NOAA Technical Memorandum NMFS-F/NEC-24

Residual Drift and Residence Time of Georges Bank Surface Waters with Reference to the Distribution, Transport, and Survival of Larval Fishes

John B. Colton, Jr., and Jacquelyn L. Anderson

Narragansett Lab., National Marine Fisheries Serv., Narragansett, RI 02882

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldridge, Secretary
National Oceanic and Atmospheric Administration
John V. Byrne, Administrator
National Marine Fisheries Service
William G. Gordon, Assistant Administrator for Fisheries
Northeast Fisheries Center

Woods Hole, Massachusetts

June 1983

ABSTRACT

Our conception of surface circulation in the Georges Bank area and its effect on the transport and survival of resident ichthyoplankton populations is reexamined, using trajectories of satellite-tracked buoys and water mass distributions inferred from satellite infrared imagery. Buoy trajectories evidenced a seasonal development of the Georges Bank gyre and a gradual increase in surface water residence times from winter (maximum 35 days) to late summer (>100 days). Comparisons of buoy, wind, and wind-driven current velocities revealed little correlation between buoy movement and wind. The movement of buoys off the shelf was often associated with warm-core ring or Gulf Stream meander-induced shelf water entrainment, while at other times rapid and direct cross-shelf movement was not associated with these features.

Shifts in distributions and decreases in numbers of larval fish cohorts were not associated with any pronounced residual drift patterns indicated by buoy trajectories, and in no case did advective processes appear to be linked to larval fish mortality estimates.

In the Appendix, a comparison of Nantucket Island and Georges Shoals wind velocity data is made to determine the feasibility of using wind adjustment factors to extrapolate Nantucket Island wind observations to Georges Bank. The wind statistics indicate that speed, but not direction adjustment factors, are required for these extrapolations. Examples of applying wind adjustment factors are given and their utility is discussed.

TABLE OF CONTENTS

Preceding page blank

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

LIST OF FIGURES (Cont.)

LIST OF TABLES

INTRODUCTION

Our understanding of surface circulation in the Gulf of Maine and over Georges Bank is based in large part on the conclusions of Bigelow (1927) following a detailed study and thoughtful interpretation of drift bottle recoveries, tidal current measurements, dynamic computations, wind-driven currents, and the distribution of temperature, salinity, and plankton. Bigelow's portrayal of the development of a two-gyre system (the Gulf of Maine cyclonic eddy and the Georges Bank anticyclonic eddy) conformed well with subsequent interpretations of circulation based on observations of the distribution and drift of zooplankton populations by Redfield (1939, 1941), Redfield and Beale (1940), and Clarke, Pierce, and Bumpus (1943), and of fish eggs and larvae by Walford (1938).

Later interpretations and summaries of drift bottle data by Day (1958), Bumpus and Lauzier (1965), and Bumpus (1973, 1976) added some detail to earlier descriptions of circulation and demonstrated marked seasonal and annual differences in circulation patterns. These studies showed that Bigelow's (1927) July-August pattern of a relatively closed circulation appears to evolve with the seasons as a result of vernal warming and the consequent formation of density structure. The residual circulation on Georges Bank, as measured using long-term moored current meter, aircraft-tracked surface drifter, and satellite-tracked drogue observations made between 1975 and 1979, has been summarized by Butman et al. (1982). These recent direct observations evidence a quasipermanent clockwise circulation around Georges Bank, but indicate that the circulation is not completely closed and that considerable variability occurs in the trajectory of an individual water particle.

Several points should be kept in mind regarding inferences concerning residual drift based on drift bottle studies which in large part form the basis of our interpretation of circulation in the Gulf of Maine-Georges Bank area: (1) Because pronounced seasonal and annual variations are observed in oceanographic and meteorological variables associated with circulation, it is reasonable to expect pronounced seasonal and annual cycles in the velocity and pattern of circulation. (2) Intermittent flow, which can exceed average flow by a factor of 10 or more, is a fundamental characteristic of continental shelf circulation, so that the "average" can be expected to occur infrequently, if at all (Hansen 1977). (3) The time between release and recovery is the maximum that any bottle would have drifted at sea. The speed of drift based on this period is a minimum value which may be much smaller than the actual speed of drift (Waldichuck 1963). (4) Interpretation of drift bottle data is understandably biased very strongly by those bottles that happen to move shoreward and thereby are recovered. For example, of 14,444 bottles released between 1948 and 1962, inclusive, in the Georges Bank area (40°N-41°N, 66°-68°W), only 423 (2.9%) were recovered and 17% of these were recovered from overseas (Bumpus and Lauzier 1965). Peak recovery was in the spring (March-May), but this amounted to only 5.5% of those released. At other seasons, the recovery rate was 1% or less with the greater proportion of bottles being recovered from overseas. This offshore flow from Georges Bank is not readily discernible in the quarterly charts of circulation [Plates 7 and 8 of Bumpus and Lauzier (1965)], although in this connection Bumpus (1976) cautioned,

> "Because there are so few returns of drift bottles and sea-bed drifters from Georges Bank, one cannot help but suspect that a great number are carried offshore rather than drifting to the west to strand. Certainly when one views the results of some drogued drifting buoy experiments . . . , one obtains the feeling that there are ample opportunities for exchanges between Georges Bank water and slope water."

