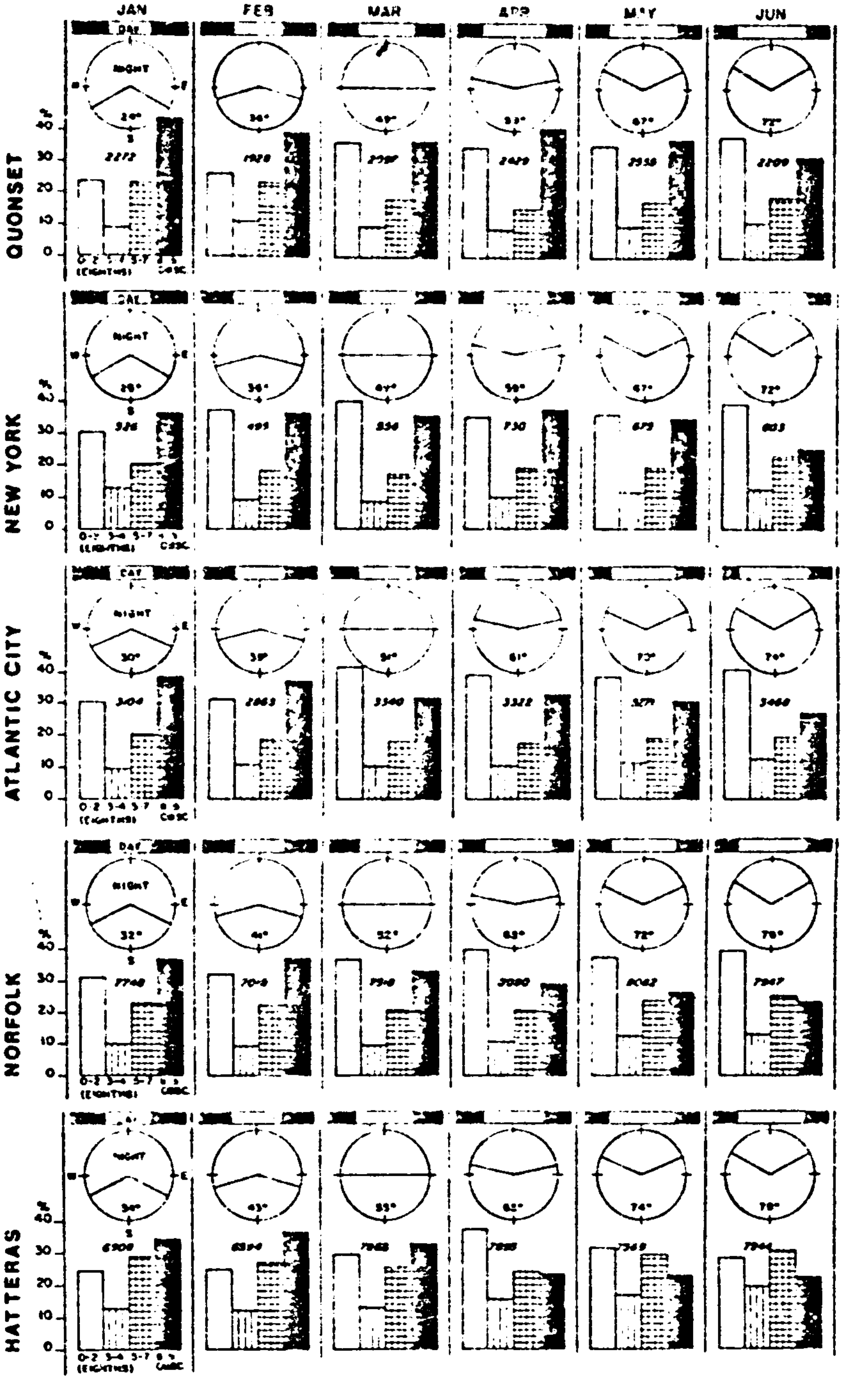
TRIGOM	FIGURE 3-4	Locations of Stations From U.S. Navy and U.S. Weather Bureau (1959)

3.2 METEOROLOGICAL PARAMETERS

3.2.1 Sky Conditions

Solar climate, day length, sun azimuth, and latitude at noon are latitudinal features and, therefore, not particularly significant in terms of inshore-offshore comparisons. The horizontal bar graphs in Figures 3-5, 3-6, and 3-7 represent relative length of daylight, while the solar diagrams represent the azimuth of tne rising and setting sun and its altitude at local noon during each month of the year. At ocean station "Hotel" and at Cape Hatteras the range of daylight is from 9.75 to 14.5 hours compared to 9.25 to 15 hours for the New York and Quonset sea areas (Havens, et al., 1973).

Maximum sky cover at all the sea areas occurs during December through February (Figures 3-5, 3-6, and 3-7) while minimum cloud cover occurs during September or October. The maximum monthly average cloud cover (6.4 eigths) occurred in March at station "Hotel" (Table 3-1) while the minimum (3.8 eigths) occurred at the Atlantic City area in October. Yearly averages indicate that station "Hotel" had a greater degree of cloud cover than the coastal areas.



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-5	Sky Cover Graphs For Each Month at the Five Coastal Areas (Havens, et al., 1973)

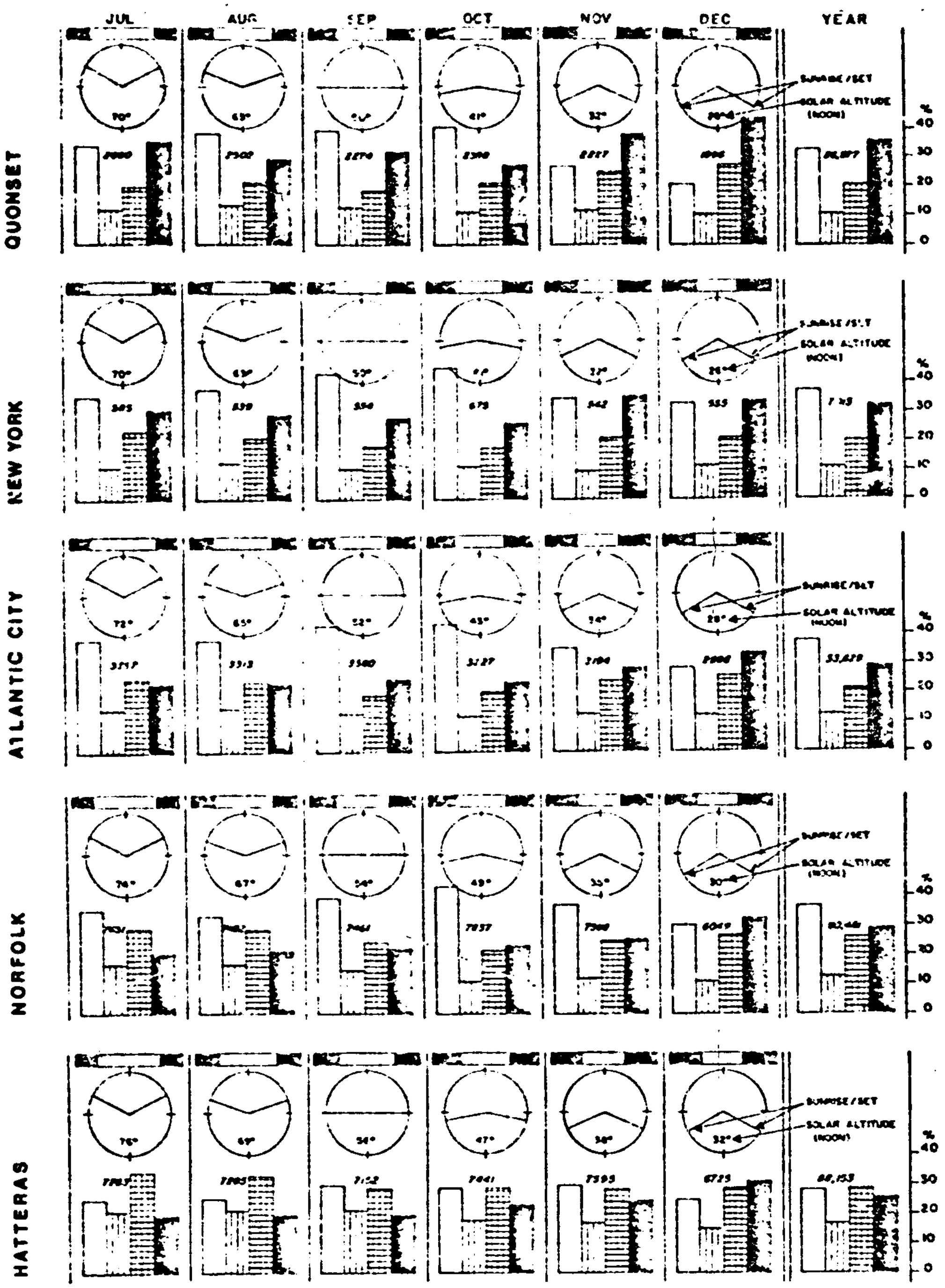
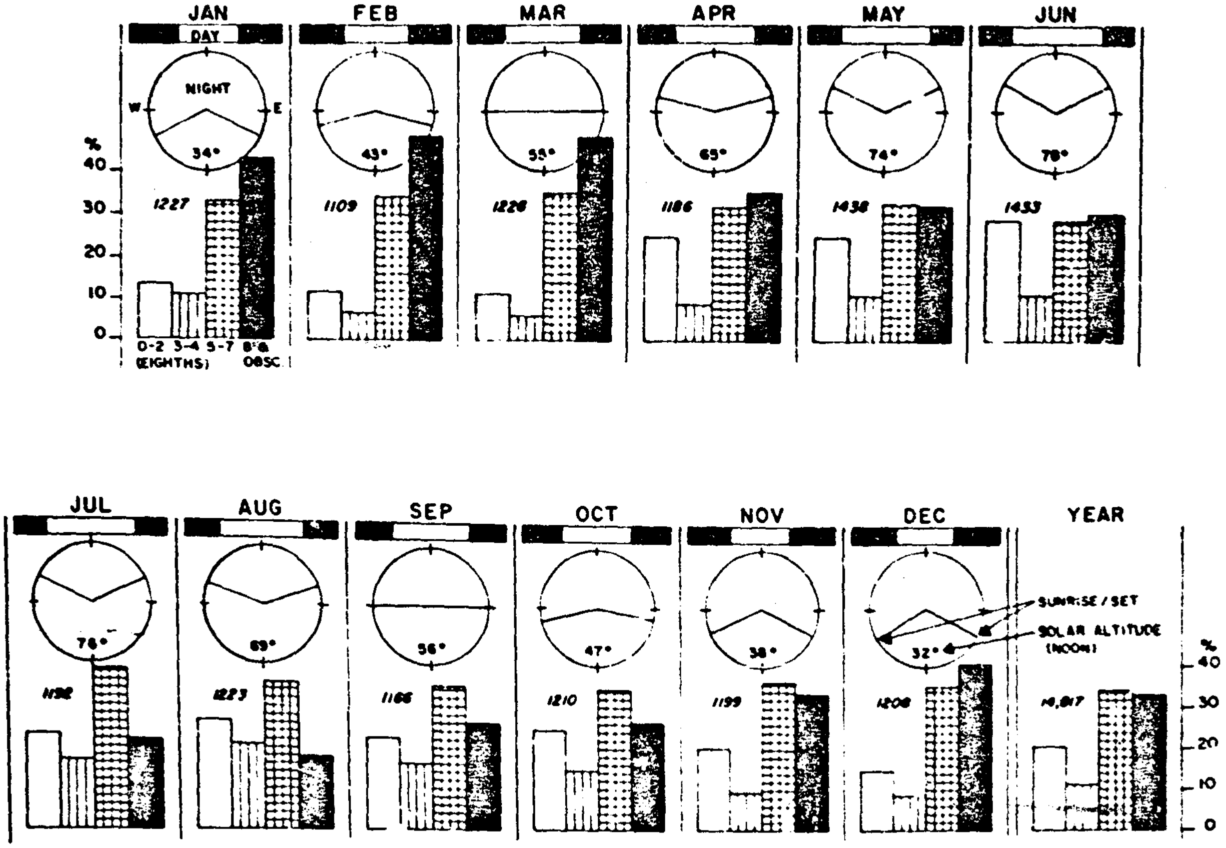


FIGURE 3-6 Sky Cover Graphs For Each Month at the Five Coastal Areas (Havens, et al., 1973)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-7	Sky Cover Graphs For Each Month at Ocean Station "Hotel" (Havens, et al., 1973)

Table 3-1. Sky Cover data summaries for six sea areas. (Havens *et al.*, 1973)

Sea Area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Sky Cover (eighths)													
Quonset	5.5	5.2	4.6	4.8	4.7	4.4	4.7	4.4	4.3	4.2	5.1	5.6	4.8
New York	4.8	4.5	4.4	4.7	4.6	4.2	4.5	4.3	4.0	3.9	4.7	4.7	4.4
Atlantic City	5.0	4.8	4.3	4.3	4.3	4.1	4.2	4.2	3.9	3.8	4.5	4.9	4.3
Norfolk	4.9	4.8	4.5	4.2	4.3	4.2	4.2	4.4	4.1	3.9	4.3	4.8	4.4
Hatteras	5.2	5.2	4.9	4.2	4.5	4.6	4.7	4.7	4.4	4.6	4.6	5.0	4.7
"Hotel"	6.1	6.3	6.4	5.3	5.2	4.9	5.0	4.7	4.4	5.1	5.7	6.1	5.5

3.2.2 AIR TEMPERATURE

Because the open ocean thermally modifies extremes of surface air temperature, the study region displays narrower ranges of seasonal air temperatures than coastal areas, however, its extended latitudinal axis results in a wide range of air temperatures within the region at any point in time.

From the data of Havens, et al. (1973) (Table 3-2, Figures 3-8, 3-9, and 3-10) averages and extremes of air temperature can be compared on a monthly basis between the five coastal areas and ocean station "Hotel". At sea area "Hotel" the annual mean temperature is 20.2°C, which is on a par with the Hatteras sea area mean of 20.0°C. The "Hotel" area had the smallest annual temperature range, 11.8°C, because of its distance from land. The greatest temperature range occurred during the winter months when the polar front, with its accompanying temperature extremes, was located near the offshore sea areas. Absolute minimal air temperatures range from -13.3°C at the Quonset sea area to a mere 0°C at "Hotel".

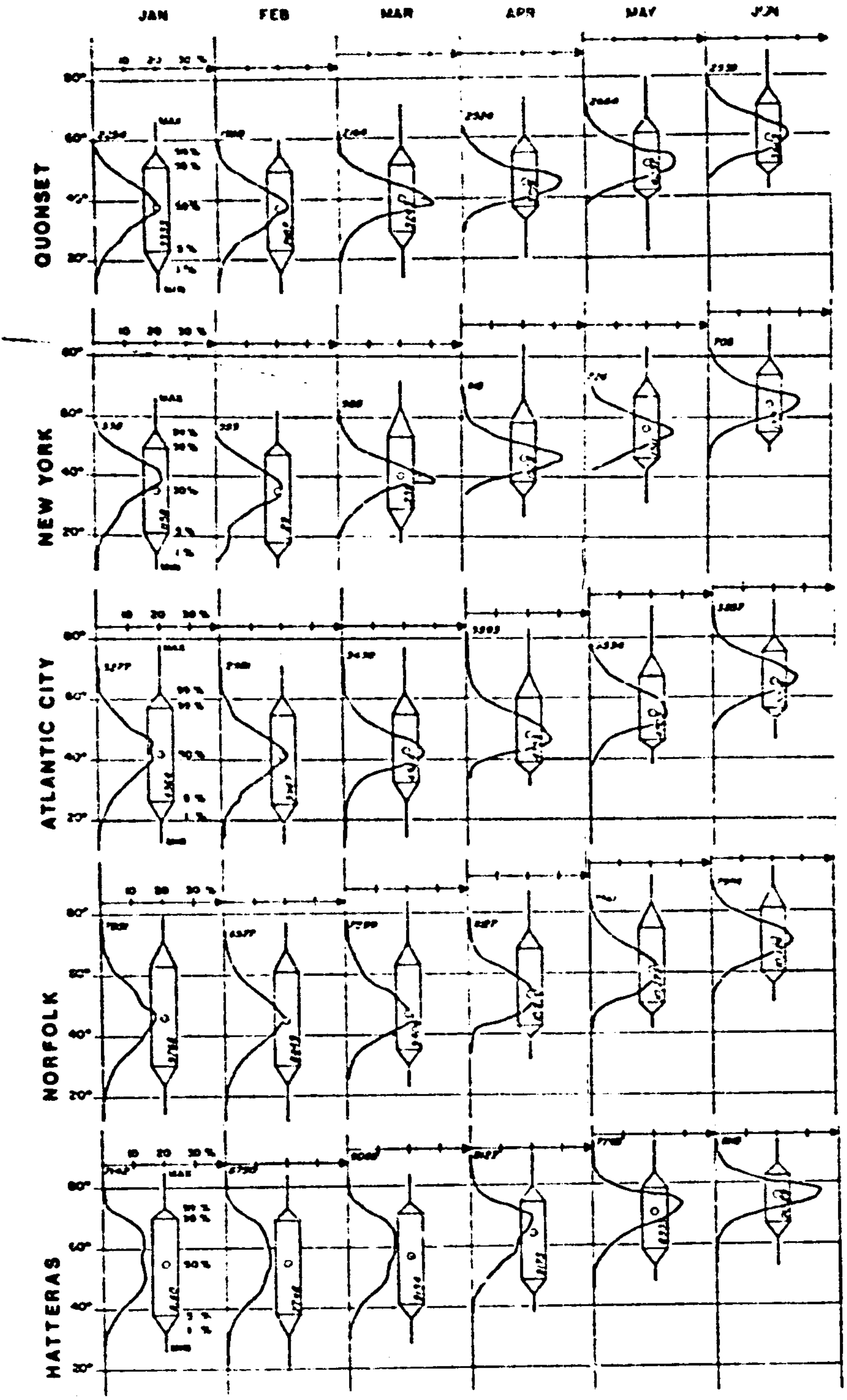
The unimodal nature of the air temperature distributions for the year as a whole contrasted with a bimodal distribution at sea areas Quonset, Atlantic City and Norfolk. Havens, et al. suggest that the bimodal frequency distribution reflects the combined influences of maritime tropical and polar air masses. This phenomenon appears to be of smaller influence in the "Hotel" area.

Air temperature data from U.S. Navy and U.S. Weather Bureau (1959) shows monthly mean temperature , percentage distribution of observed temperature and mean air temperature isotherms for the northwest Atlantic, including the slope water region (see Key, Figure 3-11). These data are presented (in degrees fahrenheit) in Figures 3-12 and 3-13. The range (gradient) of isotherms that cross the latitudinal axis of the study region varies from 20-24 degrees from November to June to 16 degrees from July to October.

Seasonal air-sea temperature differences (Figure 3-14) are shown by lines of equal differences (in degrees fahrenheit) for the northwest Atlantic. Generally, sea temperatures remain about 7 degrees below air temperature during the winter months and 3 degrees above the air temperature during the fall months with differences of only about 1 degree the rest of the year.

Table 3-2. Air Temperature data summaries for six sea areas. (Havens *et al.*, 1973)

Sea area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Air Temperature (°C)													
Quonset	3.6	2.9	4.6	7.6	11.2	16.2	20.1	20.8	18.4	14.6	10.6	5.9	11.8
New York	3.3	2.2	5.1	8.6	13.1	18.3	22.2	22.3	19.5	14.9	10.4	5.1	12.5
Atlantic City	5.7	5.0	6.7	9.9	14.1	19.5	23.7	23.8	21.2	16.7	12.3	7.6	14.1
Norfolk	8.1	7.9	9.6	12.9	17.1	22.1	25.3	25.4	23.0	18.6	14.2	9.9	16.3
Hatteras	13.2	13.4	14.6	18.0	21.7	24.7	26.8	27.0	25.2	21.7	18.1	14.7	20.0
"Hotel"	15.7	14.6	14.4	17.6	10.7	23.4	26.1	26.2	24.8	22.4	19.2	15.8	20.2

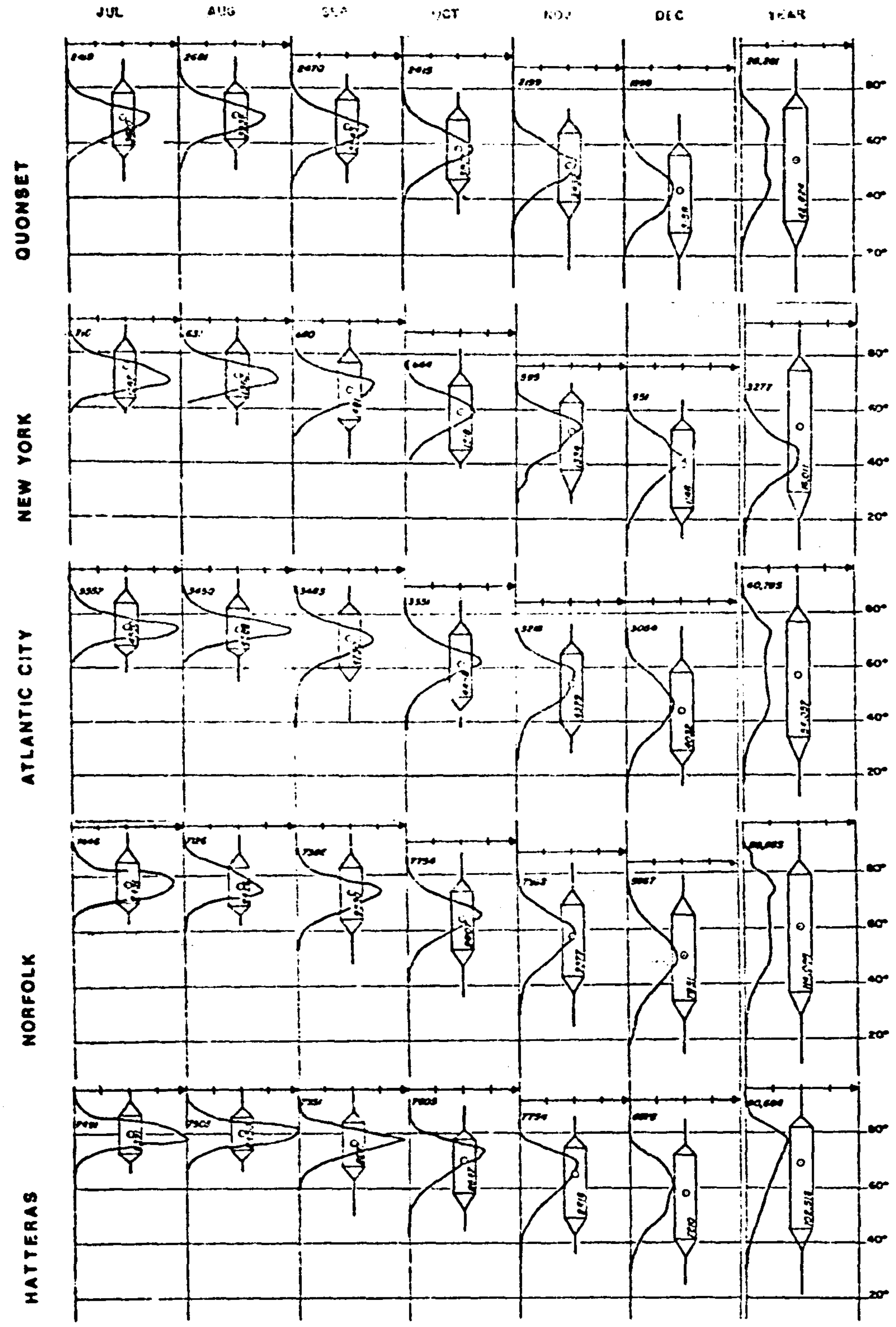


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 3-8

Air Temperature Graphs for Each Month at Five Coastal Areas (Havens, et al., 1973)

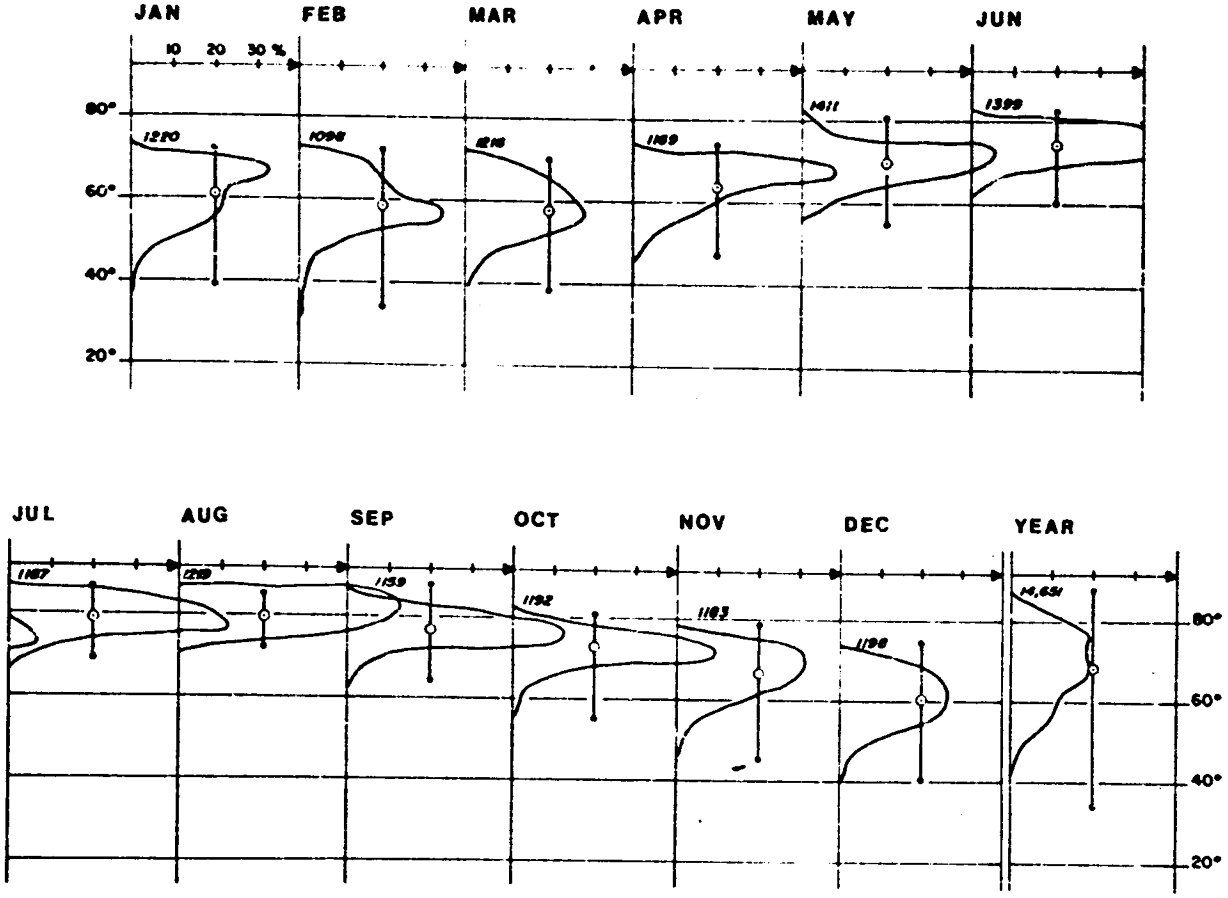


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 3-9

Air Temperature Graphs for Each Month at Five Coastal Areas (Havens, *et al.*, 1973)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE		
TRIGOM	FIGURE 3-10	Air Temperature Graphs for Each Month at Ocean Station "Hotel" (Havens, et al., 1973)

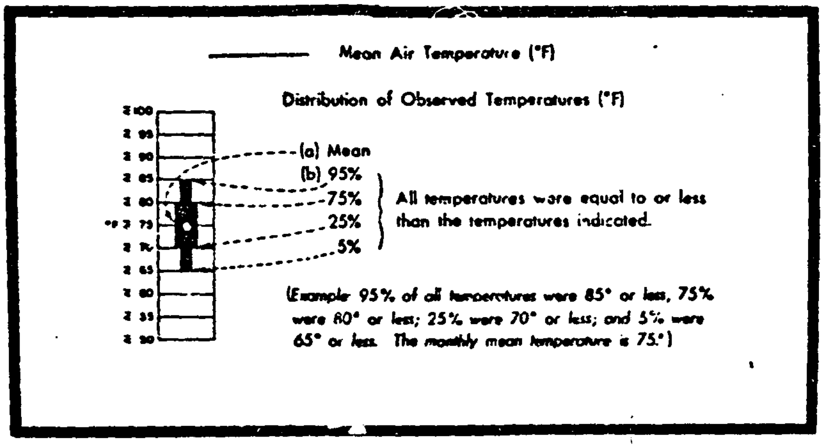
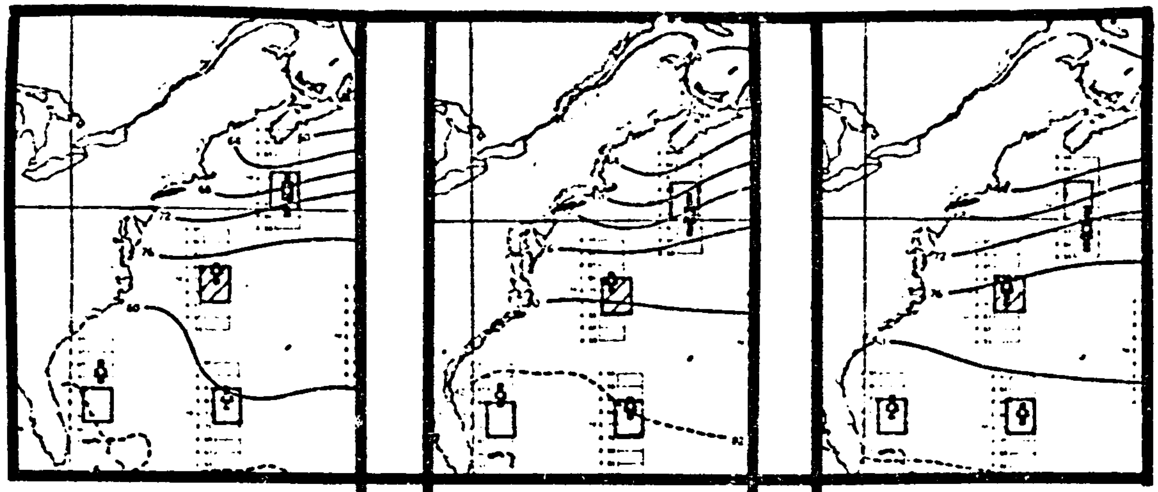
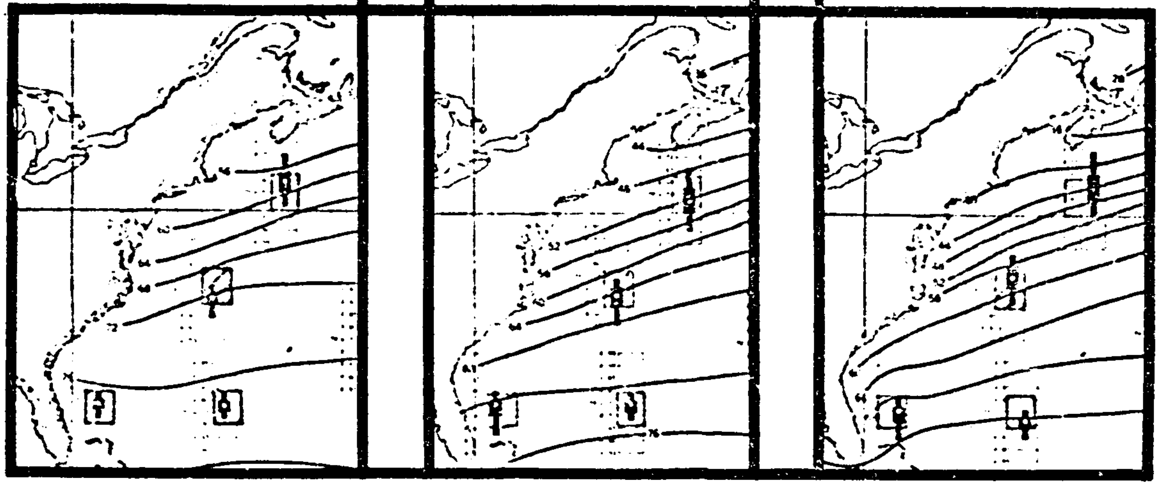


FIGURE 3-11 Key to Air Temperature Symbols (U.S. Navy and U.S. Weather Bureau, 1959).



July August September

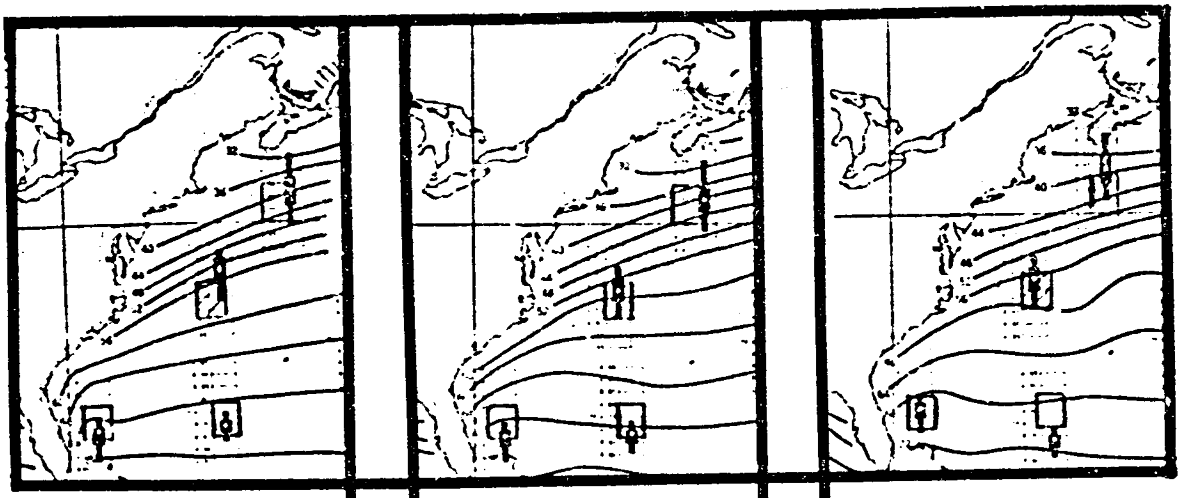


October November December

The heavily outlined boxes indicate the location represented by the symbol.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

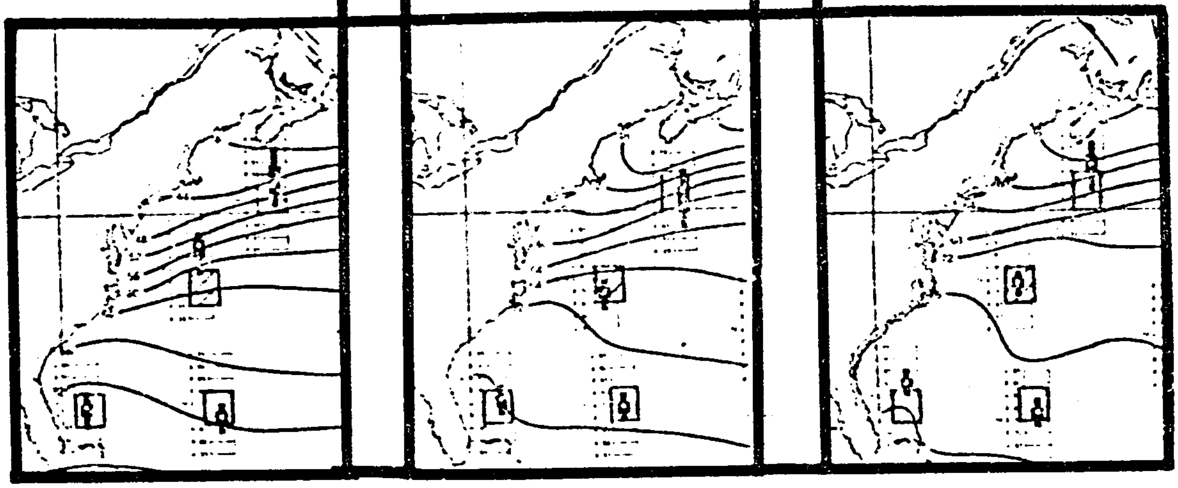
TRIGOM FIGURE 3-12 Monthly Mean Air Temperatures, Percentage Distribution of Air Temperatures, and Mean Air Temperature Isotherms (°F) Locations in the Western Atlantic (U.S. Navy & U.S. Weather Bur.,1959)



January

February

March



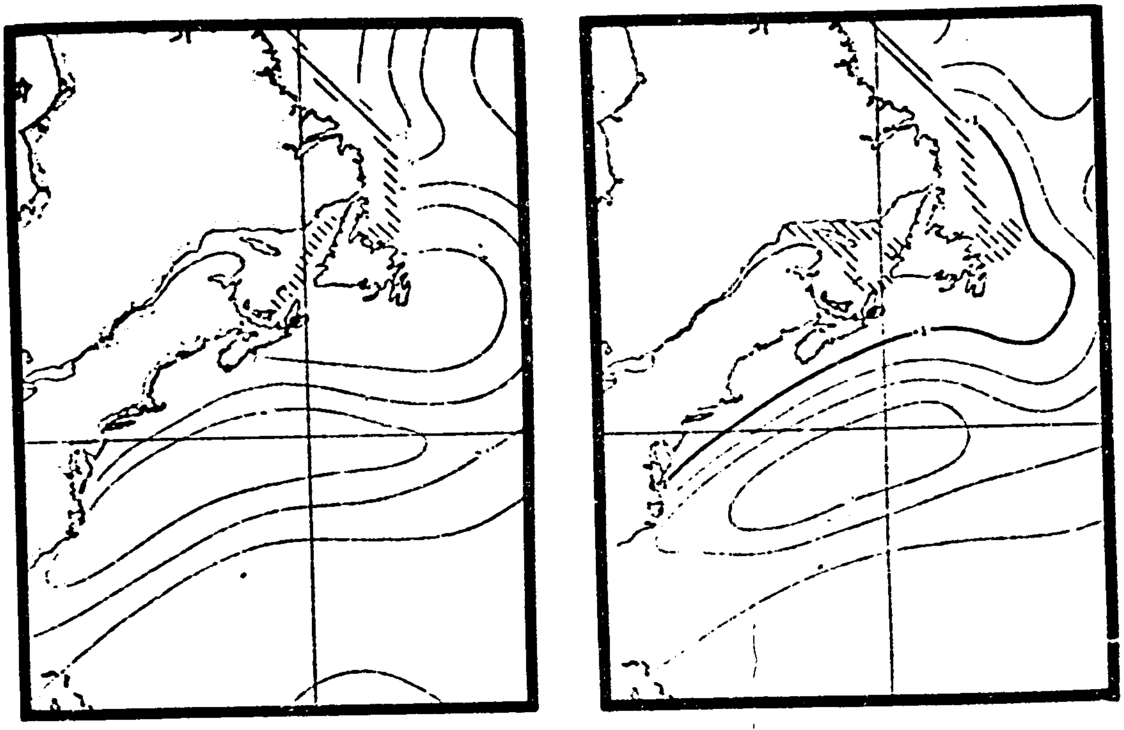
April

May

June

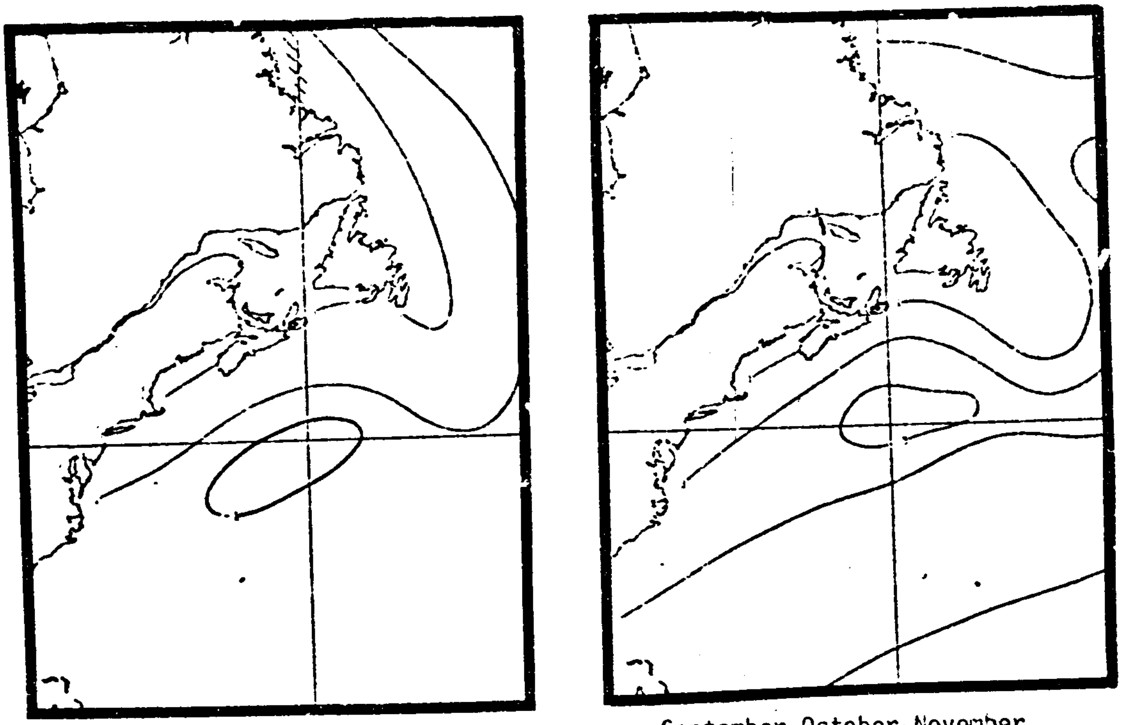
The heavily outlined boxes indicate the location represented by the symbol.

FIGURE 3-13 Monthly Mean Air Temperatures, Percentage Distribution of Air Temperatures, and Mean Air Temperature Isotherms (°F) Locations in the Western Atlantic (U.S. Navy and U.S. Weather Bur., 1959)



December-January-February

March-April-May



June-July-August

September-October-November

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

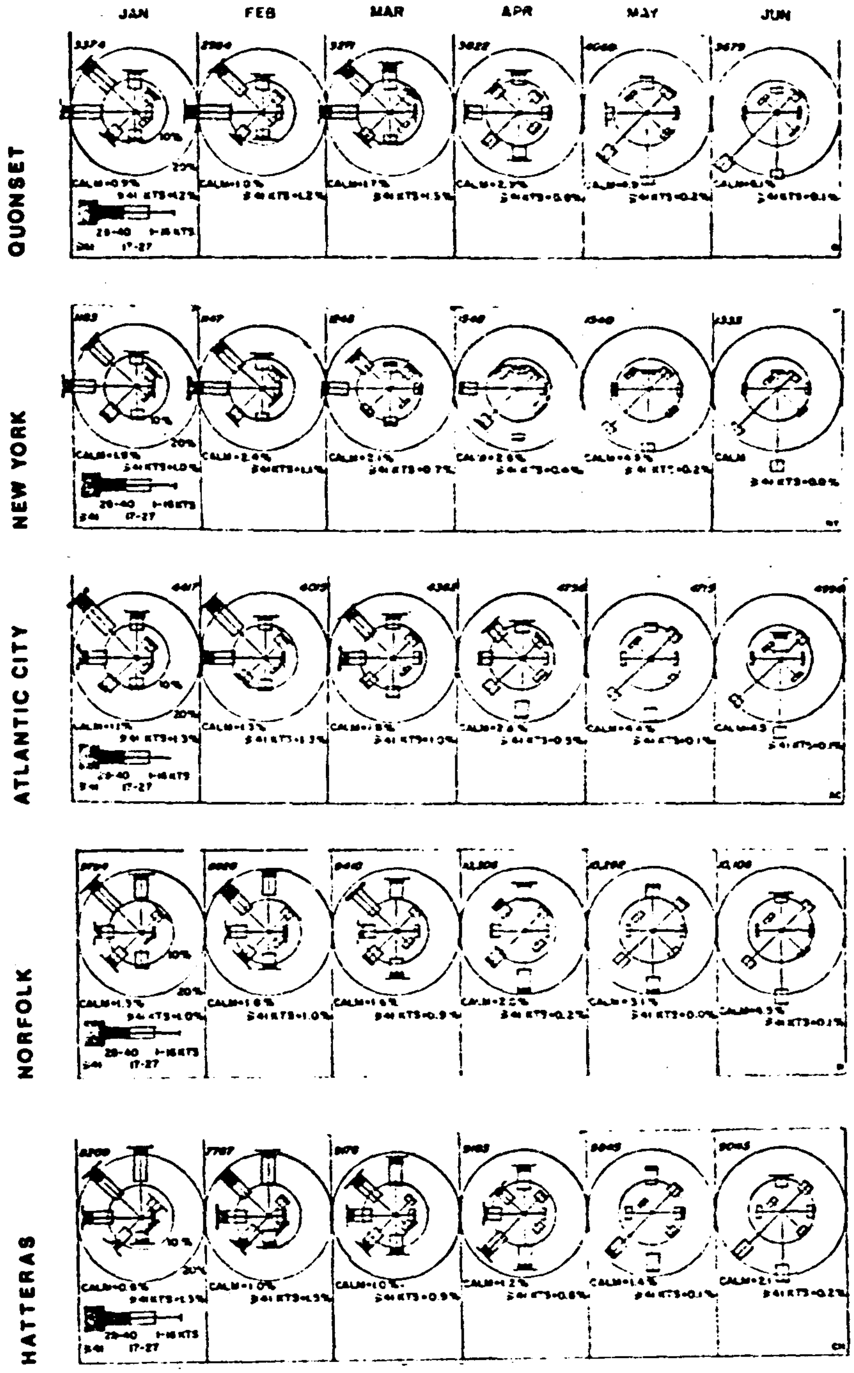
TRIGOM	FIGURE 3-14	Difference Between Mean Air and Sea Surface Temperature (°C) (U.S. Navy and U.S. Weather Bureau, 1959)

3.2.3 WINDS

In the northwest Atlantic the winds are predominantly westerly throughout the year but shift to the northwest in the winter and the southwest in the summer. Surface wind roses for the five coastal areas and ocean station "Hotel", as presented by Havens, et al. (Figures 3-15, 3-16, and 3-17) illustrate at a glance this westerly flow of air and its seasonal change to the north and south, as do the surface wind roses for the northwest Atlantic as a whole (Figures 3-19, 3-20, and 3-21) (U.S. Dept. of Commerce, 1973).

Wind speeds reflect the greater cyclonic activity that occurs during the winter months. In Table 3-3 Havens, et al. show monthly averages of wind speed. During December through March winds averaged in excess of 20 kts at ocean station "Hotel" and were generally higher there throughout the year than at the five coastal areas. The data for "Hotel" in Table 3-3 were enclosed in parentheses because a slightly different method of data reduction was used by Havens, et al. They state that these data are comparable.

The percentage of time that wind speeds are in excess of 40 kts are indicated in Figures 3-15, 3-16, and 3-17 for the five coastal areas and ocean station "Hotel" while the time in excess of 28 kts is shown in Figures 3-19, 3-20, and 3-21 for the northwest Atlantic as a whole. Winds exceeded 40 kts at ocean station "Hotel" and the five coastal areas a significant part of the time (about 1 percent) during the winter months, but were not particularly significant during the summer months. At ocean station "Hotel" a maximum of 4.8 percent was reached during February, indicating that maximum wind speeds were more prevalent at the "Hotel" sea area than the coastal areas during December through February The percentage of winds above 28 kts was also relatively significant at the open ocean areas north of a line extending out from Cape Hatteras into the northwest Atlantic (Figure 3-19, 3-20, and 3-21).

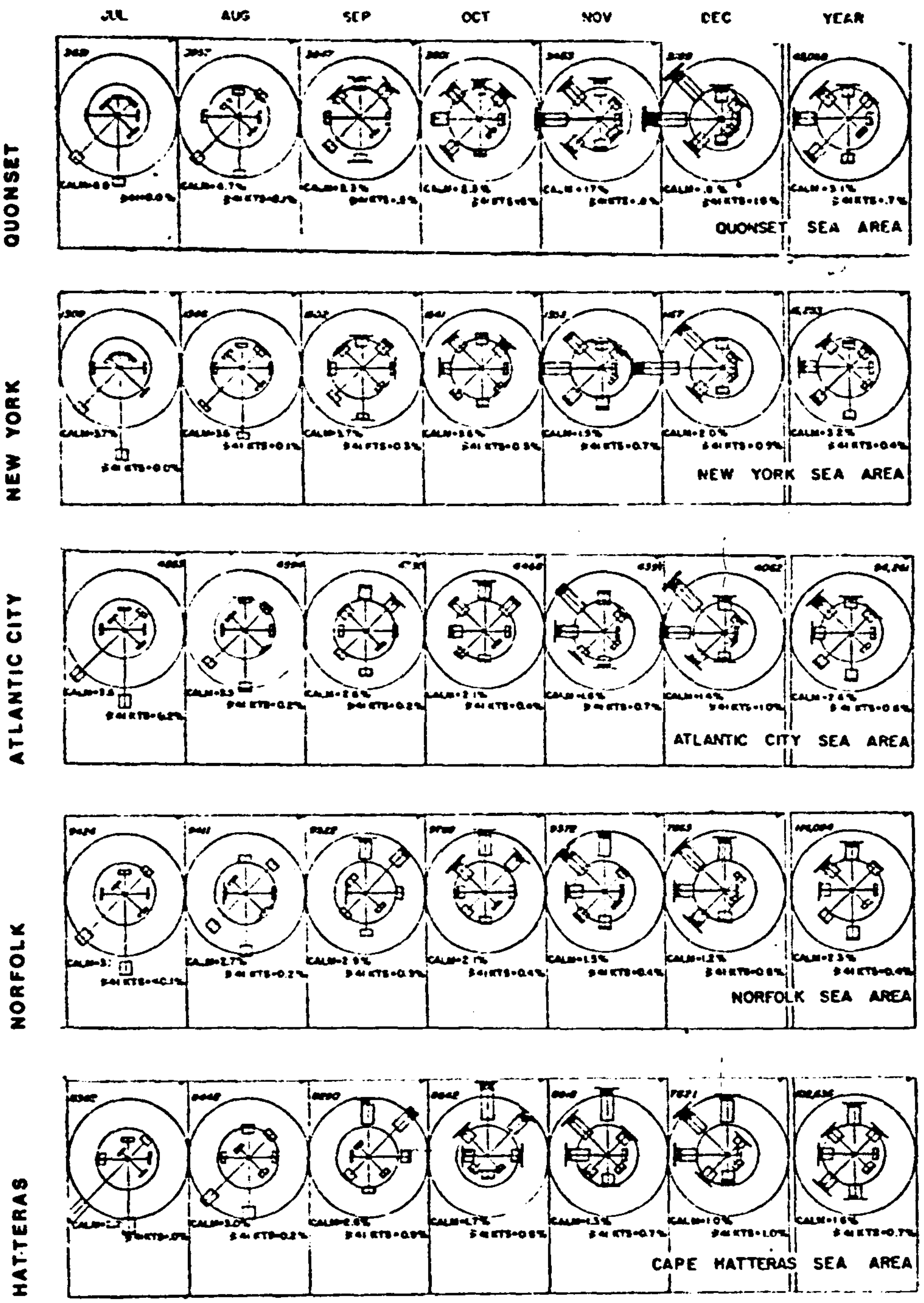


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 3-15

Wind Direction and Speed Graphs for Each Month at Five Coastal Areas (Havens, et al., 1973)

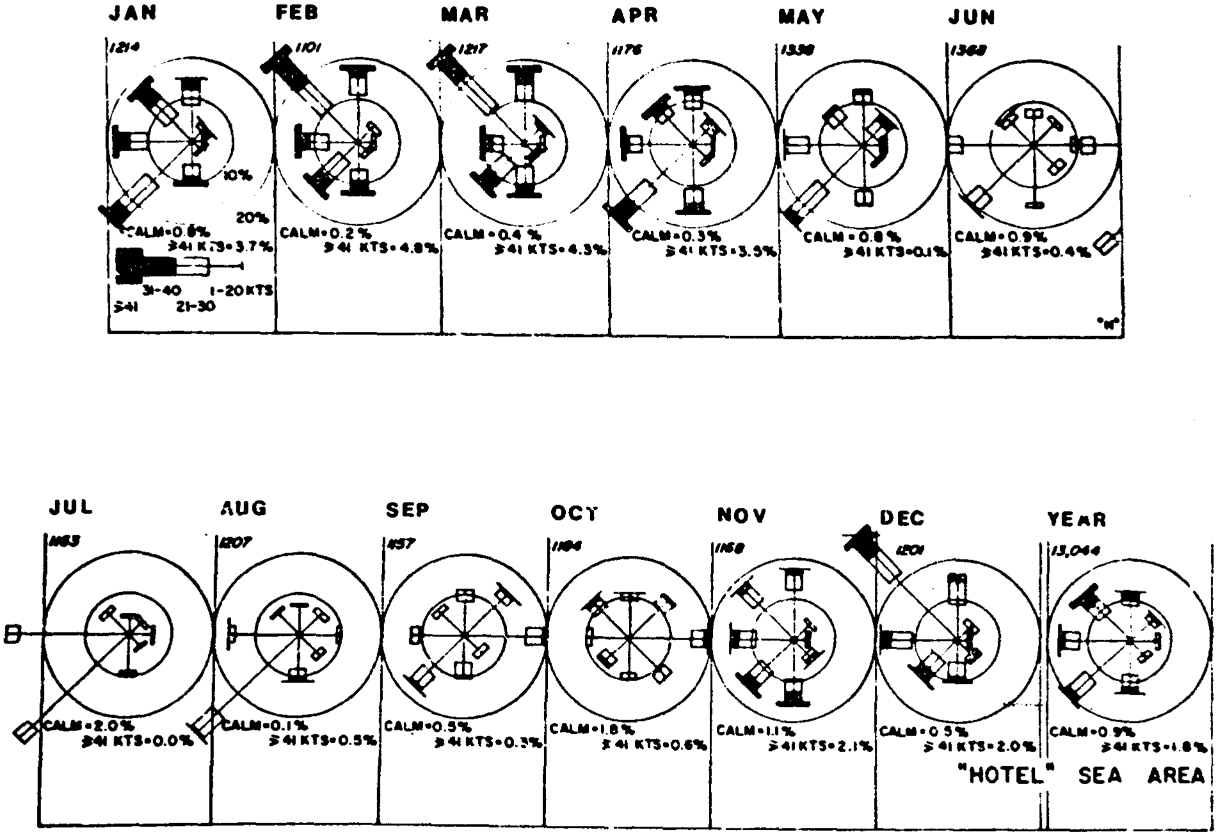


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

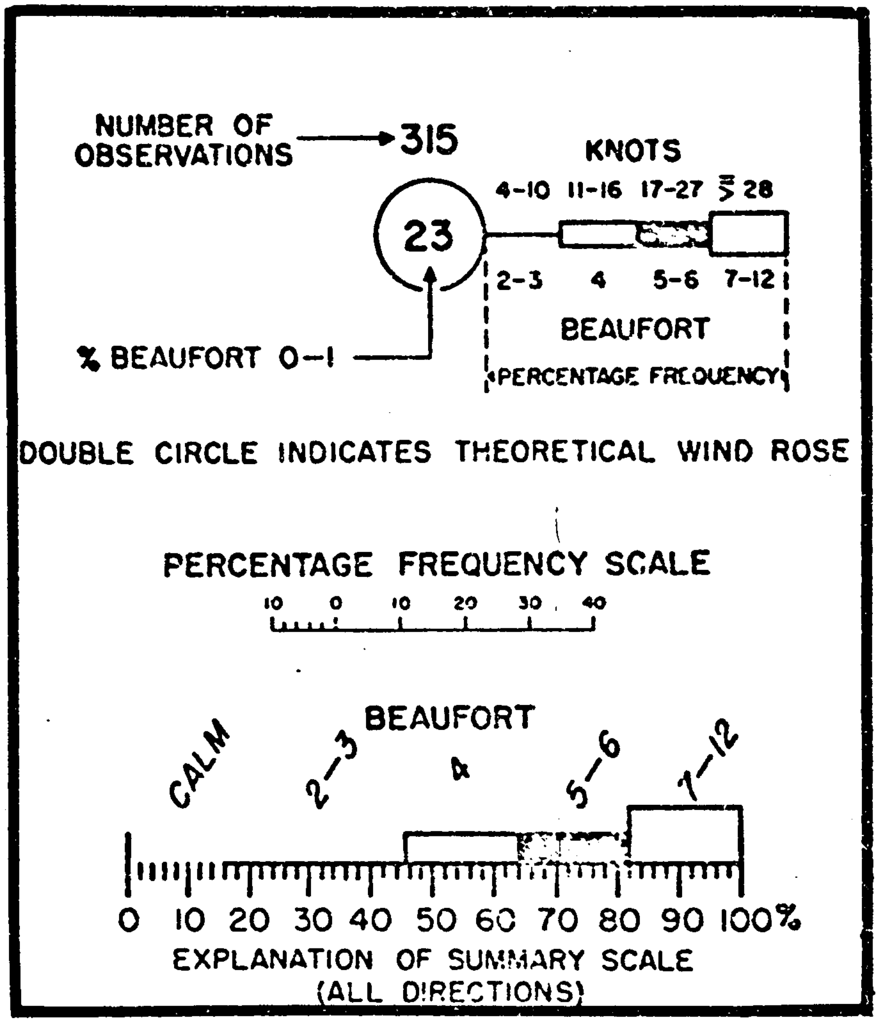
FIGURE 3-16

Wind Direction and Speed Graphs for Each Month at Five Coastal Areas (Havens, et al., 1973)



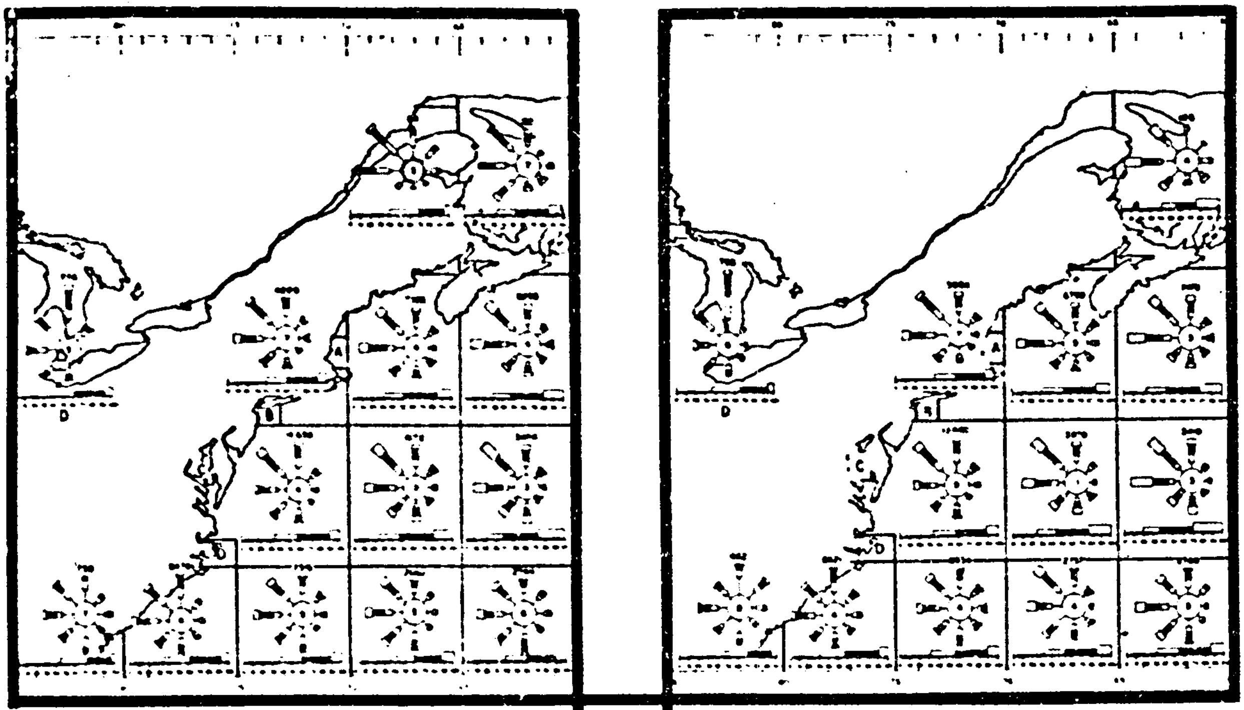
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 3-17 | Wind Direction and Speed Graphs for Each Month at Ocean Station "Hotel" (Havens, *et al.*, 1973)



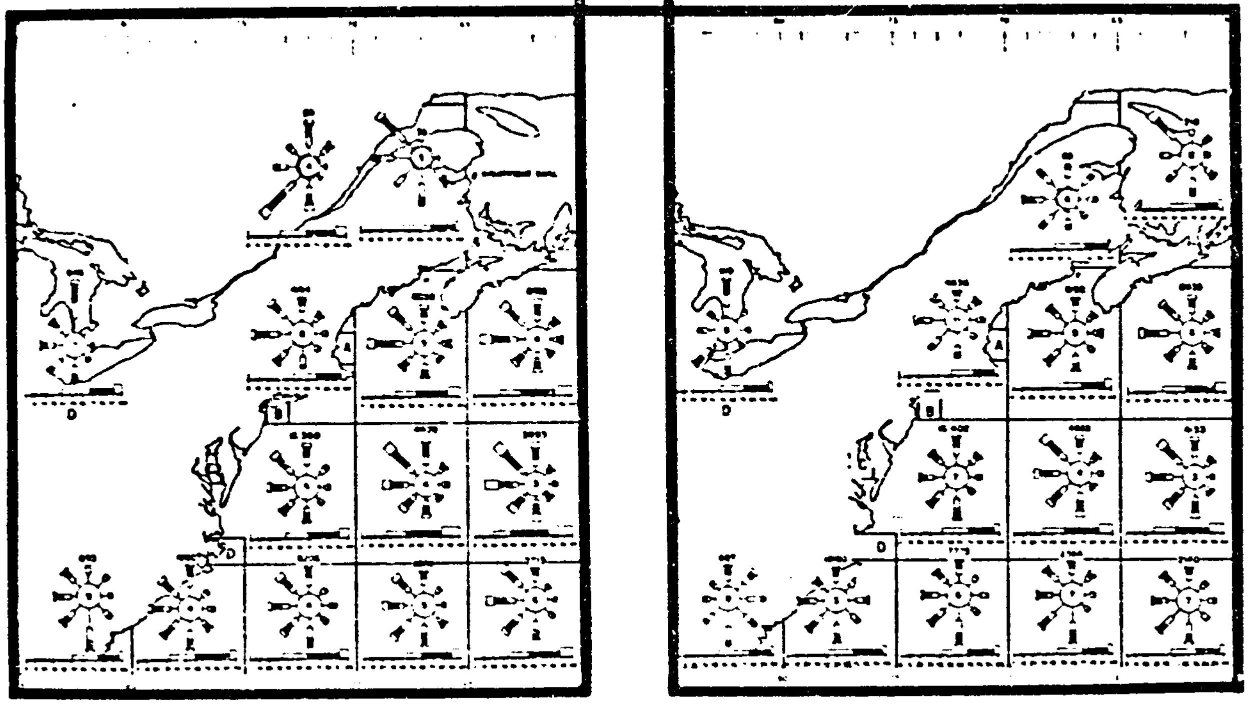
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-18 Key to Surface Wind Roses (U.S. Department of Commerce, 1973)



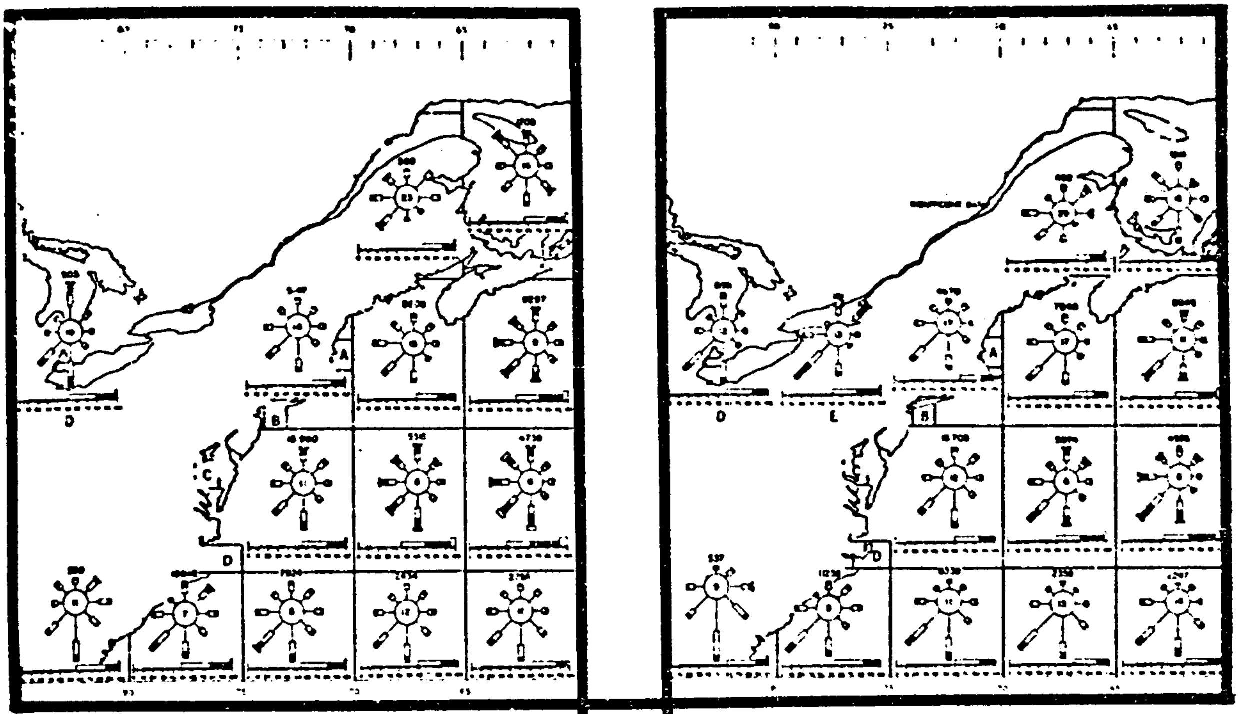
January
March

February
April



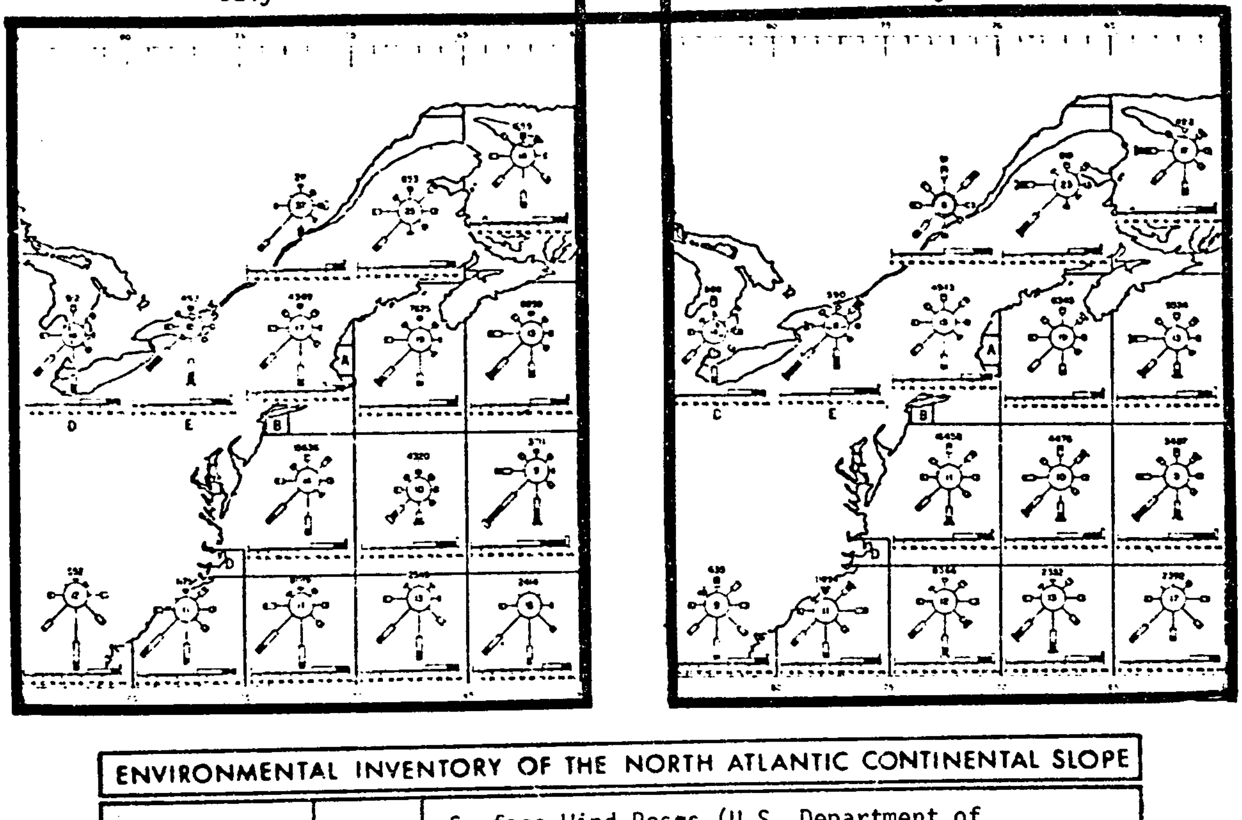
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE** 3-19	Surface Wind Roses (U.S. Department of Commerce, 1973)



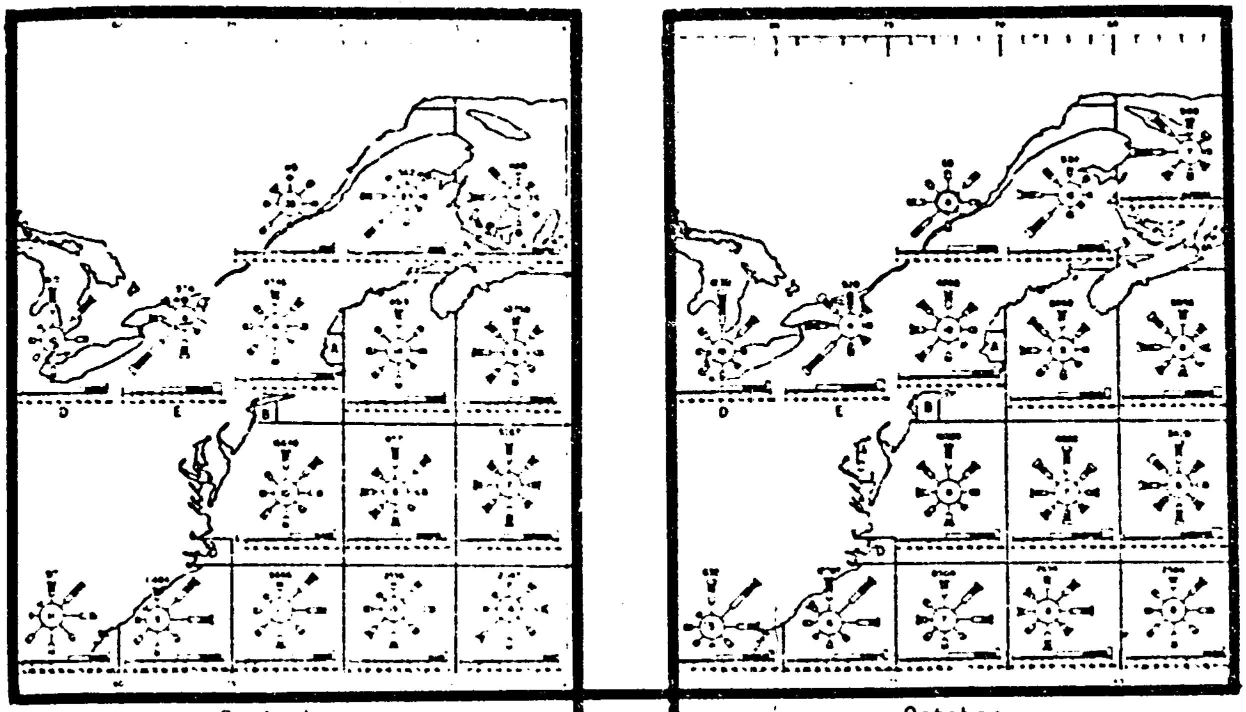
May June

July August



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-20	Surface Wind Roses (U.S. Department of Commerce, 1973)

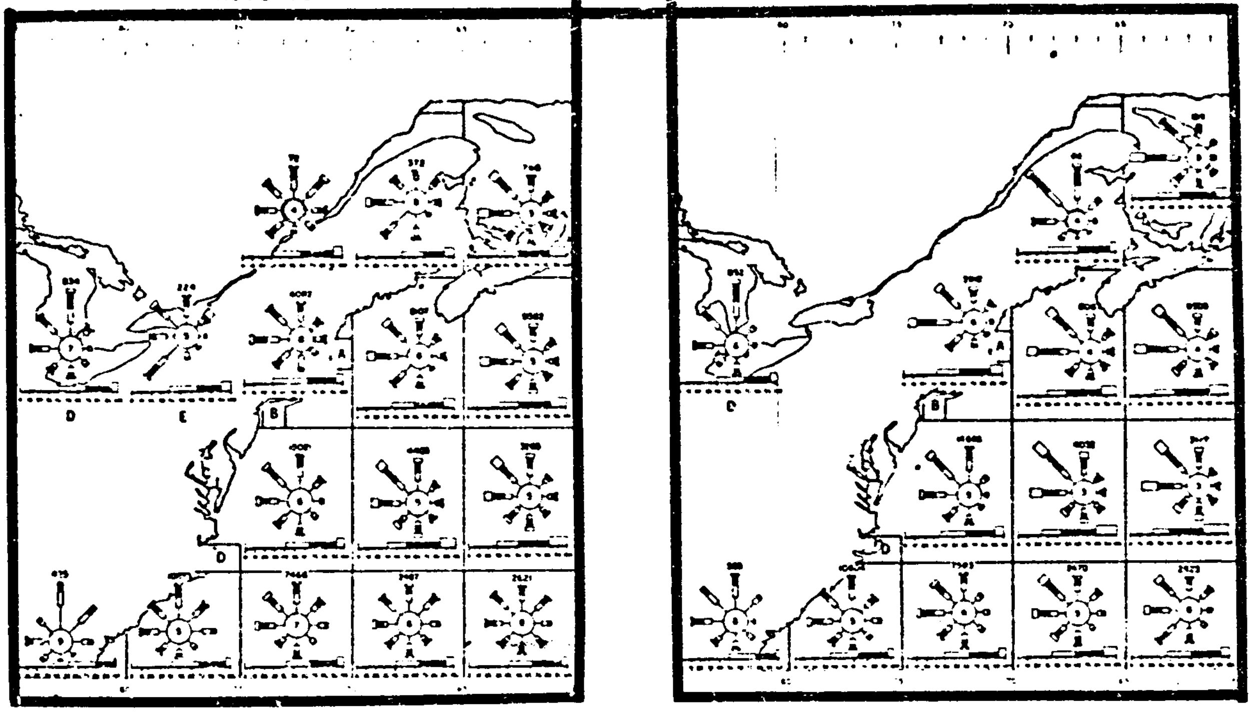


September

October

November

December



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

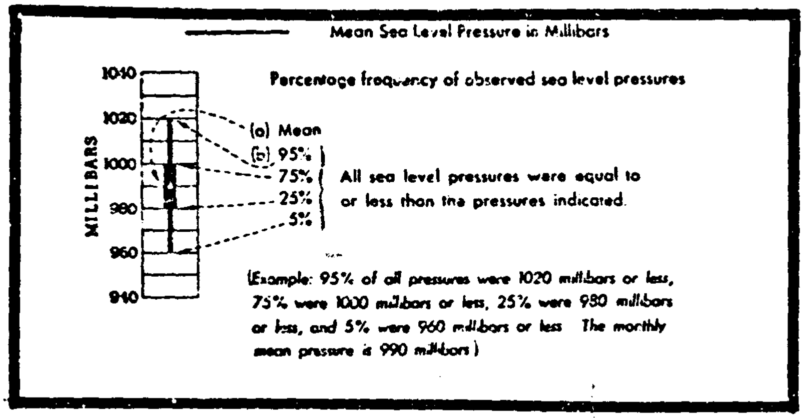
TRIGOM	FIGURE 3-21	Surface Wind Roses (U.S. Department of Commerce, 1973)

Table 3-3. Wind Speed data summaries for six sea areas. (Havens *et al.*, 1973)

Sea area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Quonset	16.9	17.0	15.7	13.3	10.7	10.1	9.4	10.3	11.6	13.7	15.4	17.1	13.2
New York	15.1	15.3	13.7	12.5	10.2	9.8	9.3	9.2	10.9	12.1	14.5	15.4	12.2
Atlantic City	16.5	16.1	15.3	13.1	10.9	10.3	10.5	10.7	11.8	13.8	15.2	15.6	13.2
Norfolk	16.1	15.7	15.4	13.8	11.8	10.9	10.7	10.9	12.2	13.9	14.7	15.2	13.4
Hatteras	17.8	18.2	17.3	15.9	13.8	12.6	12.2	11.8	13.1	15.4	15.8	16.5	15.0
"Hotel"	(21)	(22)	(22)	(19)	(17)	(13)	(12)	(15)	(16)	(15)	(18)	(21)	(18)

3.2.4 PRESSURE FIELDS

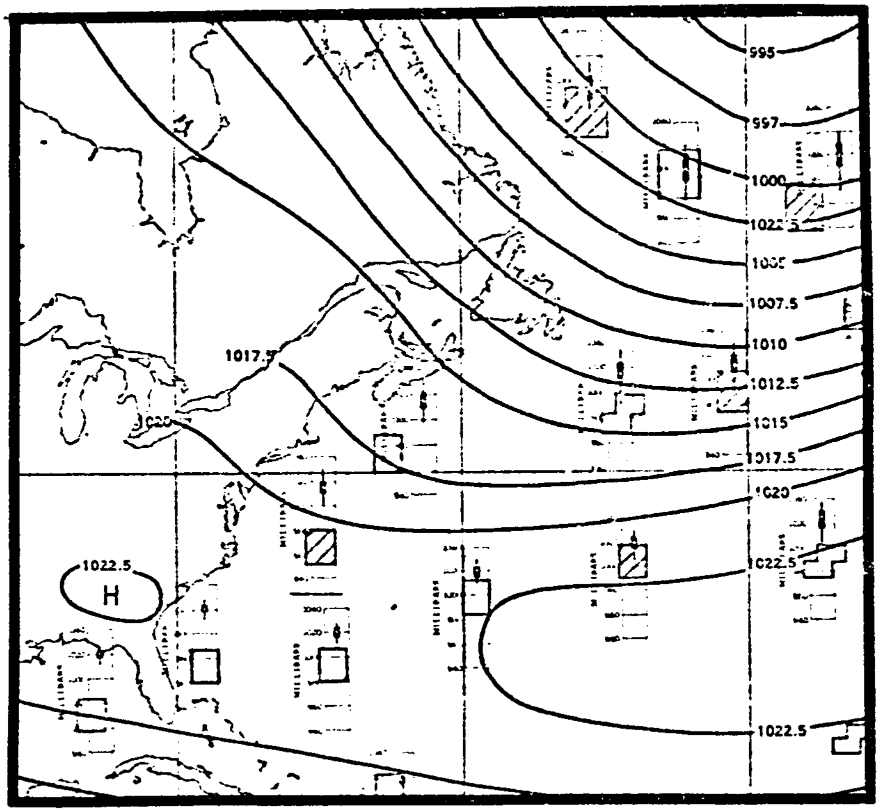
The monthly change in air pressure at sea level reflects the seasonally alternating pattern of high and low pressure that is characteristic of the northwest Atlantic, including the slope waters. Data representing the distribution of sea level pressure (in millibars) at two ocean station locations in the northwest Atlantic near the study area and lines of equal pressure for the northwest Atlantic as a whole show the characteristic seasonal pressure patterns within the study region and its relation to the ocean area as a whole (Figures 3-23 to 3-34). The seasonally shifting dominance of the Icelandic Low (about December to March) to the Bermuda-Azores High can be clearly seen for the western Atlantic. The study region seems to be in a somewhat stable pressure gradient of approximately 1015 to 1020 millibars between these two major pressure features.



(Example: 95% of all pressures were 1020 millibars or less, 75% were 1000 millibars or less, 25% were 980 millibars or less, and 5% were 960 millibars or less. The monthly mean pressure is 990 millibars.)

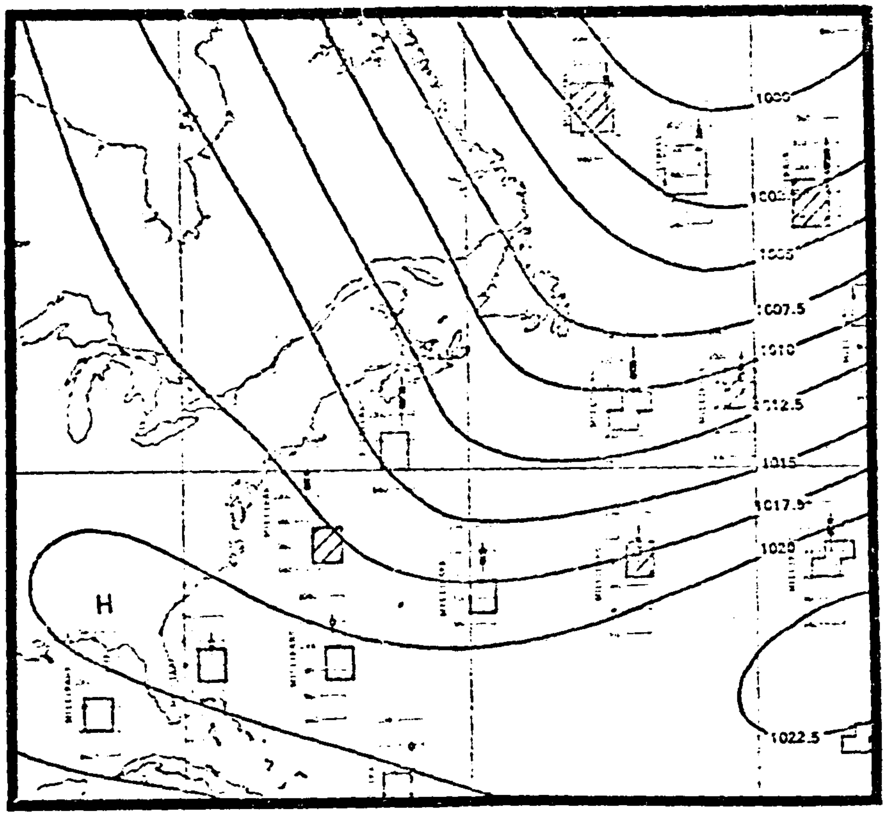
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-22	Key to Pressure Fields (U.S. Navy and U.S. Weather Bureau, 1959)



January

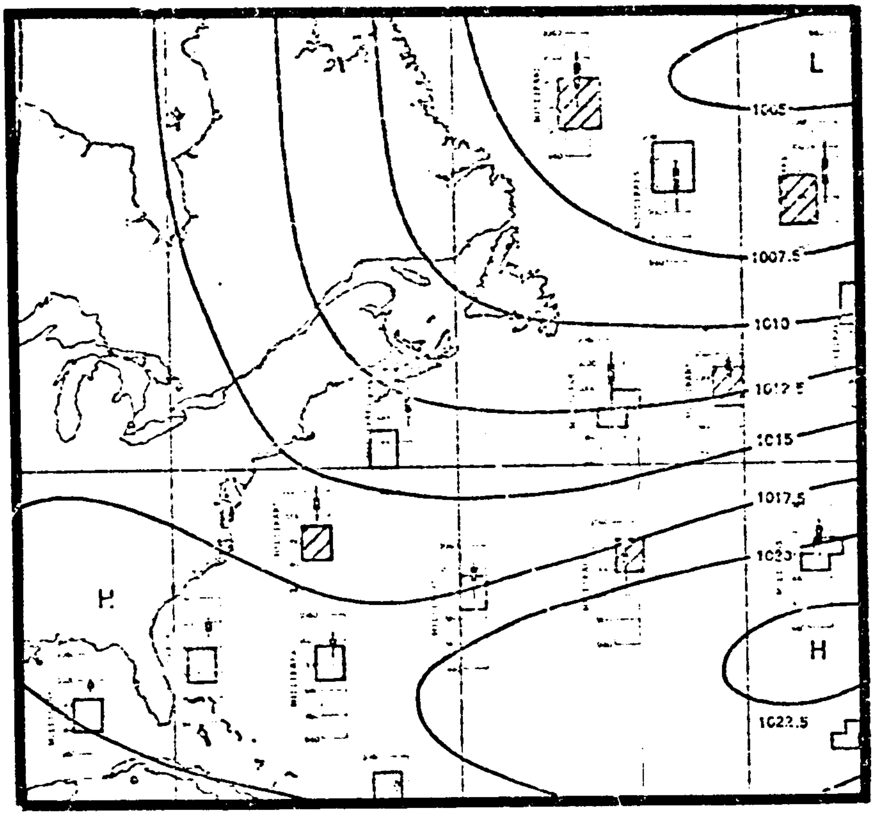
FIGURE 3-23 Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



February

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

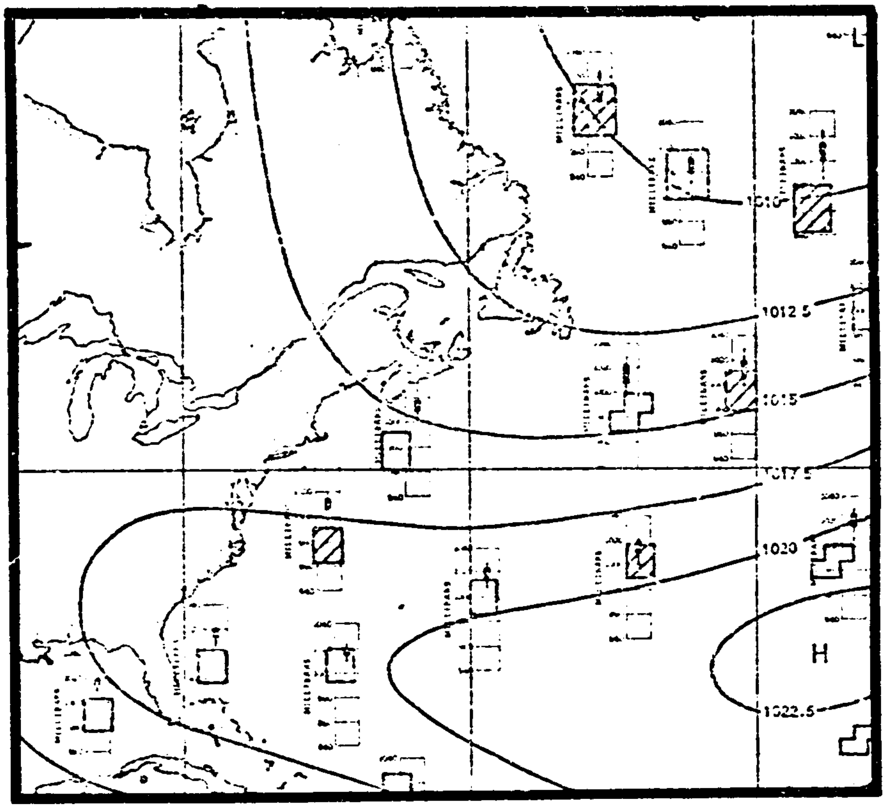
TRIGOM	**FIGURE** 3-24	Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



March

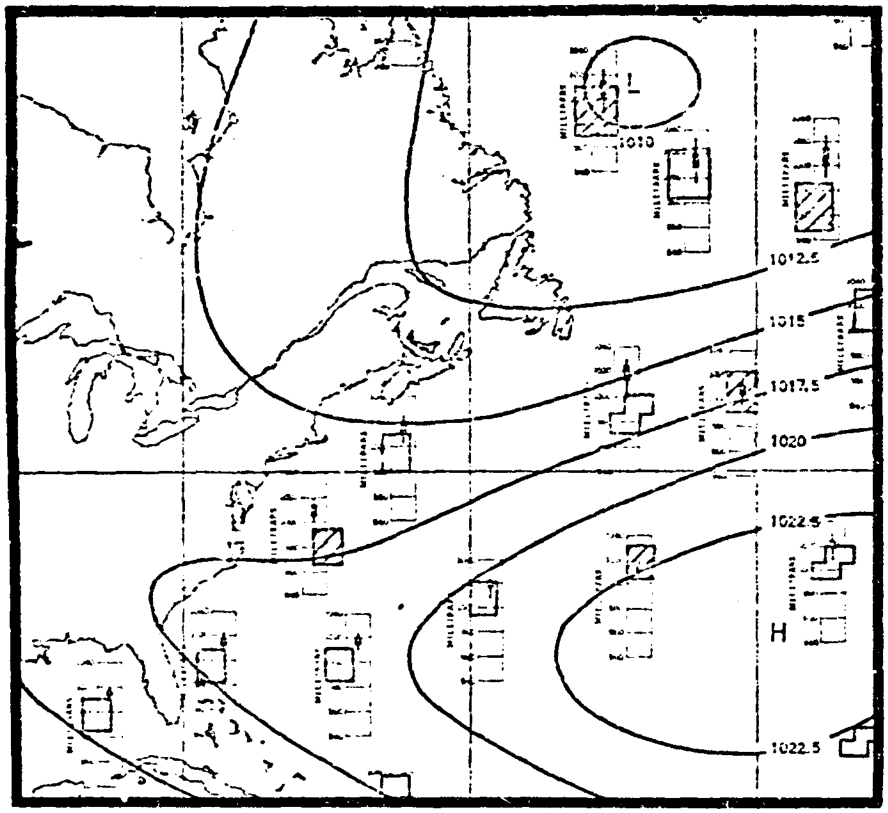
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-25 Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



April

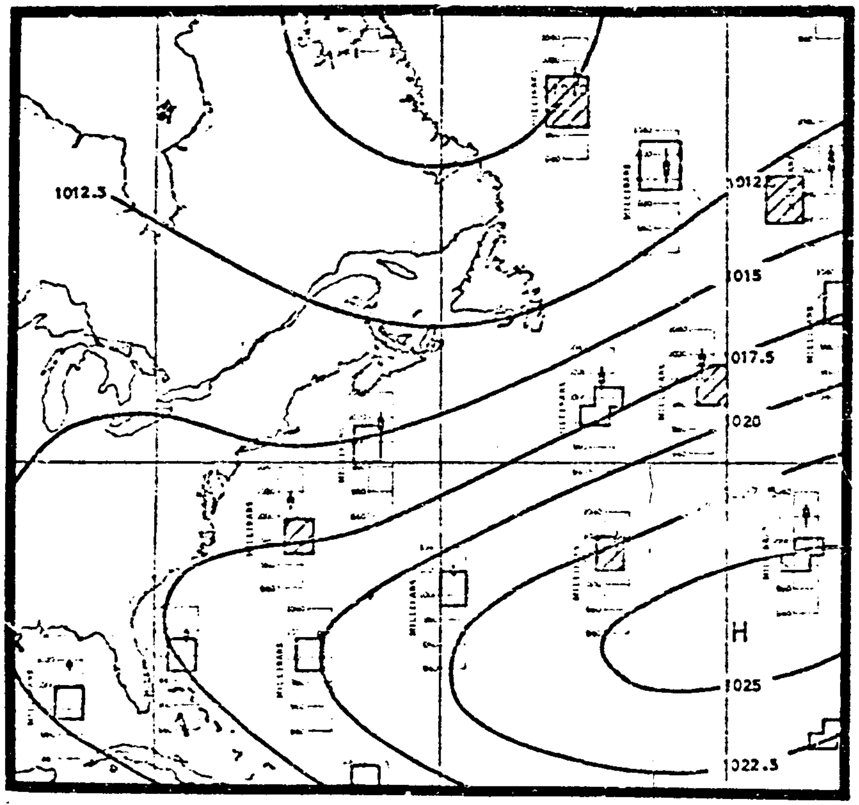
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE		
TRIGOM	FIGURE 3-26	Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



May

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

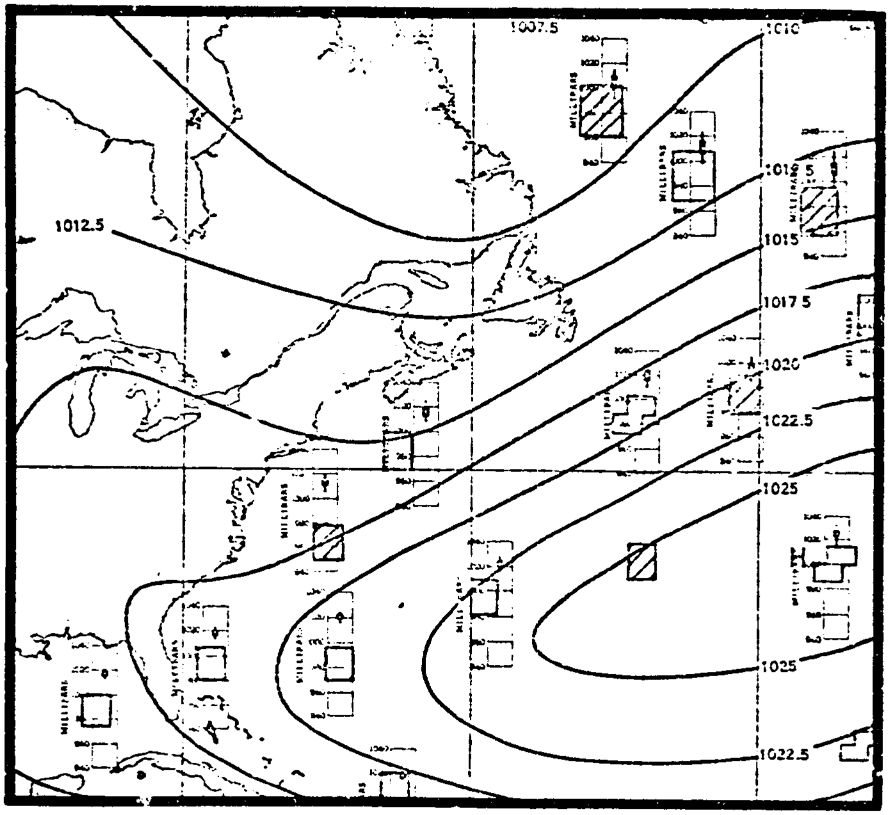
TRIGOM FIGURE 3-27 Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



June

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

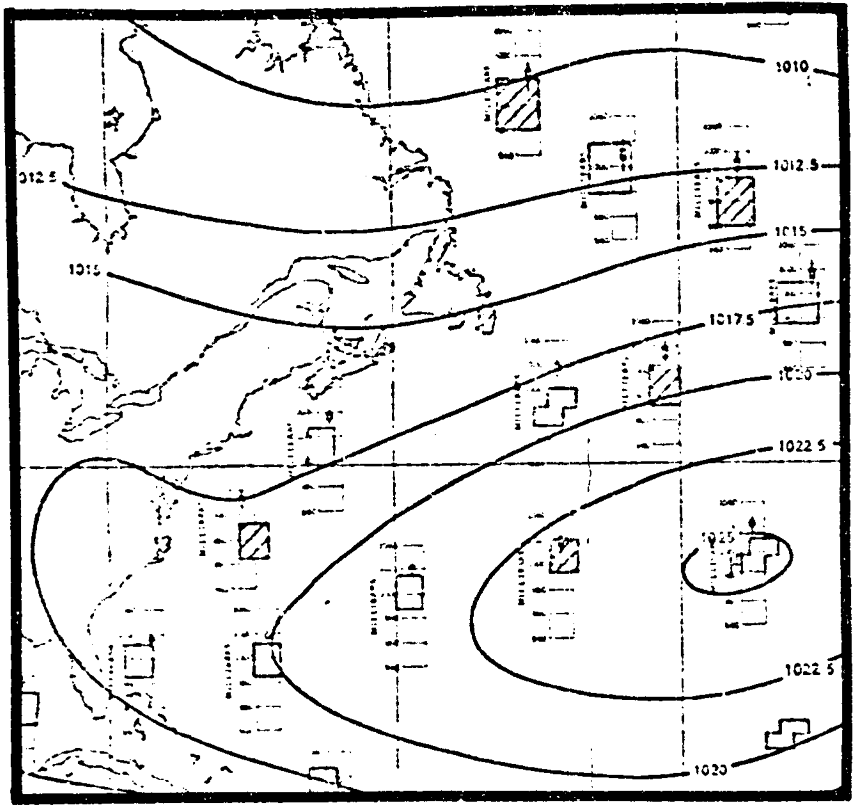
TRIGOM	FIGURE 3-28	Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



July

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

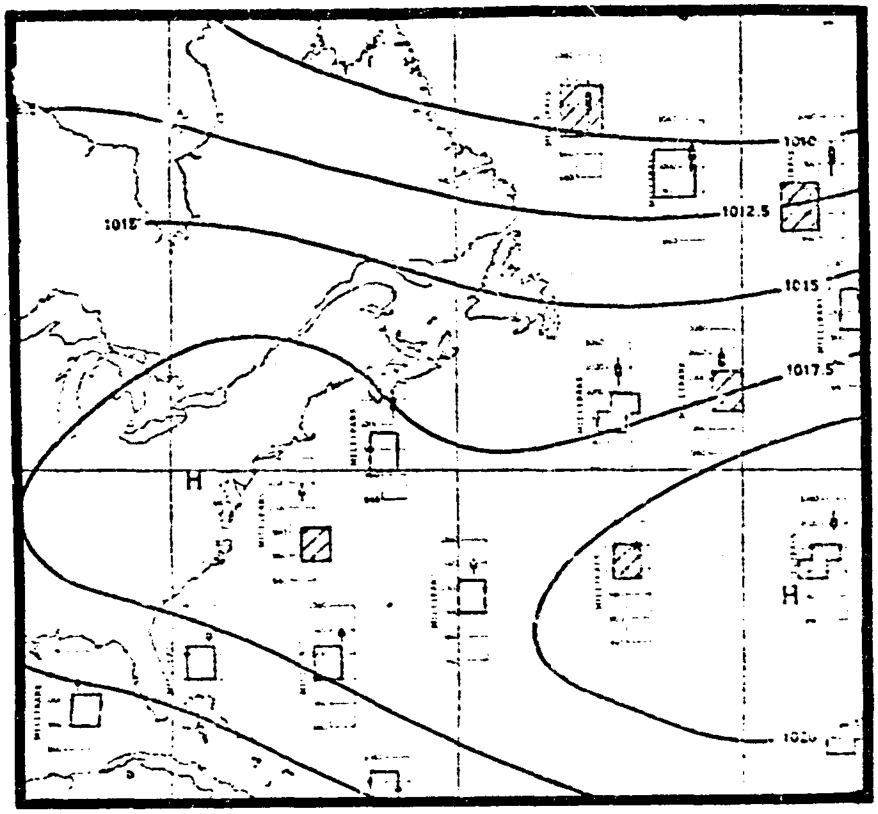
TRIGOM FIGURE 3-29 Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



August

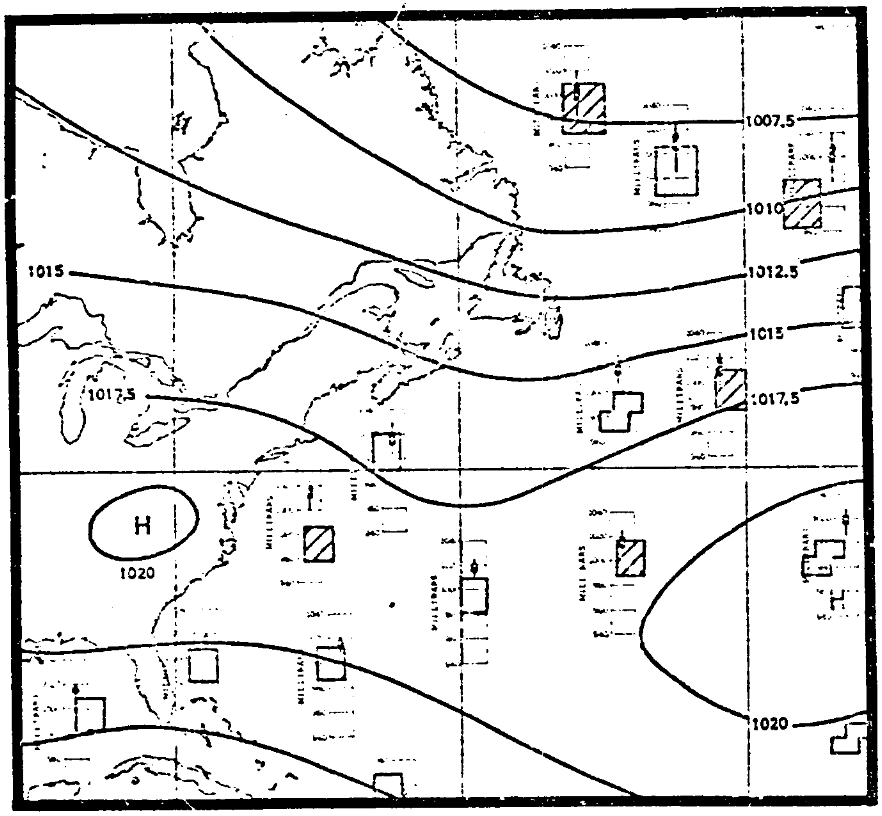
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-30	Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



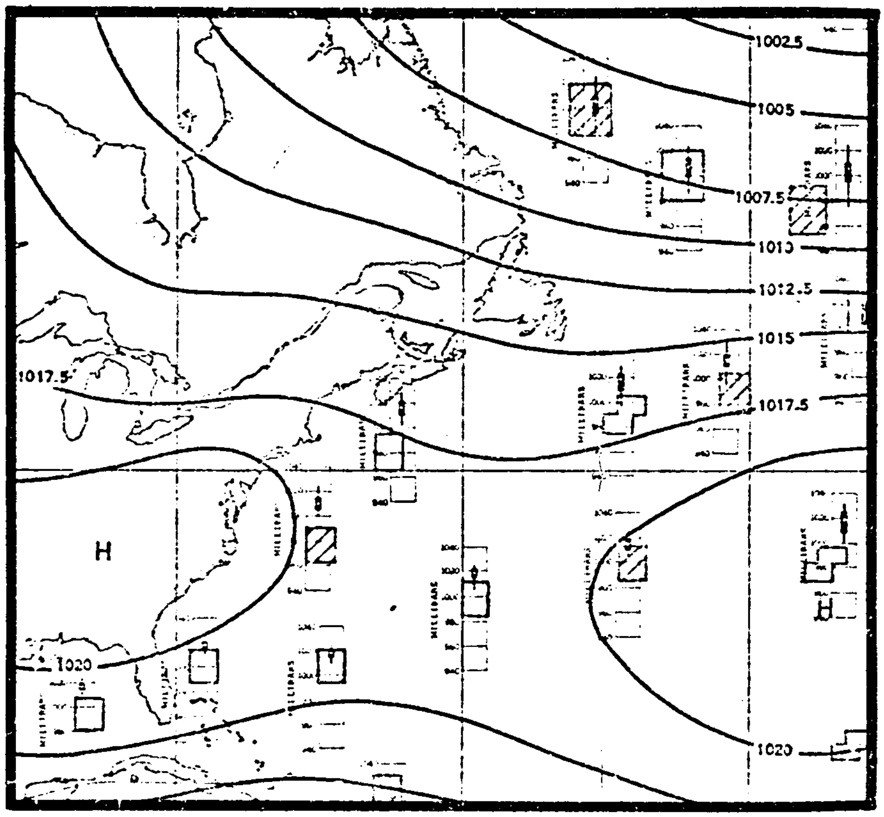
September

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE		
TRIGOM	FIGURE 3-31	Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



October

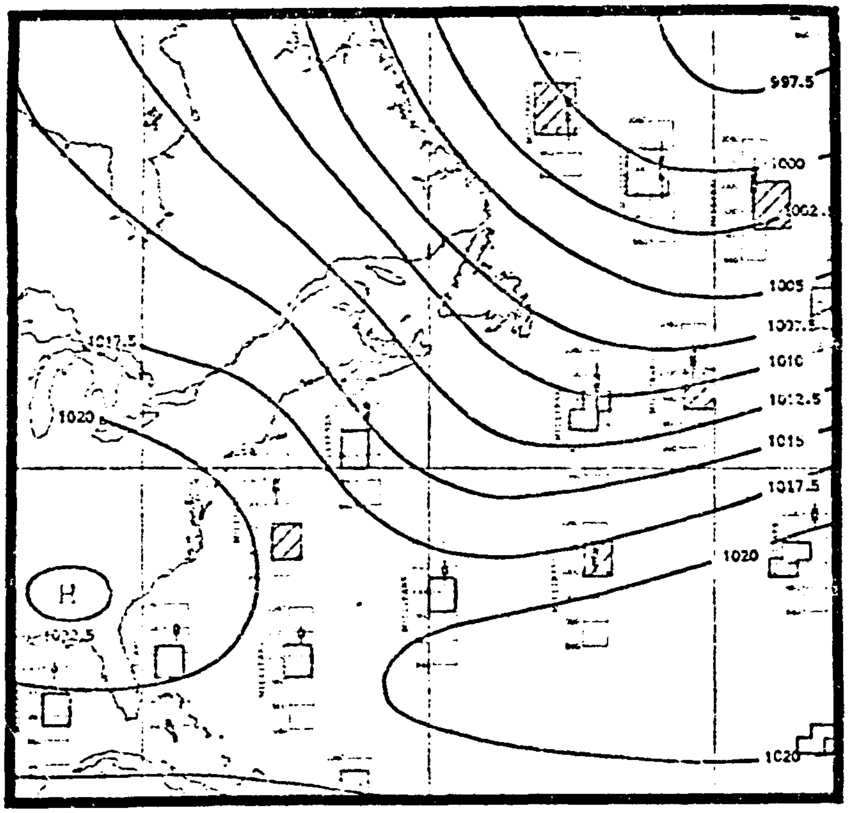
TRIGOM	FIGURE 3-32	Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



November

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-33	Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)



December

FIGURE 3-34 Sea Level Pressure (U.S. Navy and U.S. Weather Bureau, 1959)

3.2.5 VISIBILITY AND PRECIPITATION

The open ocean areas of the northwest Atlantic, including the study region, have generally better visibility than the more coastal regions. Reduction in visibility to less than two nautical miles occurred less frequently at ocean station "Hotel" than at any of the coastal reporting areas (Figures 3-35, 3-36, and 3-37) (Havens, et al., 1973) indicating that foggy and hazy conditions so common in the north coastal waters were less frequent offshore. Extremely high visibility (greater than 10 nautical miles) however, occurred significantly less frequently at "Hotel" than at the other sea areas. Havens, et al. suggest that that the prevalence of air masses that have lengthy trajectories over water might be indicated by these less frequent observations of high visibility.

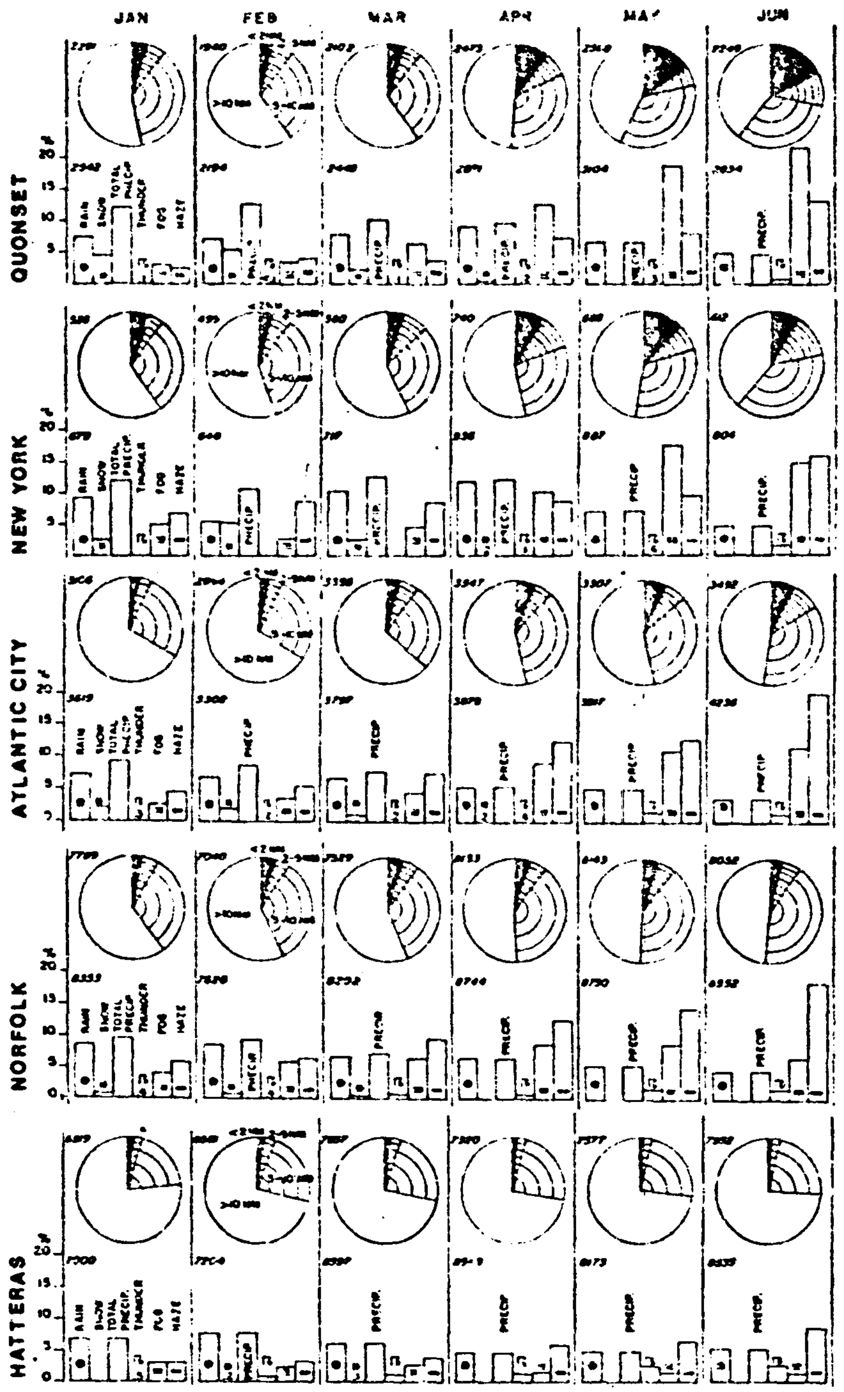
The seasonal visibility pattern in the northwest Atlantic, as expressed by the percent frequency of observations of less than five nautical miles (Figures 3-38, 3-39, and 3-40) also show the tendency toward higher visibility in the general vicinity of the study region, particularly during December through March, compared to more coastal waters. A latitudinal trend in visibility is also indicated by the data, with the higher latitudes of the study region showing a higher frequency of low visibility.

Precipitation has been described for the northwest Atlantic region in a series of maps by Jacobs (1968). These data indicated that precipitation was evenly distributed throughout the year. However, Havens, et al. found exceptions to this. In sea area "Hotel" (Figures 3-35, 3-36, and 3-37) intensive cyclonic activity gives way in the summer to the high pressure of the Bermuda-Azores High, producing a marked seasonal variation in the frequency of precipitation. Over twenty percent of the three-hourly observations at the "Hotel" area recorded precipitation during February, while only eight percent recorded precipitation during June, July, and August. Precipitation was more frequently experienced in the "Hotel" area than in the other coastal recording areas.

Likewise the data presented by the U.S. Navy and U.S. Weather Service (1959) (Figures 3-41) show a marked seasonal variation in the frequency of occurrence of precipitation, but significantly more precipitation occurred in the northern data collecting location than at the ocean station "Hotel" area. This would indicate an increasing amount of precipitation as one moves north along the latitudinal axis of the study region.

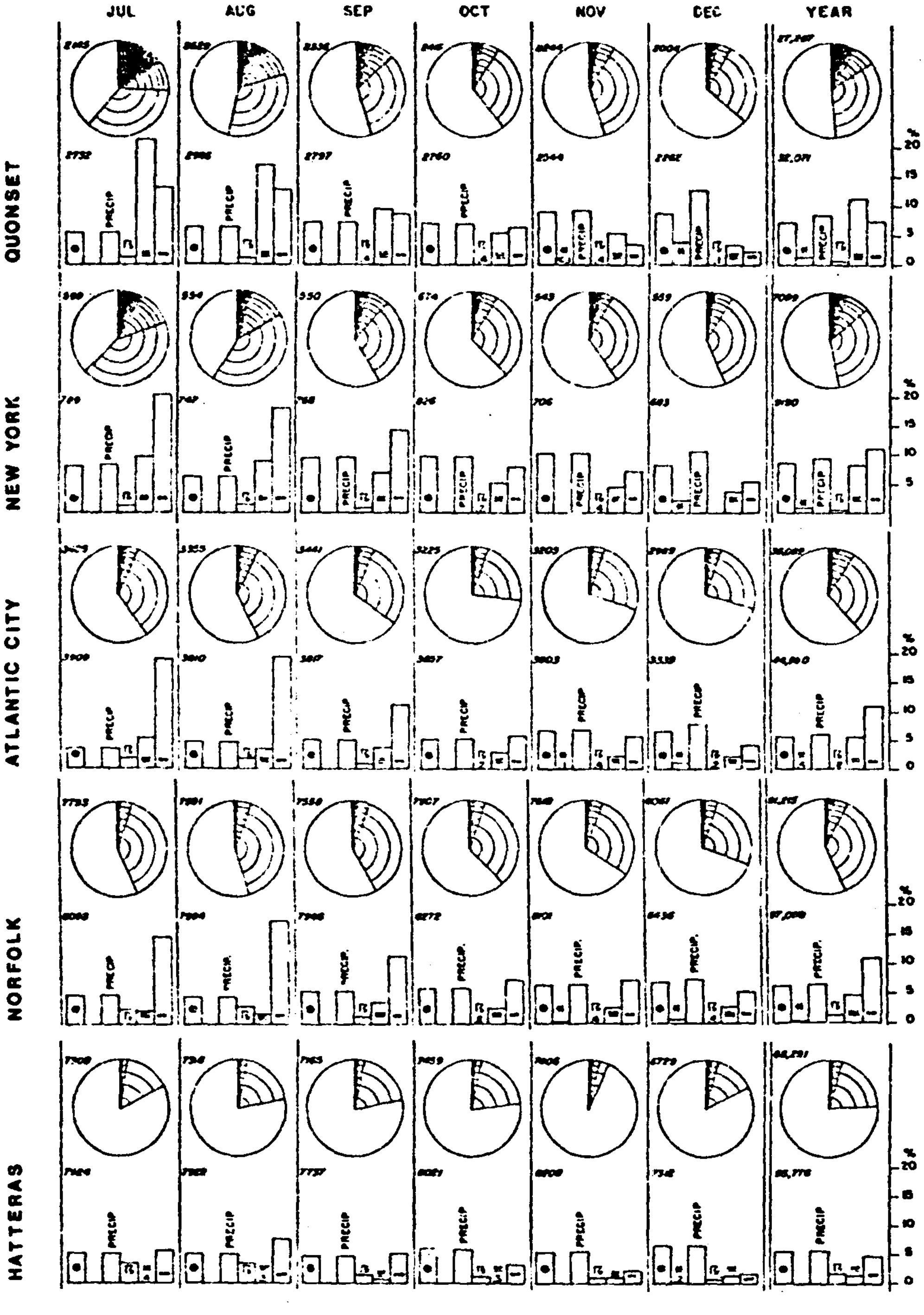
Snow has been reported at the "Hotel" sea area, but with much less frequency than rain. In the slope water region, snowfall is a function of latitude and will in all likelihood be found with increasing frequency from Cape Hatteras to the northern tip of Georges Bank.

Thunder activity is perhaps slightly higher in the "Hotel" sea area than along the coast, particularly during winter.



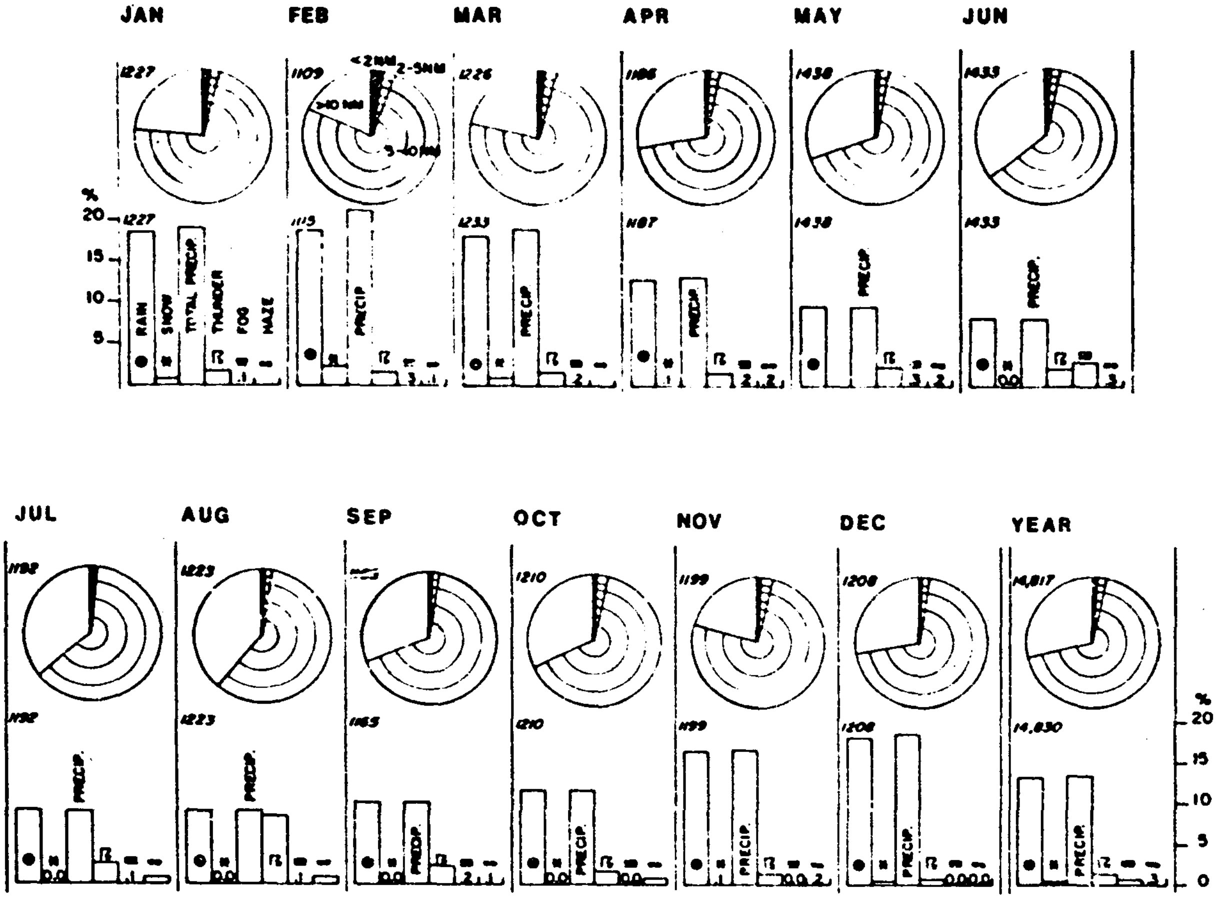
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-35	Visibility and Precipitation Graphs for Each Month at Five Coastal Areas (Havens, et al., 1973)



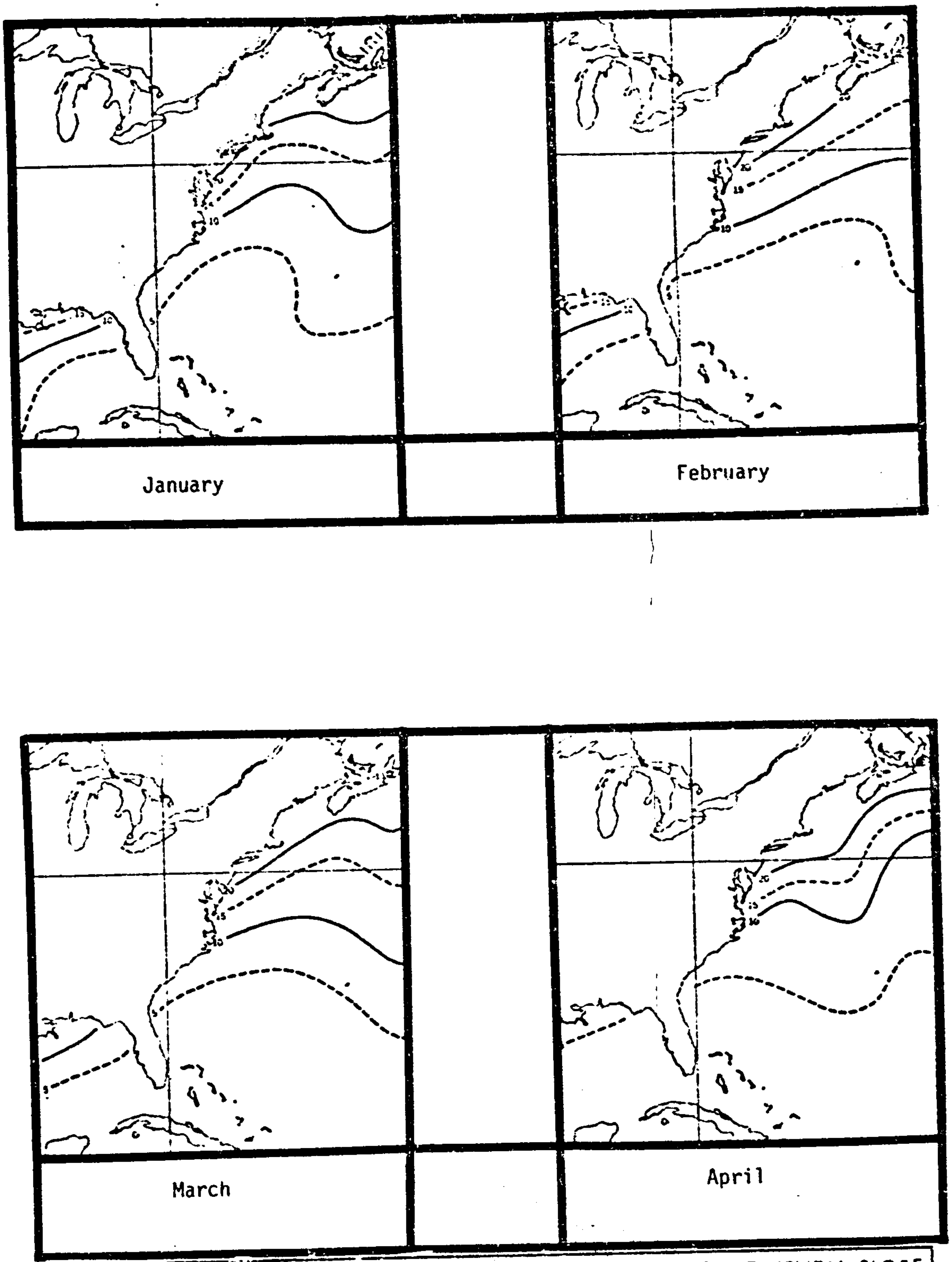
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-36	Visibility and Precipitation Graphs for Each Month at Five Coastal Areas (Havens, et al., 1973)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-37 Visibility and Precipitation Graphs for Each Month at Ocean Station "Hotel" (Havens, et al., 1973)



January

February

March

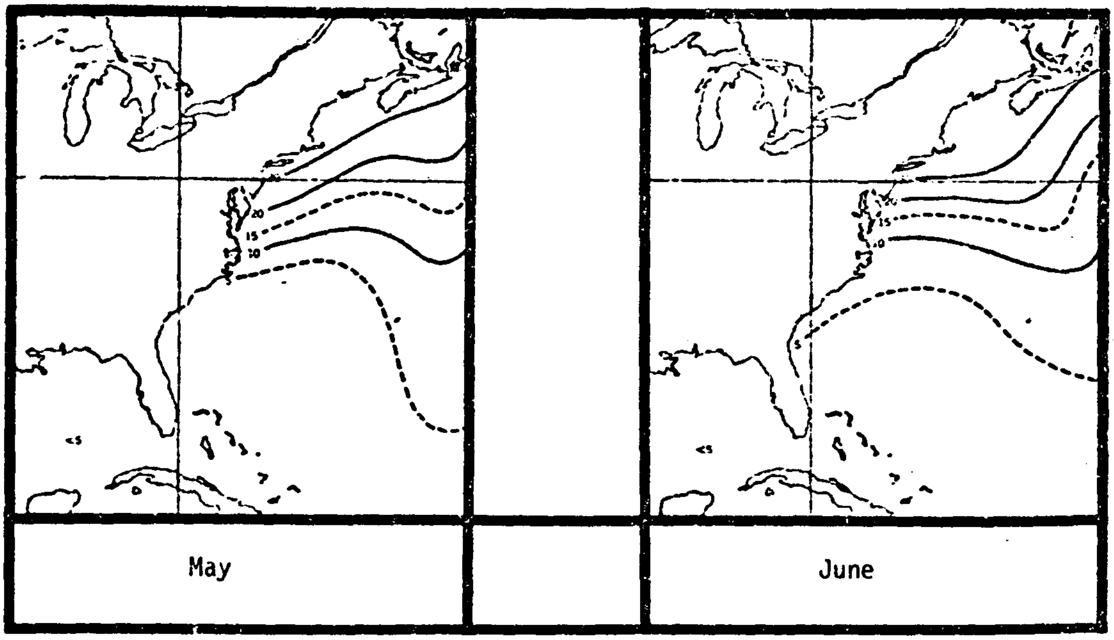
April

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

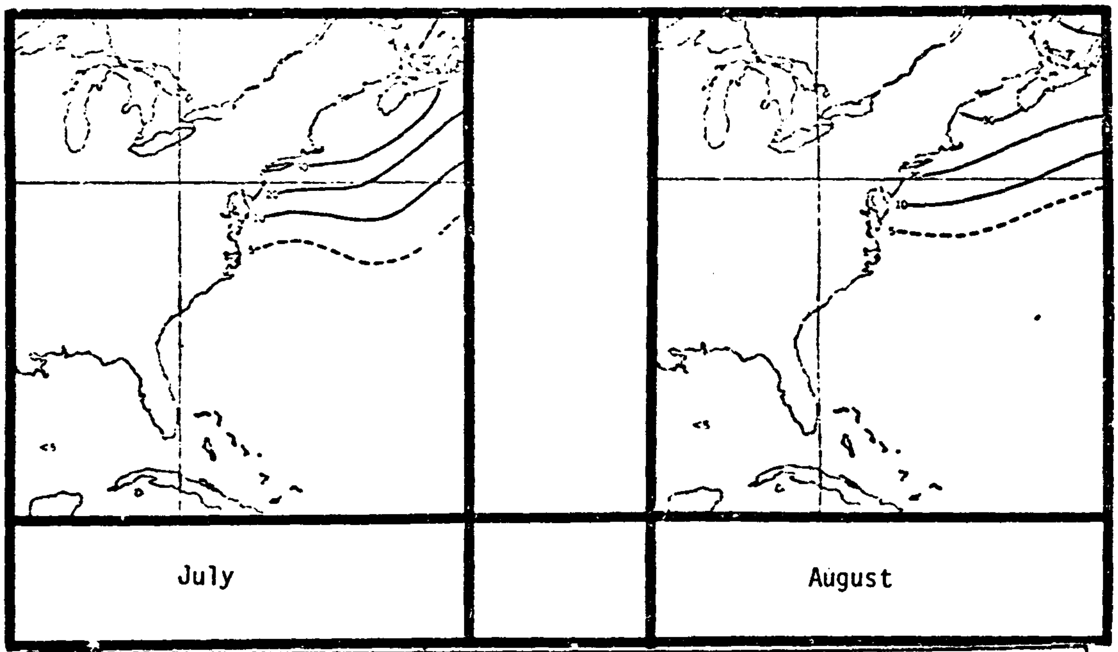
FIGURE 3-38

Seasonal Visibility in the Northwest Atlantic as Expressed by Percent Frequency of Observations Less Than 5 Nautical Miles (U.S. Navy and U.S. Weather Bureau, 1959)



May

June

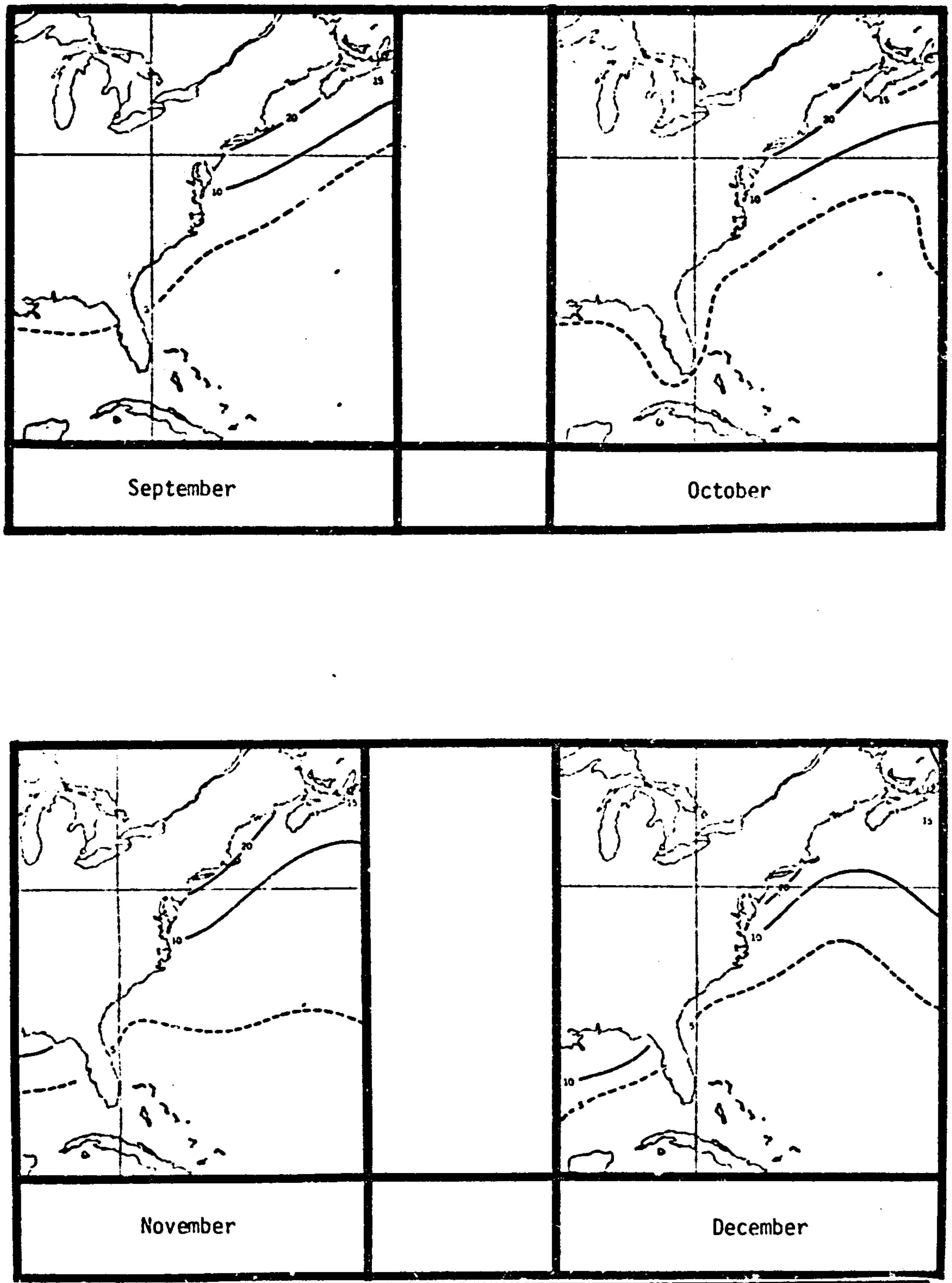


July

August

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-39	Seasonal Visibility in the Northwest Atlantic as Expressed by Percent Frequency of Observations Less Than 5 Nautical Miles (U.S. Navy and U.S. Weather Bureau, 1959)



September

October

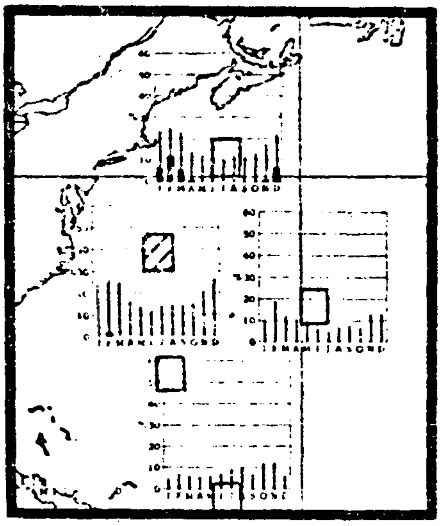
November

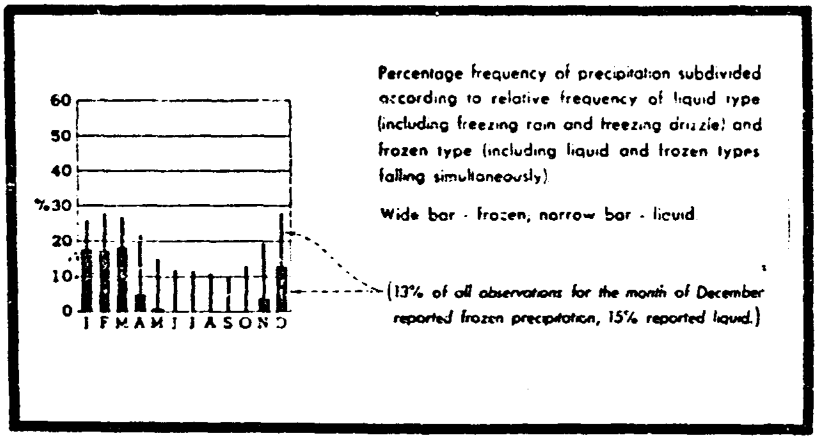
December

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-40	Seasonal Visibility in the Northwest Atlantic as Expressed by Percent Frequency of Observations Less Than 5 Nautical Miles (U.S. Navy and U.S. Weather Bureau, 1959)

Summary





Percentage frequency of precipitation subdivided according to relative frequency of liquid type (including freezing rain and freezing drizzle) and frozen type (including liquid and frozen types falling simultaneously)

Wide bar - frozen, narrow bar - liquid

(13% of all observations for the month of December reported frozen precipitation, 15% reported liquid.)

Key

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-41 Precipitation Summary for Northwest Atlantic (U.S. Navy and U.S. Weather Bureau, 1959)

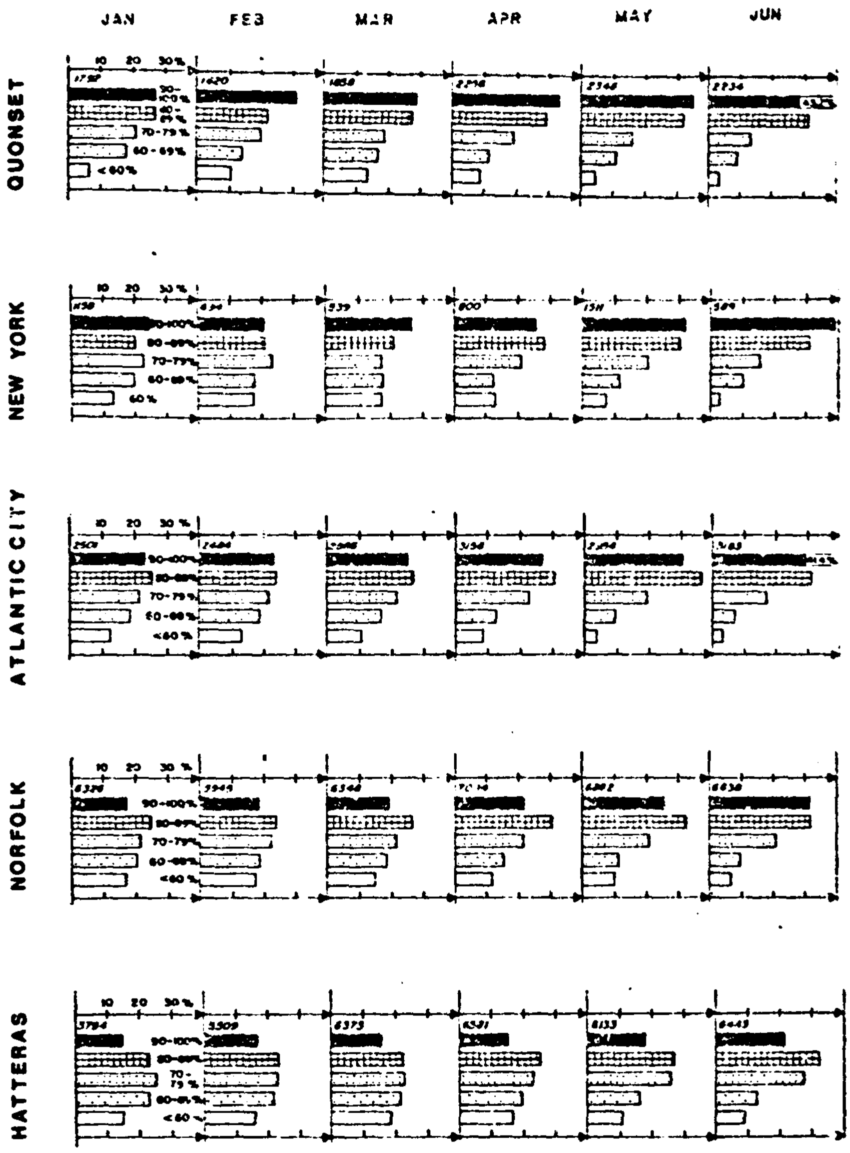
3.2.6 RELATIVE HUMIDITY AND DEW POINT

Relative humidity at all sea areas reported by Havens, et al. (Table 3-4, Figures 3-42, 3-43, and 3-44) was usually above 70 percent during all seasons and showed an annual variation of six percent or seven percent. Sea area "Hotel" had the lowest overall values of relative humidity, especially during the winter months. Havens, et al. stated that it was not immediately apparent why sea area "Hotel" should have a low average relative humidity value.

Dew point, another humidity observation, represents the air temperature at which saturation occurs and beyond which cooling will cause some of the water vapor to become liquid (Blair and Fite, 1957). Isotherms of dew point observations (in degrees fahrenheit) are presented in Figures 3-45, 3-46, and 3-47 for the northwest Atlantic, including the slope water region. As would be expected, there is a marked seasonal change in the range of dew point values along the latitudinal axis of the study region; an increased gradient during the winter months and a decreased gradient during the summer months.

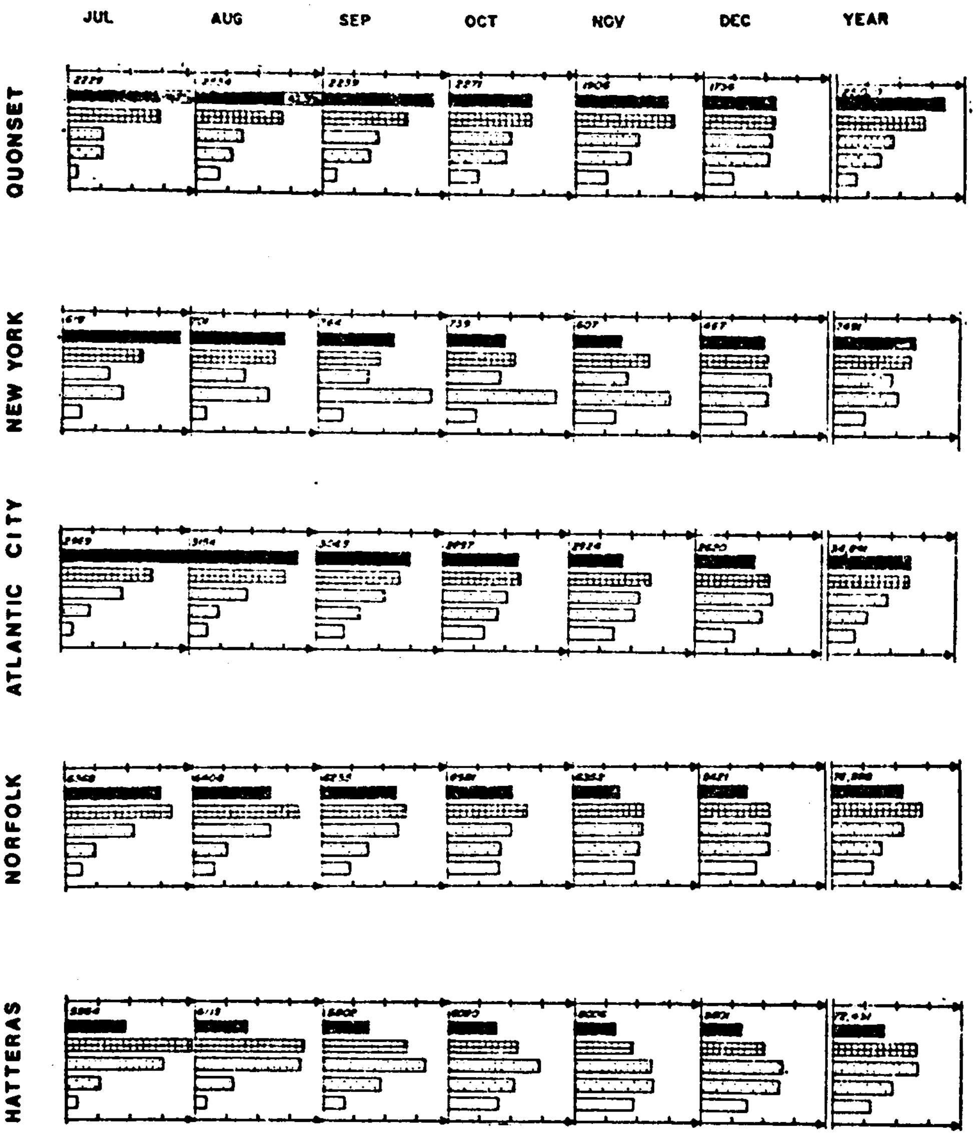
Table 3-4. Relative Humidity data summaries for six sea areas. (Havens et al., 1973)

Sea area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Relative Humidity (%)													
Quonset	80	79	79	82	83	85	86	84	82	78	79	77	81
New York	77	74	76	78	82	84	80	79	75	74	73	76	77
Atlantic City	77	77	78	80	83	85	83	82	80	77	75	76	80
Norfolk	75	74	76	78	79	81	82	80	78	76	73	74	77
Hatteras	74	74	73	74	77	80	80	79	77	74	72	73	76
"Hotel"	72	69	71	73	76	79	81	77	74	71	68	71	74



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-42	Relative Humidity Graphs for Each Month at Five Coastal Areas (Havens, et al., 1973)

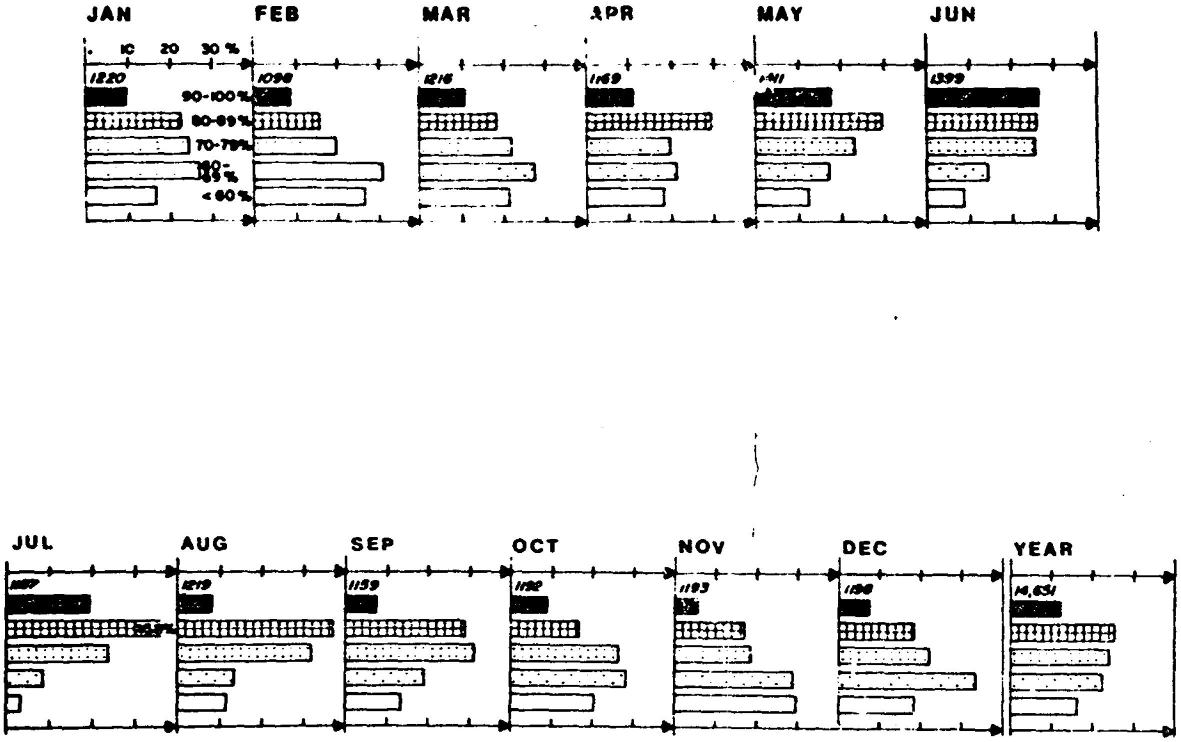


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 3-43

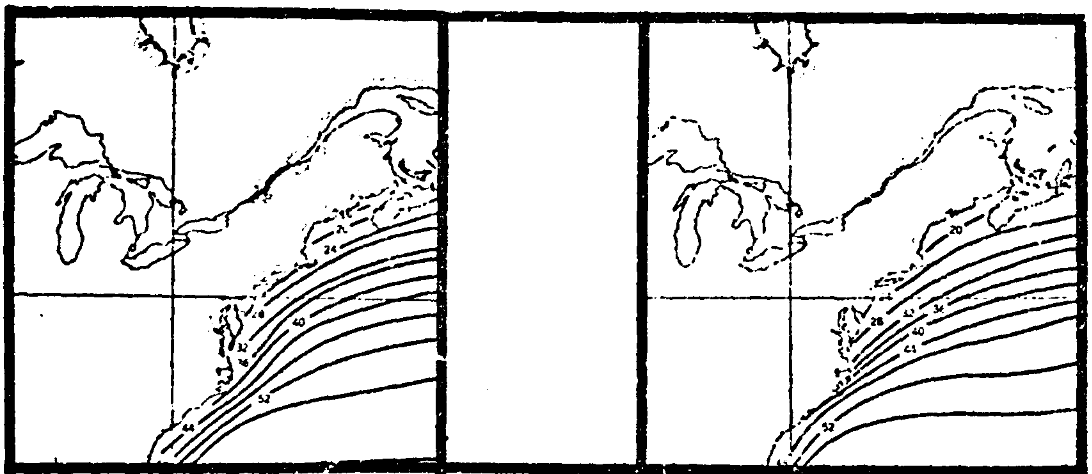
Relative Humidity Graphs for Each Month at Five Coastal Areas (Havens, et al., 1973)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

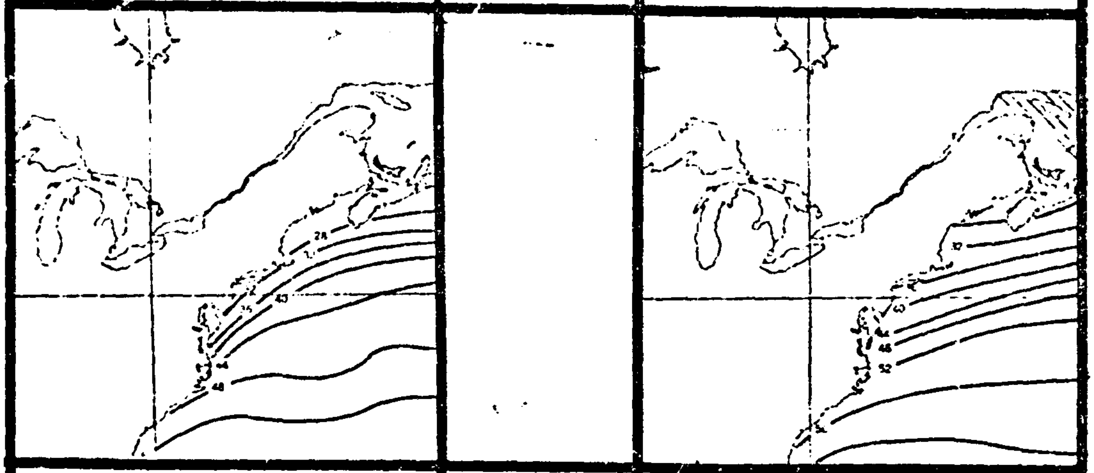
TRIGOM

FIGURE 3-44 Relative Humidity Graphs for Each Month at Ocean Station "Hotel" (Havens, *et al.*, 1973)



January

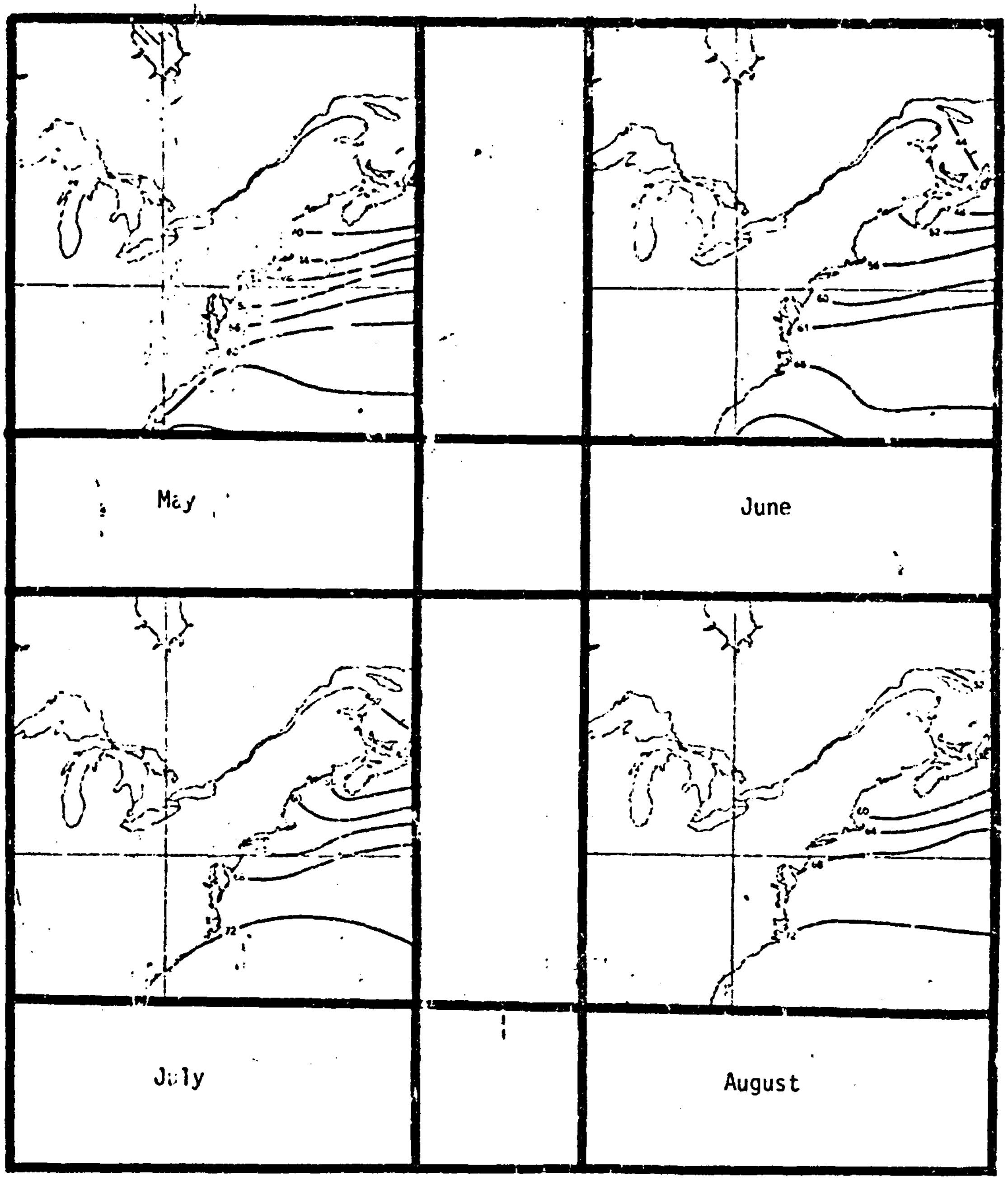
February



March

April

FIGURE 3-45 Isotherms (°F) of Dew Point Observations in the Northwest Atlantic (U.S. Navy and U.S. Weather Bureau, 1959)


May

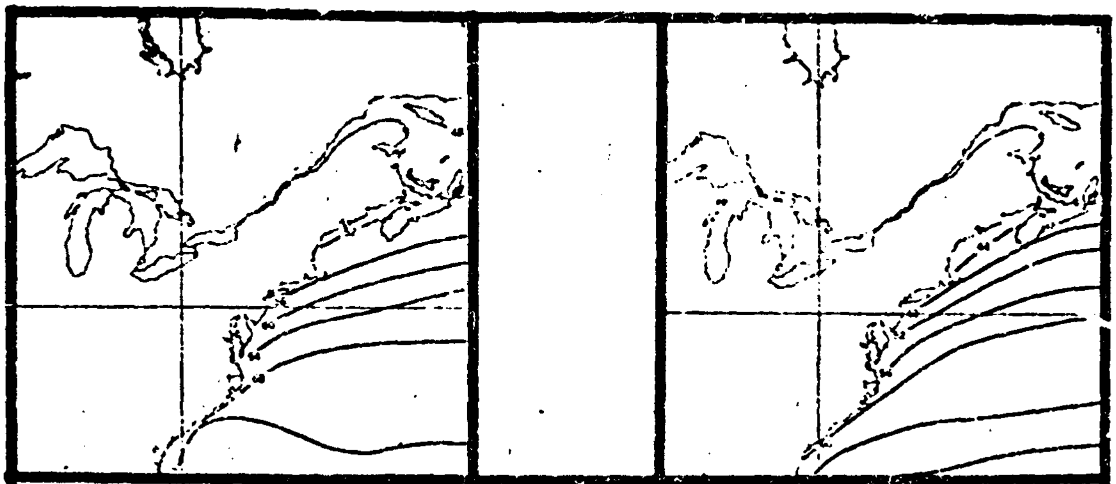
June

July

August

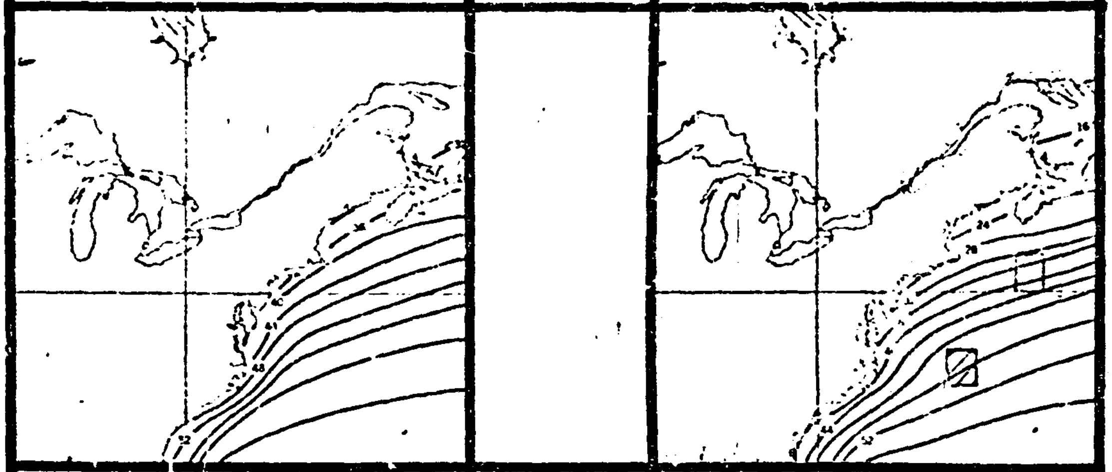
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-46 Isotherms (°F) of Dew Point Observations in the Northwest Atlantic (U.S. Navy and U.S. Weather Bureau, 1959)



September

October



November

December

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 3-47

Isotherms (°F) of Dew Point Observations in the Northwest Atlantic (U.S. Navy and U.S. Weatner Bureau, 1959)

3.2.7 CYCLONES

Two types of cyclonic patterns, distinguished by their point of origin and movement, are prevalent in the slope water region. Non-tropical cyclones are disturbances resulting from low pressure centers that originate either over the land mass of the continental U.S. or over the waters of the northwest Atlantic, and move in a generally easterly to northeasterly direction. Tropical cyclones are circulations around low pressure centers that develop over tropical oceanic areas. Most of these storms move in a westerly direction, sometimes recurving as they approach the land mass of the United States to follow a generally northerly to northeasterly track. At times this track carries the tropical cyclones through the study region.

NON-TROPICAL CYCLONES

Cyclogenesis is a dominant characteristic of the waters off the East Coast of the United States at all times of the year, particularly during the period from October to April. The slope region is a frequent recipient of non-tropical storms by virtue of its parallel orientation to the prevailing southwest to northeast storm track (Figures 3-1, 3-2). The large contrast between cold polar air masses of the continents and warmer maritime air overlying the sea surface is an important factor in storm development (Andrews, 1963). This temperature contrast is intensified by the Gulf Stream, the upper air polar front, and the upper air trough. Local factors such as temperature of the east coast shoreline, the orientation of the Appalachian mountains and differential friction between air and sea are also cited by Andrews as factors influencing non-tropical storms. As a result, three types of non-tropical cyclogenesis can be identified during the period October to April:

Type A: a cyclone first appears as a wave of a cold front;

Type B: a cyclone appears as a secondary cyclone near the Middle Atlantic coast along the warm front of an older cyclone;

Type C: a cyclone develops as a blocked low off the coast. Its formation is related to the breakdown of large-scale planetary circulation in the upper westerlies.

Although these storms commonly cross the waters of the study region, their frequency and duration are not available in the form of summarized information.

TROPICAL CYCLONES

Tropical cyclones are classified according to their intensity (Cry, 1965):

Tropical depression: a developmental and weak stage of a tropical storm

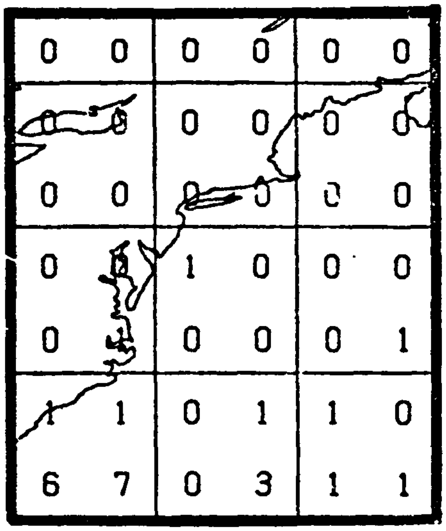
Tropical storm:	tropical cyclone with closed isobars and sustained wind speeds of 34 to 63 kts
Hurricane:	tropical cyclone with sustained wind speeds above 63 kts
Extra tropical:	tropical cyclone modified with a non-tropical air mass

Tropical storms and hurricanes originate in a broad belt across the Atlantic in tropical and sub-tropical waters. Cyclogenesis only rarely occurs in or near the waters of the study region (Figures 3-48 to 3-51). However, the paths of these cyclones, sometimes recurving after an initially westerly track, often taking them through the slope water in a generally northeasterly direction (Figures 3-52 to 3-58). Generally, the tracks that these cyclones take are determined by physical forces that control the distribution of winds in the troposphere (Cry, 1965). Recurvature is the result of the westerly moving tropical cyclones, under the influence of prevailing easterly tropical winds, moving toward the north because of the coriolis force to be influenced by the westerly trade winds.

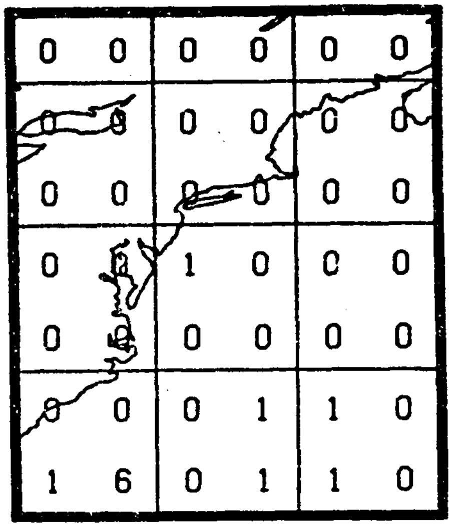
The resultant occurrences of tropical cyclones (storms and hurricanes) in the study region, in terms of percent of days present are shown by two and one-half degree squares in Figures 3-49 and 3-51. Their occurrences, direction frequency, and speed of movement are shown in Figures 3-59 to 3-64 from the U.S. Navy and U.S. Weather Bureau (1959) and in Figures 3-65 to 3-70 from Crutcher and Quayle (1974). These two sets of data are somewhat conflicting and therefore each are presented. Probably the use of data from slightly different time spans is the reason for the contradictions.

The occurrence of tropical cyclones in the slope water is quite seasonal. Generally, throughout the Atlantic as a whole these cyclones occur most frequently between August and October (Cry, 1965). However, Cry and Haggard (1962) show that in the northwest Atlantic tropical cyclones occur somewhat more evenly over a broader seasonal range (July to October). From the data presented in Figures 3-59 to 3-64 and 3-65 to 3-70 the seasonal frequency of tropical cyclones (storms and hurricanes) is most frequent between August and October, but they do occur from about May to December (with an exceptional occurrence in February).

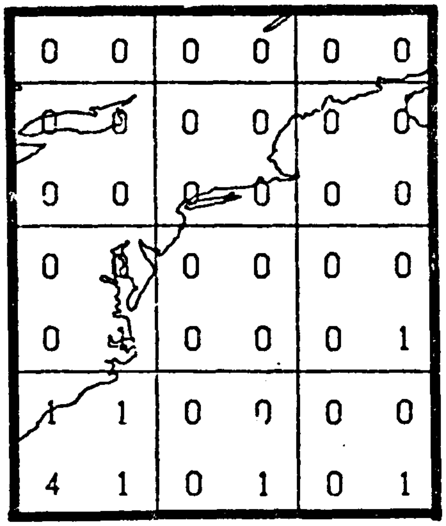
Storm damage estimates for the study region, which would apply almost exclusively to shipping, were not available. However, damage statistics for tropical cyclones reaching the U.S. coast for the years 1931 to 1973 (Hebert, 1974) are presented in Table 3-4.



All Months



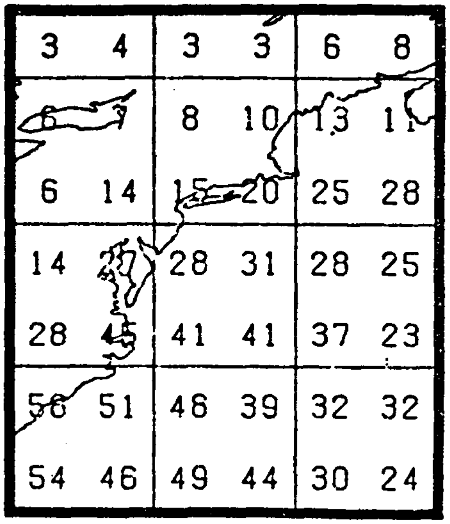
October to July



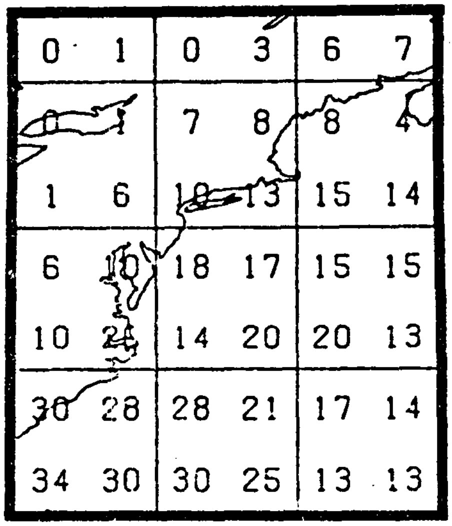
August and September

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

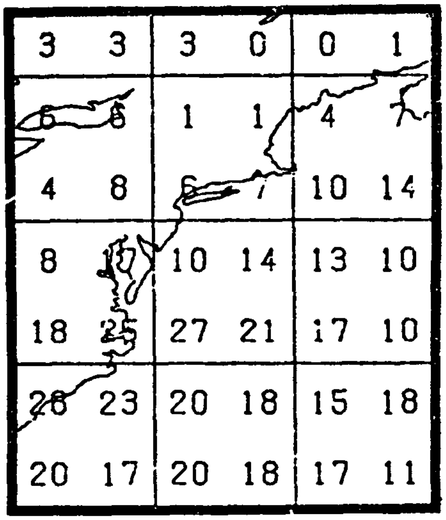
TRIGOM	FIGURE 3-48	Percent of Days Tropical Storms Originated 1899-1969 by 2½ Degree Squares (U.S. Department of Commerce, 1973)



All Months



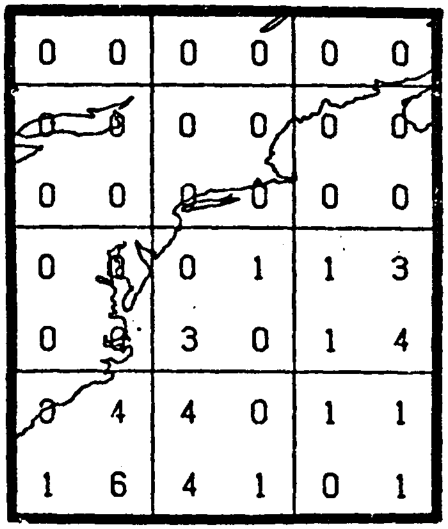
October to July



August and September

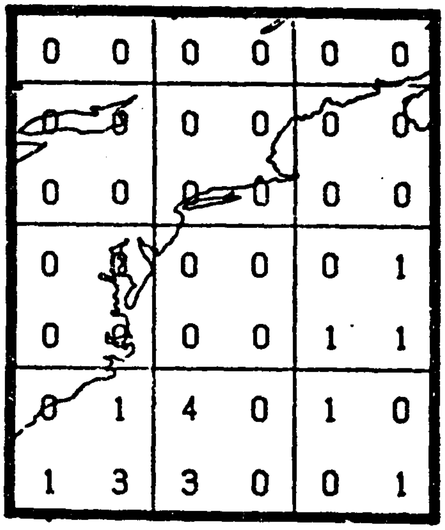
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-49 Percent of Days Tropical Storms Occurred 1899-1969 by 2½ Degree Squares (U.S. Department of Commerce, 1973)



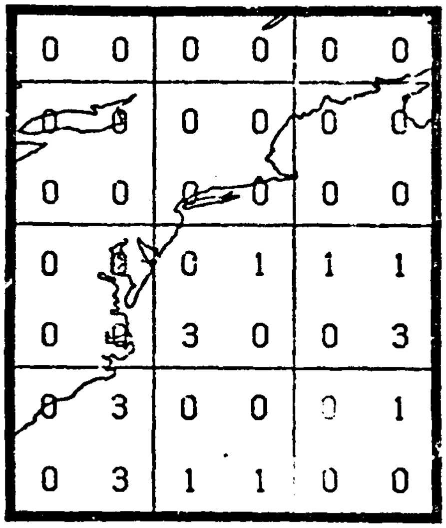
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	1	1	3
0	0	3	0	1	4
0	4	4	0	1	1
1	6	4	1	0	1

All Months



0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	1
0	0	0	0	1	1
0	1	4	0	1	0
1	3	3	0	0	1

October to July

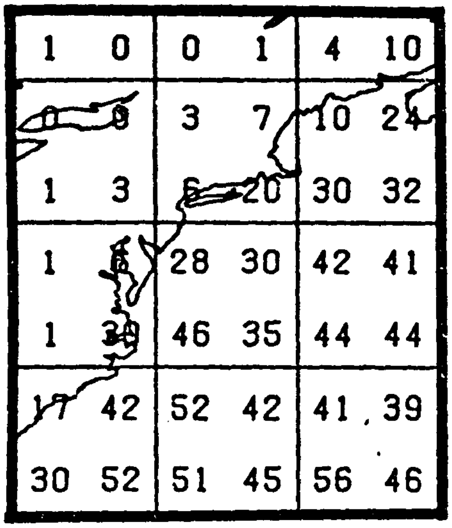


0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	1	1	1
0	0	3	0	0	3
0	3	0	0	0	1
0	3	1	1	0	0

August and September

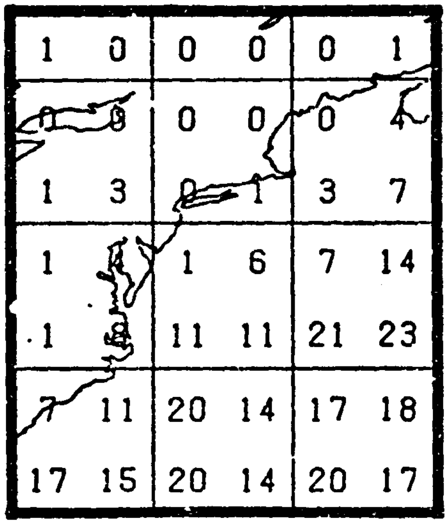
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-50	Percent of Days Hurricanes Originated 1899-1969 by 2½ Degree Squares (U.S. Department of Commerce, 1973)



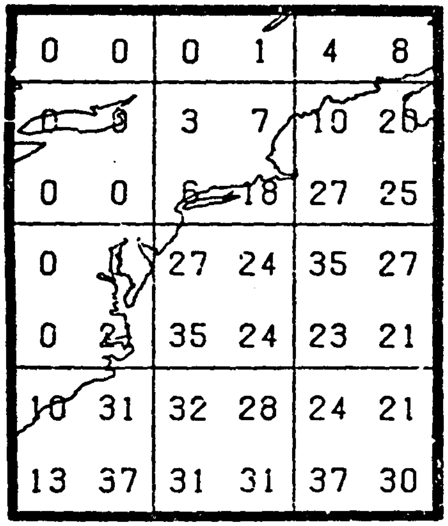
1	0	0	1	4	10
0	0	3	7	10	24
1	3	6	20	30	32
1	6	28	30	42	41
1	30	46	35	44	44
17	42	52	42	41	39
30	52	51	45	56	46

All Months



1	0	0	0	0	1
0	0	0	0	0	4
1	3	0	1	3	7
1	4	1	6	7	14
1	8	11	11	21	23
7	11	20	14	17	18
17	15	20	14	20	17

October to July

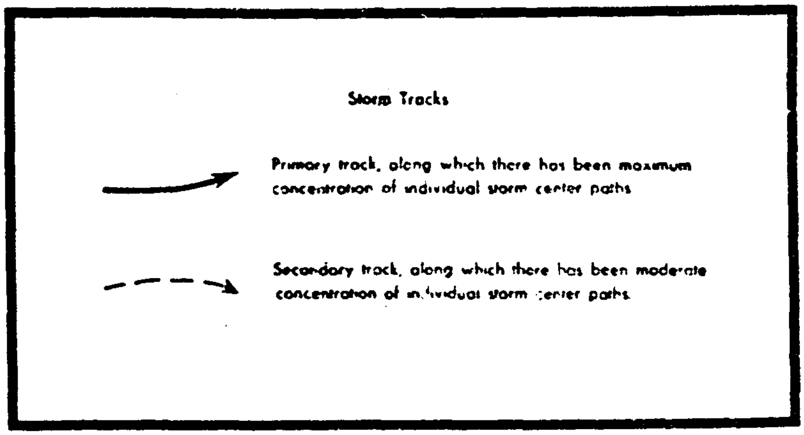


0	0	0	1	4	8
0	0	3	7	10	26
0	0	6	18	27	25
0	1	27	24	35	27
0	21	35	24	23	21
10	31	32	28	24	21
13	37	31	31	37	30

August and September

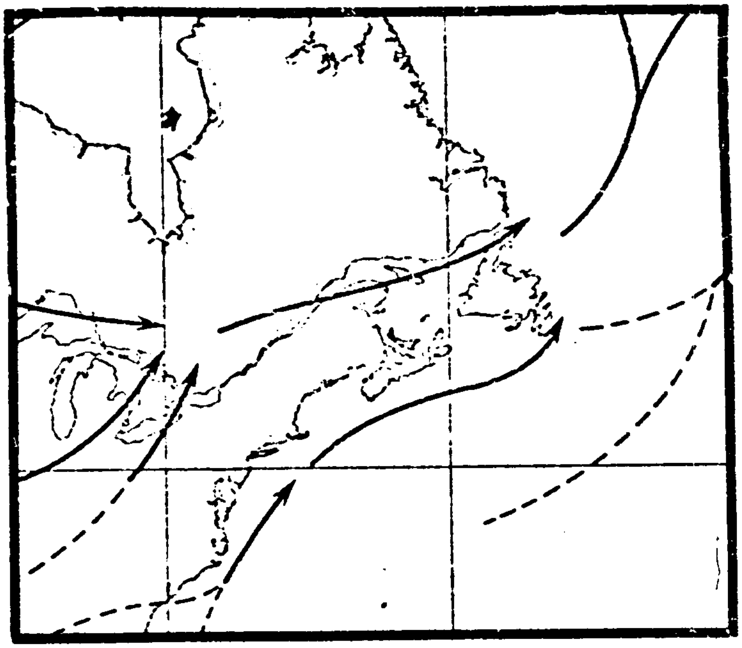
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-51	Percent of Days Hurricanes Occurred 1899-1969 by 2½ Degree Squares (U.S. Department of Commerce, 1973)



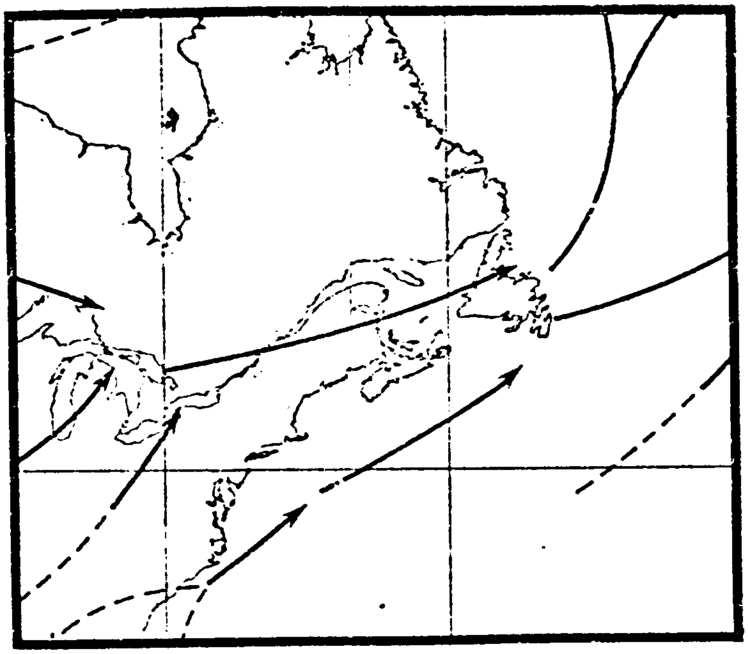
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-52 Key to Storm Track Symbols for U.S. Navy and U.S. Weather Bureau, 1959



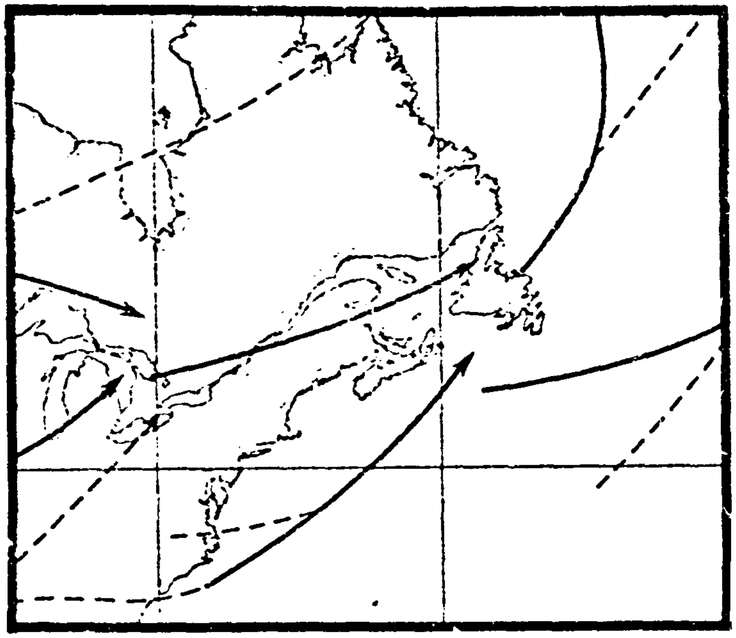
January

February

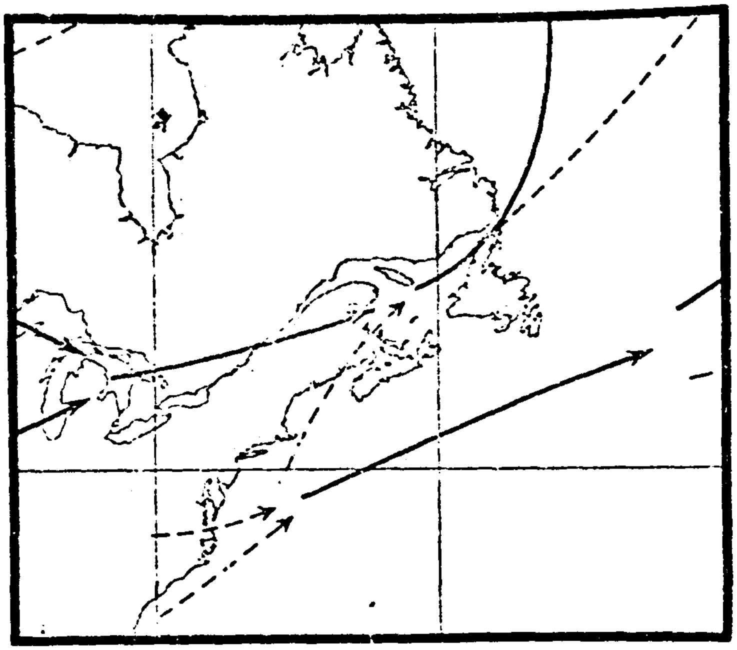


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-53 Storm Tracks (U.S. Navy and U.S. Weather Bureau, 1959)

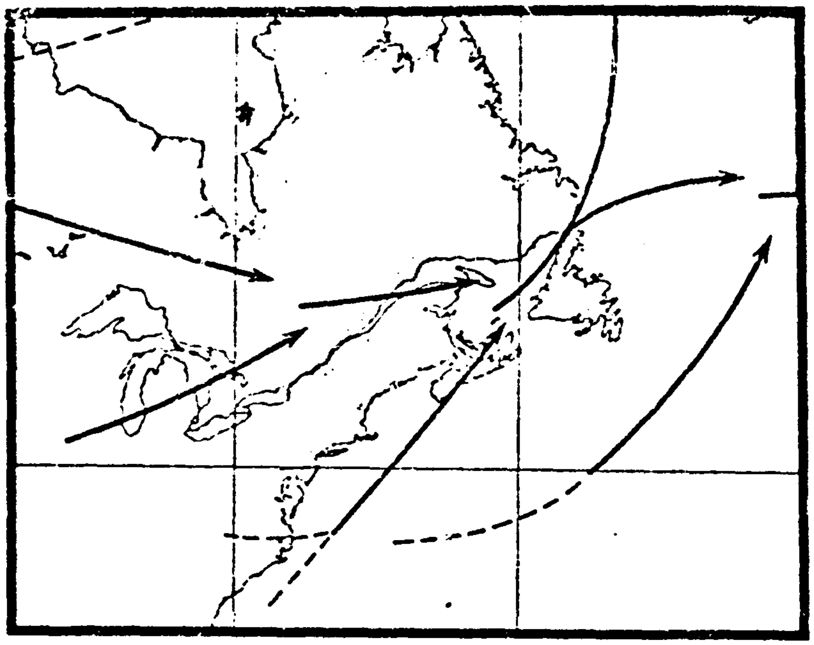


March

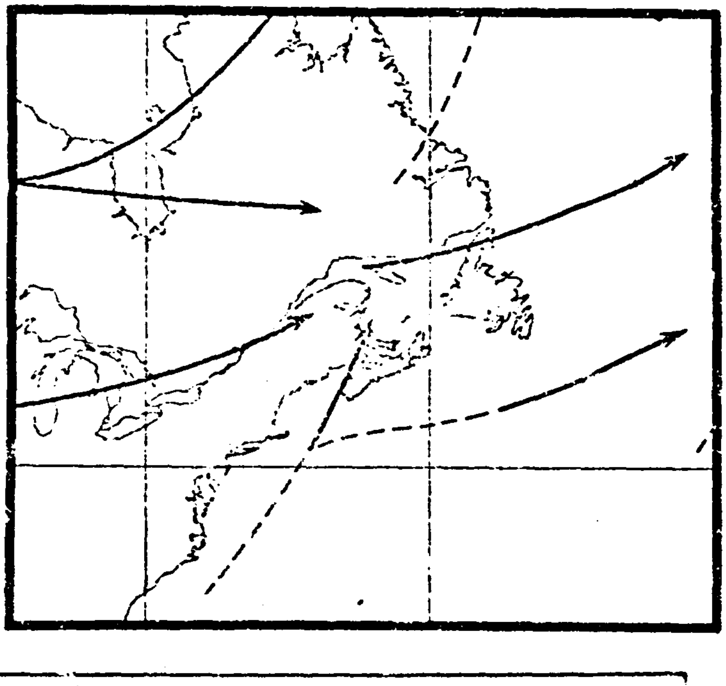


April

FIGURE 3-54 Storm Tracks (U.S. Navy and U.S. Weather Bureau, 1959)



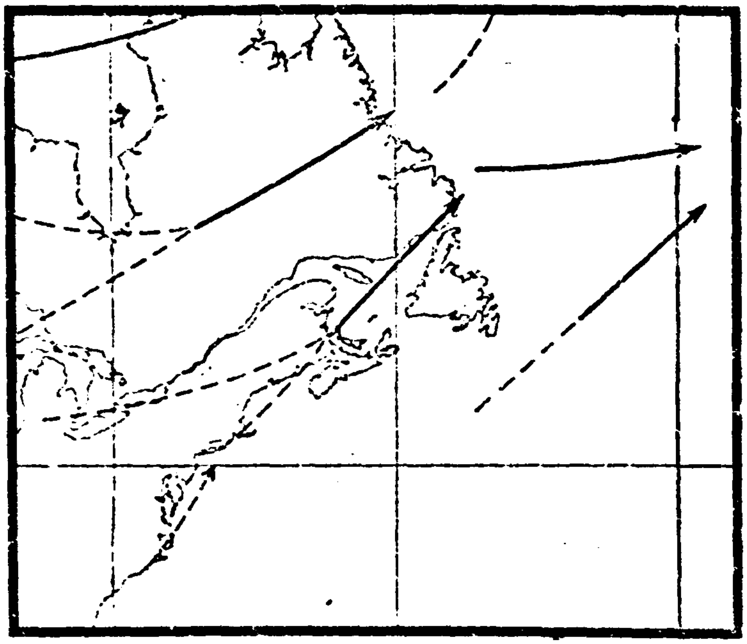
May



June

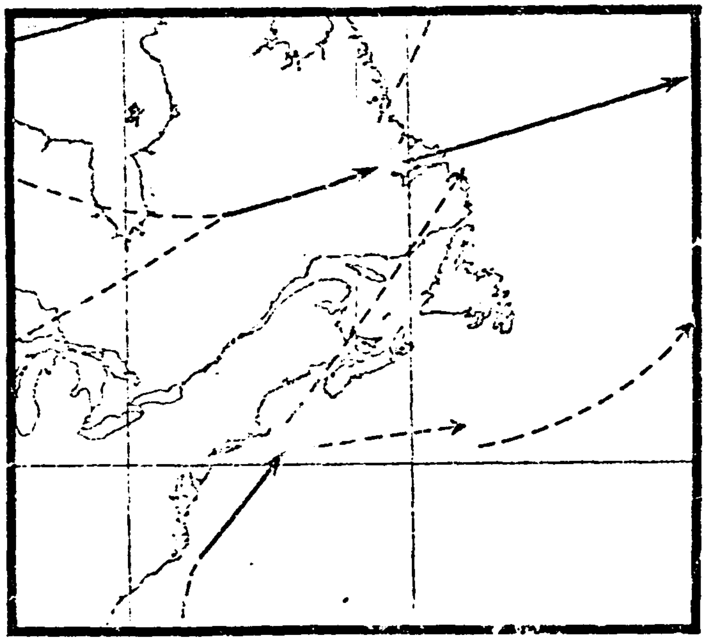
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-55	Storm Tracks (U.S. Navy and U.S. Weather Bureau, 1959)



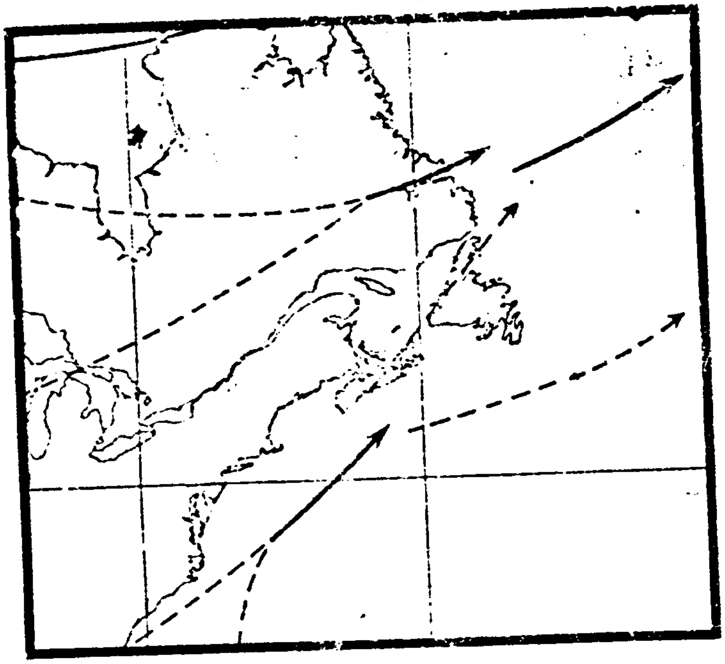
July

August

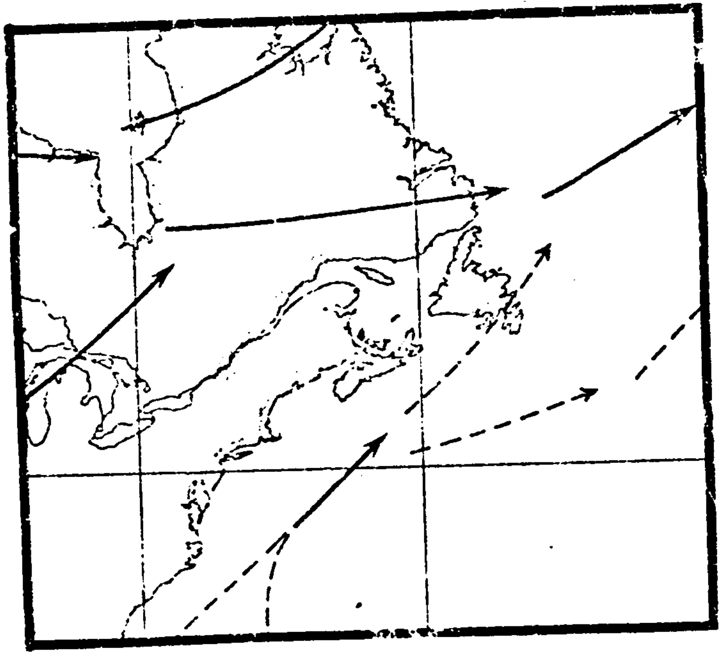


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE [illegible]6 | Storm Tracks (U.S. Navy and U.S. Weather Bureau, 1959)



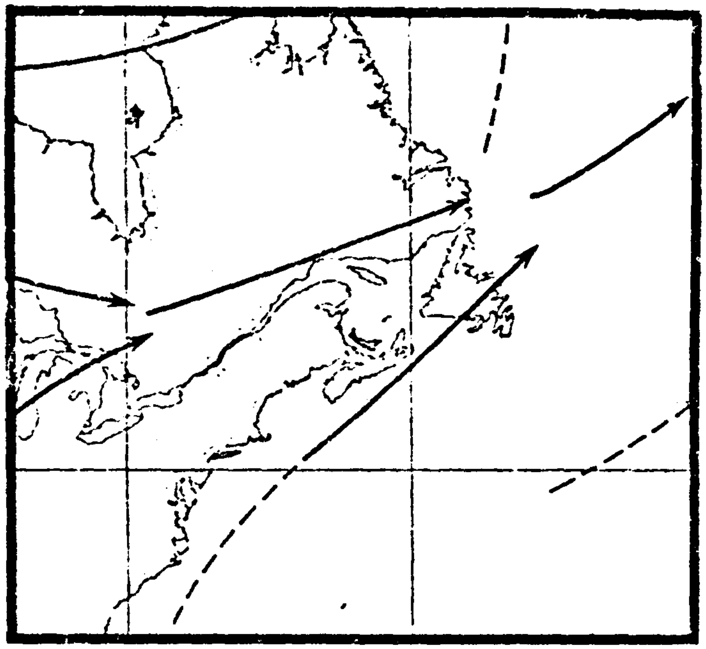
September



October

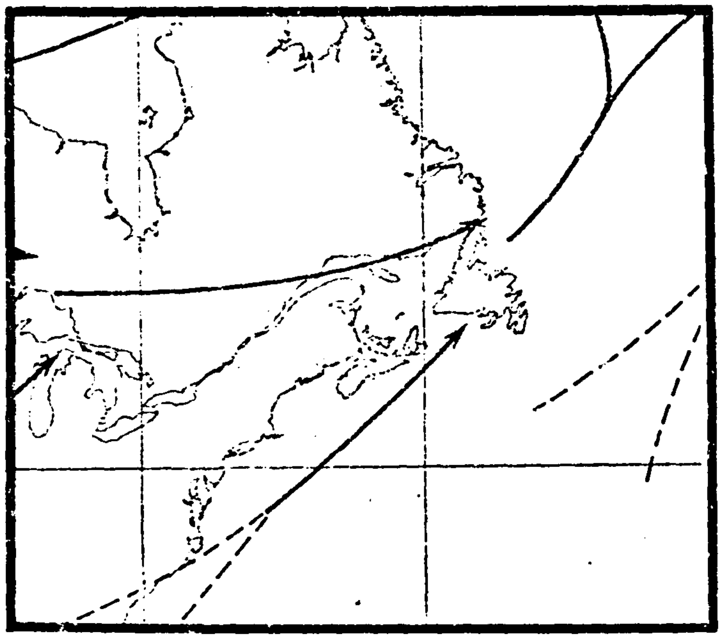
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 3-57 | Storm Tracks (U.S. Navy and U.S. Weather Bureau, 1959)



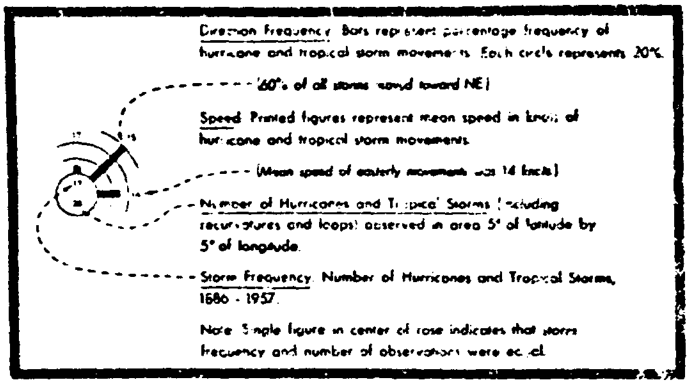
November

December



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-58 Storm Tracks (U.S. Navy and U.S. Weather Bureau, 1959)



Direction Frequency. Bars represent percentage frequency of hurricane and tropical storm movements. Each circle represents 20%.

(60% of all storms moved toward NE)

Speed. Printed figures represent mean speed in knots of hurricane and tropical storm movements.

(Mean speed of easterly movements was 14 knots)

Number of Hurricanes and Tropical Storms (including recurvatures and loops) observed in area 5° of latitude by 5° of longitude.

Storm Frequency. Number of Hurricanes and Tropical Storms, 1886 - 1957.

Note: Single figure in center of rose indicates that storm frequency and number of observations were equal.

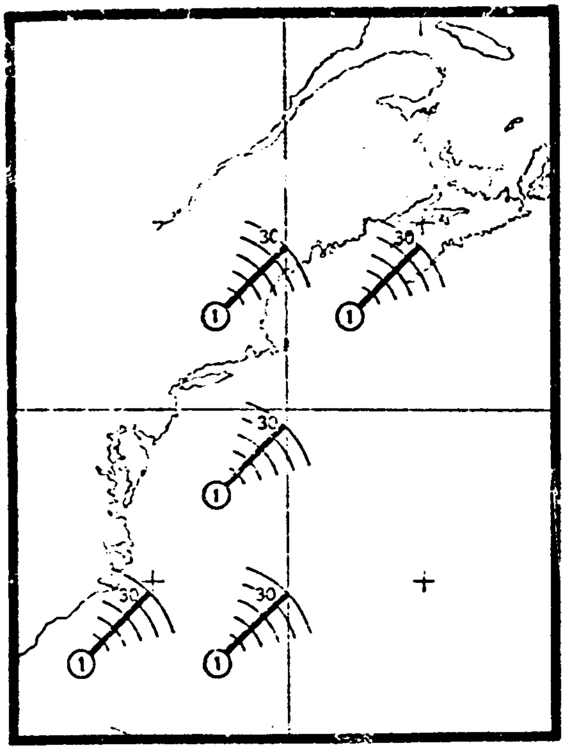
NOTE: Months for which no data are presented are months when no tropical storms or hurricanes traversed the study area. This should notbe taken as a zero storm/hurricane occurrence in the Atlantic Ocean. With the exception of April, storms and hurricanes have occurred somewhere in the Atlantic Ocean every month. No storms or hurricanes were reported for April between 1886 and 1957.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

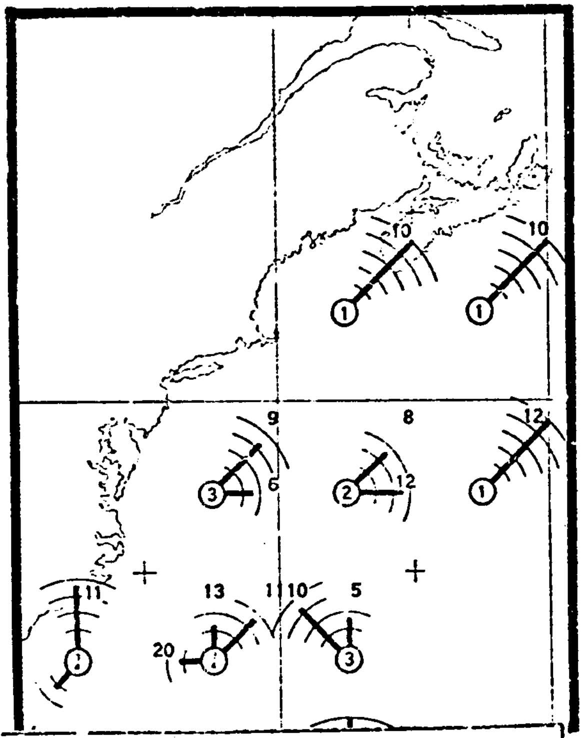
FIGURE 3-59

Key to Tropical Storm and Hurricane Frequency and Paths (U.S. Navy and U.S. Weather Bureau, 1959)



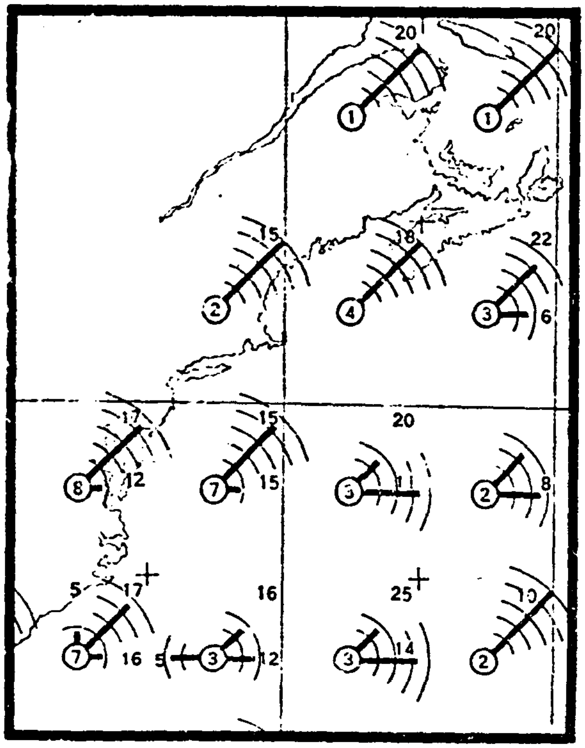
February

May

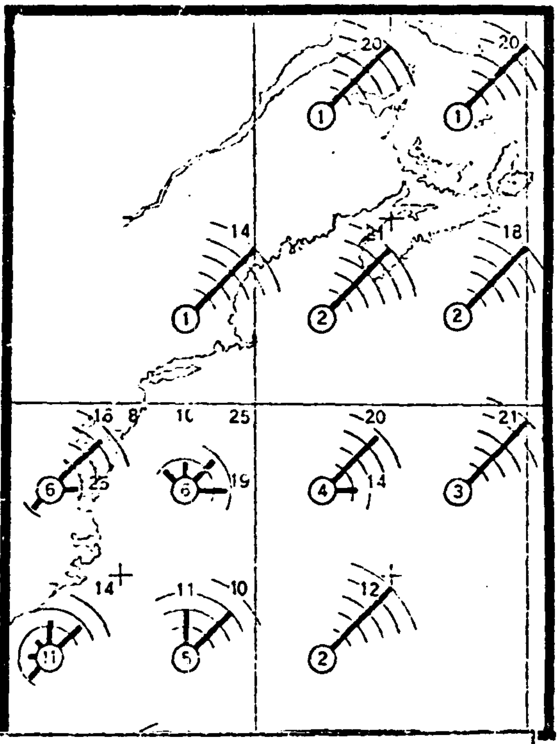


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-60	Tropical Storm and Hurricane Frequencies and Paths (U.S. Navy and U.S. Weather Bureau, 1959)



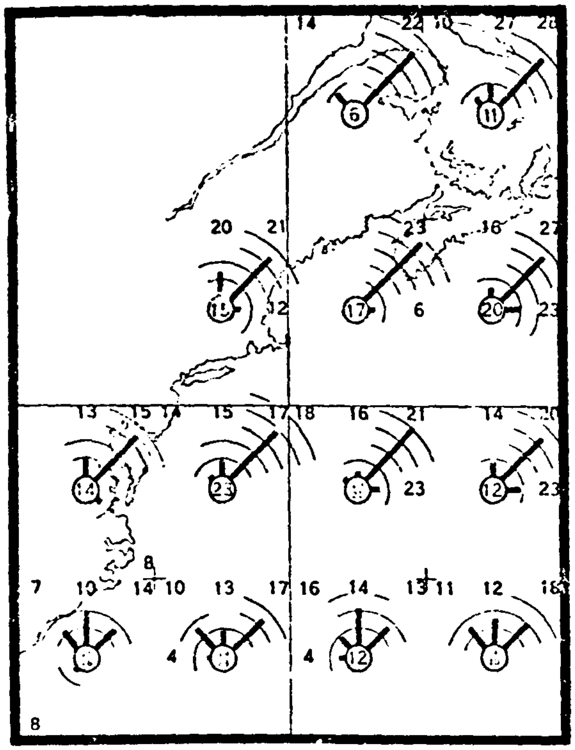
June



July

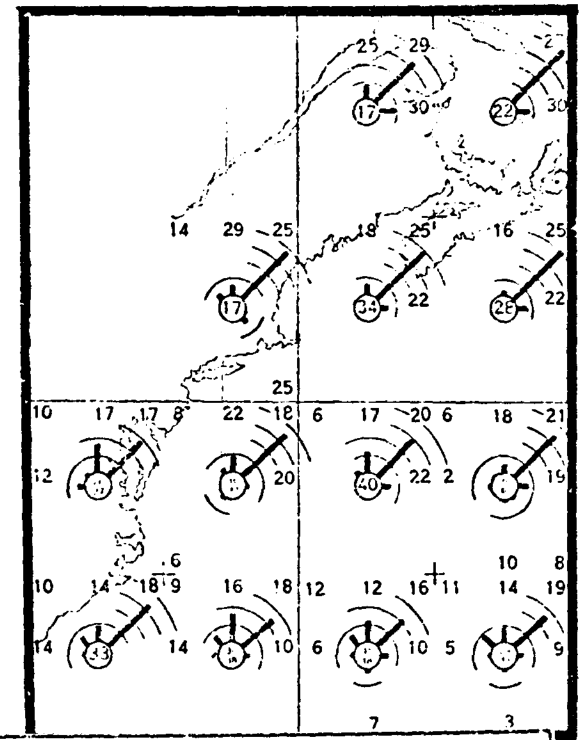
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-61	Tropical Storm and Hurricane Frequencies and Paths (U.S. Navy and U.S. Weather Bureau, 1959)



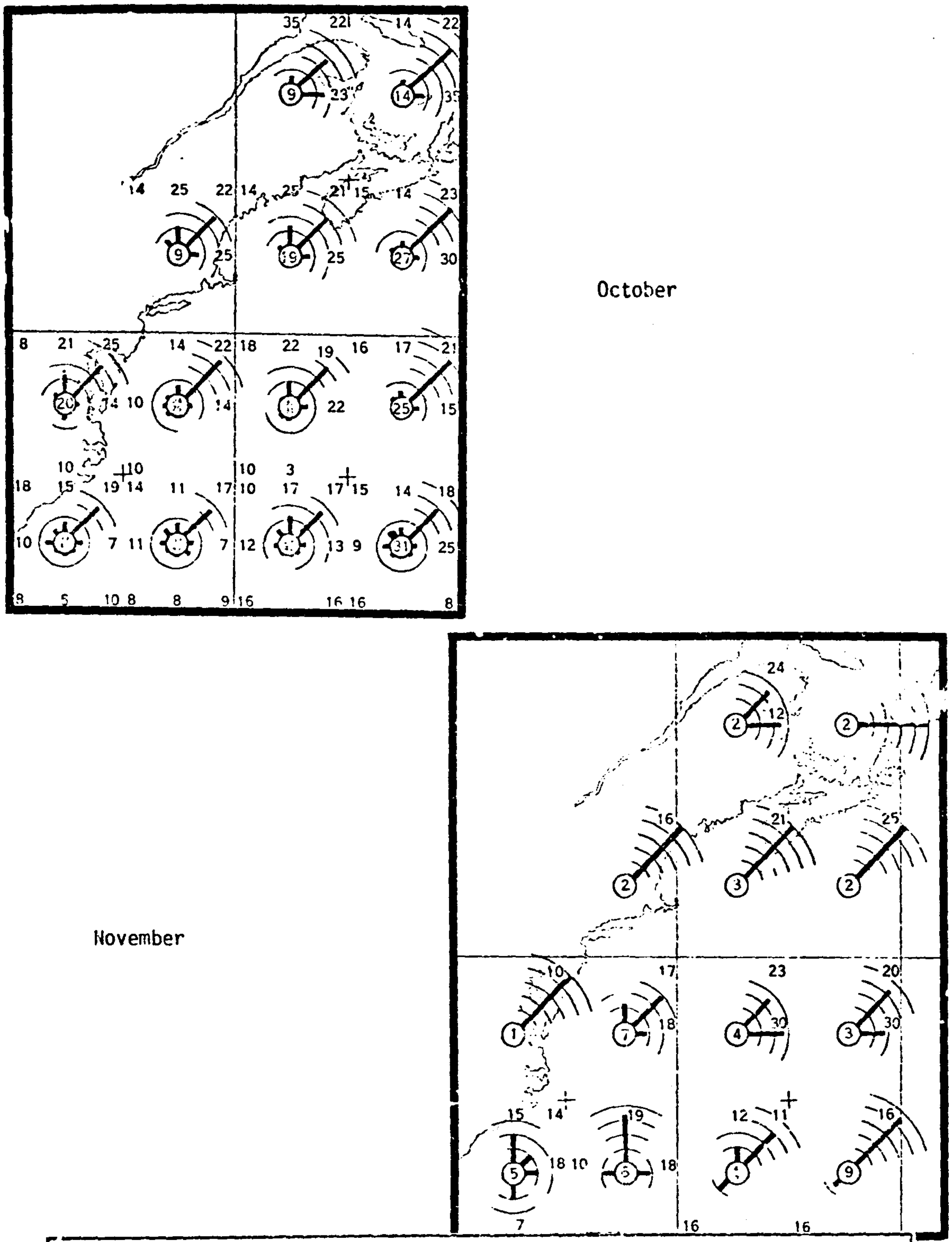
August

September



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

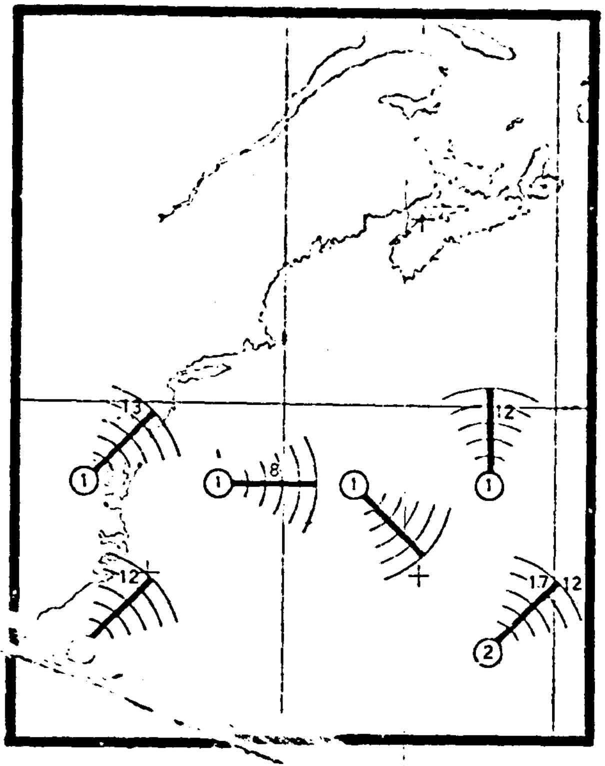
TRIGOM	FIGURE 3-62	Tropical Storm and Hurricane Frequencies and Paths (U.S. Navy and U.S. Weather Bureau, 1959)



October

November

TRIGOM	FIGURE 3-63	Tropical Storm and Hurricane Frequencies and Paths (U.S. Navy and U.S. Weather Bureau, 1959)



December

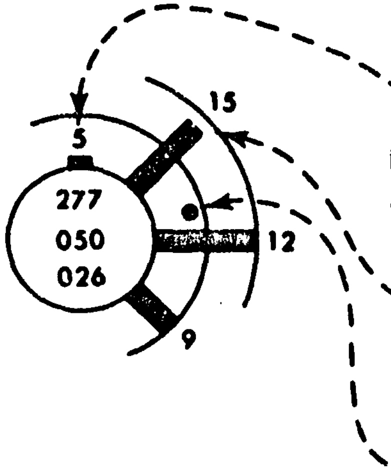
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-64	Tropical Storm and Hurricane Frequencies and Paths (U.S. Navy and U.S. Weather Bureau, 1959)

FIGURE 3-65

Key to Tropical Storm and Hurricane Frequencies and Paths (Crutcher and Quayle, 1974)

12 hourly movements of tropical cyclone centers with tropical storm intensity or greater (wind speed estimated ≥34 knots).



Mean speed: Printed figure at the end of each bar represents the mean speed of movement (in knots) toward the indicated direction.

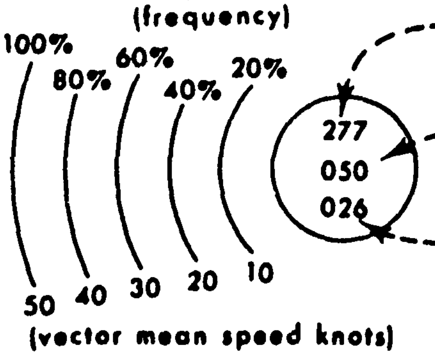
(Centers moving toward the N had a mean speed of 5 knots.)

Direction frequency: Bars represent percentage frequency of centers that moved toward each direction. Each circle represents 20%.

(35% of all tropical cyclones moved toward the NE.)

Vector mean direction and speed: Dot indicates mean vector movement. Each circle equals 10 knots.

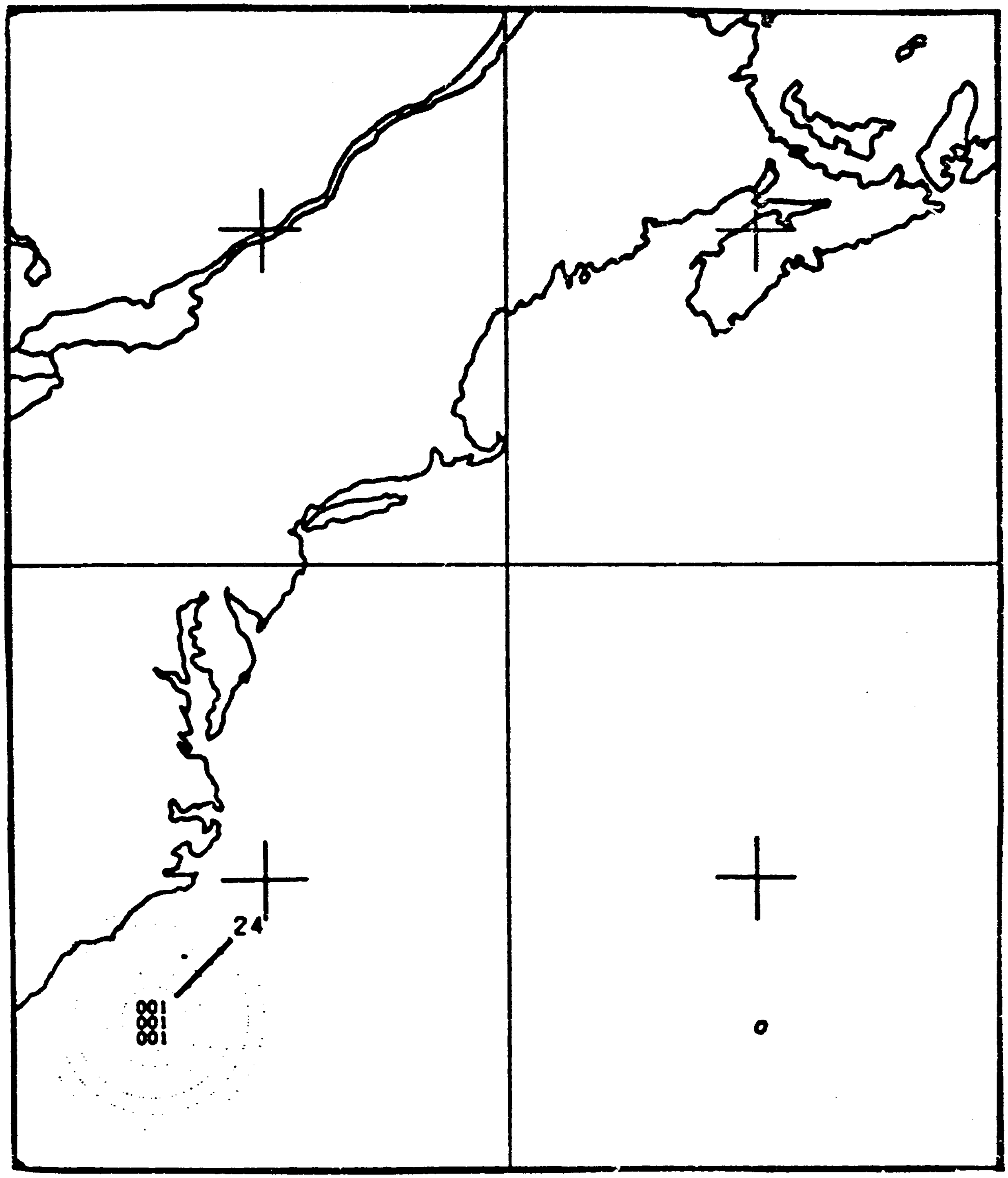
(Mean vector movement of all centers was toward 75° at 7 knots.)



Statistics for this rose are based on 277 twelve hour movements.

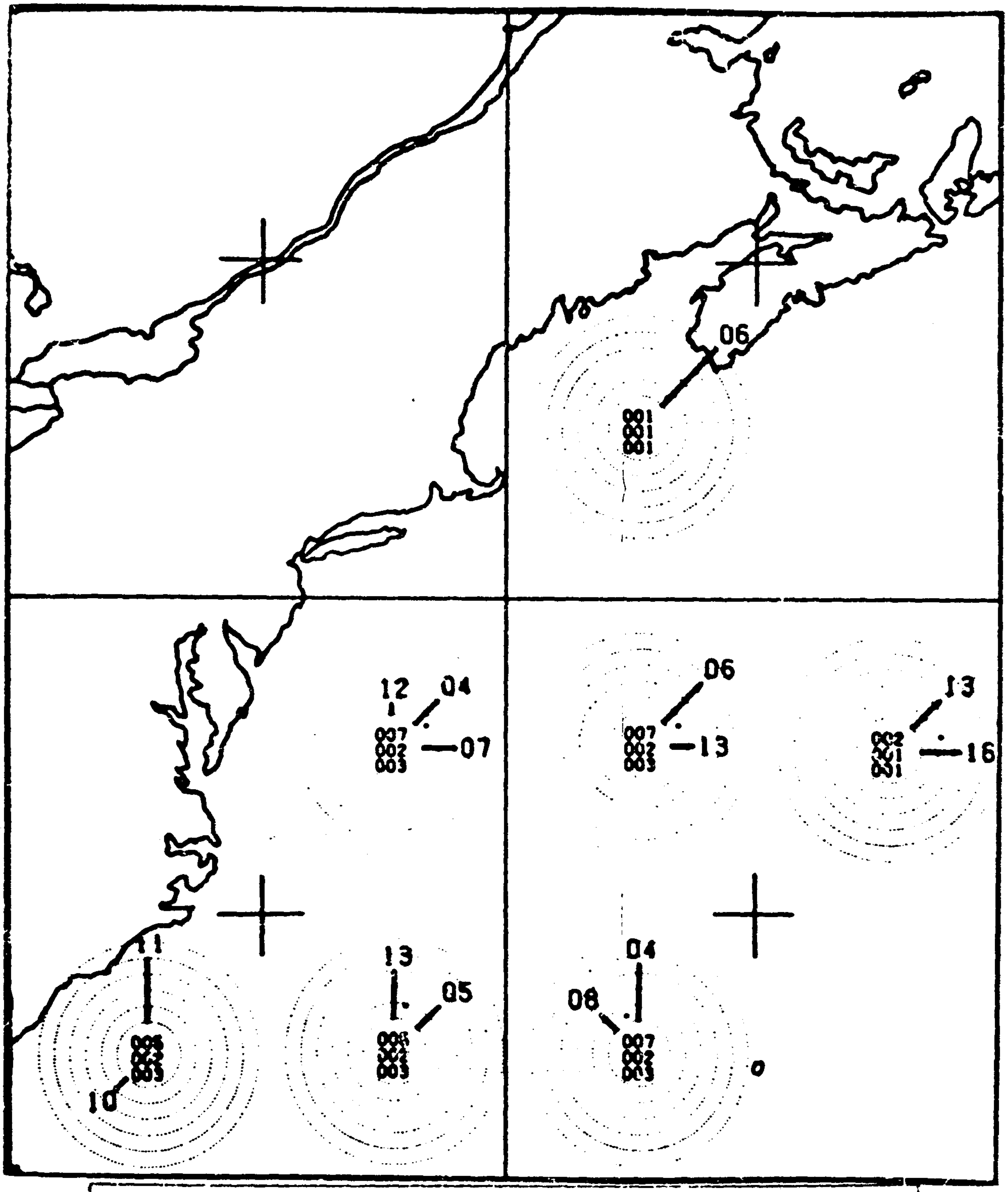
50 individual storms were observed in the 5° X 5° area during the period of record.

Probability of having at least one tropical cyclone in this area in any given year for this month is 26%.



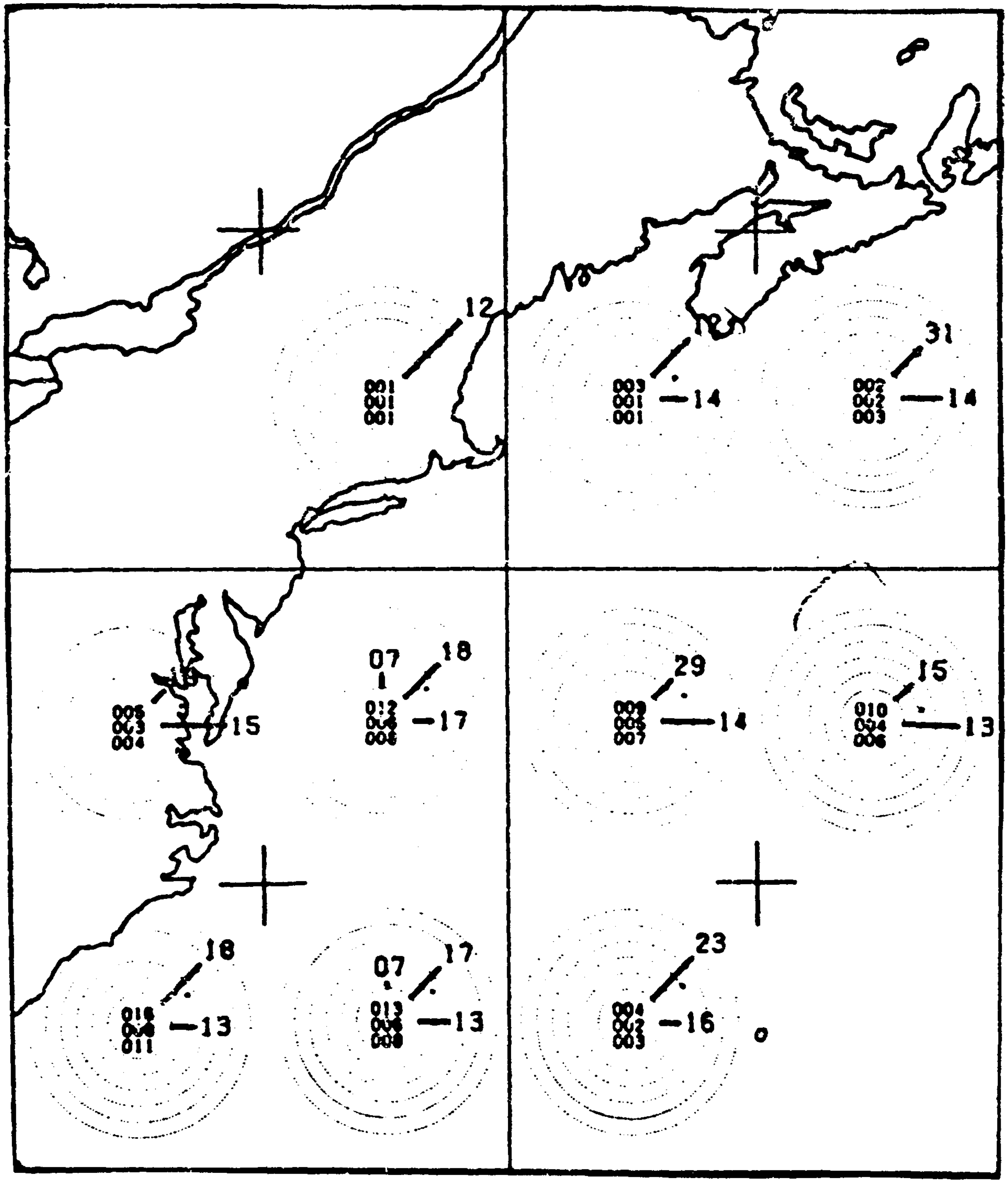
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-66a	Tropical Storm and Hurricane Frequencies and Paths, February (Crutcher and Quayle, 1974)



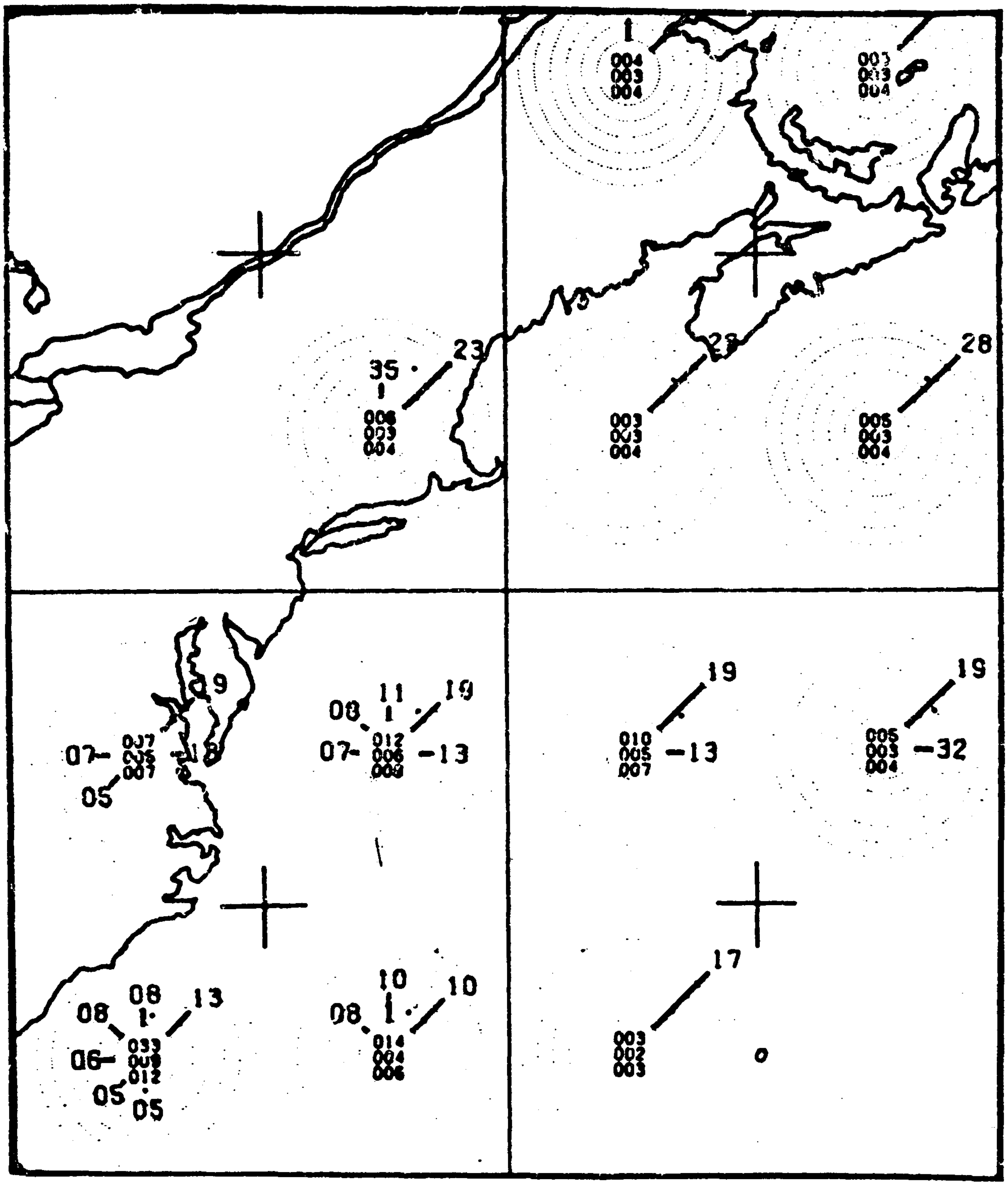
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-66b	Tropical Storm and Hurricane Frequencies and Paths, May (Crutcher and Quayle, 1974)



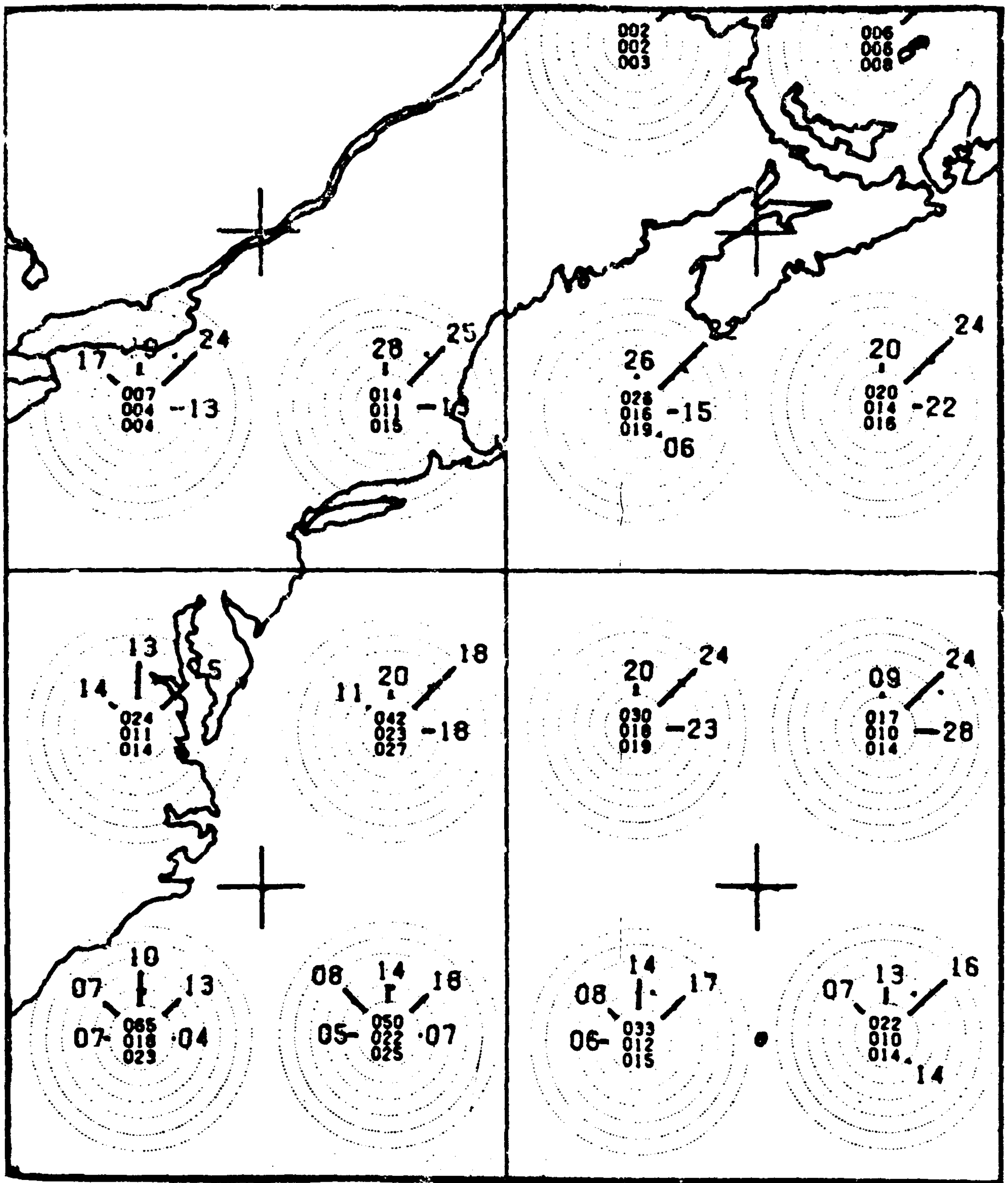
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-67a	Tropical Storm and Hurricane Frequencies and Paths, June (Crutcher and Quayle, 1974)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-67b	Tropical Storm and Hurricane Frequencies and Paths, July (Crutcher and Quayle, 1974)

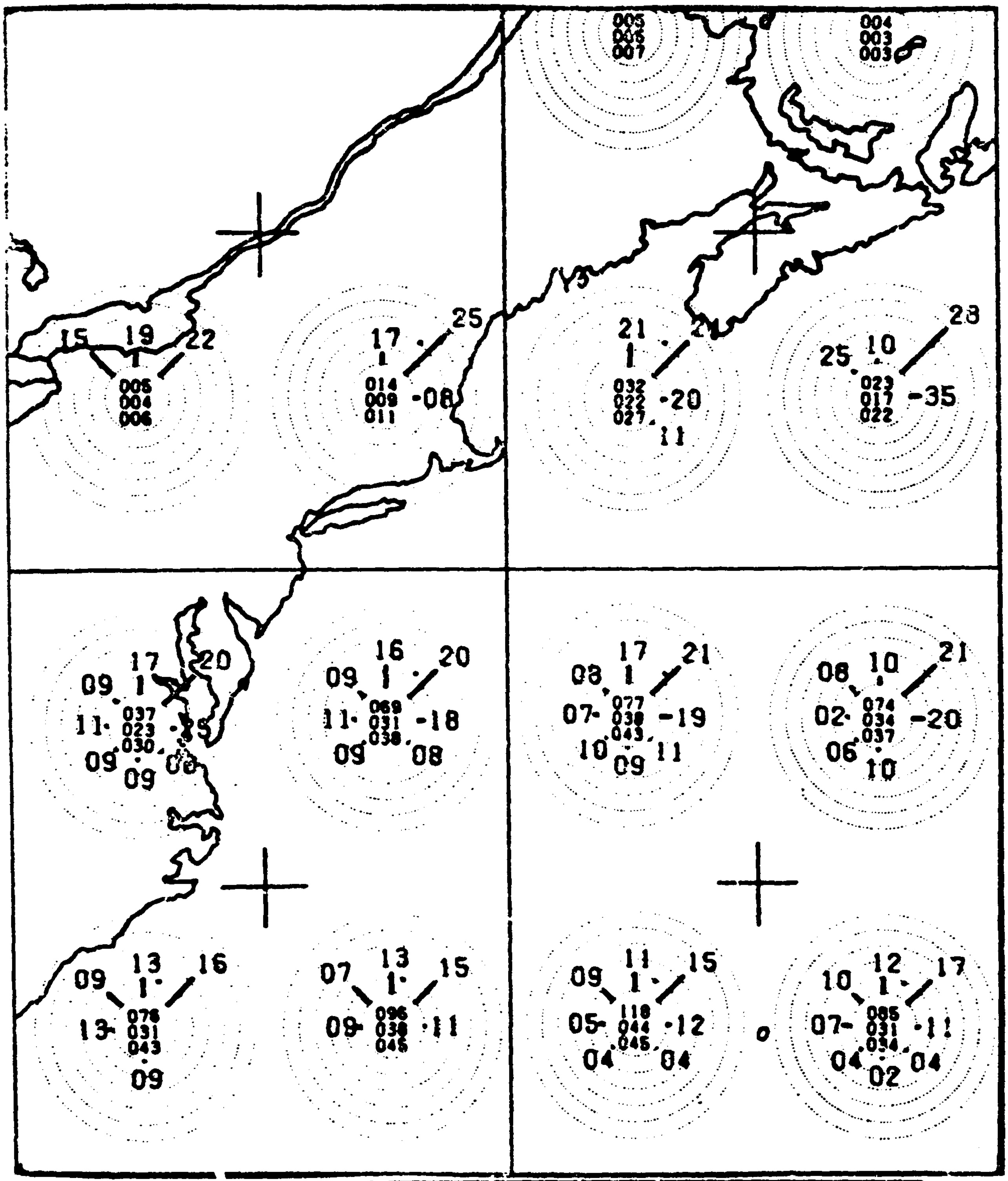


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

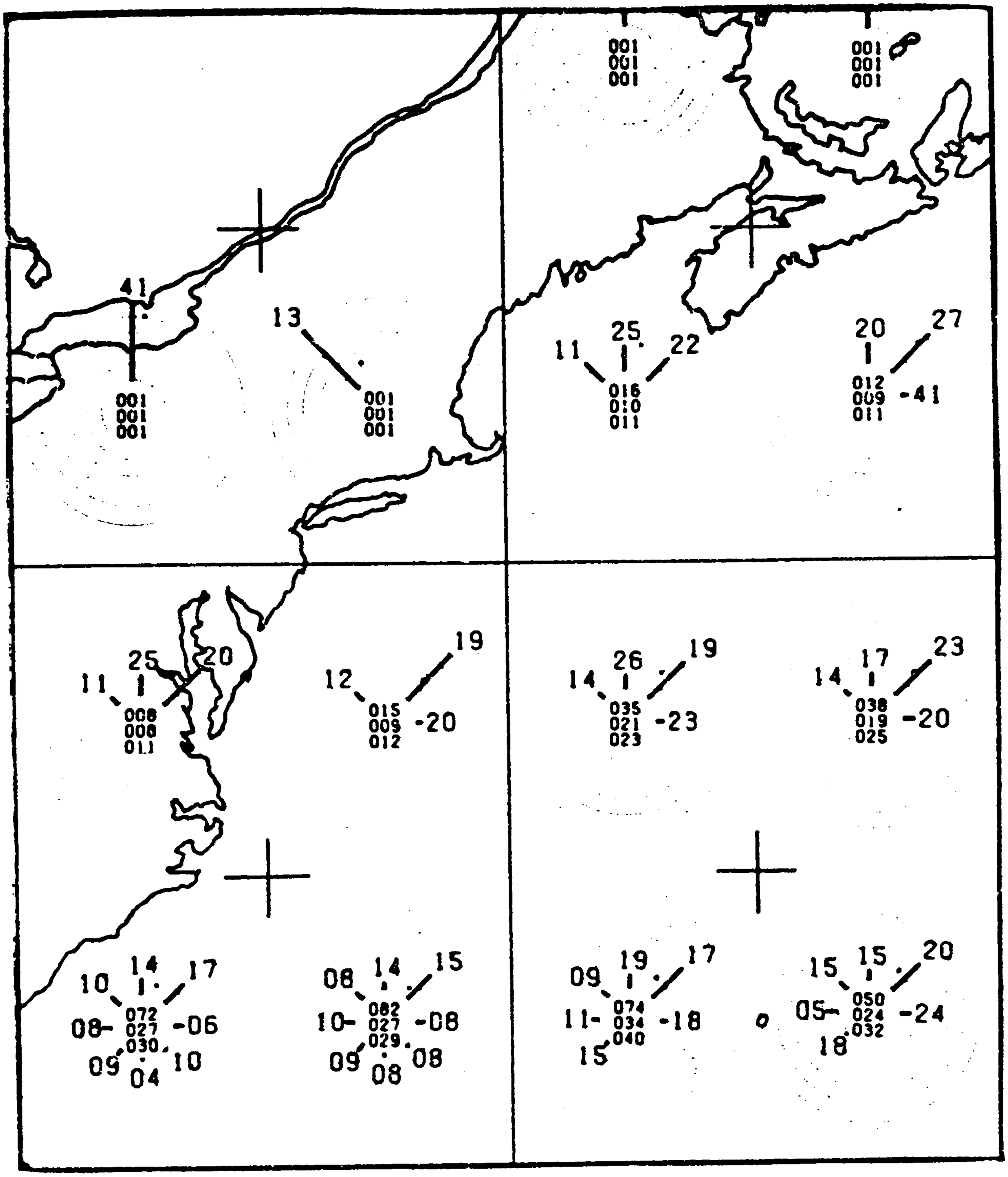
FIGURE 3-68a

Tropical Storm and Hurricane Frequencies and Paths, August (Crutcher and Quayle, 1974)



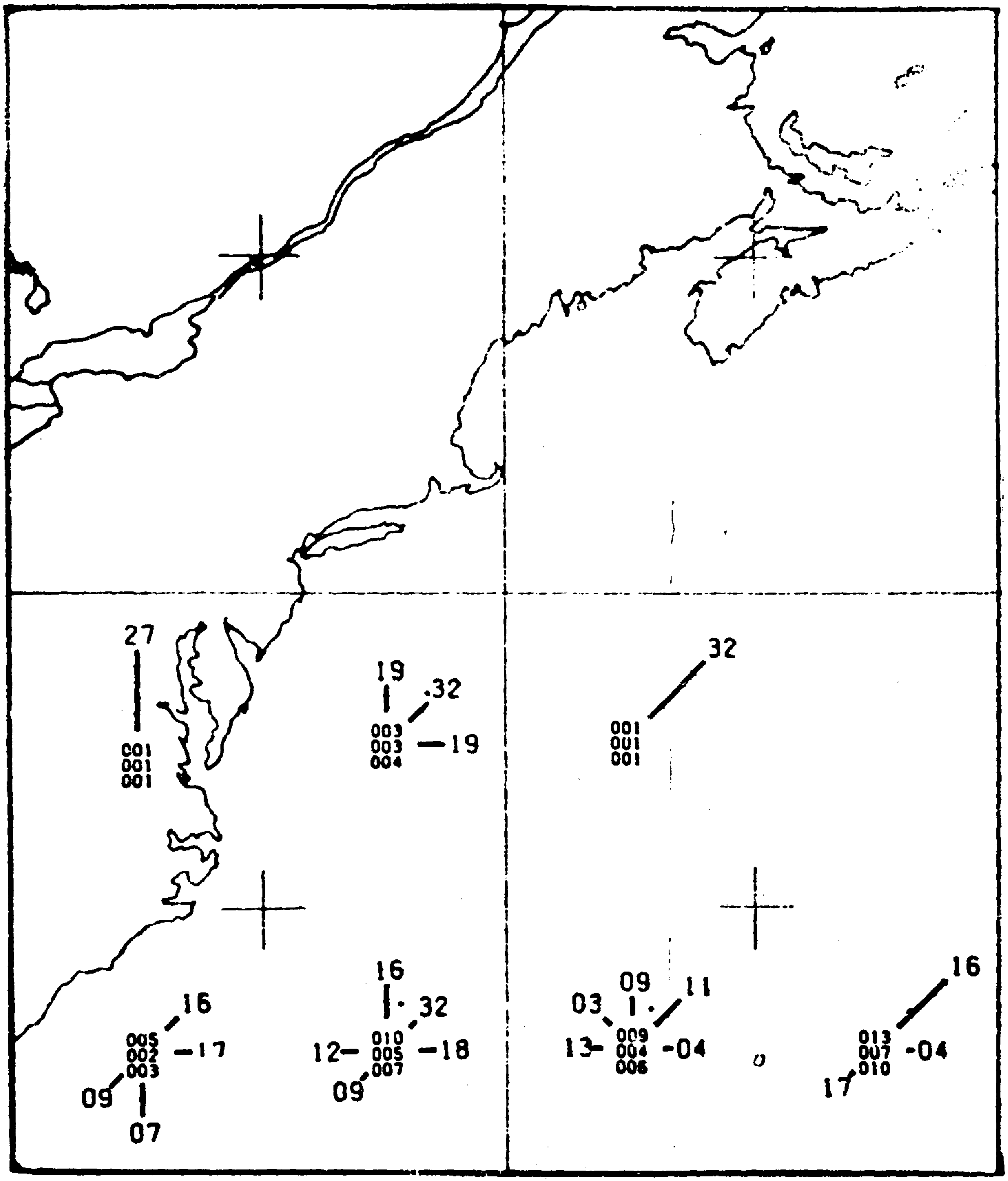
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-68b	Tropical Storm and Hurricane Frequencies and Paths, September (Crutcher and Quayle, 1974)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 3-69a | Tropical Storm and Hurricane Frequencies and Paths, October (Crutcher and Quayle, 1974)

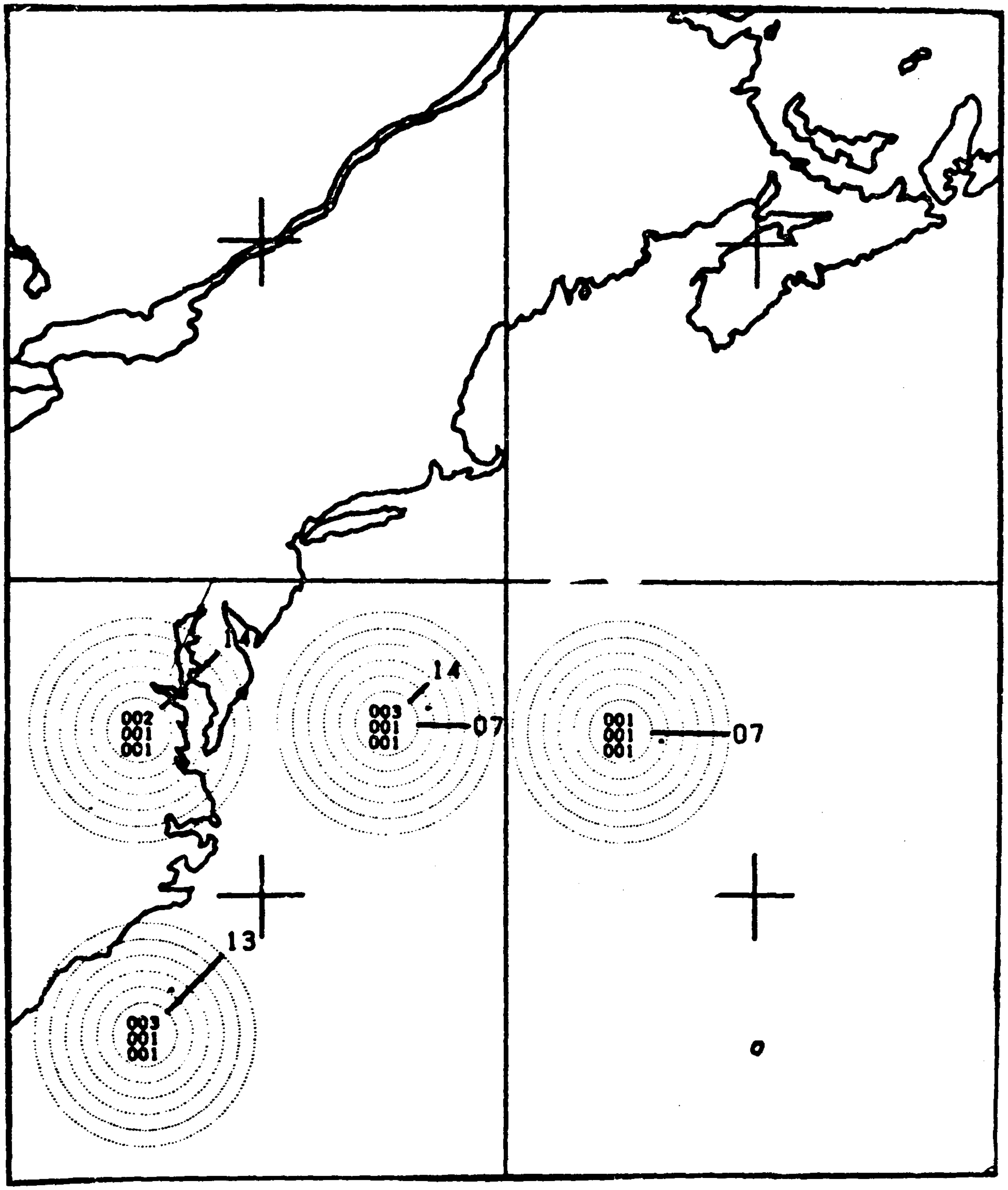


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

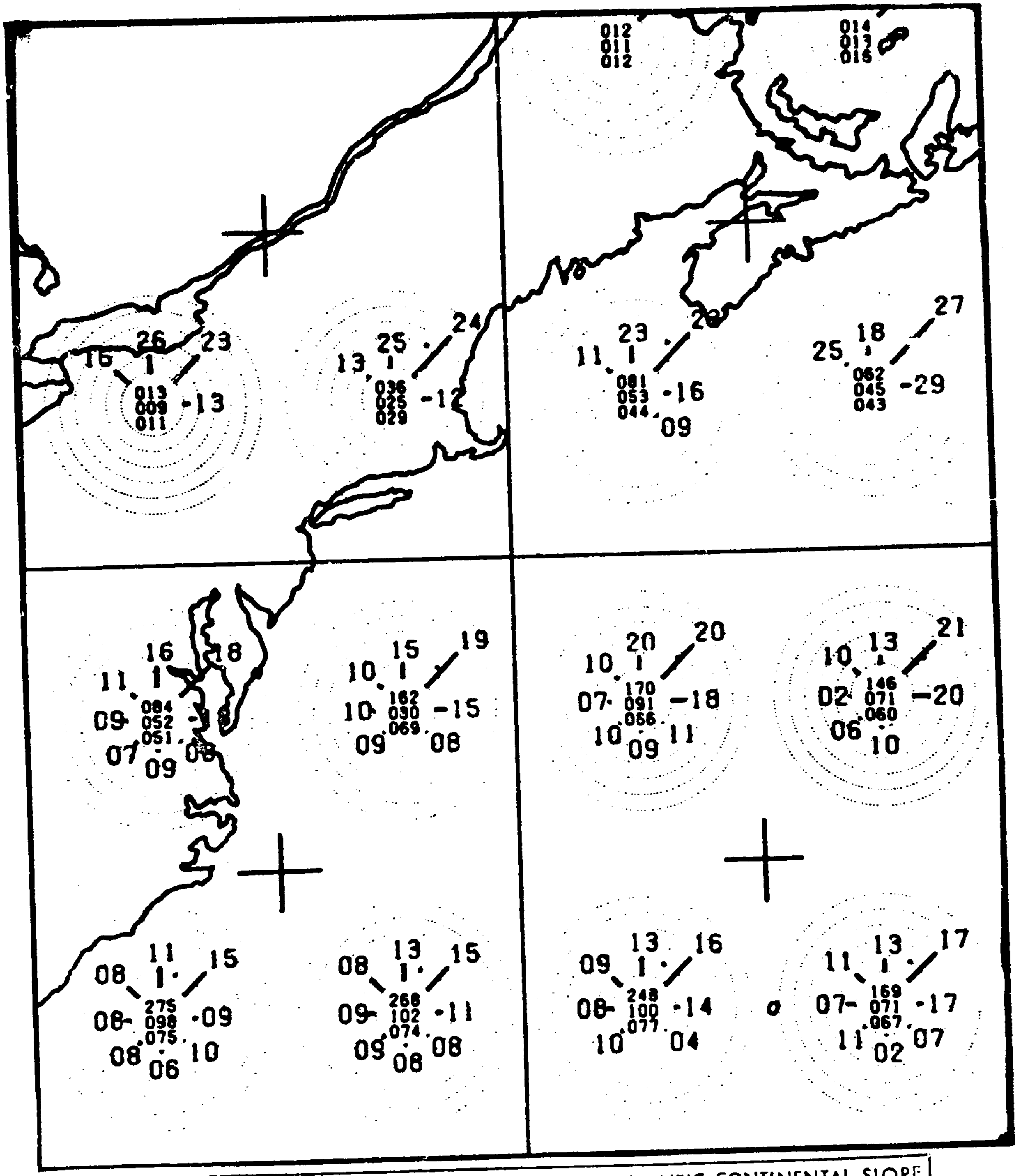
FIGURE 3-69b

Tropical Storm and Hurricane Frequencies and Paths, November (Crutcher and Quayle, 1974)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-70a	Tropical Storm and Hurricane Frequencies and Paths, December (Crutcher and Quayle, 1974)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-70b	Tropical Storm and Hurricane Frequencies and Paths, Annual (Crutcher and Quayle, 1974)

Table 3-4. North Atlantic tropic cyclone damage (in dollars) (Hebert, 1974)

Year	Total Tropical Cyclones	Total Hurricanes	Loss of Life (U.S.)	Approximate Damage Value
1931	2	0	0	
1932	5	2	0	
1933	7	5	63	$5,000,000 to 50,000,000
1934	5	3	17	$500,000 to 5,000,000
1935	2	2	414	$5,000,000 to 50,000,000
1936	7	3	9	$500,000 to 5,000,000
1937	4	0	0	$5,000 to 50,000
1938	4	2	600	$50,000,000 to 500,000,000
1939	3	1	3	$500 to 5,000
1940	3	2	51	$500,000 to 5,000,000
1941	4	2	10	$5,000,000 to 50,000,000
1942	3	2	8	$5,000,000 to 50,000,000
1943	4	1	16	$5,000,000 to 50,000,000
1944	4	3	64	$50,000,000 to 500,000,000
1945	5	3	7	$50,000,000 to 500,000,000
1946	4	1	0	$5,000,000 to 50,000,000
1947	7	3	53	$50,000,000 to 500,000,000
1948	4	3	3	$5,000,000 to 50,000,000
1949	3	2	4	$50,000,000 to 500,000,000
1950	4	3	19	$5,000,000 to 50,000,000
1951	1	0	0	$500,000 to 5,000,000
1952	2	1	3	$500,000 to 5,000,000
1953	6	2	2	$5,000,000 to 50,000,000
1954	4	3	193	$500,000,000 to 5,000,000,000
1955	5	3	218	$500,000,000 to 5,000,000,000
1956	2	1	21	$5,000,000 to 50,000,000
1957	5	1	395	$50,000,000 t0 500,000,000
1958	1	0	2	$5,000,000 to 50,000,000
1959	7	3	24	$5,000,000 to 50,000,000
1960	5	2	65	$50,000,000 to 500,000,000
1961	3	1	46	$50,000,000 to 500,000,000
1962	1	0	4	$500,000 to 5,000,000
1963	1	1	11	$5,000,000 to 50,000,000
1964	6	4	49	$500,000,000 to 5,000,000,000
1965	2	1	75	$500,000,000 to 5,000,000,000
1966	2	2	54	$5,000,000 to 50,000,000
1967	2	1	18	$50,000,000 to 500,000,000
1968	3	1	39	$5,000,000 to 50,000,000
1969	3	2	256	$500,000,000 to 5,000,000,000
1970	4	1	11	$50,000,000 to 500,000,000
1971	5	3	8	$50,000,000 to 500,000,000
1972	3	1	121	$500,000,000 to 5,000,000,000
1973	1	0	5	$5,000,000 to 50,000,000

3.2.8 SEA STATE

Sea state, although obviously a phenomena closely associated with physical oceanography, is primarily the result of, and therefore closely related to, atmospheric conditions. Sea state is discussed in the chapter on Physical Oceanography (Chapter 4.0) and also will be treated here by the presentation of three sets of data.

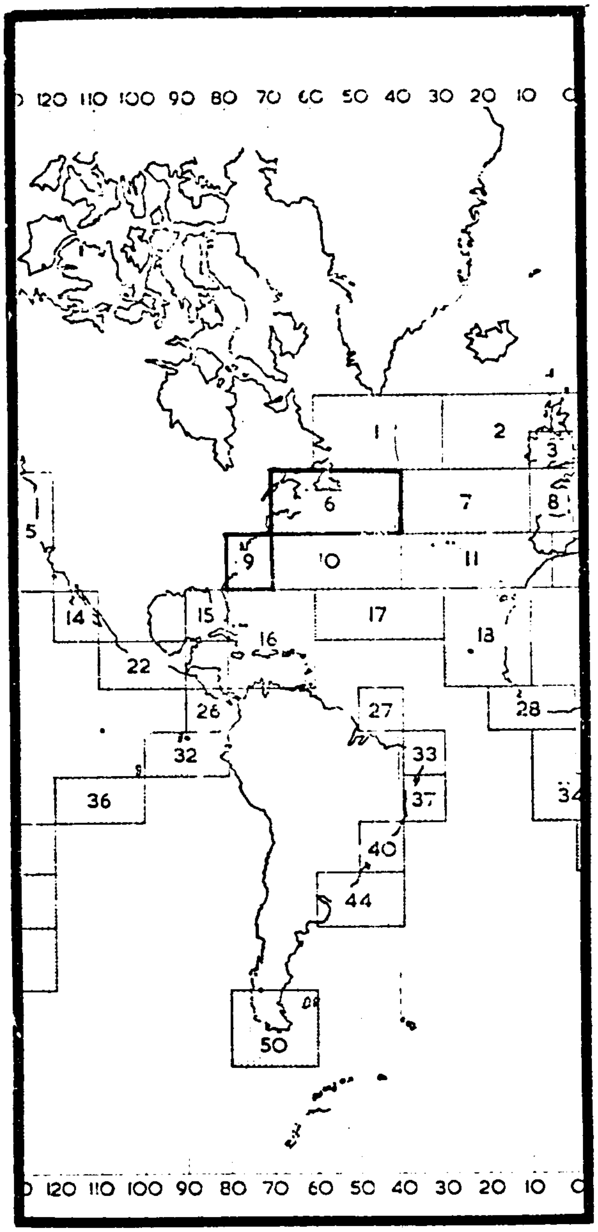
Hogben and Lumb (1967) have produced, in tabular form, wave height and period summaries for a number of ocean areas. The data are averaged within each area shown in Figure 3-71 and are presented here for areas 6 and 9 (Figures 3-73 to 3-76). The U.S. Department of Commerce (1973) has prepared graphs of wave height, period, and period-direction for a number of U.S. coastal areas (Figures 3-77). We have used their data from areas 1 and 2 which includes the study region (Figures 3-79, 3 80). Finally, sea rose data are presented for the northwest Atlantic (U.S. Dept. of Commerce, 1973) in Figures 3-81 and 3-82. All of the above are presented seasonally. Sea rose data were only available in the original document by the months of February, May, August, and November.

The data (Figures 3-73 to 3-76) from Hogben and Lumb's areas 6 and 9, include the slope but are not specific to it. Many qualifications exist regarding the data, perhaps the most stringent being the lack of continuous monitoring in specific areas to accumulate a solid data base and a possible fair weather bias.

Almost all wave observations fall under Hogben and Lumb's Wave Height Code 19 (9.5 m) and, in fact, most are below Wave Height Code 9 (4.5 m). Wave period data show the majority of intervals between wave cap passage as being under Wave Period Code 6 (12 or 13 seconds). In other words, the majority of waves observed were under 4.5 m in height with an interval of 13 seconds or less lapsing between the passage of wave peaks. Weather data for September and October, the months of highest hurricane-tropical storm incidence, do not readily correlate with any change in wave-period-height; this may be the result of a fair weather bias in the data base itself.

From December through February, the majority of wave height observations in area 6 were between 1.5 and 2.5 m with periods falling primarily between 5 (or less) and 9 seconds. During the same time span in area 9, wave height observations were primarily from one to two with wave periods remaining in the 5 (or less) to 9 second range.

During March through May, area 6 wave height observations remained approximately the same as those for the previous three months. The majority of wave heights in area 6 are recorded as being between one and 2.5 m with most wave periods staying at 5 (or less) to 9 seconds. In area 9, wave height seems somewhat lower than in the previous three months with the majority of observations falling between one and 1.5 m with a commensurate reduction in wave period to between 5 (or less) and 7 seconds.



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

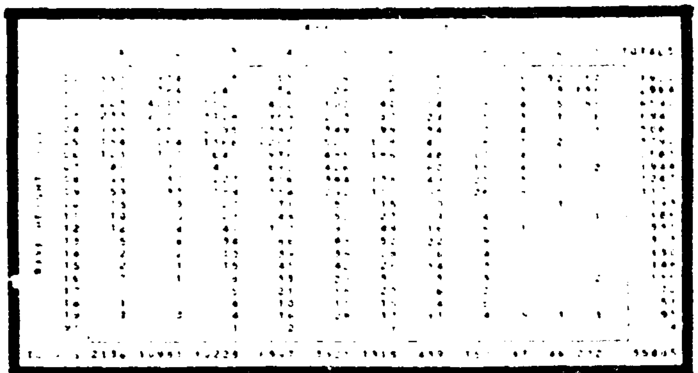
TRIGOM	FIGURE 3-71	Sea State: Statistical Areas (Hogben and Lumb, 1967)

WAVE HEIGHT CODE	WAVE HEIGHT FEET	WAVE HEIGHT METRES
00	1	0·25
01	1·5	0·5
02	3	1
03	5	1·5
04	6·5	2
05	8	2·5
06	9·5	3
07	11	3·5
08	13	4
09	14	4·5
10	16	5
11	17·5	5·5
12	19	6
13	21	6·5
14	22·5	7
15	24	7·5
16	25·5	8
17	27	8·5
18	29	9
19	30·5	9·5
90	33	10
91	36	11
92	39	12
93	43	13
94	46	14
95	49	15
96	52	16
97	56	17
98	59	18
99	62	19

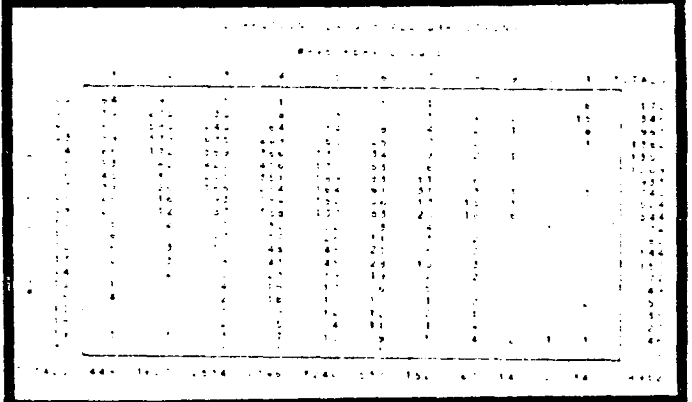
WAVE PERIOD CODE	WAVE PERIOD SECONDS
X	Calm or period undetermined
2	5 or less
3	6 or 7
4	8 or 9
5	10 or 11
6	12 or 13
7	14 or 15
8	16 or 17
9	18 or 19
0	20 or 21
1	Over 21

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

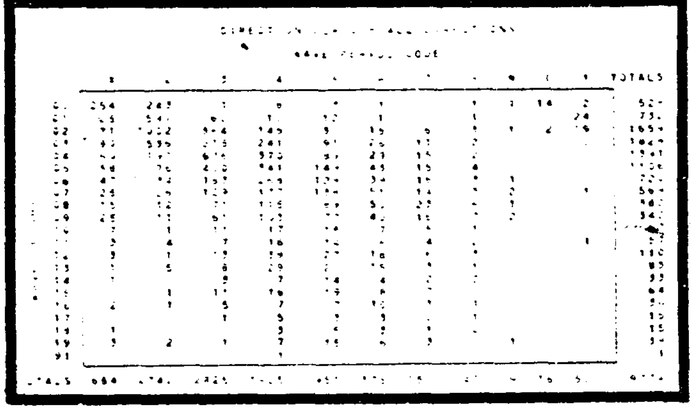
TRIGOM FIGURE 3-72 Key to Wave Height and Wave Period Codes (Hogben and Lumb, 1967)



Area 6 Annual Summary



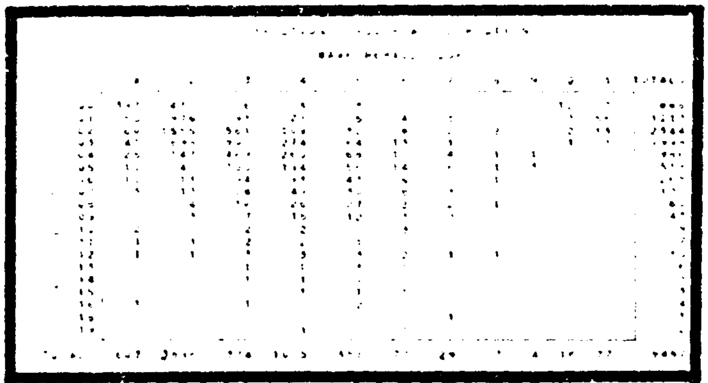
Area 6 December - February



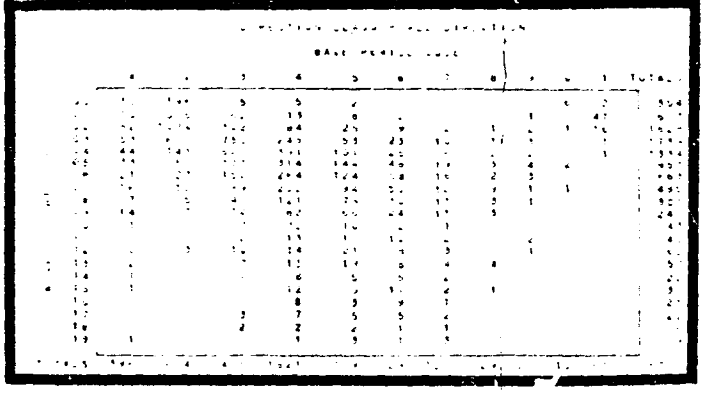
Area 6 March - May

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

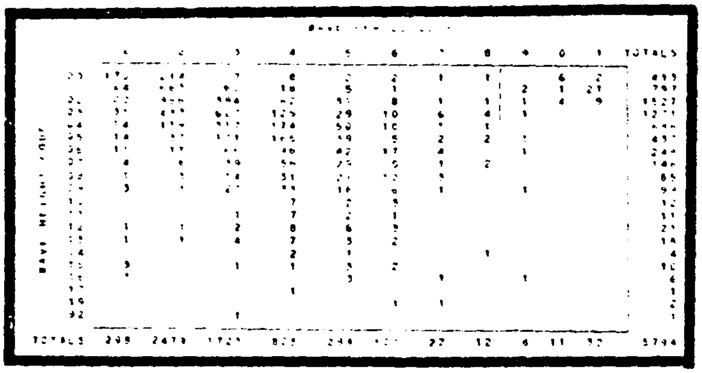
TRIGOM	FIGURE 3-73	Wave Period - Wave Height (Hogben and Lumb, 1967)



Area 6 June - August



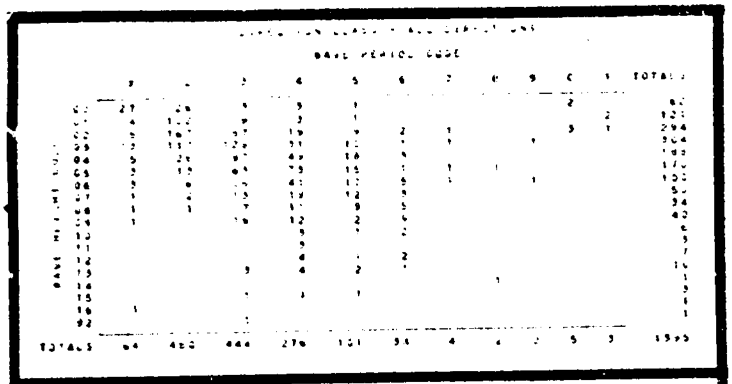
Area 6 September - November



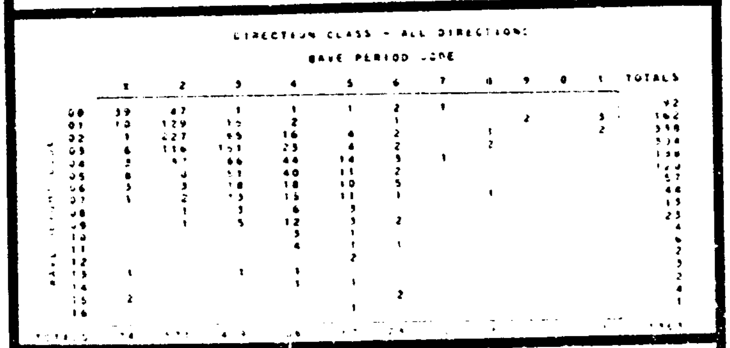
Area 9 Annual Summary

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

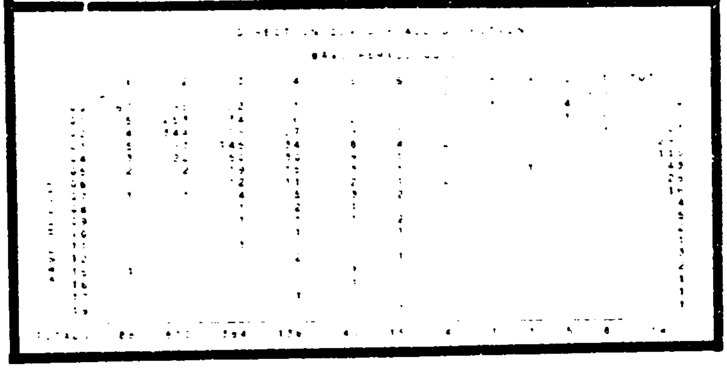
TRIGOM	FIGURE 3-74	Wave Period - Wave Height (Hogben and Lumb, 1967)



Area 9. December - February



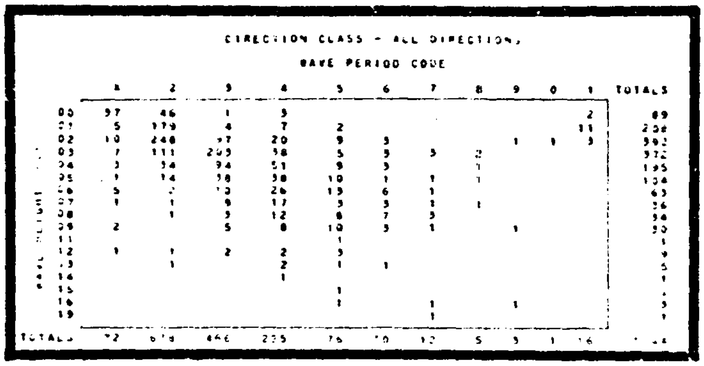
Area 9. March - May



Area 9. June - August

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-75	Wave Period - Wave Height (Hogben and Lumb, 1967)



DIRECTION CLASS - ALL DIRECTIONS

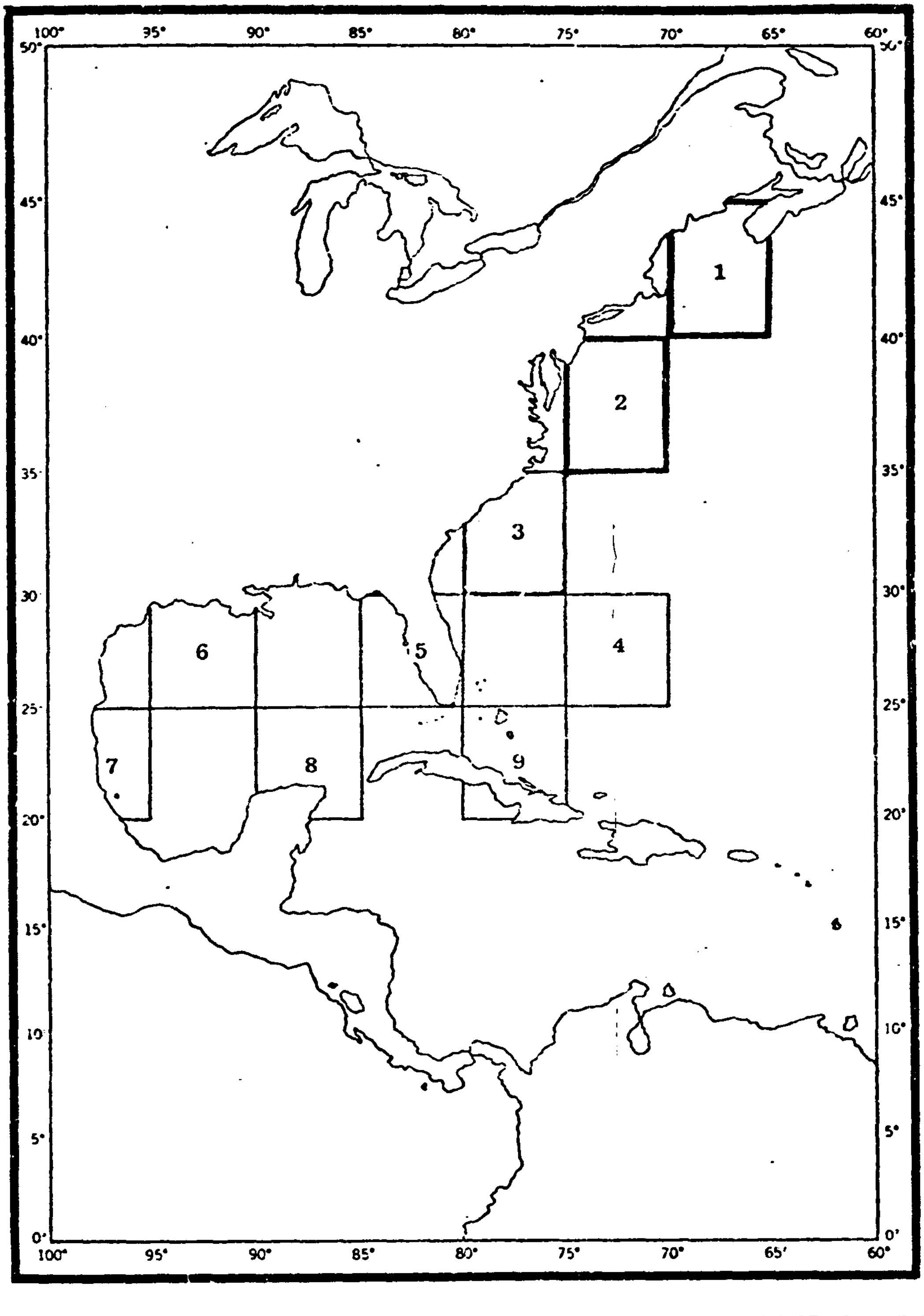
WAVE PERIOD CODE

WAVE HEIGHT	1	2	3	4	5	6	7	8	9	0	1	TOTALS
00	37	46	1	3							2	89
01	5	179	4	7	2						11	208
02	10	248	97	20	9	3			1	1	3	392
03	7	111	203	38	5	3	3	2				372
04	3	34	94	51	9	3		1				195
05	1	14	78	38	10	1	1	1				134
06	5	2	10	26	13	6	1					63
07	1	1	9	17	3	3	1	1				36
08		1	3	12	8	7	3					34
09	2		5	8	10	3	1		1			30
11					1							1
12	1	1	2	2	3							9
13		1		2	1	1						5
14				1								1
15					1							1
16					1		1		1			3
19							1					1
TOTALS	72	639	446	225	76	30	12	5	3	1	16	[illegible]

Area 9. September - November

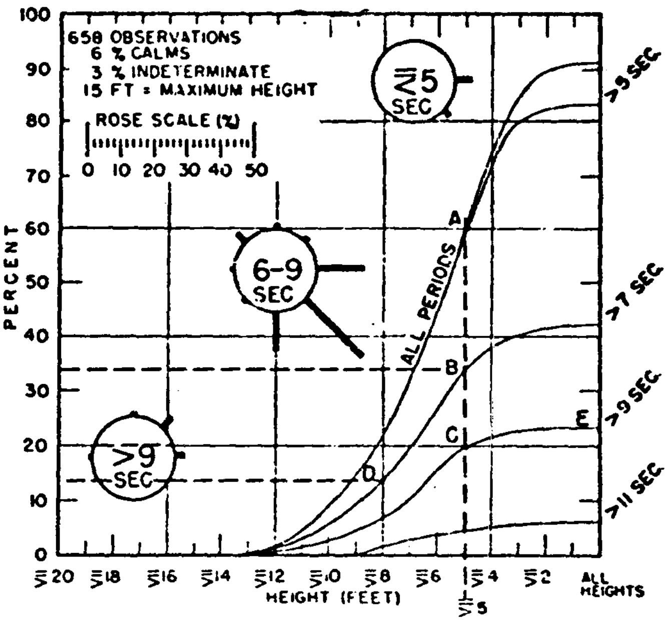
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-76	Wave Period - Wave Height (Hogben and Lumb, 1967)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

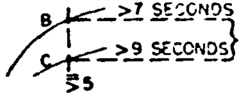
TRIGOM FIGURE 3-77 Statistical Areas for Wave Height Period and Period Direction (U.S. Dept. of Commerce, 1973)



A POINT ON THE GRAPH SHOWS THE PERCENTAGE OF ALL WAVES OBSERVED WITH PERIODS EXCEEDING, AND HEIGHTS EQUAL TO OR EXCEEDING, CERTAIN VALUES

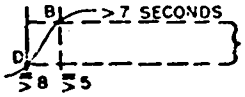
POINT A 60 % OF ALL WAVES WERE ≥5 FEET
- B. 34 % OF ALL WAVES WERE >7 SECONDS, ≥5 FEET
- C. 23 % OF ALL WAVES WERE >9 SECONDS

AN INTERVAL BETWEEN TWO POINTS OF THE SAME HEIGHT CATEGORY SHOWS THE PERCENTAGE OF ALL WAVES OF THAT HEIGHT CATEGORY WITHIN A CERTAIN RANGE OF PERIODS



14 % OF ALL WAVES WERE 7-9 SECONDS, ≥5 FEET

AN INTERVAL BETWEEN TWO POINTS ON THE SAME PERIOD CURVE SHOWS THE PERCENTAGE OF ALL WAVES REPRESENTED BY THE CURVE WITHIN A CERTAIN RANGE OF HEIGHTS:



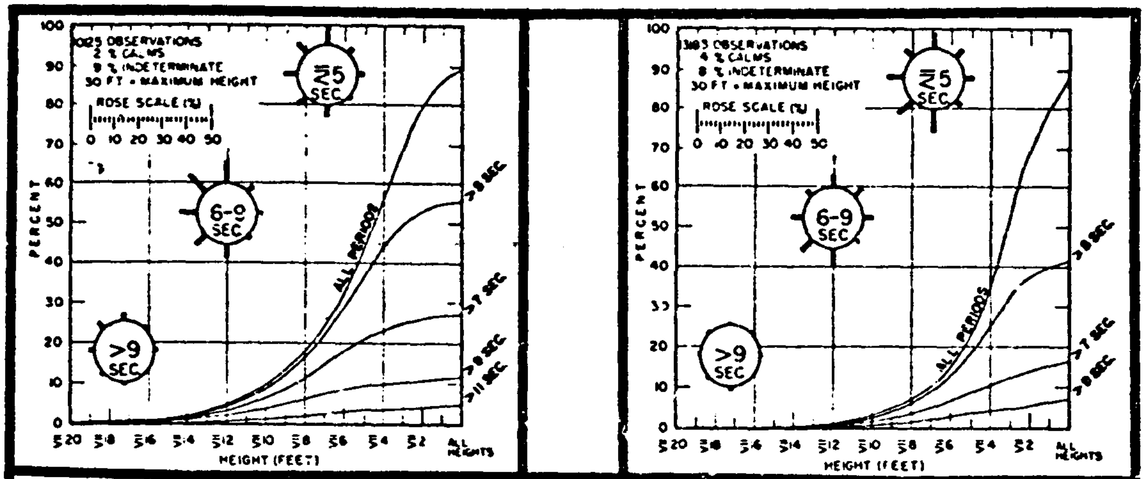
20% OF ALL WAVES WERE 5-6 FEET, >7 SECONDS

AN ARM OF A ROSE INDICATES THE PERCENTAGE OF ALL OBSERVATIONS WHICH ARE IN THE GIVEN PERIOD-DIRECTION CATEGORY:

25% OF ALL WAVES OBSERVED HAD PERIODS OF 6-9 SECONDS AND CAME FROM THE SOUTHEAST.

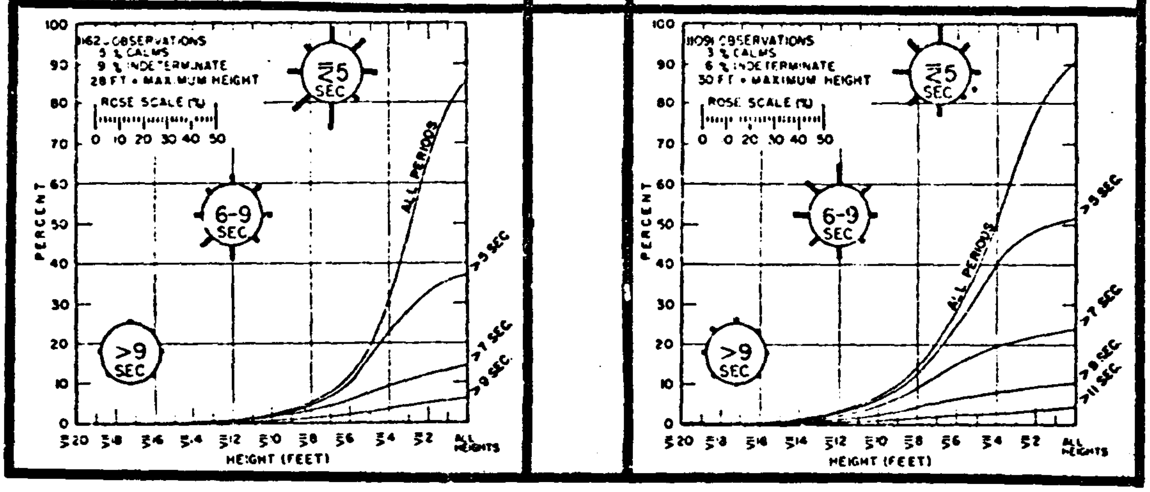
15% OF ALL WAVES OBSERVED CAME FROM THE SOUTH. 12% OF THESE WAVES HAD PERIODS OF 6-9 SECONDS AND 3% HAD PERIODS >9 SECONDS.

FIGURE 3-78 Key to Wave Height Period and Period Direction (U.S. Dept. of Commerce, 1973)



January - March

April - June

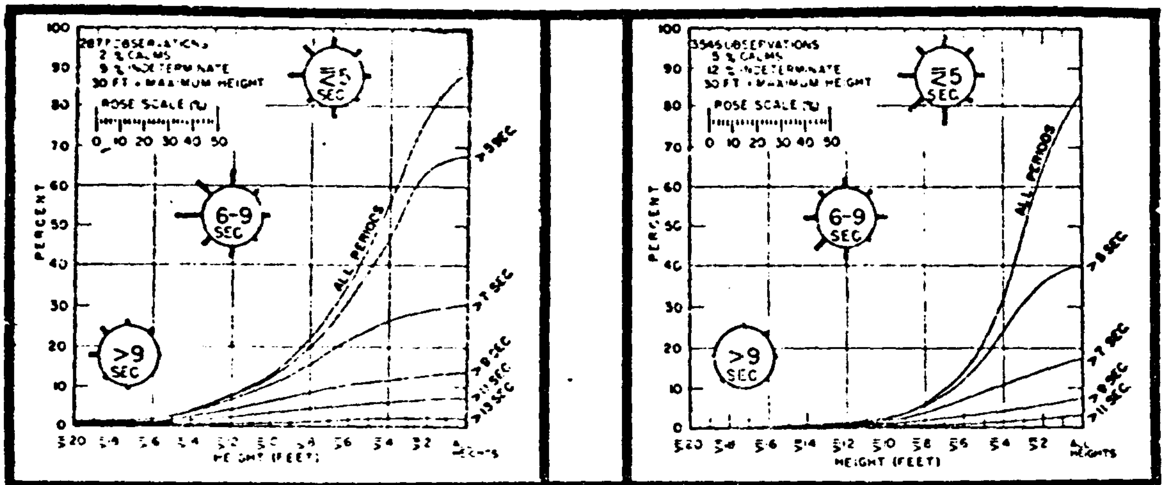


July - September

October - December

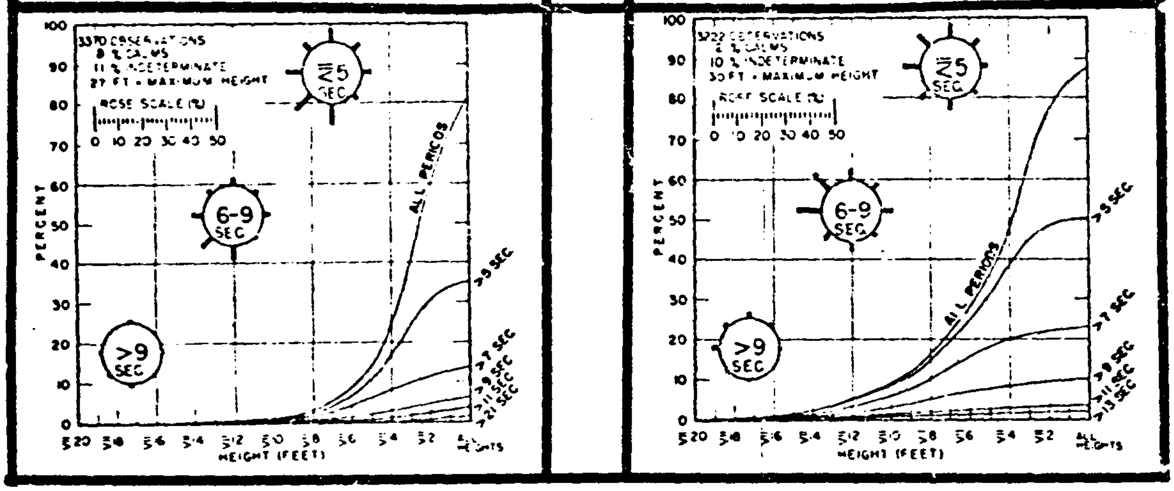
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 3-79	Wave Height Period and Period Direction - Area 2 (U.S. Dept. of Commerce, 1973)



January - March

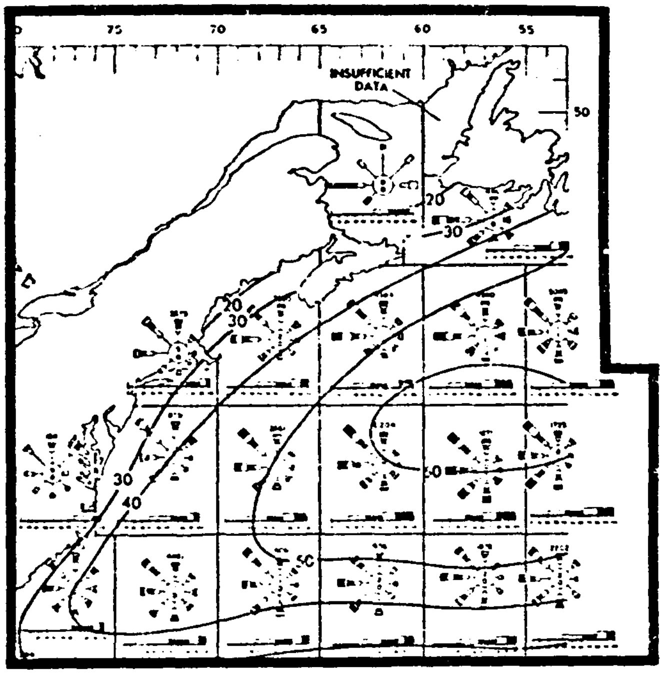
April - June



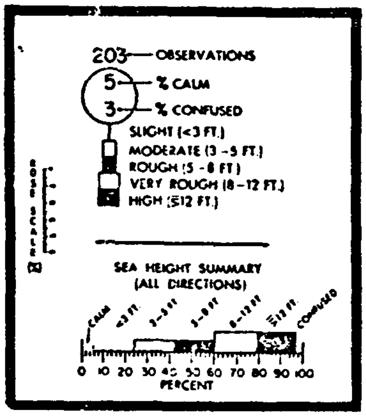
July - September

October - December

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE		
TRIGOM	FIGURE 3-80	Wave Height Period and Period Direction - Area 2 (U.S. Dept. of Commerce, 1973)

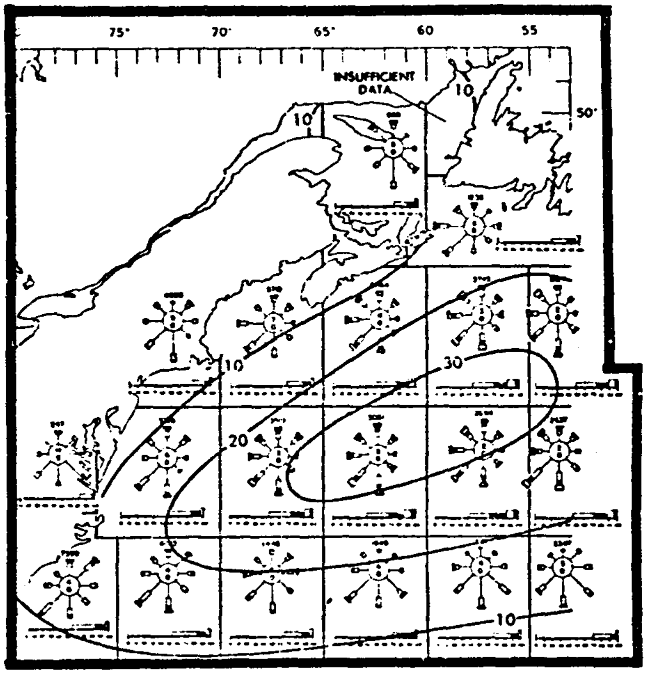


February



Key to sea roses

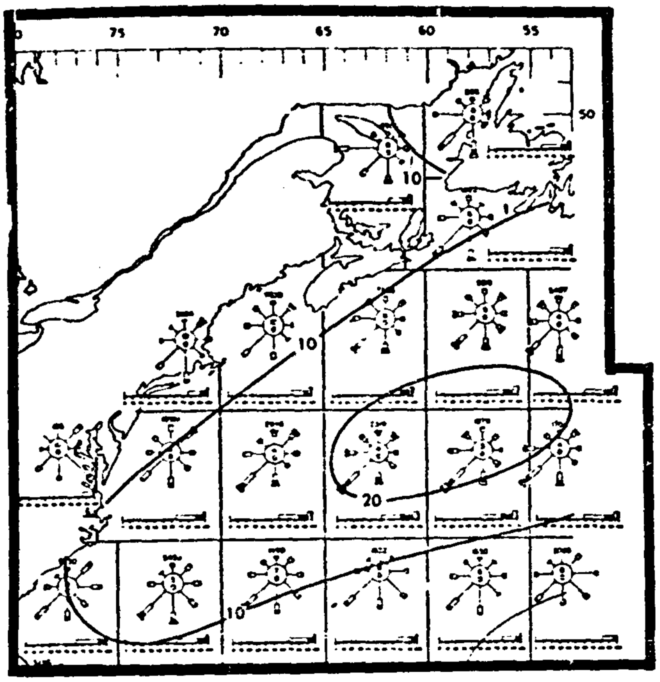
May



NOTE: Isolines show the percent of time seas are equal to or greater than the specified heights.

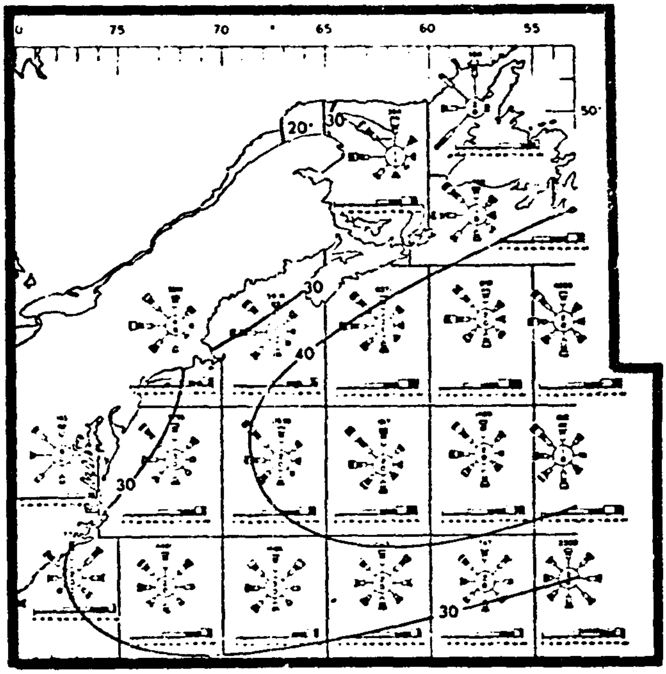
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-61 Sea Roses (U.S. Dept. of Commerce, 1973)



August

November



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 3-82 Sea Roses (U.S. Dept. of Commerce, 1973)

Observations for June through August show waves in both area 6 and area 9 as being primarily between 0.5 and 1.5 m in height and 5 (or less) to 7 seconds in period. From the data being used, this would appear to be the time of lowest wave activity.

September through November demonstrates a resurgence of wave activity. Although wave period in both areas 6 and 9 remains essentially the same as before in terms of numbers of observations, wave heights in area 6 increase to one to two meters while staying at 0.5 to 1.5 m in area 9.

Area 9, incorporating the northern slope, would appear to have - in terms of most observations - a more consistent sea state than area 6, which demonstrates a somewhat seasonal variation. But this is only in terms of highest number of observations. Thus, extremes are eliminated where perhaps they should be more carefully considered. Above all, however, these data do not give figures in numbers of days per year for the various sea conditions; consequently no concept of duration is available.

3.3 MONTHLY SUMMARIES

The weather parameters that have been presented generally exhibit a broad seasonal range and apply to a broad geographical area. These events are summarized here on a monthly or quarterly basis and apply as specifically as the data allow to the confines of the study area. We have used the U.S. Navy and U.S. Weather Bureau (1959) as the basic reference for these seasonal summaries. In the case of tropical cyclones, these data do not conform to those of Crutcher and Quayle (1974), probably because different time spans were used to analyze the data. For comparison with Crutcher and Quayle the reader is referred to Section 3.2.7, Figures 3-65 to 2-70.

JANUARY

During the month of January 50 percent of the air temperature observations were between 15.6-18.3°C off Cape Hatteras and 4.4-7.2°C off Cape Cod with no incidence of hurricanes reported in the slope area. In a south to north direction, visibility (expressed in terms of percent time less than 5 nm throughout this section) trended from 10 to 20 percent while sea level pressure fields average 1010 to 1020 mb offshore from both Cape Hatteras and Cape Cod. Surface winds were primarily out of the south, and southwest and west off Cape Hatteras with a Beaufort force of 4-5 (11-21 knots) and from the west and northwest off Cape Cod at Beaufort force 4-5 offshore from Cape Cod.

FEBRUARY

The 50 percent of observations range for air temperature (hereafter air temperature) during February were between 12.8-15.6°C offshore from Cape Hatteras, dropping 2.8-5.6°C offshore from Cape Cod with one hurricane-tropical storm reported in the study area (during this month from 1836-1957) offshore from both Capes Hatteras and Cod. Visibility trended from 10-20 percent heading south to north while the sea level pressure fields ranged from 1010-1020 mb throughout the slope area. Surface winds at both stations came primarily from the west and northwest registering a Beaufort force of 5-6.

MARCH

Air temperature during March ranged between 12.8-15.6°C at a station off Cape Hatteras and 4.4-7.2°C at a station off Cape Cod with no reports of any hurricane-tropical storm occurrence. Visibility again trended from 10-20 percent in a south to north direction with sea level pressure ranging somewhat lower than previous readings at 1005-1015 mb at stations located in the north and south of the slope area. Surface winds continued to be primarily from the west and northwest with a Beaufort force of again 5-6.

APRIL

A marked upward trend in air temperature begins in this month with offshore Cape Hatteras temperatures between 15.6-18.3°C and offshore Cape Cod temperatures between 7.2-10°C; again, there are no hurricane-tropical storm reports for this month. Visibility remained the same this month as last with sea level pressures holding at 1005-1015 mb off Cape Hatteras while increasing to 1010-1020 mb off Cape Cod. Surface winds begin to change now showing a south, southwest trend at Beaufort force 5-6 off Cape Hatteras while shifting to a more generally western orientation off Cape Cod predominantly at Beaufort force 3.

MAY

The upward trend of air temperature continues during May with ranges of 18.3-21.1°C offshore from Cape Hatteras and 12.8-15.6°C offshore from Cape Cod while hurricane-tropical storm incidence increased to 3 in the southern and one in the northern slope area. Visibility begins to decrease now, ranging from 10 percent in the south to 30 percent in the north with sea level pressures staying at April levels. The Bermuda-Azores High begins to strengthen its influence as winds shift to the southwest at Beaufort force 4-5.

JUNE

Although the sea surface pressure and visibility remain the same this month as last, hurricane-tropical storm frequency and air temperature continue to increase. Three hurricane-tropical storms are reported for this month in the slope and the air temperature range increases to 21.1-23.9°C in the south of the study area and 15.6-18.6°C in the north. Again, because of the Bermuda-Azores High, surface winds demonstrate a southwesterly orientation at Beaufort force 5-6 in both the north and south.

JULY

The air temperature range continues to rise, reaching 23.9-26.7°C off Cape Hatteras and 20-22.2°C off Cape Cod. Furthermore, tropical storm-hurricane incidence continues to climb with five reported in the southern slope area and two in the northern. Visibility begins to improve in the south, with five percent reported off Cape Hatteras, while remaining at 30 percent in the north. The sea surface pressure range is the same as in June. With summer well underway, surface winds show a strong southwesterly trend, some reaching 12 on the Beaufort scale (in the south), but most remaining in the range of 4-7.

AUGUST

The air temperature range reaches an apex during August with ranges of 23.9-26.7°C off Cape Hatteras and 20.6-23.3°C off Cape Cod. Hurricane-tropical storm frequency takes a marked jump, up to 12 in the south and 20 in the north slope, denoting the beginning of the storm season. This upward trend in storm activity should continue until the early autumn when the Icelandic Low begins to dominate meteorological conditions and cyclogenesis decreases. Visibility remains the same as in July while sea surface pressure fields show some variation with ranges of 1005-1015 mb off Cape Hatteras and 1010-1020 off Cape Cod. Surface winds are still southwesterly but without the strength of July; Beaufort scale readings are primarily 4-5 in the south and from 3-4 in the north.

SEPTEMBER

Air temperature readings show the beginning of cooler weather moving in with temperature ranges dropping to 18.3-21.1°C in the north while maintaining 23.9-26.7°C range in the south. Visibility begins to improve in the north while getting a bit worse in the south of the study area, the overall trends being from 10 percent off Cape Hatteras to 20 percent off Cape Cod. Visibility will remain at approximately this level until December when it is pretty much uniform at 10 percent throughout the study area. Again a significant jump occurs in the number of hurricanes and tropical storms recorded: 36 in the southern slope area and 28 in the north. Sea surface pressures off Cape Hatteras still show some variation with a range of 1010-1020 mb while readings off Cape Cod remain within the same range as in the prevous five months, 1010-1020 mb. Surface winds are fairly diffuse, with no outstanding orientation. This is to be expected in as much as the Bermuda-Azores High is weakening and the Icelandic Low is gaining strength, which will give the wind a more northwesterly orientation. For this meteorological transition period, the greatest direction frequency noted off Cape Hatteras is southeasterly with winds reaching 4-5 on the Beaufort scale; winds off Cape Cod are from a more generally northern direction also at 4-5 on the Beaufort scale.

OCTOBER

The lowering trend in air temperature range continues with ranges of 21.1-23.9°C at offshore Cape Hatteras and 12.8-15.6°C at offshore Cape Cod. Hurricane-tropical storm frequency peaks with 39 recorded for the southern slope and 27 recorded in the northern slope area; after this month hurricane-tropical storm activity shows a dramatic decrease. Sea surface pressure remains at 1010-1020 mb off Cape Cod and will stay here through December while off Cape Hatteras readings stay at September levels. Surface winds again appear to be fairly diffuse and generally from the north registering 3-5 on the Beaufort scale at both stations.

NOVEMBER

By now the Icelandic Low has become a significant influence on slope weather. Surface winds from the northwest appear with greater frequency; some with a Beaufort force of six, but most remain in the 4-5 range. The air temperature range continues to drop, now to 18.3-21.1°C off Cape Hatteras and 10-12.8° off Cape Cod. Hurricane-tropical storm frequency decreases drastically with four reported in the south of the study area and two in the north. Sea surface pressures off Cape Hatteras continue to drop, ranging from 1005-1015 mb.

DECEMBER

Overall, this month has the lowest air temperature range, 12.8-15.6°C offshore Cape Hatteras and 5.6-8.3°C offshore Cape Cod. These lower temperatures and the decreasing difference between temperatures at the southern and northern extremes of the slope are, in part, responsible for the minimal hurricane-tropical storm activity over the next few months (only one reported in the slope for December) since there is only a weak south-north thermal gradient to support storm activity. Sea surface pressure off Cape Hatteras continues to vary, going back up to 1010-1020 mb.

3.4 DATA GAPS

The deficiencies in our knowledge of continental slope meteorological characteristics result from two major causes: an inadequate data base to draw on for summarized information, and inadequate methods of analysis for data that already exist

Obviously, for an ocean area with so varied a climate, one permanent weather recording station is totally insufficient to take into account the variation in meteorological conditions within the slope water region. A completely satisfactory in-depth analysis of offshore weather (beyond the continental shelf) will have to await the establishment of more recording stations.

It has been pointed out by Mr. Joseph Chase of the Woods Hole Oceanographic Institution (personal communication) that the analysis of various weather data that does exist for the northwest Atlantic in many cases, does not provide answers that are needed for day-to-day offshore operations. Average meteorological parameters are not suitable for determining the number of days per year that operable weather conditions would be expected in a given area. What is needed is an analysis of daily weather observations over a long period (10 to 20 years) from the 8 or 10 recording stations that do exist in the coastal and offshore northwest Atlantic that emphasizes the frequency of occurrence of various levels of meteorological events, i.e. number of expected days of severe conditions, (visibility, winds, etc.) This data would have to be extracted from the records of daily weather observations that reside in the U.S. Weather Service data banks.

3.5 REFERENCES

Andrews, J.F. 1963. Cyclogenesis along the Atlantic Coast of the U.S. Mariners Weather Log, 7(2): 43-46.

Blair, T.A. and R.C. Fite. 1957. Weather elements. New Jersey, Prentice-Hall, Inc. 414 p.

Bowditch, N. 1958. American practical navigator. U.S. Navy Hydrographic Office, Washington, D.C. 1524 p.

Chase, J. (personal communication, 1975). Woods Hole Oceanographic Institution, Woods Hole, Mass.

________. 1975. Weather of the Baltimore Canyon region. In: Proceedings of the Estuarine Research Federation, Outer Continental Shelf Conference and Workshop, College Park, Maryland, Dec. 2, 3,4, 1974, p. 98-102.

Crutcher, H.L. and R.G. Quayle. 1974. Mariners world-wide climatic guide to tropical storms at sea. U.S. Dep. of Commer., NOAA-EDS, Nat. Climatic Center. 118 p.

Cry, G.W. 1965. Tropical cyclones of the North Atlantic Ocean: tracks and frequencies of hurricanes and tropical storms, 1871-1963. U.S. Dep. of Commer., Weather Bur., Tech. Pap. 55. 148 p.

Cry, G.W. and W.H. Haggard. 1962. North Atlantic tropical cyclone activity, 1901-1960. Monthly Weather Rev., 90(8): 341-349.

Havens, M.M., D.M. Shaw, and S.R. Levine. 1973. Offshore weather and climate. In: Saila, S.B. (ed.), Coastal and offshore environmental inventory, Cape Hatteras to Nantucket Shoals. Univ. R.I., Grad. Sch. Oceanogr., p. 11-1 to 11-43.

Hebert, P.J. 1974. North Atlantic tropical cyclones. Nat. Oceanic and Atmos. Admin, Nat. Hurricane Center, Miami, Florida.

Hogben, N. and F.E. Lumb. 1967. Ocean wave statistics. Min. of Technol., Nat. Phys. Lab., London, England.

Klein, W.H. and J.S. Winston. 1958. Geographical frequency of troughs and ridges on mean 700 mb charts. Mon. Weather Rev., 86(9): 344-358.

Lapedes, D. (ed) 1974. McGraw-Hill dictionary of scientific and technical terms. McGraw-Hill Book Co., New York. 1632 p. plus append.

Mather, M.R., H. Adams. and G.A. Yoshioka. 1964. Coastal storms of the eastern United States. J. Appl. Meteorol., 3: 693-706.

Mather, J.R., R.T. Field and G.A. Yoshioka. 1966. Storm damage hazard along the east coast of the United States. J. Appl. Meteorol., 6: 20-30.

U.S. Department of Commerce. 1973. Environmental conditions within specified geographic regions, offshore east and west coasts of the United States and in the Gulf of Mexico. Washington, D.C., Nat. Oceanic and Atmos. Admin. 735 p.

U.S. Navy and U.S. Weather Bureau. 1959. Climatological and oceanographic atlas for mariners, I: North Atlantic Ocean. Washington, D.C., U.S. Dep. of Commer. 125 p.

CHAPTER 4.0

PHYSICAL OCEANOGRAPHY

W. REDWOOD WRIGHT

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Chapter 4.0 Physical Oceanography

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4.0 PHYSICAL OCEANOGRAPHY - THE WESTERN SLOPE WATER

4.1 INTRODUCTION

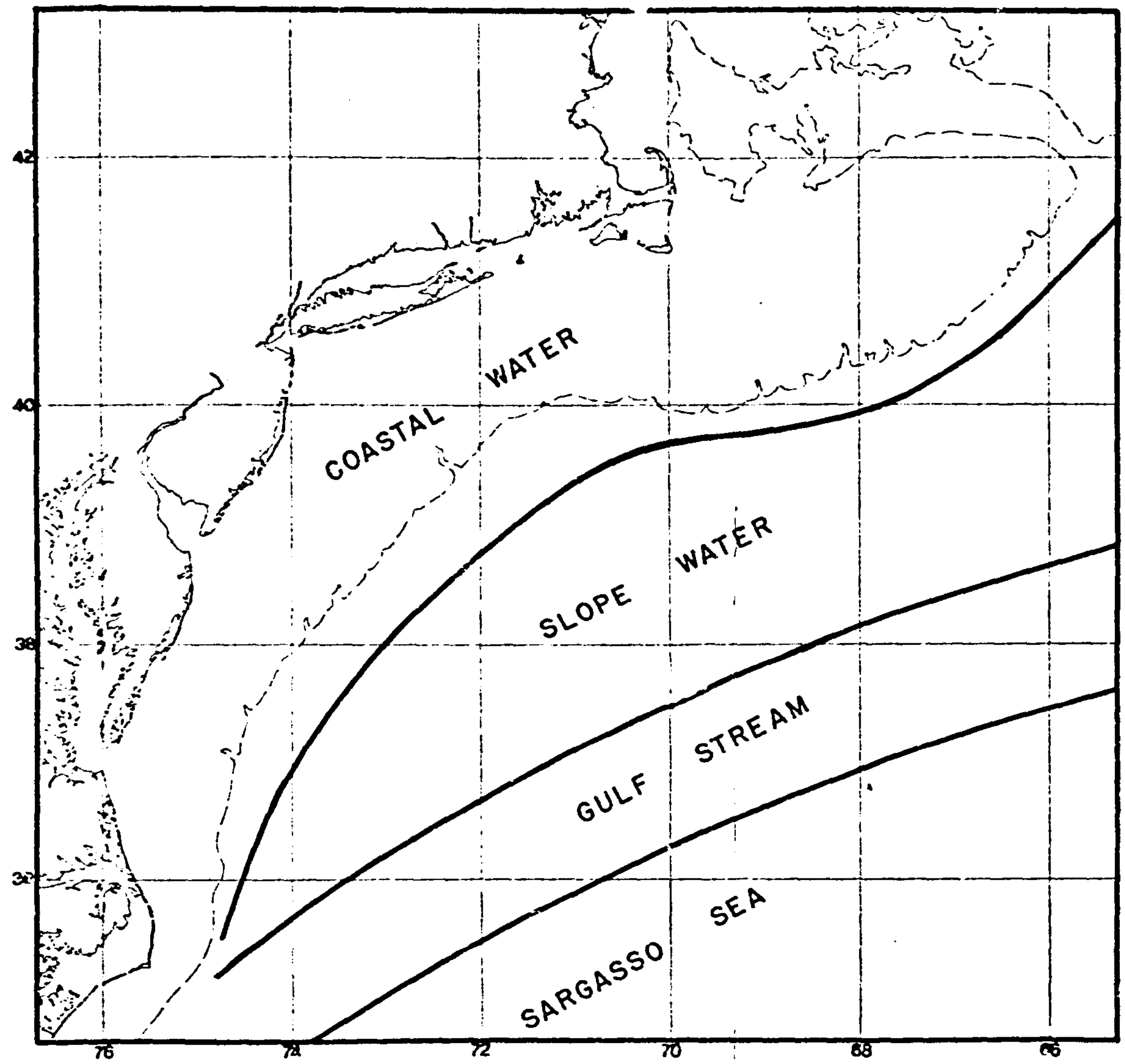
The western slope water off the East Coast of the United States, beginningat Cape Hatteras, occupies the space between the Gulf Stream on the south, the coastal waters of the continental shelf on the north, and the eastern (or Canadian) slope waters on the east. Winter storms, northeast gales, and hurricanes disturb its surface layers. The Gulf Stream meanders north and south and occasionally sheds rings of current which carry slope water into the Sargasso Sea or vice versa. The shelf water boundary fluctuates widely in position; discrete parcels of shelf water are either caught up in the northern edge of the Gulf Stream at Cape Hatteras or bled off into the slope water at mid-depth all along the shelf edge while slope water intrudes shoreward underneath. Occasional intrusions of Labrador Sea water affect the temperature-salinity characteristics of the thermocline and surface layers while, at greater depths, the Western Boundary Undercurrent carries water of Norwegian Sea origin southwestward along the continental rise to cross under the Gulf Stream at Cape Hatteras. The sea floor itself is the only stable boundary.

The four distinctive bands of water lying off the coast of the northeastern United States (Figure 4-1) were described by Iselin (1936):

> "Proceeding from the land outward, there is first the relatively fresh (< 35 o/oo) coastal water covering the continental shelf, and extending often near the surface at a point somewhat beyond the 200 m curve. Then, between the continental slope and the Gulf Stream lies a band of water having intermediate values in salinity (35 to 36 o/oo) in the surface layers and relatively low temperatures in mid-depths, while beyond the Gulf Stream true Central Atlantic Water of higher salinity (< 36 o/oo) is found."

Recognizing that the second band appeared to be continuous from Cape Hatteras to the Grand Banks, Iselin named it "slope water" and described it further as follows:

> "The band of water between the edge of the continental shelf and the Gulf Stream averages about 60 miles wide in the Chesapeake Bay section and about 170 miles wide off Nova Scotia. It is characterized by being the mixing zone, in the upper layers (down to 200 m), for coastal water which has escaped from over the continental shelf, and Gulf Stream water which has been carried west of the current's path. At mid-depths, the relatively cold waters of this intermediate belt are very consistent in character but do not quite resemble the Central Atlantic Water in temperature-salinity ratio."



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-1 Diagrammatic Representation of Hydrographic Subdivisions Within the Western North Atlantic (Iselin, 1936)

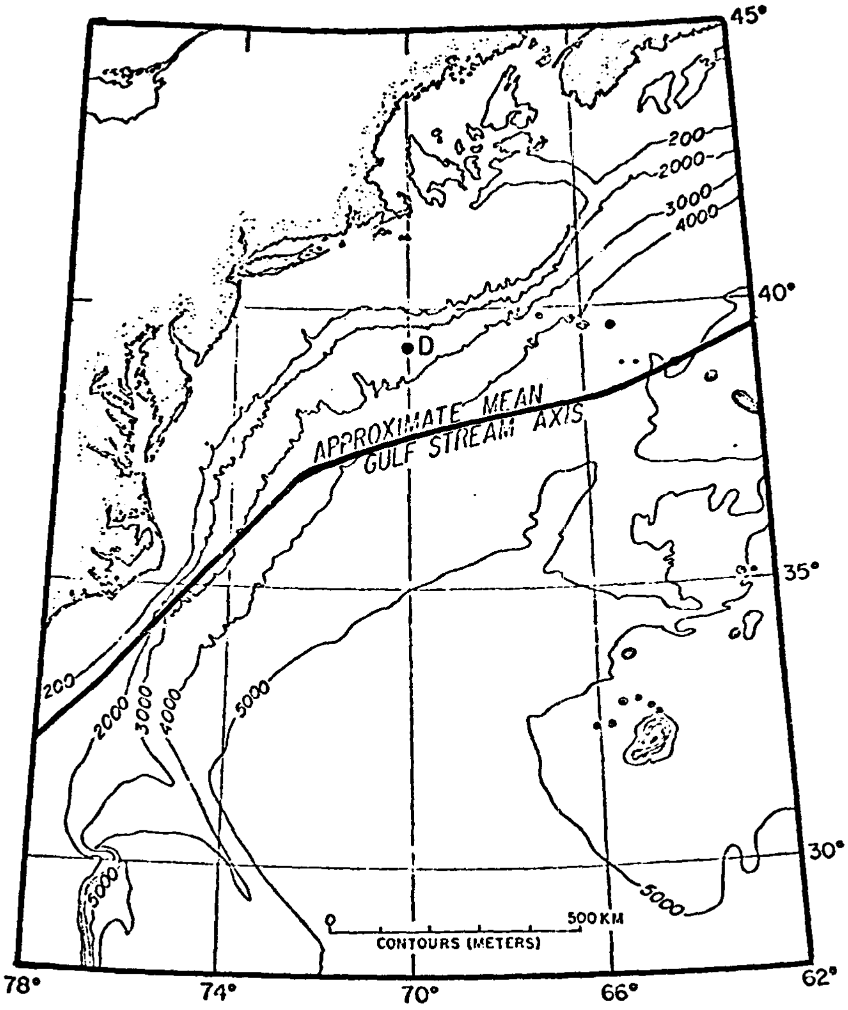
This chapter shall discuss the western section of the slope water band, roughly that portion between Cape Hatteras (Figure 4-2) and 66°W, even though much of what is known about the slope water is based on observations east of that meridian and there is no real oceanographic reason for choosing such a boundary. In contrast, the northern and southern boundaries of the slope water, the Gulf Stream and the shelf water front, respectively, are oceanographically distinct. However, their position and character fluctuate in time and they have profound effects upon the slope water itself so that those fluctuations and interactions must also be considered.

The western slope water, then, has a surface area of about 180,000 km^2 and a volume of about 650,000 km^3. Both values are ± 20 percent depending upon the instantaneous position of the boundaries. The area is approximately the same as that of the United States continental shelf east of Cape Hatteras but the volume is 20 to 25 times greater than the shelf water volume. The total area and volume of the North Atlantic Ocean, by comparison, are 40 million km^2 and 137 million km^3, (Wright and Worthington, 1970) so in each case the western slope water represents about 0.5 percent.

Topics covered concerning the western slope water will be as follows: a description of the general characteristics of the slope water itself; the variability introduced along its boundaries; circulation - the sources of the slope water currents and flow patterns; tides, waves, storms, and other surface phenomena; and, finally, a summary of gaps in knowledge and some suggestions for filling them.

4.2 WATER MASS CHARACTERISTICS

Like most oceanographic regimes, the western slope water can be divided vertically into three layers: the surface waters, which display a seasonal pattern and are affected by storms; the thermocline region, where the temperature and salinity decrease relatively rapidly with increasing depth; and the deep water, in which the gradients are more gradual. There are also horizontal differences which are much less pronounced and are most easily distinguished by salinity. These increase at any depth in the offshore direction and decrease toward the northeast. Complicating the picture at all depths are the meandering nature of the Gulf Stream itself and, in the shallow layers, the shifting boundaries between shelf water and slope water. There also appear to be relatively rare but important incursions of anomalously cold and fresh water from the east. This picture is especially complex at Cape Hatteras where the Gulf Stream, shelf water, and slope water all come together and interact; this interaction will be considered in some detail in the section on circulation.



The position of the approximate mean Gulf Stream axis is taken from U.S. Navy Oceanographic Office charts.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE		
TRIGOM	FIGURE 4-2	Location of Site D (39°20'N, 70°00'W) in the Western North Atlantic (Webster, 1969)

4.2.1 SEA SURFACE

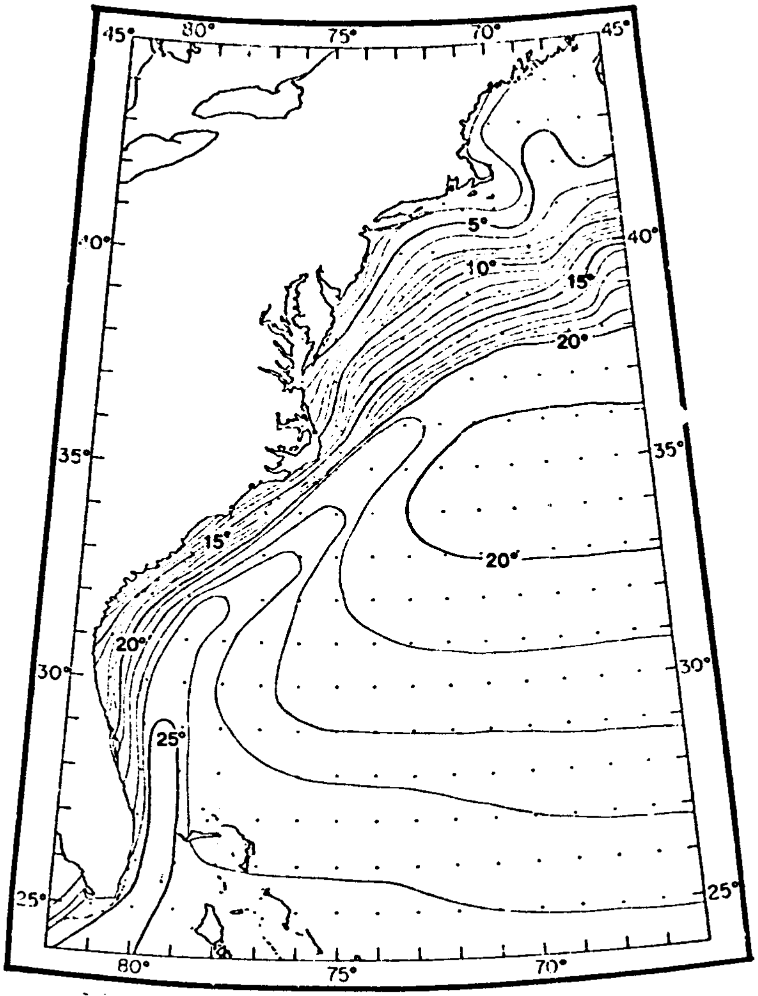
TEMPERATURE

Some feeling for the complexity of the sea surface temperature structure in the slope water is now being revealed by high resolution satellite imagery, which will be described later. The "average" picture, described next, is clearly an oversimplification that tends to smooth out the convoluted fronts and sharp gradients which may exist at any time.

The average temperature at the sea surface west of 66°W has been plotted by Schroeder (1966) on the basis of nearly 200,000 research vessel observations going back more than 30 years. Schroeder produced charts for each of the 12 months, each of the four seasons, and for the maximum range. The average temperature for the coldest and warmest months, March and August respectively, and the annual temperature range are shown (Figures 4-3,4,5). In March, the principal features are the seaward increase in temperature with packed isotherms around 10°C at the shelf break and around 15 to 20°C at the inshore edge of the Gulf Stream. This feature is visible as a tongue of warm water extending northeast from Cape Hatteras with isotherms roughly parallel to the coastline. In August, the isotherms run more nearly east-west and their gradients are much smaller; there is also an indication of the counter-rotating eddies in the Gulf of Maine and over Georges Bank. The annual temperature range (Figure 4-5) in the slope water is 10 to 15°C as compared with 15 to 20°C over the shelf and less than 10°C in the Gulf Stream and Sargasso Sea.

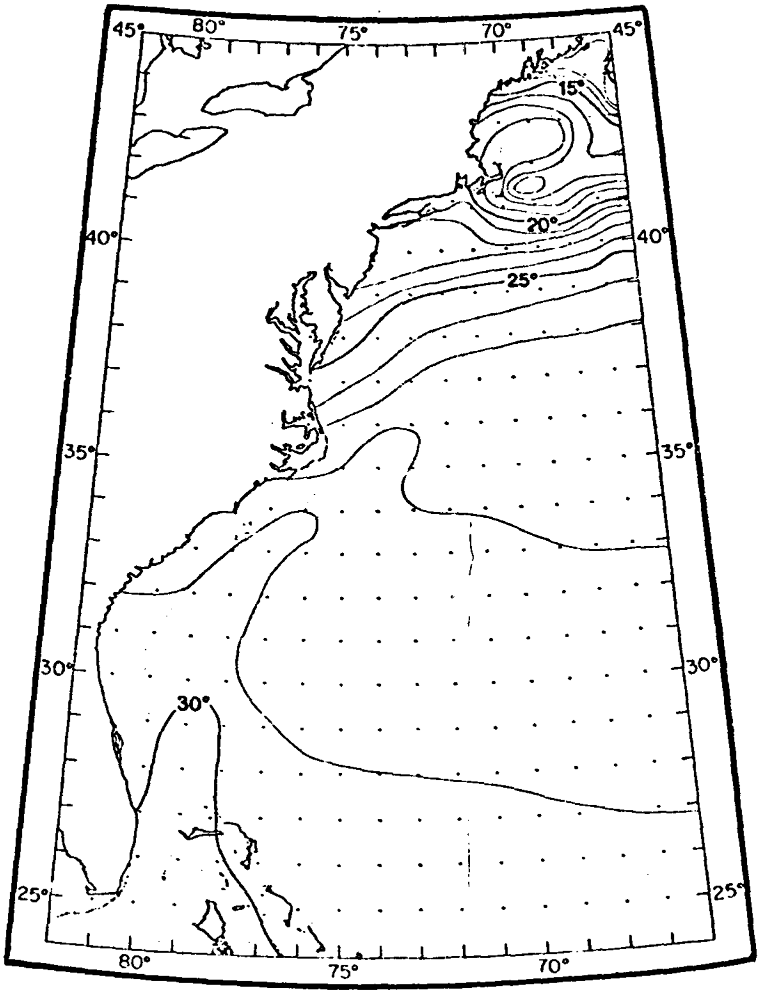
Another approach to sea surface temperatures has been the use of airborne radiation thermometry (ART) from aircraft flying patterns along the edge of the Gulf Stream (U.S. Navy) or the continental shelf (U.S. Coast Guard). These flights are useful in locating the region of sharp gradients (Figure 4-6), but the section spacing makes interpretation ambiguous (Bumpus, personal communication). Except for special studies, ART will probably be supplanted by satellites which provide both better resolution and broader coverage and are more nearly instantaneous.

Currently, the best satellite monitoring is by ITOS (Improved TIROS Operational Satellites) which are in circular, near-polar, sun synchronous orbits at an altitude of 1,450 km and provide almost twice daily coverage of the slope water region. These satellites carry a VHRR (Very High Resolution Radiometer) sensitive to energy in the visible spectrum (0.6 to 0.7 um) and in the infra-red window (10.5 to 12.5 um). They have a limited storage capacity but a readout station at Wallops Island, Virginia, is in an ideal location.



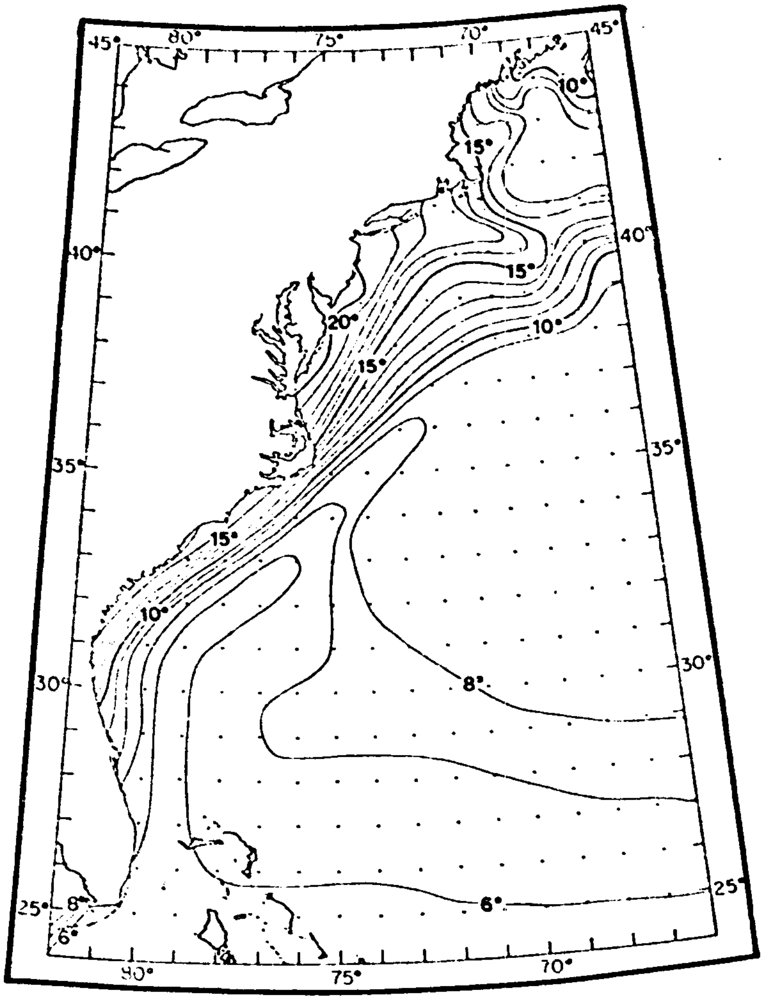
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-3 Average Surface Temperature for March (Schroeder, 1966)



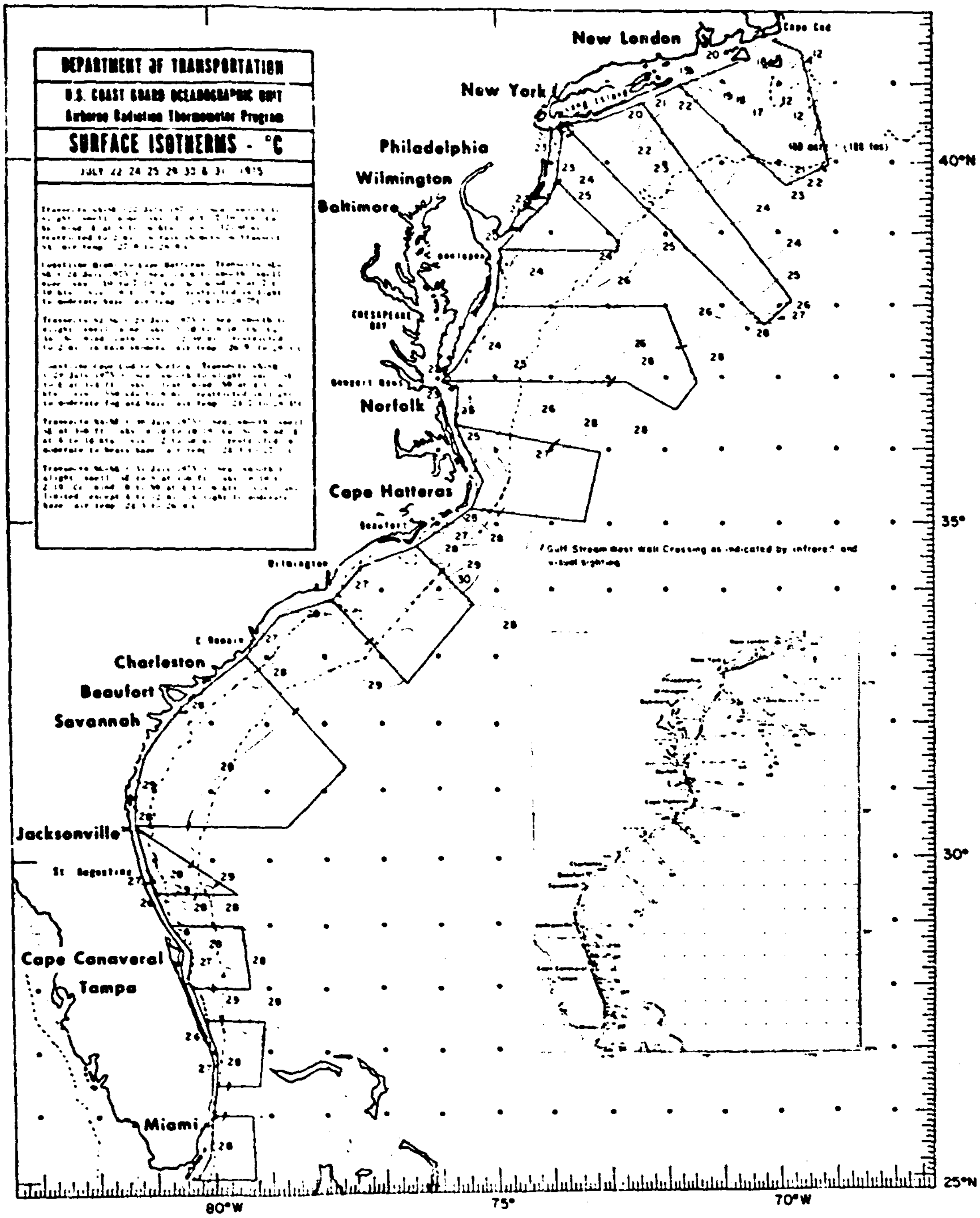
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 4-4 | Average Surface Temperature for August (Schroeder, 1966)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-5	Average Annual Range of Surface Temperatures (Schroeder, 1966)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-6	Sea Surface Temperatures Through U.S. Coast Guard Airborne Radiation Thermometer (U.S. Coast Guard Oceanographic Unit, 1975)

One operational product based on these images is the Experimental Gulf Stream Analysis which has been produced weekly by NOAA for two years (Stumpf, 1974). Each analysis, based on several days of observation, shows the positions of the major thermal fronts in schematic form, the locations of cold and warm eddies, and identifies the different water masses. Two of these analyses (Figures 4-7 and 8) show that conditions can range from the relatively simple to the extraordinarily complicated; both are for the same month (April) but in two different years.

Another promising development is the Synchronous Meteorological Satellite (SMS), which operates from a fixed position 36,000 km above the equator at 75°W, with coverage to 60°N and S, and from 15° to 135°W. It measures both visible and infra-red radiation at half-hour intervals. Resolution is only 8 km, but sea surface temperature is believed to be accurate to ± 1°C, and the frequent observations from a fixed point permits mapping of time changes (Legeckis, 1975).

Satellites will be used again in the sections on variability and circulation. They are extremely valuable tools, but they do have limitations (McClain, 1975):

(1) At best, they record only the skin temperature of the ocean, as opposed to the bulk temperature measured by ordinary immersed thermometers. Except during periods of unusual calm, the normal stirring by waves eliminates this as a serious problem. However, even bulk surface temperatures are not reliable indicators of deeper temperature patterns.

(2) More serious is the effect of water vapor in the intervening atmosphere on the satellite measurements. These errors can be corrected to some extent by using an assumed water vapor profile from a model atmosphere. A better solution will be possible with the forthcoming advanced VHRR which will have two infra-red bands which respond quite differently to water vapor so that the differences in measured radiance can be used to determine the atmospheric correction. It is expected that absolute temperatures should be accurate to about 1°C.

(3) Cloud cover remains the only serious limitation to satellite mapping, for sea surface temperatures can be received only when the satellite pass happens to coincide with a cloud-free period. It appears that oceanic phenomena change more slowly than those in the atmosphere so that the continually improving coverage in time will eliminate much of this problem except for periods of extended cloud cover.

For most purposes, the best regular reports on sea surface temperature are provided by "Gulfstream", a monthly publication of the National Weather Service since January, 1975, and before that, was issued as "The Gulf Stream" by the U.S. Naval Oceanographic Office. The reports are

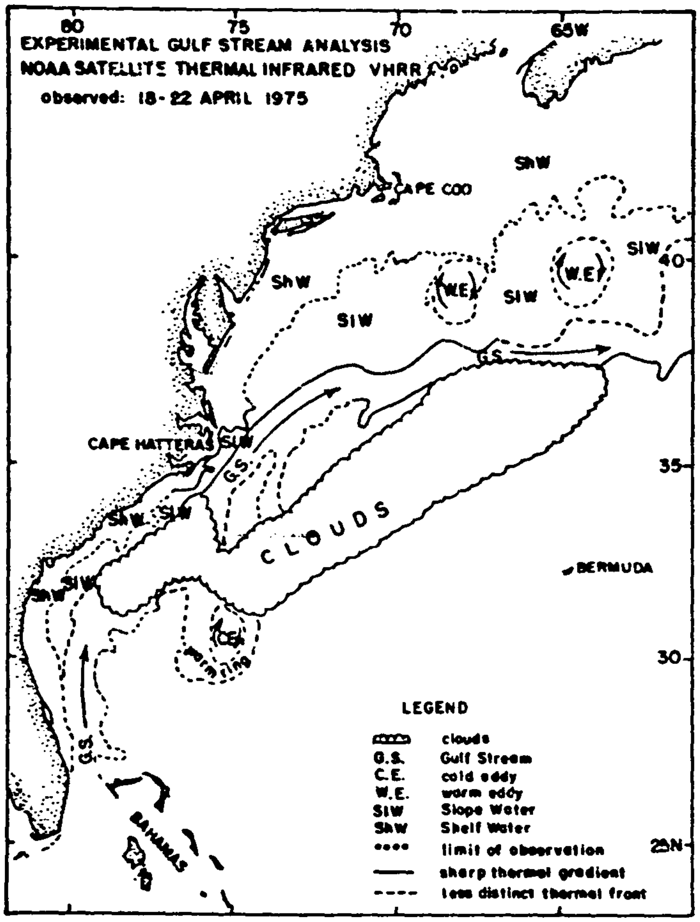


FIGURE 4-7 Experimental Gulf Stream Analysis Produced by NOAA Satellite Monitoring

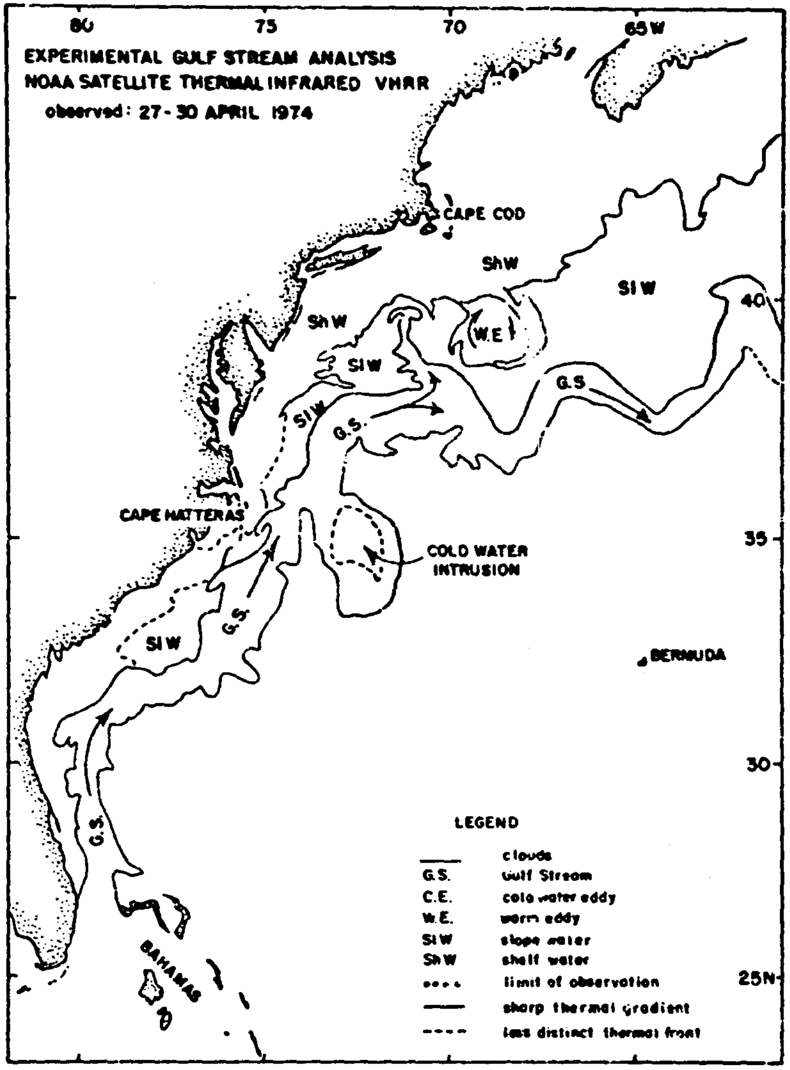


FIGURE 4-8 Experimental Gulf Stream Analysis Produced by NOAA Satellite Monitoring

based on all available information from ships, aircraft, and satellites. Each issue includes a schematic drawing of the locations of the fronts and rings, a selection of bathythermograms (BTs), and charts giving the mean sea surface temperature for the month, data base, anomaly from the 100-year mean for the month, and the change from the previous month, all on a one-degree grid from 25° to 45°N and 55° to 35°W (Figures 4-9, 10, and 11) Fig. 4-10 shows temperature isotherms above and mean temperature and frequency of observation below. Fig. 4-11 shows monthly mean greater then historical mean (dark) and smaller (light) in above figure. Below, present month higher than previous month (dark) and present month less than previous (light) are shown. Special reports on one aspect of the Gulf Stream system are an increasingly regular feature.

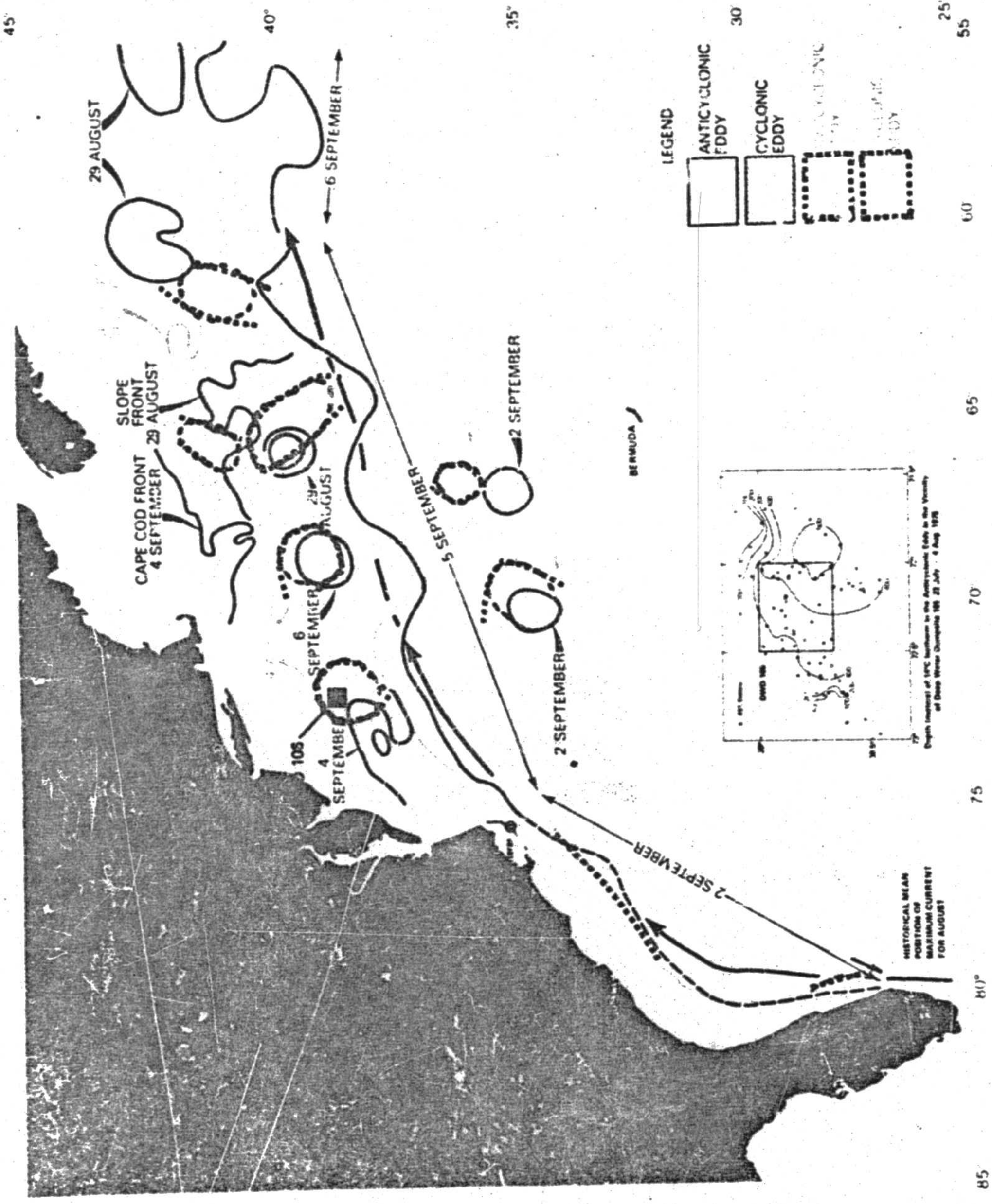
SALINITY

Probably the sea surface salinity is as variable as the sea surface temperature, although its seasonal range is not as great. However, since salinity is measured routinely only by research vessels, the detail cannot now be plotted. Sea surface salinity charts for February (Figure 4-12) and August (Figure 4-13) show little seasonal variation in the slope water region, except that the gradient is sharper in the winter. In both instances the salinity increases sharply in the offshore direction across the shelf. During winter the shelf break is marked by the 34 o/oo isoline, however, in the summer that line is further seaward due to the influence of the spring runoff. The chart of salinity at 30 m (Figure 4-14) clearly shows the band of low-salinity (less than 34.5 o/oo) water originating in the polar regions on both sides of Greenland and hugging the North American Coast as far south as Cape Hatteras. Here again, the averaging process wipes out the sharp gradients which are found in individual sections across the shelf and slope waters.

Because there is a large seasonal change in temperature and not in salinity, there is also a seasonal density difference at the sea surface, with the warmer and less dense water creating a more stable surface layer in the summer.

4.2.2 TOP TWO HUNDRED METERS

Two hundred meters can be taken as the bottom of the surface regime in the slope water; it is below the depth of any marked seasonal change (Figure 4-15) and, as the boundary between the continental shelf and continental slope, it is the limit of coastal water influence. Average temperatures at 200 m in the North Atlantic are given by Fuglister (1954) and by Schroeder (1963). Part of Schroeder's Plate Two is reproduced (Figure 4-16) to show the slope water region. The 15°C isotherm marks the mean position of the northern edge of the Gulf Stream, and from there to the intersection with the sea floor at the edge of the shelf there is a gradual decrease to about 11°C. Schroeder also prepared a chart showing temperature range which indicates an extreme variability (5 to 10°C) in the slope water; it is believed that this is due more to Gulf Stream fluctuations and incursions of Labrador Sea water than to seasonal variations. The 100 m charts of Colton and Stoddard (1972) show only 4 to 5°C seasonal change even at that depth



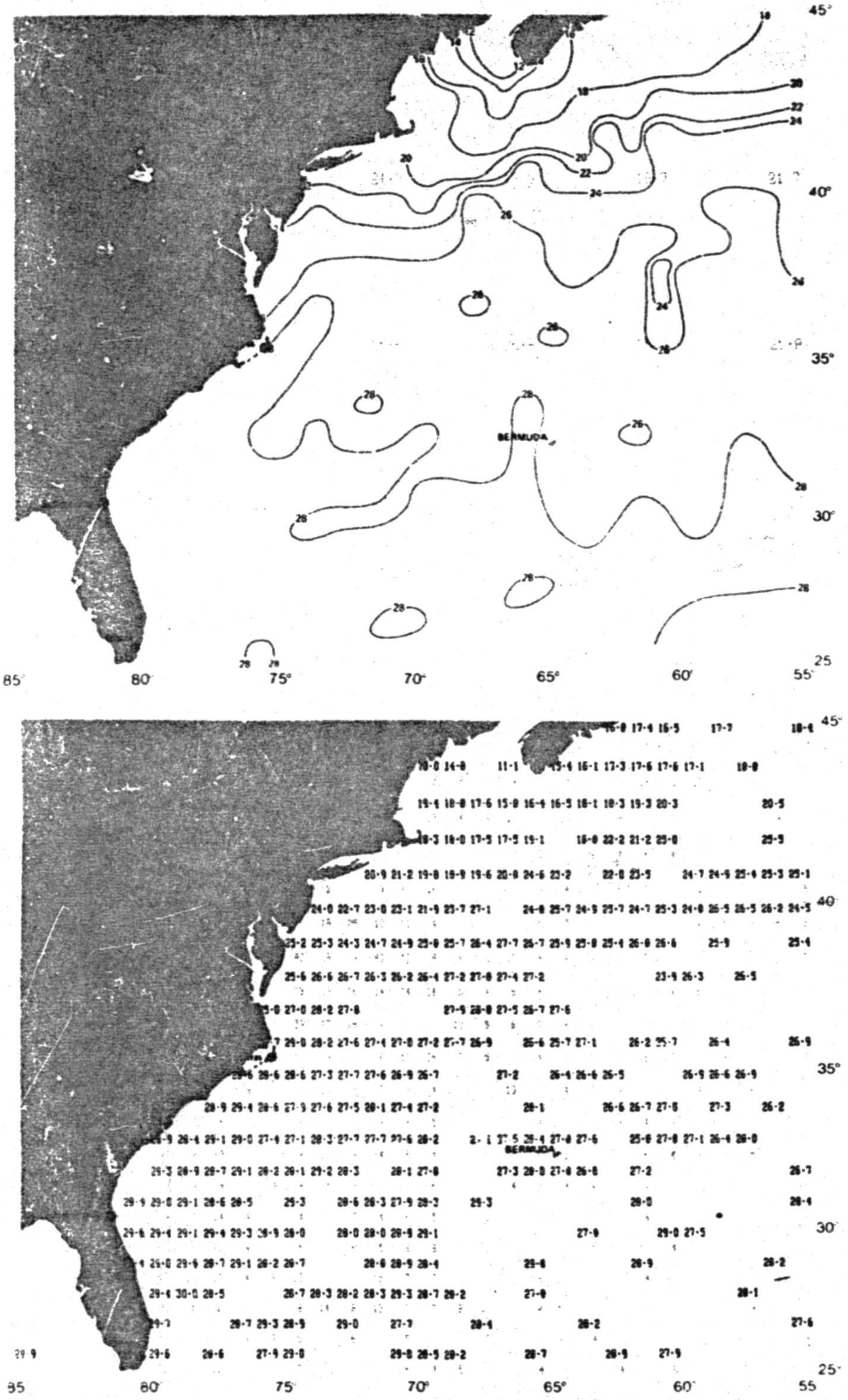
The northern edge of the Gulf Stream is shown in black for the beginning of the month; the lighter shade and ······· for the end of the month.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

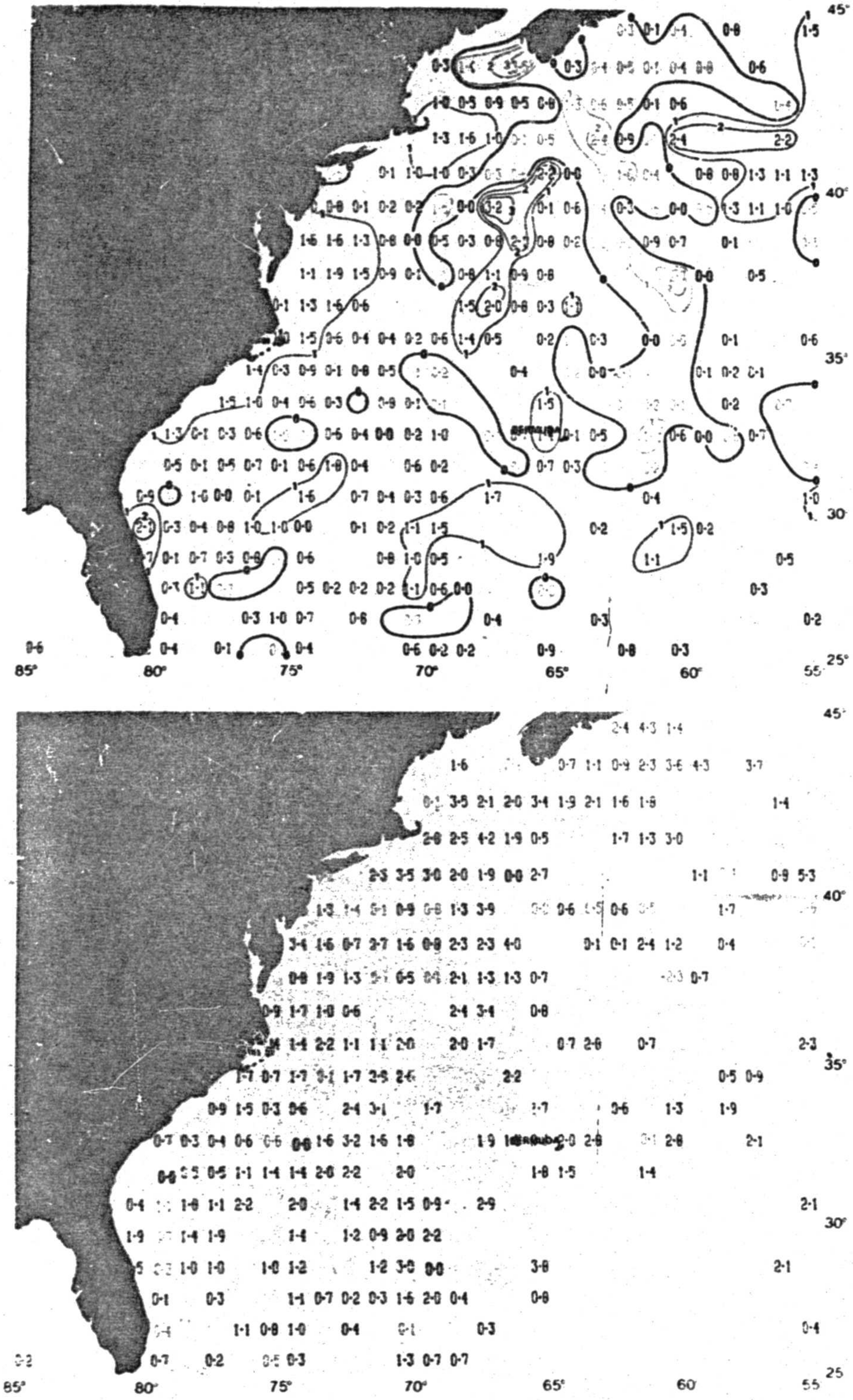
FIGURE 4-9

Gulf Stream Position and Location of Fronts and Rings, August, 1975 (National Weather Service, 1975)



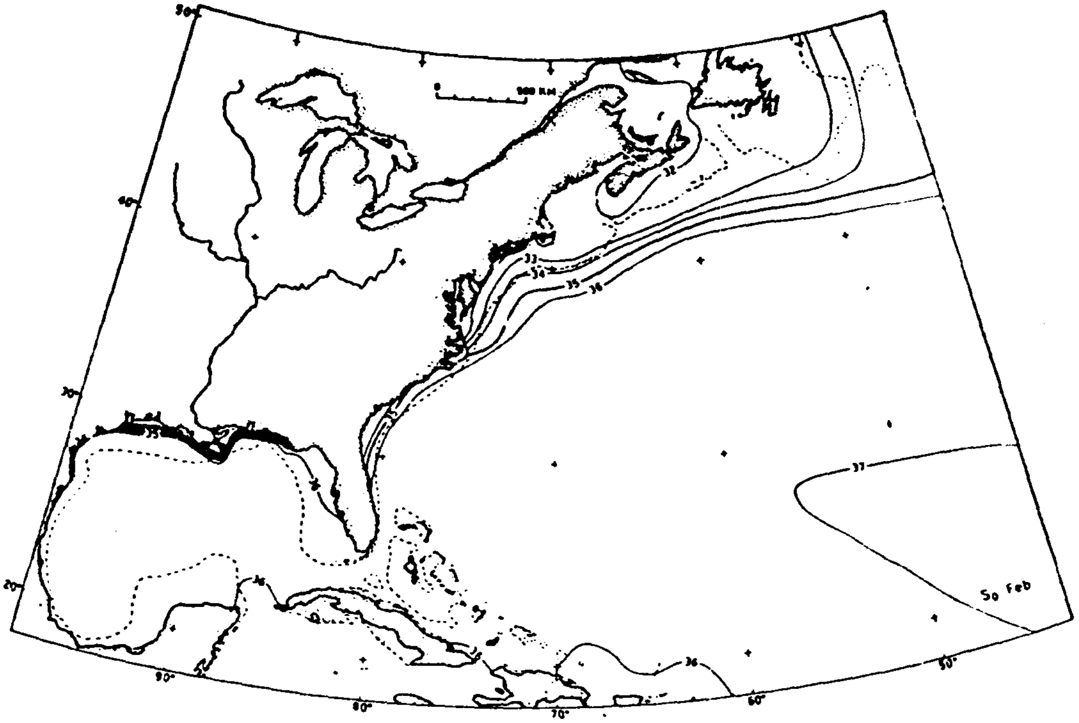
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-10	Mean Sea Surface Temperatures (°C), August, 1975 (National Weather Service, 1975) (see text)



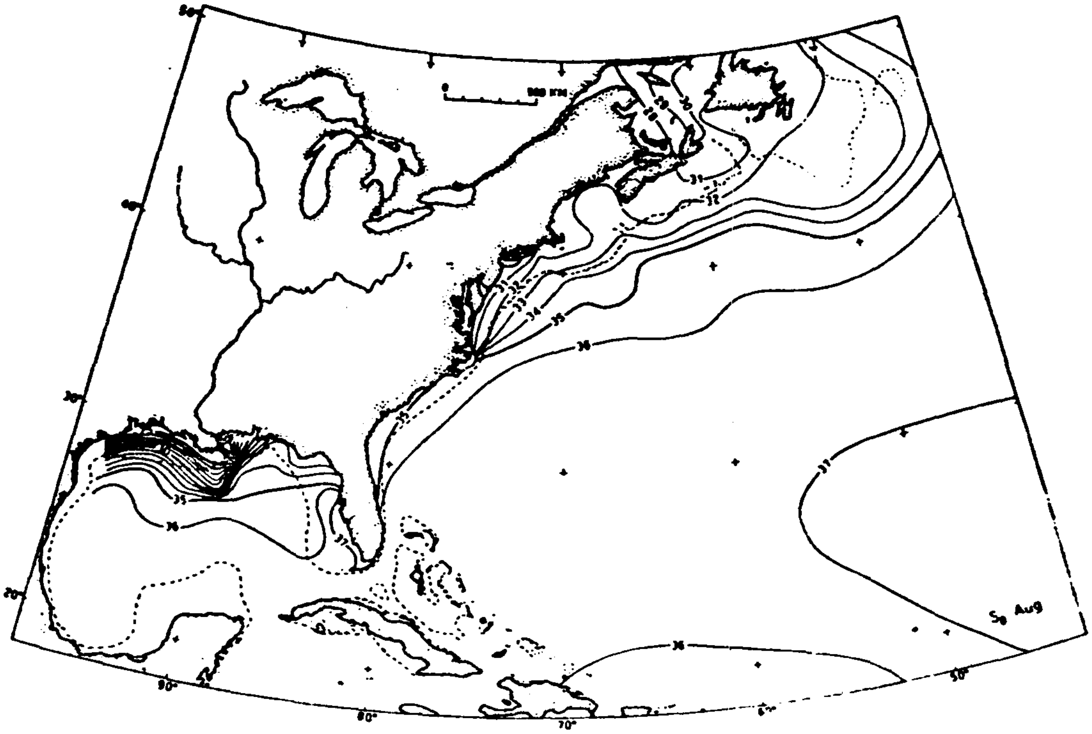
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 4-11 | Sea Surface Temperature Anomaly (°C), August, 1975 (National Weather Service, 1975) (see text)



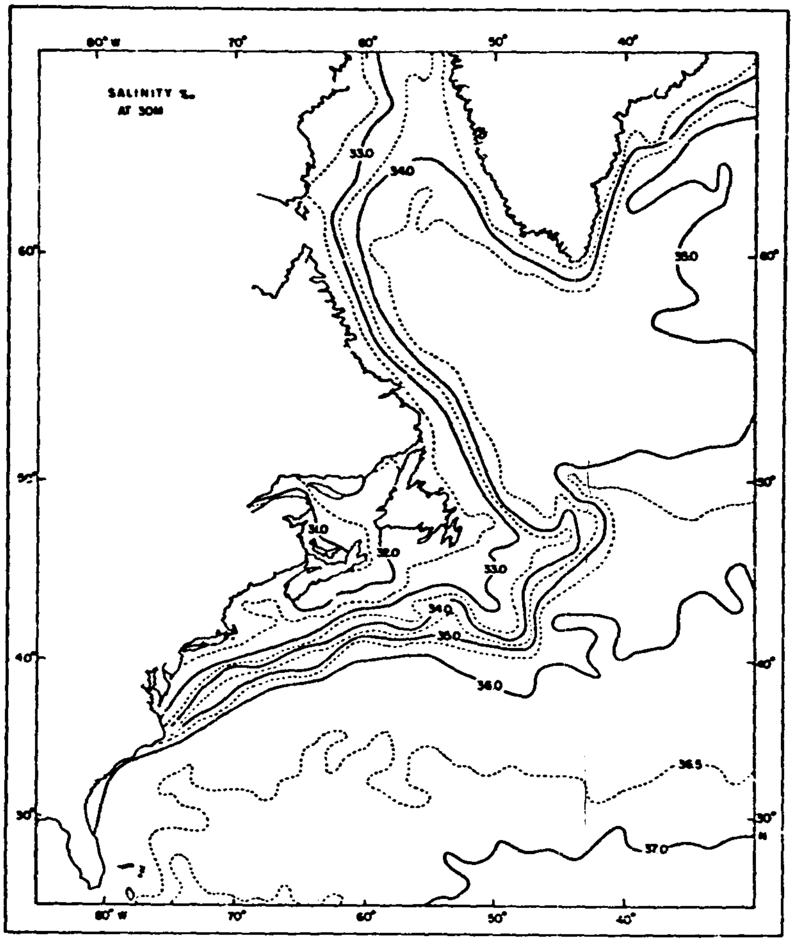
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE** 4-12	Surface Salinity of the Western North Atlantic Ocean during February (Emery and Uchupi, 1972)



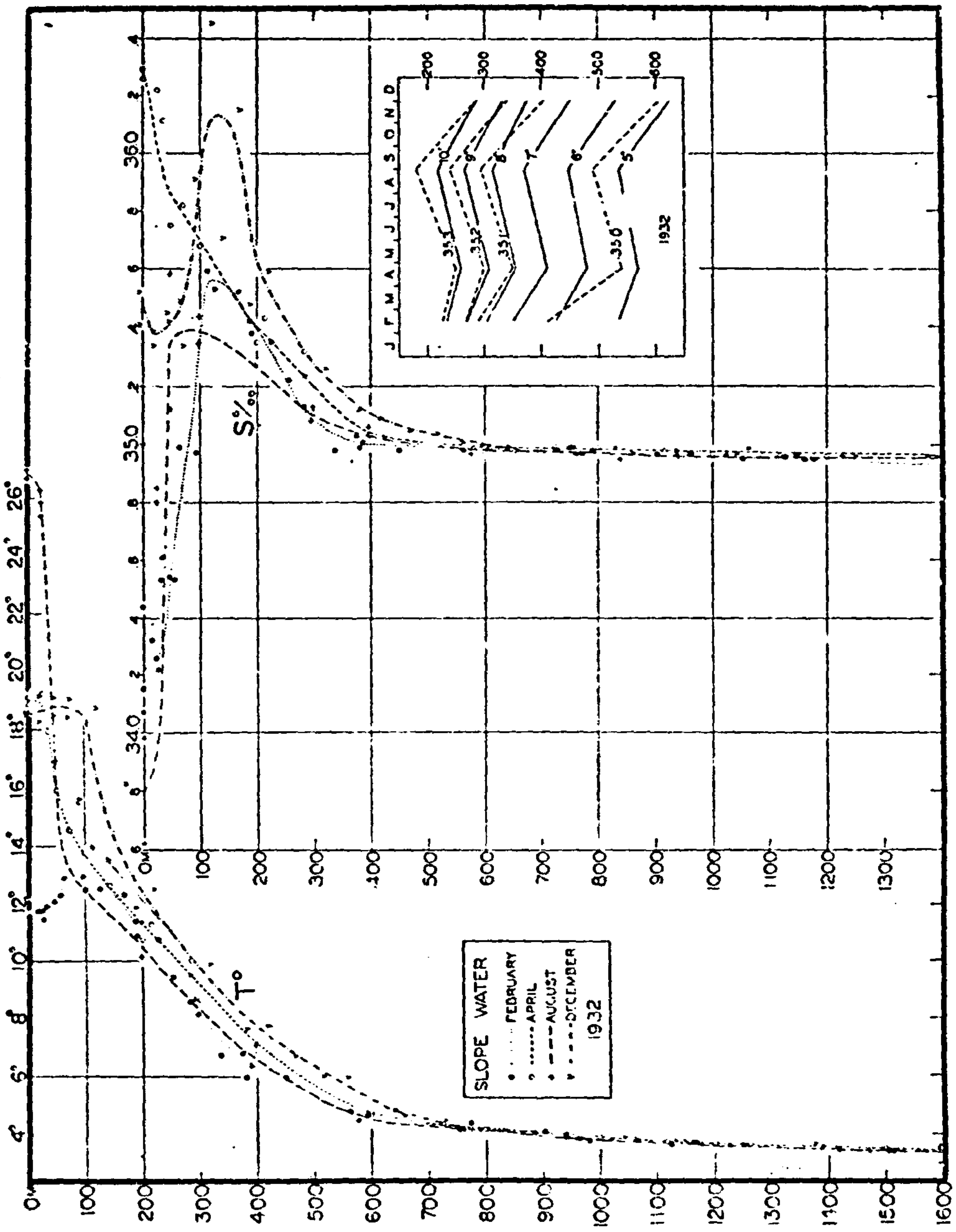
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-13 Surface Salinity of the Western North Atlantic Ocean During August (Emery and Uchupi, 1972)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

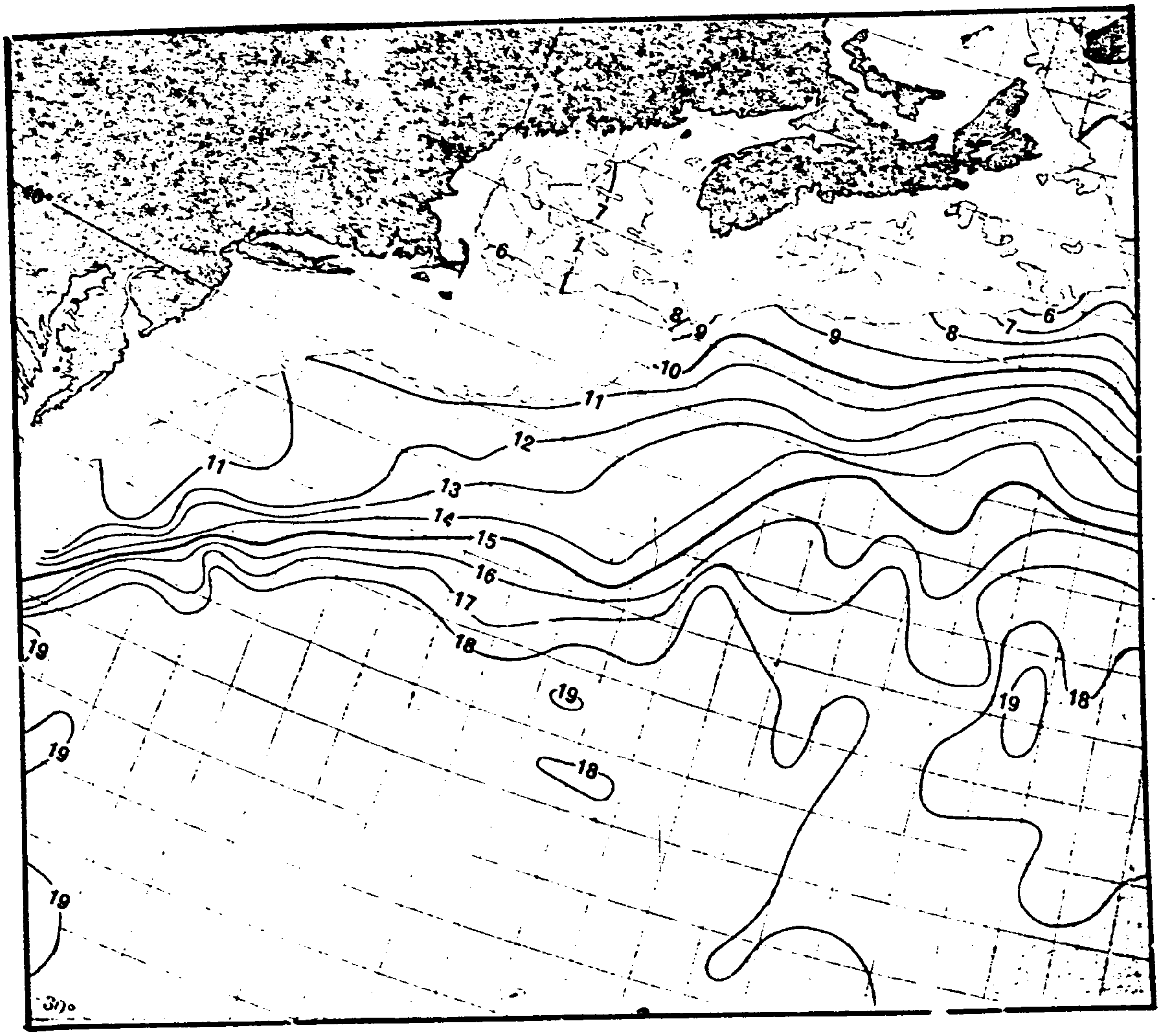
TRIGOM	FIGURE 4-14	Salinity Distribution at 30 m., North Atlantic (Worthington, in press)



The small insert diagram shows the changes at mid-depths plotted against time.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 4-15 | Average Variation of Temperature and Salinity With Depth From Profile to Profile at "Atlantis" Slope Water Stations Off Chesapeake Bay (Iselin, 1936)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-16 Average Temperatures at 200 m in Slope Water (Schroeder, 1963)

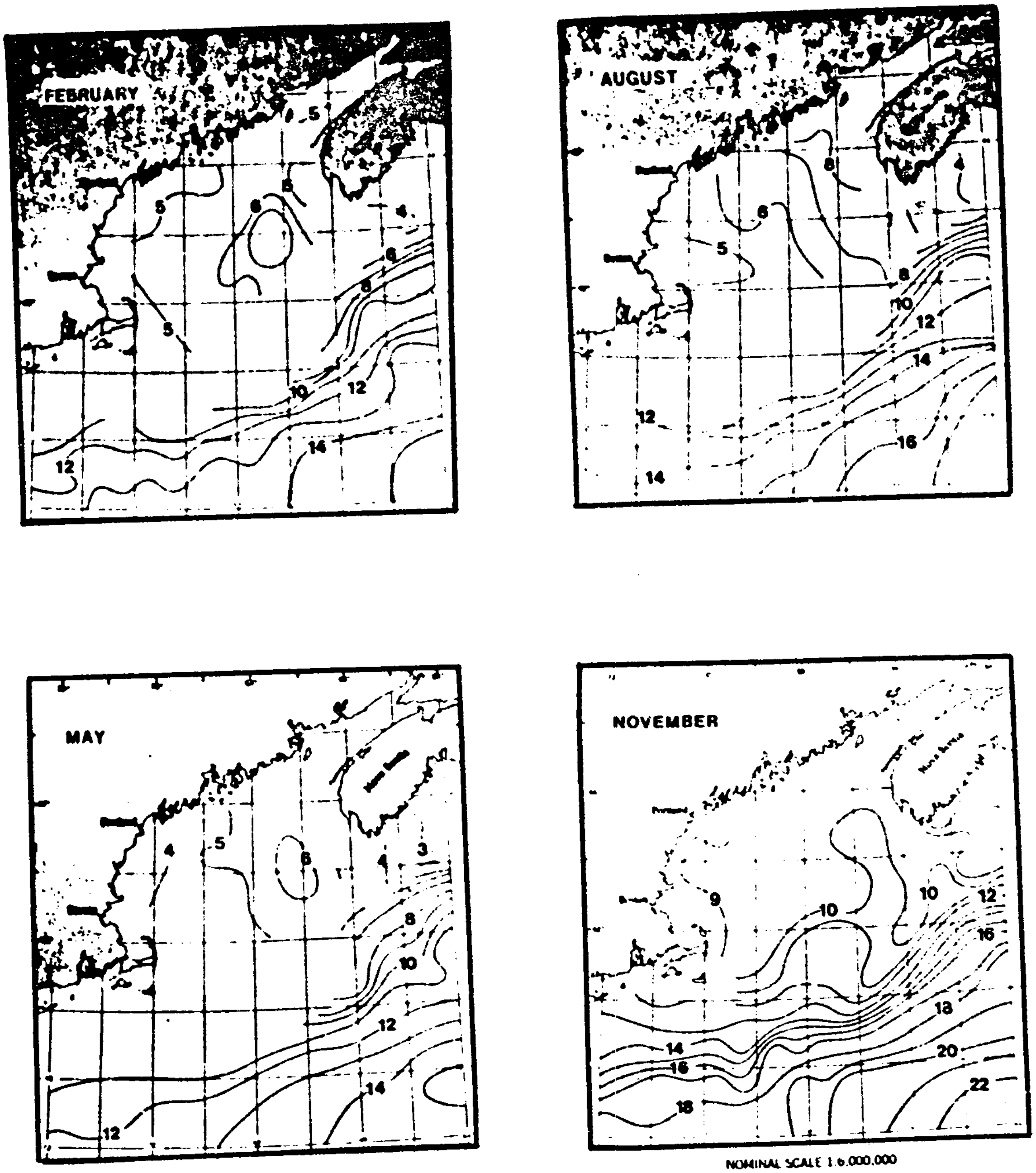
(Figure 4-17). Their charts also show monthly average temperatures at shallower depths (surface, 10, 20, 30, 50, and 75 m) in the region north of 39°N and from 64° to 72°W. The continuity of the temperature structure parallel to the bottom topography is evident throughout. Average monthly north-south temperature profiles to 100 m are shown for every degree of longitude from 64° 30' to 71° 30'. This nicely displays the seasonal changes in the shelf/slope boundary as well as the development of the summer thermocline (Figure 4-18), but it doesn't come close to indicating the complicated shelf edge structure which may exist at any particular time (Figure 4-7). Similar sections to 300 m are provided by Schroeder (1965). It must be remembered that all such vertical sections are drawn with tremendous vertical exaggeration: it is 4000:1 in Schroeder's paper but more customarily 200:1 or 500:1 in other papers; the reader should realize that gradients which appear nearly vertical in the drawing are more nearly horizontal in the ocean.

The monthly progression of temperature in the top 100 m at a slope water location (39° 45' N, 67° 30' W) shows that seasonal variation is most evident in the upper 50 m, with only about 4°C change at 100 m (Figure 4-19).

Strack (1953) analyzed BT crossings of the slope water and drew mean curves (Figure 4-20) of temperature as a function of distance offshore for the sea surface, 100 m depth and 200 m depth. The summer and winter surface curves are parallel but about 6°C apart with the deeper curves following the same pattern except that the gradient at the shelf slope front is less pronounced. On all the curves, the sharp temperature increase at the northern edge of the Gulf Stream is preceded by a slight drop in temperature; this is probably related to the presence of colder shelf water which has been entrained by the Stream at Cape Hatteras (See Section 4.3.2). Despite the similarities of the curves, Strack noted that the surface temperature can be used to locate the subsurface Gulf Stream only in the winter and that it is never a good indicator of deeper temperatures in the slope water. The surface temperature maximum is a better indicator of subsurface Gulf Stream position than the surface gradient; but even that varies from 125 km inshore to 16 km offshore of the 200 m position (Khedouri, 1972).

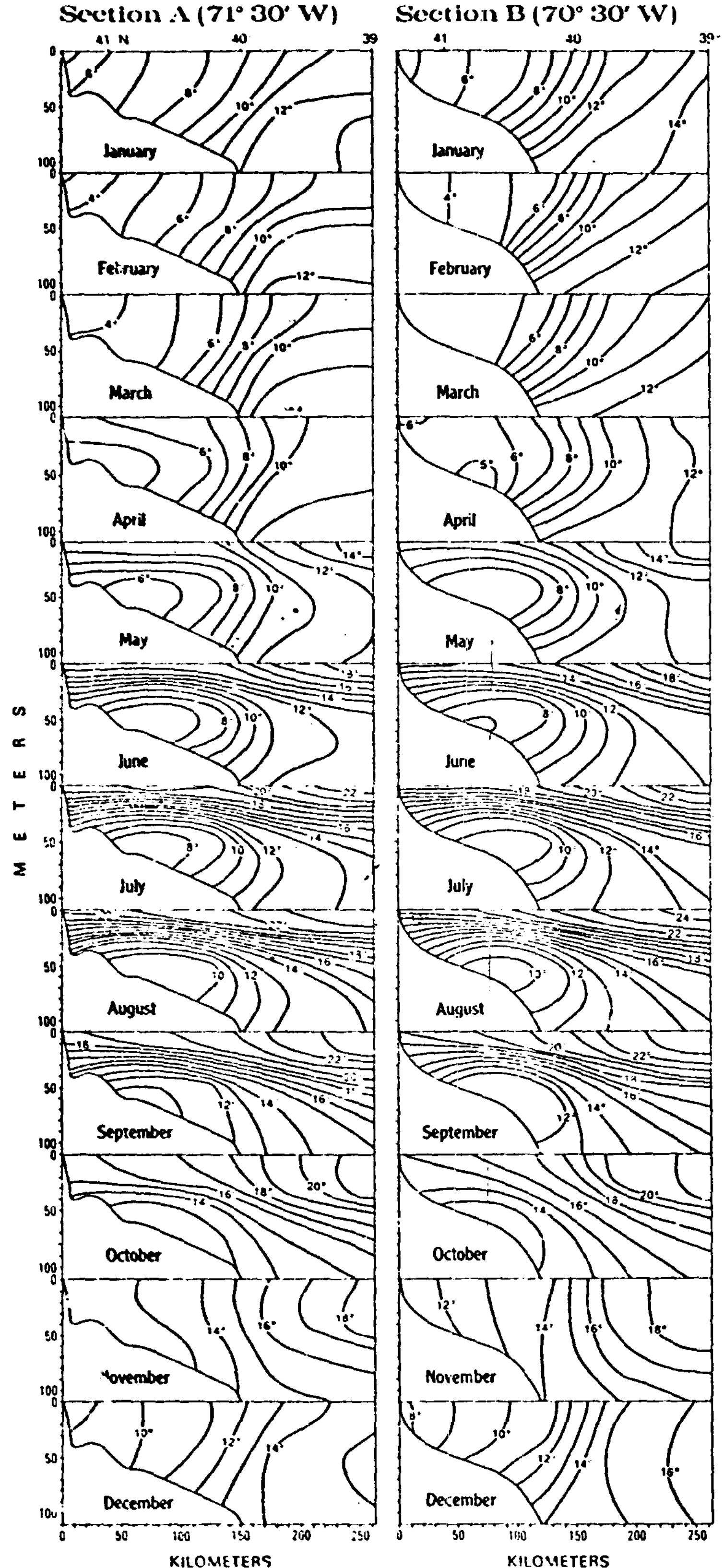
Along the northern edge of the slope water, at the shelf break, there are several notable phenomena:

(1) Shelf water bulge. The boundary that separates the warmer, saltier slope water from the colder, less saline shelf water is not vertical and most of the time there is a wedge of shelf water extending from about the 100 m curve to the sea surface some 30 to 50 km seaward (Wright, 1976). The position of the boundary is highly variable at the sea surface and less so at the sea floor; its mean positions, summer and winter, are shown in Figure 4-21.



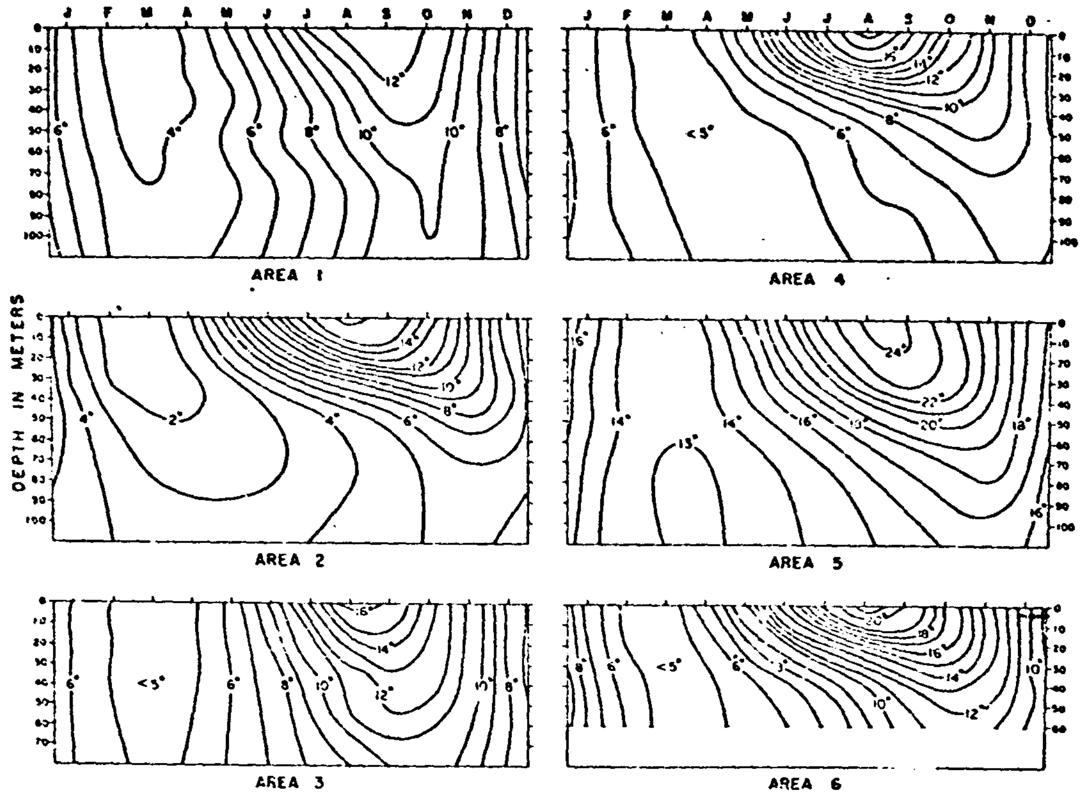
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-17 Average Monthly Temperatures at 100 meters (Colton and Stoddard, 1972)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

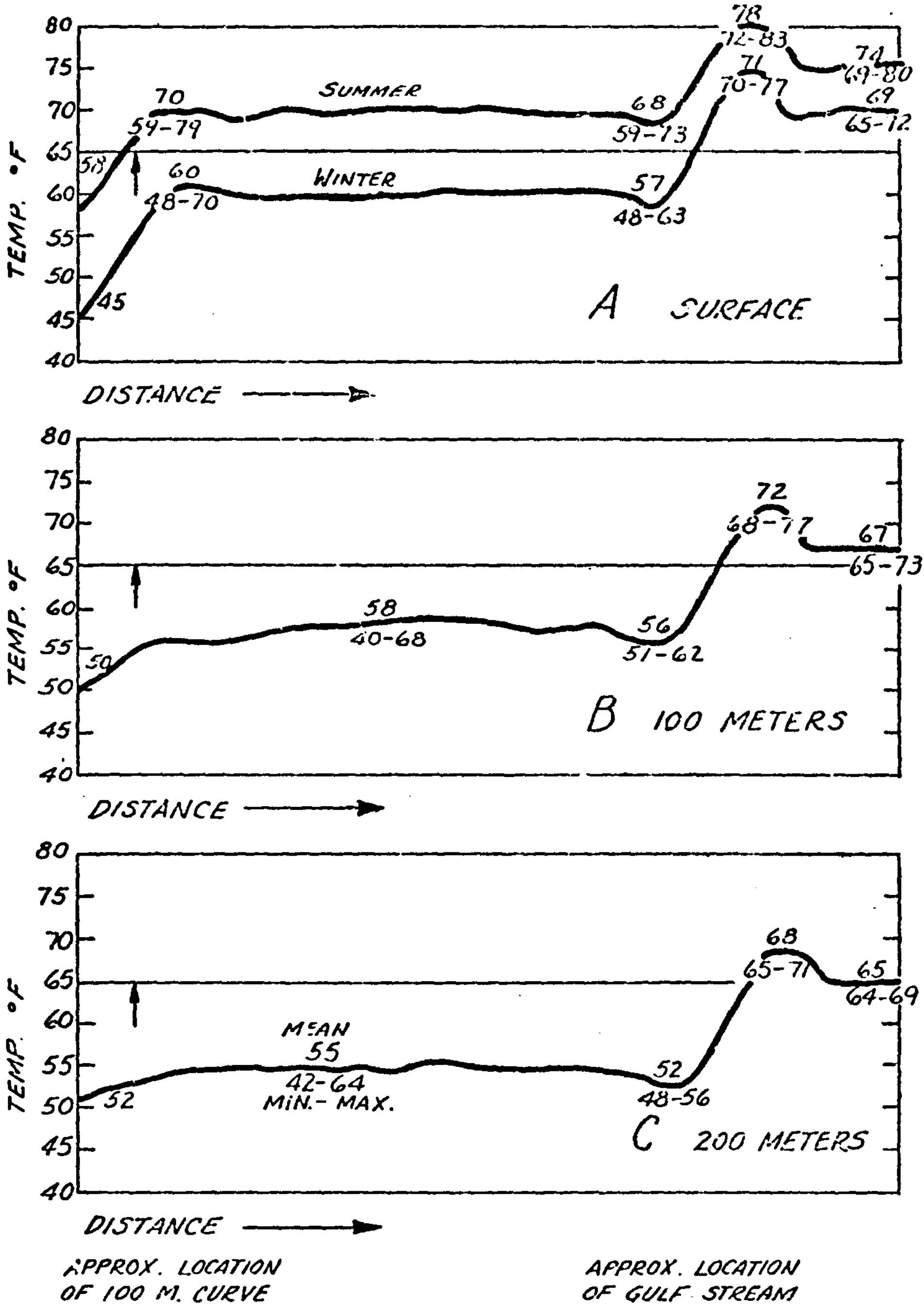
TRIGOM	FIGURE 4-18	Temperature Profiles at Shelf/Slope Boundary (Colton and Stoddard, 1972)



The slope water location (Area 5) is at 39°45'N, 67°30'W.

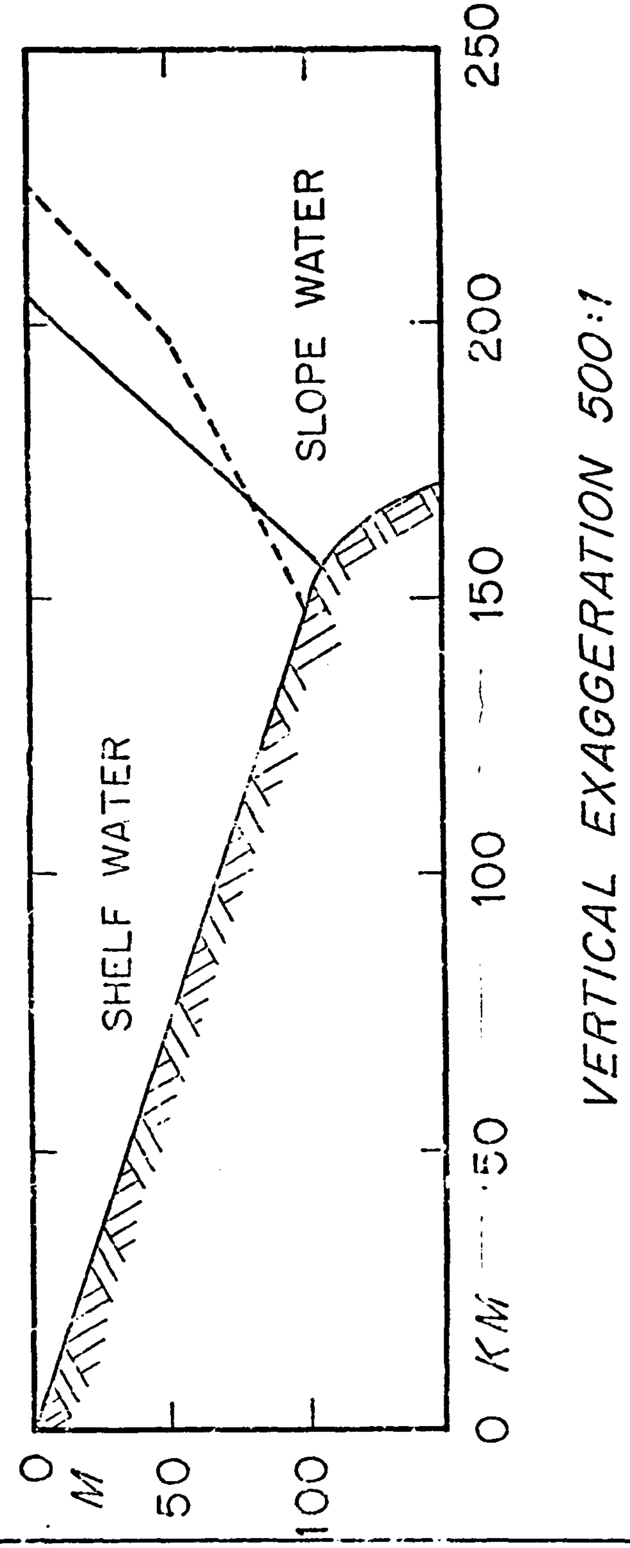
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-19	Monthly Progression of Temperature in Top 100 meters (Colton and Stoddard, 1972)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-20	Mean Temperature Distance Curves Across Slope Waters (Strack, 1953)



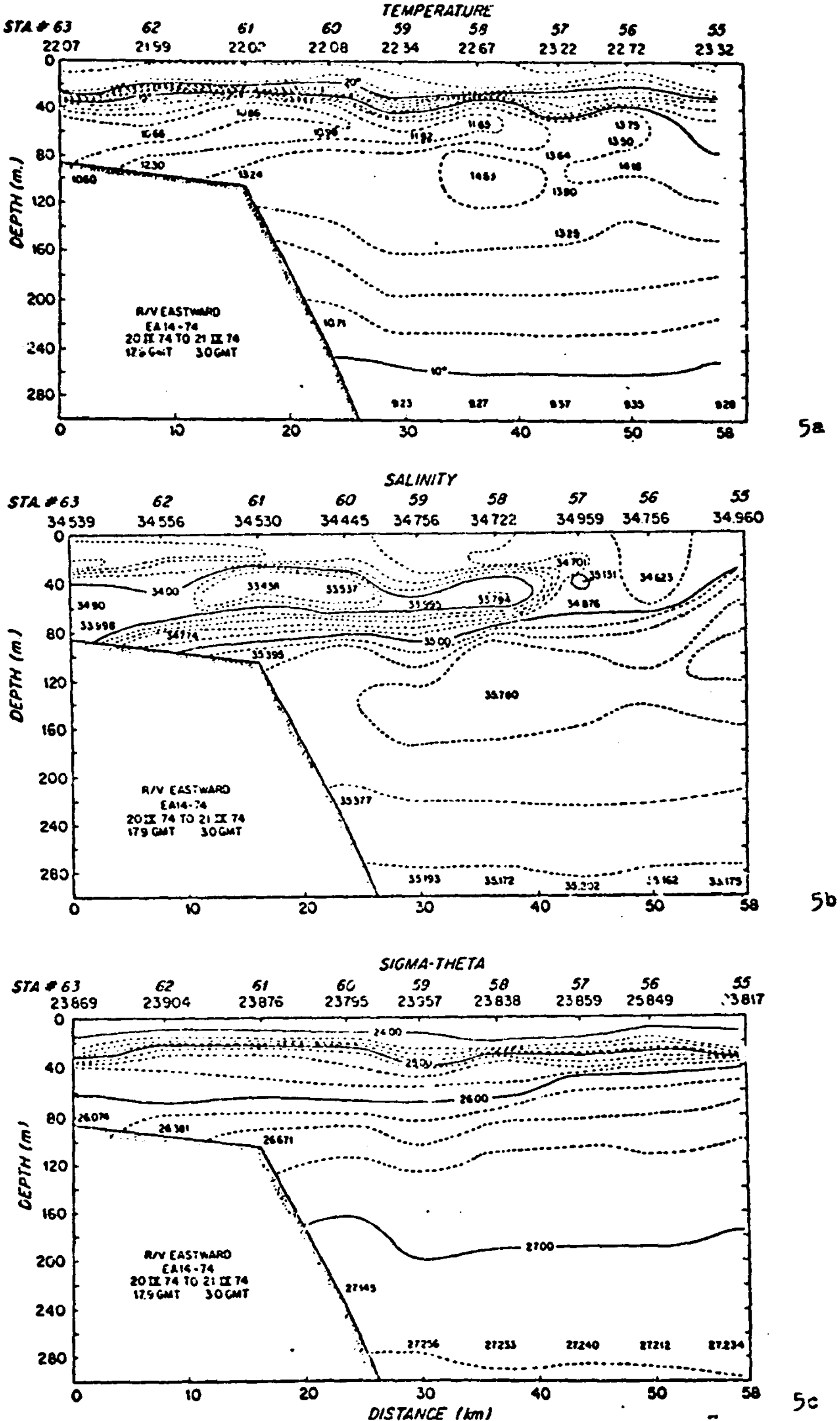
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-21 Location of Shelf/Slope Boundary (Wright, 1976)

(2) Cold Water Pool. Part of the shelf water bulge is water that has been cooled by winter convection and storms so that it is colder than the slope water immediately below; there is no density inversion because the shelf water salinity is much lower than that of the slope water. In the summer, this cold water is overlain by the seasonal thermocline so that it appears as a tongue at depths of 50 to 80 m (Figure 4-22); the cold water is also of low salinity so that the density structure is relatively undisturbed. The temperature in the cold tongue can be as low as 6°C and the salinity less than 33 o/oo. The water warms slowly during the summer but usually retains its identity until renewed by the winter cooling cycle (Ketchum and Corwin, 1964; Wright, 1976).

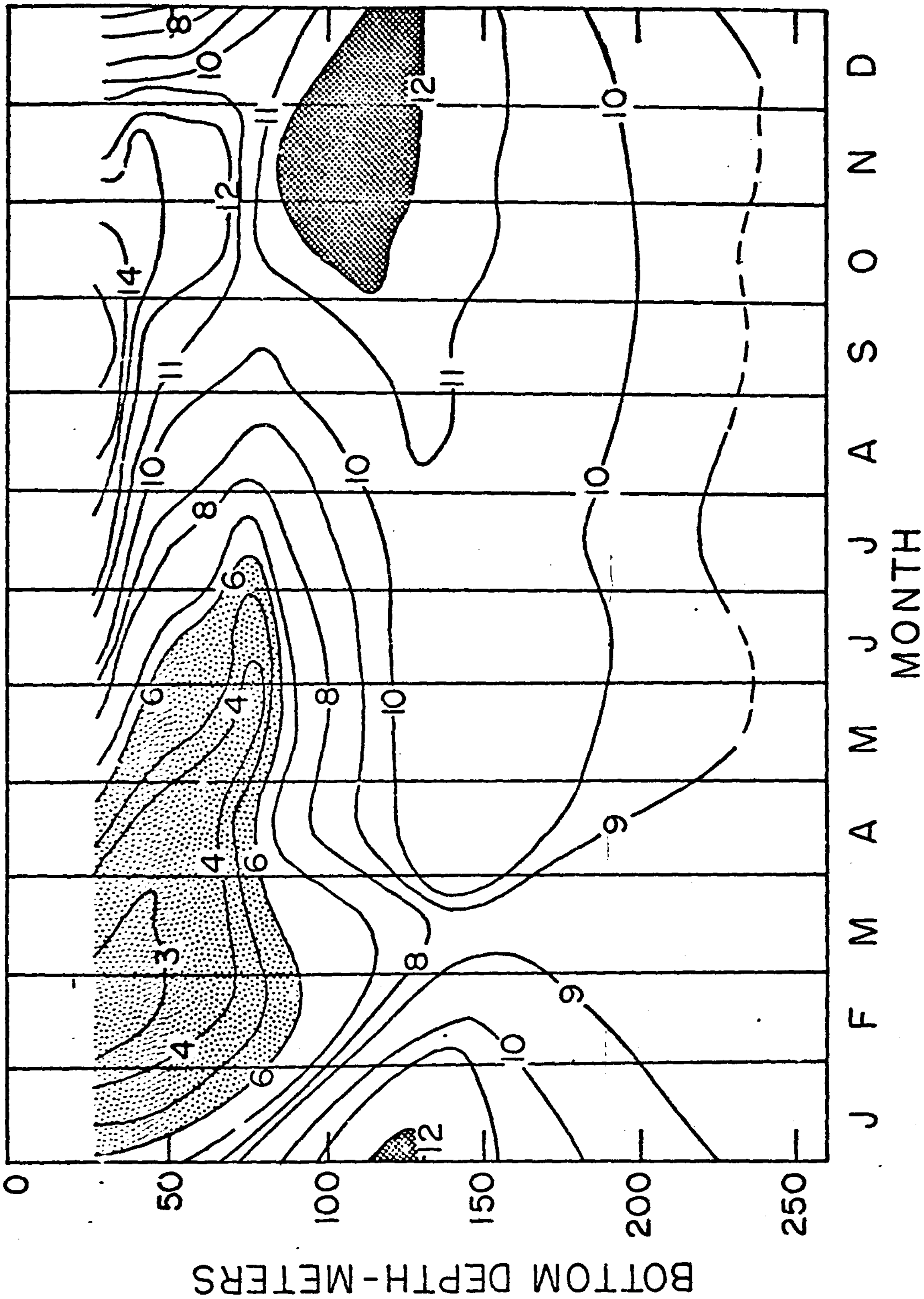
(3) Warm Band. Because of the shelf water bulge there is a temperature maximum zone some 40 to 80 m thick centered at about 120 m depth near the edge of the shelf and usually associated with a salinity maximum of about 35.5 o/oo (Figure 4-22). This feature exists throughout the year and creates a band of warm water on the sea floor at the shelf break. This band of water appears to be related to the presence of a number of commercially important demersal fish species in that region (Edwards, et al., 1962). A plot of mean monthly bottom temperatures from 20 to 250 m in depth (Figure 4-23) shows a temperature range from 9 to 12°C in the warm band (4 to 11°C in the overlying cold pool); however, individual years can vary widely: in 1974, the temperature in the warm band never fell below 12°C (Chamberlin, 1975). Below the warm band the bottom temperature decreases steadily and seasonal influences are absent.

(4) Homogeneous Bottom Layer. Introduction of the expendable BT, STD, and other instruments capable of continuous vertical profiling close to the bottom have revealed the existence of another feature of the shelf edge which has come to be known as the Homogeneous Bottom Layer (HBL). It is a layer of water up to 30 m thick in which there is little or no vertical change in temperature or salinity. Similar layers have also been observed in the abyssal ocean (Millard, 1974) and in the Straits of Florida (Weatherly and Niiler, 1974). These layers may be more common than presently believed. In the most extensive study of the shelf edge HBL to date (Parker and Wright, personal communication), it was present in about one-third of more than 500 XBTs deployed. The HBL was found in depths ranging from 70 to 250 m and occurred on both sides of the shelf/slope boundary. The layer was at its thickest about four miles north and south of the boundary and became thin or absent in the immediate vicinity of the boundary (Figure 4-24). Temperatures in the HBL ranged from 11.9°C in the shelf water up to 14°C in the slope water and were nearly 13.0°C at the boundary; (oceanographically, it was an exceptionally warm year). Also, bottom drifters in the HBL region inshore



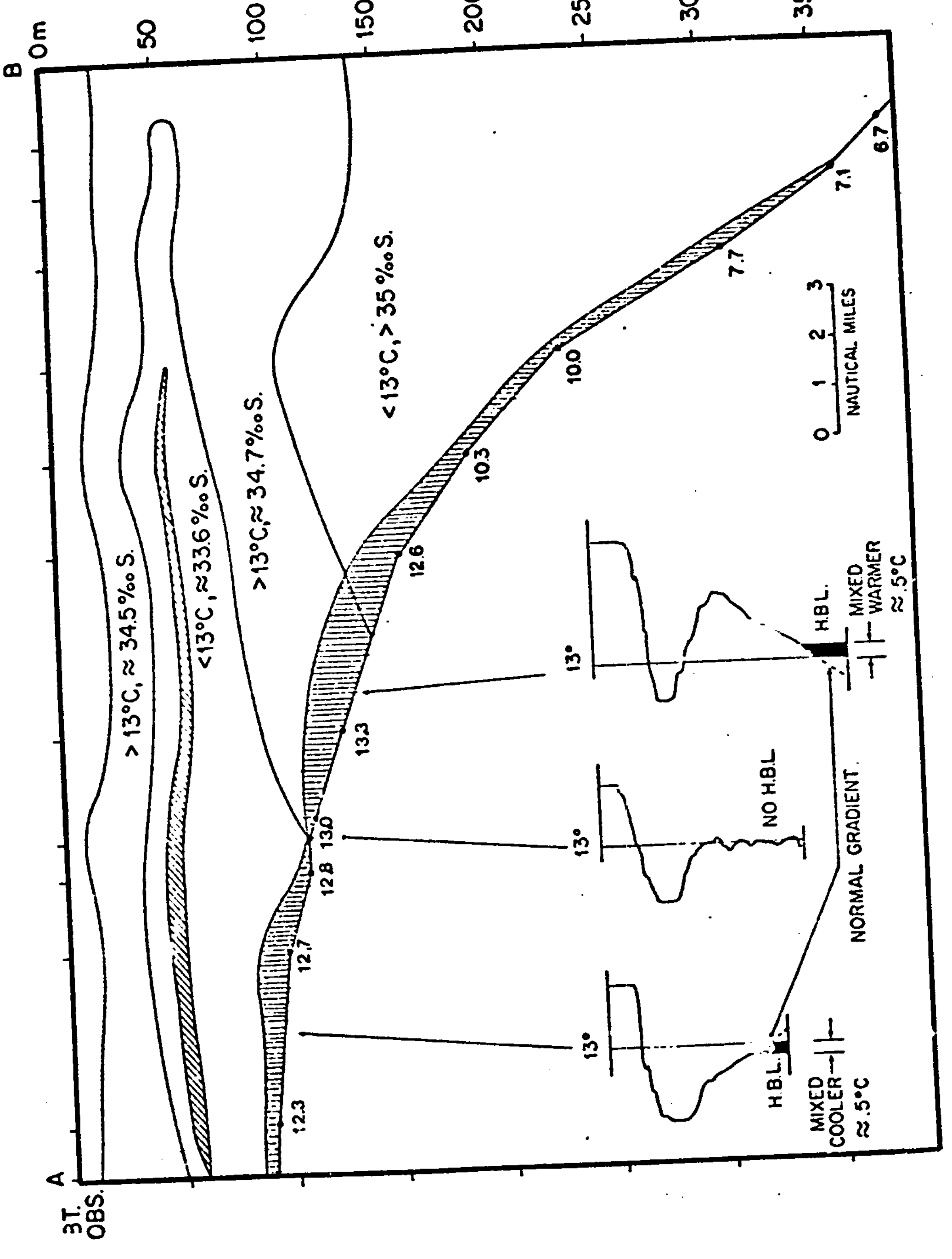
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-22 The Distribution of Temperature, Salinity, and Sigma-Theta in September, 1974, South of Cape Cod (Parker, 1975)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-23	Mean Monthly Bottom Temperatures on the Continental Shelf and Slope South of New England, 1940-1966 (Chamberlin, 1975)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-24	Schematic of Homogenous Bottom Layers and BT Traces and Their Relationship to Position and Shape of the Cold Tongue of Shelf Water and Interior Isothermal Layer (Parker, 1975)

of the boundary have shown a seaward component of motion (Bumpus, 1965). Several possible explanations have been advanced for the HBL (Parke, 1972): shoaling of internal waves which "break" at a critical bottom slope; generation of baroclinic tides at the shelf break; a boundary layer resulting from a geostrophic current of about 10 cm/seconds; and double diffusion processes resulting from the superposition of a cold, fresh layer over a warm, salty layer on a slope. Some experimental support does exist for the breaking internal wave theory (Cacchione, 1970) and observers have witnessed vertical motions as large as 50 m in the slope water at the shelf break (Voorhis, 1974).

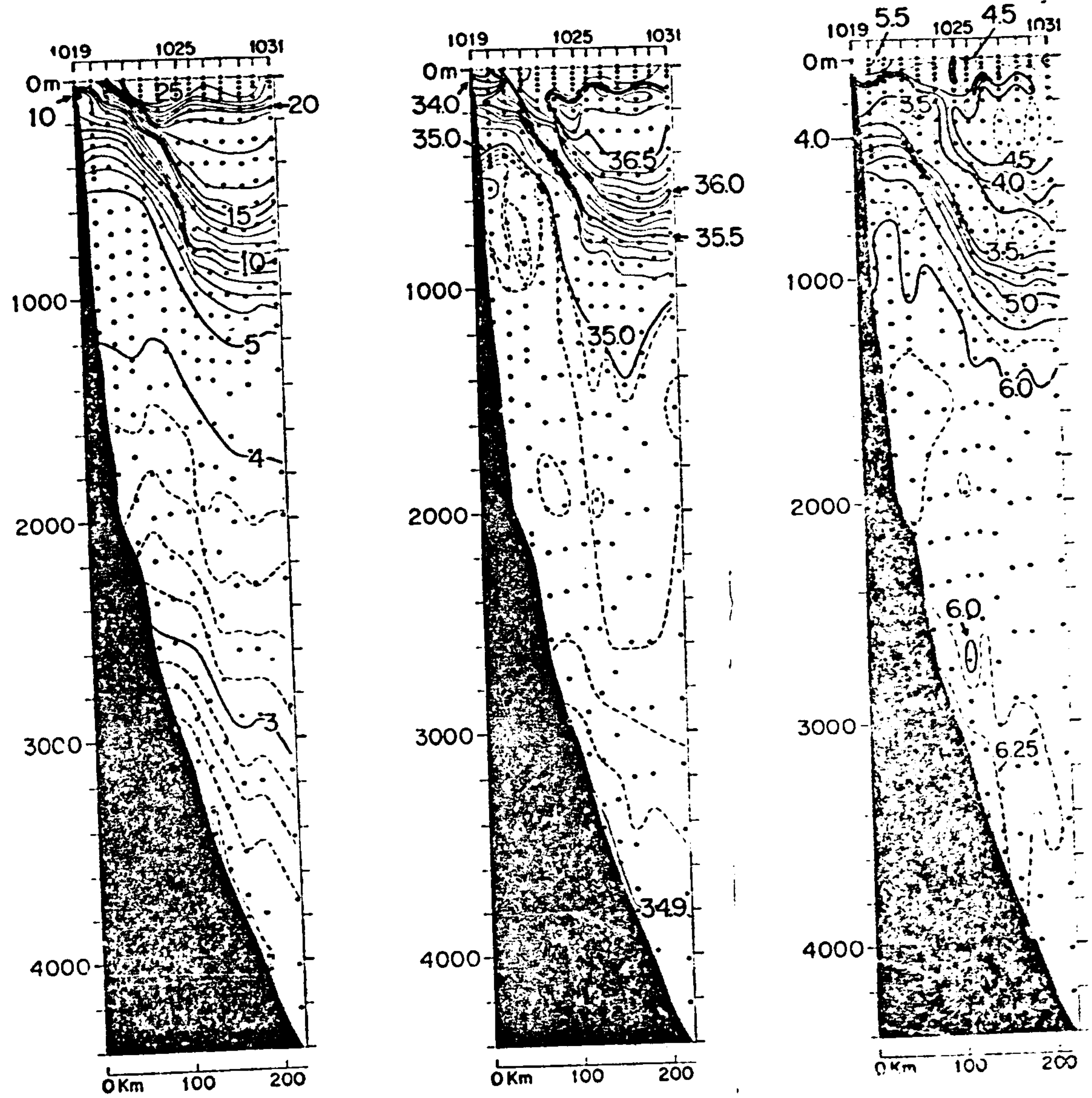
4.2.3 MAIN THERMOCLINE

The main thermocline in the slope water begins below both the cold pool and the warm band previously mentioned at a depth of about 200 m and extends down to 500-600 m. It is roughly delineated by the 5°C isotherm. (For this, and the succeeding section, it will be helpful to refer to the temperature, salinity, and oxygen sections - Figures 4-25 to 30 - which start in the vicinity of Cape Hatteras and progress eastward to 64° 30'W). In the thermocline region, the temperature gradient is about 1°C to 80 m depth; in contrast with this, a gradient of about 1°C in 1000 m exists in the deep water. The halocline, a decrease in salinity from about 35.7 to 35.0 o/oo, coincides roughly with the thermocline but is centered in a somewhat shallower area; from Cape Hatteras eastward there is also a general freshening in the halocline of perhaps 0.02 o/oo. Also associated with the thermocline is the oxygen minimum with values usually between 3.0 and 3.5 milliliters per liter and with the higher values being in the east (Figure 4-31).

The most striking characteristic of the thermocline and halocline is the sharp increase in depth across the Gulf Stream so that the same values are found about 700 m deeper in the Sargasso Sea. This characteristic is clearly seen by comparing typical traces for temperature and salinity on both sides of the Stream (Figure 4-32).

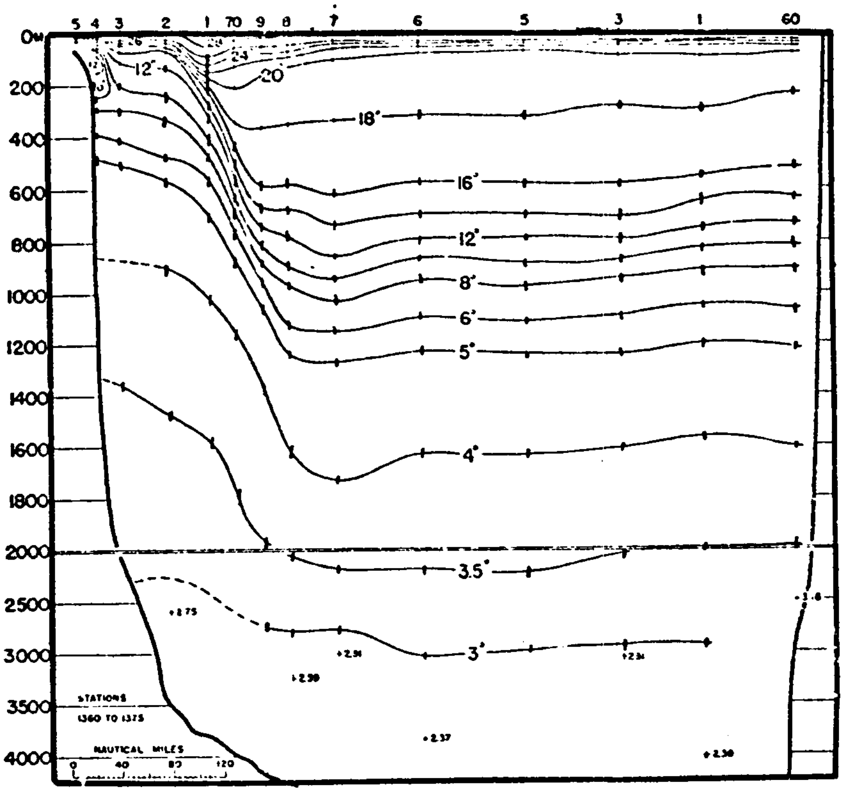
4.2.4 DEEP WATER

Below the thermocline, temperature continues to decrease with increasing depth down to a minimum of about 2.2°C at about 4,000 m; below that depth, there is a slight increase, perhaps as much as 0.01°C. This apparent warming is a result of high pressure at great depths; if the pressure effect were removed, the temperature (called potential temperature in that case) would continue to decrease regardless of depth. Salinity also decreases as depth increases, but not quite so smoothly as the temperature; however, the salinity gradient is very small - about 0.1 o/oo in 3000 m - and oxygen increases to about 6.3 ml/l. Even in the deeper layers there is a pronounced gradient across the Gulf Stream.



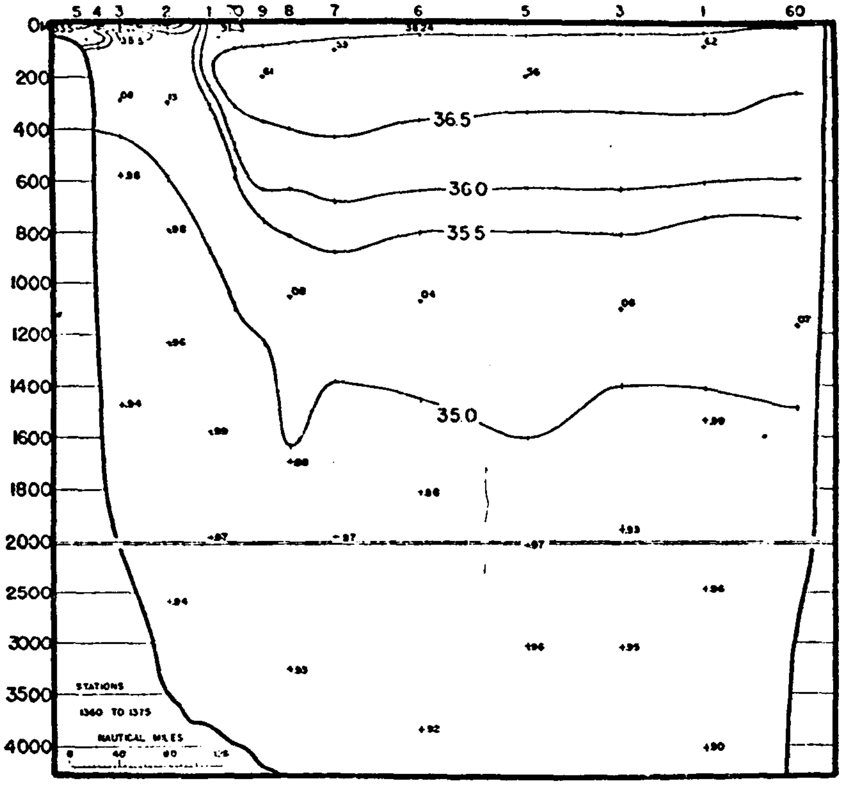
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-25	Temperature, Salinity, Oxygen Sections Across Slope Water (Worthington and Kawai, 1972)



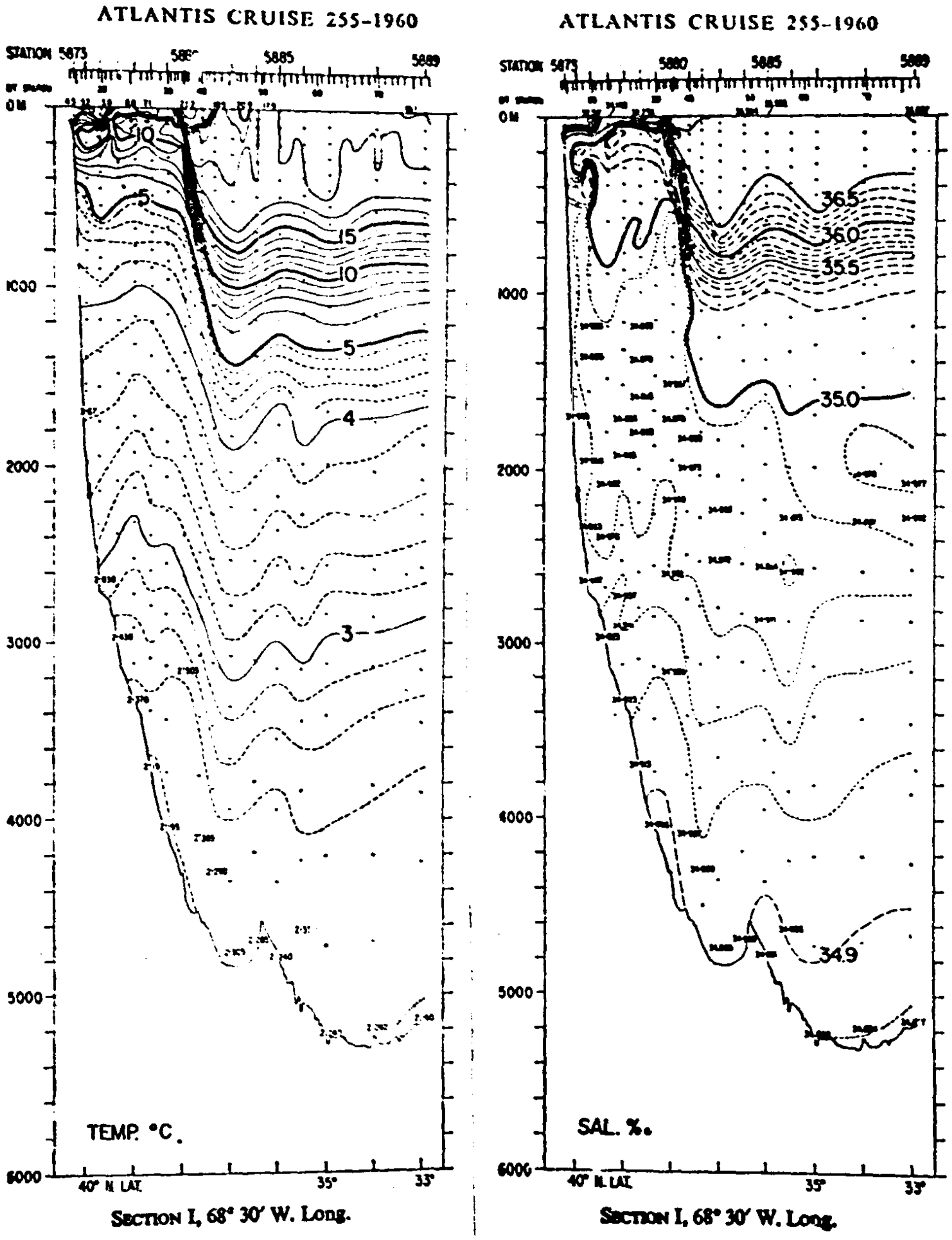
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-26	Temperature Section, Chesapeake Bay-Bermuda August 28-Sept. 3, 1932 (Iselin, 1936)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

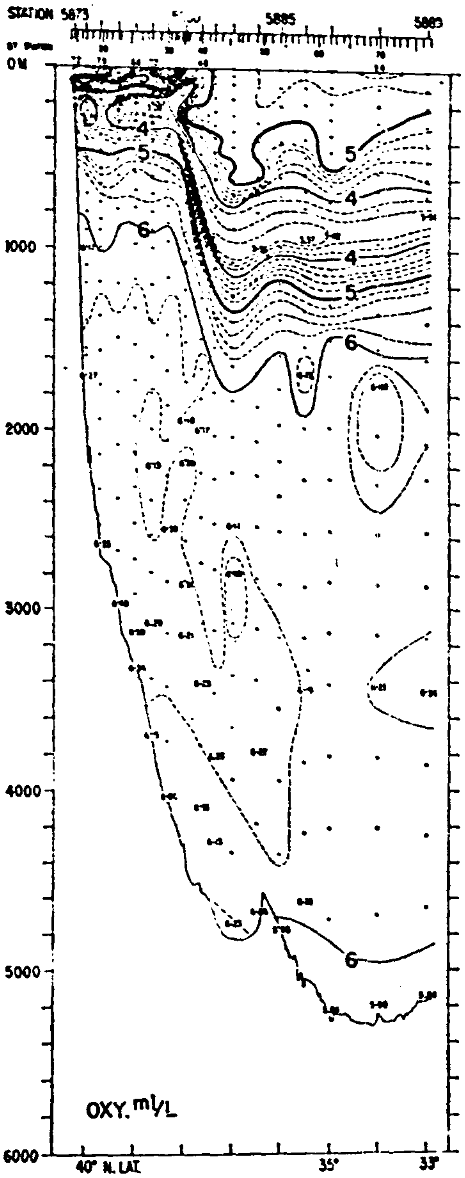
TRIGOM	FIGURE 4-27	Salinity Section, Chesapeake Bay-Bermuda August 28-Sept. 3, 1932 (Iselin, 1936)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-28	Temperature and Salinity Sections Across Slope Water (Fuglister, 1963)

ATLANTIS CRUISE 255-1960



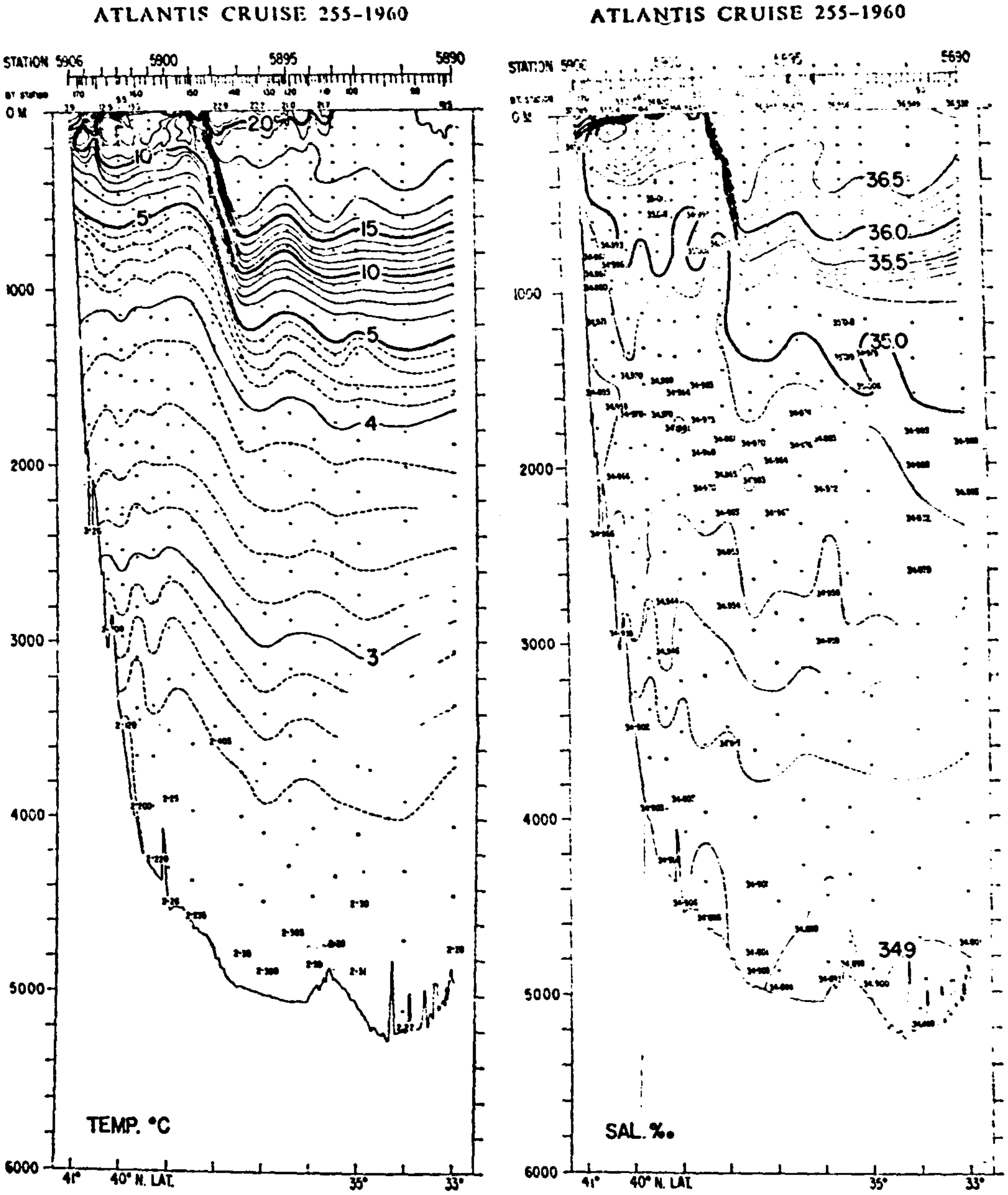
SECTION I, 68° 30′ W. Long.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 4-28c

Oxygen Section Across Slope Waters (Fuglister, 1963)



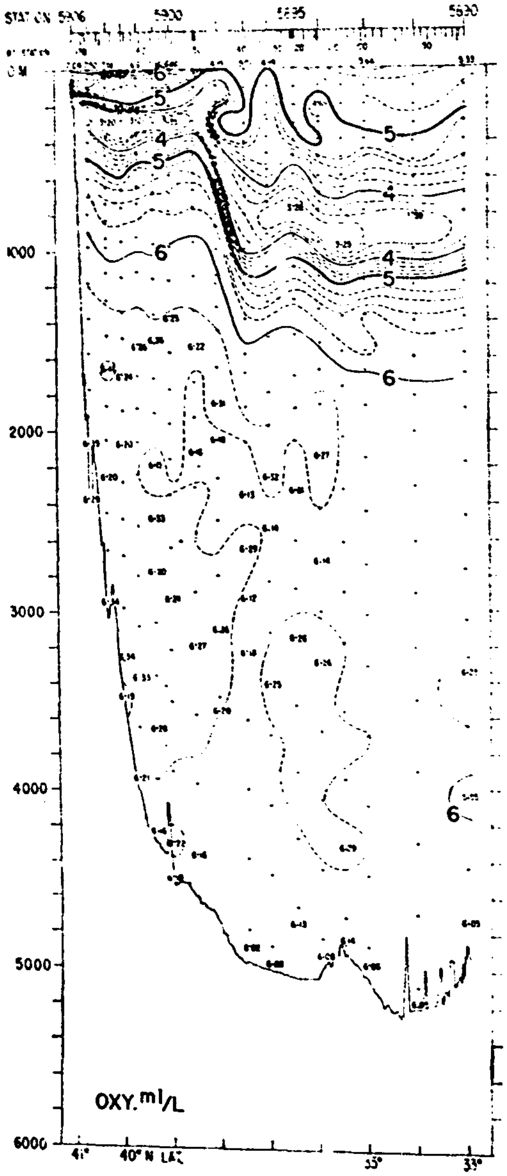
SECTION II, 66° 30' W. Long.

SECTION II, 66° 30' W. Long.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-29 a&b	Temperature and Salinity Sections Across Slope Water (Fuglister, 1963)

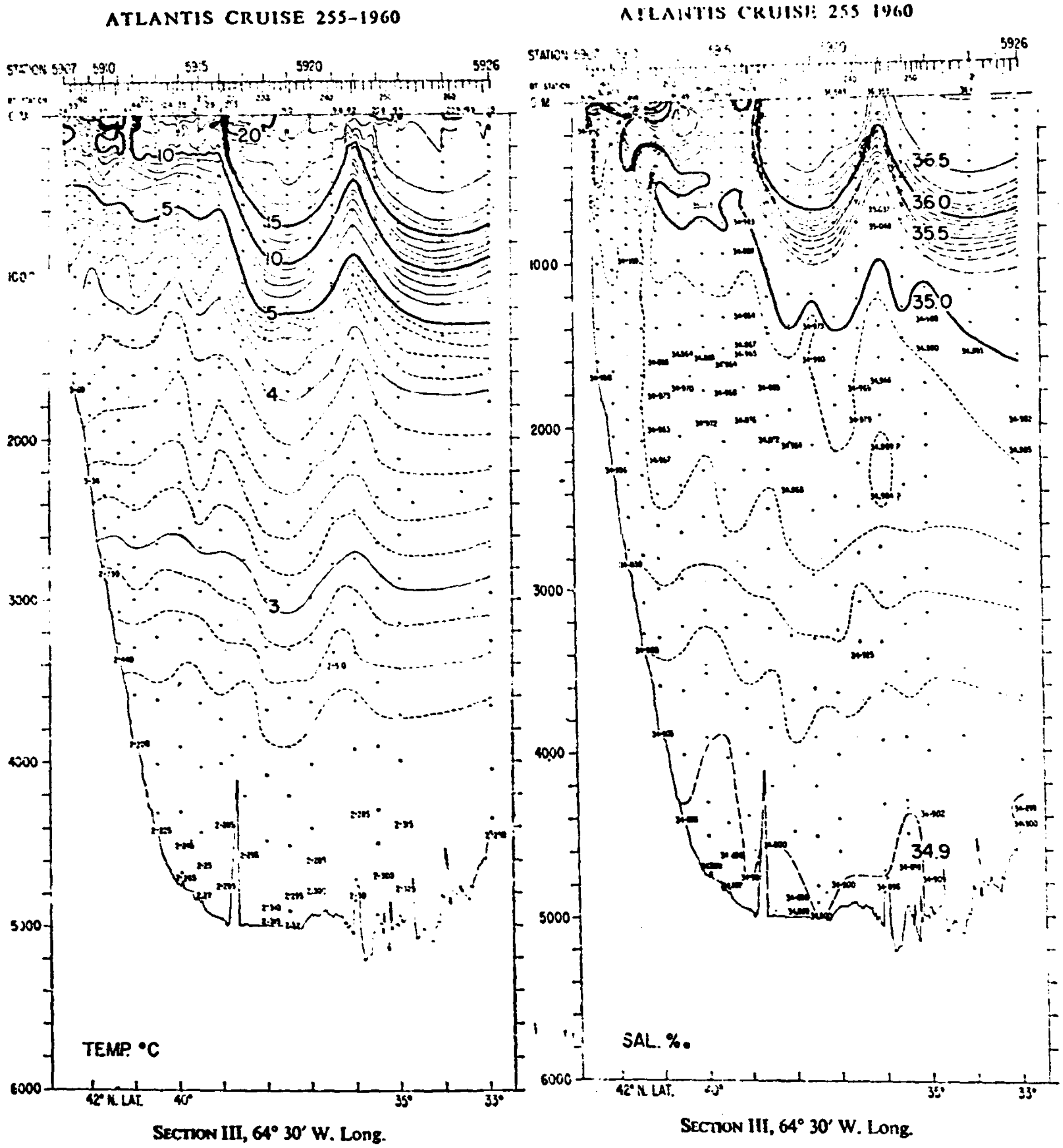
ATLANTIS CRUISE 255-1960



Section II, 66° 30′ W. Long.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

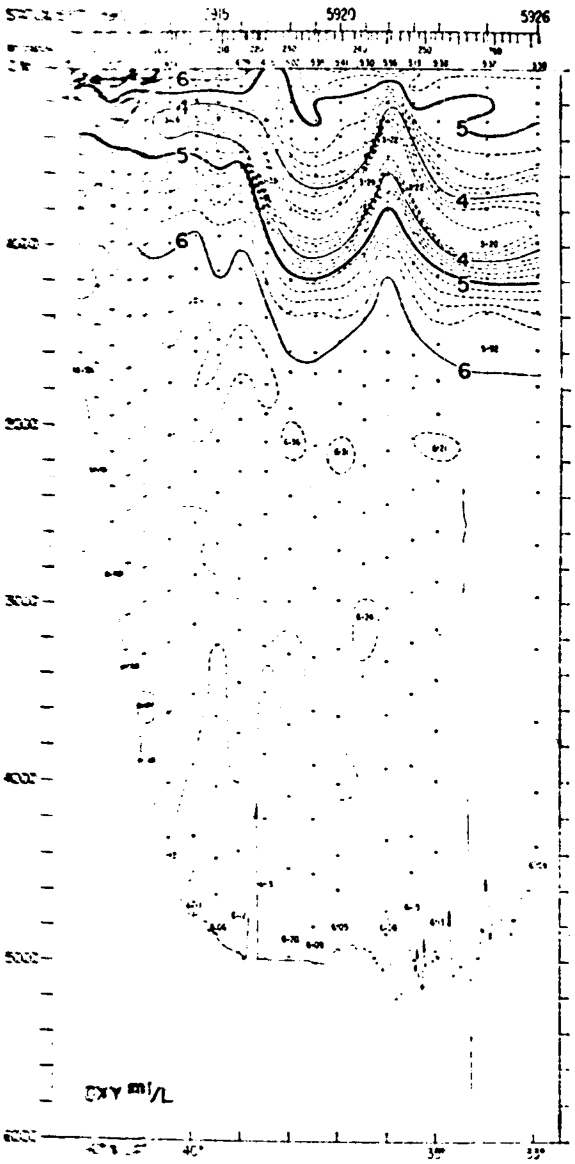
TRIGOM	FIGURE 4-29 C	Oxygen Section Across Slope Water (Fuglister, 1963)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-30 a & b	Temperature and Salinity Sections Across Slope Water (Fuglister, 1963)

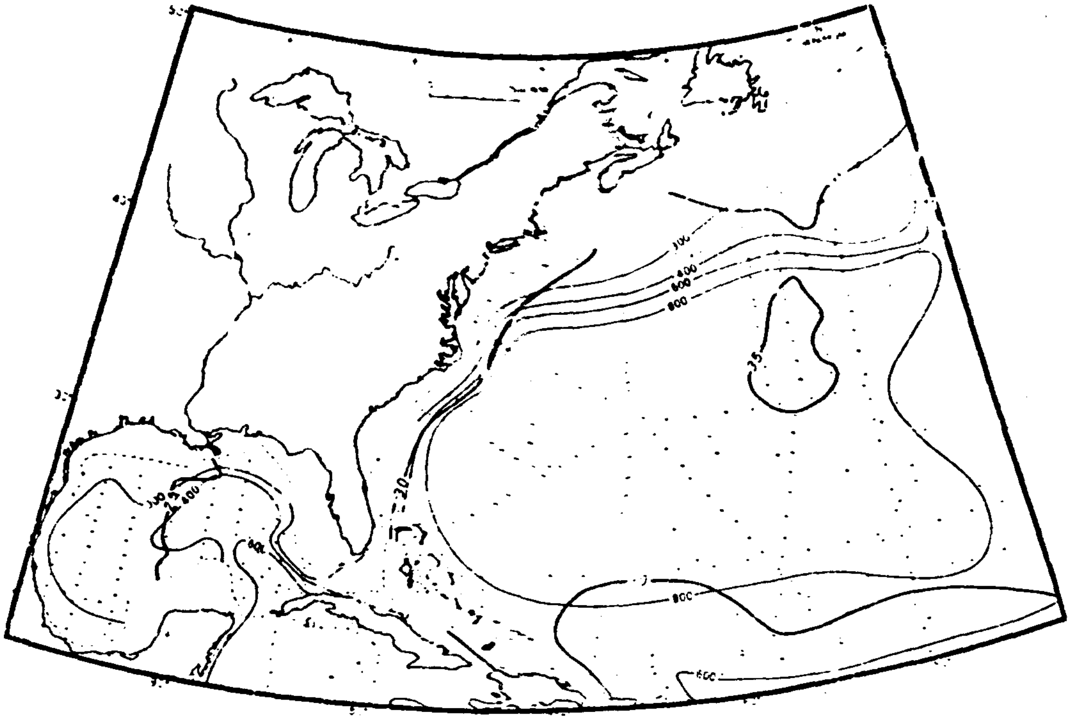
ATLANTIS CRUISE 255-1960



Section III 64° 30' W. Long.

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE [illegible] | Oxygen Sections Across Slope Water (Fuglister, 1963)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-31	Depth of Oxygen Minimum in Meters and Minimum Content of Oxygen in ml/l (Emery and Uchupi, 1972)

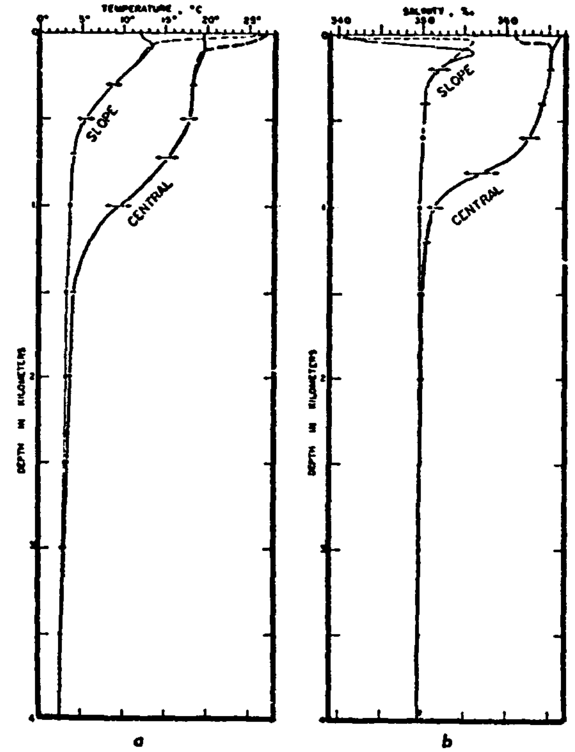


FIGURE 4-32

Temperature and Salinity Soundings on Either Side of the Gulf Stream (Stommel, 1958)

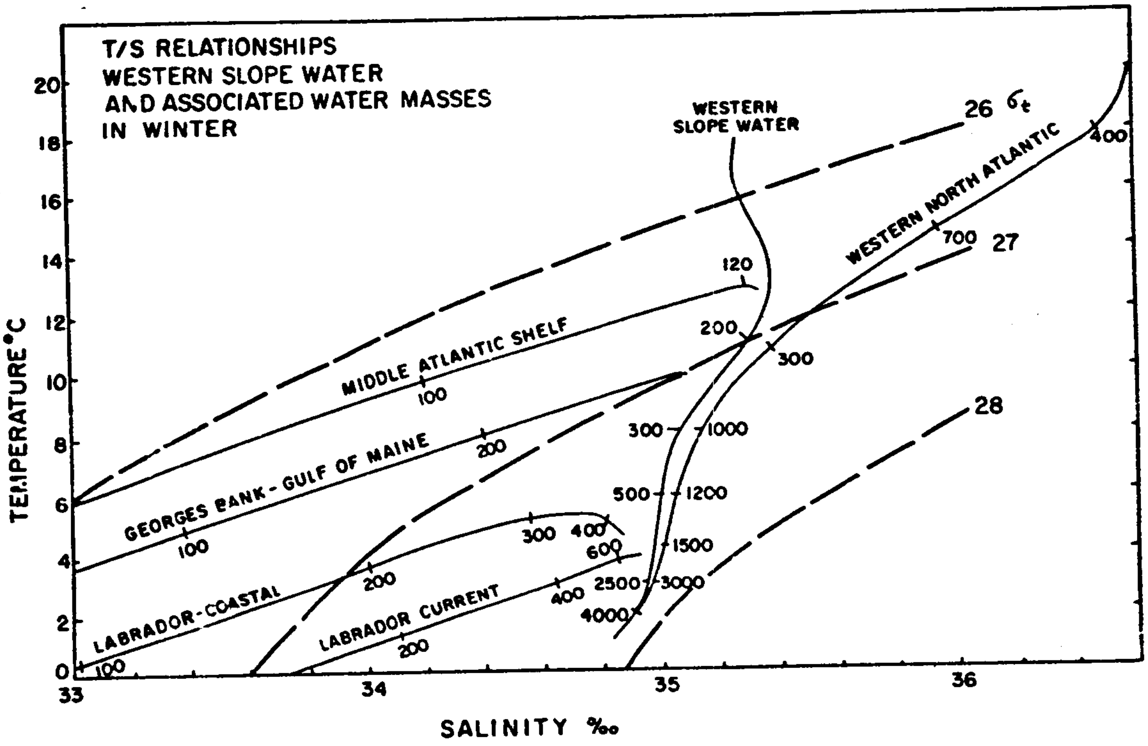
The salinity and oxygen maxima and minima, though not always discernible at individual stations, are persistently present and are diagnostic of three distinct water masses of northern origin. The shallowest of these, marked by a salinity minimum (< 34.98 o/oo) between about 4.5°C and 6°C, has been named Subarctic Intermediate Water or North Atlantic Intermediate Water. It is apparently formed in the southern part of the Labrador Sea by relatively fresh, cold surface water sliding under the warmer, more saline Atlantic water along a density surface of about 27.6 sigma-t (Lazier, 1973). There is a second salinity minimum, around 34.96 o/oo in the temperature range 3.5°C to 4°C (roughly 1400 to 1800 m), which is associated with an oxygen maximum of about 6.25 ml/l at a density of about 27.8 sigma-t. This water mass is formed at the surface of the Labrador Sea in the winter time, either by sinking along density surfaces or by convective overturning (Lazier, 1973). It is called Arctic Intermediate Water or Labrador Sea Water, the latter being less confusing. Finally, there is a lower oxygen maximum, also around 6.25 ml/l at temperatures below 2.4°C and salinities below 34.94 o/oo. This represents the core of the Western Boundary Undercurrent and originates as water flowing out of the Norwegian Sea across the sills between Greenland and Scotland. Note that traces of origin for all three of these water masses can be seen in the deeper waters of the Gulf Stream. This is an indication that some of the water transported by the Gulf Stream comes from the slope water (Warren and Volkmann, 1968; Lambert, 1974).

Nutrient values in the slope water tend to be the inverse of oxygen distribution: they are low in the surface layer where oxygen is high, reach a maximum at the depth of the oxygen minimum in the main thermocline, diminish in the lower thermocline, and change very little in the deep water. There is also a west-to-east decrease in silicate in the very deepest sections which will be considered in the section on circulation.

Suspended sediments are generally low in the slope water (MacIlvaine, 1973); however, there are two regions with high levels near the bottom. One is in the vicinity of the shelf break and the other is at depths below about 2,500 m along the lower continental slope and rise (Eittreim, Ewing, and Thorndike, 1969). In between, on the upper continental slope, suspended sediment is low, even close to the bottom.

4.2.5 TEMPERATURE - SALINITY RELATIONSHIP AND DENSITY

Except for incursions of coastal and Gulf Stream water and the seasonal variations near the surface, there is a definite relationship between temperature and salinity in the slope water. Furthermore, because temperature and salinity are the two factors which determine the density of sea water, the density of subsurface slope water is closely related to the temperature. These relationships are shown in Figures 4-33 and 34. Figure 4-33 gives characteristic T/S curves for slope and shelf water, coastal water from several locations, the Labrador Current,



Numbers within figure indicate depth in meters

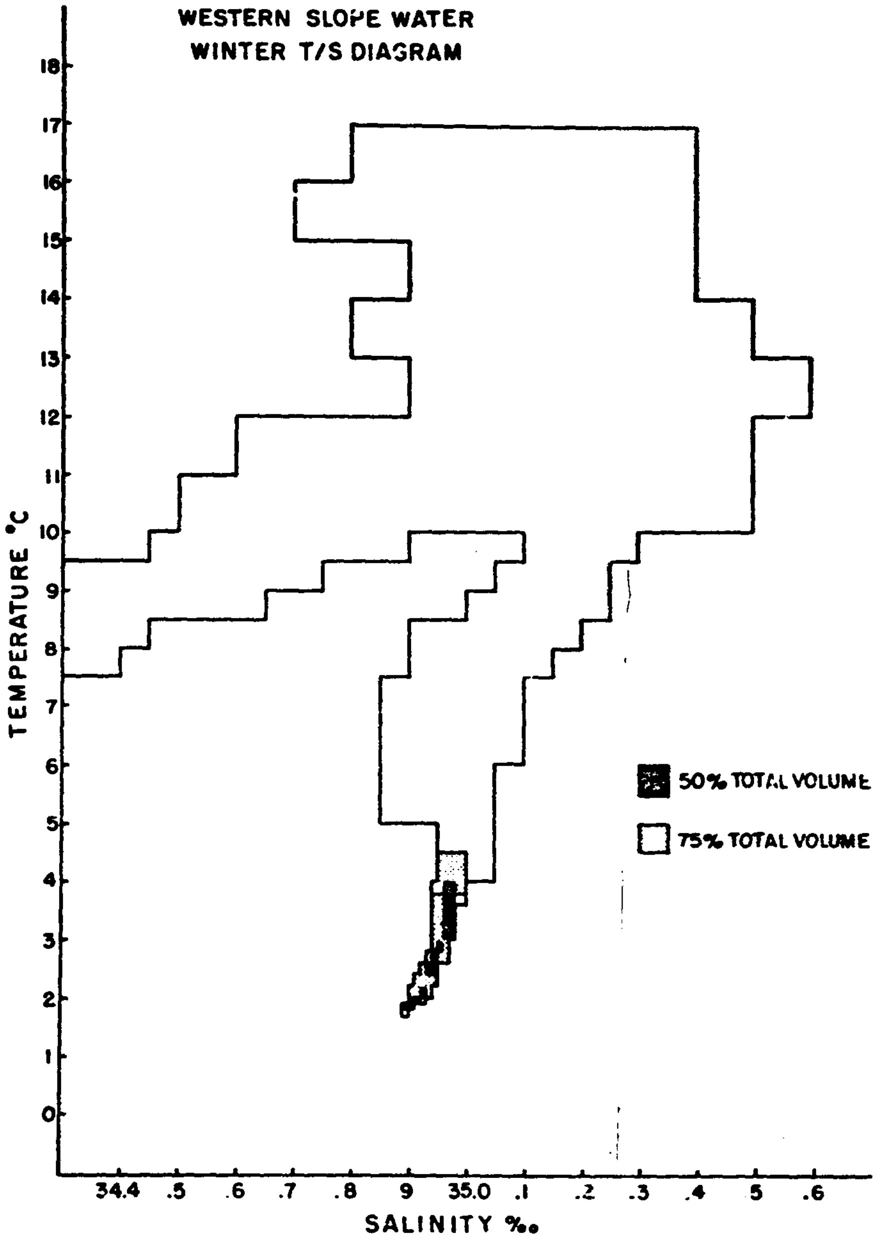
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-33	T/S Relationships Western Slope Water and Associated Water Masses in Winter

and western North Atlantic Water, which is characteristic of both the Gulf Stream and the Sargasso Sea. Density lines (sigma-t) and some indication of the depth are included. The principal features are: the slope water curve is very similar to that for western North Atlantic water; it is fresher by 0.02 to 0.1 o/oo at all temperatures; and the points on the slope water curve occur several hundred meters shallower than the corresponding points on the western North Atlantic curve. The similarity between the two curves indicates a close relationship between the water masses. The lower slope water salinity indicates an admixture of fresher water of northern origin, and the depth difference is a reflection of the Gulf Stream's role as a dynamic boundary between the slope water and the Sargasso Sea. The salinity difference between slope water and western North Atlantic water increases toward the east. a reflection of the east-west gradient within the slope water itself. Note that the Middle Atlantic Shelf and Georges Bank-Gulf of Maine curves, although relatively cold, are everywhere less dense than 27.0 sigma-t. This restricts them to the upper layers of the ocean. Labrador-Coastal water (sometimes called Scotian Water) occasionally invades the western slope water region, but unmodified Labrador current water is never found there.

The winter envelope of temperature-salinity observations in the western slope water is given in Figure 4-34. The summer situation, which is not shown, affects only the warmer surface layers. The relationship between temperature and salinity is very tight below 5°C and relatively consistent below 10°C (the tail of fresher water at 8°C to 10°C represents coastal intrusion); it is only above the thermocline that temperature is not a reliable indicator of salinity. Most of the water is concentrated in a very narrow range of temperature and salinity: the black region in the figure represents 50 percent of all the slope water and the hatched region 75 percent.

A density section through the slope water (Figure 4-35) looks much like those for temperature and salinity, except that the gradients across the Gulf Stream are not so strong. This is because the density effect of decreasing salinity tends to counteract that of decreasing temperature. Note that the vertical density gradient in the deep water is very slight indeed - only one sigma-t unit (or 1 gm/l) in three km - and the horizontal gradient is even smaller. Nevertheless, these small differences support geostrophic currents of considerable magnitude. (The density section shown here does not include the effect of increasing pressure; if it did, it would consist of equally spaced horizontal lines everywhere below the surface layers and the value at 5,000 m would be about 50 sigma-t units. The pressure effect is linear and virtually the same everywhere in the ocean, which is why it is omitted).



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-34	Winter Envelope of Temperature-Salinity Observations in the Western Slope Water

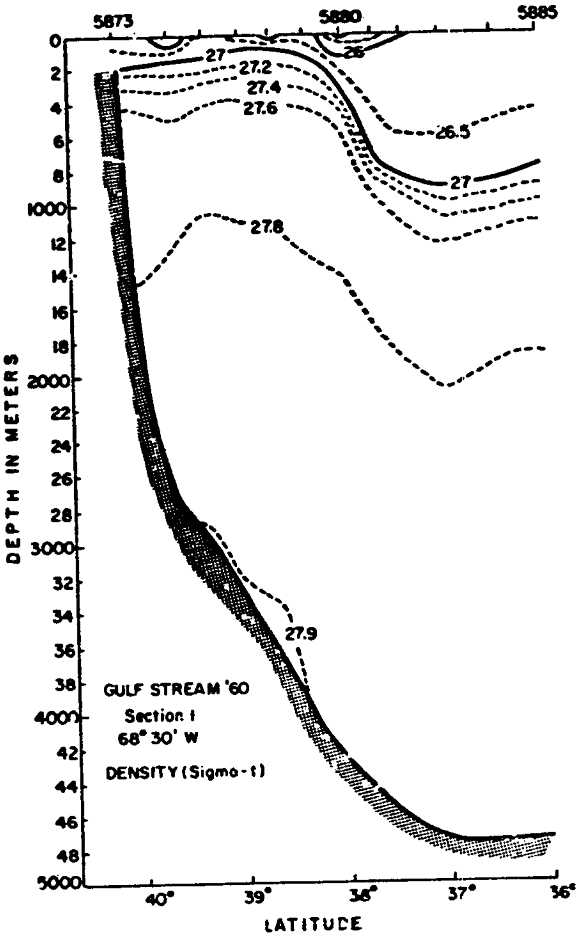


FIGURE 4-35 Density Sections Through the Slope Water

4.3 WATER MASS VARIABILITY

The foregoing section describes the western slope water as if it were a relatively stable oceanic environment, but that is not the case. Western slope water is strongly influenced by variations in the Gulf Stream and, to a lesser extent, in the surface layers by events along the shelf water boundary. In addition to this, there is evidence of occasional, massive incursions of alien water from the northeast. These complications are described below.

4.3.1 THE GULF STREAM

At Cape Hatteras the Gulf Stream moves off the Blake Plateau, about 800 m deep, into the deep ocean; when it crosses the 66th meridian it is in 5,000 m or more. Throughout this distance it appears to be a continuous current reaching from the sea surface to the bottom (Fuglister, 1963), but with pronounced variation in character and position.

TRANSPORT VARIATIONS

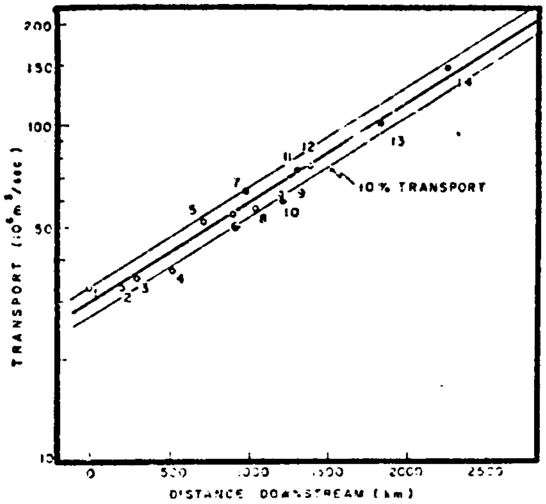
From a relatively shallow stream carrying about 60 sverdrups (a sverdrup, abbreviated sv, is one million m^3/sec.), the Gulf Stream increases to a transport of about 150 sv south of Georges Bank (Barrett, 1965; Richardson and Knaus, 1971; Fuglister, 1963). Beyond 65°W the transport begins to diminish again. It is about 110 sv at the 50th meridian and drops below 60 sv further east. These large changes in volume transport - first, a doubling and then a halving of this largest of all ocean currents - requires massive interaction with the surrounding waters. Most of the increase between Cape Hatteras and 65° W is in the deep water, colder than 4°C (Table 4-1). It is believed that most of the cold water is drawn from the deep Sargasso Sea and recycled south of the Grand Banks (Worthington, in press), however, there is some evidence in the temperature and salinity distribution that there is also a contribution form the western slope water. Knauss (1969) has estimated that all the increase could be provided from the Sargasso Sea by a steady flow of about 1.5 cm/sec - which is too small to measure. The increase, from the Straits of Florida to Nova Scotia, is close to seven percent per 100 km of distance downstream (Figure 4-36). The figure also indicates a ten percent variability in transport estimates around the mean.

MEANDERS

Shifts in position of the Gulf Stream and changes in direction have been known to mariners for centuries but it was not until after World War II that these were clearly recognized as large meanders in the path of the Stream. First in multiple surveys, then with continuously towed temperature sensors, and more recently with the aid of satellites, the changing nature of the Gulf Stream path is being revealed.

Table 4-1. Transport in sverdrups (X 10^6 m^3/sec) at different temperature intervals on selected sections across the Gulf Stream (Worthington, in press).

	Cape Fear	Cape Hatteras	Woods Hole	Nova Scotia	50° West	Gain: Hatteras to Nova Scotia
Warm Water (> 17°C)	34	35	41	36	29	1
Upper Thermocline (12 - 17°C)	15	15	22	19	17	4
Mid Thermocline (7 - 12°C)	10	10	14	12	13	2
Lower Thermocline (4 - 7°C)	4	10	16	21	14	11
Deep Water (< 4°C)	2	15	25	62	37	47
Total	65	85	118	150	30	65



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-36	Volume Transport of the Gulf Stream as a Function of Distance (Knauss, 1969)

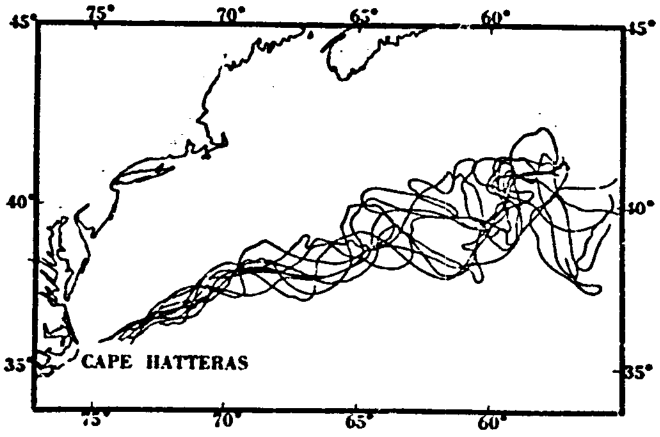
After a year of tracking the Stream at monthly intervals, Hansen (1970) described the dominant pattern as "a quasi-geostrophic wave pattern with a 200 to 400 km wave length moving east with phase speeds of 5 to 10 cm/sec." With some exceptions, the amplitudes of the meanders increase toward the east. A composite plot of nine of the paths (Figure 4-37) shows a nearly linear increase in the width of the envelope of the meanders from about 100 km off Cape Hatteras to more than 300 km south of the Scotian Shelf, about 1 km for every 5 km of distance downstream. (The monthly Gulf Stream summaries are a continuing source of information about meanders, at least as they appear on the sea surface.) Of course, the eastward propagation of large, wave-like meanders has profound effects on the surrounding waters; but there has been very little investigation of the effects in the slope water.

There is no technique at present for synoptic tracking of the deeper path of the Stream, but there is evidence that the meander structure persists to or near the bottom. Warren (1963) demonstrated that the major observed meander pattern could be accounted for by the effects of sloping bottom topography on the curvature of the current, assuming that the stream extended to the bottom. Fuglister (1963) reported deep swallow float drifts which showed that "over a period of 11 days, the deep flow was essentially in the same direction as the flow at the surface and at a depth of 700 meters." A 1969 experiment with a line of current meters moored under the Gulf Stream at 70°W (Schmitz, Robinson, and Fuglister, 1970) showed deep current fluctuations that appeared to be coupled with those observed at the surface by airborne radiation thermometry and shipboard tracking.

GULF STREAM RINGS

The meanders of the Gulf Stream, both north and south of its mean position, occasionally become elongated and pinched off to form separate rings of current which retain their identity for long periods of time. The rings, which break off in the Sargasso Sea, rotate in the counterclockwise, or cyclonic, sense and enclose slope water, which at any depth is colder than the surrounding Sargasso Sea water (Figure 4-38). Therefore, they are called cyclonic or cold-core rings or eddies. Conversely, those which break off in the slope water rotate clockwise and contain water that is anomalously warmer; they are known as anti-cyclonic or warm core rings or eddies (Figure 4-39).

The cyclonic rings, which have been more intensively studied (Parker, 1971; Fuglister, 1972), move off through the Sargasso Sea and either dissipate after about a year or are reassimilated within the Gulf Stream. They are associated with the slope water only as a mechanism for transferring slope water across the Gulf Stream. Their rate of production is not known. Fuglister (1972) estimates five to eight yearly but the rings are small compared with the Sargasso Sea and do not markedly alter its general character. In contrast the warmer core rings which bring Sargasso and Gulf Stream water into the slope water

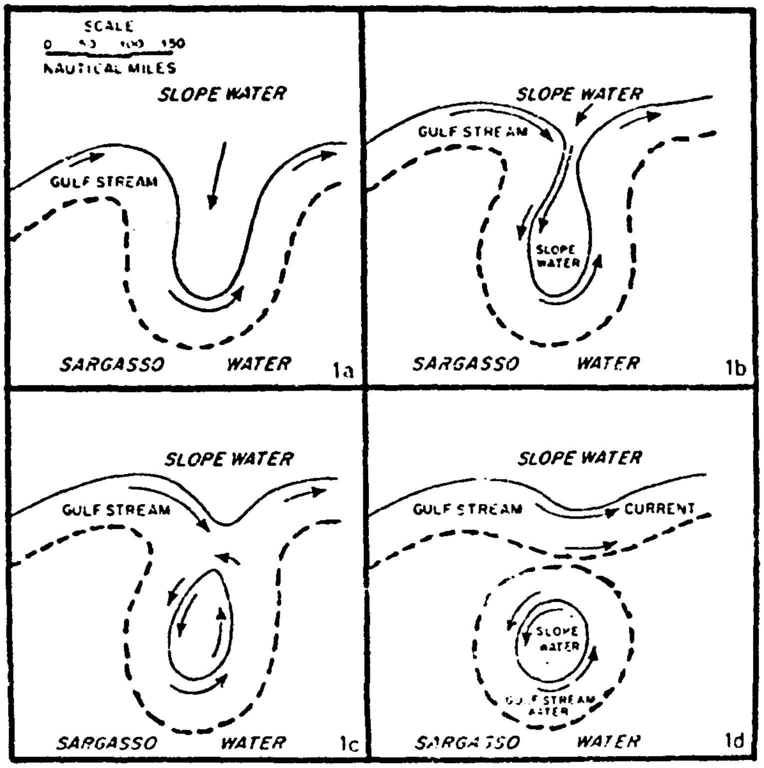


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 4-37

Composite Plot of Nine Consecutive Positions of the 15°C Isotherm at 200 m Depth (Hansen, 1970)

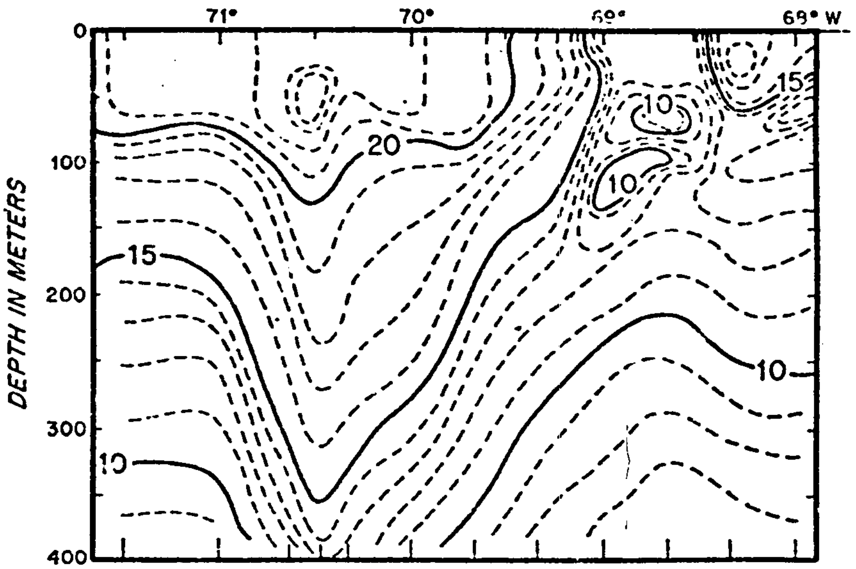


Solid lines represent the position of the 15°C isotherm at 200 m. Dashed lines represent the approximate limit of the Sargasso site of the Gulf Stream. Meander development (1a); separation from the Stream (1b)

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE** 4-38	Diagram of Ring Formation from Meander Development to Separation from the Stream (Parker, 1971)

NOVEMBER 17, 1969



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-39	Isotherms in °C on an East-West Section Along 39°10'N, 17 November, 1969 (Saunders, 1971)

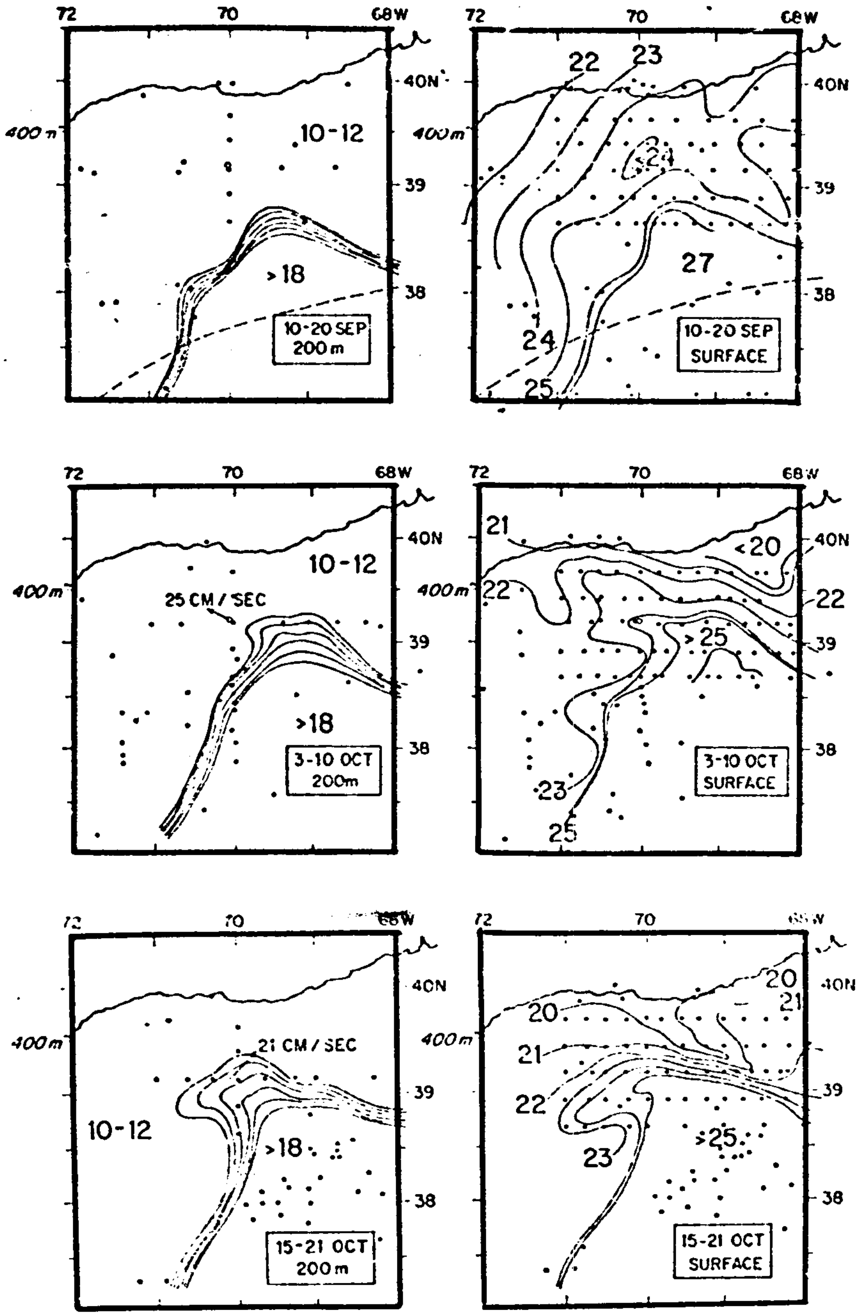
are relatively much more important because of the limited area of the slope water and because of the significant role they are believed to play in determining its character and circulation.

The occurrence and movement of warm core rings are being better documented by both satellite imagery and ART aircraft flights and the monthly "Gulfstream" summaries now regularly show their shape and position (Figure 4-8 and 4-9). There is some evidence (Wright, 1976) that the production of rings is a cyclic phenomenon with two or three very productive years followed by several lean years. In recent years there have been abundant observations of rings in 1973 and 1974 and the early months of 1975. Most warm-core rings appear to develop in the region of large Gulf Stream meanders east of 66° W, but some are formed in the western slope water. An east-west temperature cross-section through such a ring is shown in Figure 4-39; the dipping isotherms on both sides of the warm core of Sargasso Sea water are in the rotating ring itself flowing north at the left and south in the middle of the illustration. In the right of the figure is normal November slope water. This ring can easily be recognized down to 400 m; most extend to the bottom of the thermocline. (A cyclonic ring appears south of the Gulf Stream in Figure 4-30; note the humped-up isotherms indicating a cold core). The development of the warm-core ring in Figure 4-39 is shown in Figures 4-40 and 4-41 from Saunders (1971) and includes surface and 200 m temperature distributions. The slow westward movement of the ring is typical of what has been observed; Gotthardt and Potocsky (1974) found a mean westward speed of 2 to 3 cm/sec, and Parker's composite drawing (Figure 4-42) suggests a preferred path along the northern edge of the western slope water. At the same time that the ring is moving it is also rotating with speeds near the outer edge ranging up to about 1 knot (50 cm/sec). From satellite observations it appears that the rotating rings entrain surface shelf water along the shelf slope boundary and draw it out into the slope water in long, narrow filaments. Warm-core rings begin to decay shortly after formation; first the surface cools to the temperature of the surrounding slope water, then the warm water begins to mix away around the circumference. The lifetime of a ring is estimated at six months to a year, but many appear to be reabsorbed by the Gulf Stream before they lose their identity.

4.3.2 SHELF WATER

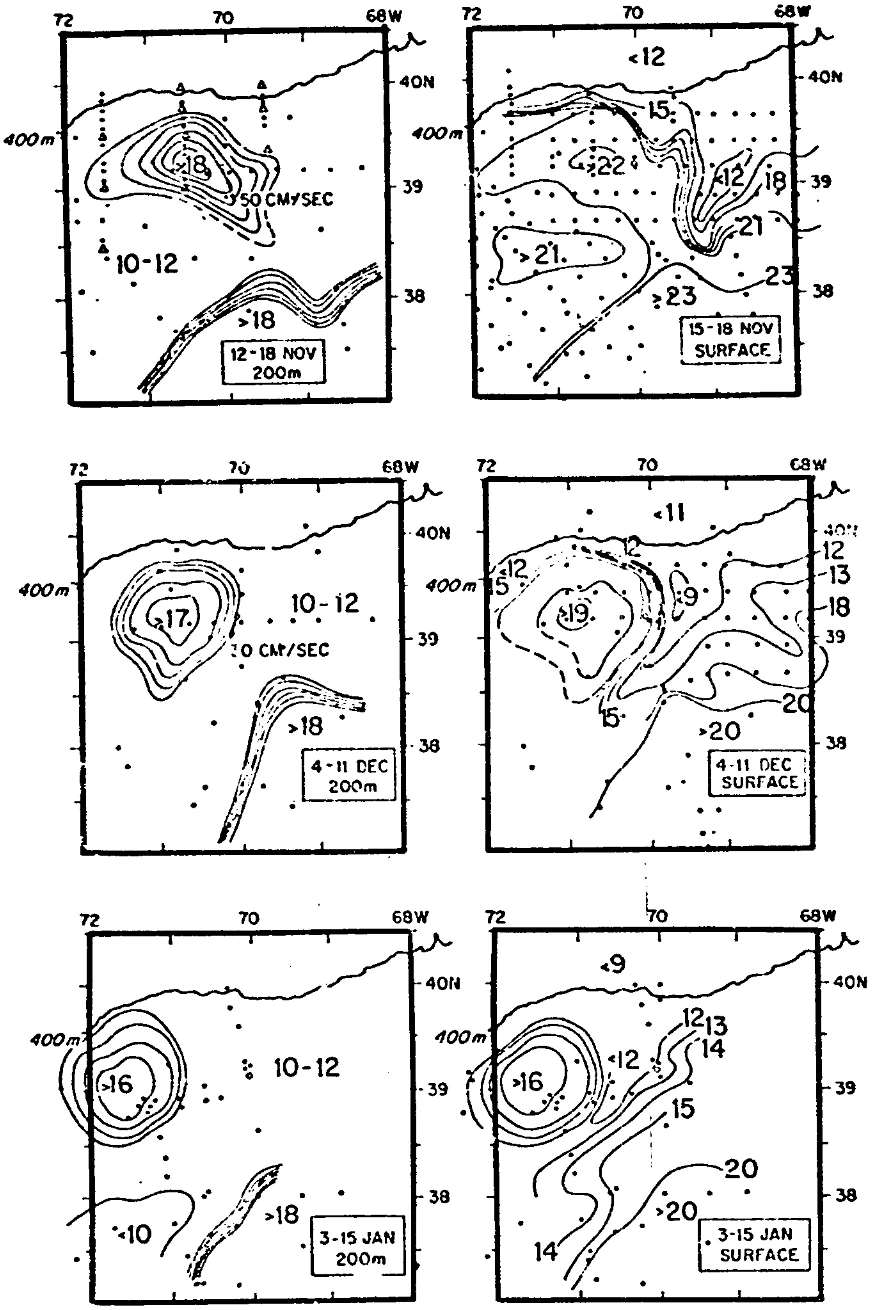
BOUNDARY FLUCTUATIONS

The boundary between the fresher, colder shelf water and the more saline, warmer slope water also fluctuates and occasionally sheds parcels into the slope water; but these effects are limited to the upper 120 m or so. From BT and XBT sections it has long been known that the boundary is complicated in vertical structure (Figures 4-43 and 4-44). From satellite photographs and detailed shelf-edge surveys it is now becoming clear that there is just as much convolution in the horizontal (Figures 4-7 and 4-45). There is some evidence that the meanders in



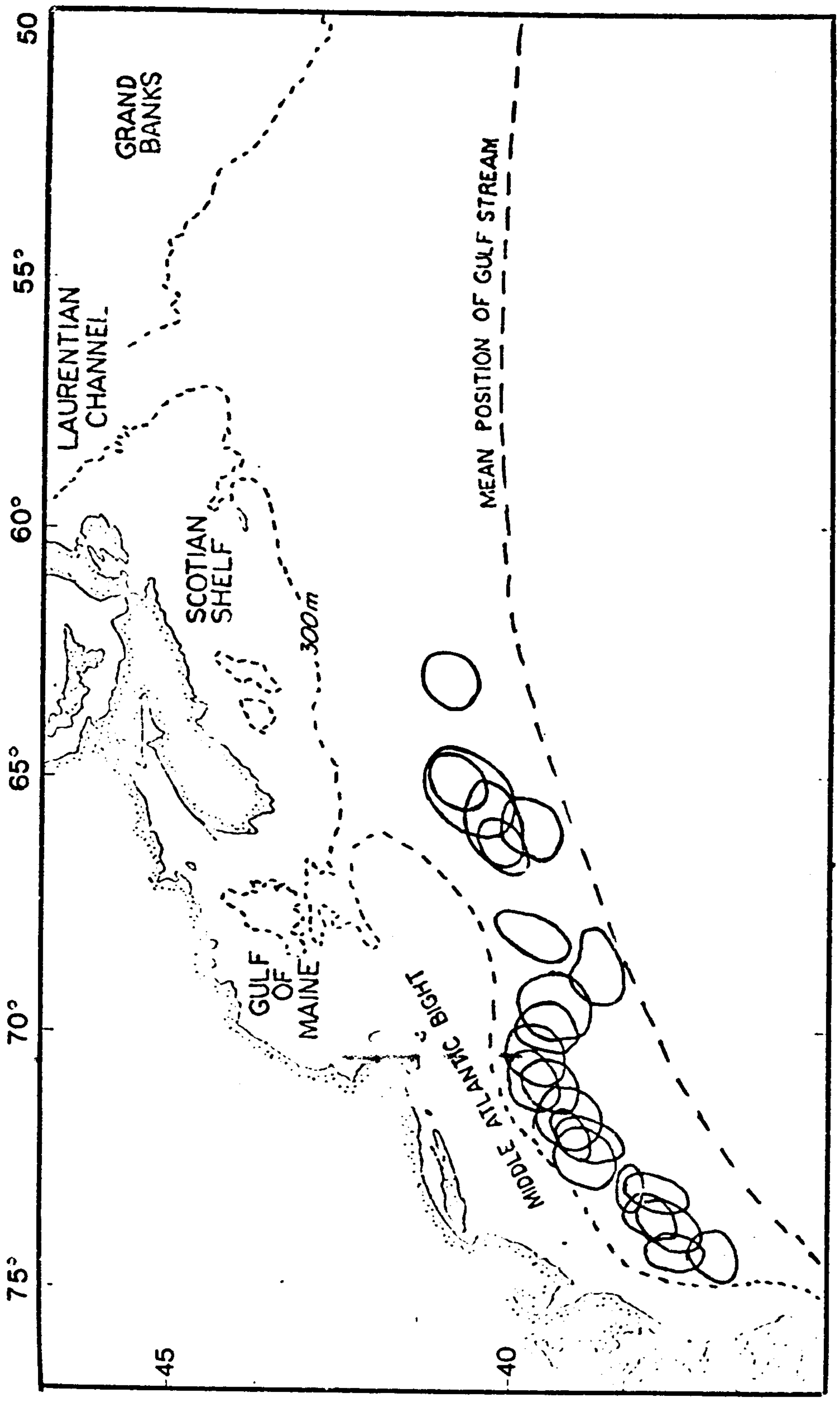
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE 4-40**	Development of a Warm Core Ring (Saunders, 1971)



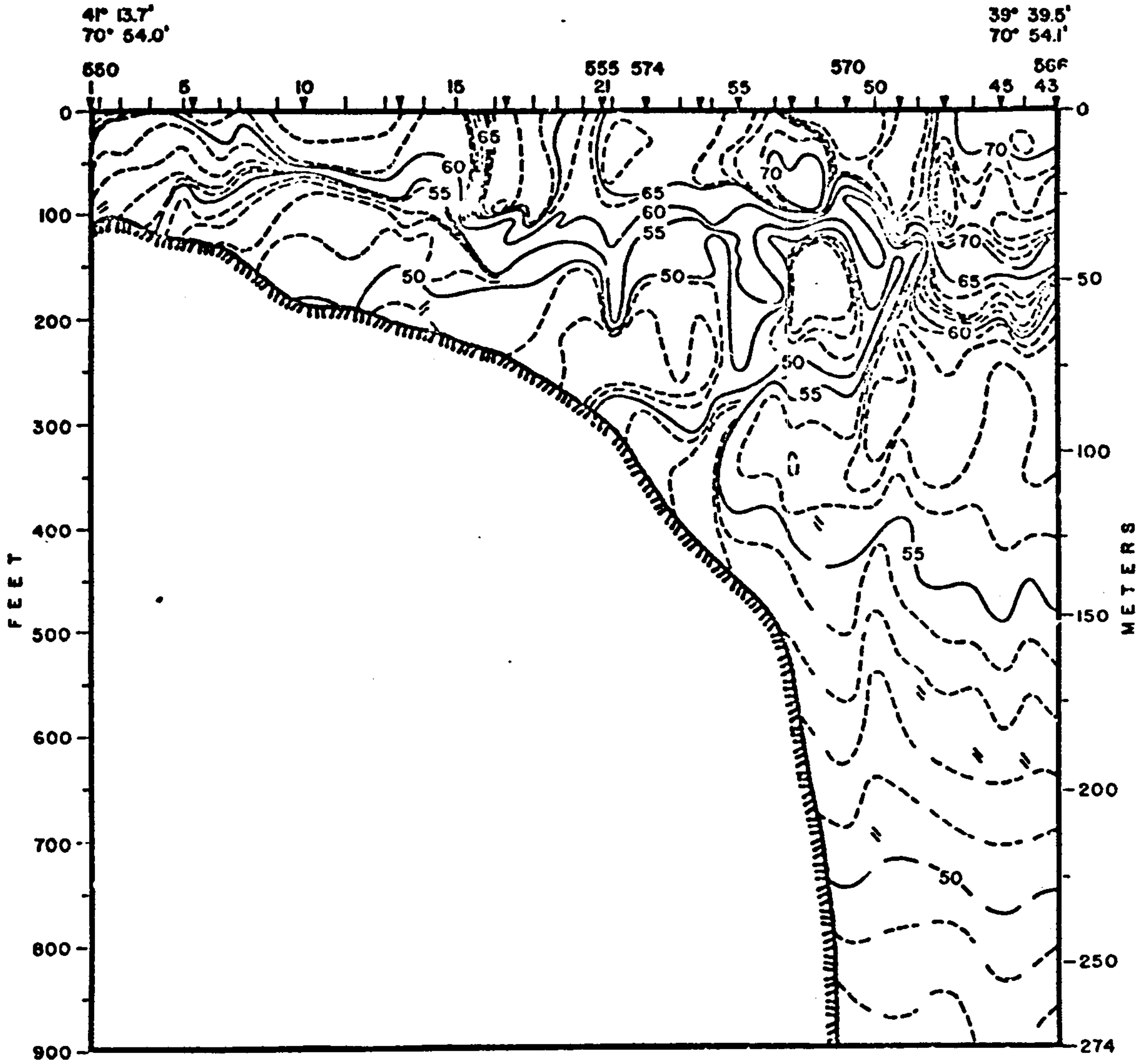
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-41	Development of a Warm Core Ring (Saunders, 1971)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-42	Composite of Anti-Cyclonic Eddies from the Gulf Stream (Parker, 1975)



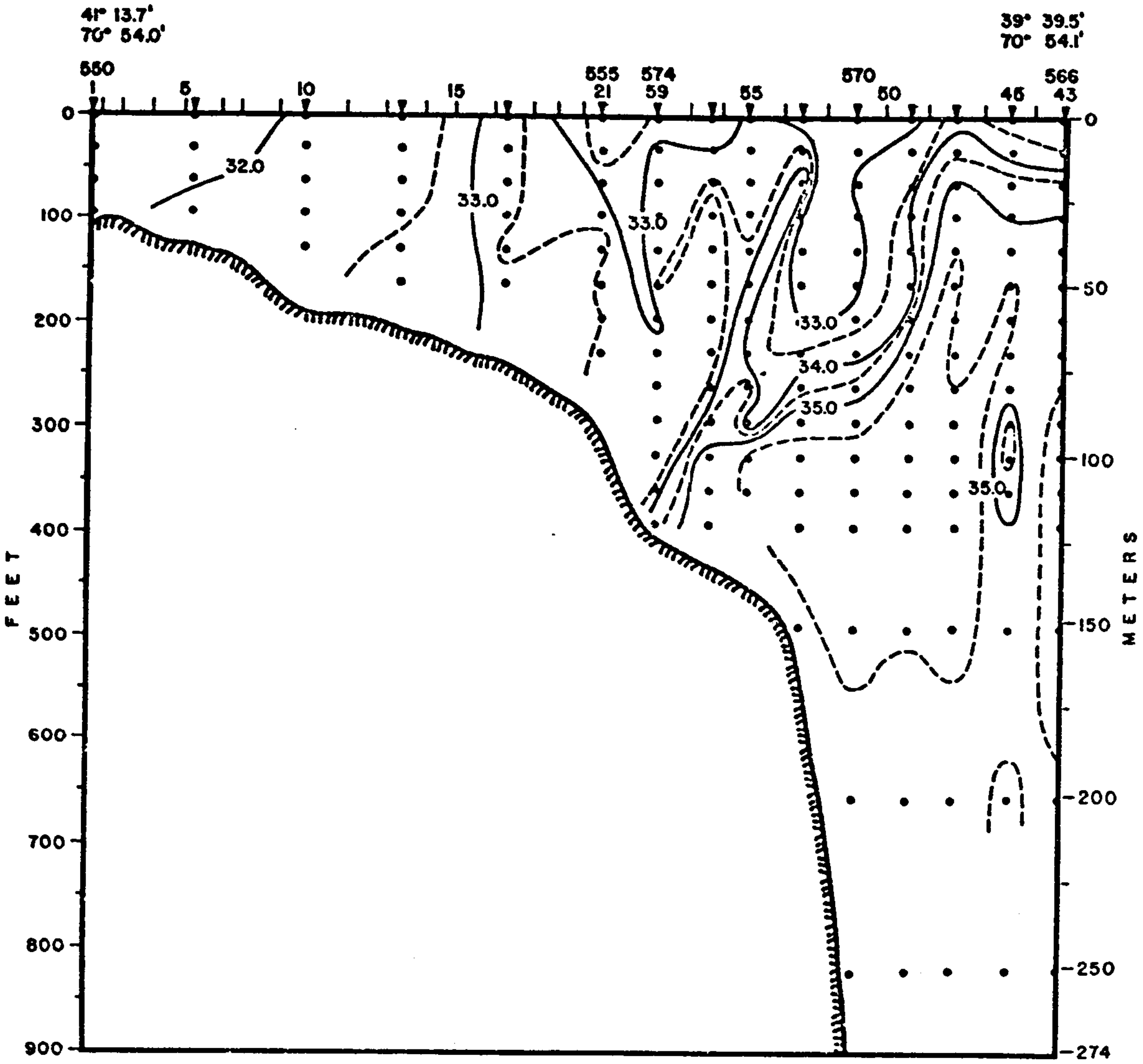
BATHYTHERMOGRAPH SECTION - °F
BEAR 198

SEPT. 23-24, 1958
1840-2400; 0000-0300 EDT

SEPT. 24-25, 1958
1655-2400; 0000-0652 EDT

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-43	Temperature Sections Showing Complicated Vertical Structures at Shelf/Slope Boundary (Cresswell, 1967)



SALINITY SECTION ‰

BEAR 198

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ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 4-44 Salinity Sections Showing Complicated Vertical Structures Across Shelf/Slope Boundary (Cresswell, 1967)

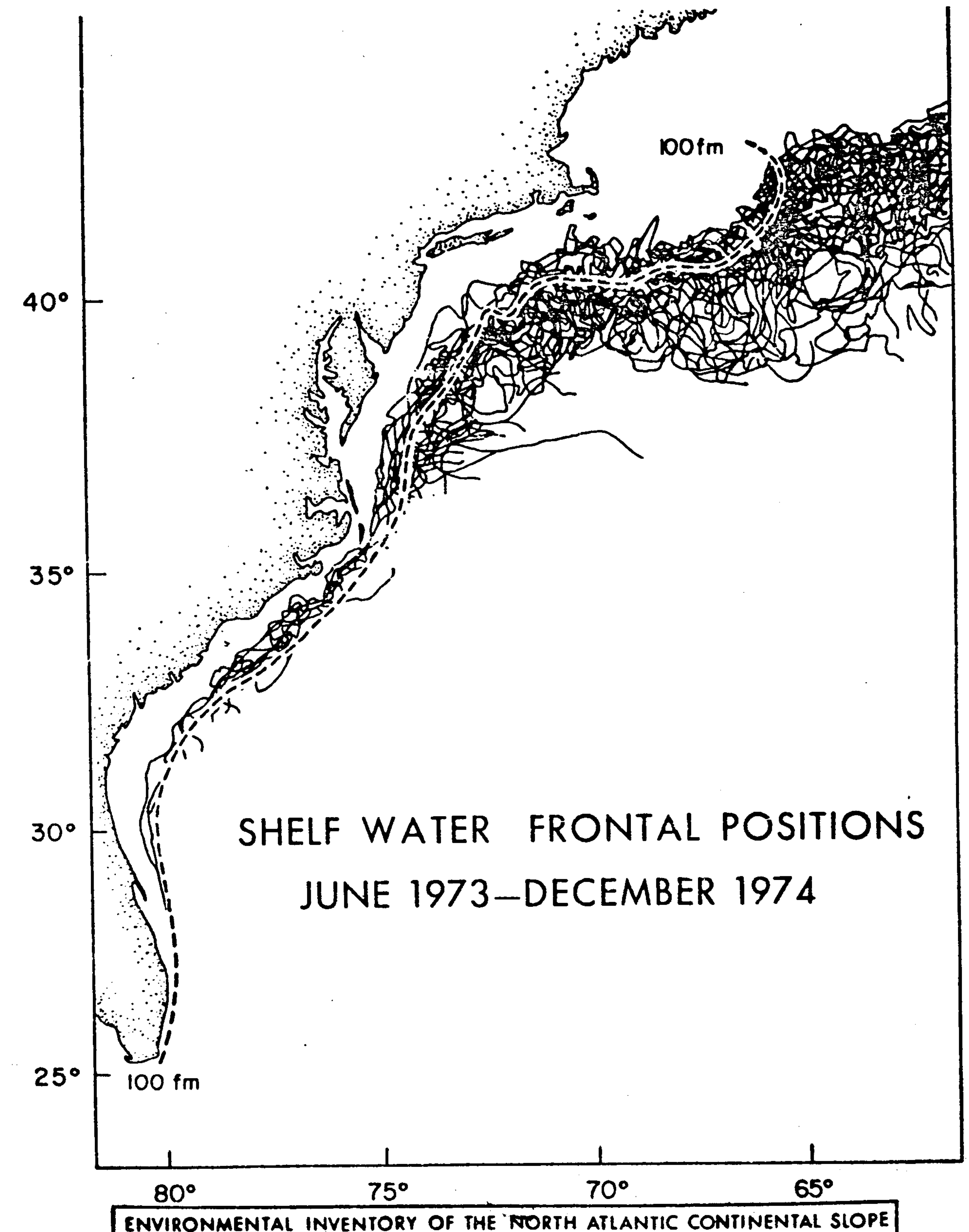


FIGURE 4-45 Composite Plot of Positions of the Shelf Water Front as Observed by Satellite During June, 1973-December 1974 (Ingham, 1974)

the shelf/slope front propagate westward toward Cape Hatteras (Parker and Wright, personal communication, "Gulfstream", February, 1971). The boundary south of Cape Cod has been studied in some detail and is probably typical of other sections. Seen in simplified cross section, it is a sloping front which changes position seasonally (Figure 4-21); the increased summer tilt being a reflection of seaward movement of fresher coastal water on the surface and shoreward penetration of more saline slope water along the bottom, estuarine-fashion. There is some evidence that in the western part of the region the slope intrusion occurs above the cold pool in summer (Boicourt and Hacker, 1975). In winter, the shelf/slope boundary is easy to detect by temperature sensors at the sea surface, when the temperature contrasts are strong; but in summer, when the seasonal thermocline has developed, salinity is a better tracer, (Figure 4-22).

The position of the boundary on the sea floor rarely wanders far from the 100-m curve; but there is a regular seasonal progression a few km shoreward in the summer, a few seaward in the winter. The seaward limits of the shelf water at the sea surface also show some seasonal change, but it is superimposed on much wider fluctuations: the average position was 52 km seaward of the 100-m curve in winter and 72 km seaward in summer, but the standard deviation from these means was 29 and 40 km, respectively.

The cold core of shelf water extending beyond the shelf edge has been mentioned before. There is cold water over the shelf year round, but a well-developed temperature minimum layer exists only from May, when the vernal surface warming begins, through October, when autumn cooling and storms break down the summer thermocline (Figure 4-22). The mean temperature minimum inside the cold core varies from about 5.5°C in March and April to 10°C in November with a range of ± 4°C from those means. The slope water maximum, lying under and seaward of the minimum, also goes through a seasonal cycle, but its range is only about 1°C with the annual mean being 13.2°C and the range being from 12.3 to to 14.6°C. The last few years have been warmer than usual.

DETACHED PARCELS

From time to time, parcels of shelf water become detached from the parent water mass and move off into the slope water. Existence of these parcels, which had been caught up in the inshore edge of the Gulf Stream, presumably at Cape Hatteras, was documented 20 years ago (Ford, Longard, and Banks, 1952; Ford and Miller, 1952). They have since been observed to "calve" all along the length of the shelf edge and have been identified throughout the western slope water (Figure 4-46) (Cresswell, 1967; Moore, 1972; and Schlitz, personal communication). Very little is known of the characteristic size, shape, frequency of formation, or rate of decay of such parcels; most often they are noted on a single BT trace or a pair of T/S values from a single Nansen bottle near the inshore end of a section. Because of the inevitable contouring of such observations, the parcels have come to be known as bubbles but the term is misleading. Actually, they are thin lenses, which appear to range in thickness from 20 to 80 m and in horizontal extent from 10 to 20 km. Of course, it is also possible that they are long strips like those along the inshore edge of the stream or even filaments that are still attached to the parent water mass.

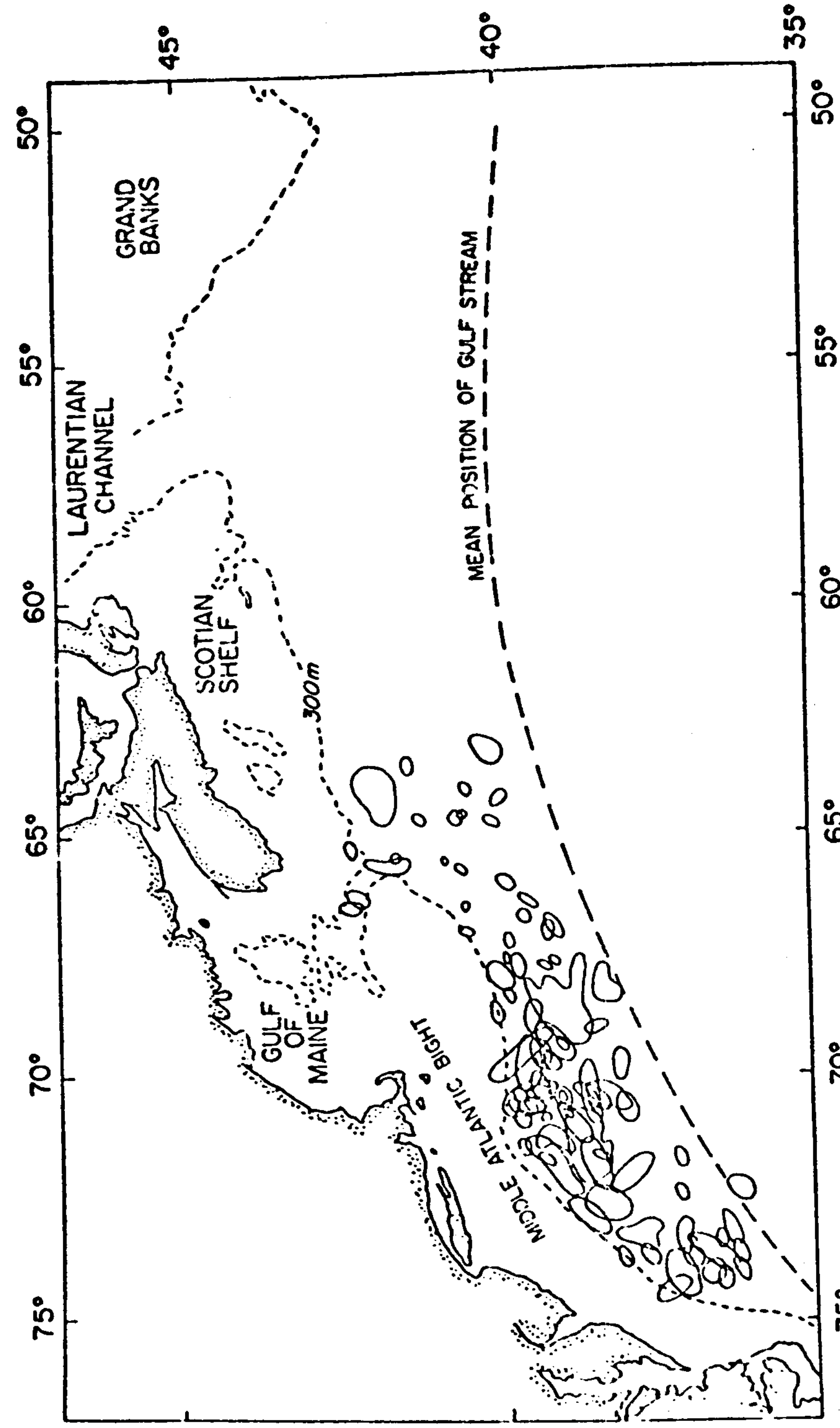
Two principal categories of detached parcels have been distinguished (Wright, 1976): A) those which can be identified only by temperature at the sea surface, and B) those which can be identified only by subsurface observations. In Type A, the temperature minimum typically extends to a depth of 50 to 80 m with little change; in Type B, the minimum is around 50 m with water of 13°C to 15°C below and (depending on the season) 13°C to 24°C above. The percentage distribution of the two types by month (Figure 4-47) and the few salinity observations available suggest that in most cases Type B parcels are simply Type A parcels with the surface temperature signature erased by seasonal warming. Figure 4-47 also illustrates the ubiquitous nature of the parcels: they are found more than 90 percent of the time from March through July and more than 60 percent of the time from December through September. These parcels appear to be more abundant west of Nantucket Shoals than to the east (Figure 4-46).

The shelf water parcels found on the inshore side of the Gulf Stream seem to occur as long strips, some with a surface expression and some without. During one multiple ship survey of the Gulf Stream (Operation Cabot, 1950) shelf water was encountered in 57 out of 97 crossings of the edge of the Stream. The actual entrainment process was observed in May, 1969, in the vicinity of 36° N, 74° 30' W (Fisher, 1972). The parcel of shelf water, originally about 14 km wide, elongated and narrowed to a width of about 2 km as it was carried northeast with the Gulf Stream; the surface water in the entrainment region dropped below 13°C as opposed to more than 15°C in the slope water and 24°C in the Gulf Stream. At 100 m the temperature of the entrained water was less than 8°C.

4.3.3 INCURSIONS FROM THE EAST

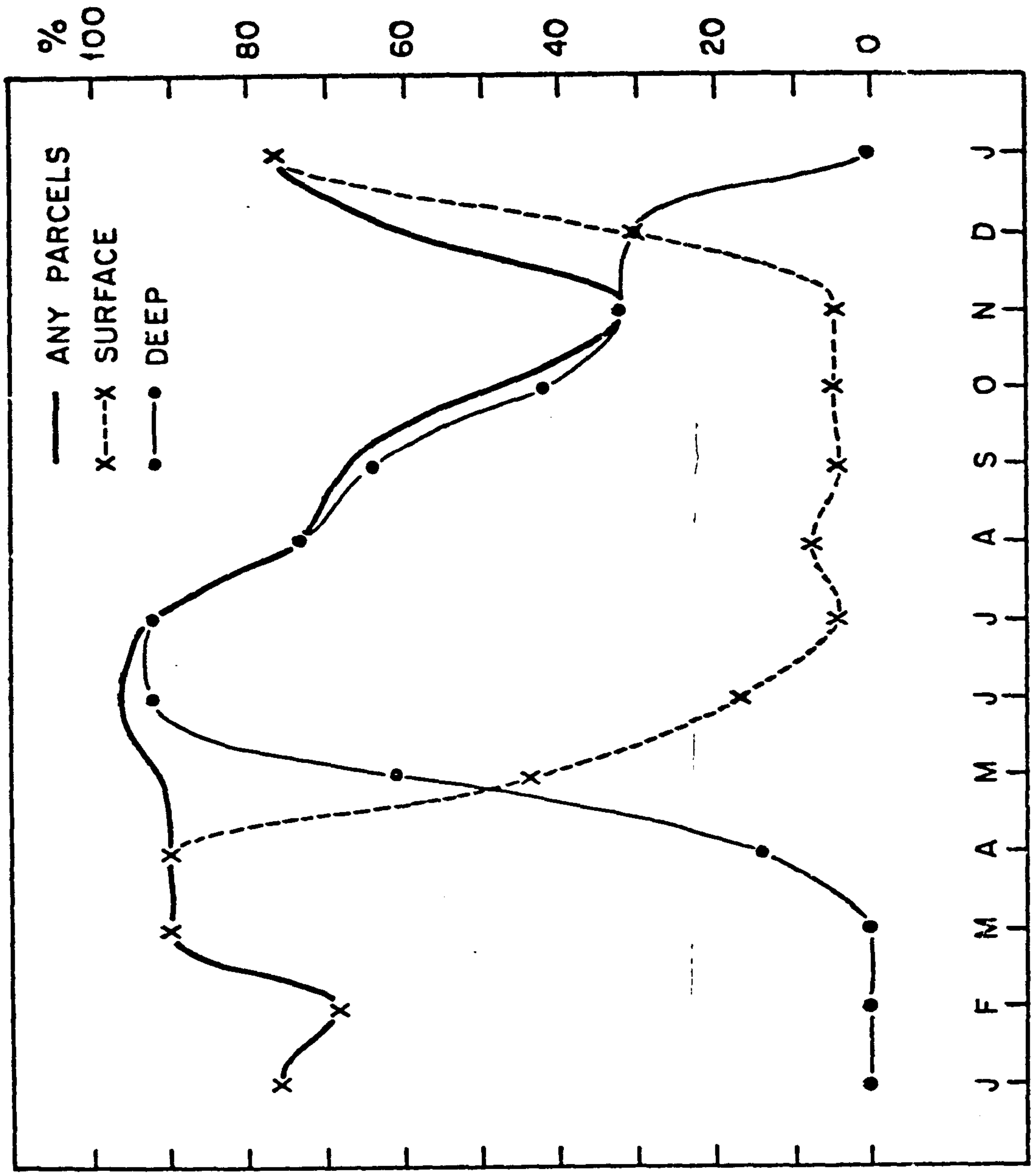
At least three instances of large-scale, mid-depth influxes of eastern slope water and/or Labrador Water into the western slope water have been documented in the past 100 years and there undoubtedly have been more. These incursions could have a marked effect on the living organisms in the region; they do not appear to have a long-term effect on the hydrography.

The first instance is related to the destruction of the tilefish industry in 1882 (Hachey, 1955). These fishes live on the bottom in the "warm band" described earlier and their disappearance was attributed to massive influx of water of 0 to 4°C of Labrador Current origin. Worthington (1964) describes such an occurrence in 1959, when the water was



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE** 4-46	Distribution of Cold Shelf Water Bubbles (at 50 m) in the Slope Water, 1960-1965 (Parker, 1975)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-47 Percentage Distribution of Surface and Subsurface Detached Parcels (Wright, 1976) colder at all depths than in either 1950 or 1960. Negative temperature anomalies from 3 to 10°C were found in May and June over much of the slope water region (Figure 4-48). By a fortunate coincidence, deep current measurements were made in the slope water in 1959 and 1960 (Volkmann, 1962): a westward flow of 60 sv was measured in 1959 which had dropped to 17 sv by 1960. Worthington estimated it would take about eight months to replace half the slope water at the higher rate. In 1965 both temperature and salinity were considerably lower than normal in the slope water during all seasons (Colton, 1968). It was not an unusually cold year atmospherically, not enough to account for the cooling, so the water must have been advected from the east (Beardsley, personal communication). Other evidence of similar incursions have been mentioned (Pollak, 1947); but there is no estimate of their frequency or their overall significance to the slope water region.

4.4 CIRCULATION

Because the Gulf Stream and shelf water fronts converge at Cape Hatteras, the western slope water region is essentially a cul-de-sac, at least above 1,500 m. In these upper layers there is some exchange across both the northern and southern boundaries; but there is no major current system and most water flowing in at the eastern end of the region probably leaves, somewhat modified, by the same door. There is some evidence of a slow, southwest flow in the northern part of the slope water and a flow to the northeast in the southern part, along the edge of the Gulf Stream. Below 1,500 m, the flow is dominated by the western boundary undercurrent which transports water of northern and eastern origin along the deeper flanks of the continental slope and rise. This water crosses through and/or under the Gulf Stream in the Cape Hatteras region in a manner not yet clearly understood.

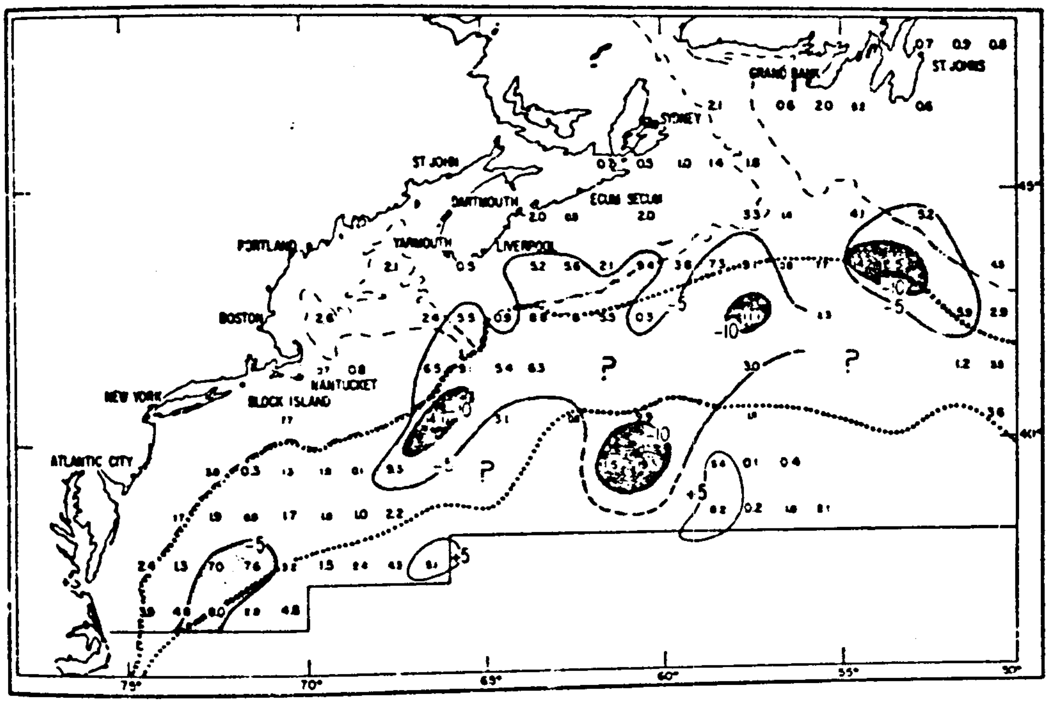
4.4.1 SOURCES OF WESTERN SLOPE WATER

The previous section on variability introduced most of the sources of western slope water, at least in the upper levels. The following is an attempt to quantify them.

TOP 200 METERS

The surface layers of western slope water are clearly an incomplete mixture of Gulf Stream and shelf water with a background of slope water from the east. The mixing is accomplished to some extent by the wind, which blows surface coastal water offshore - particularly during the winter northwest gales (Chase, personal communication); and frequently blows surface Gulf Stream water northward away from the deeper Stream. However, most of the transfer is a result of the dynamics of the boundaries themselves.

At the shelf edge there are three processes: 1) entrainment of shelf



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

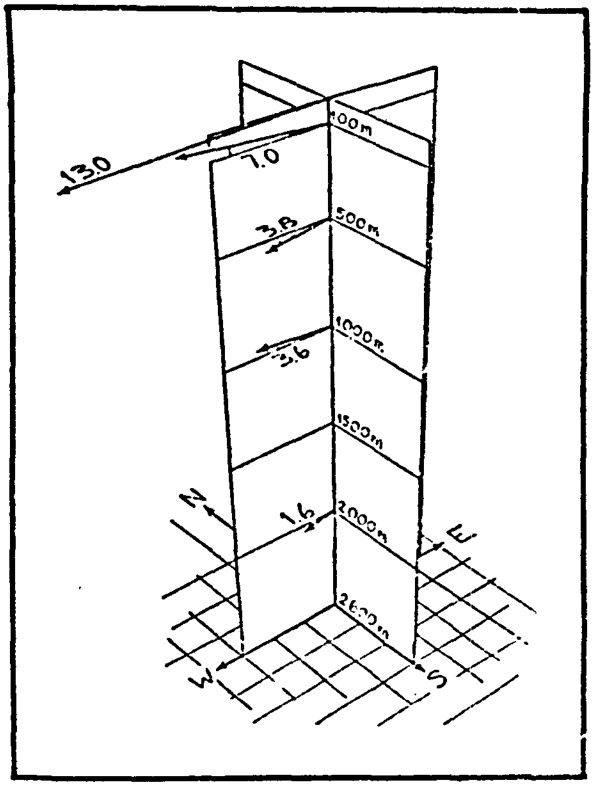
TRIGOM

FIGURE 4-48

Variation (^{o}F) From Average Temperature at 100 m in May and June, 1959 (Worthington, 1964) water at the north edge of the Gulf Stream at Cape Hatteras; 2) calving of parcels of shelf water all along the edge and 3) influx of slope water required to maintain the salinity balance in the shelf water region. Estimates of entrainment volumes vary widely from 300 km^3/year (Stommel, 1953 and Fisher, 1972) to 8,000 km^3/year (Beardsley, Boicourt, and Hansen, 1975). The latter figure is based on direct current measurements at three sections across the continental shelf and agrees with evidence from drogues and surface drifters (Howe, 1962; Bumpus, 1973). These current measurements show that most of the shelf water transport along the continental shelf takes place during major storms, at least in winter time (Beardsley and Butman, 1974; Beardsley and Flagg, 1975). Even that number is less than half of one percent of the transport in the upper 200 m of the Gulf Stream. Much of the shelf water entrained at Cape Hatteras undoubtedly is carried out of the region to the east; but some of it must eventually decay and mix with the surrounding slope water. Even less is known about the contribution of detached shelf water; but a reasonable estimate would be 2,000 to 4,000 km^3/year based on the apparent size and abundance of the parcels (Wright, 1976). An estimate of the shoreward flow of slope water, based on the annual fresh water input to the U.S. continental shelf east of Cape Hatteras, is apparently 250 km^3/yr (Bue, 1970; Emery and Uchupi, 1972). In order to create shelf water with a mean salinity of 33 o/oo, about 4,250 km^3/year of 35 o/oo slope water must mix across the shelf/slope boundary.

The three estimates given above do not balance and can be made consistent only by assuming a flow of water along the continental shelf from further east, amounting to about 6,000 km^3/year. Efforts to identify such a flow are now under way (Voorhis and Parker, personal communication) and may require drastic modification of the present estimates.

The net contribution of Gulf Stream rings in the surface slope water is probably much greater than that of the shelf water, although it is also a two-way process. Each anticyclonic ring introduces both Sargasso Sea and Gulf Stream water into the slope water; but each cyclonic ring removes only the central core of cold slope water surrounded by the rotating Gulf Stream water. A Gulf Stream ring is much larger than a shelf water bubble with a horizontal cross section of about 18,000 km^2 (Fuglister, 1972), or about ten percent of the total area of western slope water. Annual production of rings is estimated at five to eight of each type (Fuglister, 1972), but some are recaptured by the Gulf Stream before they dissipate. An assumed net contribution to the slope water of three to five rings each year gives a replacement time of two to three years from the combined effect of rings and shelf water parcels. The continuity of slope water characteristics suggests that there must also be some influx from the east. This eastern slope water is formed, according to McLellan (1957), of roughly equal parts of Gulf Stream and Labrador coastal water. Long term measurements at Site D (39° 10' N, 70° W) suggest an average velocity to the west of about 7 cm/sec in the upper 200 m (Webster, 1969) (Figure 4-49): this implies an influx of about the same magnitude as the combined effect of both



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-49 A Perspective Drawing of the Mean Velocity Vectors at Site D (Webster, 1969) rings and shelf water and a resulting residence time of a little more than a year for the upper slope water. Measurements of radioactive Cesium 137 and Radium 228 by Kupferman and Feely, (1974), indicate a residence time of about two years.

THERMOCLINE

The close correspondence in shape of the western slope water temperature-salinity curve below 12°C with that for the Sargasso Sea and its consistently lower salinity indicate that slope water in the thermocline is formed by a mixture of Gulf Stream water and eastern slope water. There is very little direct evidence of the eastern slope water influx except the Site D measurements mentioned above showing a mean westward flow of about 3.5 cm/sec from 500 to 1,500 m, which could mean an influx of 2 to 3 Sv. The input of Sargasso and Gulf Stream water by rings is approximately the same, so that the residence time of thermocline slope water is the order of one year.

Sargasso water may also be transferred to the slope water by a mechanism proposed by Rossby (1936) associated with his wake stream theory of ocean currents. The theory requires that deep Sargasso water be drawn into the Gulf Stream and discharged into the slope water at shallower depths some distance downstream, having moved along sloping density surfaces. This process also brings nutrient-rich deeper waters into the euphatic zone in the slope water (Yentsch, 1974). The biological implications of this are discussed in Chapter 7.1. The composition of the eastern slope water itself has been carefully analyzed by McLellan (1957) who concluded that it consists of about four parts western North Atlantic water and one part Labrador-Coastal water which mix isentropically (along density surfaces).

DEEP WATER

Below 4°C the temperature-salinity characteristics of western slope water are only faintly distinguishable from that of western North Atlantic water, but it is somewhat fresher at all temperatures (Figure 4-33). Furthermore, this salinity difference appears to be increasing, by a barely discernible 0.001 o/oo per year (Barrett, 1969), which implies either a higher proportion of water from the northeast or a freshening of that water.

Estimates of the production of deep water by sinking in the Labrador Sea vary from 2 to 4 Sv (Smith, Soule, and Mosby, 1937; Wright, 1972; and Worthington, in press); it probably varies from year to year beyond those limits, and, of course, it is not a continuous year-round process. The colder deep water, which originates in the Norwegian Sea but entrains Atlantic water enroute south, has been more consistently estimated at 10 Sv (Swallow and Worthington, 1969, and Worthington, 1970), but something less than half of that is diverted into the deep northeasterly east of the Grand Banks so that perhaps 6 sv continue toward the southwest (Worthington, in press). The spreading (and weakening influence) of this water can be seen in the low silicates values from Greenland to Cape Hatteras in Figure 4-50. There is no solid evidence that deep western North Atlantic water is transferred across the Gulf Stream, but there is a hint, in the T/S characteristics of the Gulf Stream, that it picks up some slope water east of Cape Hatteras, as mentioned earlier (Warren and Volkmann, 1968).

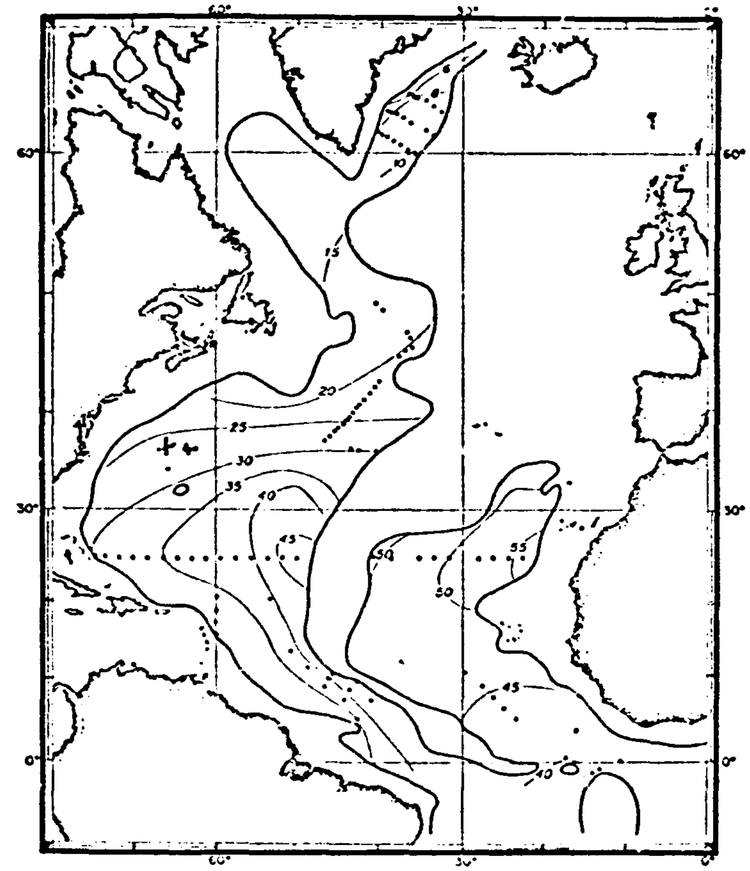
The sources of slope water and some quantitative estimates appear in Table 4-2. The suggestion is that the various western slope water masses have residence times ranging from six months to a little more than two years, which makes it remarkable that the hydrographic characteristics have changed so little during the past several decades of study. One explanation may be that 80 percent or more of the western slope water is drawn either directly or indirectly from the very stable and virtually inexhaustible reservoir of the Sargasso Sea.

4.5 CURRENTS

It should be noted at the outset that short period current measurements must be viewed with caution, whether made by moored or drifting sensors, because the instantaneous currents are always stronger than the mean and even several weeks of observation may not reveal a true mean. The problem is illustrated in Figure 4-51, which represents three weeks of observation with a fixed current meter moored in the western slope water just seaward of the shelf water boundary; clearly a "mean" velocity based on such a record would have little meaning. The kinetic energy spectrum for the same series of measurements (Figure 4-52) shows that 85 percent of the energy is at the inertial and semidiurnal frequencies. From the long term records at Site D, Webster (1969) has found that the mean speed, regardless of direction, is two to three times the mean velocity at any depth, but the peak speed never exceeded the mean by more than a factor of six.

4.5.1 SURFACE

There is no well-defined current system in the surface layers of the western slope water, although there is one further east where an eastward flowing slope water current is separated from the Gulf Stream by a somewhat weaker westward counter current. To the north and east of these, pressed against the continental slope, is the westward flowing Labrador Current which loses its distinctness somewhere west of the Grand Banks. The Slope Water Current is estimated from 10 to 20 sv and the Labrador Current carries about 4 sv (McLellan, 1957 and Worthington, in press). Although this multiple current system is reflected in the composition of western slope water, the only permanent current in the region is the Gulf Stream itself and this is permanent only in



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TRIGOM	FIGURE 4-50	Silicate Concentration in μg-atoms/l at Potential Temperature at 2°C (Metcalf, 1969)

Table 4-2. Sources of western slope water and residence times. See text for estimates.

	SV(x10^6 m^3/sec)	x10^3/1cm^3/yr.	Residence Time
Upper 200 m			
Shelf Water	< 1/4	4 - 8	
Gulf Stream Rings	1/2 - 3/4	12 - 20	
Eastern Slope Water	1	30	
Total	1 1/2 to 2	46 - 58	6 Mos. to 1 Yr.
Thermocline			
Gulf Stream Rings	3 - 5		
Eastern Slope Water	2 - 3		
Rossby Effect	?		
Total	5 to 8		$\sim$1 Year
Deep Slope Water			
WBUC	4 to 12		1 to 3 Years
TOTALS	10 to 20		1 to 2 Years

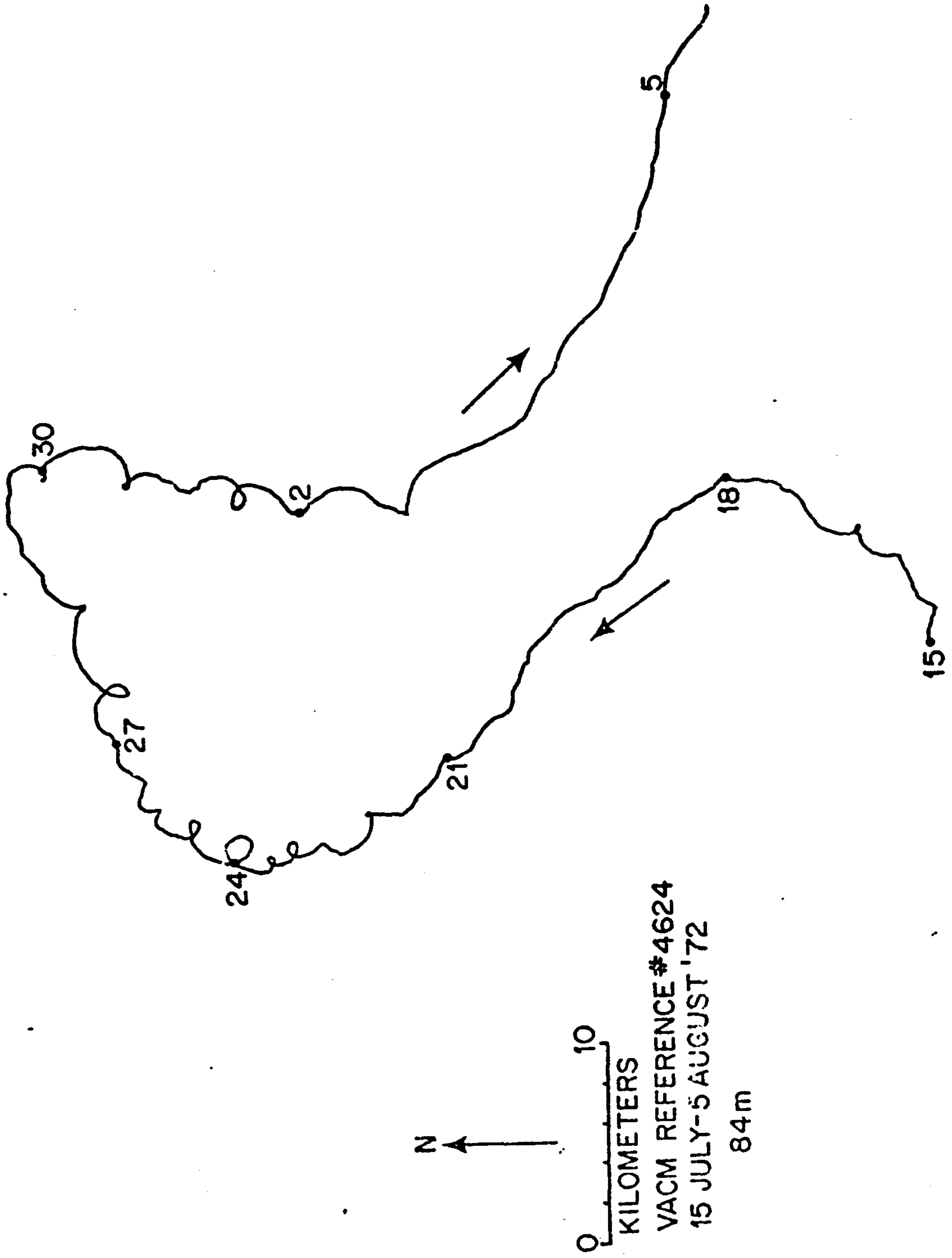

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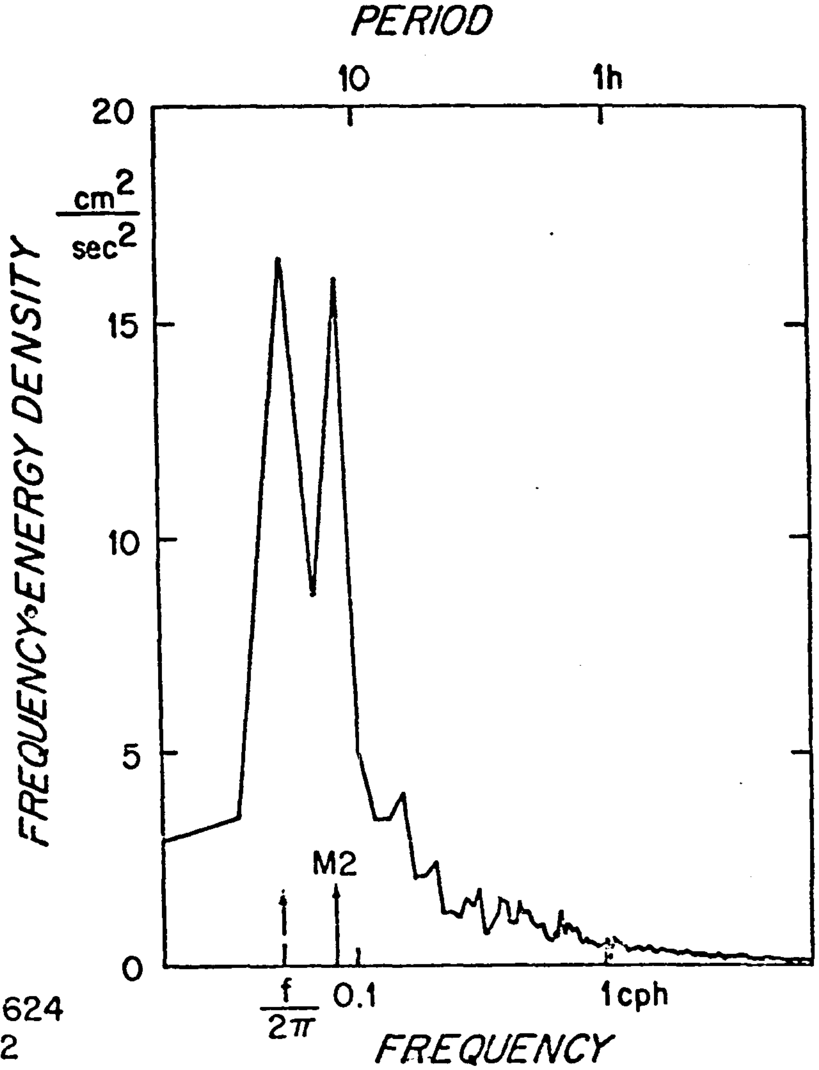
FIGURE 4-51

Progressive Vector Diagram from Moored Current Meter Observations Over a Three Week Period, July 15-Aug. 5, 1972 (Zenk and Briscoe, 1974)



VACM REFERENCE #4624
15 JULY-4 AUGUST '72
84m

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TRIGOM	FIGURE 4-52	Kenetic Energy Spectrum from Moored Current Meter Observations Over a Three Week Period, July 15-Aug. 5, 1972 (Zenk and Briscoe, 1974)

the sense that it is always present, for it changes in both position and volume transport and its direction at any given place and time can be almost anything but west.

There is some evidence of a sluggish flow to the westward in the northern part of the region, i.e., the Site D measurements and the drift of Gulf Stream rings (Figure 4-53). Furthermore, some short-term measurements with drogues and drifters appear to confirm this flow (Bumpus, 1958; Wright and Parker, personal communication). However, there are exceptions (Shonting and Cook, 1964; and Bumpus, 1975). It seems that the westward drift is readily interrupted by storms and other special events. A better interpretation of surface flow may come from aircraft or satellite imagery through repeated mapping of surface isotherms (Saunders, 1973).

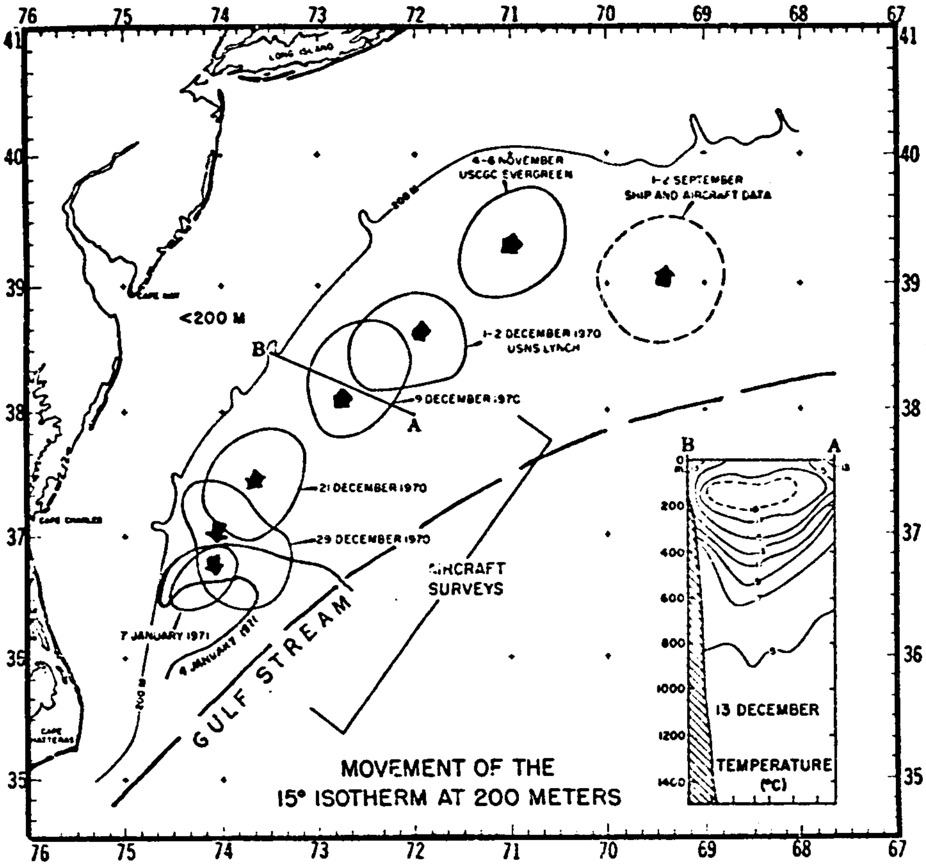
A special situation exists in the Cape Hatteras region, roughly south of 37° N and west of 73° W, where the Gulf Stream, at times, meanders into direct contact with the shelf water (Figure 4-54). The presence of an experimental Environmental Research Buoy for several months in this region has given some insight into the flow patterns (Parker, 1973). Despite gaps in the data, the monthly sequence of water types past the buoy shows a succession from shelf water to slope water to Gulf Stream, then back toward slope water; at the same time the direction of flow changed from generally west to generally east and back. The slope water nearest the Stream was moving east like the Stream, but that near the shelf water had a westerly tendency. The Stream thus acts like a double action pump, drawing slope water and then shelf water after it as it moves offshore and forcing them toward the northeast as it moves back.

4.5.2 THERMOCLINE

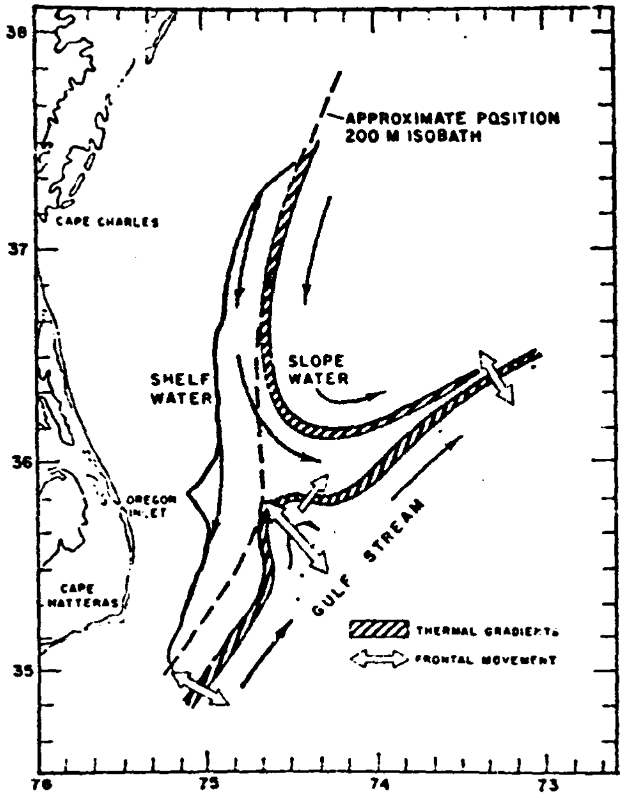
At intermediate depths, there are no long-term current meter observations, except those at Site D, and no indication that the flow pattern is any different than at shallower depths. Westward currents up to 70 cm/sec were measured near the bottom in 1,350 m west of Alvin Canyon but the sediment showed no sign of erosion (Emery and Ross, 1968). In another series of ALVIN dives at about the same depth, currents of 5 to 15 cm/sec were regularly observed but with no preferred direction (Grassle, et al., 1975). Undisturbed bottom sediments and low concentrations of suspended particulates (MacIlvaine, 1973) also indicate minimal current action in the lower continental slope, but recent measurements of low Radon close to the bottom in the same region (Biscaye, et al., 1975) appear to contradict this interpretation.

4.5.3 DEEP

In the deeper water there is the western boundary undercurrent (WBUC), a broad and persistent flow that carries water of northern origin through the slope water region and beyond to the south. The WBUC is inshore of



TRIGOM	FIGURE 4-53	Movement of 15^{o}Isotherms at 200 meters (Gulfstream, 1971)



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TRIGOM	FIGURE 4-54	Water Masses and Simplified Circulation Model of the Survey Area (Fisher, 1972)

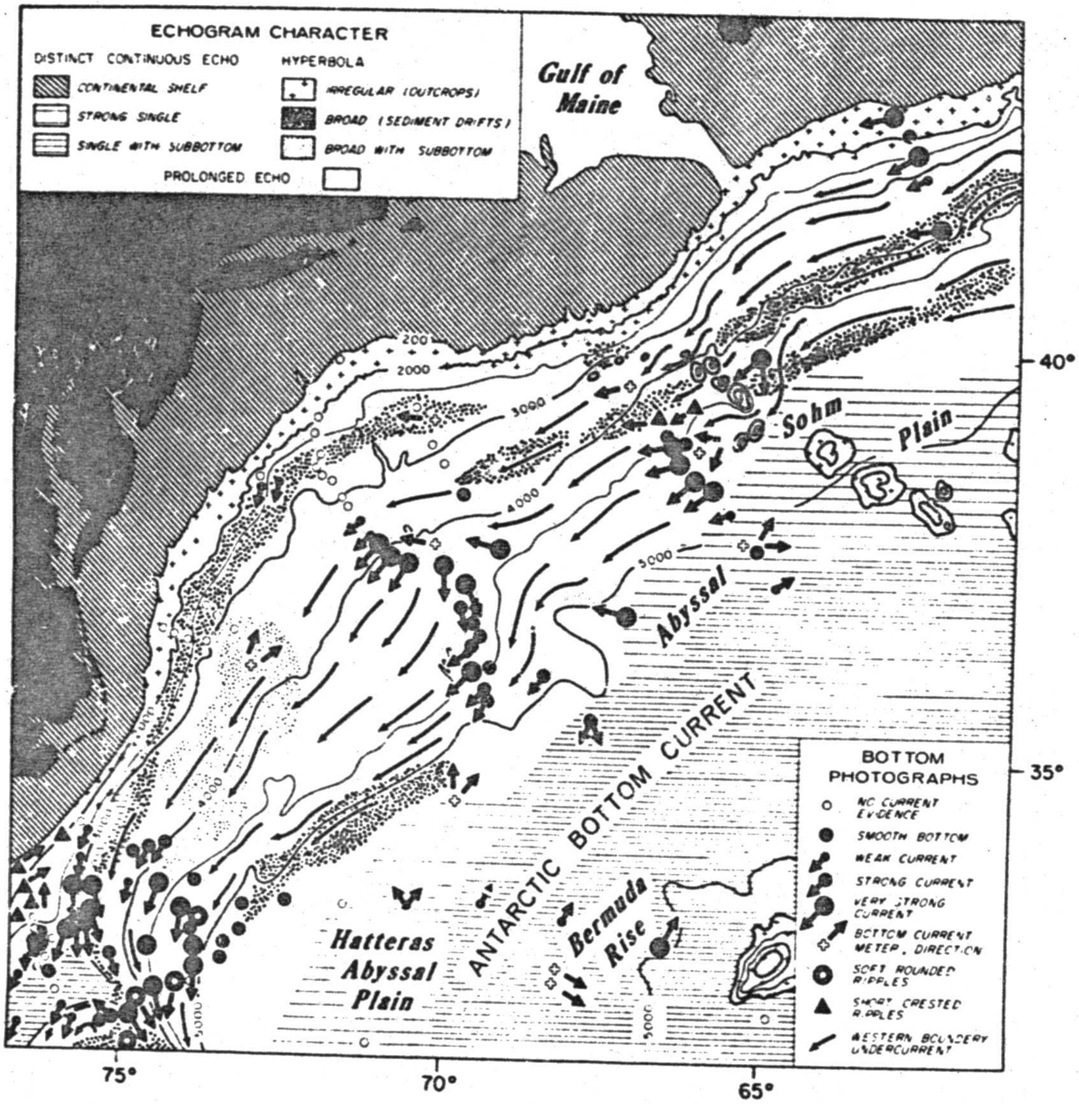
the Gulf Stream, except in the Hatteras region, and the Gulf Stream itself appears to persist as an eastward flowing current down to the sea floor. Speeds of 11 to 17 cm/sec were observed in the deep Gulf Stream with swallow floats during Gulf Stream '60 (Fuglister, 1963) and speeds as high as 44 cm/sec were measured with current meters (Schmitz, Robinson, and Fuglister, 1970).

The WBUC is slower and carries much smaller quantities of water than the Gulf Stream. Except for the anomalous observations of 1959 (Volkmann, 1962), estimates of volume transport range from 2 to 22 sv, with a mean of 11 sv (Barrett, 1965; Worthington and Kawai, 1972; Amos, et al., 1971; Swallow and Worthington, 1961; and Richardson and Knauss, 1971). Speeds are of the order of 10 cm/sec but range as high as 47 cm/sec (Zimmerman, 1971 and Richardson, 1973) with the highest velocities closest to the continental slope.

The water carried by the WBUC is all colder than 5° and most of it is colder than 4°C. It includes the deeper two of the three water types of northern origin mentioned above and their characteristics have been used to trace the current well beyond Cape Hatteras (Barrett, 1965) as far as the Greater Antilles Outer Ridge north of the Puerto Rico Trench (Tucholke, et al., 1973). Photographic evidence of current scour on the sea floor, while normally not as convincing as the combination of current measurements and dynamic calculations, is ample in the case of the WBUC (Hollister and Heezen, 1972; Rowe and Menzies, 1968; Schneider, et al., 1967; Rowe, 1971; and Zimmerman, 1971) (See Figure 4-55).

The current has been observed as shallow as 1,000 m but most observations are deeper than 3,500 m and range as deep as 5,000 m. The WBUC is wider than the Gulf Stream - perhaps 300 km - and appears to shift position north and south from time to time (Schmitz, Robinson, and Fuglister, 1970).

Two solutions have been offered to the problem of how the WBUC and Gulf Stream cross. One possibility, based on observations in 1967, which showed southwest flow on both sides of the Stream, is that the WBUC blends with the Stream and is carried eastward for a time as it passes through so that there is a seaward component to the deep flow directly under the surface stream (Richardson and Knauss, 1971) (Figure 4-56). More recently, Richardson (1973) found that the Gulf Stream does not always extend to the bottom in the Hatteras region so that the WBUC may simply pass directly under it. In either case, the WBUC is believed to contribute some of its water to the more powerful eastward flow of the Gulf Stream and consequently, the transport of the WBUC to the south and west of Cape Hatteras is much reduced (Swallow and Worthington, 1961, and Tucholke, Wright, and Hollister, 1973).



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TRIGOM	FIGURE 4-55	Current Patterns of the Western Boundary Undercurrent as Indicated by Bottom Photography (Heezen and Hollister, 1971)

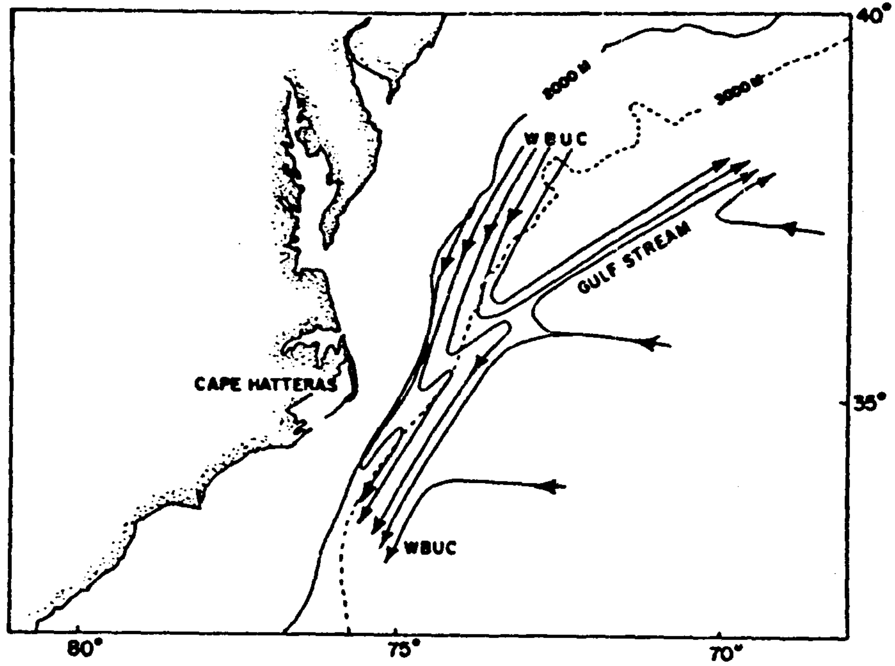

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FIGURE 4-56

Schematic Representation of the Crossing of the Gulf Stream and the Western Boundary Undercurrent

4.6 SURFACE EFFECTS

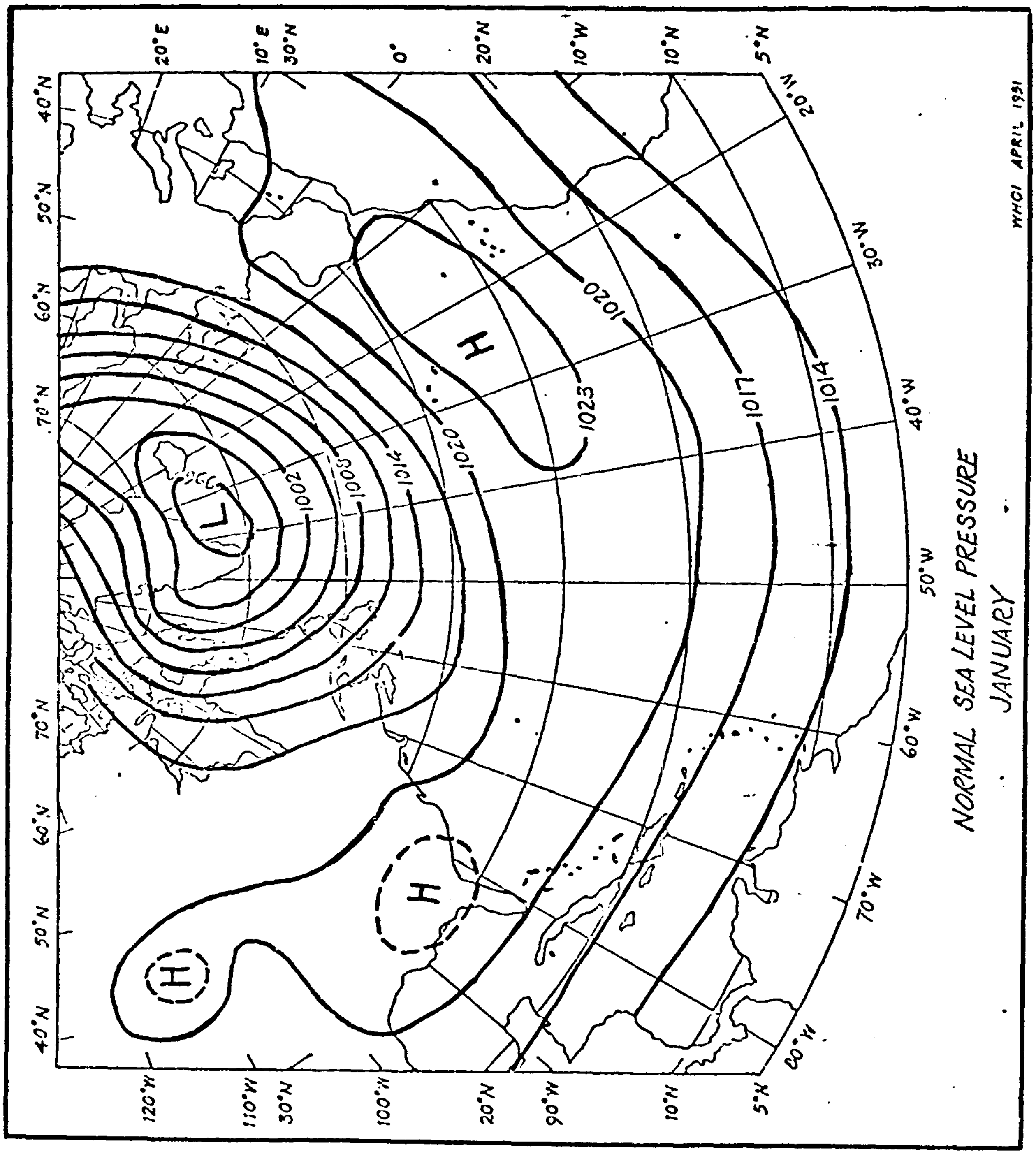
4.6.1 WINDS AND WAVES

The offshore waters of the northeastern United States lie in the zone of the prevailing westerly winds of the Northern Hemisphere. The winds and weather are controlled to a large extent by the relative strength and position of two semipermanent pressure centers: the Icelandic Low and the Bermuda-Azores High (Chase, 1975) (Figures 4-57 and 4-58). In winter, when the Icelandic Low is strong, the prevailing winds and waves are northwest; in summer, the Bermuda-Azores High strengthens and shifts westward and southwest winds and waves predominate. The generally northeast tracks of hurricanes and other storms through the region are also influenced by the pressure pattern as they tend to move with the general air circulation.

The warm water at the sea surface (See Section 4.2.1.) is an energy source which enables storms to intensify in the region of Cape Hatteras and move up the coast as northeast gales at any season. Rapid cyclogenesis occurs over frontal zones, particularly in the winter, as cold polar air moves over warm water and takes up both heat and moisture; high evaporation, both summer and winter, helps to deepen the low pressure storm centers (Laevastu, Rabe, Harding, and Larson, 1975). The slope water and Gulf Stream together form a principal region of heat loss to the atmosphere (Bunker, 1975) (Figure 4-59).

Surface wind data have been compiled by the U.S. Navy Hydrographic Office for areas of five degrees of latitude and longitude (U.S. Navy, 1963). The region from 35 to 40° N, 65 to 70° W, is closest to the middle of the western slope water. For February, winds are in the northwest quadrant 60 percent of the time, with velocities greater than Force 5 (17 knots) 56 percent of the time and greater than Force 7 (28 knots) 22 percent of the time. Nearly 70 percent of the winds greater than Force 5 are between west and north. In May, the southwest quadrant predominates with 42 percent of the observations, but only 31 percent are greater than Force 5 and four percent greater than Force 7. In August, the southwest quadrant accounts for 50 percent of all observations, but only 22 percent are stronger than Force 5 and three percent stronger than Force 7. In November, the northwest pattern has returned, with 56 percent of all observations of which half are greater than Force 5 and 16 percent greater than Force 7.

The monthly variation in wind speed at the sea surface is shown in Table 4-3A (U.S. Department of Commerce, 1973). The column at the left is the percentage of observations in which the wind speed in knots was equal to or less than the value listed in the column for each month. Thus, in February, 95 percent of the observations are 37 knots or less; only five percent are stronger than that.



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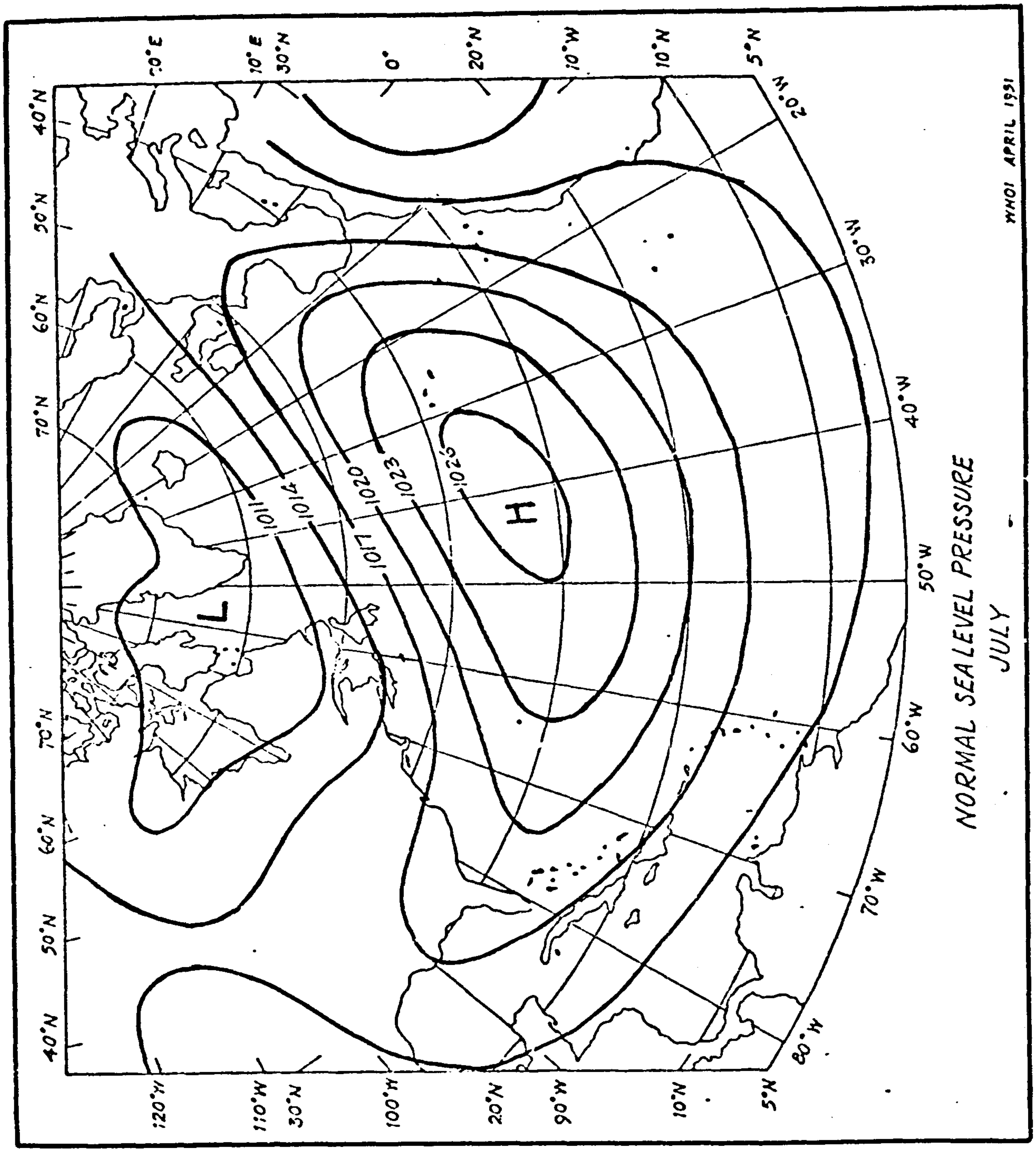
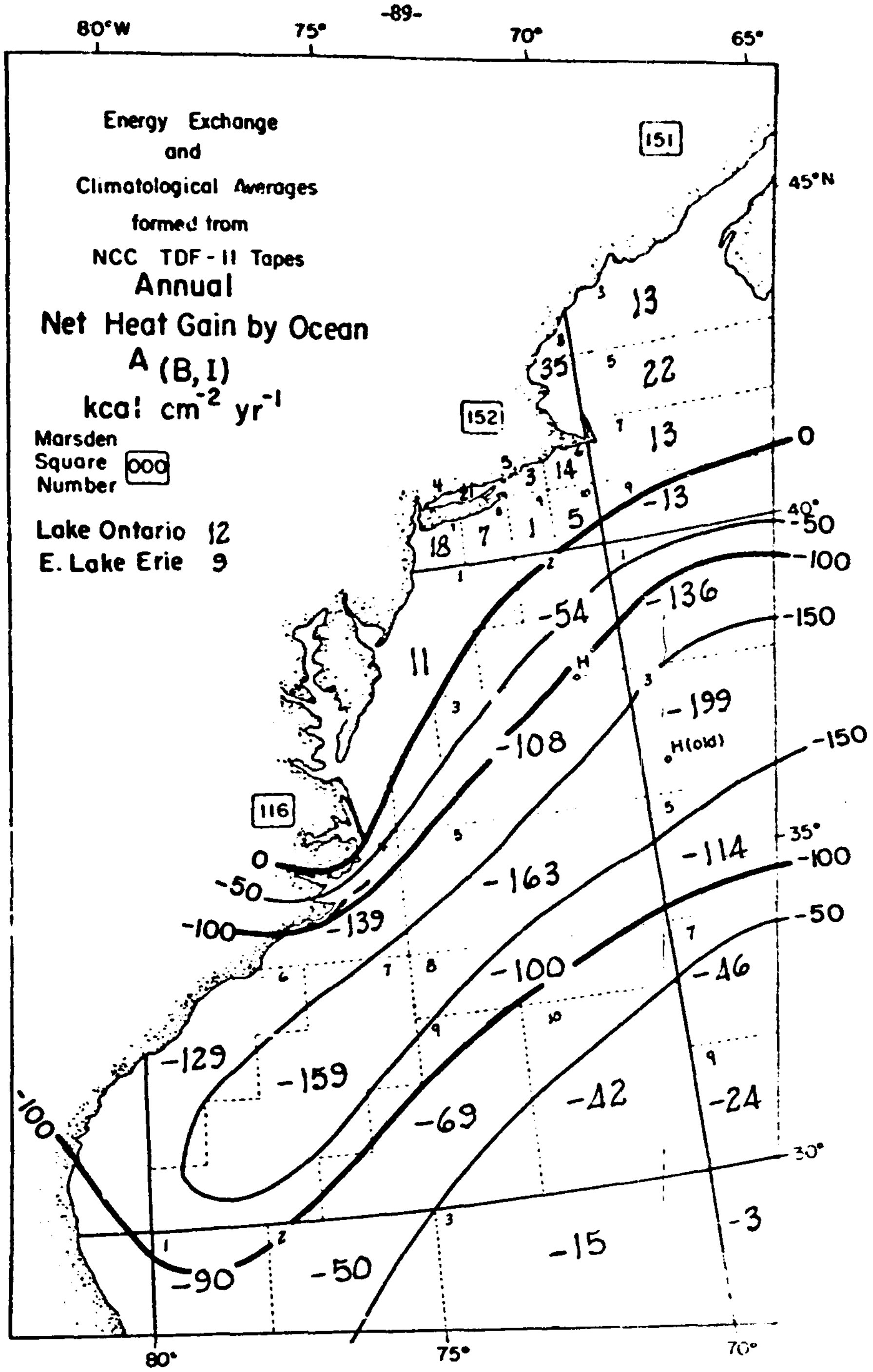
TRIGOM	**FIGURE** 4-57	Prevailing Winter Pressure Patterns in the North Atlantic (Chase, 1975)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-58	Prevailing Summer Pressure Patterns in the North Atlantic (Chase, 1975)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-59	Heat Exchange Patterns in the Slope Water (Bunker, 1975)

Table 4-3. Monthly variation (percent) in A. wind speed and B. wave height off the northeastern United States (U.S. Department of Commerce, 1973).

Percent	J	F	M	A	M	J	J	A	S	O	N	D
Min.	0	0	0	0	0	0	0	0	0	0	0	0
01	0	0	0	0	0	0	0	0	0	0	0	0
05	5	5	5	2	2	2	2	2	2	3	4	5
25	11	11	10	8	7	6	6	6	7	8	9	10
50	17	17	15	14	11	10	10	10	12	13	15	16
75	26	27	24	22	18	21	15	15	19	21	24	26
95	35	37	34	30	25	32	20	21	26	30	33	37
99	45	50	44	44	34	30	25	30	37	40	42	50
Max.	68	65	56	70	55	44	40	62	70	52	55	68
Range (1 - 99)	45	50	44	44	34	30	25	30	37	40	42	50

A. Wind Speed (Kt)

- -

Min.	0	0	0	0	0	0	0	0	0	0	0	0
01	0	0	0	0	0	0	0	0	0	0	0	0
05	2	0	0	0	0	0	0	0	0	0	0	2
25	3	2	2	1	1	1	1	1	1	2	2	3
50	5	5	5	3	3	3	3	3	3	5	5	5
75	10	10	9	8	5	5	5	5	6	9	9	9
95	15	15	13	12	8	8	7	7	10	12	13	13
99	16	20	16	13	13	8	7	10	13	18	15	23
Max.	28	31	31	26	23	16	15	25	28	30	26	31
Range (1 - 99)	16	20	16	13	13	8	7	10	13	18	15	23

B. Wave Height (Ft)

Percentiles by month, 39^{0} - 40^{0} N, 70^{0} - 72^{0} W

Wave heights resulting from these winds are shown in Table 4-3 B and in Figure 4-60). Wave heights increase in the offshore direction and are clearly greater in winter than summer, with 10 percent greater than 6.3 m in the western slope water in February but only two percent in August (Bumpus, Lynde, and Shaw, 1973). Occurrence of wave height greater than 6.3 m is extremely rare from May through September and exceeds the five percent level only from November to April (Table 4-3 B).

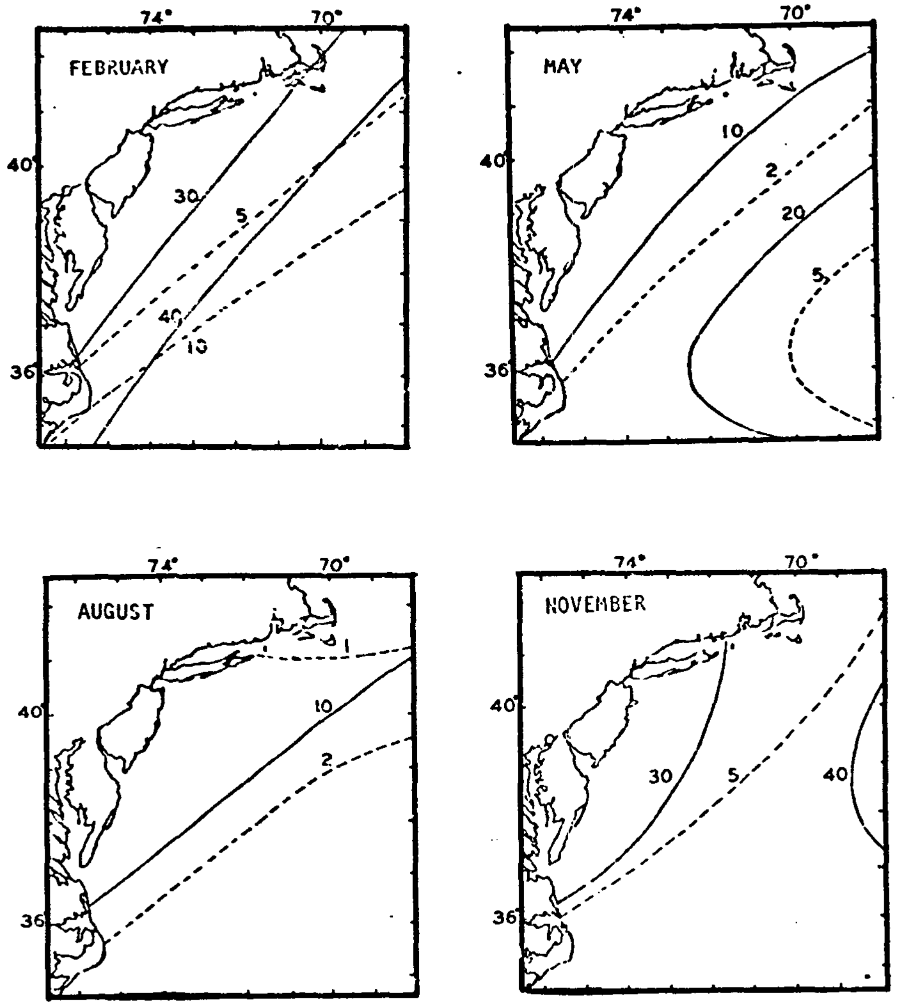
Table 4-4 gives monthly variation of several parameters in the region 38° to 40° N, 70° to 72° W. Note that the incidence of low visibility (fog) is at its height in April, May, and June when there is a flow of warm air from the southwest over water which has not yet responded to the seasonal warming trend. Visibility is less than two miles nearly 10 percent of the time in June.

4.6.2 HURRICANES

The western slope water is directly in the preferred path for tropical hurricanes that move to the northeast at the rate of one or two per year in late summer and early fall (Figures 4-61 and 4-62). Hurricanes are tropical cyclones that contain winds greater than 65 knots, sometimes reaching as high as 150 knots near the center. Those with winds of 34 to 65 knots are classed as tropical storms but can also cause severe damage to shipping and coastal sections with torrential rains and heavy seas in addition to the winds.

Tropical cyclones are intense low pressure centers surrounded by counterclockwise winds. They are usually 150 to 300 miles in diameter but sizes range from 25 to 500 miles (Tannehill, 1956). In a "typical" hurricane the center moves westward at about 15 knots in the spawning region south of 20° N. Under the influence of the Coriolis effect and upper level winds the storm recurves to the north and then northeast and picks up speed so that it may be moving at 30 knots or more as it passes Cape Hatteras. However, it should be stressed that most hurricanes exhibit irregular motion to some degree, sometimes lingering for days in the western slope water and occasionally regaining intensity after having apparently begun to dwindle. Passage of a hurricane is usually marked by a drop of 1 or 2° in temperature of the upper 50 to 100 m (Cheney, 1974, and Iselin, 1936) as it draws its energy from the heat stored in the upper ocean.

August, September, and October are the peak hurricane months in this region. The frequency varies widely from year to year. For the North Atlantic as a whole, the average is seven hurricanes per year but there have been as few as two and as many as 21 (Bowditch, 1962). Some years no hurricanes get north of Cape Hatteras, sometimes as many as four. The likelihood of hurricanes and tropical storms has been computed by the U.S. Department of Commerce on the basis of data from 1899 to 1969. In Figure 4-63, the solid contours represent the number of days in 100

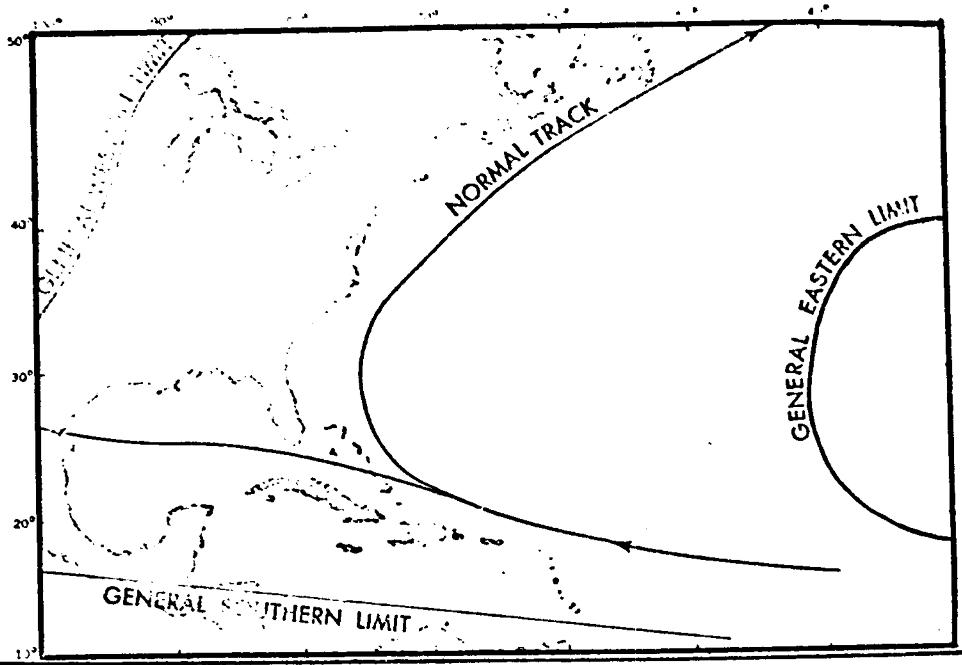


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-60	Percentage Frequency of Waves Equal to or Greater Than 5 Feet (solid lines) and Equal to or Greater Than 12 Feet (dashed lines): Selected Months (Bumpus, Lynde, and Shaw, 1973)

Table 4-4. Monthly variation of meteorological parameters in the region of 38°to 40°N and 70°to 72°W (U.S. Dept. of Commerce, 1973)

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
SEA LEVEL PRESSURE (MB)												
5% ≤	999.3	998.6	998.1	1000.3	1005.1	1007.0	1008.6	1009.1	1007.1	1003.2	1002.7	1000.3
MEDIAN	1017.6	1016.8	1016.0	1016.0	1016.4	1016.0	1016.9	1016.7	1018.0	1018.0	1017.3	1018.3
95% ≤	1031.5	1031.5	1029.2	1030.1	1027.1	1024.4	1024.7	1023.7	1026.1	1028.1	1030.1	1030.8
AIR TEMPERATURE (DEGREES F)												
5% ≤	30.9	28.4	34.0	40.6	46.9	57.0	66.9	68.0	62.1	52.5	44.1	34.0
25% ≤	39.0	37.0	40.5	46.0	53.1	63.0	71.6	72.0	68.0	59.0	50.9	42.1
MEDIAN	44.6	42.0	45.0	50.0	57.9	68.0	73.9	75.0	71.6	64.0	56.5	48.0
75% ≤	50.0	46.9	51.1	55.9	62.6	72.0	77.0	78.1	75.0	68.0	62.1	55.0
95% ≤	60.1	57.9	60.1	64.0	69.9	77.0	81.0	81.5	80.0	74.1	68.0	63.0
SEA SURFACE TEMPERATURE (DEGREES F)												
5% ≤	43.0	39.2	39.2	40.6	45.0	55.0	66.0	69.1	65.3	59.0	53.1	46.4
MEDIAN	54.0	50.2	50.0	50.4	56.1	66.0	73.9	75.9	73.9	68.0	63.0	57.9
95% ≤	64.9	57.6	64.0	66.0	69.1	77.0	80.1	82.0	80.1	75.9	73.0	63.1
MEAN RELATIVE HUMIDITY (%)	79	79	73	82	82	85	84	81	79	76	77	76
WEATHER (AT OBSERVATION TIME)												
% FREQUENCY OF PRECIPITATION	12.0	13.2	8.6	6.9	5.9	4.6	4.1	4.5	6.1	5.1	8.4	10.8
% FREQUENCY OF THUNDER AND LIGHTNING	1.9	1.3	1.4	1.1	1.1	1.5	2.9	3.3	2.2	1.8	2.0	1.7
CLOUDINESS (TOTAL SKY COVER)												
% FREQUENCY 0-2 OKTAS	16.6	16.4	28.9	36.4	37.4	37.9	33.2	35.8	26.5	34.3	24.9	15.7
% FREQUENCY 7-8 OKTAS OR OBSCURED	58.2	57.3	46.3	41.8	33.0	36.0	32.5	29.5	31.4	33.4	44.0	55.6
VISIBILITY (% FREQUENCY < 2 N. MI.)	3.2	5.3	5.5	7.8	8.5	9.8	4.6	2.5	2.3	1.8	2.3	2.5
WIND SPEED (KNOTS)												
% FREQUENCY ≥ 34 KNOTS	5.8	7.7	5.3	3.4	1.0	.5	.1	.6	1.8	2.8	4.8	7.0
5% ≤	5.0	5.0	5.0	2.0	2.0	2.0	2.0	2.0	2.0	3.0	4.0	5.0
MEDIAN	17.0	17.0	15.0	14.0	11.0	10.0	10.0	10.0	12.0	13.0	15.0	16.0
95% ≤	35.0	37.0	34.0	30.0	25.0	22.0	20.0	21.0	26.0	30.0	33.0	37.0
WAVE HEIGHT (FEET, HIGHER OF WAVE OR SWELL)												
5% ≤	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6
MEDIAN	4.9	4.9	4.9	3.3	3.3	3.3	3.3	3.3	3.3	4.9	4.9	4.9
95% ≤	14.8	14.8	13.1	11.5	8.2	8.2	6.6	6.6	9.8	11.5	13.1	13.1
% FREQUENCY ≥ 5 FT	65.7	63.0	57.5	49.3	33.6	26.6	23.9	28.2	38.4	51.6	58.1	62.9
% FREQUENCY ≥ 8 FT	29.8	31.7	23.6	17.5	8.4	5.1	3.8	4.9	13.0	19.9	25.1	27.4
% FREQUENCY ≥ 12 FT	12.2	13.4	10.4	6.4	2.6	1.3	.3	1.3	4.8	6.5	9.0	10.8



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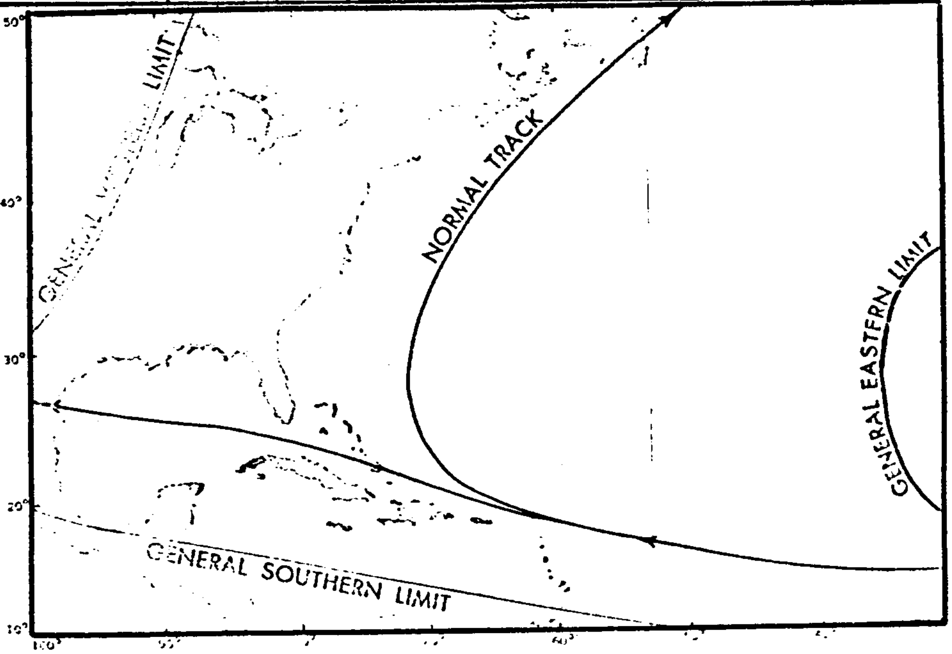
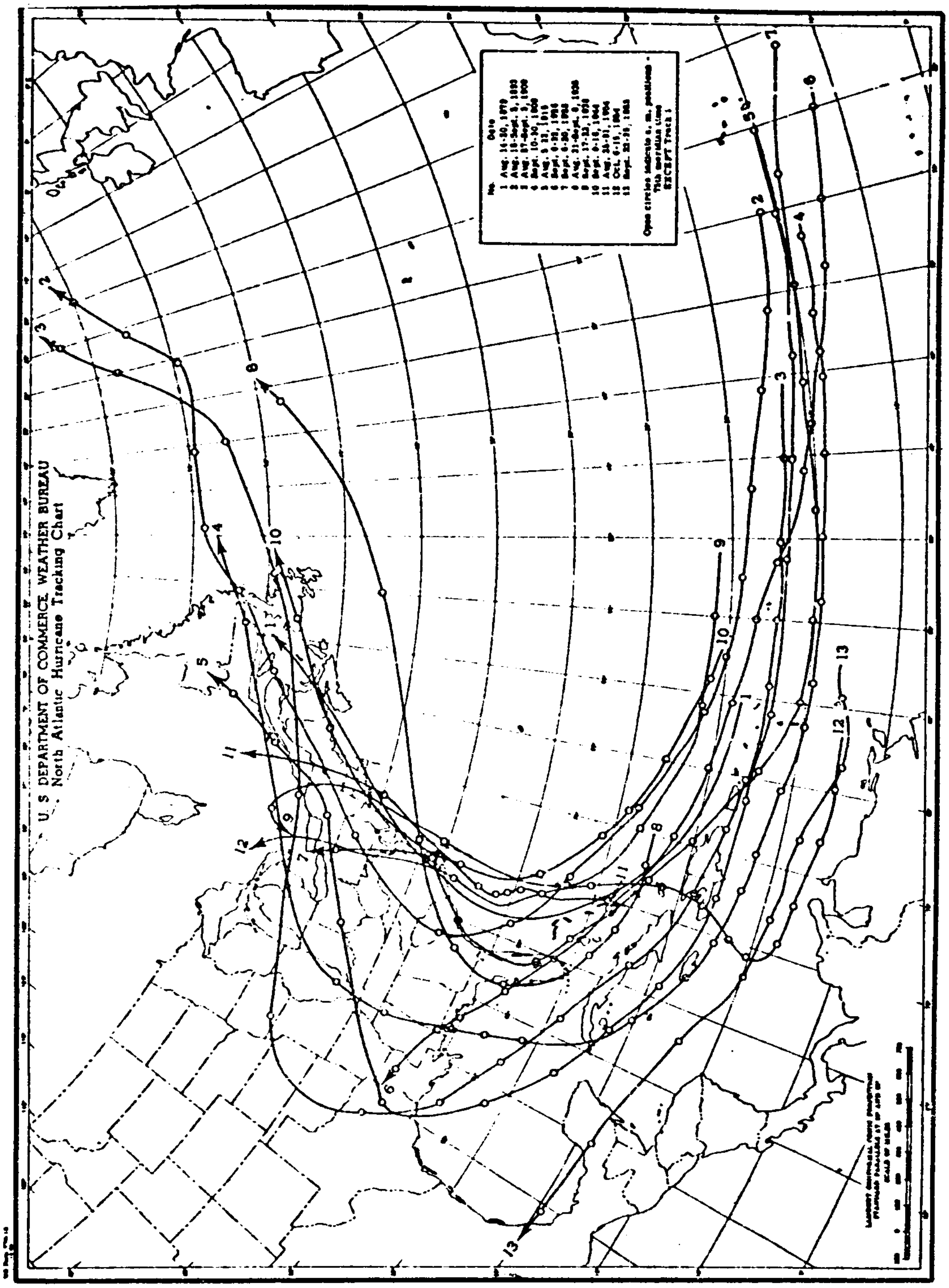
TRIGOM	FIGURE 4-61a	Average North Atlantic Storm Tracks in August, (Bowditch, 1962)



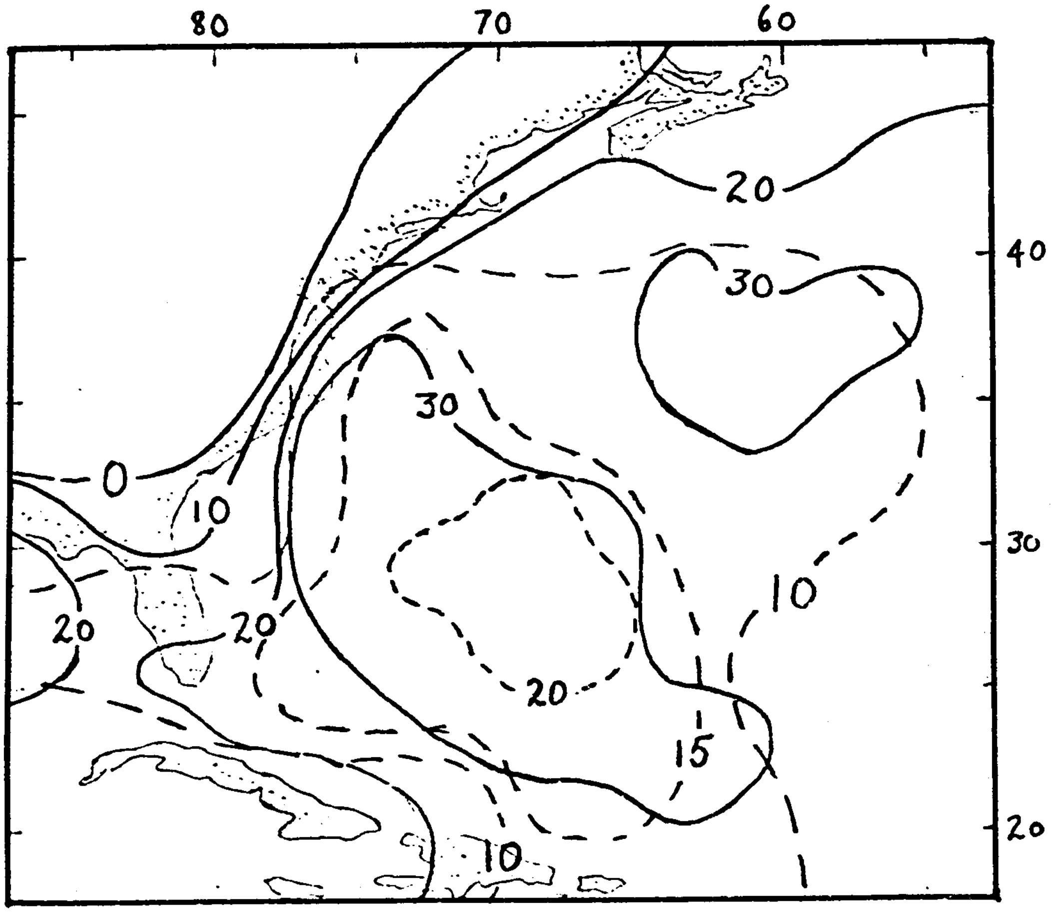
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 4-61b	Average North Atlantic Storm Tracks in September (Bowditch, 1962)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE** 4-62	Tracks of Some Devastating North Atlantic Hurricanes (Tannehill, 1956)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 4-63 Probability of Hurricanes and Tropical Storms, Number of Days Per 100 Years

years when hurricanes are to be expected in August and September; the dashed lines are for those with winds above 100 knots. The statistical chances of tropical storms are somewhat lower than for hurricanes, and they are not concentrated quite so heavily in August through October.

4.6.3 ICE

Floating ice is almost never a problem in the western slope water, but spray freezing in the rigging can be very serious in the winter months when the air temperature drops below the freezing point of seawater (about -2°C). Fishing vessels and other small craft have been known to capsize with a top-heavy load of ice.

Sea ice forms in the regions north of Newfoundland and in the Gulf of St. Lawrence. In the spring, it moves south, but disintegrates quickly upon coming into contact with warmer water and occasional observations of small pieces of sea ice (less than iceberg size) have been recorded since 1900 in the northwest Atlantic shelf and slope waters (Havens, et al., 1973). In occasional heavy ice seasons, dangerous floes extend west and south to the Grand Banks or even to Sable Island, but almost never west or south of that point (Dinsmore, 1972). Icebergs - those floes the size of a house or larger, which are carried out of Greenland waters by the Laborador Current, are not found in the western slope water. They frequently reach the Tail of the Banks (43°N, 50°W) before disintegrating, but there have been only four sighting south of 40°N since 1900, only a handful west of 60°W (Dinsmore, 1972) (also see Section 11.4.6. Chapter 11).

4.6.4 TIDES

Very few observations of tidal rise and fall have been made in the western slope water because of the water depth, although tidal currents have been quite frequently observed since the development of continuously recording current meters. Neither is of any consequence to shipping or bottom-mounted installations.

Two sets of tide gauge measurements were made at the shelf edge in a six-day period in August, 1964 (Hicks, Goodheart, and Isely, 1965). One station was in about 200 m, 139 km southeast of Nantucket, the other at 250 m, 117 km south of Block Island. In both, the mean range was about one meter and the cotidal hour was 11.85. The high tide crest appears to be parallel to the shoreline from Cape Hatteras to Cape Sable and arrives at the shelf edge about 12 hours after the moon's transit of the Greenwich meridian. More information about tides in deep water is being obtained with the successful development of pressure-sensitive deep sea tide gauges

Tidal currents tend to be rotary in the clockwise sense, both on the continental shelf and in deeper water. Speeds are generally less than 10 cm/sec, or 0.2 kts, and the tidal signal is often masked by other small scale motions. The semi-diurnal tide usually appears as a peak in the horizontal kinetic energy spectrum (see Figure 4-52) but energy of the same magnitude is also generally found at the inertial period (about 18 hours in the western slope water), for which there is no astronomical cause.

4.7 PROGNOSIS FOR FUTURE STUDIES

The present state of knowledge of the physical oceanography of the western slope water is described in the previous sections. In this section, brief consideration will be given to the areas of inadequate knowledge, descriptions of work now in progress or contemplated, and some suggestions for future research.

The hydrography of the western slope water and its seasonal changes have been well described, particularly in the upper layers, but there is a paradox: most of what we know in the surface layers is based on temperature observations by BT, aircraft, or satellite; while that in the deep water comes from standard oceanographic stations with both temperature and salinity. Yet, it is in the deep water that the temperature-salinity relationship is close and predictable and in the surface layers that temperature is not a reliable guide to either salinity or density. Many more salinity observations are needed.

Thanks to airborne and satellite techniques, the fluctuations of both the shelf/slope boundary and the Gulf Stream are regularly observed and reported and the development and fate of Gulf Stream rings, both warm-core and cold-core, is getting intensive study. More reliable estimates of the exchange of slope water and Sargasso Sea water through the Stream should soon be available (for example, Cheney, 1975). However, exchange across the shelf/slope boundary is more difficult to assess because smaller parcels are involved and the shelf water parcels are not always discernible at the sea surface and because the shoreward flux of slope water is presumably very small compared to the longshore flow, and, therefore, hard to distinguish. The distribution of the homogeneous bottom layer in space and time, and its significance, remain problems. There are evidently several inter-related processes involved at the shelf edge. For example, Riley (1975) has identified a few: upwelling due to wind stress, entrainment of underlying water into the surface layer by freshwater outflow, and enhanced vertical mixing associated with internal tides.

Fortunately, there are currently several programs aimed at unscrambling some of these complexities at the shelf edge: at the Chesapeake Bay Institute, William Boicourt and Peter Hacker have combined long-term current measurements with frequent, closely-spaced hydrographic surveys in the region between Delaware Bay and Cape Hatteras; Robert Beardsley, Charles Flagg, and Bradford Butman of Woods Hole Oceanographic Institution and M.I.T., have been doing the same sort of work south of Cape Cod, they are now combining their efforts to see if there is any coherence between widely separated sets of marine measurements and the movement of large-scale atmospheric pressure systems and the W.H.O.I.-M.I.T. group have extended their observations eastward to Georges Bank, in cooperation with Ronald Schlitz and Samuel Nickerson, of the National Marine Fisheries Service in Woods Hole.

With ERDA sponsorship (Forster, 1975), G. Csanady of Woods Hole, G. Riley of Dalhousie University, and B. Manowitz of Brookhaven National Laboratory are investigating the physical processes at the shelf edge which are responsible for the nutrient enrichment of coastal waters. C.N.K. Mooers, at the University of Delaware, has been studying the effects of barotropic and baroclinic waves on shelf exchange processes (NSF GA-34009) and the physical dynamics of the frontal zone (NSF GX-33052) and P.P. Niiler, now at Oregon State University, has NSF support for experimental studies of the generation of water movements on the continental shelf by strong meteorological disturbances.

There is less effort at present on the equally demanding problems of the circulation within the western slope water itself, the seasonal and long-term fluctuations, and the influence of atmospheric events. What, for example, is the fate of the Labrador Current, which brings approximately 4 sv of relatively fresh and cold water southwestward around the Tail of the Banks? How often do massive invasions of eastern slope water occur and what is their effect on the circulation and the biota of the western slope water? What are the fluctuations in speed and transport of the western boundary undercurrent and how do they relate to the variations in the Gulf Stream or the weather in the Norwegian Sea? How effective is the WBUC in transporting sediment?

These are fundamental questions which can be answered only by lengthy investigations involving extensive surveys by large and well-equipped vessels, and the combined efforts of meteorologists, biologists, and geologists, as well as physical oceanographers. At least one more long term current meter mooring like that at Site D should be established in the western slope water.

There are some promising beginnings. At Woods Hole, Charles Parker and Arthur Voorhis are examining historical data in both Canadian and U.S. slope waters for clues to the abundance and influence of shelf water parcels and Gulf Stream rings (NSF GA-36499). Andrew Bunker and L.V. Worthington, also of Woods Hole, are mining the vast archive of meteorological data housed by the National Weather Service at Asheville, North Carolina, for information about the exchange of energy and mass across the sea surface. Willard Pierson at C.U.N.Y, and his associates, are developing numerical wave forecasting models and expect to improve their capabilities significantly with the launching of the SEASAT-A satellite in 1978 (Pierson, 1975). Stuart Kupferman, at the University of Delaware, is using radioactive tracers to investigate residence times (NSF GA-28752X). This U.S. Coast Guard is continuing its standard sections in the western slope water, one south of Georges Bank and the other off Cape Hatteras; and the physical oceanographers at Canada's Bedford Institute of Oceanography are turning their attention to shelf/slope problems.

The special problems of submarine canyons have not received the attention they deserve in connection with their role in the transport of both water and sediment. J. Musick, at Virginia Institute of Marine Science, is continuing his investigations in Norfolk Canyon; while Gordon, Biscaye, Amos and others at Lamont Geological Observatory of Columbia University, with ERDA support, are looking at water mass, circulation, and mixing in the Hudson Canyon vicinity.

Some advantage is being taken of ships of opportunity: non-research vessels which happen to be crossing the slope water and which can make useful observations underway. Bunker (1975) has used these in his study on heat exchange and the U.S. Navy Oceanographic Office has fitted several merchant ships with XBT's for serial observations between the East Coast and Bermuda. These efforts should be expanded where possible and it is hoped that an expendable salinity probe will be developed to round out the temperature observations, which are all that can now be obtained below the surface from a ship of opportunity.

4.8 REFERENCES

Amos, A.F. 1975. The New York Bight and Hudson Canyon in October, 1974, I: Hydrography, nephelometry, bottom photography, currents. Tech. Rep. ERDA Contract AT(11-1) 2185, Lamont-Doherty Geol. Observ., Palisades, N.Y. (in press).

Amos, A.F., A.L. Gordon, and E. D. Schneider. 1971. Water masses and circulation patterns in the region of the Blake-Bermuda outer ridge. Deep-Sea Res., 18(2): 145-166.

Barinov, A.A. and V.A. Brysantsev. 1972. A volumetric statistical T/S analysis of the Nova Scotia shelf and Georges Bank water masses. Int. Comm. Northw. Atl. Fish. Res. Bull., 9: 21-25.

Barrett, J.R., Jr. 1965. Subsurface currents off Cape Hatteras. Deep-Sea Res., 12: 173-184.

_________. 1969. Salinity changes in the western North Atlantic. Deep-Sea Res., 16: 7-16.

Beardsley, R.C., W.C. Boicourt, and D.V. Hansen. 1975. Physical oceanography of the Middle Atlantic Bight. ASLO Spec. Symposium on the Middle Atlantic Continental Shelf and New York Bight, New York City, Nov. 3-5, 1975. Abstract only.

Beardsley, R.C. and B. Butman. 1974. Circulation on the New England continental shelf: response to strong winter storms. Geophys. Res. Lett., 1(4): 181-184.

Beardsley, R.C. and C.N. Flagg. 1975. Winter-time circulation on the New England continental shelf. Seventh Liege Colloquium on Ocean Dynamics, 1975 (Abstract only).

Biscaye, P.E. and C.R. Olsen. 1975. Suspended particulates in the New York Bight: concentrations and compositions in relation to water masses and bottom sediments. ASLO Special Symposium in the Middle Atlantic Continental Shelf and New York Bight, New York City, Nov. 3-5 (Abstract only).

Boicourt, W.C. and P.W. Hacker. 1975. Circulation on the Atlantic continental shelf of the United States, Cape May to Cape Hatteras. Seventh Liege Colloquium on Ocean Dynamics (Abstract only).

Bowditch, N. 1962. American practical navigator, 1962 edition. U.S. Navy Hydrogr. Office, Pub. 9: Washington, D.C. 1524 pp.

Bue, C. 1970. Streamflow from the United States into the Atlantic Ocean during 1931-60. U.S. Geol. Surv. Water Supp. Pap. 1899-L, Washington, D.C. 36 p.

Bumpus, D. F. 1958. Investigations of climate and oceanographic factors influencing the environment of fish. Woods Hole Oceanogr. Inst. Ref. 58-45. (Unpublished manuscript).

_________. 1965. Residual drift along the bottom on the continental shelf in the Middle Atlantic Bight area. Limnol. Oceanogr. Suppl. 10: R50-R53.

_________. 1973. A description of the circulation on the continental shelf of the east coast of the United States. Progress in Oceanogr. 6: 111-156.

_________. 1975. Review of the physical oceanography of Georges Bank. Presented at Ann. Int. Comm. Northw. Atl. Fish. Meet. Aberdeen, June, 1975.

Bumpus, D. F., R. E. Lynde, and D. M. Shaw. 1973. Physical oceanography. In: Coastal and offshore environmental inventory: Cape Hatteras to Nantucket Shoals. Mar. Pub. Ser. 2, Univ. of R.I.: 1-1 - 1-72.

Bunker, A. F. 1975. Energy exchange at the surface of the western North Atlantic Ocean. Woods Hole Oceanogr. Inst. Tech. Rep. 75-3. 107 p.

Cacchione, D. A. 1970. Experimental study of internal waves on a slope. Mass. Inst. of Technol./Woods Hole Oceanogr. Inst. Thesis.

Chase, J. 1975. Weather of the Baltimore Canyon region. Proc. Outer Continental Shelf Conf. and Workshop, Estuarine Res. Fed., College Park, Md., Dec. 1974, p. 99-108.

Chamberlin, J. L. 1975. Bottom temperatures on the continental shelf and slope south of New England during 1974. Prep. for Nat. Mar. Fish. Serv. rept. on the status of the environment.

Cheney, R. E. 1974. Sea surface cooling due to Hurricane Becky. The Gulf Stream, 9: 11.

_________. 1975. A census of rings in the Gulf Stream system. Trans. Amer. Geophys. Union (EOS) Nov. 1975, p. 1007 (Abstract only).

Colton, J. B., Jr. 1968. A comparison of current and long-term temperatures of continental shelf waters, Nova Scotia to Long Island. Int. Comm. Northw. Atl. Fish Res. Bull., 5: 110-129.

_________. 1968. Recent trends in subsurface temperatures in the Gulf of Maine and contiguous waters. J. Fish. Res. Bd. Can. 25(11): 2427-2437.

Colton, J. B., Jr. and R. R. Stoddard. 1972. Average monthly sea-water temperatures, Nova Scotia to Long Island, 1940-1959. Amer. Geogr. Soc. Serial Atlas of the Marine Environment. Folio 21. 2 p. 10PL.

Cresswell, G. H. 1967. Quasi-synoptic monthly hydrography of the transition region between coastal and slope water south of Cape Cod, Mass. Woods Hole Oceanogr. Inst. Ref. 67-35. (unpub. man.).

Dillon, W. P. and H. B. Zimmerman. 1970. Erosion by biological activity in two New England submarine canyons. J. Sediment. Petrol., 40(2): 542-547.

Dinsmore, R. P. 1972. Ice and its drift into the North Atlantic Ocean. Int. Comm. Northw. Atl. Fish. Spec. Publ. 8: 89-128.

Eittreim, S., M. Ewing, and E. M. Thorndike. 1969. Suspended matter along the continental margin of the North American Basin. Deep-Sea Res., 16: 613-624.

Emery, K. O., and D. A. Ross. 1968. Topography and sediments of a small area of the continental slope south of Martha's Vineyard. Deep-Sea Res., 15: 415-422.

Emery, K. O. and E. Uchupi. 1972. Western North Atlantic Ocean: topography, rocks, structure, water, life and sediments. Amer. Petrol. Geol. Memoir 17. 532 p.

Fenner, P., G. Kelling, and D. J. Stanley. 1971. Bottom currents in Wilmington submarine canyon. Nature, London, 229(2): 52-54.

Fisher, A., Jr. 1972. Entrainment of shelf water by the Gulf Stream northeast of Cape Hatteras. J. Geophy. Res. 77(18): 3248-3255.

Flagg, C. N. and R. C. Beardsley. 1975. The 1974 MIT New England shelf dynamics experiment data report. Part 1: Hydrography. Rept. Mass. Inst. Tecnnol. 75-1. 87 p.

Ford, W. L., J. R. Longard and R. E. Banks. 1952. On the nature, occurrence and origin of cold, low salinity water along the edge of the Gulf Stream. J. Mar. Res., 11(3): 281-293.

Ford, W. L. and A. R. Miller. 1952. The surface layer of the Gulf Stream and adjacent waters. J. Mar. Res. 11(3): 267-280.

Forster, W. O. 1975. A survey of ERDA-sponsored coastal zone research in the northeast. ASLO Special Symposium on the Middle Atlantic Continental Shelf and New York Bight, New York City. Nov. 3-5. (Abstract only).

Fuglister, F.C. 1947. Average monthly sea surface temperatures of the western North Atlantic Ocean. Mass. Inst. Technol./Woods Hole Oceanogr. Inst. Pap. Phys. Oceanogr. and Meteorol., 10(2): 25 p.

________. 1954, Average temperature and salinity at a depth of 200 m in the North Atlantic. Tellus, 6(1): 46-58.

________. 1960. Atlantic Ocean atlas of temperature and salinity profiles and data from the international geophysical year of 1957-1958. Woods Hole Oceanogr. Inst. Atlas Ser. 1209 p.

________. 1963. Gulf Stream '60. Progress in Oceanogr., 1: 265-373.

________. 1972. Cyclonic rings formed by the Gulf Stream, 1965-66. In: A. Gordon (ed.), Studies in physical oceanography. New York, Gordon and Breach Sci. Publ., 1: 137-168.

Gordon, A.L., A.F. Amos, and R.D. Gerard. 1975. New York Bight water stratification. ASLO Special Symposium on the Middle Atlantic Continental Shelf and New York Bight, New York City, Nov. 3-5 (abstract only),

Gotthardt, G.A. and G.J. Potocsky. 1974. Life cycle of a Gulf Stream anticyclonic eddy observed from several oceanographic platforms. J. Phys. Oceanogr., 4(1): 131-134.

Grassle, J.F., H.L. Sanders, R.R. Hessler, G.T. Rowe, and T. McLellan. 1975. Pattern and zonation: a study of the bathyal megafauna using the research submersible ALVIN. Deep-Sea Res., 22(7): 457-482.

Hachey, H.B. 1955. Water replacements and their significance to a fishery. Deep-Sea Res., Suppl to 3: 68-73.

Hansen, D.V. 1970. Gulf Stream meanders between Cape Hatteras and the Grand Banks. Deep-Sea Res., 17(3): 495-511.

Heezen, B.C. and C.D. Hollister. 1971. The face of the deep. Oxford Univ. Press, New York. 659 p.

Heezen, B.C., C.D. Hollister, and W.F. Ruddiman. 1966. Shaping of the continental rise by deep geostrophic contour currents. Science, 152: 502-508.

Hicks, S.D., A.J.M. Goodheart, and C.W. Iseley. 1965. Observations of the tide on the Atlantic continental shelf. J. Geophys. Res., 70: 1827-1830.

Hollister, C.D. and B.C. Heezen. 1972. Geologic effects of ocean bottom currents: western North Atlantic. In: A. Gordon (ed.), Studies in physical oceanography. Gordon and Breach Sci. Publ., N.Y., 1: 37-66.

Howe, M.R. 1962. Some direct measurements of the non-tidal drift on the continental shelf between Cape Cod and Cape Hatteras. Deep-Sea Res., 9: 445-455.

Ingham, M.C. 1974. Variations in the shelf water front off the Atlantic Coast between Cape Hatteras and Georges Bank. Prep. for Nat. Mar. Fish. Serv., Report on the status of the environment.

Iselin, C. O'D. 1936. A study of the circulation of the western North Atlantic. Mass. Inst. Technol./Woods Hole Oceanogr. Inst. Pap. Phys. Oceanogr. and Meteorol., 4(4).

________. 1939. Some physical factors which may influence the productivity of New England's coastal waters. J. Mar. Res., 2: 74-85.

________. 1955. Coastal currents and the fisheries. Deep-Sea. Res. Suppl. to 3: 474-478.

Keller, G.H., D. Lambert, G. Rowe, and N. Staresinic. 1973. Bottom currents in the Hudson Canyon. Science, (April): 181-183.

Ketchum, B.H. and N. Corwin. 1964. The persistence of "winter" water on the continental shelf south of Long Island, N.Y. Limnol. and Oceanogr., 9(4): 467-475.

Khedouri, E. 1972. Surface manifestation of the North Wall. Monthly Summary, the Gulf Stream, (Feb.). 7 p.

Knauss, J.A. 1969. A note on the transport of the Gulf Stream. Deep-Sea Res., 16 suppl. (Fuglister v.): 117-123.

Kupferman, S. and H. Feely. 1974. The use of tracers to investigate residence times of the northeast shelf and slope waters. Conference on Physical Oceanography of the Continental Shelves, Annapolis, Md., April 1974 (Abstract only).

Laevastu, T., K. Rabe, J. Harding, and S. Larson. 1975. Ocean atmosphere interactions in the area of Middle Atlantic continental shelf and New York Bight. ASLO Special Symposium on the Middle Atlantic Continental Shelf and New York Bight., New York City, Nov. 3-5 (Abstract).

Lambert, R.B., Jr. 1974. Small-scale dissolved oxygen variations and the dynamics of Gulf Stream eddies. Deep Sea Res., 21: 529-545.

Lazier, J.R.N. 1973. The renewal of Labrador Sea water. Deep-Sea Res., 20: 341-353.

Legeckis, R. 1975. Application of synchronous meteorological satellite data to the study of time dependent sea surface temperature changes along the boundary of the Gulf Stream. Geophys. Res. Lett., 2(10): 435-438.

MacIlvaine, J.C. 1973. Sedimentary processes on the continental slope off New England. Ph.D. Thesis, Mass. Inst. Technol./Woods Hole Oceanogr. Inst., WHOI Ref. 73-58. 211 p.

McClain, E.P. 1975. The availability and limitations of NOAA satellite-derived sea surface temperature products. Paper presented at I.C.E.S. 63rd. Statutory Meeting, Montreal, Sept. 1975.

McLellan, H.J. 1957. On the distinctness and origin of the slope water off the Scotian Shelf and its easterly flow south of the Grand Banks. J. Fish. Res. Bd. Can., 44(2): 213-239.

Metcalf, W.G. 1969. Dissolved silicate in the deep North Atlantic. Deep-Sea Res., Suppl. to 16: 139-145.

Millard, R. 1974. Bottom-layer observations from MODE and IWEX. MODE Hot-Line News, 65, Woods Hole Oceanogr. Inst. (unpub. doc.)

Moore, D. E. 1972. Shelf water eddies in slope water. Gulf Stream Monthly Summary, U.S. Naval Oceanographic Office, 7(4). 7 p.

Parke, M.E. 1972. A bottom homogeneous layer near the shelf margin south of Cape Cod. Woods Hole Oceanogr. Inst. (unpub. manuscript).

Parker, C.E. 1971. Gulf Stream rings in the Sargasso Sea. Deep-Sea Res., 18: 981-993.

________. 1973. The natural rhythm of the speed and position of the Gulf Stream. In: Final Rep. NASA contract NAS 8-16881. Task B. Continued study of data from environmental research buoy.

________. 1975. Currents at the edge of the continental shelf south of Cape Cod. Proposal submitted to Nat. Sci. Found. by Woods Hole Oceanogr. Inst., Woods Hole, Mass.

Pierson, W.J. 1975. Recent progress in the numerical prediction of ocean waves. ASLO Special Symposium on the Middle Atlantic Continental Shelf and New York Bight, New York City, Nov. 2-5 (Abstract only).

Pollak, M.J. 1947. Hydrography of the western Atlantic: hydrography of the subsurface slope water. Woods Hole Oceanogr. Inst. Tech. Rep. 5. 15 p.

Richardson, P.L. 1973. Current measurements under the Gulf Stream near Cape Hatteras, North Carolina. Ph.D. Dissert., Univ. of R.I., Kingston. 181 p.

Richardson, P.L. and J.A. Knauss. 1970. Transport and velocity of the Gulf Stream at Cape Hatteras. Narragansett Mar. Lab., Univ. of R.I., Tech. Rep. 31, Ref. 70-1. 110 p.

________. 1971. Gulf Stream and western boundary undercurrent observations at Cape Hatteras. Deep-Sea Res., 18: 1069-1110.

Riley, G. 1975. Nutrient enrichment in the Gulf of St. Lawrence and the continental shelf of northeastern North America. ASLO Annu. Meet., Halifax, June 1975 (Abstract only).

Ross, D.A. 1968. Current action in a submarine canyon. Nature, 218: 1242-1245.

Rossby, C.G. 1936. Dynamics of steady state ocean currents in light of experimental fluid mechanics. Pap. Phys. Oceanogr. Meteorol., 5.

Rowe, G.T. 1971. Observations on bottom currents and epibenthic populations in Hatteras submarine canyon. Deep-Sea Res., 18(6): 569-581.

Rowe, G.T. and R.J. Menzies. 1968. Deep bottom currents off the coast of North Carolina. Deep-Sea Res., 15: 711-719.

Saunders, P.M. 1971. Anticyclonic eddies formed from shoreward meanders of the Gulf Stream. Deep-Sea Res., 18: 1207-1219.

________. 1973. Tracing surface flow with surface isotherms. Mem. Soc. Roy. des Sciences de Liege, 6(IV): 99-108.

Schmitz, W.J., Jr., A.R. Robinson, and F.C. Fuglister. 1970. Bottom velocity observations directly under the Gulf Stream. Science, 170: 1192-1194.

Schneider, E.D., P.J. Fox, C.D. Hollister, H.D. Needham, and B.C. Heezen. 1967. Further evidence of contour currents in the western North Atlantic. Earth and Planet. Sci. Lett., 2: 351-359.

Schroeder, E.H. 1963. North Atlantic temperatures at a depth of 200 m. Ser. Atlas of Mar. Environ., Folio 2, Amer. Geogr. Soc., New York. 9 pl.

________. 1965. Average monthly temperatures in the North Atlantic Ocean. Deep-Sea Res., 12: 323-343.

________. 1966. Average surface temperatures of the western North Atlantic. Bull. Mar. Sci., 16(2): 302-323.

Shonting, D.H. and G.S. Cook. 1964. Drogue-current observations in the THRESHER search area (29 May to 3 June 1963). U.S. Naval Underwater Ordnance Sta. (Newport, R.I.) Tech. Memo 307. 14 p.

Smith, E.H., F.M. Soule, and O. Mosby. 1937. The Marion and General Green expedition to Davis Strait and Labrador Sea. U.S. Coast Guard Bull. 19 Scientific results, Part 2: Physical oceanography. 259 p. Washington, D.C.

Stommel, H. The Gulf Stream, a physical and dynamical description. Univ. of Cal. Press, Berkeley and Los Angeles. 202 p.

Strack, S.L. 1953. Surface temperature gradients as indicators of the position of the Gulf Stream. Ref. 53-53, Woods Hole Oceanogr. Inst., Woods Hole, Mass.

Stumpf, H.G. 1974. A satellite-derived experimental Gulf Stream analysis. Mar. Weather Log, 18(3): 149-152.

Swallow, J.C. and L.V. Worthington. 1961. An observation of a deep counter-current in the western North Atlantic. Deep-Sea Res., 8: 1-19.

________. 1969. Deep currents in the Laborador Sea. Deep-Sea Res., 16: 77-84.

Tannehill, I.R. 1956. The hurricane. U.S. Dep. of Commer., Weather Bur., Washington, D.C. 22 p.

Tucholke, B.E., W.R. Wright, and D. Hollister. 1973. Abyssal circulation over the Greater Antilles Outer Ridge. Deep-Sea Res., 20(11): 973-995.

U.S. Department of Commerce. 1973. Environmental conditions within specified geographical regions: offshore east and west coasts of the United States and in the Gulf of Mexico. Final Rep., Nat. Oceanic Data Center, Environ. Data Serv., Nat. Oceanic and Atmos. Admin., Washington, D.C. 735 p.

U.S. Coast Guard Oceanographic Unit. 1975. Surface isotherms - °C: July 22, 24, 25, 29, 30 & 31, 1975. Airborne Radiation Thermometer Program, Washington, D.C. map.

U.S. Navy. 1963. Oceanographic atlas of the North Atlantic Ocean, Section IV, sea and swell. Hydrogr. Office Publ. 700.

U.S. Weather Service. 1975. Gulf Stream. Published since 1975 by Nat. Weather Service., from 1966 to 1974 by Naval Oceanogr. Office, as "Monthly Summary, the Gulf Stream". U.S. Dep. of Commerce, NOAA, Washington, D.C.

Volkmann, G.H. 1962. Deep current observations in the western North Atlantic. Deep-Sea Res., 9: 493-500.

Voorhis, A. D. 1974. Lagrangian currents along the shelf edge south of New England. Conference on Physical Oceanography of the Continental Shelves, Annapolis, Md., April 1974 (abstract only).

Warren, B.A. 1963. Topographic influences on the path of the Gulf Stream. Tellus, 15(2): 167-183.

Warren, B.A. and G.H. Volkmann. 1968. Measurement of volume transport of the Gulf Stream south of New England. J. Mar. Res., 26(2): 110-126.

Weatherly, G.L. and P.P. Niiler. 1974. Bottom homogeneous layers in the Florida current. Geophys. Rep. Lett., 1(7): 316-319.

Webster, F. 1969. Vertical profiles of horizontal ocean currents. Deep-Sea Res., 16: 85-98.

Worthington, L.V. 1964. Anomalous conditions in the slope water area in 1959. J. Fish. Res. Bd. Can., 21: 327-333.

_________. 1970. The Norwegian Sea as a Mediterranean basin. Deep-Sea Res., 17(1): 77-84.

_________. (in press). On the North Atlantic circulation. Johns Hopkins Oceanogr. Studies.

Worthington, L.V. and H. Kawai. 1972. Comparision between deep sections across the Kuroshio and the Florida current and Gulf Stream. In: H. Stommel and J. Yoshida (eds.), Kuroshio, its physical aspects. Chap. 10: 371-385. Univ. of Tokyo Press.

Wright, W.R. 1972. Northern sources of energy for the deep Atlantic. Deep-Sea Res., 19: 865-877.

_________. 1976. The limits of shelf water south of Cape Cod, 1941-1972. J. Mar. Res. (in press).

Wright, W.R. and L.V. Worthington, 1970. The water masses of the North Atlantic Ocean: a volumetric census of temperature and salinity. Amer. Geogr. Soc. Ser. Atlas of Mar. Environ. Folio 19, New York.

Yentsch, C. 1974. The influence of geostrophy on primary production. Tethys, 6: 111-118.

Zenk, W. and M.G. Briscoe. 1974. The Cape Cod experiment in near surface internal waves. Woods Hole Oceanogr. Inst. Tech. Rep. 74-87.

Zimmerman, H.B. 1971. Bottom currents on the New England continental rise. J. Geophys. Res., 76: 5865-5876.

CHAPTER 5.0

GEOLOGICAL OCEANOGRAPHY

EDWARD H. SHENTON

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Chapter 5.0 Geological Oceanography

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5.1 GEOLOGY OF THE CONTINENTAL SLOPE

5.1.1 GENERAL DESCRIPTION

The continental slope area, while small in comparison with the shelf and the greater ocean depths, is the most significant topographic discontinuity of the earth's crust. It is the area of contact between the low density rocks of the continent and the higher density rocks of the ocean floor. The point of contact is not easy to delineate or define, however, since heavy sedimentation, cutting of submarine canyons, and faulting tend to obscure any specific boundary (Emery and Uchupi, 1972). The continental slope off eastern North America extends for nearly 10,000 km with an average width of approximately 100 km. Each segment of the slope is different in origin and character. The area from Nova Scotia to Cape Hatteras (Figure 5-1) is considered by Emery and Uchupi (1972) to be most like the classical concept or textbook description of a continental slope area. The range of slope angle varies from 1° to 15° throughout this entire area; the general variation is from 3° to 6° seaward.

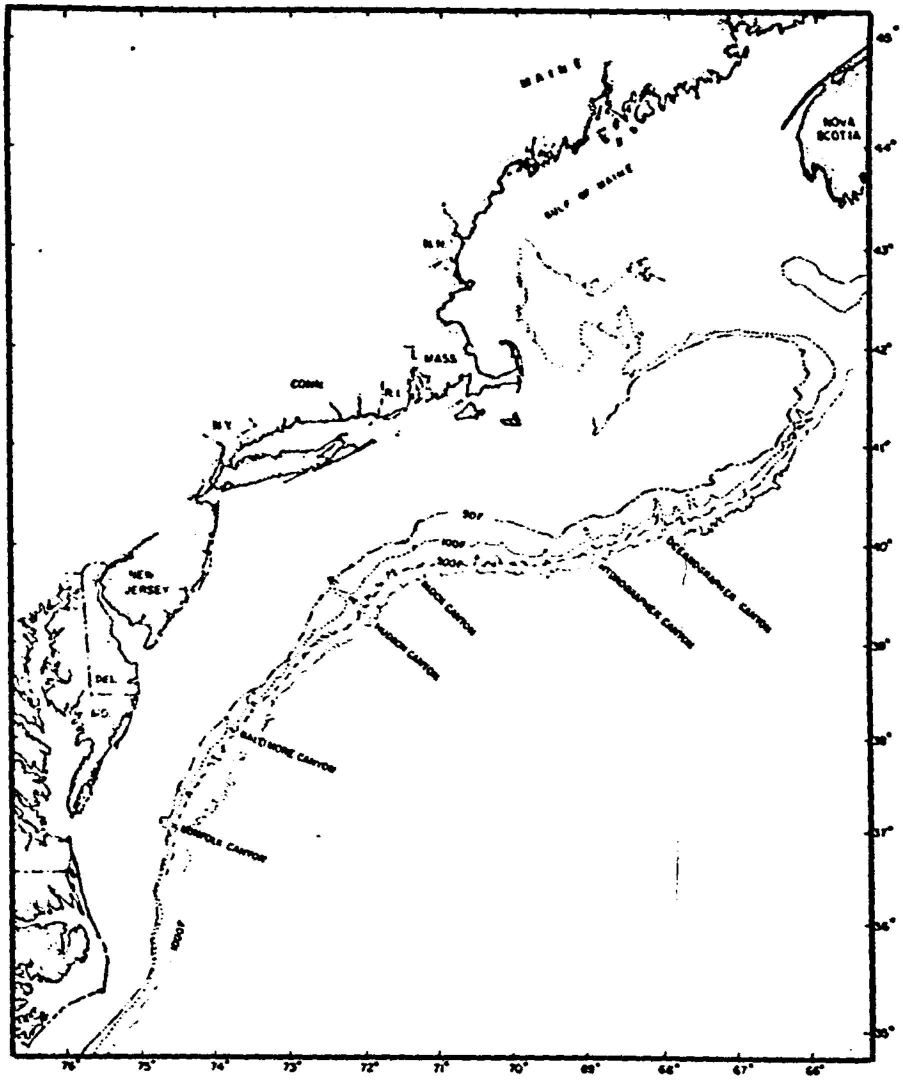
5.1.2 ORIGINS OF SLOPES

Shepard (1963) suggests four different ways for the continental slope to have originated: wave built, forset beds or deltas, down warping, or a fault scarp or zone. Examples of these are shown in Figure 5-2. At the present time, the most accepted cause of the slope's origin seems to be faulting (Shepard, 1963).

Shepard cites a number of arguments in support of this: deep trenches occur near the base of at least half the continental slopes of the world, earthquakes occur along some of the slopes where no trenches exist, and straight trenches occur along slopes bordered by trenches with sharp angular (rather than curving) changes of direction. Furthermore, the rock outcrops dredged from slopes and canyon walls are best explained by faulting. An alternative fault interpretation, based on work by Emery (1950), suggests high angle thrust faults which would elevate the margins and allow cutting by canyons before submerging again. It seems agreed upon by most workers that there are a variety of ways in which the continental slope could have originated.

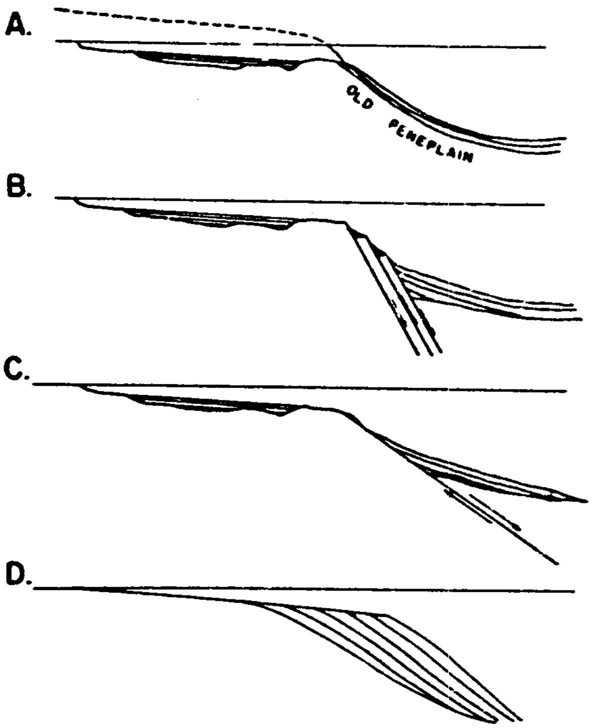
5.1.3 GEOLOGIC HISTORY

The general theory of continental drift is well established as a fundamental part of the geologic history of the northern Atlantic. However, some disagreement continues on the exact mechanisms and sequence of events. During much of the pre-Cambrian Epoch, the continents of North America and Africa were joined and the plates folded and metamorphosed into the rocks which form the present basement. During this time, there was no marine environment in either the New England region or Gulf of Maine continental margin. Sometime towards the end of the late



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 5-1 The Continental Slope From Georges Bank to Cape Hatteras



A. Downbending of an old peneplain

B. Step faulting

C. Low-angle normal fault

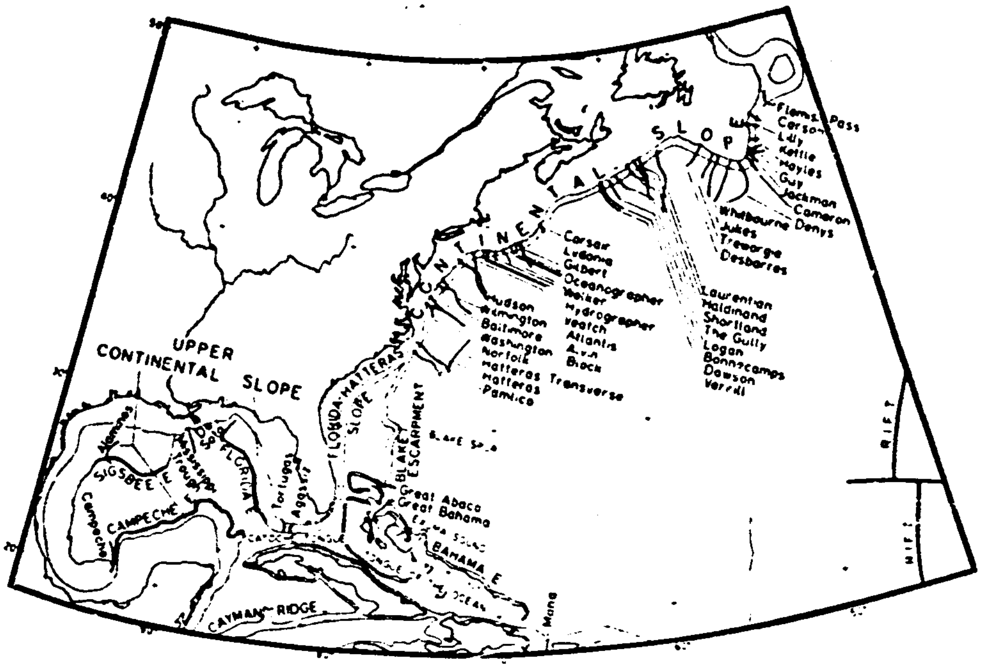
D. Wave built terrace

FIGURE 5-2 Several Possible Origins of the Continental Slope (Shepard, 1963) pre-Cambrian these land masses began to separate and, during the Triassic, the opening of the North Atlantic took place (Hallam, 1971). The forces occurring at this time - tension and separating of the plates - would probably have initiated normal faults controlling the large structures such as Baltimore Canyon Trough and Georges Bank Trough. Depression of these troughs continued with the added weight of continuing sedimentation; uplift of the land to the west of the Baltimore Canyon Trough during the late Triassic could have provided a great volume of sediment during the Jurassic time. During the Jurassic, uplifting of the shelf edge ridge probably kept pace with the deposition of sediments in the Baltimore Canyon Trough forming a barrier. Behind the barrier, various types of sediments were probably deposited in the late Cretaceous or earlier. When the fault movement stopped, sediments increased and spilled over the ridge onto the continental slope and rise. During this time, sedimentation diminished in the northern region of the Georges Bank basin and a thicker section was deposited in the central part. As it did in the Baltimore Canyon, the sediment wedge built out over the ridge to introduce marine clays onto the continental slope.

A structural nonconformity over much of Georges Bank occurred during the late Cretaceous followed by deposition of tertiary sand, clays, and silt stone. Finally, the Pleistocene glaciers enlarged the valleys in the Gulf of Maine and delivered large quantities of glacial sands and gravels forming moraines and outwash plains farther out. These Pleistocene deposits are now a thin blanket of reworked glacial outwash across Georges Bank, cut by numerous channels now mostly buried. During the Pleistocene and Holocene, the continued reworking and redistribution of the gravel debris carried much material down submarine canyons and created a series of shoals in the shallower areas. The slope going south and west of Hydrographer Canyon, on casual examination, appears less incised and indented and has approximately eight distinct canyons cutting across its surface from Hydrographer down to Hudson Canyon. Of these, the major canyons are Veatch, Atlantis, Alvin, and Block. The bathymetry of the region has been compiled from U.S. Coast and Geodetic Survey and U.S. Bureau of Commercial Fisheries (1967). Figure 5-3 shows the major canyons which dissect the continental slope.

5.1.4 BATHYMETRY

The continental slope is a complex feature representing the link or transition between two principal levels on the earth's surface. Based on the recovery of tertiary and cretaceous rocks from the slope, Pratt (1968), Stetson (1936), and Northrup and Heezen (1951), believe that most of the escarpment is primarily in an area of slow sedimentation. Since there are canyons present, however, there is also some erosional activity. Typical sounding profiles along the slope show two separate types of bottom accompanied by a change in gradient. One is a steep irregular upper slope and the other is a smoother lower slope.



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-3	Major Named Canyons That Dissect the Slope (Emery and Uchupi, 1972)

Another method of classifying the Atlantic Coast continental slope is by dividing it into three types of sedimentary environments: glacial in the north, terrigenous in the Middle Atlantic, and carbonate in the south. Pratt (1968) combines the southern New England and Middle Atlantic slope as typical of an unglaciated, non-carbonate environment.

5.1.5 GENERAL STRUCTURE

Structural understanding of the past history of the continental margin is somewhat restricted because of the lack of good recent geophysical data. What is known concerning the deep structure of the study area results from gravity magnetic data together with seismic refraction profiling. More is known of the post-Cretaceous shallow structure, at least in the depth to about 2 km. Good reviews of the general structure in history have been presented by Drake, et al., (1968), Emery and Uchupi (1972), Emery (1970), and Milliman (1973).

The major magnetic feature found along the Atlantic continental margin is the slope anomaly which extends over the outer shelf and upper midslope with values generally exceeding 600 gammas. The slope anomaly trends more or less parallel and continuously from Georges Bank to the northern part of the Blake Plateau (Figure 5-4). Most authors assume this anomaly to represent a deeply buried ridge behind which most of the continental shelf sediments have accumulated. Gravity anomalies, both simple Bouguer and free air, show greatest gradients or excursions in the shelf edge area where the transition from continental to oceanic basement is thought to occur.

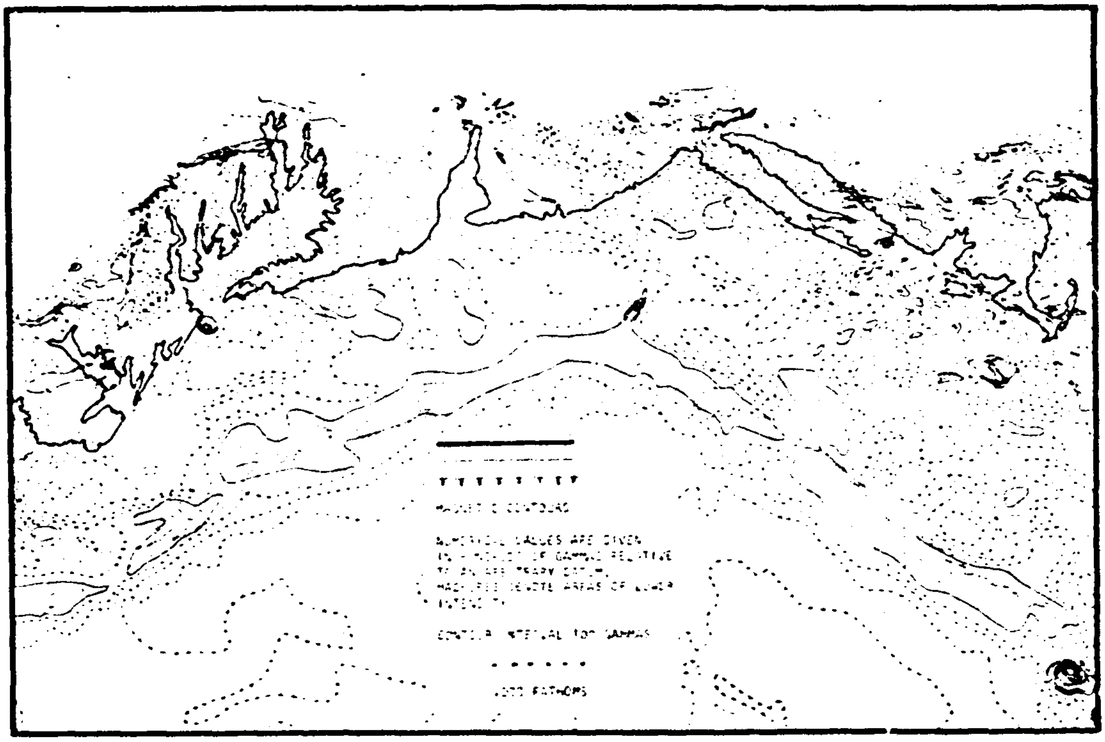
5.1.6 ORGANIZATION OF THE CHAPTER

The description of various segments of the slope and its geology have been arranged according to the origin and difference of some of the areas, as well as the more conventional regional boundaries. There seems to be substantial reason for separating the Georges Bank slope from the region immediately to the south and west, based on the origin and unusual nature of the Gulf of Maine. Therefore, these are three areas which will be described in the following order: the Georges Bank slope, the North Atlantic slope (southern New England), and the Mid-Atlantic area. This division fits with the one previously used in TRIGOM (1974) which divided Georges Bank and the North Atlantic shelf into separate physiographic provinces.

5.2 GEORGES BANK SLOPE

5.2.1 BATHYMETRY

South of Georges Bank the continental slope covers an area of 9,000 km^2 and water depth reaches a maximum of 2,000 m. The slope width is about 20 to 25 km with an average grade of 6° The surface is best character-



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-4	Magnetic Anomalies Over the Northeastern United States (Taylor, et al., 1968)

ized as being hummocky with gullies and terraces cutting across the surface and numerous submarine canyons. The major canyons are hundreds of kilometers long by several kilometers wide and several hundred meters deep. On Georges Bank, near the shelf, there are indentations of up to 25 km which form six major submarine canyons. From west to east there are: Hydrographer, Walker, Oceanographer, Gilbert, Lydonia, and ~~Corsair~~ Canyons. These canyons were probably eroded during late glacial stages in the Quaternary and late Tertiary when sea level stood at the present shelf edge (Schlee, et al., 1975). Intersecting the slope at about 68^{o} W longitude is the New England Sea Mount Chain. Consisting of a large number of volcanic cones, probably of basalt, this feature stretches some 1,200 km southeast from Georges Bank.

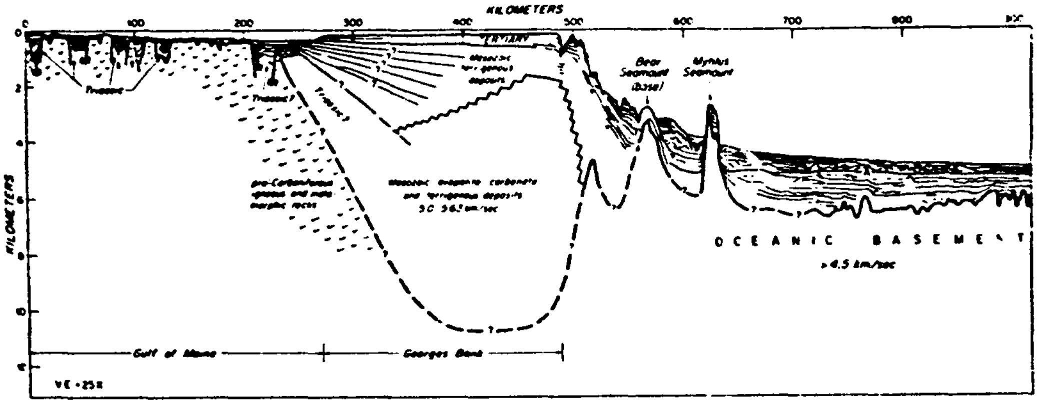
Several detailed bathymetric charts have been prepared giving an idea of the microrelief in small areas not visible or discernible from shipboard sonic devices. One of these, by Emery and Ross (1968), was conducted 170 km south of Martha's Vineyard, which had appeared to be a gentle surface incised by a few broad gullies over an area of 50 km^{2}. The detailed survey, however, of an area 12 km^{2} showed the slope to be inclined to the south and crossed every 1/2 to 3/4 km by a down-trending ridge approximately 100 m wide and 2 to 10 m high. The slope area in question is much more intricately channeled and steeper than the area to the north off the Scotian shelf and it is extensively cut by large submarine canyons (Schlee, et al., 1975). This probably results from a lesser amount of deposition from glacial sources (Uchupi, 1963; Schlee and Pratt, 1970). Another example of microscale relief on the slope was gained from the search for the submersible ALVIN. It was lost in 1,540 m of water in 1968; consequently, a detailed topographic chart of the area was constructed using a 20-m contour interval (Emery and Uchupi, 1972). This detailed survey of a 10-by-16 km area revealed about 10 small submarine valleys which might be tributary to a larger canyon. These submarine valleys were not found by previously conducted surveys using wider spaced sounding traverses. Another example using ALVIN occurred in 1967 when ALVIN lost her manipulator arm in about 1,350 m of water. The ALVIN crew conducted a search resulting in a map on a 50 m contour interval. Soundings from the surface ship showed the slope to be smooth, located adjacent to a tributary of a submarine canyon. However, observations from the submersible revealed the presence of six parallel ridges which measured 2 to 10 m high, about 100 m wide and at least 1.5 km long. These ridges were not revealed by surface soundings because they extended down the slope instead of parallel with it (Emery and Uchupi, 1972). The origin of the ridges is unknown but could be related to large slump blocks.

5.2.2 STRUCTURE

This section of continental slope is immediately adjacent to the shelf area of Georges Bank, a structural part of the total Gulf of Maine. The irregular nature of the shelf break forming the border between the slope and the shelf is described by Palmer in TRIGOM (1974). The Gulf of Maine and the continental borderland off southern California are the only two areas that do not have a relatively flat seaward sloping shelf terminating at about 200 m. In California, the deep basins between the shelf edge and the mainland are the result of Tertiary tectonism. However, in the Gulf of Maine, the shallow basins reflect the periods of erosion that accompanied glacial epochs of the Pleistocene superimposed on a tectonic framework. A number of early New England geologists have published descriptions of rocks dredged from areas around Georges Bank (Verrill, 1878; Upham, 1894; Dall, 1925; and Johnson, 1925). Only recently has the internal structure of the Gulf been examined by seismic refraction using continuous seismic profilers to determine the upper stratigraphy on the Bank (Drake, Worzel, and Beckman, 1954; and Knott and Hoskins, 1968).

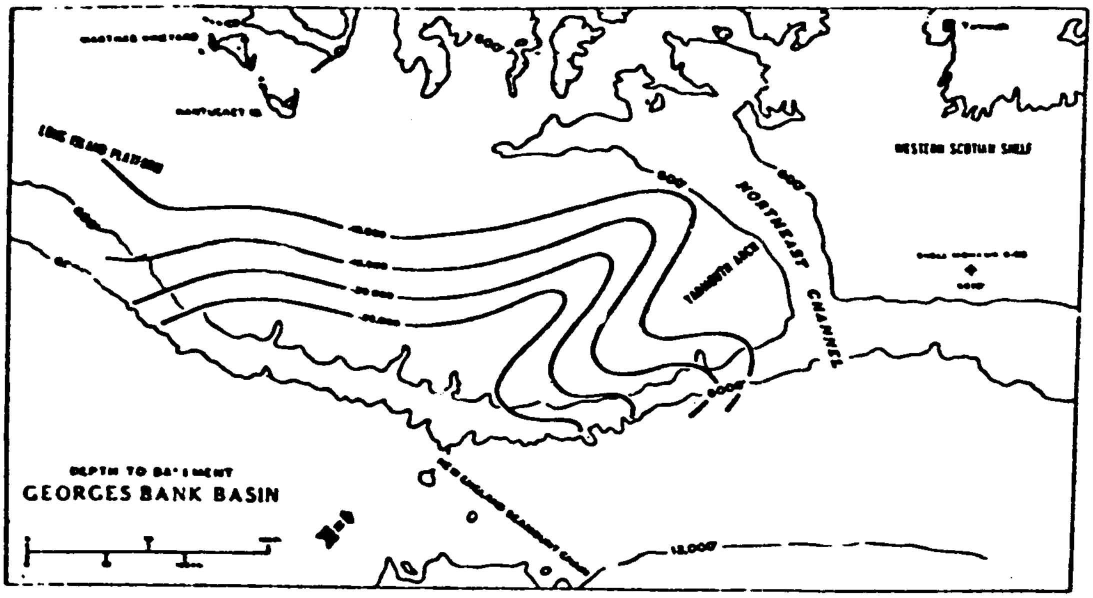
Cretaceous sediments are present on Georges Bank with a gentle seaward dip and project to outcroppings somewhere on the continental slope. In 1936, Stetson dredged Upper Cretaceous and Tertiary fossils on the upper slope that were recovered from rocks at the heads of canyons crossing the shelf break. The depth of this Cretaceous contact was between 480 and 600 m. In Figure 5-5, Emery and Uchupi (1972) show a fixed series of Mesozoic terrigenous deposits, Triassic red beds, and at even greater depths, Mesozoic evaporates and carbonates. The "basement" is thought to consist of pre-carboniferous igneous and metamorphic rocks similar to those forming deep foundations in the Gulf of Maine. The closest drill hole information to the shelf comes from Brown's Bank where Shell's Mohawk B-93 well is located about 125 m from the eastern end of Georges Bank which may relate closely to the immediate upper slope. This section is shown in Figure 5-6. A recent tectonic map (Ballard, 1974) shows the pre-Jurassic basement for Georges Bank. The map also includes the slope area which is paralleled by several faults showing Triassic basaltic intrusives lying just to the south of the slope (Figure 5-7).

In 1973, the U.S. Geological Survey produced seismic profiles across Georges Bank which extended out to the continental slope. These profiles are shown in Figures 5-8 and 5-9. The seismic data indicate that the major structural features within the sedimentary sections of Georges Bank Trough are directly related to basement structures. A diffused, buried ridge, 20 km across at depth which partly overlies the slope, will be noted in Figure 5-8 on the southern edge of the basin. Mattick and others (1974) inferred that the ridge is a southward extension of the Yarmouth Arch. This feature is an unfaulted structural crystalline basement high extending southward from the inner Scotian Shelf to the seaward edge of Georges Bank. Ballard (1974) suggests that the ridge is a narrow spur of the Yarmouth Arch continuing on the southern edge of Georges Bank's upper continental slope, buried by less than 5,000 m of sediment along the U.S.G.S, shotline. He believed the ridge to be a horst, formed through the intrusion of oceanic basalt that moved in during the separation of Africa and North America.



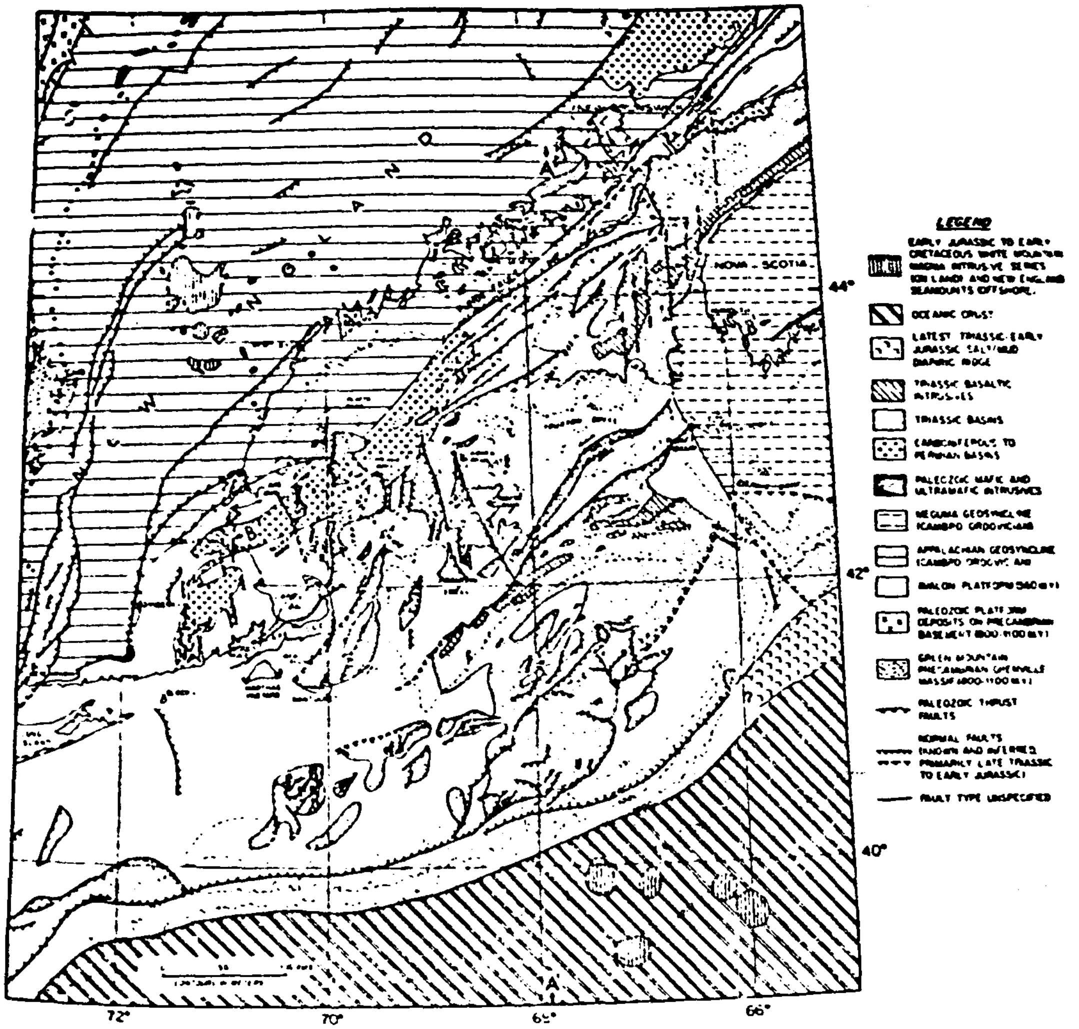
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 5-5 Bottom Sediments Across Georges Bank (Emery and Uchupi, 1972)

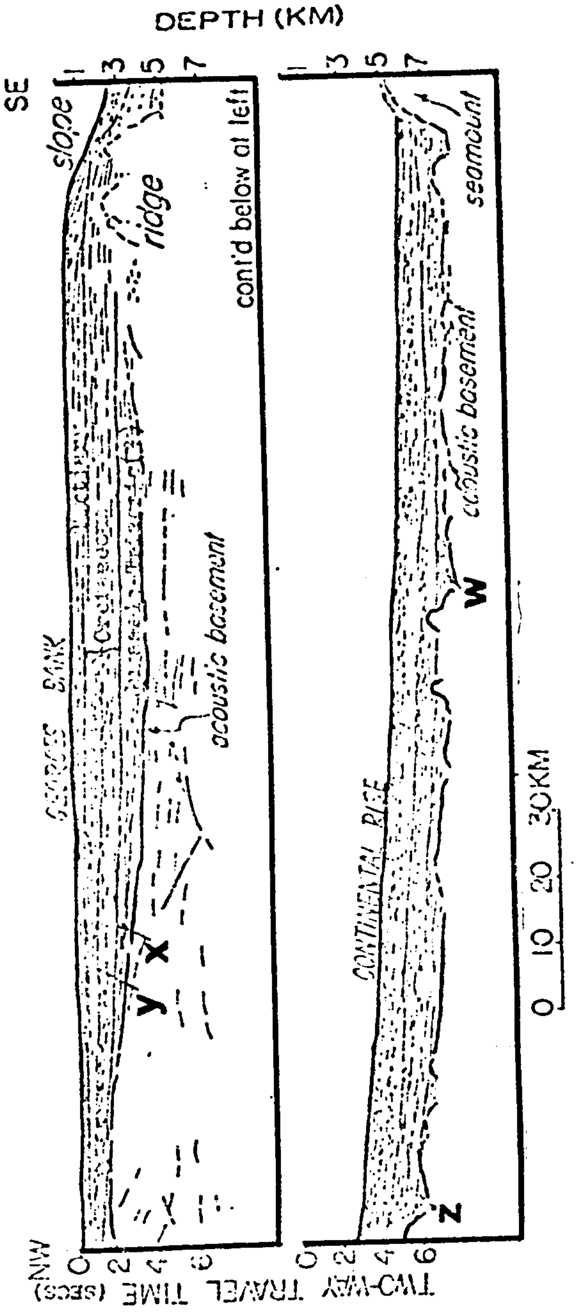


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-6	Structure Contour Map of Depth to Pre-Mesozoic Basement. Contour Interval 5000 ft (Schultz and Grover, 1974)

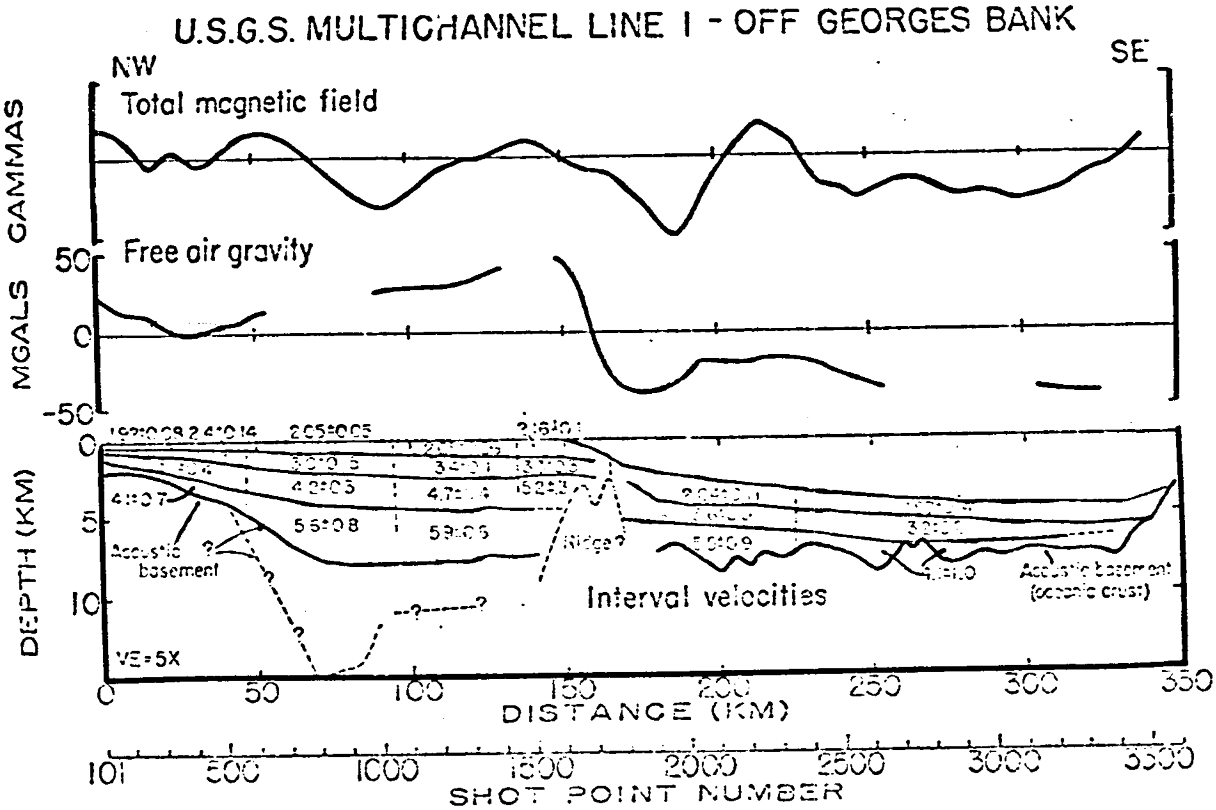


TRIGOM | **FIGURE 5-7** | Tectonic Map of Pre-Jurassic Basement for Georges Bank, Gulf of Maine, and Eastern New England (Ballard, 1974)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-8	Interpretive Section Along USGS-CDP Profile (Schlee, <u>et</u> <u>al</u>., 1975)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-9	A Generalized Structural Profile Across Georges Bank (Schlee, et al., 1975)

It is possible that this ridge is related to deeper volcanic structures (seamounts) which intersect the continental margin.

Seaward of the Georges Bank ridge the sedimentary section thins from 4 to 5 km under the slope to less than 3 km. The oceanic basement can be traced on the Georges Bank line right up to the base of the continental slope where the sediment cover is estimated to be about 4.5 km thick (Figure 5-9) (Schlee, et al., 1975). Before it is masked, the acoustic basement comes within a few kilometers of the ridge that underlies the continental slope. There is no evidence for a thick belt of sediment beneath the lower slope on the Georges Bank line.

Rabinowitz (1974) examined a number of free-air gravity profiles across the continental margin. Three profiles ran across the Georges Bank slope section. On all the profiles he found that the free-air gravity high corresponded almost exactly with the shelf-slope boundary.

A diagram presented by Sheridan (1974) shows a composite structural cross section across Georges Bank into deep water (Figure 5-10). One difference has been mentioned between Georges Bank and the Scotian shelf by Schultz and Grover (1974). They feel that sedimentary deposits of the Triassic age may exist at the bottom of the down faulted Georges Bank basin.

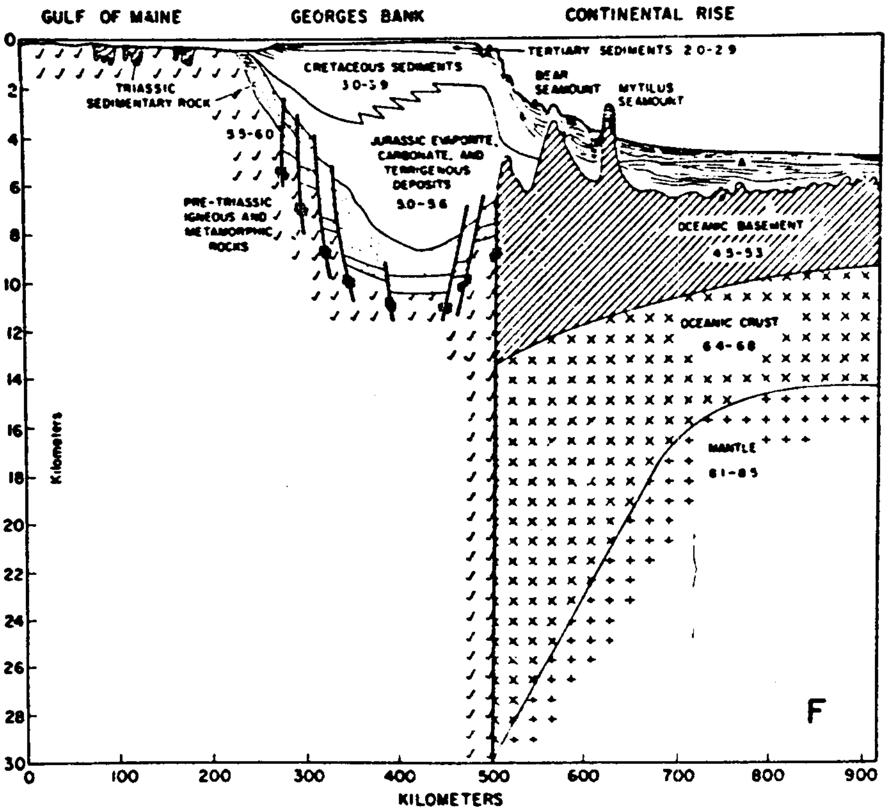
One of the most important geophysical features of the continental margin is a series of magnetic highs called the East Coast slope anomaly. This is most commonly a pair of broad high amplitude highs. This anomaly, in general does not overlie the continental slope. It is found far out over the continental rise by the Scotian Shelf and comes well in onto the continental shelf south of New Jersey. While many investigators feel that it is some expression of the boundary between the continental and oceanic crust, few agree on its exact significance (Rabinowitz, 1974; Emery, et al., 1970; Keen , 1969; Taylor, et al., 1968).

5.3 THE NORTH ATLANTIC SLOPE

5.3.1 BATHYMETRY

The nominal boundary between Georges Bank area and the southern New England shelf and slope has been selected as Great South Channel. This depression is an erosional feature partially buried in its outer section. The channel trends north-south in such a way that it may have had previous connections with the Hydrographer submarine canyon.

The shelf break in this section generally occurs at a water depth of 140 to 160 m. This shelf edge, like Georges Bank, has a number of incised canyons which include Veatch, Atlantis, Alvin, Block, and Hudson Canyons. Hudson Canyon is supposedly the most studied of all the east coast submarine canyons. It extends across the shelf into New York



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

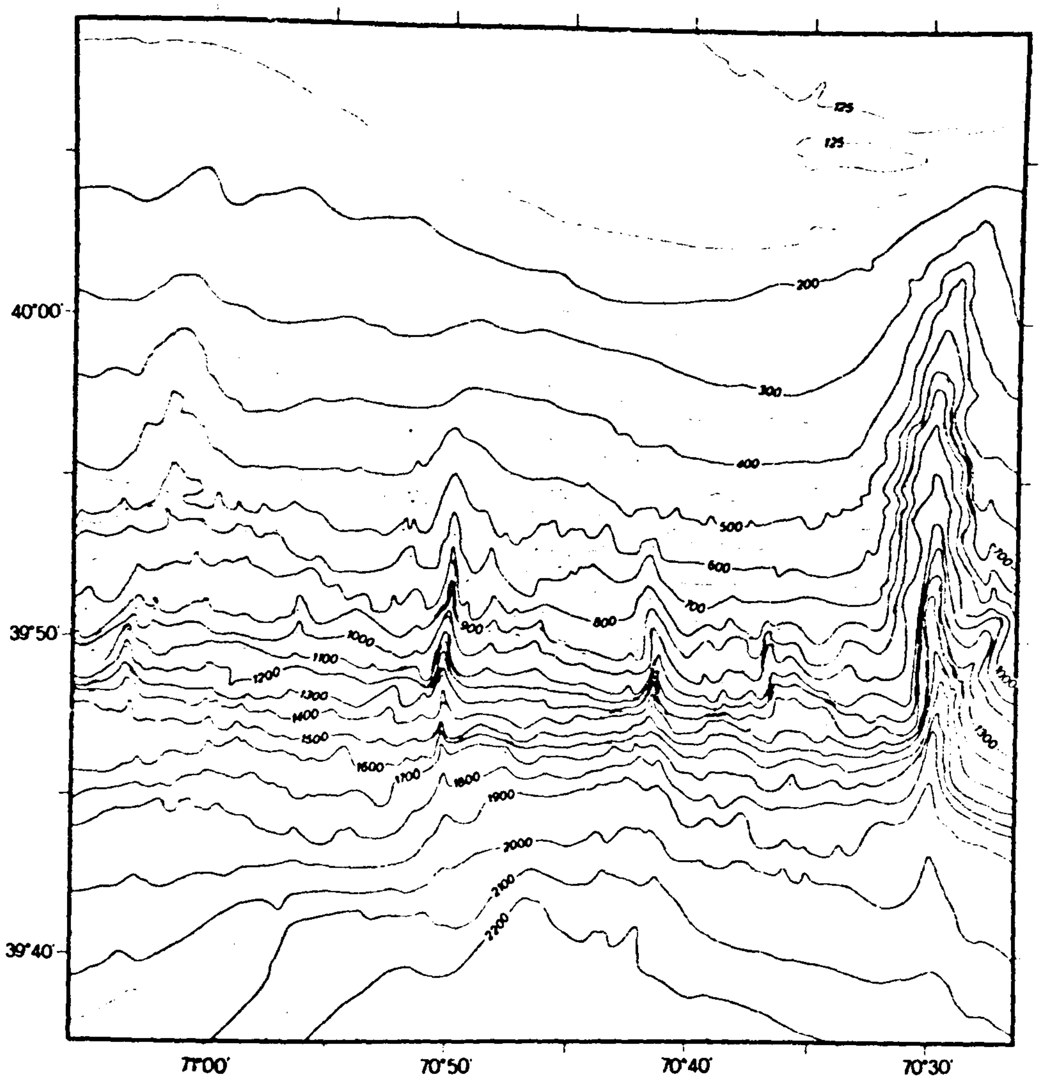
TRIGOM	FIGURE 5-10	Diagrammic Structural Cross Section Across the Gulf of Maine and Georges Bank (Sheridan, 1974)

Harbor. The series of seismic profiles of the upper and lower slope in the section from Block Island to Hudson Canyon show a number of slumps and hummocky shapes. These are more characteristic of the lower slope area and upper rise (Uchupi, 1967).

Work conducted by MacIlvaine (1973), over a study area of about 500 km^2 on the slope south of Cape Cod, Massachusetts, presents an excellent insight into the detail in a small area of the slope. He investigated the sedimentary processes active in the area, and how the processes control deposition and erosion. The most striking feature in the study area was the Alvin submarine canyon at 70°30' W longitude, which has steep sides with slopes of 10° to 15° on the walls. These walls cut to a depth of about 600 m below the slope surface. The upper slope begins at the shelf break between 120 and 150 m with a gentle inclination of about 1.4°. Between 750 m and 1,800 m, the slope steepens to an average of 7.6°. The general bathymetry (Figure 5-11) shows that the upper continental slope is generally smooth with steep-sided gullies dissecting the surface and with seaward-facing scarps. The gullies may be tens of meters deep with hummocky floors while the scarps, which occur near the transition between the upper slope and the lower slope, may be hundreds of meters in relief. The sediments of the upper continental slope grade from rapidly deposited Pleistocene clayey silts with abundant fragments of sedimentary rocks to Holocene sandy silts and silty sands. The lower continental slope, which is relatively steep in comparison, is dissected by steep V-shaped gullies without the layer of disturbed material which was seen in the upper slope. The sediments in the lower part are stiff, cohesive, and resistant to erosion by bottom currents and show a rapid increase in shear strength with depth. The sedimentary activities which appear to be ongoing, include gravitational (turbidity currents, creep, and slumping), hydrodynamic, and biological processes.

Gravitational processes cause erosion of the Pleistocene deposits on the slope. These are evidenced by slump scars and have been confirmed by seismic profiles, bottom photographs, and direct observation from submersibles. In areas of large scale slumping, where the thickness is over 100 m, Eocene rocks and some reworked Tertiary rocks were exposed at the surface. Medium scale slumping, in the order of 10 m of thickness, occurs mostly in the upper slope. Small scale slumping, 1 m or less in thickness, occurs generally in the lower slope. Turbidity currents generated by slumping have apparently eroded gullies and swept the bottom clear of glacial erratics on the steep slope floor.

Hydrodynamic processes are most influential near the shelf break. Here they are likely to control the deposition and transportation of sediments. Internal waves may also generate strong bottom currents resulting in the suspension of the grained materials. However, most of the surface of the continental slope is extremely resistant to



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 5-11 General Bathymetry of 500 km^2 of Slope South of Cape Cod, Mass. (MacIlvaine, 1973) erosion by bottom currents (MacIlvaine, 1973).

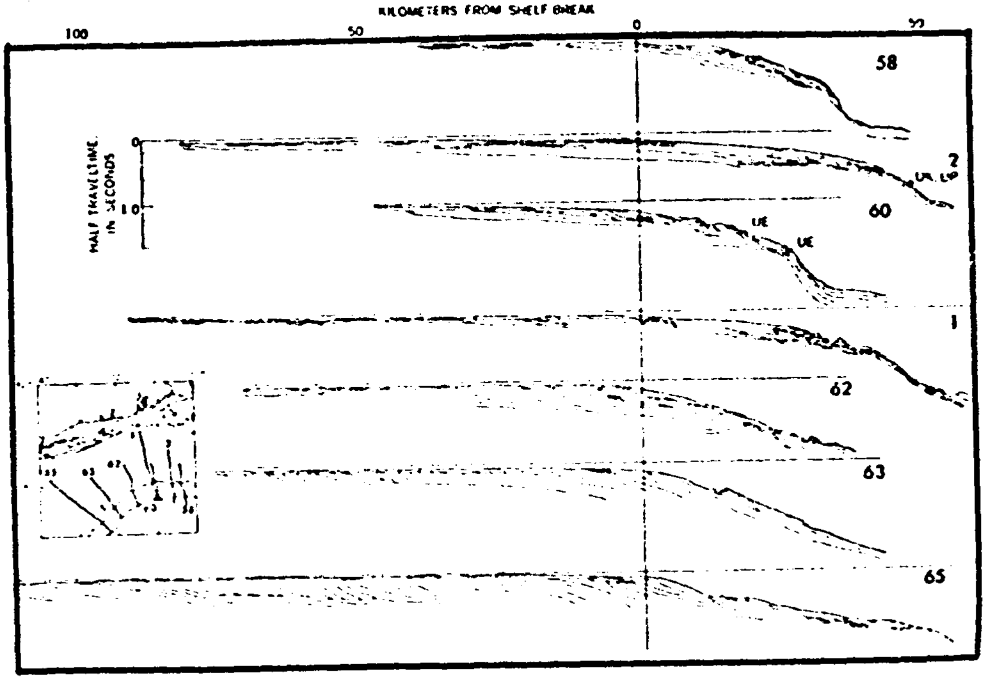
Biological activity is zoned according to depth and the species composition of benthic fauna varies going down the slope. Over the years, bottom organisms tend to smooth the irregularities in the bottom and stiffen the sediment surface. Thus, it becomes more resistant to erosion by currents. This kind of bioturbation may cause significant net downslope movement of sediments.

MacIlvaine's recent and quite detailed study (1973) shows how a fine-grained survey can yield information of value on the slope in the microscale and how it can be especially enhanced by direct observations and by echosounder measurements from submersibles.

5.3.2 STRUCTURE

Profiles taken across the outer edge of the shelf and continental slope, due south from Block Island to New Jersey, show structures that are part way in between those off Nova Scotia and those off Georges Bank (Uchupi, 1970). In Profile 58, shown in Figure 5-12, the horizon appears to outcrop near the base of the continental slope. A similar structure was found farther east in Profile 2. Profile 1, which lies between Block and Atlantis Canyons, shows layers on the upper slope which appear to have slid in a seaward direction. Two rectangular blocks at the base, probably slumped from farther up the slope. Uchupi (1967) mentions evidence of massive slumping detected from an earlier survey. Strata within this upper continental slope area show evidence of folding owing to the strata sliding in a seaward direction. This activity probably occurred during the Pleistocene, when the shoreline was near the present shelf break. Profile 63 is considered simple, with layers truncated by the shelf but still traceable to the base of the slope. Rock samples from the Hudson Canyon area indicate a deep reflector cropping out on the slope near the Tertiary or Cretaceous boundary. Uchupi (1970), adding to previous theories of slope origin with seismic refraction data, suggests an origin of the slope off New York which may be structural and which has resulted from faulting or folding. The "terrace" east of New York, according to the author, was modified by turbidity current erosion, slumping, and glacial erosion, but it appears to be principally an out-building of the slope.

Two prominent magnetic features occur on the slope off southern New England. The first is the slope anomaly which runs from the outer shelf to the upper mid-slope with values greater than 600 gm. This anomaly is more or less unbroken from Georges Bank to the Blake Plateau. Based on preliminary calculations (Drake, et al., 1959; Drake, Ewing, and Stoddard, 1968; and Emery, 1968), it may be a buried ridge system behind which much of the continental shelf accumulated. The magnetic body causing this anomaly appears to be 8 to 10 km below the sediment surface. It is considerably deeper than a similar ridge feature seen in



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-12	Seismic Reflection Profile off Southern New England and Long Island (Uchupi, 1970)

the southeastern United States. Emery and Uchupi (1972) suggest that a considerable amount of sedimentary strata may have accumulated on the ridge before the entire feature was buried.

The second major magnetic feature is an east-west magnetic anomaly located approximately 40°N (Drake and Woodward, 1963). This feature has been referred to as the Cornwall-Kelvin Transcurrent Fault. It may connect the New England Sea Mounts with the proposed fault system in northern New Jersey. More recently, Taylor, Zietz, and Dennis (1968) have argued that there is insufficient data to establish this. A third major magnetic feature is the hypothesized Boston-Ottawa fault zone which is mentioned on page 5-52.

5.4 MID-ATLANTIC SLOPE

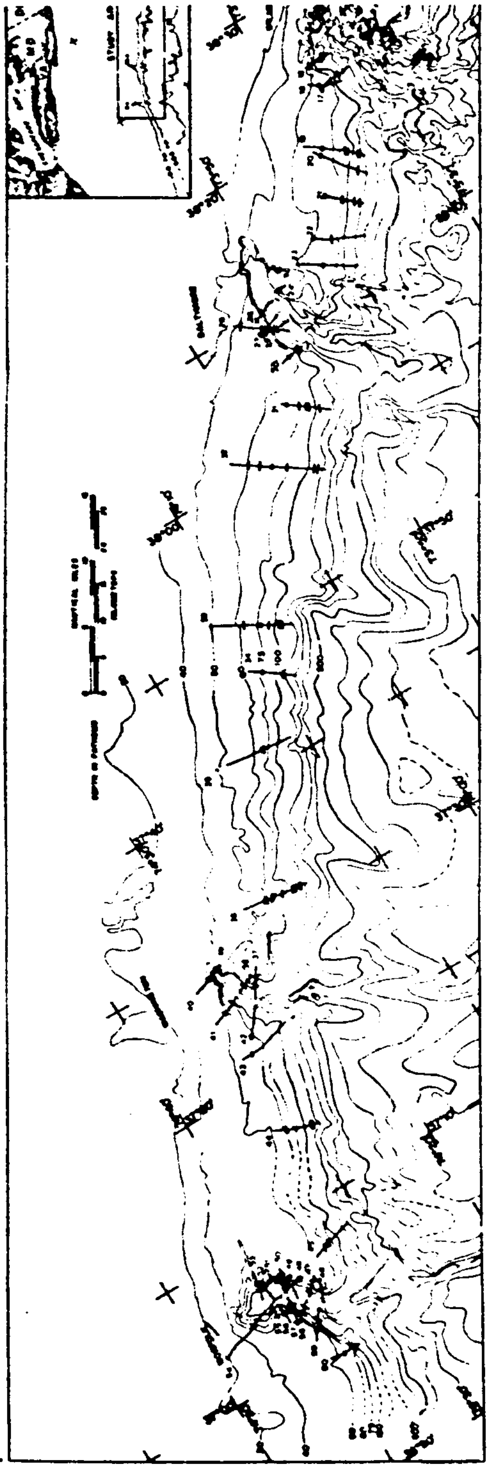
5.4.1 BATHYMETRY

The continental slope in the Mid-Atlantic area, between Hudson Canyon and Cape Hatteras, runs in a general northeasterly direction. There are four major submarine canyons in this segment. Starting from the north, these are: Wilmington, Baltimore, Washington, and Norfolk. Of course, the largest of the eastern canyons is Hudson Canyon which forms the northern boundary of the section. This Mid-Atlantic region from Hudson Canyon to offshore Cape Henry has a slope which is quite irregular. It has a gradient of about 123 m per km with many incised smaller canyons (USGS) open file 75-61). South of Cape Henry to Cape Lookout, the slope gradient steepens slightly to nearly 153 m per km. Here, the slope is cut by many small gullies which coalesce off Cape Hatteras to form Hatteras Canyon.

In this region, depths at the shelf break range from 82 to 146 m. The shallower breaks are concentrated within the heads of canyons incised into the shelf (Wear, Stanley, and Boula, 1974). A total of 173 terraces were identified during a survey of the upper slope by Wear, _et al._, (1974). Norfolk, Washington, Baltimore, and Wilmington Canyons were also included. Figure 5-13 illustrates the upper slope and shelf bathymetry based on the surveys. The shallower terraces (at about 120 m) may be wave cut features of a lower sea level stand. However, the sea level stand was probably not low enough to effect the deeper terraces which range to 150 m. Wear, _et al._, (1974) suggest the possibility that these trenches may be stratigraphic benches or slump scars.

5.4.2 STRUCTURE

The structural geology of the Mid-Atlantic continental margin has been well described (Milliman, 1973; Uchupi, 1970; Drake, _et al._, 1968; and Emery and Uchupi, 1972). Most of the papers show the margin as a wedge of Mesozoic and Cenozoic sediment thinning at the edge of the continental slope onto the continental rise (Schlee, _et al._, 1975). The sediment wedge thickness in the Baltimore Canyon trough off New Jersey, Delaware, Maryland, and Virginia is about 13 km. Emery and Uchupi



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE** 5-13	Upper Slope and Shelf Bathymetry (Wear, *et al.*, 1974)

(1972) suspect slump deposits cover a buried ridge which extends from the Laurentian Channel to Cape Hatteras. The lower slope and rise may be thick prisms of deep sea turbidities, clays, and slump deposits lying on top of oceanic basement (Drake, et al., 1968).

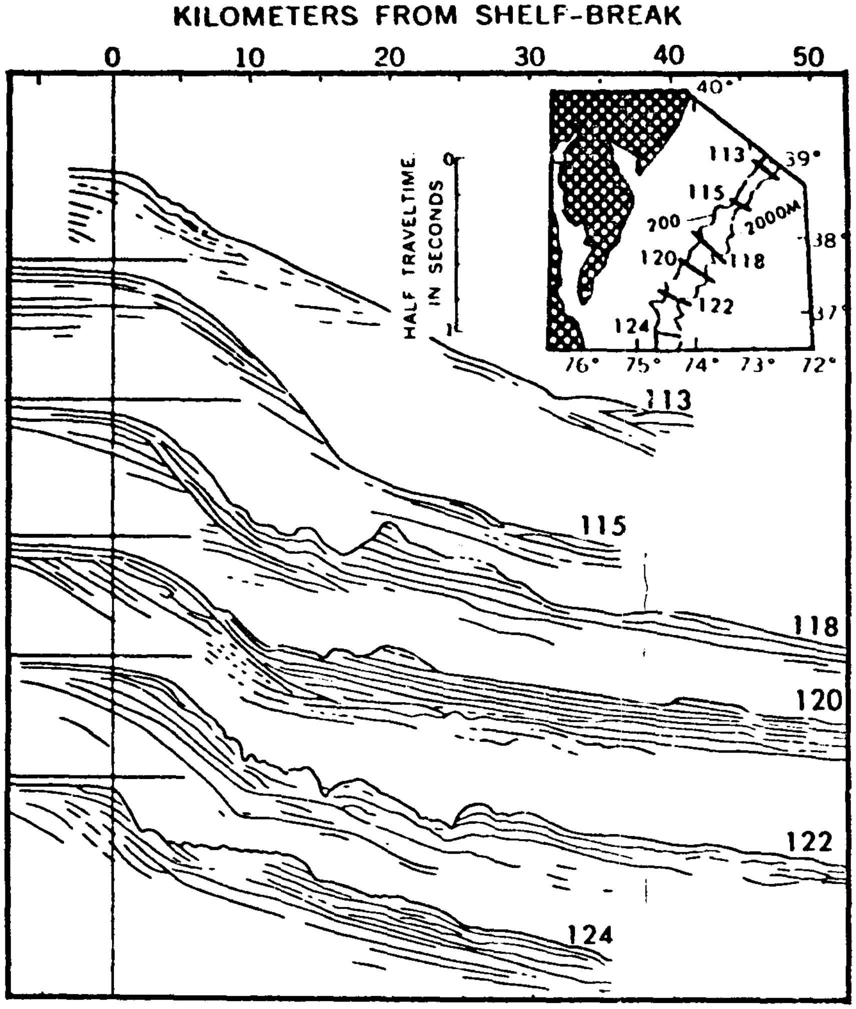
The shallow structure of the continental slope between New Jersey and Cape Hatteras has more structural types than any other sector of the slope (Profiles 113, 115, 116, and 130) (Uchupi, 1970). The strata are truncated by the slope as shown in Figures 5-14 and 5-15. The most complex structure in this area of the slope is along Profiles 118, 120, and 126. All show evidence of renewed deposition after truncation. According to Dietz (1963), the sediments from the rise overlapped the slope; then underwent a subsequent erosional cycle resulting in the present shape of the slope.

The present continental margin appears to be tectonically quiet. The proposed Cornwall-Killiman fault has probably not been active since the Mesozoic or earlier (Milliman, 1973). There is some activity in the Ramapo fault in New Jersey where this epicenter parallels the Cornwall Kevin fault system. Emery and Uchupi (1972) propose a Norfolk fracture zone based on earthquake epicenters off Virginia.

Schlee, et al., (1975) describe the results of multi-channel continuous seismic reflection profiling conducted by Digicon, Inc., during 1973-1974. Two multi-channel profiles were taken and analyzed across the Baltimore Canyon Trough. This deep structure delineation used 24-fold processing of the outer shelf-slope section (55 km long) on the line off New Jersey and 12-fold processing on the Maryland line. The single channel and multi-channel records were overlaid to highlight key reflectors and show apparent nonconformities. The results of this survey of the Maryland profile show the main sedimentary wedge with sub-horizontal reflectors dipping gently seaward.

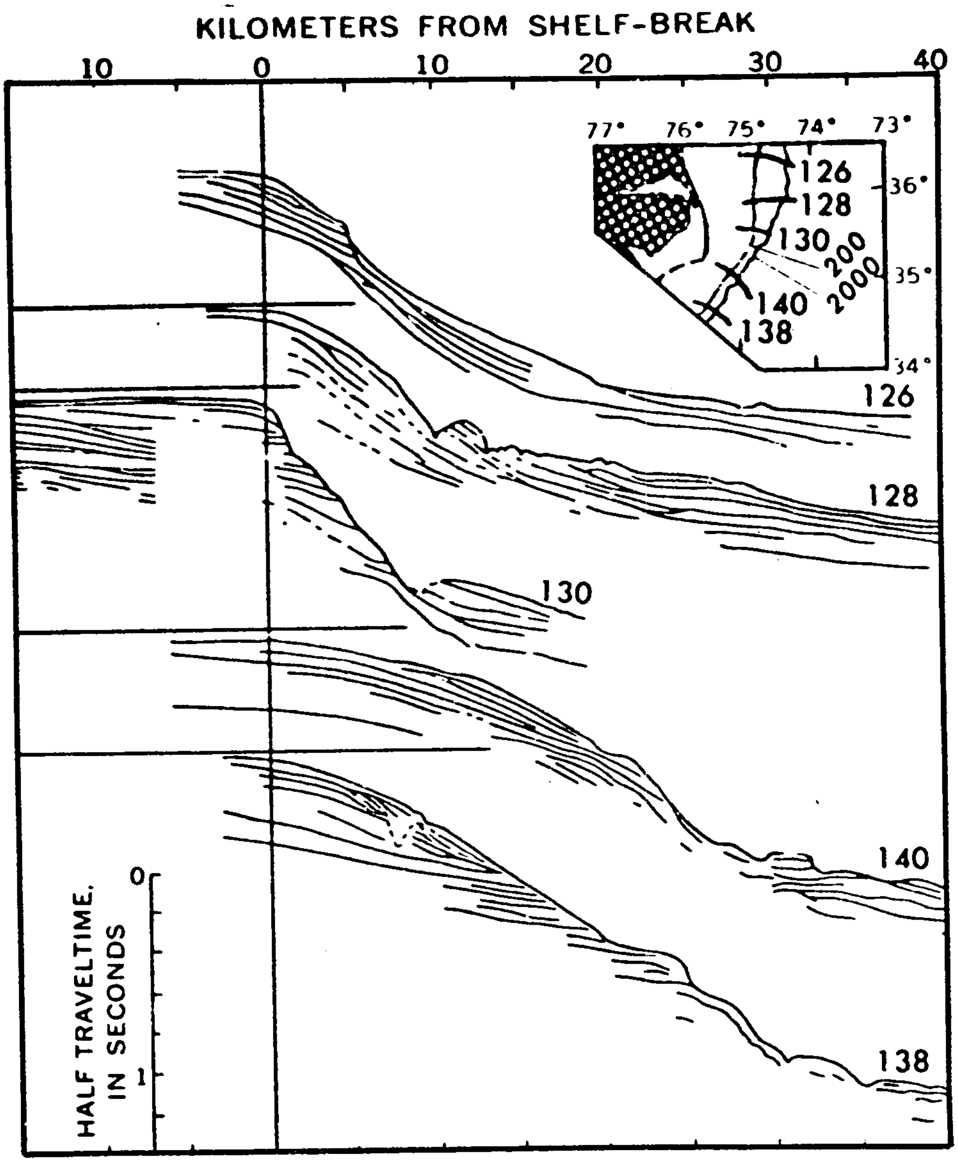
The slope transition area of the New Jersey and Maryland sections can be described as an eastward thickening of the sediment beneath the shelf combined with a draping across broken crustal blocks beneath the upper slope (Schlee, 1975). In the New Jersey profile, the fairly strong subhorizontal reflectors identified beneath the outer shelf become faint, discontinuous, and bowed near the first of two deeply buried, steeply dipping faults. These led Schlee to infer that a reef overlies the buried fault block. The steeply truncated nature of the slope floor and the fact that it is largely erosional in character suggest the recent nature of the slope as a bathymetric feature.

The lower part of the slope is constructional, ending in a lobate fan of sediment thickening onto the rise to about 3 km. Velocities in this area, determined by DSDP drill holes, average 2.0 km per second with comparison of 1.7 km per second for upper sandy, silty clay to 1.94 km per second for compacted hemepelagic mud. The deep structure



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE** 5-14	Seismic Profiles on the Outer Shelf, Slope and Rise Between New Jersey and Cape Henry (Uchupi, 1970)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 5-15 Seismic Profiles off Cape Hatteras (Uchupi, 1970) for the Maryland portion of the continental slope is similar in that the reflectors continue under the upper slope. The velocities indicated are about 2.5 to 2.8 km per second above this structure with some weak reflectors draped over it. This, as in New Jersey, appears to be zonal faulting.

5.5 SEDIMENTS

5.5.1 INTRODUCTION

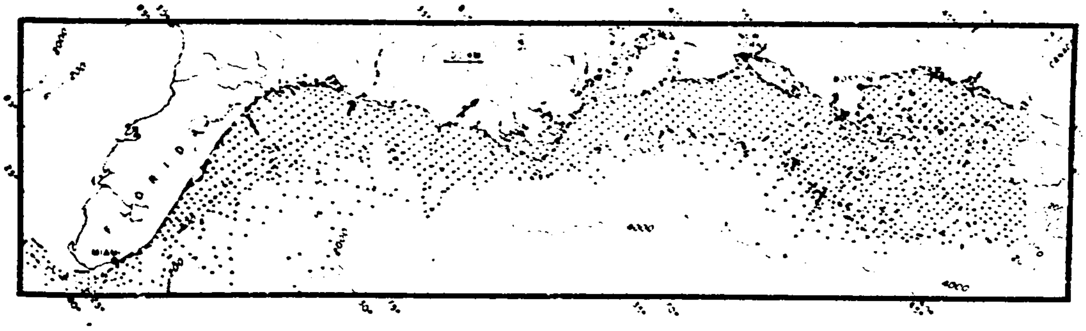
Basic data on the sediments on the Atlantic continental margin result from a survey conducted jointly by Woods Hole Oceanographic Institution and the U. S. Geological Survey of the entire east coast. These papers include ones by the following authors: Hulsemann(1967); Ross (1967, 1969); Schlee and Pratt (1970); Hathaway (1971, 1972); Trumbull (1972); and Schlee (1973). Over 4,000 samples were collected. 915 are cited by Emery and Uchupi (1972) as being taken deeper than 200 m on the continental slope or off into the continental rise. Samples are shown in Figure 5-16. From this, it is easy to see that there are relatively few samples taken on the slope in the study area. The overall sample density for the shelf and slope is 325 km (Palmer, 1974). No figure is cited for the density of the slope alone, although it is probably far less. With this type of sample density, there is high likelihood of local, small-scale variability. However, there are probably some distinctions in sediment-type from the Georges Bank area slope through the Mid-Atlantic area towards Cape Hatteras. Milliman (1973) and others have treated this entire area as one large sedimentary section and it is referred to in this context as the Mid-Atlantic Bight.

5.5.2 SEDIMENT SIZE

While the continental shelf sediments are dominated by sands, the areas seaward off the shelf and down the slope are primarily silts and clays as shown in Figure 5-17. The sand that occurs is calcareous or biogenic (biological in origin) with patches of terrigenous sand occurring in the axes of some of the canyons (Hathaway, 1971; and Keller, et al., 1973).

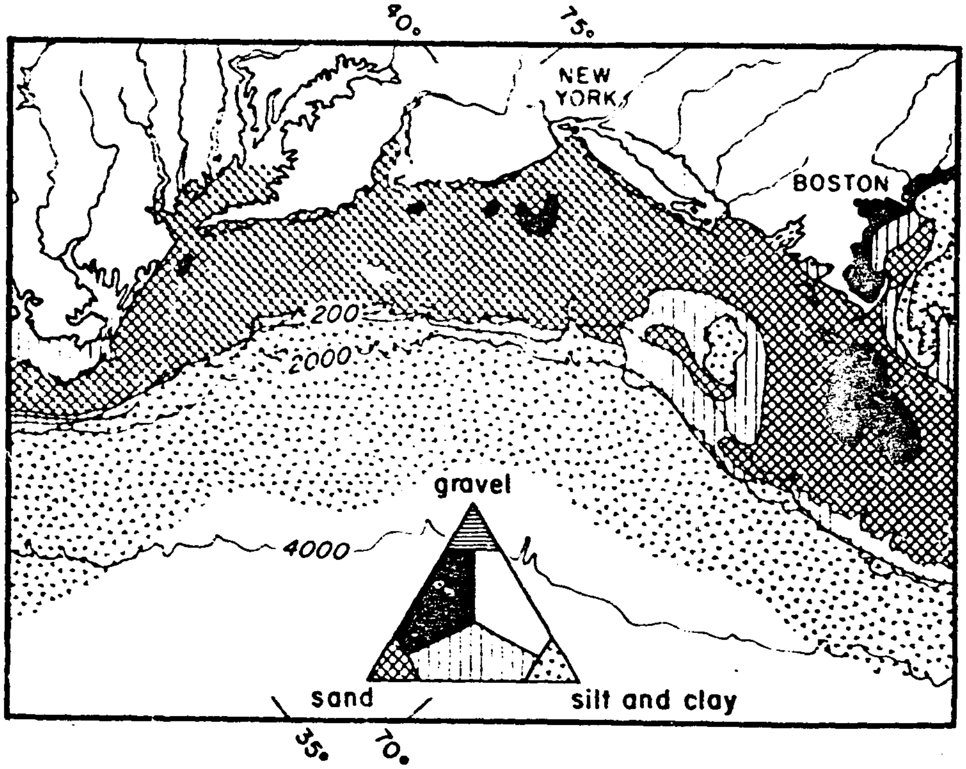
5.5.3 IRON STAINING

Iron staining has been cited as a common characteristic of many of the sediments in the study area both on the shelf and, to some extent, down the slope. Stanley (1969) has concluded that the olive and brown colors on the slope are mostly a function of a relatively oxygen rich environment. This would be due, in part, to the active circulation in the area. Hathaway (1971, 1972) and Schlee (1973) mention that the slope is covered with a pale to grayish-olive silty sand and silty clay composed of quartz and moderately low amounts of layered silicates. Milliman (1973) feels that the iron staining is probably due to a depositional history, although it may be a reflection of the sediment source.



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-16	Distribution of Surface Sediment Samples on the Continental Margin off the Eastern United States (Milliman, 1973)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-17	Distribution of Model Sizes of Sediments from the Middle Atlantic Continental Margin (Milliman, et al., 1972)

5.5.4 CALCIUM CARBONATE CONCENTRATIONS

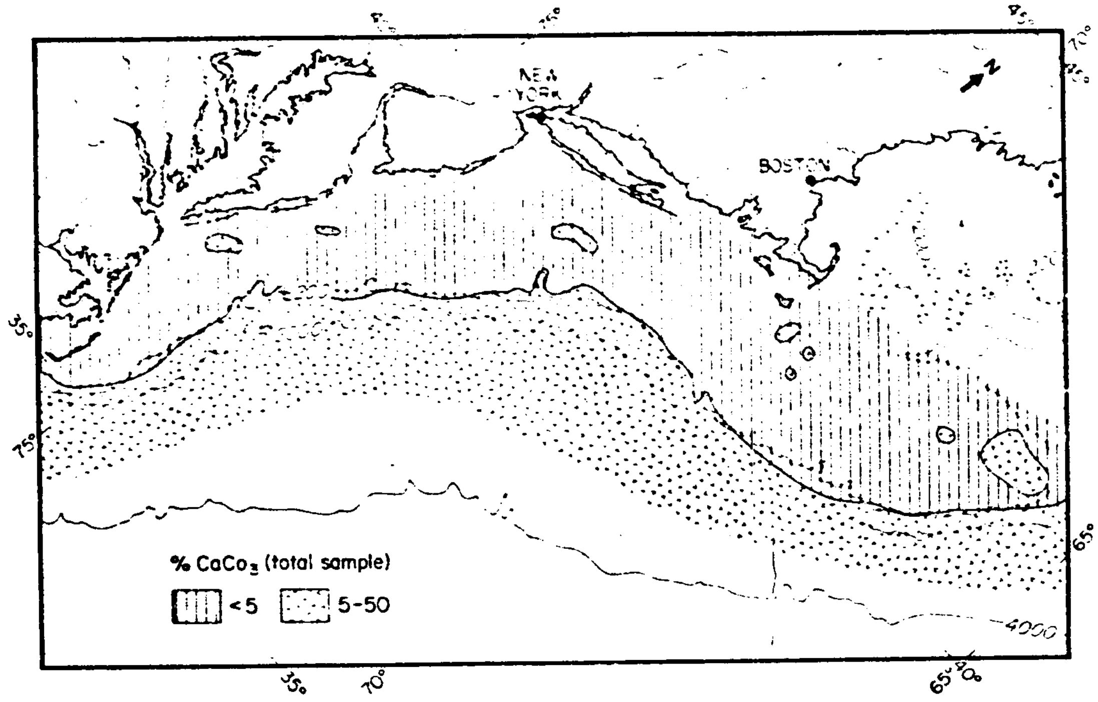
Most of the shelf sediments in the study area have less than 5 percent carbonate. On the slope, however, Milliman, et al. (1972) show a higher carbon content, although it seldom reaches 75 percent. In contrast to southern regions, the Mid-Atlantic Bight has low values of calcium carbonate. These slope sediments are dominated by the tests of planktonic foraminifera, benthonic foraminifera, and echinoid plates. Coccoliths are common in some places but rarely are abundant. Figure 5-18 shows the distribution of calcium carbonate in the surface sediments for the entire Mid-Atlantic continental margin.

5.5.5 HEAVY MINERALS

The composition and distribution of heavy minerals along the continental shelf has been reported by Ross (1970), Hathaway (1972), and Milliman, et al. (1972). However, relatively little specific reference is made to slope mineral identification. Figures 5-19 through 5-24 show the occurrence of various heavy minerals in the shelf area. Milliman (1973) shows the distribution of heavy minerals on the shelf and slope and notes that there is less than two percent of heavy minerals in sand for almost the entire slope area (Figure 5-19). Amphiboles, on the other hand, are fairly abundant on the slope off New Jersey and Delaware; somewhat less so on the Georges Bank slope (Figure 5-20). Epidote, with a heavy mineral fraction, occurs in scattered amounts (five to 15 percent) proceeding from south to north and is patchy in areas along the slope. The distribution of garnet is the same, quite patchy, fairly scarce (15 to 45 percent), and occurring in narrow sections along the slope. The distribution of staurolite is from zero to five percent up to Hudson Canyon then increasing slightly (six to 10 percent), except for a small patch of somewhat higher concentration just south of Cape Cod. MacIlvaine (1973) found four different heavy mineral assemblages on the outer shelf and on the slope south of Martha's Vineyard. Garnet is characterized at the shelf break; the lower slope and the upper rise by hornblend; and parts of the lower slope by pyrite which he assumes to be authigenic. It is possible that these different asserblages represent either different sources or different depositional environments.

5.5.6 LIGHT MINERALS

The sand-size minerals with a density less than 2.37 are composed mostly of quartz, feldspar, and glauconite. Sediments also contain small quantities of diatoms (Milliman, 1973). While there is adequate information on light minerals occurring along the shelf, there seems to be scant data along the slope. Schlee (1973) comments on the larger calcareous fraction from planktonic foraminifera going down the slope accompanied by a decrease in sediment size and an increase in layer silicates and feldspar-quartz ratio. Milliman, et al. (1972) show (Figure 5-24) the ratio of feldspar to quartz plus feldspar in the surface sediments.

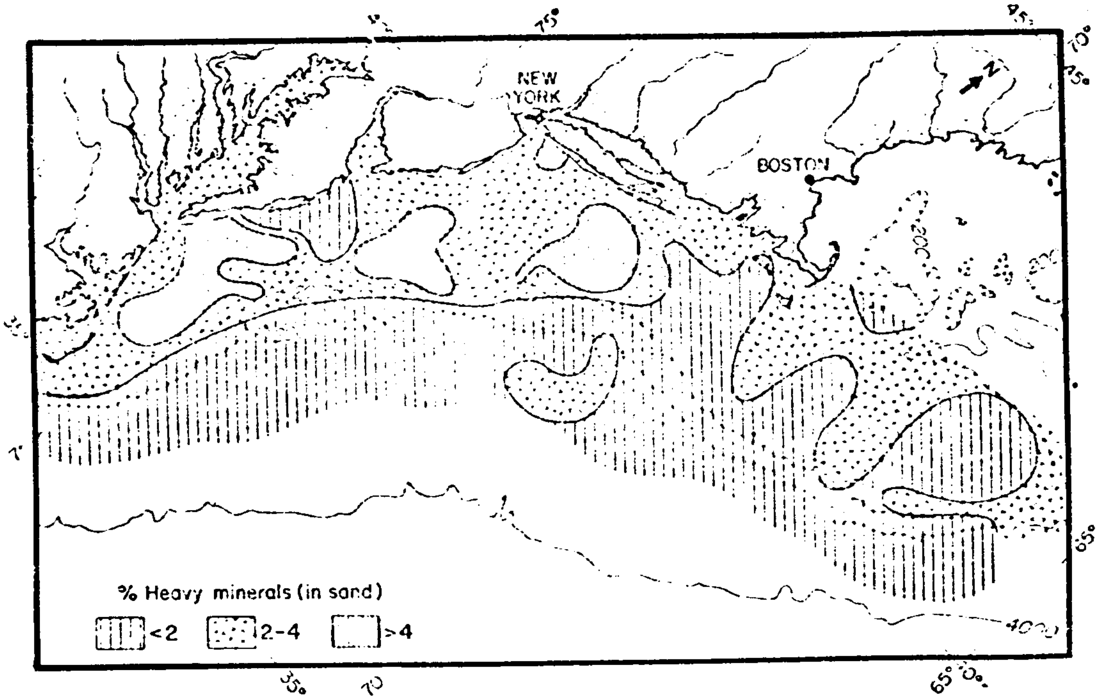


ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

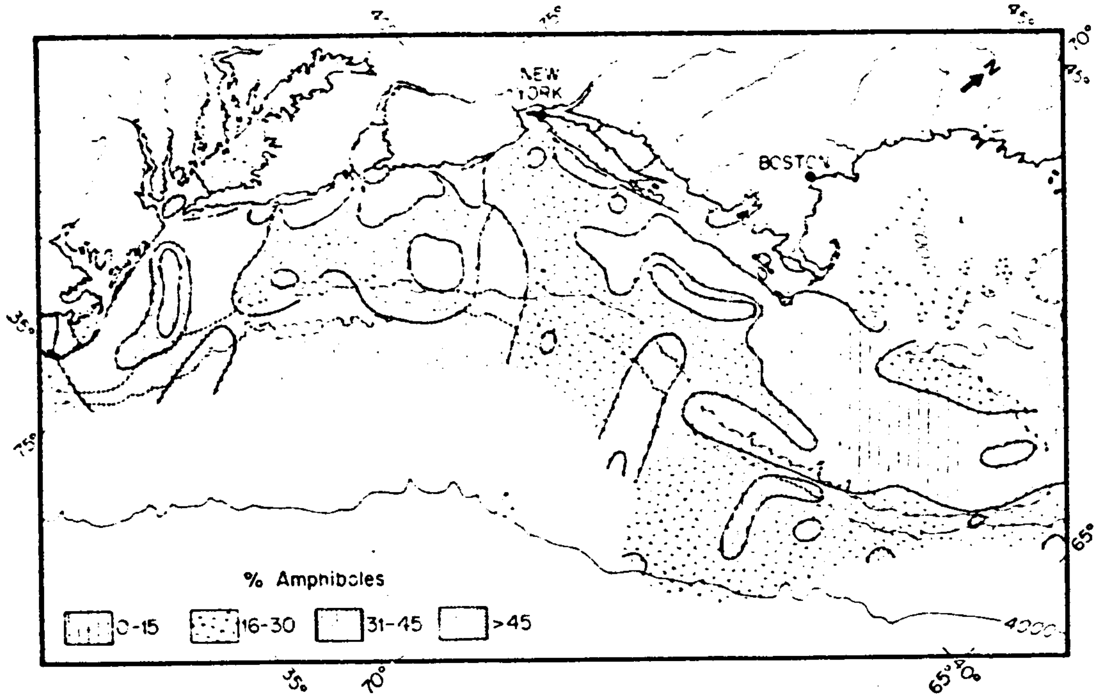
FIGURE 5-18

Distribution of Calcium Carbonate in the Surface Sediments on the Middle Atlantic Continental Slope (Milliman, et al., 1972)



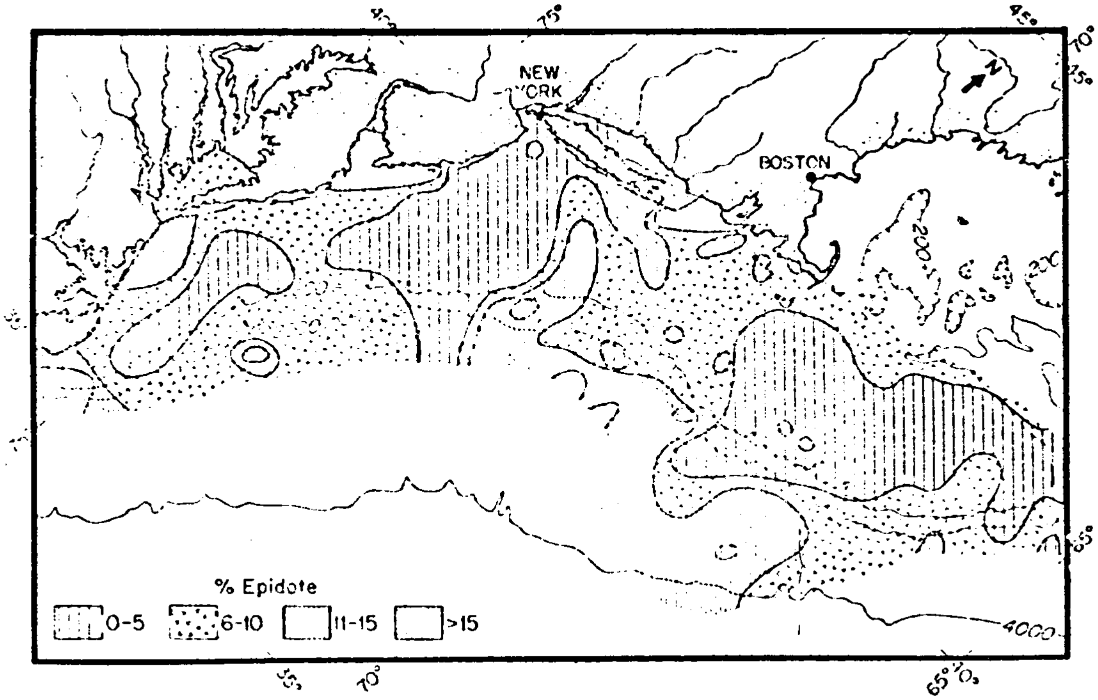
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-19	Distribution of Heavy Minerals on the Continental Shelf and Slope (Milliman, 1973)



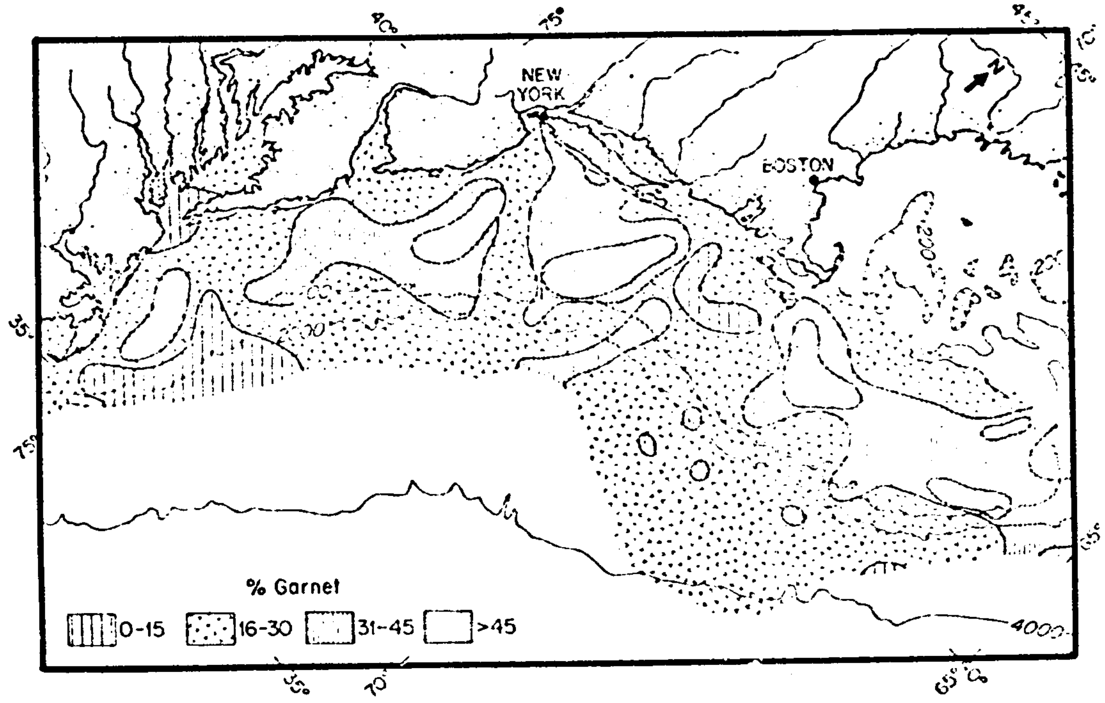
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	**FIGURE** 5-20	Distribution of Amphiboles Within the Heavy Mineral Fraction (D.A. Ross, unpublished data)



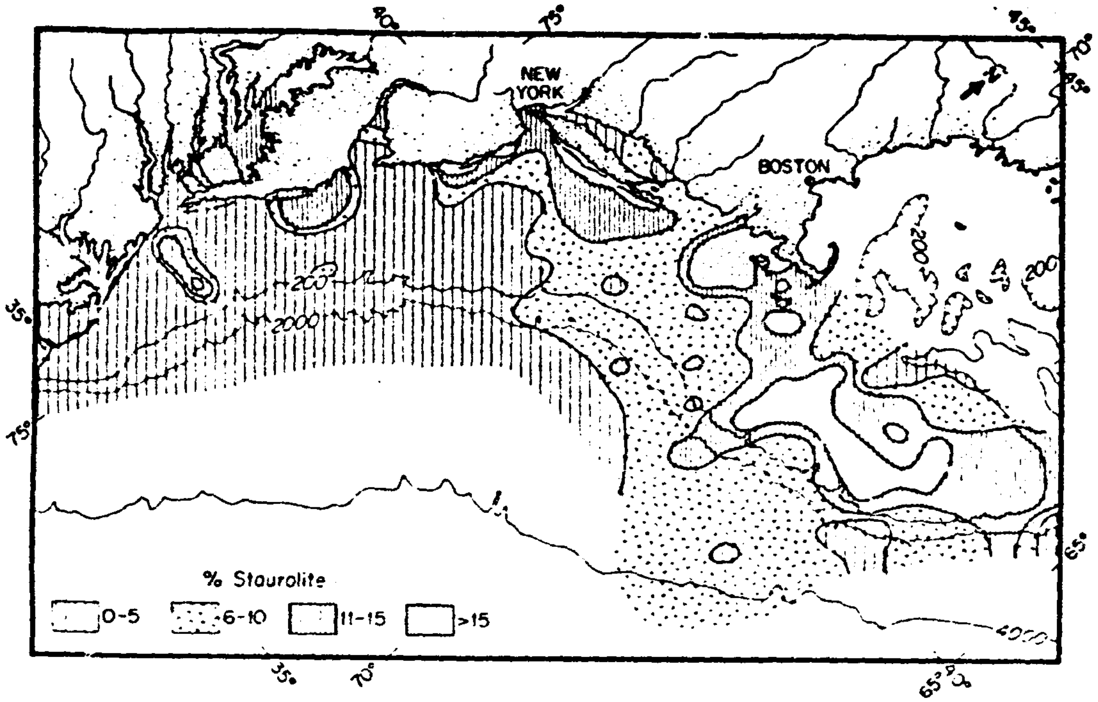
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-21	Distribution of Epidote Within the Heavy Mineral Fraction (Milliman, et al., 1972)



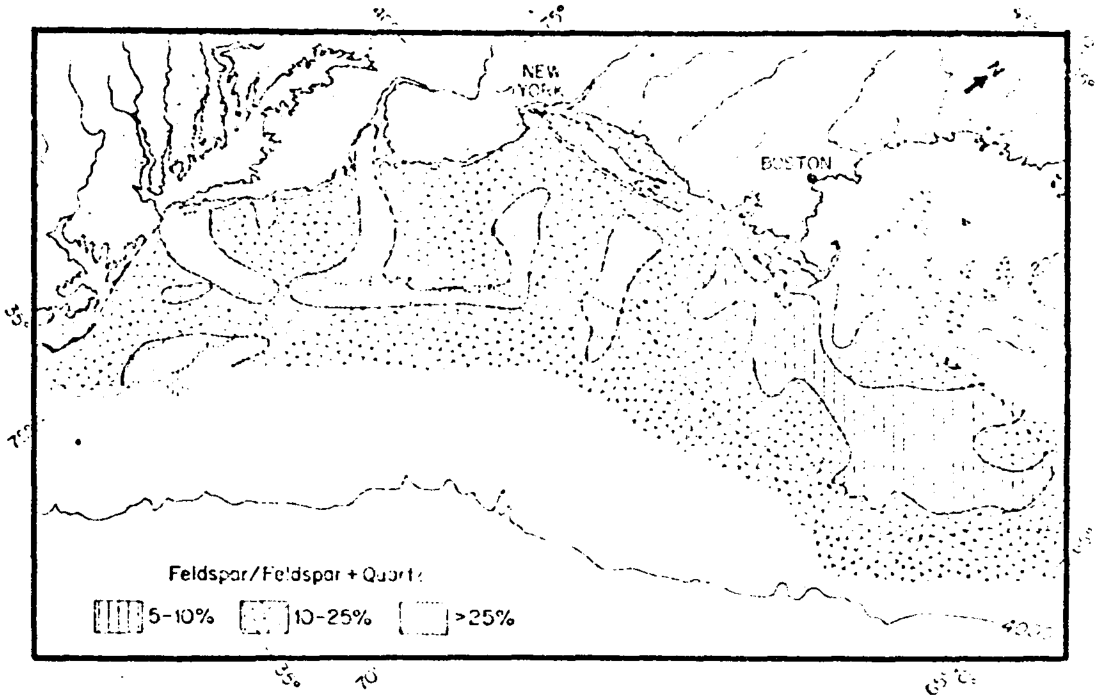
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 5-22 | Distribution of Garnets Within the Heavy Mineral Fraction (Milliman, et al., 1972)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | **FIGURE** 5-23 | Distribution of Staurolite in the Heavy Mineral Fraction (D.A. Ross, unpublished data)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 5-24 | Ratio of Feldspar to Quartz and Feldspar in the Surface Sediments on the Continental Margin (Milliman, et al., 1972)

5.5.7 CLAY MINERALOGY

The composition and distribution of layered silicates along the continental margin of the east coast has been summarized by Hathaway (1971, 1972). He describes the almost complete lack of clay-size materials on the continental shelf. The various distributions of illite, chlorite, and kaolinite in the clay fractions along the entire margin are shown in Figures 5-25, 5-26, and 5-27. The Mid-Atlantic Bight sediments appear to contain larger quantities of illite and chlorite and smaller amounts of kaolinite and montmorillonite. However, south of Chesapeake Bay the kaolinite increases markedly while the illite and chlorite decreases (Figure 5-27). This probably reflects the increased influence of chemical weathering in the warmer southern climates and is reported as being a typical trend in the slope area (Biscaye, 1965). The source of the illite and chlorite-rich clays is the relatively immature crystalline and methamorphic rocks found in both northern and southern New England (Palmer, 1974).

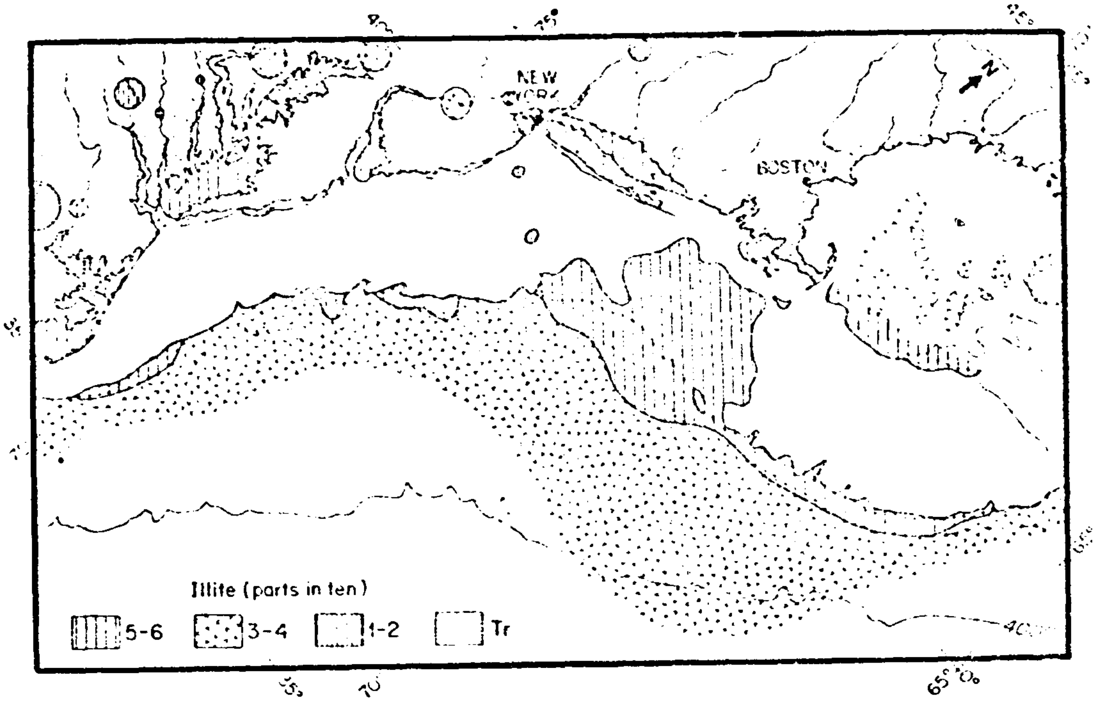
5.5.8 ORGANIC MATTER

The quantity of organic matter within a sediment can be expressed in terms of nitrogen content, organic carbon, and total combustible material. Many workers favor the Kjeldahl nitrogen analysis because of the greater reproducibility and accuracy. Normal values along the Mid-Atlantic Bight shelf are usually less than 0.1 percent and may range to 0.01 percent. In contrast, off the continental slope the organic content can be greater than 0.2 percent, decreasing gradually as one reaches the rise. Figure 5-28 shows the distribution of Kjeldahl nitrogen measurements along the margin with slope values ranging from .1 to .2 percent in southern areas. The higher values occurred in the southern areas.

Emery (1960) used the ratio of organic carbon to nitrogen to measure organic material within the sediment. He has suggested that C/N ratios of greater than 10/1 are indicative of terrestial sources of supply while values of 5/1 indicate oceanic origin. However, Figure 5-29 shows that the distribution of organic carbon/nitrogen for slope sediments are almost entirely between six and ten for the northern section of the Mid-Atlantic Bight (along the slope). Milliman (1973) cites slope sediments with ratios ranging from 6.5/1 to 8.5/1 throughout much of the slope area. Values nearer shore range considerably higher at the mouths of the estuaries, harbors, and canyon areas. See Figure 5-30 for the total slope distribution of organic carbon to Kjeldahl nitrogen measurements.

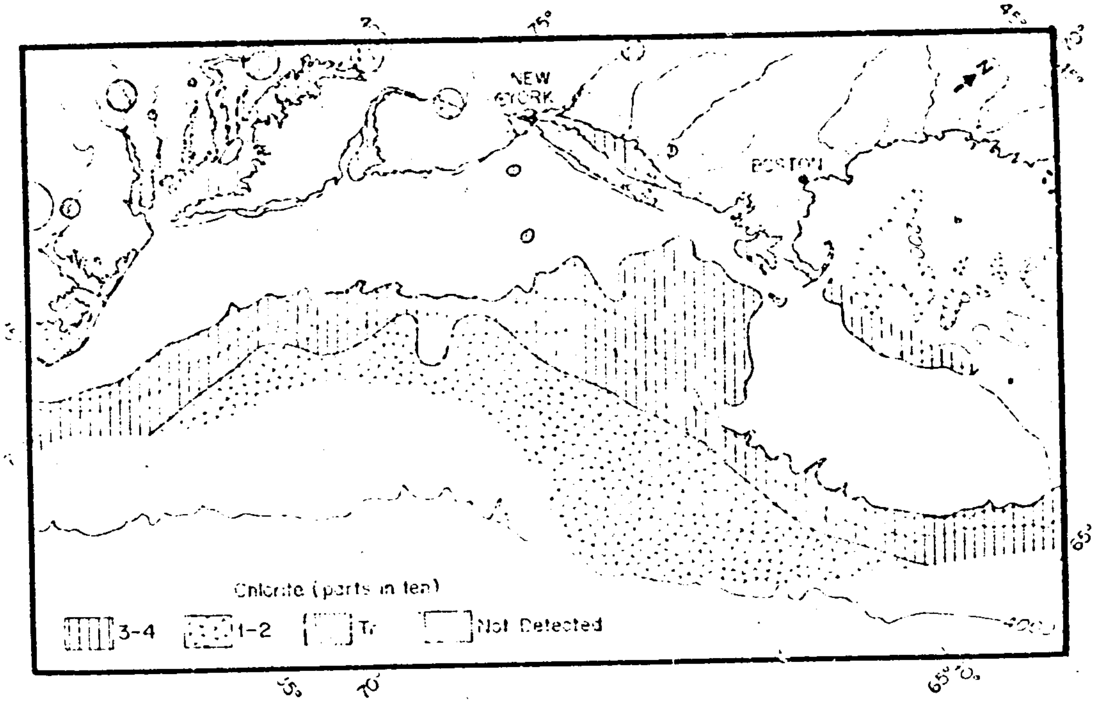
5.5.9 RADIOACTIVITY

A series of studies summarized by Emery and Uchupi (1972) show gamma counts with the highest values residing in the Gulf of Maine, in estuaries, and along the upper continental slope (Figure 5-31). Although



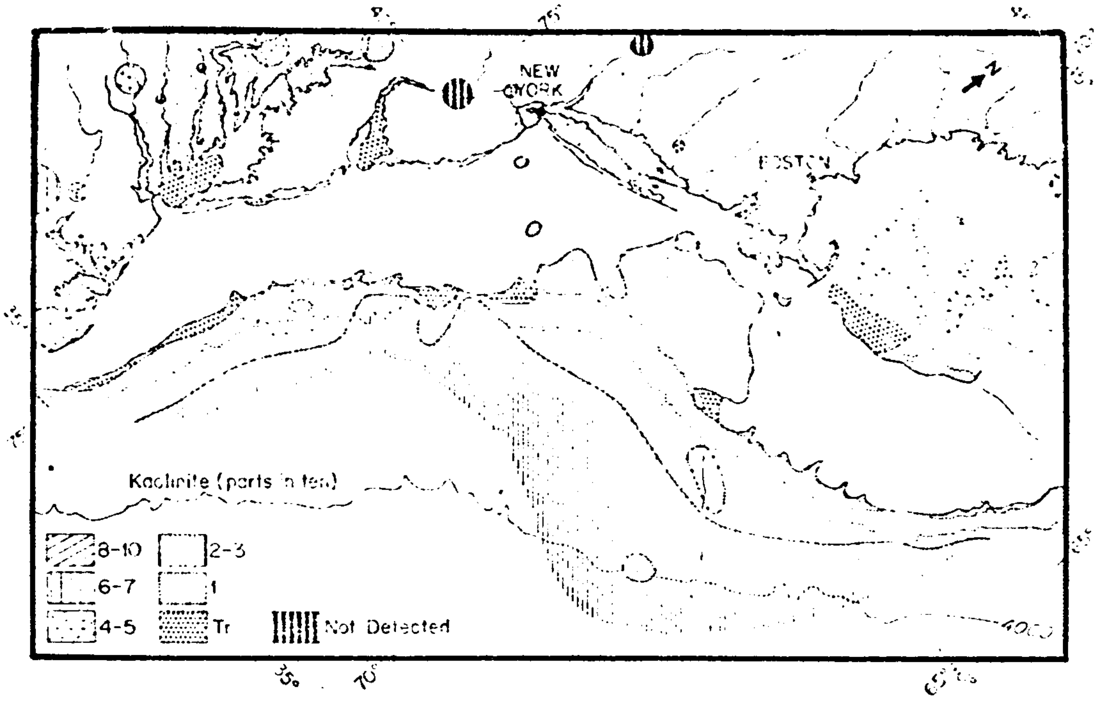
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-25	Distribution of Illite in the Clay Fraction (Finer Than Two Microns) (Hathaway, 1972)



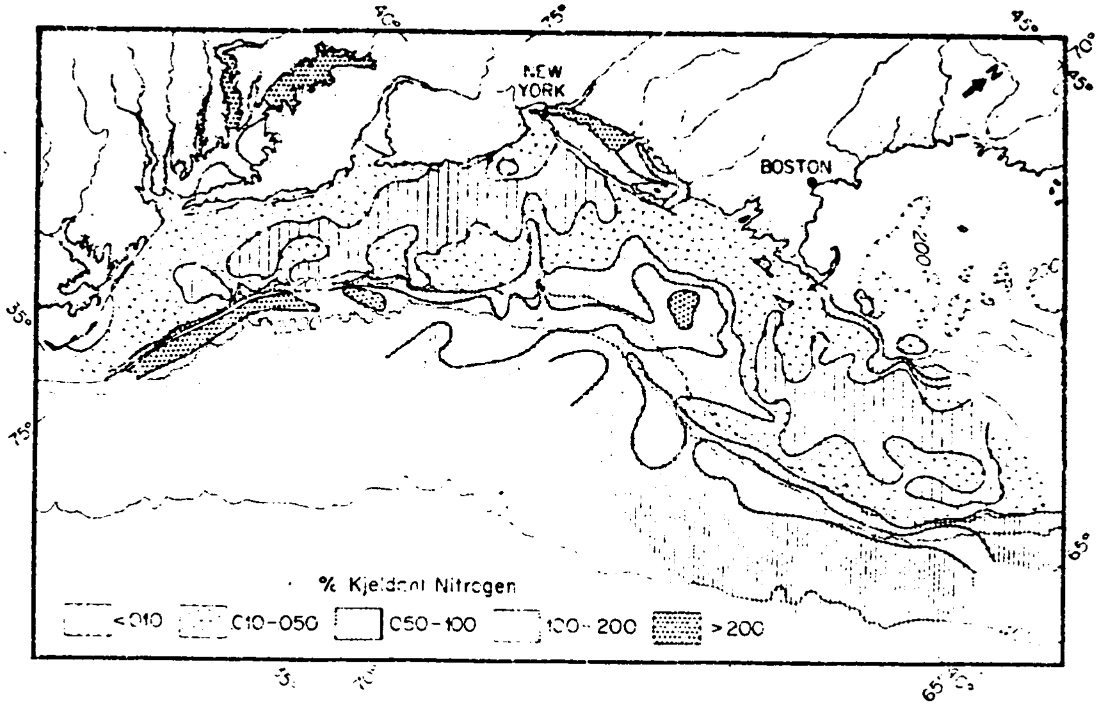
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-26	Distribution of Chlorite in the Clay Fraction (Hathaway, 1972)



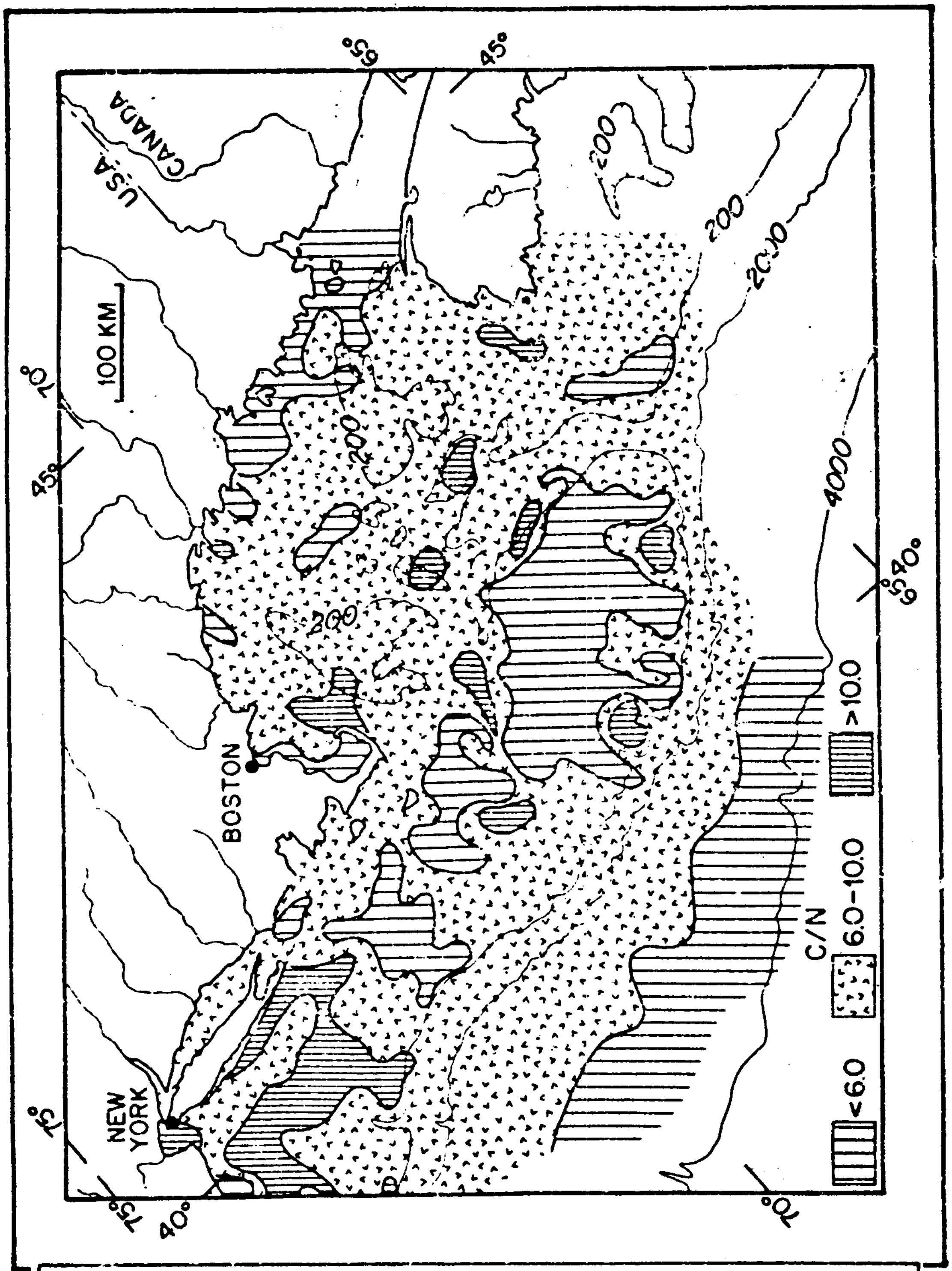
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-27	Distribution of Kaolinite in the Clay Fraction (Hathaway, 1972)



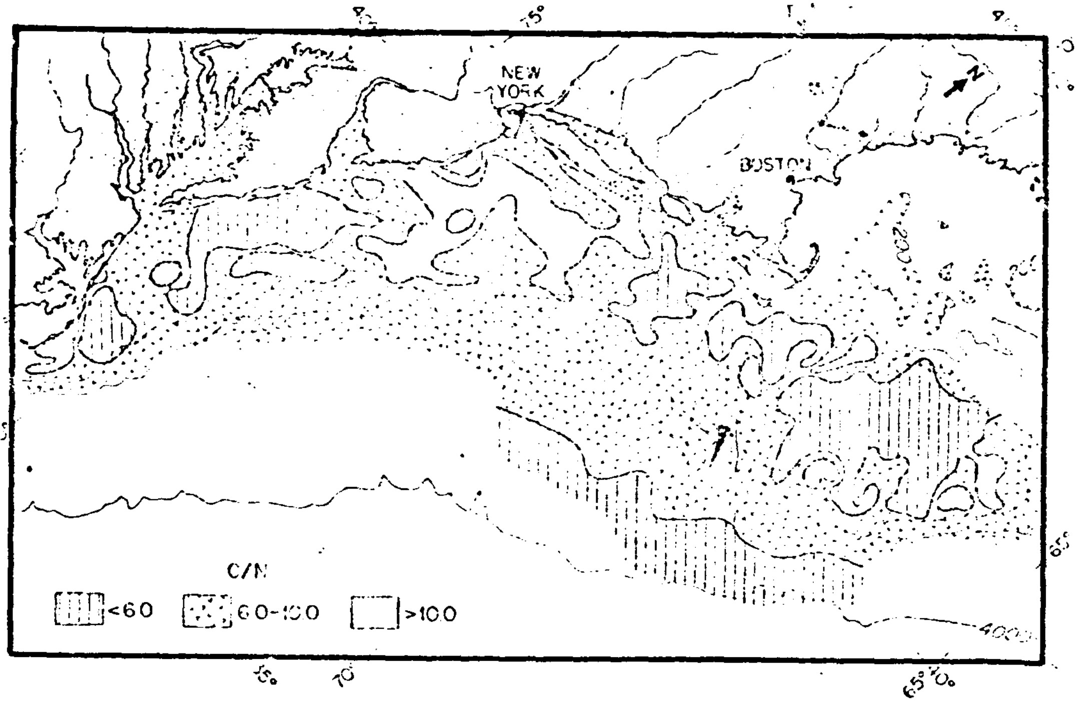
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-28	Distribution of Kjeldahl Nitrogen in the Continental Margin Sediments (Milliman, 1973)



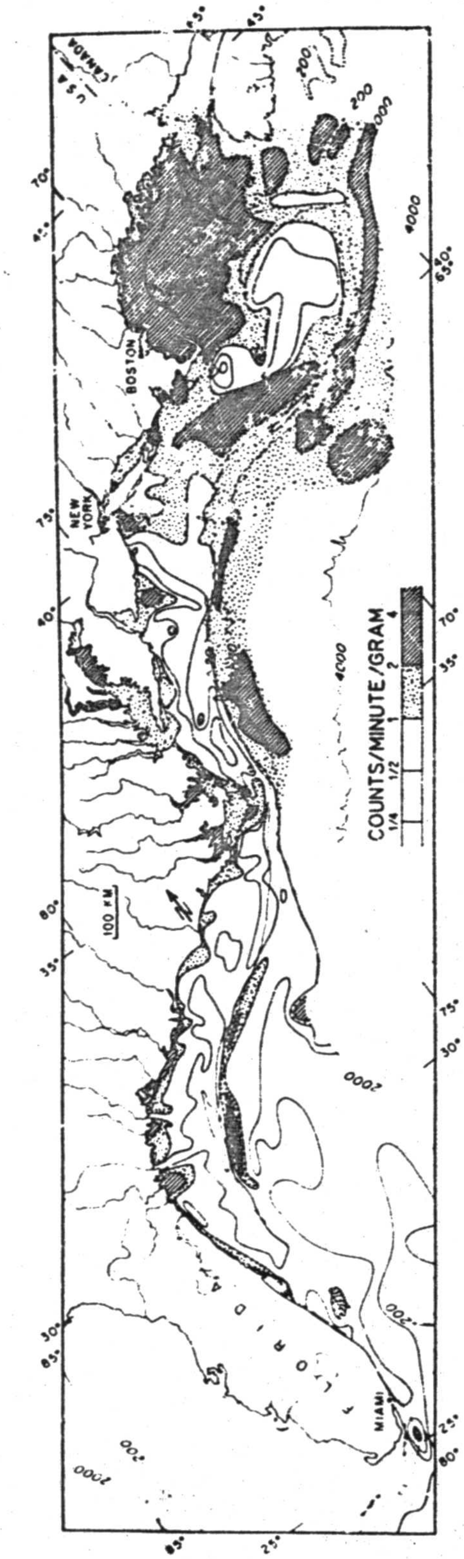
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-29	Distribution of Organic Carbon/Nitrogen (C/N) Ratio Within the Shelf and Slope Sediments (TRIGOM, 1974)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-30	Distribution of Organic Carbon to Kjeldahl Nitrogen in Continental Margin Sediments (Milliman, 1973)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 5-31

Distribution of Radioactivity in Surface Sediments of the Atlantic Continental Shelf and Slope (Emery and Uchupi, 1972) their plots are not highly correlated, there is also a general tendency for high counts of nitrogen. These studies show that natural radioactivity of the sediments is a function of sediment grain size, minerals, and of the post-depositional modification by organisms and diagenesis.

5.5.10 SEDIMENT SOURCE AND AGE

A simple framework for presenting the source and age of continental margin sediments for the Mid-Atlantic Bight has been described by Milliman, et al. (1972) and Milliman (1973). These sediments are usually of three general ages: modern, relict (deposited during the last lower stand of sea level), and residual (from subaqueous outcrops or from older sediments). The sediments are also from three sources: fluvial, glacial, and biogenic. The combination of these two factors - age and source - is shown in a broad general history of the Mid-Atlantic sediments in Figure 5-32.

Deposits that fall closely in the slope area are modern, with some minor encroachment of relict fluvial types. They are presently accumulated on most parts of the continental slope; however, average sedimentation rates are poorly defined at the present. MacIlvaine (1973) found the accumulation greater than 15 cm/1,000 years on the upper slope off southern New England during the Holocene period; while on the lower slope it may have been as low as 2 cm per 1,000 years. Greater deposition and greater erosion apparently occurred during the Pleistocene period. This is evidenced by higher sedimentation rates in upper slope cores as well as observations of numbers of massive slump deposits. Upper slope deposition rates south of Hudson Canyon averaged 6.8 cm/1,000 years, decreasing to about half of this on the lower rise (Ericson, et al., 1961).

5.5.11 SEDIMENTARY PROCESSES

The total load of sediment input from rivers entering the Mid-Atlantic Bight has been estimated at 7,618,800 metric tons per year (Curtis, Culbertson and Chase, 1973). This low quantity of suspended load is the result of Pleistocene glaciers which scraped off erodible sediments and left only a hard indurated substrate (Meade, 1969a). Furthermore, human activity over the last two centuries has affected the sediment load through erosion and land-clearing practices. As a result, the suspended loads in present rivers may be four to five times that of the pre-man era in the New England-Middle Atlantic Bight area (Meade, 1969b). Fairly recent information from studies of the Gulf of Maine (Spencer and Sachs, 1970) show that the total concentration of terrigenous matter suspended in the various basins of the Gulf of Maine is calculated at 3.7 times 90,700,000 metric tons. This is more than an order of magnitude higher than the annual load of all the New England rivers. It would suggest a resuspension of the underlying sediments and bottom sediments for the shelf and slope, not an introduction of fluvially-derived sediments.

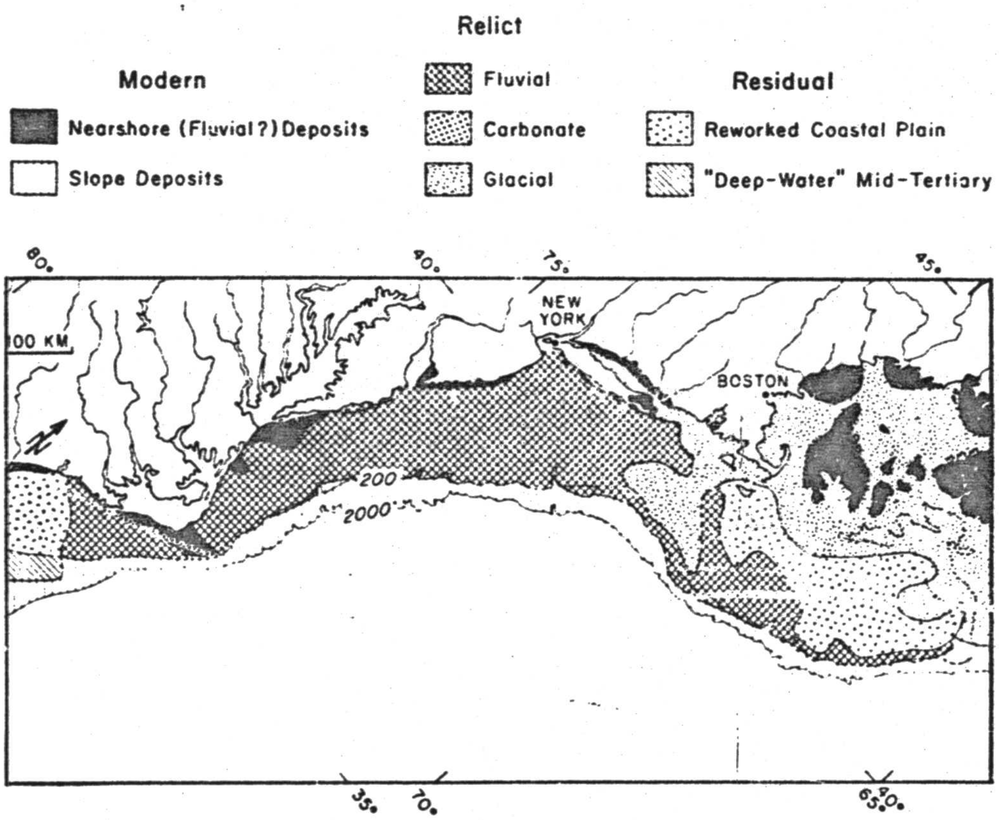


FIGURE 5-32 Source and Age of Sediments from the Middle Atlantic Continental Margin (Milliman, *et al.*,1972

One likely mechanism for this resuspension is the periodic high enery storms. These storms may contribute large quantities of sediments to the near shore and, to a lesser degree, the upper slope areas through a reworking of the deposits. The fact that sediment is accumulating on the slope at rates of 15 cm/1,000 years would indicate that modern sediment is transported and deposited in the deeper areas along the slope. Presumably, sediment movement occurs preferentially, down the axes of canyons and gullies (Trumbull and McCamis, 1967; and Kelling and Stanley, 1970). Although some measurements show alternating magnitudes and directions of currents in canyon axes, the net transport is down gradient.

Emery and Ross (1968) found that a current of 70 cm/seconds on the upper slope south of Martha's Vineyard caused little sediment erosion. Furthermore, MacIlvaine (1973) found that tracks and marks in the slope made by the submersible, ALVIN, were visible three years later, indicating that current-induced erosion was minimal during this particular period. Probably the most important mechanisms in downslope transport are the turbidity currents (Ericson, et al., 1961; Eittreim, et al., 1969; and Shepard and Dill, 1966) and mass movements by creep, slump, and land slide. Observations from submersibles in the Pacific and Atlantic Coasts have indicated a high degree of activity caused by burrowing and excavating organisms as they work and rework the upper tens of centimeters of unconsolidated sediments (Emery and Ross, 1968).

5.6 ECONOMIC GEOLOGY AND RESOURCES OF THE CONTINENTAL SLOPE

Discussions by Milliman (1973), Emery and Uchupi (1972), and others, indicate that the major economic deposits in the offshore area can be defined as fossil fuels and sediments.

5.6.1 PETROLEUM

A potential petroleum resource exists on Georges Bank (Emery, 1965a, 1968b) where the presence of salt diapirs and Jurassic carbonates may provide favorable petroleum traps and reservoirs (Schultz and Grover, 1974). Another area with a high petroleum potential occurs on the shelf and is associated with the Baltimore Canyon trough. The considerable discussion regarding the shelf basin deposits of petroleum is well documented in U.S. Geological Survey Open File Report 75-353. Little or no reference is made to the potential off the shelf on the continental slope. The evidence of thickening sedimentary deposits would lend some support for various types of petroleum traps lying in the slope area. However, the above report comments on the difficulty of having no drilling data on which to make any projections of petroleum potential.

On Georges Bank, the Lower Cretaceous rocks lying beneath are considered to have the best hydrocarbon potential. The varied lithology of the Lower Cretaceous section (marine sandstone, shale, and limestone) is expected to provide ample probabilities for potential reservoir rocks and source rocks (U.S. Geological Survey, 1975). Comparisons are made to areas with Lower Cretaceous reservoir sands that have been drilled, both to the north and to the south of our study area (Smith, 1975). One of these is the Sable Island E-48 well on the Scotian Shelf. Palmer (1974) describes two of the best locations in the Georges Bank basin as being (1) along the southeast and east flank which appears to be fault-controlled and (2) the southern part of the Georges Bank Trough which is flanked on the south by another possible basement high associated with the east coast slope anomaly. This high is a fault-controlled basement horst. It may also have had active faulting in its formation during the early Cretaceous period, thus providing possible stratographic traps in the overlying section (Ballard, 1974). The possibilities of petroleum on the slope has been suggested in the literature; however, it is beyond the scope of this report to speculate further.

5.6.2 SAND AND GRAVEL SEDIMENTS

A very distinct break occurs in the size of sediments in the slope and rise area with silt and clay predominating. No specific reference has been made about the possibility of economic deposits of sand or gravel lying beyond the shelf, as seen in Figure 5-17. However, there are areas along the upper slope where some fine sands may occur. These areas appear to be at too great a distance for any economically feasible recovery as industrial sand and gravel. If, as has been stated, the shelf deposits offer poor economic return, then the slope deposits, which are of poorer quality and greater distance from market, are even less economically attractive.

5.6.3 MUD

Palmer (1974), using information from Manheim (1972), has suggested that muds (combinations of silts and clays) might well be used at some future time for construction materials. Although retrieval of muds would be more economically desirable from the nearshore area, there are particular properties in the continental slope muds that would make them of some value. There do not seem to be any serious attempts to estimate the value of such a resource on the slope in the literature.

5.7 GEOLOGIC HAZARDS AND IMPACTS

As the development of the outer continental shelf and, subsequently, the development of the slope occurs, consideration of environmental hazards and impacts is necessary. Although many geologic features are relatively insensitive to hazards and impacts, proper planning for the installation of structures or conducting of practices is important. A hazard can be defined as a potentially detrimental situation or condition on a structure; while an impact is the effect a structure has on the marine environment. Thus, as Palmer (1974) pointed out, there is little hazard in sea floor mineral extraction while the impacts may be serious. There are few, if any, data or considerations given to the continental slope as an operating area. Thus, much has to be extrapolated from the considerations given to the continental shelf. A brief description based on Palmer (1974) and Milliman (1973) follows.

5.7.1 SEISMICITY

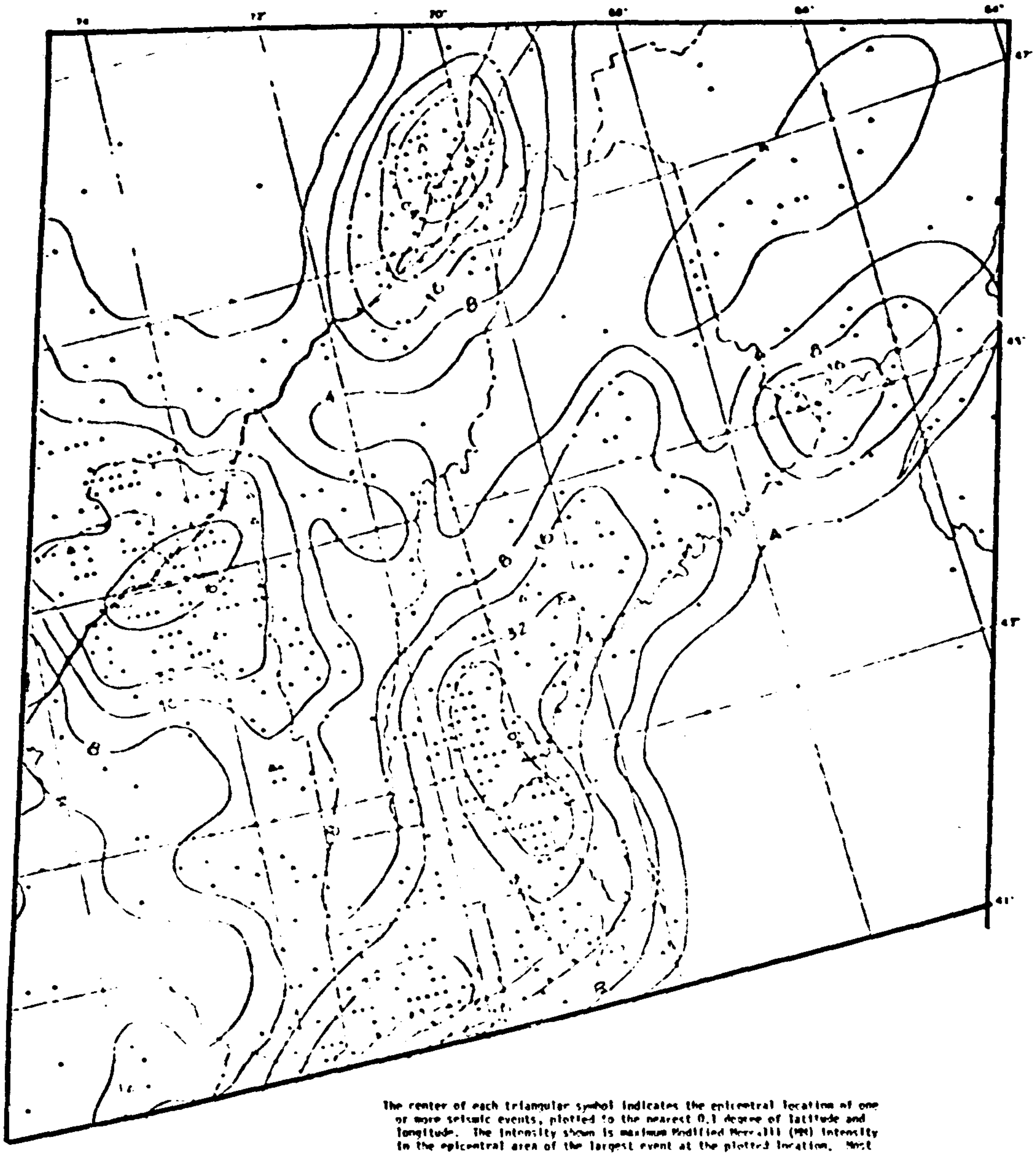
The USGS Report 75.353 (1975), cites seismic risks in the Georges Bank area using data from Hadley and Devine (1974). These data show very few epicenters off eastern New England and a moderate to high level of seismic activity in the coastal area of southeastern New England. The earthquake epicenters, recorded between 1800 and 1972 and between 1900 and 1974, on land for all of New England, are shown in Figures 5-33 and 5-34. Hadley and Devine (1974) conclude that a level two exists for much of the coastal area which signifies "seismic frequencies generally more than eight and less than 32, and no earthquake in the area has had a maximum epicenter intensity greater than modified Mercalli IV." A hazard index for the Georges Bank area of between an average of 6.94± 1.18 for the Maritime Provinces is cited by Howell (1973). Sbar and Sykes (1973) project the Boston-Ottawa seismic activity southeast to the New England sea mount chain. Ballard (1974) shows a basement horst trending northeast to southwest under the slope and thought to be a seismically dead feature. He considers this zone to be an active, complementary set of fractures and to be the northeast-southwest shear set in the western Gulf of Maine. Based on seismic reflection profiles from Georges Bank, Oldale, et al. (1974) have found no indication or evidence of shallow faulting. One of the reasons for lack of substantial data has been the difficulty in focusing shore-based seismographs on offshore earthquakes.

5.7.2 TSUNAMI

Although there is little possibility of destructive seismic sea waves (Tsunami) occurring along the Atlantic Coast, they should be considered because of the single occurrence following the 1929 Grand Banks earthquake. In this case, a single wave struck the south end of Newfoundland and, due to simultaneous high tides, there was damage and loss of life. It is not possible to predict this phenomena for the continental slope.

5.7.3 SEDIMENT MOVEMENT

MacIlvaine (1973) discusses in some detail the sedimentary processes which he found active along the continental slope in southern New England. These included gravitational (turbidity currents, creep, and slumping), hydrodynamic, and biological processes. MacIlvaine's treatment of large, medium, and small scale slumping is an extremely good review of the total process as it applies to the Atlantic continental slope. In summary, he states the downslope movement of sediment by



The center of each triangular symbol indicates the epicentral location of one or more seismic events, plotted to the nearest 0.1 degree of latitude and longitude. The intensity shown is maximum Modified Mercalli (MM) intensity in the epicentral area of the largest event at the plotted location. Most locations are based on observations of intensity rather than on instrumental records.

— 8 —

Seismic frequency contour represents the areal distribution of earthquake epicenters with epicentral intensity of MM III and greater, as indicated by the total number per $10^4 km^2$ during the period 1800-1972. Contour intervals are 0-4, more than 4 but less than 8, more than 8 but less than 16, more than 16 but less than 32, more than 32 but less than 64 and more than 64. The contours are considerably generalized and are shown only as a guide for estimating regional seismicity. They have no value for precise location of seismic boundaries.

NOTE: This map was compiled in 1973 from earthquake data of the Environmental Data Service of the National Oceanic and Atmospheric Administration and from data of the Dominion Observatory, Ottawa, Canada

SCALE 1:5,000,000

1 inch equals approximately 80 miles

EXPLANATION

Modified Mercalli Intensity

● III-VI

▲ VII

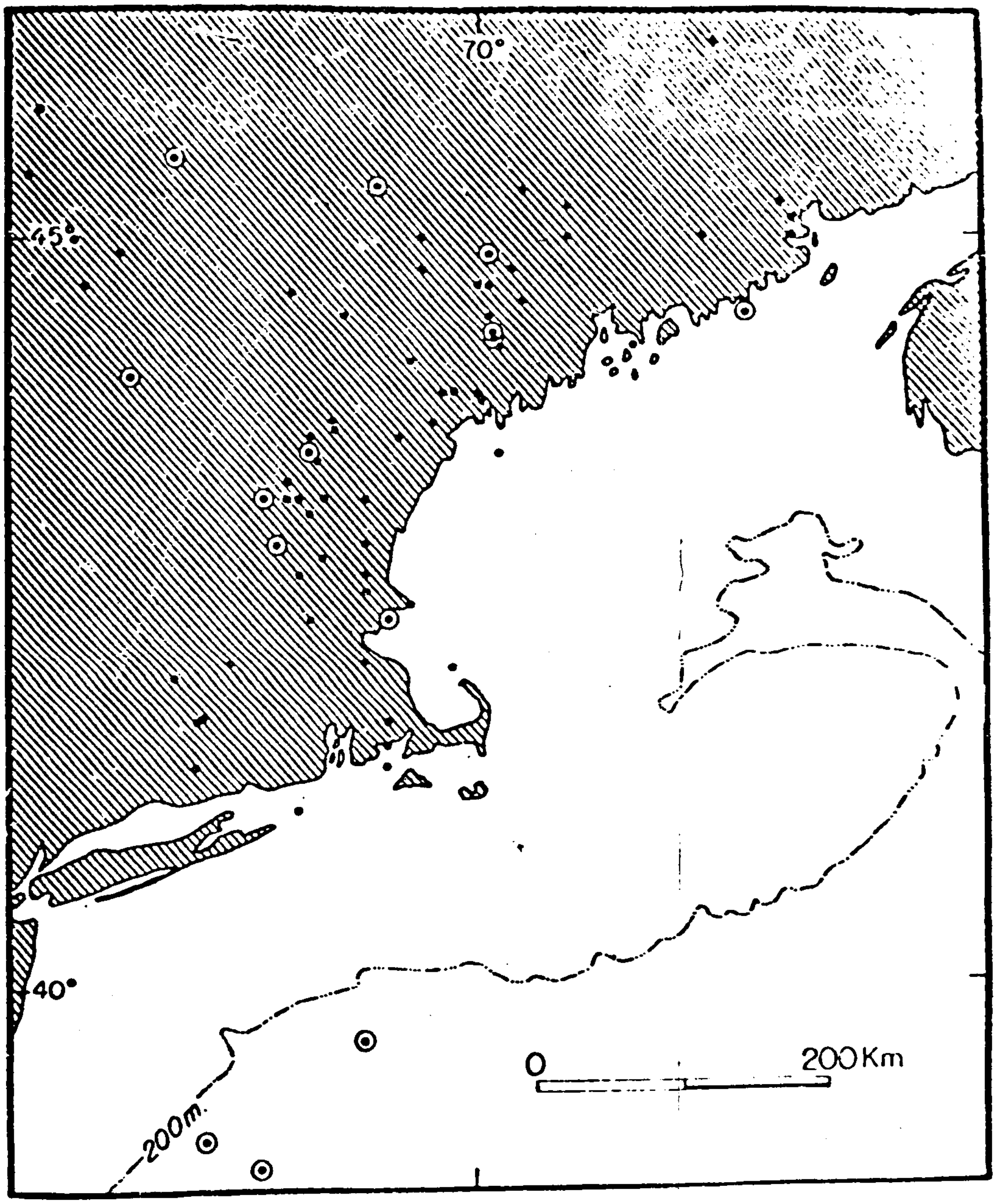
▲ VIII

△ IX-X

△ XII

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 5-33	Earthquake Epicenters Recorded Between 1800 and 1972 (Hadley and Devine. 1974)



(Double circles show epicenters recorded between 1961 and 1974)

TRIGOM FIGURE 5-34 Earthquake Epicenter Map of All Earthquakes Recorded Between 1900 and 1974 (Schlee, et al., 1975) gravitational processes was enhanced by the increased sediment supply and rapid deposition during the glacial periods. The steepness of the bottom controls the amount of material which can be deposited without a sediment failure. Therefore, only a few meters of rapid deposition is stable on the steeper, lower continental slope. Especially large slumps occur at the increase in gradient from the upper slope to the lower slope. There is still a lack of direct evidence indicating turbidity currents as a means of transporting sediments. Owen and Emery (1967) have photographed erosional features at 1,523 m on the lower continental slope that were attributed to the passage of two small turbidity currents. The V-shaped gullies incised in the lower continental slope suggest this type of erosion.

Current velocities sufficient to move sand-size sediments downslope are initiated by internal waves breaking near the upper slope or at the shelf break according to Cacchione (1970). However, on the deeper portions of the slope bottom currents appear to have little influence on the sediment surface. We may conclude from this that certain sedimentary processes would, when stability was exceeded, cause various types of hazards, at least, along the upper slope.

5.7.4 HAZARDS AND IMPACTS FOR STRUCTURES

Palmer (1974) has prepared a list, Table 5-1 and 5-2, of hazards to structures, taking into consideration the construction and placement of various types of structures on the shelf. Much of these data can be extrapolated to the slope area as far as types and causes. However, as in earlier sections, both the deeper water and continued lack of data for the slope area makes any specific estimates difficult.

5.8 DATA GAPS

Although nearly each of the topical sections is fairly incomplete in the sort of detail that should be available, the ones most lacking are data on sediments and geologic hazards.

SEDIMENTS

The major sediment sampling program conducted by USGS which produced some 4,000 samples along the entire North Atlantic continental margin only cites some 900 as being on the slope or rise. Thus there are very few samples on which to base data for the slope. This is probably an area that needs the greatest attention and where the least is known. Lack of these data not only affect all topics discussed under Sediments but also sediment stability and movement information for the Hazards section. Sediment movement and transport down canyons and over the slope in general need far more specific investigation since the process are poorly documented and less well understood.

HAZARDS

As has been the case with the shelf areas, there is little reliable seismicity data for the slope. High interest areas need to have bottom-mounted seismometers for additional data.

Table 5-1. Hazards to structures: environmental effects on objects

STRUCTURAL HAZARD	CAUSE	DATA REQUIRED FOR DESIGN OR REMEDIAL ACTION
Submarine slumps	Liquifaction of soils due to earthquakes, storm waves, structural motion (wind, machinery), erosion	Wave spectra, current data, soils information on cohesion, friction angle, ground acceleration
Scour	Wave-induced surge, tidal currents, bio-excavation	Wave and current data, sediment properties, benthonic biota data
Failure of soils under load	Insufficient shear strength of soils	Cohesion, density, shear strength, friction angle
Settlement	Variations in soil properties under structure, compressible soils, seismic loading	Density, bearing capacity, consolidation data
Excessive lateral loads	Waves, winds, currents	Oceanographic data (waves, currents)
Pullout (breakout)	Low shear strength	Cohesion data, density, friction angle

Table 5-2. Impacts of structures: object effect on environment

EFFECT	CAUSE	DATA REQUIRED FOR ANALYSIS
Regional erosion or deposition	Alteration in local current regime (littoral drift, wave refraction)	Wave and current data, textural data for sediments, structural configuration, bathymetry
Localized scour (erosion)	Obstruction of local flow, placement of discharges	Flow rate (current data), object geometry, discharge rate and orientation, sediment texture, bathymetry
Localized deposition	Obstruction of local flow, dumping of spoil or other solids	Sediment texture, current and wave data, volume of material, bathymetry, toxicity
Spills	Accidental discharge of materials	Nature of materials, currents, waves, volume of material, buoyany, toxicity

5.9 REFERENCES

Ballard, R.D. 1974. The nature of Triassic continental rift structures in the Gulf of Maine. Woods Hole Oceanogr. Inst., Ref. 74-71. 96 p.

Biscaye, P.E. 1965. Mineralogy and sedimentation of recent deep sea clay in the Atlantic Ocean and adjacent seas and oceans. Geol. Soc. Amer. Bull., 76: 803-832.

Burk, C.A. and C.L. Drake. 1974. The geology of continental margins. New York, Springer-Verlag. 1009 p.

Cacchione, D.A. 1970. Experimental study of internal waves on a slope. Ph.D. Thesis, Mass. Inst. Technol. and Woods Hole Oceanogr. Inst. 226 p.

Curtis, W.F., J.K. Culbertson, and E.B. Chase. 1973. Fluvial sediment discharge to the oceans from the conterminous United States. U.S. Geol. Surv. Circ. 670. 17 p.

Dall, W.H. 1925. Tertiary fossils dredged off the northeastern coast of North America. Amer. J. Sci., 5th. ser., 10: 213-218.

Dietz, R.S. 1963. Collapsing continental rises: an actualistic concept of geosynclines and mountain building. J. Geol., 71: 314-333.

Drake, C.L., J.I. Ewing, and H. Stoddard. 1968. The continental margin of the eastern United States. Can. J. Earth Sci., 5: 993-1010.

Drake, C.L., M. Ewing, and G.H. Sutton. 1959. Continental margins and geosynclines: the East Coast of North America north of Cape Hatteras. In: Physics and chemistry of the earth. New York, Pergammon Press, p. 110-198.

Drake, C.L. and H.P. Woodward. 1963. Appalachian curvature, trench faulting and offshore structures. N.Y. Acad. Sci. Trans., ser. II, 26: 48-63.

Drake, C.L., J.L. Worzel, and W.C. Beckman. 1954. Geophysical investigations in the emerged and submerged Atlantic coastal plain: Part IX, Gulf of Maine. Geol. Soc. Amer. Bull., 65: 957-970.

Eittreim, S., M. Ewing, and E.M. Thorndike. 1969. Suspended matter along the continental margin of the North America basin. Deep-Sea Res., 16: 615-624.

Emery, K.O. 1950. A deep fathogram across the North Atlantic Ocean. Amer. J. Sci., 248: 100-106.

________. 1960. The sea off southern California. John Wiley and Sons, New York. 366 p.

________. 1965. Geology of the continental margin off eastern United States. In: W.F. Whittaid and R. Bradshaw (eds.), Submarine geology and geophysics. London, Buttersworths, p. 1-20.

________. 1968a. Shallow structure of continental shelves and slopes. Southeast. Geol., 9: 173-194.

________. 1968b. Relict sediments of continental shelves of the world. Amer. Assoc. Petrol. Geol. Bull., 52: 445-464.

________. 1970. Continental margins of the world. In: Geology of the East Atlantic continental margin, I: General and economic papers, ICSU/SCOR Working Party, 31 Symp., Cambridge 1970, Rep. 70-13: 7-29.

Emery, K.O. and D.A. Ross. 1968. Topography and sediments of a small area of the continental slope south of Martha's Vineyard. Deep-Sea Res., 15: 415-422.

Emery, K.O. and E. Uchupi. 1972. Western North Atlantic Ocean: topography, rocks, structure, water, life, and sediments. Amer. Ass. Petrol. Geol. Mem. 17. 532 p.

Emery, K.O., E. Uchupi, J.D. Phillips, C.O. Bowen, E.T. Bunce, and S.T. Knott. 1970. Continental rise of eastern North America. Amer. Ass. Petrol. Geol. Bull., 54: 44-108.

Ericson, D.B., M. Ewing, G. Wollin, and B.C. Heezen. 1961. Atlantic deep-sea sediment cores. Geol. Soc. Amer. Bull., 72: 193-286.

Hadley, J.R. and J.F. Devine. 1974. Seismotectonic map of the eastern United States. U.S. Geol. Surv. Map MF-620, 3 sheets and text.

Hallam, A. 1971. Mesozoic geology and the opening of the North Atlantic. J. Geol., 79: 129-157.

Hathaway, J.C. 1971. Data file, continental margin program, Atlantic Coast of the United States, v. 2, sample collection and analytical data. Woods Hole Oceanogr. Inst., Ref. 71-15. 489 p.

________. 1972. Regional clay mineral facies in estuaries and continental margins of the United States East Coast. In: B. Nelson (ed.), Environmental framework of coastal places: estuaries. Mem. Geol. Soc. Amer., 133: 293-316.

Howell, B.F., Jr. 1973. Earthquake hazard in the eastern United States. Pa. State College of Earth and Mineral Sci., Univ. Park, Pa., 42(6): 41-45.

Hulsemann, J. 1967. The continental margin off the Atlantic Coast of the United States: carbonate in sediments. Nova Scotia to Hudson Canyon. Sedimentology, 8: 121-145.

Johnson, D.W. 1925. The New England-Acadian shoreline. New York, John Wiley and Sons. 608 p.

Keen, M.J. 1969. Possible edge effect to explain magnetic anomalies off the eastern seaboard of the U.S. Nature, 222: 72-74.

Keller, G.H., D. Lambert, G. Rowe, and N. Staresinic. 1973. Bottom currents in the Hudson Canyon. Science (April): 181-183.

Kelling, G. and D.J. Stanley. 1970. Morphology and structure of Wilmington and Baltimore submarine canyons, eastern United States. J. Geol., 78: 637-660.

Knott, S.T. and H. Hoskins. 1968. Evidence of Pleistocene events in the structure or the continental shelf off northeastern United States. Mar. Geol., 6: 5-43.

Komar, P.D. 1970. The competence of turbidity current flow. Geol. Soc. Amer. Bull., 81: 1555-1562.

MacIlvaine, J.C. 1973. Sedimentary processes on the continental slope off New England. Woods Hole Oceanogr. Inst., Tech. Rep. WHOI-73-58. 211 p.

Manheim, F.T. 1972. Mineral resources off the northeastern coast of the United States. U.S. Geol. Surv. Circ. 669. 28 p.

Mattick, R.E., R.Q. Foote, N.L. Weaver and M.S. Grim. 1974. Structural framework of United States outer continental shelf north of Cape Hatteras. Amer. Assoc. Petrol. Geol. Bull., 58(6): 1179-1190.

McIver, N.L. 1972. Cenozoic-Mesozoic stratigraphy of the Nova Scotia shelf. Can. J. Earth Sci., 9: 54-70.

Meade, R.H. 1969a. Landward transport of bottom sediments in estuaries of the Atlantic coastal plain. J. Sediment. Petrology, 39: 222-234.

________. 1969b. Errors in using modern stream load data to estimate natural rates of denudation. Geol. Soc. Amer. Bull., 80: 1265-1274.

Milliman, J.D. 1973. Marine geology. In: S.D. Saila (ed.), Coastal and offshore environmental inventory, Cape Hatteras to Nantucket Shoals, complement volume, Mar. Exp. Sta., Univ. R.I., p. 10-1 to 10-91.

Milliman, J.D., O.H. Pilkey, and D.A. Ross. 1972. Sediments of the continental margin off the eastern United States. Geol. Soc. Amer. Bull, 83: 1315-1334.

Northrop, J. and B.C. Heezen. 1951. An outcrop of Eocene sediments on the continental slope. J. Geol., 59: 396-399.

Oldale, R.N., J.C. Hathaway, W.P. Dillon, J.D. Hendricks, and J.M. Robb. 1974. Geophysical observations on northern part of Georges Bank and adjacent basins of Gulf of Maine. Amer. Ass. Petrol. Geol. Bull., 58(12): 2411-2427.

Owen, D.M. and K.O. Emery. 1967. Current markings on the continental slope. In: J.B. Hersey (ed.), Deep-sea photography. Baltimore, Johns Hopkins Press, p. 167-172.

Palmer, H. 1974. Offshore region, geology of offshore provinces. In: A socio-economic and environmental inventory of the North Atlantic region, p. 3-1 to 3-74. Produced by TRIGOM for the Bur. of Land Manage., Washington, D.C., 8 v. 4,900 p.

Pratt, R.M. 1968. Atlantic continental shelf and slope: physiography and sediments of the deep-sea basin. U.S. Geol. Surv. Prof. Pap. 529-B. 44 p.

Rabinowitz, P.D. 1974. The boundary between oceanic and continental crust in the western North Atlantic. In: C.A. Burk and C.L. Drake (eds.), The geology of continental margins. New York, Springer-Verlag, p. 67-84.

Ross, D.A. 1967. Heavy mineral assemblages in the nearshore surface sediments of the Gulf of Maine. U.S. Geol. Surv. Prof. Pap. 575-C: 77-80.

________. 1969. Geological observations from ALVIN. Woods Hole Oceanogr. Inst. Sum. Invest. Conducted in 1968, 1969: 71-72.

________. 1970. Atlantic continental shelf and slope : heavy minerals of the continental margin from southern Nova Scotia to northern New Jersey. U.S. Geol. Surv. Prof. Pap. 529-G. 40 p.

Sbar, M.L. and L.R. Sykes. 1973. Contemporary compressive stress and seismicity in eastern North America: an example of intra-plate tectonics. Geol. Soc. Amer. Bull., 84: 1861-1882.

Schlee, J. 1973. Atlantic continental shelf and slope of the United States: sediment texture of the northeastern part. U.S. Geol. Surv. Prof. Pap. 529-L. 64 p.

Schlee, J., J.C. Behrendt, R.E. Mattick, and P.T. Taylor. 1975. Structure of continental margin off Mid-Atlantic States (Baltimore Canyon Trough). U.S. Geol. Surv. Open File Rep. 75-60. 59 p.

Schlee, J. and R.M. Pratt. 1970. Atlantic continental shelf and slope of the United States; gravels of the northeastern part. U.S. Geol. Surv. Prof. Pap. 529-H. 39 p.

Schultz, L.K. and R.L. Grover. 1974. Geology of Georges Bank basin. Amer. Ass. Petrol. Geol. Bull., 58(6): 1159-1168.

Shepard, F.P. 1963. Submarine geology. New York, Harper and Row, 2nd. ed. 557 p.

Shepard, F.P. and R.F. Dill. 1966. Submarine canyons and other sea valleys. Rand McNally and Co., New York. 381 p.

Sheridan, R.E. 1974. Atlantic continental margin of North America. In: C.A. Burk and C.L. Drake (eds.), The geology of continental margins. New York, Springer-Verlag, p. 391-407.

Smith, H.A. 1975. What is the geology of West Sable structure? Oil and Gas J., (June): 170-172.

Spencer, D.W. and P.L. Sachs. 1970. Some aspects of the distribution, chemistry and mineralogy of suspended matter in the Gulf of Maine. Mar. Geol., 9: 117-136,

Stanley, D.J. 1969. Atlantic continental shelf and slope of the United States' color of marine sediments. U.S. Geol. Surv. Prof. Pap. 529-D. 15 p.

Stetson, H.C. 1936. Geology and paleontology of the Georges Bank canyons, I: geology. Geol. Soc. Amer. Bull., 47: 339-366.

Taylor, P.F., I. Zietz, and L.S. Dennis. 1968. Geologic implications of aeromagnetic data for the eastern continental margin of the United States. Geophysics, 33: 755-780.

The Research Institute of the Gulf of Maine (TRIGOM). 1974. Socio-economic and environmental inventory of the North Atlantic region. Prepared for Bur. of Land Manage., Washington, D.C. 8 v., 4900 p.

Trumbull, J.V.A. 1972. Atlantic continental shelf and slope of the United States: sand size fractions of bottom sediments, New Jersey to Nova Scotia. U.S. Geol. Surv. Prof. Pap. 529 -K. 45 p.

Trumbull, J.V.A. and M.J. McCamis. 1967. Geological exploration in an east coast submarine canyon from a research submersible. Science, 158: 370-372.

Uchupi, E. 1963. Sediments on the continental margin off eastern United States. U.S. Geol. Surv. Prof. Pap. 475-C: 132-137.

________. 1965. Maps showing relation of land and submarine topography, Nova Scotia to Florida. U.S. Geol. Surv., Misc. Geol. Inv. Map I-451, scale 1:1,000,000. 3 sheets.

________. 1967. The continental margin south of Cape Hatteras, North Carolina: shallow structure. Southeast. Geol., 8: 155-177.

________. 1968. Atlantic continental shelf and slope: physiography. U.S. Geol. Surv. Prof. Pap. 529-C. 30 p.

________. 1970. Atlantic continental shelf and slope of the United States: shallow structure. Geol. Surv. Prof. Pap. 529-I. 44 p.

U.S. Coast and Geodetic Survey and U.S. Bureau of Commercial Fisheries. 1967. (Bathymetric maps of the Atlantic continental shelf and slope from Delaware to outer Cape Cod.) U.S. Coast and Geodetic Surv., C &GS 0807N-51 through 57, 0808N-51 through 55, 0708N-51, through 53, 15 sheets, scale 1:125,000.

U.S. Geological Survey. 1975. Sediments, structural framework, petroleum potential, environmental conditions, and operational considerations of the United States North Atlantic continental shelf. U.S. Dept. of Interior, Open File Rep. 75-353.

________. 1975. Sediments, structural framework, petroleum potential, environmental conditions, and operational considerations of the Mid-Atlantic area. U.S. Geol. Surv. Open File Rep. 75-61. 143 p.

Upham, W. 1894. The fishing banks between Cape Cod and Newfoundland. Amer. J. Sci., 47(3rd. Ser.): 123-129.

Veatch, A.C. and P.A. Smith. 1939. Atlantic submarine valleys of the United States and the Congo Submarine Valley. Geol. Soc. Amer. Spec. Pap. 7. 101 p.

Verrill, A.E. 1878. Occurrence of fossiliferous Tertiary rocks on the Grand Bank and Georges Bank. Amer. J. Sci., 16(3rd. Ser.): 323-324.

Wear, C.M., D.J. Stanley, and J.E. Boula. 1974. Shelfbreak physiography between Wilmington and Norfolk Canyons. Mar. Technol. Soc. J., 8(4): 37-48.

CHAPTER 6.0

CHEMICAL OCEANOGRAPHY

GUY MCLEOD

T. R. GILBERT

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6.0 CHEMICAL OCEANOGRAPHY OF THE CONTINENTAL SLOPE

6.1 INTRODUCTION

The purpose of this chapter is to summarize and synthesize existing knowledge of the chemical oceanography of the continental slope waters which are bounded by continental shelf waters on the landward side and the Gulf Stream on the seaward side, and extending from Cape Hatteras to the northeast tip of Georges Bank. The areas of particular interest are those included between the 200 and 2000 meter isobaths. Most of the information available on this subject is derived from two types of environmental studies: those of the coastal region in which the sampling grid extended some distance beyond the continental shelf, and from deep sea oceanographic studies transecting the continental slope, Gulf Stream, and Sargasso Sea. Few investigations seem to have dealt with slope waters and the upper continental rise exclusively.

During the International Decade of Ocean Exploration (IDOE), two programs, the Geochemical Ocean Sections Study (GEOSECS) and the Pollutant Transfer Studies, are currently generating considerable information on the oceanic cycles of such trace constituents as heavy metals, petroleum residues, and chlorinated hydrocarbons. Because of recent advances in sampling and analysis techniques, these studies are supplying, in many cases, the first reliable information on baseline oceanic levels of the above pollutants. Current investigations are also supplying a clearer picture of the mechanisms controlling the movement of pollutants from land sources to the oceans. Whether the transport mechanisms are principally atmospheric with subsequent deposition on the sea surface or via the seaward movement of coastal water masses, data from the slope region supply important "intermediate" information on the concentration and chemical form of organic and inorganic pollutants.

6.2 HEAVY METALS

Perhaps not surprisingly, then, most of the reliable information available on heavy metal form and concentration in slope waters is of recent vintage and from the work of participants in the above two IDOE studies. Fitzgerald and Hunt (1974) have investigated the distribution of reactive mercury compounds, i.e. reduced at pH 1.6-2.2 by Sn(II), and inorganically associated mercury compounds in the surface microlayer and subsurface waters of the northwest Atlantic. Analysis of samples collected on a cruise between Bermuda and Narragansett, Rhode Island, showed relatively low (~10 ng/l) and uniform levels in the western Sargasso Sea. From more recent studies of the Sargasso Sea, Fitzgerald's group has determined the Hg concentration to a depth of 750 m to be 8 ± 3 ng/l (NSF-IDOE, 1974a). A sharp increase in the concentration of mercury occurred in samples from the continental slope (Table 6-1) with further increases in both reactive and organically associated Hg levels on the continental shelf. According to the authors:

Table 6-1. Average mercury concentrations in surface sea water versus geographical region of the northwest Atlantic Ocean[1]

Ocean Region	Hg Concentration (ng/l)					
	Surface Microlayer			Subsurface		
	Reactive	Total	Organically Associated[2]	Reactive	Total	Organically Associated[2]
Open Ocean (Stations 1-6)	6	7		6	8	
Continental Slope (Station 7)	8	42	34	12	41	29
Continental Shelf (Station 8)	34	89	55	41	122	81
Long Island Sound[3] (August-October, 1972)				29	61	32

[1] From Fitzgerald and Hunt (1974)

[2] Mercury strongly associated with organic material is determined as the difference between the total Hg measurement in photo-oxidated sea water and the amount of Hg determined in raw acidified sea water.

[3] Fitzgerald and Lyons (1973)

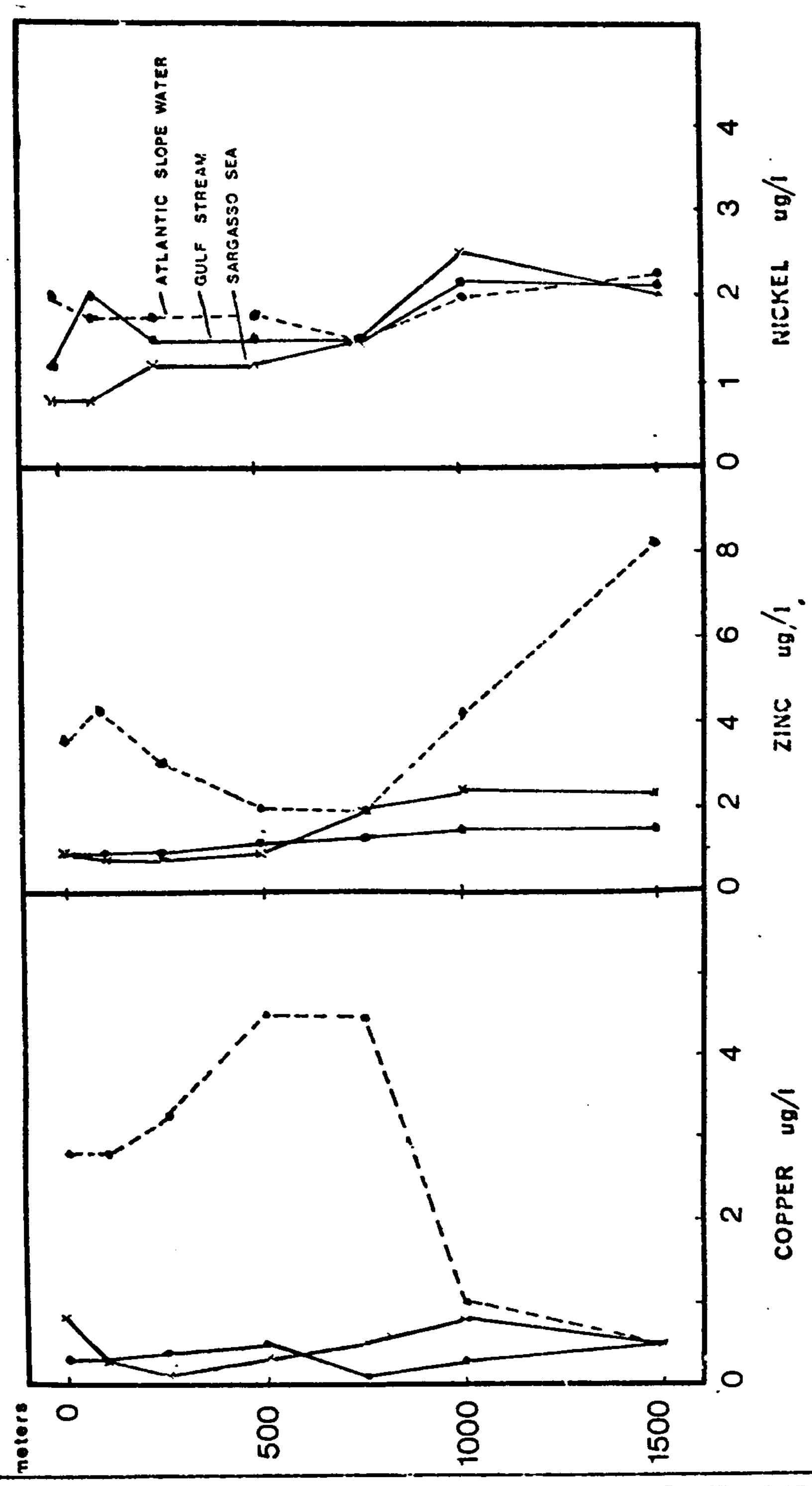
> "... The Hg distribution follows a pattern characteristic of many river-derived constituents in the northwest Atlantic Ocean. That is, the mercury concentrations decrease with increasing salinity and increasing distance from terrestrial courses."

However, this distribution of Hg does not indicate whether the principal transport mechanism is gaseous transport or continental run off. That only small differences in microlayer and subsurface Hg levels were found does not argue for atmospheric transport unless Hg species in the microlayer are readily returned to the atmosphere or migrate into the bulk water phase.

A similar distribution pattern was observed in the concentrations of copper, zinc and nickel in the northwest Atlantic (Spencer and Brewer, 1969). The data in Table 6-2 are average concentration values for water samples from 0-200 m taken on cruises through the slope to the Sargasso Sea that included sections through an anti-cyclonic eddy which had broken off from the Gulf Stream into the Sargasso Sea with cold slope water trapped in the center. They show no detectable differences between the Gulf Stream and the Sargasso Sea, but consistently higher metal concentrations in the slope water north of the Gulf Stream and in the center of the eddy. Degeneration of the eddy on the October cruise was manifested in decreased metal concentrations in its center. Vertical profiles to 1500 m taken on the October cruise are presented in Figures 6-1, 2, and 3. Nickel and zinc in the Gulf Stream and Sargasso Sea gradually increase with depth. The considerable variation in copper and zinc in slope waters with depth may be due to its heterogenous nature: the highest values approximate those observed in onshore waters while the lowest resemble the Gulf Stream and Sargasso Sea data.

In a similar study, Bewers, et al. (1975) have recently examined the distribution of particulate matter, iron, manganese, zinc, copper, nickel, cadmium, and cobalt in coastal, Atlantic slope and Central Atlantic waters, on and adjacent to the Scotian shelf. Slope water contained the lowest concentrations of Fe, Mn, Cu, Ni, and Zn, while Cd and Co showed no differences between the various water masses and Mn levels were the lowest in the Central Atlantic water (see Table 6-3). The reason for the low levels for several of the metals in the slope water is not clear; the authors' suggestion that the decrease is due to biological uptake of trace metals in the slope water and sinking of the metal-enriched detritus into the deeper Central Atlantic Water is not supported by the results of Spencer and Sachs (1970). Moreover, the significance in the differences in metal concentrations between water masses is not clear since the dissolved concentrations of all the metals were below analytical detection levels in at least some of the samples.

In an extensive sampling program, Spencer and Sachs (1970) have sur-



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM FIGURE 6-1,6-2 6-3 Average concentrations in the Western North Atlantic

Table 6-2. Average concentrations of copper, zinc, and nickel in the northwest Atlantic Ocean[1]

	June 1967	August 1967	October 1967
		Copper (µg/kg, 0-200 m)	
Sargasso Sea	0.6	0.6	0.6
Gulf Stream	0.6	1.0	0.3
Continental Slope	2.3	2.4	2.8
		Zinc (µg/kg, 0-200 m)	
Sargasso Sea	2.7	2.6	1.2
Gulf Stream	3.4	2.0	1.6
Continental Slope	10.9	10.8	3.9
		Nickel (µg/kg, 0-200 m)	
Sargasso Sea	0.7	0.8	0.8
Gulf Stream	0.7	0.9	1.6
Continental Slope	1.4	1.6	1.9

[1] From Spencer and Brewer (1969)

Table 6-3. Average concentrations of metals in the northwest Atlantic Ocean[1]

	Metal concentrations in µg/l								
	Fe_U	Fe_F	Mn_U	Mn_F	Cu	Zn	Ni	Cd	Co
Open Ocean	2.27	1.78	0.08	0.1	0.39	1.07	0.23	0.044	0.023
Continental Slope	1.82	1.61	0.15	0.08	0.24	0.72	0.17	0.034	0.019
Continental Shelf	3.23	1.46	0.47	0.33	0.56	1.11	0.25	0.036	0.013

[1] From Bewers, et al. (1975)

U = Unfiltered

F = Filtered

veyed the suspended matter in the Gulf of Maine, including waters greater than 200 m deep. Their data show that while there is considerable seasonal variation in surface waters, there are no apparent differences in suspended matter at depth. Levels increase exponentially as the bottom is approached and the mineralogy of the inorganic particulates closely resembles that of the bottom sediments. Both of these observations indicate that the principal source of inorganic suspended matter in the Gulf of Maine is the sediment layer. The copper and zinc content of the deep water particulates, summarized in Table 6-4 do not show any evidence of metal transport to deep water by settling detritus. Rather, most of the metal is regenerated in the surface waters.

Further characterization of the chemical form of heavy metals in the water column has recently included the bubble flotation experiments of Wallace and Duce (1975). Through this technique particulate trace metals are stripped from the sample and concentrated in an organic froth. The results of such analyses on samples of Sargasso Sea, Atlantic slope and continental shelf waters off the northeastern United States are summarized in Table 6-5.

The foam fraction data show relatively small differences in concentrations of iron, zinc, nickel, chromium and aluminum between Sargasso Sea and slope waters, but generally higher levels were recovered from the coastal sample. Slope waters contained higher levels of copper, manganese, lead and cadmium in the foam fraction than were found in the Sargasso Sea samples, while the highest levels of all but cadmium were again in the coastal water. Preliminary calculations of bubble transport of particulate trace metals to the air/sea surface using these data indicate that this mechanism is a more important one in determining trace metal levels on the surface layer than was previously believed.

In Table 6-6 the original particulate trace metals data are compared with those from subsurface microlayer samples collected at the same stations. The data are generally in good agreement and together are among the lowest values for the particulate form of these metals yet reported (NSF-IDOE Report, 1974a)

6.3 PETROLEUM AND CHLORINATED HYDROCARBONS

Reliable information on the concentration of these pollutants in the environment has become available only recently. With the development of refined extraction and identification techniques investigators are able to more accurately discriminate between geochemical and biogenic hydrocarbon residues and between DDT and its metabolites, other pesticides, and polychlorinated biphenyls (PCB's). A coastal area in which the concentration and distribution of hydrocarbons have been extensively studied is the New York Bight and the adjacent Atlantic slope. The area has served as a disposal ground for industrial wastes,

Table 6-4. Average copper and zinc concentrations of deep water particulate in the Gulf of Maine[1]

		Particulate Matter (percent)	
		Copper	Zinc
Station	Depth (m)		
179	234	0.0067	0.017
180	235	0.0120	0.0230
181	236	0.0034	0.0114
182	236	0.013	0.0188
185	347	0.015	0.0144
186	212	0.0066	0.0131
187	215	0.0098	0.0258

[1] From Spencer and Sachs (1970)

TABLE 6-5. Particulate trace metal concentrations in the original sample and in residue and foam fractions from floatation experiments[1]

	Cu			Fe			Zn		
Location	Original ng/l	Residue ng/l	Foam ng/l	Original µg/l	Residue µg/l	Foam µg/l	Original ng/l	Residue ng/l	Foam µg/l
Sargasso Sea									
Sta. 62	10±13	5±2	0.54±0.45	0.75±0.32	0.26±0.10	16±6	23±19	6±21	0.6±1.8
Sta. 64	3±2	18±17	0.76±0.13	0.08±0.07	0.06±0.03	28±8	11±23	0±35	4.1±1.5
Sta. 65	5±4	7±9	0.90±0.44	0.16±0.08	0.08±0.02	11±4	4±11	≤ 20	≤ 3.5
Continental Slope									
Sta. 66	2±1	2±2	0.95±0.35	0.17±0.07	0.07±0.05	34±8	≤ 35	≤ 25	≤ 3.5
Sta. 67	2±2	5±1	1.2±0.1	0.12±0.05	≤ 0.05	20±3	14±31	≤ 25	1.1±1.3
Continental Shelf									
Sta. 69[2]	29±12	12±8	2.0±0.3	1.0±0.2	0.04±0.08	153±8	21±43	≤ 70	3.6±1.9

[1] From NSF-IDOE Report (1974a). Samples were taken on Bermuda-Narragansett, Rhode Island, transect, R/V Trident Cruise TR-137.

[2] Original concentrations for the station are known to be low due to loss of parts of both replicates for this sample during sample workup.

TABLE 6-5, continued

Location	Cr			Al			Cd		
	Original ng/l	Residue ng/l	Foam ng/l	Original ng/l	Residue ng/l	Foam µg/l	Original ng/l	Residue ng/l	Foam µg/l
Sargasso Sea									
Sta. 62	22±12	10±3	0.94±0.19	0.42±0.07	0.18±0.07	23±1	1.5±1.0	0.1±0.5	82±20
Sta. 64	16±12	8±1	Grossly contaminated	0.17±0.10	0.09±0.0.06	16±4	≤ 0.1	≤ 0.07	25±12
Sta. 65	7±3	4±3	0.82±0.16	0.10±0.03	0.03±0.01	12±3	1.1±0.3	0.12±0.21	≤ 10
Continental Slope									
Sta. 66	9±2	3±1	0.72±0.17	0.16±0.01	0.08±0.05	31±4	≤ 0.1	0.07±0.10	≤ 10
Sta. 67	10±1	6±1	0.82±0.09	0.22±0.05	0.08±0.05	24±2	1.4±0.3	0.2±0.7	273±24
Continental Shelf									
Sta. 69[2]	16±2	2±3	1.3±0.4	0.69±0.22	0.11±0.04	270±3	12±16	9±7	174±25

Location	Mn			Pb			Ni		
Sargasso Sea									
Sta. 62	6.2±1.5	2.8±1.6	0.29±0.06	12±11	4±2	0.35±0.25	56±10	13±7	1.5±1.9
Sta. 64	3.3±0.6	0.4±0.4	0.41±0.05	5±7	1±2	0.56±0.15	7±7	1±5	≤ 0.8
Sta. 65	5.2±0.6	0.6±0.5	0.48±0.13	4±2	2±1	0.62±0.49	1±4	2±2	≤ 1.2
Continental Slope									
Sta. 66	33±2	4.4±1.2	3.4±0.5	1±2	0.3±0.8	0.75±0.31	≤ 12	≤ 9	2.0±2.1
Sta. 67	14±1	2.3±0.1	1.3±0.1	3±3	≤ 2.8	0.73±0.15	≤ 16	2±10	≤ 0.8
Continental Shelf									
Sta. 69[2]	238±12	20±3	27±3	15±12	≤ 8	2.7±0.2	351±19	≤ 24	3.0±2.5

Table 6-6. Particulate trace metal concentrations in bucket and subsurface microlayer samples of continental slope waters[1] (ng/l)

Station	Cu	Fe	Zn	Mn	Pb	Cr
			Bucket			
66	2±1	0.17±0.07	35	33±2	1±2	9±2
67	2±2	0.12±0.05	14±31	14±1	3±3	10±1
			Subsurface Microlayer			
66	2±2	290±60	6±4	33±4	10±2	3±2
67	10±2	430±80	27±7	20±4	21±2	6±2

[1] From NSF-IDOE Report (1974a) (See Table 6-5)

polluted dredge spoil and sewage, all likely to contain substantial levels of petroleum products.

In a recent survey of petroleum and chlorinated hydrocarbons in the western North Atlantic (NSF-IDOE Report, 1974b), elevated levels of petroleum hydrocarbons were found in the sediments of the New York Bight, and also in the Hudson Canyon at a location where fine grain sediments are swept down the canyon and deposited (Station K-33-2-10 in Table 6-7). Sediments from other areas within the canyon contain levels comparable to those of the adjacent continental slope. These data represent intermediate values: generally smaller than those found in surface sediments of coastal and continental shelf areas off the northeastern United States, but slightly higher than in the sediments of the abyssal plain of the western North Atlantic. However, if obviously polluted coastal sediments are not considered, then the differences in total hydrocarbon concentration between shelf, slope, and deep water sediments do not appear to be significant.

Analyses of the distribution of hydrocarbons, determined by a gas chromatograph-mass spectrometer-computer system, seem to supply considerably more information on transport and fate of these substances. For example, n-alkanes in the C_{21}-C_{31} range were found to have a strong odd carbon predominance in all areas except the New York Bight. Such a distribution is indicative of land plant material but not of marine flora or fauna, nor is it characteristic of petroleum residues. That this n-alkane distribution was found in abyssal plain sediments indicates the transport of plant detritus from land suspended in either the water column or the atmosphere.

A group of compounds with GC retention times near n-C_{17} predominated the continental shelf sediments outside the New York Bight region, but were absent or not dominant in abyssal plain sediments. Since these compounds are found in marine algae and zooplankton, they are very likely of marine origin.

Another group of unresolved alkanes and cyclohexanes, found in crude and heavy fuel oil, was barely detectable in abyssal plain samples, but was increasingly predominant on the transect to the New York Bight. Whether the existence of traces of these hydrocarbons in slope and abyssal plain sediments is due to transport of polluted sediments from the Bight through the Hudson Canyon or due to low level oil pollution on a much broader scale is a question not yet resolved.

The principal difficulty in measuring the hydrocarbon content of sea water samples is that the very low solubilities of most of these compounds keep their concentrations in the water column very low. Thus, most of the continental shelf and slope samples analyzed recently for particulate and dissolved hydrocarbon levels contained less than measurable amounts (NSF-IDOE Report, 1974b).

Table 6-7. Petroleum hydrocarbons in the sediments of the western North Atlantic[1]

	μg hydrocarbons/g dry wt sediments			
	f_1*	f_2*	f_3*	Total
Continental Shelf				
Outside New York Bight (K-19-5-15)	8.6	4.1	12.3	24.7
New York Bight (K-19-5-16)	399	65.5	95.3	559
(K-19-5-18)	1810	618	484	2912
(K-19-5-20)	25	4.6	5.9	35.5
Continental Slope				
Outside Hudson Canyon Average 3 Stations	5	4	6	14
Inside Hudson Canyon				
(K-33-2-8)	5	4	10	19
(K-33-2-9)	5	2	7	14
(K-33-2-10)	55	6	--	--
(K-33-2-11)	4	2	9	15
Abyssal Plain (K-19-5-3)	0.8	0.2	0.1	1.1

*f_1= alkanes, cycloalkanes, some alkenes

*f_2= alkenes, one and two ring aromatic compounds, some three ring aromatic compounds

*f_3+ three to six ring aromatic compunds, traces of methyl ketones

[1] From NSF-IDOE Report (1974b)

A second group of organic pollutants, the chlorinated hydrocarbons, have been the subject of increased investigation in recent years. Of major concern are the pesticides such as the DDT's, the chlorodanes and dieldrin and the polychlorinated biphenyls (PCB's), a group of compounds that until recently had found wide industrial use. A number of techniques based on preconcentration through solvent extraction or sorption on polyurethane foam followed by gas chromatography with electron capture detection have enabled us to measure part per trillion levels of these substances in environmental samples.

In a recent survey of the waters of the North Atlantic, Harvey, et al. (1973) measured PCB levels at 41 locations, including stations on the continental shelf and slope off the northeastern United States. Their data show a widespread distribution in the North Atlantic, with an average concentration of PCB's of 35 ng/kg for all stations. Slightly lower surface concentrations of PCB's (27 ng/kg) were found in the Sargasso Sea, which were not significantly lower than the 30 and 29 ng/kg found in surface waters of the continental shelf and slope, respectively. The authors conclude that their results support the proposition that the atmosphere is the predominant transportation medium.

Verification of the importance of atmospheric transport may come from the work of Olney and Bidleman (NSF-IDOE Report, 1974a), who examined the chlorinated hydrocarbon levels of atmospheric samples from the North Atlantic. On a cruise between Narragansett, Rhode Island, and Bermuda, R/V Trident Cruise TR-137, the chlorinated hydrocarbon content of five air samples showed no clear correlation with distance from the coast. Similarly the PCB and p,p'-DDT content of surface microlayer and subsurface samples showed little difference between open ocean stations and those on the continental slope and shelf (Table 6-8).

Harvey, et al. (1974) have measured the distribution of chlorinated hydrocarbons in Atlantic Ocean organisms. Their observations support the contention that these pollutants show neither horizontal concentration gradients from nearshore to the open sea nor food chain magnifications. The concentrations of PCB's in Atlantic plankton do not reveal any horizontal gradient. Atmospheric measurements of PCB's do show that these pollutants are being delivered to the coastal areas and open sea. Presumably, the particulate matter in the water mediates the quantity of PCB's available for uptake. The higher particulate load in coastal waters allows for greater adsorption, scavengering and sedimentation of PCB's. There is a decrease in suspended matter seaward to about 100 times less than inshore concentration. Thus, most of the PCB's and DDT delivered to the ocean are available in the dissolved phase. The open ocean is made even more vulnerable to chemical contamination by the slow sedimentation rate. If there is a gradient in the ocean, it should be seen in the sediments and bottom feeders, which is substantiated by the tenfold higher concentration of chlorinated hydrocarbons seen in the groundfish.

Analysis of the data for pelagic organisms shows there is no magnification

Table 6-8. Chlorinated hydrocarbons in the continental shelf waters[1]

	Concentration 10^{-9} g/l			
	PCB		pp' - DDT	
	SM[2]	SS[3]	SM	SS
Sargasso Sea (9 samples)	3.8-42.0	<1-3.6	0.2-2.1	<0.15
Bermuda-Narragansett transect (5 samples: 2 of slope waters)	3.7-7.3	<1-2.4	0.2-0.5	<0.15
Continental Shelf (Chesapeake Bay: 4 samples)	4.8-20.0	< 0.8	0.6-1.9	<0.08-0.11

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[1] From Bidleman, pers. comm.

[2] SM = Surface Microlayer

[3] SS = Subsurface Sample

of chlorinated hydrocarbons on a wet or lipid basis, and the authors explain this as follows:

> "The lipid stores of organisms are major repositories for chlorinated hydrocarbons. Lipid composition varies among species, within species, at different seasons and ages, and at different parts of the body. Some of these different lipids will be better hydrocarbon solvents than others regardless of trophic level. Furthermore, some organisms will have equilibration times with the water that are significantly different from others as a result of metabolic activity, blood supply, and surface to volume ratios. The result is a diverse interspecies relationship reported."

Based on production and release estimates, there should be more DDT than PCB's in the ocean. However, this is not the case, and suggests that PCB's and DDT's behave differently in the marine environment.

The authors conclude that they have observed no evidence of the effects of PCB's or DDT's on marine life, nor have they seen any evidence of a decline in the abundance of various populations sampled, at least none that is measurable by reference to comparable collections made in the last 20 years by the staff at WHOI. The authors do point out that PCB levels in phytoplankton in the range of hundreds of parts per million must be affecting marine biota, perhaps in subtle ways such as susceptibility to diseases, impairment of instincts, or reduction of reproductive potential. These effects might easily require several generations to become evident in population reduction.

6.4 NUTRIENTS

The nutrient cycles in the surface water of the continental slope are not well documented, but should essentially follow that of the continental shelf. We have reproduced, in part, Section 3.3, Chemical Oceanography from TRIGOM (1974) which discusses the nutrient cycle in the Gulf of Maine and have added such information as is available on the cycles in slope waters.

6.4.1 GULF OF MAINE

The Gulf of Maine has been the location of nutrient-cycling research by scientists from Woods Hole Oceanographic Institution and other laboratories for a number of years. Studies on nitrate, nitrite, phosphate, and dissolved oxygen were first carried on by Rakestraw (1933). More detailed work on the nutrients, including ammonia and silicate, was continued by Gran and Braarud (1935), Redfield, Smith and Ketchum (1937), Redfield and Keys (1938), Ketchum and Corwin (1965), Ketchum (1967, 1968), Colton, Marak, Nickerson, and Stoddard (1968), Apollonio and Applin (1972), Gran (1933), and others.

The distribution of dissolved oxygen in the Gulf of Maine area follows a pattern similar to most east-coast areas in temperate latitudes. During April, Ketchum and Corwin (1965) ran a series of stations in the Wilkinson Basin. They followed a plankton bloom and found supersaturation of dissolved oxygen (123 to 132 percent) down to nearly 50 m depth.

Because of the phytoplankton bloom during early summer the surface waters were generally supersaturated with oxygen to an average depth of 25 m. The deeper water was undersaturated with oxygen and contained about the same amount of oxygen as waters flowing into the Gulf of Maine along the eastern margin (Gran and Braarud, 1935). During the summer months in the deeper waters the oxygen content appears to decrease steadily. During August the surface water to a depth of 20 to 40 m was slightly supersaturated with oxygen (100 to 113 percent), at 9 stations located in the Gulf of Maine and on Georges Bank (Rakestraw, 1932). The maximum level was associated with the greatest abundance of diatoms. Below this supersaturated zone, which corresponded essentially to the mixed layer, the saturation of oxygen decreased to the bottom even though the actual oxygen concentration increased.

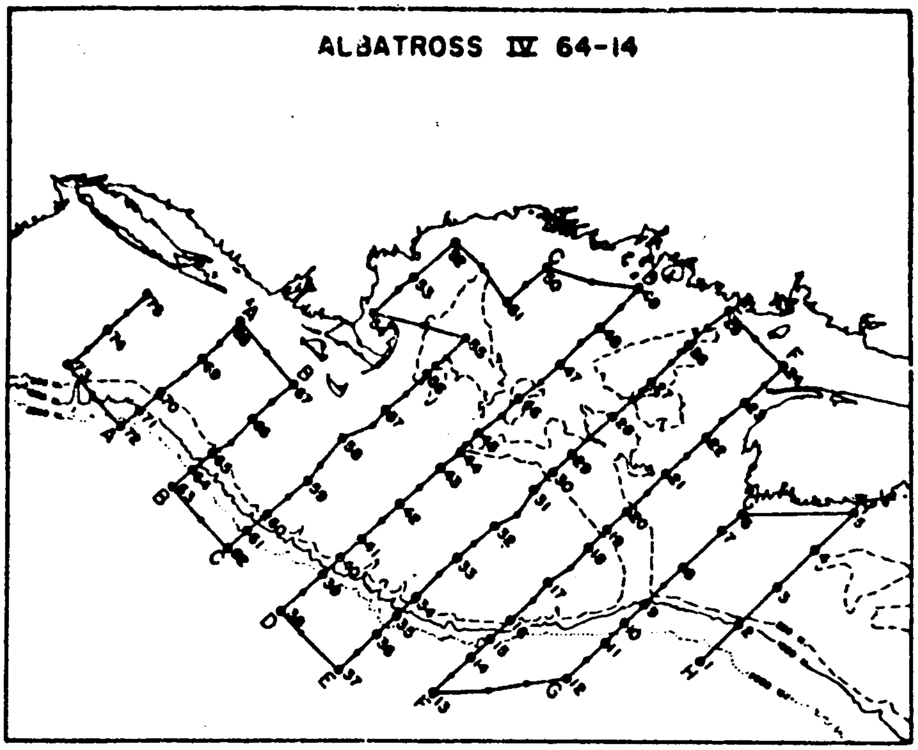
A more detailed survey of dissolved oxygen and hydrographic parameters in the Gulf of Maine and Georges Banks area was made by Colton, et al. (1968) in the months of March, May to June, September, and December. Figure 6-4 shows the location of all their stations. The distribution of dissolved oxygen for transects C, E and G is shown in Figures 6-5 to 6-8. For each transect two years of data are shown. Differences between years should be noted even though samples were taken at nearly the same time each month.

Phosphorus cycling has been studied in detail in the Gulf of Maine by Redfield, et al. (1937) and Ketchum and Corwin (1965). In both those studies the inorganic, the particulate, and the dissolved organic phosphorus were measured in order to understand changes in the various fractions during different seasons. The surface concentration of inorganic phosphate during May (1934) was considerably lower than the deeper water (Redfield, et al., 1937) (Table 6-9).

The values at the surface were higher near the mouth of the Bay of Fundy and on Georges Bank and lowest in the western central Gulf of Maine. The reverse was true at 60 m; at 120 m and 180 m the distribution was consistent.

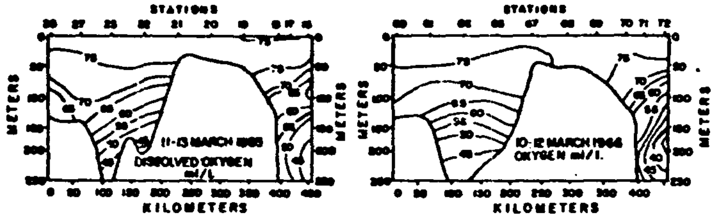
Rakestraw analyzed phosphates during August, 1932, for five stations in the Gulf of Maine and four on Georges Bank. He found low values (several tenths of a µg-at PO_4-P/l) throughout both areas, but nowhere did phosphate reach zero.

The relative amounts of inorganic phosphorus, particulate organic phosphorus, and dissolved phosphorus have been studied in the Gulf of Maine by Redfield, et al. (1937), Ketchum and Corwin (1965) and



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 6-4	Approximate Location of Stations Used by Albatross IV (Colton, *et al.*, 1968)



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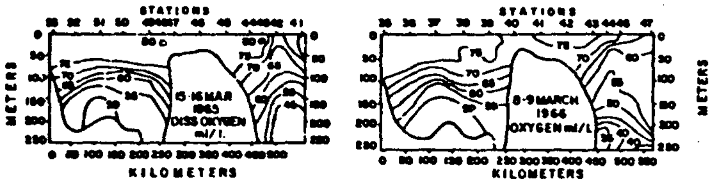

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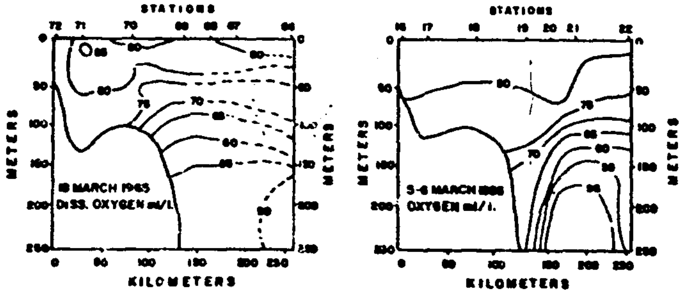
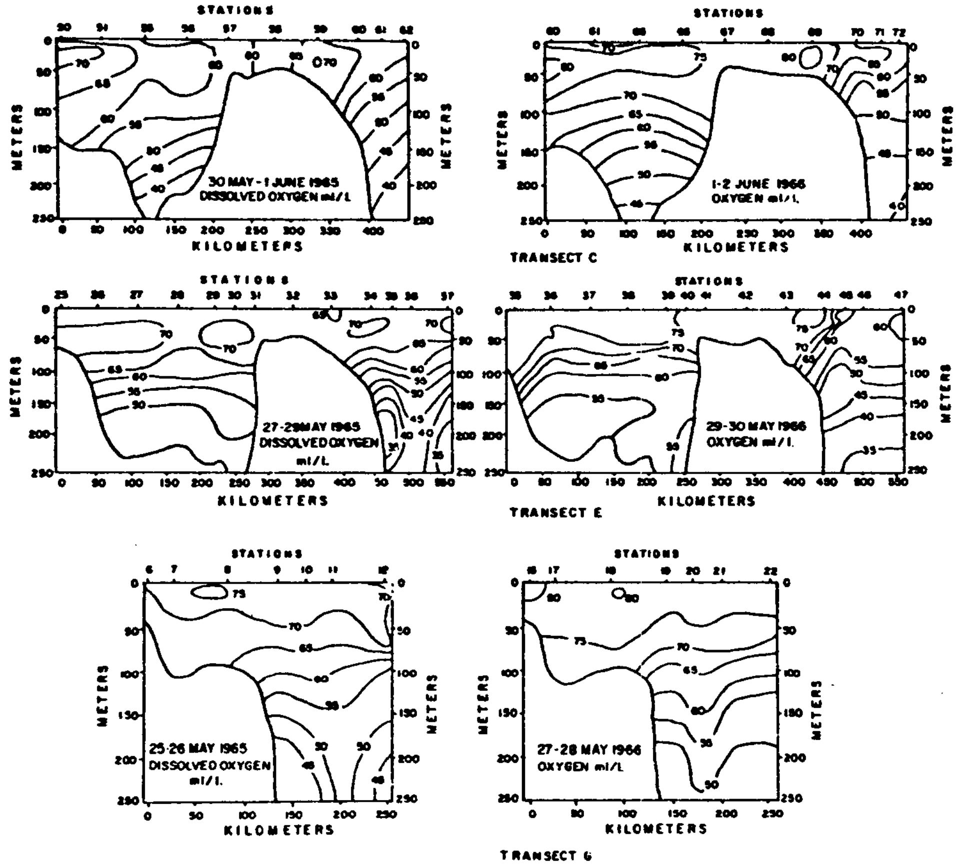


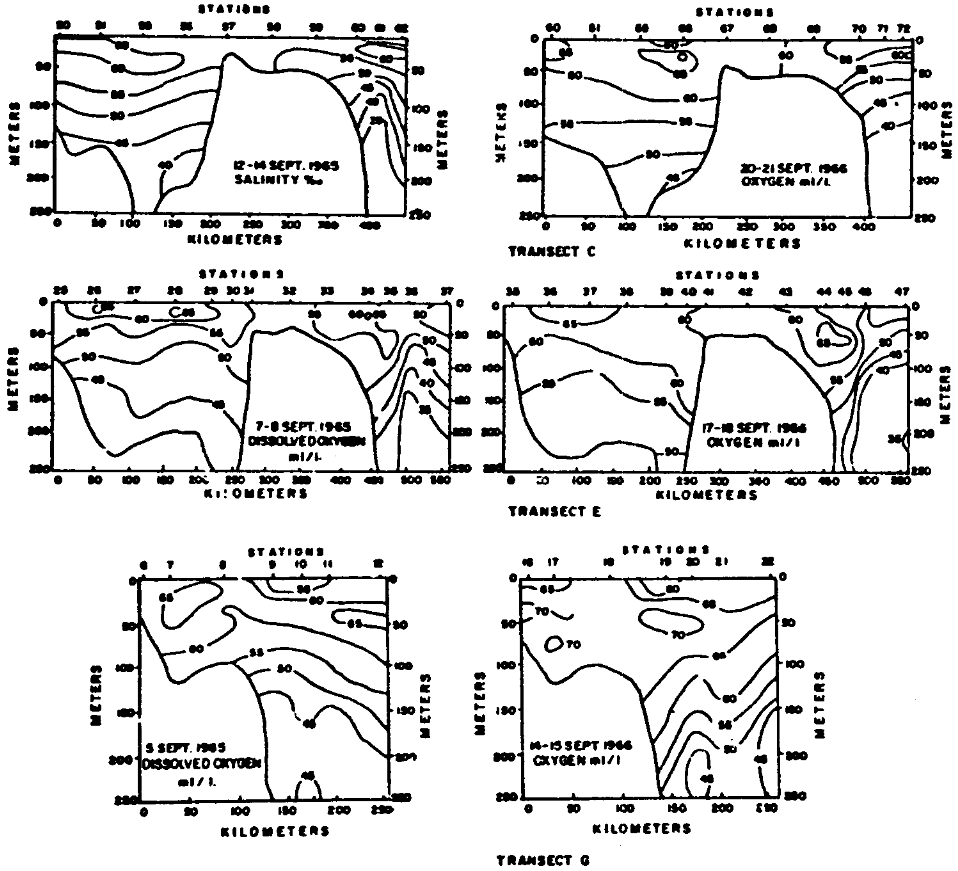
TRANSECT G

FIGURE 6-5 Dissolved Oxygen Concentration for Albatross IV - Transects C.E.G. March 1965-1966 (Colton, *et al.*, 1968)



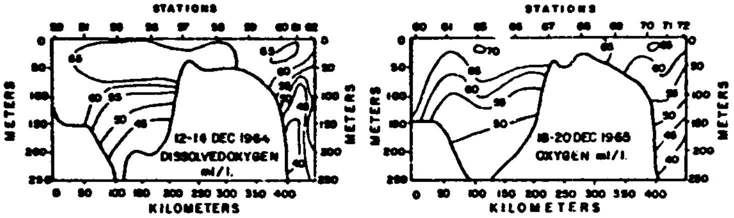
ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 6-6	Dissolved Oxygen Concentation for Albatross IV - Transects C.E.G. May 1965-1966 (Colton, et al., 1968)



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM | FIGURE 6-7 | Dissolved Oxygen Concentration for *Albatross IV* Transects C.E.G. September 1965-1966 (Colton, *et al.*, 1968)



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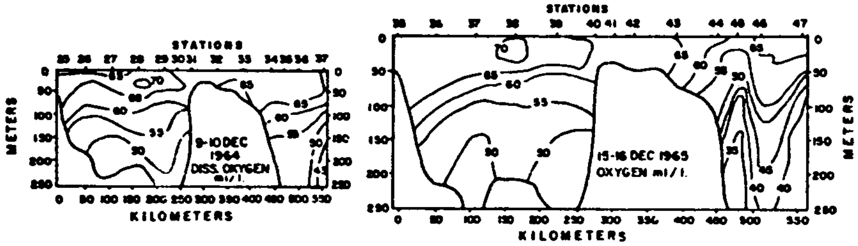

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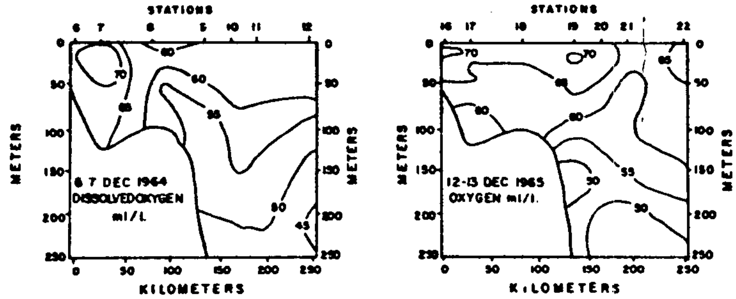


TRANSECT G

ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM

FIGURE 6-8

Dissolved Oxygen Concentration for Albatross IV-Transects C.E.G. December 1964-1965 (Colton, et al., 1968)

Table 6-9. Average concentrations of inorganic phosphate during May (Redfield, *et al*., 1937)

Depth	# of Samples Averaged	Average Inorganic Phosphate (μg-at PO_4-P/l)
Surface	21	0.44
60 m	21	0.91
120 m	14	1.2
180 m	11	1.3

Table 6-10. Average amounts of inorganic phosphorus, particulate organic phosphorus, and dissolved organic phosphorus for a station located in the Gulf of Maine at about 42°20'N, 69°33'W (Redfield, *et al*., 1937)

Depth (m)	Fraction	May 18 1935	Aug 21 1935	Nov. 8-9 1935	Feb 26 1936	May 14 1936
1-20	Inorg. P	0.34	0.27	0.39	1.1	0.14
(3 samples)	P. Org. P	0.19	0.15	0.13	0.05	0.18
	D. Org. P	0.15	0.47	0.30	0.07	0.16
30-60	Inorg. P	0.79	0.99	0.88	1.0	1.0
(3 or 4 samples	P. Org. P	0.13	0.07	0.07	0.04	0.07
samples)	D. Org. P	0.02	0.26	0.24	0.04	0.13
80-250	Inorg. P	1.4	1.3	1.2	1.2	1.5
(7 or 8	P. Org. P	0.05	0.04	0.06	0.04	0.05
samples)	D. Org. P	-0.01	0.21	0.34	0.09	0.17

Ketchum (1968) in order to better understand phosphate-uptake and cycling. All authors worked in the western Gulf of Maine about 50 to 80 km east of Cape Ann.

The data of Redfield, et al. (1937) are summarized in Table 6-10 and show the relative amounts of each component at different times during the year. Inorganic phosphorus reaches a maximum at the surface during February and a minimum during the late summer. It remains relatively high during the year in the water column between 30 to 60 m and below 80 m is essentially unchanged. Particulate organic phosphorus was highest during the spring and dropped off to a low during February for depths 0 to 60 m. No seasonal effect was noted below 80 m. Dissolved organic phosphorus reached a peak during late summer and fall at all depths.

Ketchum (1968) reported data collected during both the fall (1966) and the spring (1967) just before the bloom. At both times they found about 0.6 to 0.7 μg-at PO_4-P/l in surface waters increasing to over 1.0 μg-at PO_4-P/l below 150 m. They also related dissolved and particulate organic carbon, and chlorophyll to the phosphorus. They found that a large amount of the organic matter produced during the winter months accumulates as dissolved organic material because of a low turnover rate during the winter.

The distribution of nitrogen nutrients in the Gulf of Maine has been described by Rakestraw (1933, 1936), Redfield and Keys (1938). Nitrate values for August were reported by Rakestraw (1933) who found that surface values were low (several μg-at NO_3-N/l) but nowhere did he report zero nitrate values. He did find zero nitrite values at five of the nine stations sampled during August. Redfield and Keys (1938) measured ammonia during both May and September and found that ammonia occurred at minimal concentrations at the surface and at depths below 60 m. In May in the maximum concentration was about 3 μg-at NH_3-N/l between depths of 30 and 60 m. In September ammonia values were lower and were rather uniform at all depths.

Dissolved organic carbon was found to be high at the surface (80 to 120 μg-at/l) and then uniform from 50 m depth to the bottom (50 t0 70 μg-at/l) for three different diurnal stations off Cape Ann during September and April (Ketchum, 1967). No significant differences among the three observations at different times were apparent. The ratio of dissolved organic carbon to dissolved organic phosphorus was found nearly uniform in depth (275 to almost 600 m). This indicates a more rapid release of phosphorus from dissolved organic matter than particulate organic matter. The upper 20 m had an average C/P ratio of 112. The ratio increased to a maximum of 325 at 100 m and then slightly decreased with depth (Ketchum, 1967). Chlorophyll was found to be decomposed more rapidly than either phosphorus or carbon from the particulate matter (Ketchum, 1967).

Studies of suspended matter in the Gulf of Maine and adjacent waters can be divided into three types: (1) studies of total suspended matter concentrations by weight using a filtration method or by volume using the Coulter counter; (2) studies of particulate organic matter determined from particulate organic carbon (POC) or particulate phosphorus analyses; and (3) studies of water turbidity using a Secchi disk, beam transmissometer, or a photometer.

Spencer and Sachs (1970) and Ketchum (1967, 1968) studied the suspended matter in the central portions of the Gulf of Maine and Georges Bank during three cruises in September, 1966, March to April 1967, and October, 1967. The cruises in September and October were conducted when the water column was stratified whereas the March to April cruise was during isothermal conditions. The objective of this work was to determine the composition and origin of the suspended matter.

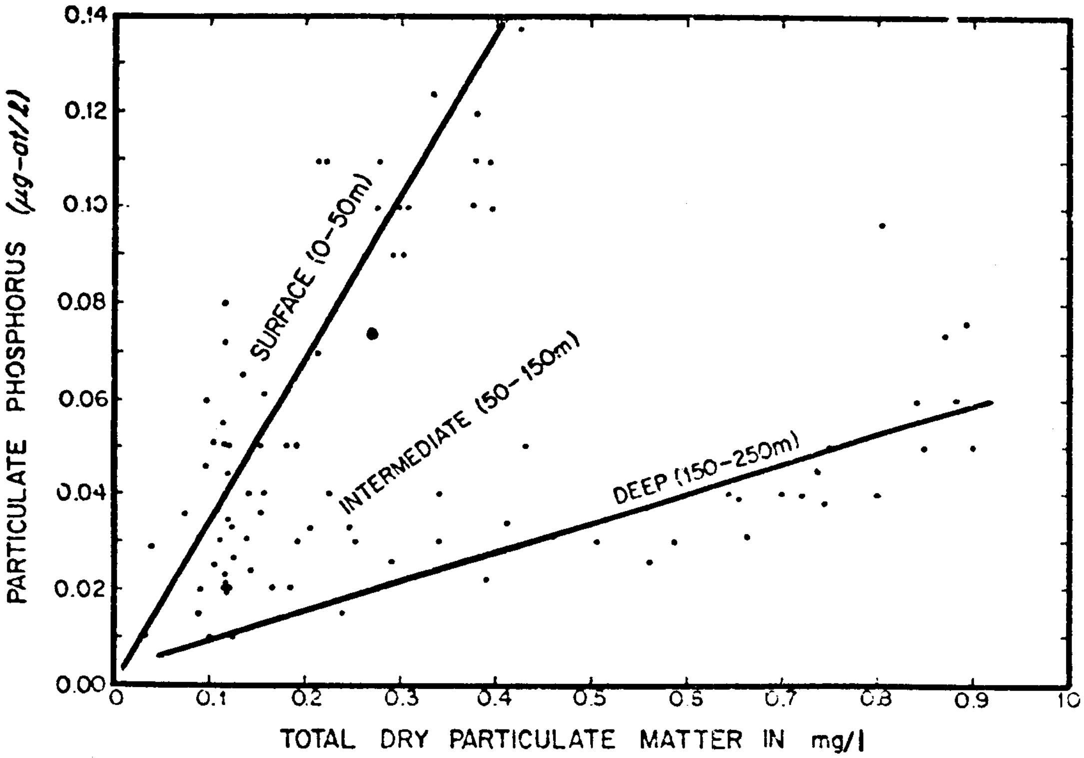
The approximate amount (3.7×10^{10}kg) of inorganic suspended matter was computed for the Gulf of Maine (Spencer and Sachs, 1970). This amount is an order of magnitude greater than the annual contribution of the North Atlantic coastal-plain rivers (Livingstone, 1965).

The surface distribution of suspended material showed a seasonal change in composition. An increase in particulate aluminum during the winter was caused by a decrease in the phytoplankton population in addition to the mixing of near-bottom resuspended sediment to the surface (Spencer and Sachs, 1970).

In general suspended matter decreased from the surface to about 50 m (the seasonal thermocline) then increased exponentially to the bottom. The source of suspended material was primarily biological productivity in the surface water and silicates at depth (Fig. 6-9). The causes for the resuspension of bottom sediments are probably storm activity (Armstrong, 1958), bottom currents (Ewing and Thorndike, 1965; Spencer and Sachs, 1970) and/or bottom organisms which rework the bottom muds (Rhodes, 1963). Average concentrations, as well as the percent of inorganic material for the Gulf of Maine proper, are summarized in Table 6-11).

6.4.2 SLOPE

Primary productivity in slope waters may be less than in waters closer to shore because of reduced levels of nutrients. In a study of the Atlantic off New England, Vaccaro (1963) observed steadily decreasing concentrations of nitrate during a cruise across the continental shelf and slope south of Montauk Point during January. Dissolved phosphate levels, however, did not change significantly with distance from the coast. Depth profiles showed no stratification in ammonia concentrations to 1200 m at the slope stations, rather the data varied considerably, from 0.50-3.44 μg A/l. Nitrite levels were usually, but not always depleted in deep waters (200+ m); most values were less than



ENVIRONMENTAL INVENTORY OF THE NORTH ATLANTIC CONTINENTAL SLOPE

TRIGOM	FIGURE 6-9	Covariation of Particulate Phosphorus and Total Particulate Matter (Spencer and Sachs, 1970)

Table 6-11a Average concentrations of suspended matter in the Gulf of Maine (in mg/kg of sea water) (Spencer and Sachs, 1970)

	September 1966	March 1967	October 1967	
			(47 mm)	(142 mm)
Surface (0-25 m)	0.30	0.13	0.31	0.35
Intermediate (25-150 m)	0.14	0.17	0.17	
Deep (150 m-bottom)	0.88	0.56	0.72	1.40

Table 6-11b Average concentrations of filter ash (500°C), as percent of total suspended matter (Spencer and Sachs, 1970)

	September 1966	March 1967	October 1967
Surface (0-25 m)	38	75	25
Intermediate (25-150 m)	90	90	68
Deep (150 m-bottom)	91	96	87

0.10 μg a/l. Menzel and Ryther (1964) examined the composition of particulate matter from samples at the same stations. Their data for deep water from the slope and Sargasso Sea show that phosphorus is rapidly regenerated during the decay of phytoplankton detritus since no detectable amounts of particulate phosphorus were found below the euphotic zone. Furthermore, the carbon:nitrogen ratio of suspended solids decreases with depth below the euphotic zone, indicating that detrital nitrogen is more resistant to microbial degradation.

The distribution of four nitrogen forms: nitrate, nitrite, ammonia, and urea were measured in slope waters between Cape Cod and Cape May (Remsen, 1971). His data, summarized in Table 6-12, show that urea may provide an important secondary source of nitrogen for phytoplankton populations during the summer when nitrate levels are depressed.

Ketchum, et al. (1958) examined the annual cycle of nitrogen and phosphorus in shelf and slope waters south of Long Island. Their data (Ketchum and Ryther, 1965), collected over two years, show that during the summer when density stratification is the greatest, nutrient levels are the lowest in surface waters and that in water below 100 m nutrient concentration correlates closely with density. By November density stratification has decreased and the concentrations of nitrogen and phosphorus have increased in surface waters, 0-50 m on the continental shelf and to depths below 100 m. At greater depths the concentrations of nitrate-nitrogen and inorganic phosphorus are not significantly affected by seasonal variations in primary productivity taking place in the waters above. At all times the samples from deep stations contained an excess of phosphorus, mean value 0.22 μ a/l, based on an N:P ratio of 15 in marine phytoplankton. This excess was less than that found in shallow inshore waters which ranged from 0.32 to 0.55 μ a/l. Finally, a plot of phosphorus vs. nitrogen of all deep water samples showed variations greater than that accounted for by analytical uncertainty. The authors assign this excess variation to inhomogeneity in the water masses that were not accompanied by related changes in temperature and salinity.

Further discussion of the relationship of nutrient enrichment in the surface slope water and primary productivity will be found in the chapter on phytoplankton (Chapter 7.1).

6.5 SEDIMENTS

The continental slope is a topographic boundary between the continents and the ocean basin and generally a region of slow sedimentation. Sounding profiles show two types of bottom: a steep, irregular upper slope, and a smooth lower slope, reflecting a change from an eroded upper surface to a slumped and debris covered lower region (Pratt, 1968).

The texture of the sediments on the slope between Nova Scotia and Cape Hatteras ranges from silty sand to silt and clay with the grain size decreasing with distance away from the shelf break (Schlee, 1973). Fora-

Table 6-12. Concentrations of inorganic nitrogen sources in offshore waters between Cape Cod and Cape May, September 1969[1] (μg A/1)

	0 m		25 m		50 m		100 m		1000 m	
	Concn	Per-cent	Concn	Per-cent	Concn	Per cent	Concn	Per-cent	Concn	Per-cent
Urea	0.69	39.8	0.91	61.8	0.61	6.7	0.81	5.1	0.71	3.7
Ammonia	0.83	47.4	0.46	31.4	0.38	4.1	0.40	2.5	0.85	4.4
Nitrite	0.03	1.6	0.04	2.7	0.06	0.6	0.04	0.2	0.03	0.1
Nitrate	0.04	2.2	0.06	4.1	8.05	88.6	12.99	93.2	17.57	91.8

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[1] From Remsen (1971). Data are averages from 6 stations

minifera and pteropod tests tend to increase with distance from the break so that the lower reaches of the slope consist to a greater extent of foraminiferal and pteropod sand and ooze. At greater depths, organic matter is more likely to be decomposed before reaching the bottom, so these sediments are more likely to be aerobic. At shallower depths, deposition rates are greater and the sediments are more reduced (Stanley, 1969).

Sediments with the high organic content occur in deep water (greater than 200 m) basins northwest of Georges Bank. The sediments are silts and clays with a median size less than 0.05 mm and an organic content between 3.0 and 3.4 percent. North of Great South Channel in water depths greater than 200 m there is an offshore (west to east) gradient in organic content. Organic matter in nearshore samples ranges from 2.2 to 3.4 percent, compared with 0.1 percent or less in the easternmost samples (Wigley, et al., 1975).

The Hudson Canyon is another area in which high organic carbon levels have been encountered. Many of the sediments there contain 3.0 to 3.5 percent organic carbon or 2 to 3 times that reported for adjacent areas on the continental slope (Keller, et al., 1973). This study of the canyon from the ALVIN has also revealed a net sediment transport down-canyon. High current velocities (20-27 cm/sec) occur periodically in the upper and central portions of the canyon. Beyond 800 m velocities are 2-5 cm/sec. Sediment texture changes from sand with well-rounded pebbles in the canyon head to silt and clayey silt to depths of 400 m and silty clay to the 2000 m isobath.

In the central portion of the canyon there is a blanket of very turbid water plus sediments of low cohesion and density indicating high rates of sedimentation. The biomass concentration is greater in the canyon than elsewhere in the North Atlantic, suggesting that nutrient rich material is going into the canyon from the continental shelf.

The U.S. Geological Survey, Woods Hole, has collected a large number of deep sediment cores off the Delaware coast in a project designed to examine slumping along the continental slope. At this writing no chemical analyses have been performed on any of these samples (Knebel, personal communication).

The National Marine Fisheries Service (NOAA) has extensively sampled the continental shelf and selected areas of the continental slope as a part of the Marine Ecosystem Analysis (MESA) project, and the Continental Margin Project (Hathaway, 1971). Collections were terminated in 1968 and the benthic groupings, biomass and density profiles of 669 samples of the MESA program will be published this fiscal year. Ten thousand samples to 4000 m are still in the process of being worked up for the continental shelf-slope program.

6.6 BIOCHEMISTRY

The reviewers found little information dealing with the impact of chemicals on biological systems in the continental slope, or on the effect and fates of the organisms involved. What is available is presented in chapters on phytoplankton (Chapter 7.1), zooplankton (Chapter 7.2), benthic biology (Chapter 7.3), environmental quality (Chapter 9.0), and submarine canyons (Chapter 8.0). Much of the current research in this area is being conducted under the Pollution Transfer and Biological Effects studies of the International Decade of Ocean Exploration (IDOE) and NOAA programs of impact assessments at ocean dumpsite areas.

While several investigators are studying the movement of pollutants from the coastal zone to the open ocean and examining their behavior in marine ecosystems, the only information dealing with the continental slope of the northeastern United States is found in the publications and reports cited previously. For example, among their observations on the distribution of chlorinated hydrocarbons in Atlantic Ocean organisms, Harvey, et al. (1974) saw no horizontal concentration gradients from the near shore to the open ocean, nor do their results show consistent evidence of food chain magnification. While not directly related to the slope, the fact that fish from Georges Bank contained ten times the chlorinated hydrocarbon concentrations of those from the Denmark Straits may indicate the existence of a horizontal concentration gradient in the sediments.

6.7 SUMMARY

The data available to us on the distribution of chemical constituents of the continental slope of the northeastern United States fall into essentially two categories. Nutrients such as nitrate and nitrogen, and certain pollutants, e.g. mercury and heavy petroleum residues, appear to be present in slope waters and sediments at levels below those found on the adjacent continental shelf, but above those of the waters of the Gulf Stream and Sargasso Sea, and in the sediments of the North Atlantic abyssal plain. Other compounds such as PCB's appear to be more widely dispersed and do not show a decrease with distance from the coast.

For those organic and inorganic pollutants that are present at elevated levels in the slope environment, neither the precise transport mechanisms nor the effect and fate of the material has been established. Thus, the mercury distribution observed by Fitzgerald and Hunt (1974) may be indicative of direct injection of mercury compounds from rivers and outfalls along the coastline, but could also be due to the fallout of atmospheric particulates and aerosols. The proportion of these geochemical processes must also be assessed. Estimates of the atmospheric input of a number of heavy metals to oceanic systems based on current urban air values and concentrations in the earth's crust have been formulated by Rice, et al. (1973).

Analyses of the surface microlayer have so far offered only limited insights into transport mechanisms. While the enrichment of heavy metals in this layer that has been observed in coastal waters may indicate atmospheric transport and deposition, the investigations of Duce and coworkers into bubble flotation phenomena indicate that this mechanism may be an important one in the transport of heavy metals to the air/sea interface. On the other hand, the absence of elevated concentrations in the surface layer does not necessarily mean that atmospheric transport is not important, as Fitzgerald and Hunt (1974) have pointed out.

In several of the references cited, the authors have noted the need to determine the chemical form as well as the total concentration of such pollutants as the heavy metals. Certainly this information is necessary in characterizing transport mechanisms of waterborne metals from the coastal zone, through the slope to the open ocean. Gibbs (1973), for example, analyzed the transport of Fe, Cu, Co and Mn in natural waters with respect to five possible processes. These included: (1) (a) dissolving of ionic species and inorganic associations, (b) complexing with organic molecules; (2) absorption on solids; (3) precipitation on solids (metallic coatings); (4) incorporation in solid biological materials; and (5) incorporation in crystalline structures. Thus there appears to be a need for additional information of the sort supplied by Fitzgerald and Hunt (1974) on the association of mercury with organic materials, and by Spencer and Sachs (1970) on the significance of the uptake and release of Cu, Zn, and Ni by plankton populations. As to the necessity of precisely determining the physicochemical species distribution of a substance, Bowen (1972) has argued:

> "It isn't always obvious that we need to know the chemical species of toxic elements. In a considerable number of cases, it can be shown that the rate of the uptake process by organisms or of the geochemical removal process is slow relative to the rate of equilibration among the various physicochemical species involved. It can also be shown that the stability of the biological form or the geochemical immobilized form is high compared to these. In that case, all one needs to know is the total concentration because the total concentration will be effective in driving the reaction toward the combined form. It is necessary that we know in some detail the process with reference to which the measurements are to be made; otherwise the speciation question is of considerable academic interest from the physicochemistry of the system, but it can't be shown to be necessary to the environmentalist."

In a relatively recent review of prospects in chemical oceanography, Anderson and Richards (1973) commented that it will be necessary to use

> "... chemical properties to characterize and

> trace water masses, to predict areas of primary and secondary organic productivity, and to understand the formation, dilution, and diagenisis of sediments."

The North Atlantic slope waters represent the convergence of several different water masses, e.g. Gulf Stream, Labrador Current, coastal waters. When differentiated by the usual oceanographic techniques, e.g. temperature and salinity, these various masses are often indistinguishable. However, their heterogeneity becomes readily evident when the distribution of trace nutrients and pollutants are accurately measured. Predictions of productivity areas can be made from the existing nutrient data, while considerably more reliable information is necessary to accurately characterize the geochemical fluxes controlling the formation and stabilization of sediments.

6.8 DATA GAPS

Chemical oceanography in the study area seems to be in developing stage, with a higher level of data collecting activity than in the recent past, but with few summarized or analyzed results. There is still a great deal of information needed on both naturally occurring chemical constituents and those originating from human activity. In only a few specific instances have there been published results of studies on the chemical constituents of even small portions of the slope region. Discussion of the effects of these constituents on the biota and of topics concerning the biochemistry of the microenvironment, particularly in the deep water, is limited by the lack of analyzed data, but is treated, where possible, in other sections of this report.

6.9 REFERENCES

Anderson, N.R. and F.A. Richards. 1973. Prospects in chemical oceanography. Limnol. Oceanogr., 8: 815-817.

Apollonio, S. and H.H. Applin, Jr. 1972. An atlas of the distribution of inorganic nutrients in coastal waters of the western Gulf of Maine. Me. Dept. of Mar. Resour., W. Boothbay Harbor, Me. 130 p.

Armstrong, F.A.J. 1958. Inorganic suspended matter in sea water. J. Mar. Res., 17: 23-24.

Bewers, J.M., B. Sundby, and P.A. Yeats. 1975. Trace metals in the waters overlying the Scotian Shelf and Slope. Paper presented at ICES 63rd Statutory Meeting, Montreal, Sept. 1975.

Bidleman, T.F. 1975. (personal communication, 1975) Dept. of Chemistry, Univ. of South Carolina.

Bowen, V.T. 1972. Key to progress on national problems in analytical chemistry. Meinke, W.W. and J.K. Taylor (eds.), NBS Spec. Publ. 351, 1 422.

Colton, J.B., Jr., R.R. Marak, S. Nickerson, and R.E. Stoddard. 1968. Physical, chemical, and biological observations on the continental shelf, Nova Scotia to Long Island, 1964-66. Bur. of Commer. Fish., Woods Hole, Mass., U.S.F. and W.S Data Rep. No. 23.

Ewing, M. and E.M. Thorndike. 1965. Suspended matter in deep ocean water. Science, 147: 1291-1294.

Fitzgerald, W.F. and C.D. Hunt. 1974. Distribution of mercury in the surface microlayer and in subsurface waters of the northwest Atlantic Ocean. J. Rech. Atmos.: 629-637.

Fitzgerald, W.F. and W.B. Lyons. 1973. Organic mercury compounds in coastal waters. Nature, 242-452.

Gran, H.H. 1933. Studies on the biology and chemistry of the Gulf of Maine, II: Distribution of phytoplankton in August, 1932. Biol. Bull. 64: 159-181.

Gran, H.H. and T. Braarud. 1935. A quantitative study of the phytoplankton in the Bay of Fundy and the Gulf of Maine (including observations on hydrography, chemistry, and turbidity). J. Biol. Bd. Can., 1: 279-467.

Harvey, G.R., W.G. Steinhauer, and J.M. Teal. 1973. Polychlorobiphenyls in North Atlantic ocean water. Science, 180: 643-644.

Harvey, G.R., H.P. Miklas, V.T. Bowen, and W.G. Steinhauer. 1974. Observations on the distribution of chlorinated hydrocarbons in Atlantic Ocean organisms. J. Mar. Res., 32: 103-118.

Hathaway, J.C. 1971. Samples collected and analytical data. Continental Margin Program, Atlantic Coast of the United States, vol. 2. WHOI Ref. No. 71-15, Woods Hole Oceanogr. Inst., Woods Hole, Mass.

Keller, G.H., D. Lambert, G. Rowe, and N. Staresinc. 1973. Bottom currents in the Hudson Canyon. Science, 180: 181-183.

Ketchum, B.H. 1967. Biological, chemical, and radiochemical studies of marine plankton. WHOI Tech.,Rep. 67-27. 119 p.

_________. 1968. The phosphorus cycle and productivity of marine phytoplankton. WHOI Contrib. No. 2146.

Ketchum, B.H. and B. Corwin. 1965. The cycle of phosphorus in a plankton bloom in the Gulf of Maine. Limnol. Oceanogr., 10 (Supplement): R148-R161.

Ketchum, B.H. and J.H. Ryther. 1965. Biological, chemical, and radiochemical studies of marine plankton. WHOI Ref. No. 65-47, Woods Hole Oceanogr. Inst., Woods Hole, Mass.

Ketchum, B.H., R.F. Vaccaro, and N. Corwin. 1958. The annual cycle of phosphorus and nitrogen in the New England coastal waters. J. Mar. Res., 17: 282-301.

Knebel, H. 1975. (personal communication, 1975). U.S. Geol. Survey, Woods Hole, Mass.

Livingstone, R. 1965. Preliminary bibliography with KWIC index on the ecology of estuaries and coastal areas of eastern U.S. Spec. Sci. Rep., Fish. No. 507, U.S. Fish and Wildlife Serv.

Menzel, D.W. and J.H. Ryther. 1964. The composition of particulate organic matter in the western North Atlantic. Limnol. Oceanogr., 9: 179-186.

National Science Foundation-IDOE. 1974a. Atmospheric pollutant transport and deposition on the sea surface. Grant GX-33777.

_________. 1974b. Input and loss of petroleum and chlorinated hydrocarbons to the deep North Atlantic Ocean. Grant GX-35212. Unpubl. rep. cited by permission of J.W. Farrington, co-investigator.

Pratt, R.M. 1968. Atlantic continental shelf and slope of the United States: physiolography and sediments of the deep-sea basin. U.S.

Geol. Surv. Prof. Pap., No. 529-B, 44 p.

Rakestraw, N.W. 1932. Phosphorus and nitrogen in the neritic waters of the Gulf of Maine. Int. Rev. Hydrobiol., v. 27, no. 1: 151-160.

________. 1933. Studies of the biology and chemistry of the Gulf of Maine. In: Chemistry of the waters of the Gulf of Maine in August, 1932. Biol. Bull., 64: 149-158.

________. 1936. The occurrence and significance of NO_3 in the sea. Biol. Bull., 71: 133-167.

Redfield, A.C. and A.B. Keys. 1938. The distribution of ammonia in the waters of the Gulf of Maine. Biol. Bull., v. 74, no. 1: 83-92.

Redfield, A.C., H.P. Smith, and B.H. Ketchum. 1937. The cycle of organic phosphorus in the Gulf of Maine. Biol. Bull., 73: 421-441.

Remsen, C.C. 1971. The distribution of urea in coastal and oceanic waters. Limnol. Oceanogr., 16: 732.

Rhodes, D.C. 1963. Rates of sediment reworking by Yoldia limatula in Buzzards Bay, Mass. and Long Island Sound. J. Sediment. Petrol., 33: 723-727.

Rice, H.V., G.C. McLeod, and D.A. Leighty. 1973. The effects of some trace metals on marine phytoplankton. CRC Crit. Rev. in Microbiol., v. 3, no. 1: 27-49.

Schlee, J. 1973. Atlantic continental shelf and slope of the United States: sediment texture of the northeastern part. U.S. Geol. Surv. Prof. Pap. No. 529-L, 64 p.

Spencer, D.W. and P.G. Brewer. 1969. The distribution of copper, zinc, and nickel in sea water of the Gulf of Maine and the Sargasso Sea. Geochim. Cosmochim. Acta, 33: 325-339.

Spencer, D.W. and P.L. Sachs. 1970. Some aspects of the distribution, chemistry, and mineralogy of suspended matter in the Gulf of Maine. Mar. Geol., 9: 117-136.

Stanley, D.J. 1969. Atlantic continental shelf and slope of the United States: color of marine sediments. U.S. Geol. Surv. Prof. Pap. No. 529-D, 15 p.

Theroux, R.B. (personal communication, 1975) Nat. Mar. Fish. Serv., Woods Hole, Mass.

TRIGOM. 1974. A socio-economic and environmental inventory of the North Atlantic region. Prepared for the Bur. Land Manage., Washington, D.C. 4,900 p., 8 v.

Vaccaro, R.F. 1963. Available nitrogen and phosphorus and the biochemical cycle in the Atlantic off New England. J. Mar. Res., 21: 284-301.

Wallace, G.T. and R.A. Duce. 1975. Concentration of particulate trace metals and particulate organic carbon in marine surface waters by a bubble flotation mechanism. Mar. Chem., 3: 157.

Wigley, R.L., R.B. Theroux, and H.E. Murray. 1975. Deep-sea red crab, Geryon quinquedens, survey off northeastern United States. Mar. Fish. Rev., 37: 1-21.