The likelihood of appreciable offshore movement of Georges Bank surface waters has stimulated our interest in the question of how populations of fishes maintain themselves under conditions conducive to the loss of spawning products (eggs and larvae). Several attempts have been made to elucidate the role of circulation on the drift and survival of ichthyoplankton in the Georges Bank area. Walford (1938), on a basis of drift bottle recoveries and the distibution of haddock (Melanogrammus aeglefinus) eggs and larvae, concluded that in 1931 eggs and larvae were retained in a clockwise gyre and carried northward to Georges Shoals with no significant loss to other regions, while in 1932, the circulation was such that large numbers of larvae were carried into deep water to the north and south of the bank where conditions were unfavorable for survival. Colton and Temple (1961) inferred from observations on the time and location of spawning of haddock and Atlantic herring (Clupea harengus harengus) and the drift of bottles and transponding buoys that with the exception of midsummer when the Georges eddy is most pronounced, surface drift is offshore in direction of slope water and that under average conditions most fish larvae were carried away from Georges Bank.

We emphasize that these inferences regarding the transport of fish eggs and larvae are based in large measure on drift bottle returns and movements of transponding buoys rather than on the drift of ichthyoplankton cohorts. A conspicuous and significant aspect of the larval fish distribution in the Georges Bank area is the almost total segregation of coastal (boreal) and oceanic (tropical and subtropical) species north and south of the coastal/slope water front which coincides approximately with the 100-200 m isobaths (Colton and Byron 1977). Oceanic species of larval and juvenile fishes are frequently collected over Georges Bank and in the Gulf of Maine following intrusions of slope water (Colton 1961; Colton and St. Onge 1974), but young stages of boreal coastal species have not been observed in the slope water area or in entrained shelf water, albeit sampling in areas south of the 200-m isobath (especially in entrained shelf waters) has been infrequent.

Since about the middle 1970's, there has been a resurgence of interest in continental shelf oceanography (especially circulation), partly as a result of public concern over possible effects of impending offshore gas and oil exploration and production, and also due to improved monitoring capabilities through technological advances in data sensing, logging, and telemetry. The remote sensing capabilities of satellites provide more frequent and synoptic coverage of sea surface conditions by means of infrared (IR) and visible imagery, radar, and altimetry. Satellite coverage has proved to be particularly useful for monitoring surface temperatures, position of ocean fronts and eddies, and large-scale water mass movements. Gulf Stream rings and meanders are ubiquitous features of these data, and as a result, we now have a much better understanding and appreciation of the magnitude, complexity, frequency, and causes of coastal and oceanic water mass exchange. This imagery has been especially informative regarding the frequency and extent of shelf water entrainment from the western Scotian Shelf and along the southern edge of Georges Bank generated by the presence of warm-core rings and Gulf Stream meanders.

In this paper, we attempt to update and refine our conception of surface circulation in the Georges Bank area and its probable effect on the drift and survival of resident ichthyoplankton populations on a basis of these recent and innovative monitoring efforts. Our main sources of information, in addition to satellite imagery, were seasonal observations of near-surface circulation, based on the trajectories of satellite-tracked buoys and the distribution of larval fishes during roughly similar time periods. We emphasize here that the two sets of data were not obtained concurrently or with the objectives of this study in mind, but our interest in the problem prompted us to examine this additional information in hopes of elucidating the role of residual drift on larval transport and survival.

DATA SOURCES

Satellite-Tracked Buoy Experiments

Drogued buoys were deployed on Georges Bank during four discrete Lagrangian experiments commencing in December 1978 and March, May, and August 1979 as part of the New England Outer Continental Shelf Physical Oceanography Program sponsored by the U.S. Bureau of Land Management. Each experiment incorporated 4-6 buoys and lasted 8-10 weeks. The field work and instrumentation were provided by Raytheon Ocean Systems Company and data processing and analysis by EG&G Environmental Consultants. The COSRAMS buoys used in these studies were manufactured by Polar Research Corp. and were fitted with 2 x 11-m window shade drogues centered at a depth of 11 m, and with drogue tension and temperature sensors. Positions accurate to a few kilometers (Richardson, Wheat, and Bennett 1979) were determined from the Doppler shift of the signals received by Nimbus 6 satellite. Position errors were further reduced by eliminating suspect fixes and through the use of a cubic spline function to compute buoy positions and velocities evenly spaced in time. Buoy specifications and data editing and processing are given by EG&G (1979a,b,c; 1980) and Richardson, Wheat, and Bennett (1979). Computer outputs of edited data (four evenly spaced daily positions and temperatures provided by EG&G Environmental Consultants) were used to compute the daily mean buoy positions and water temperatures utilized in this study. Dates of buoy positions are given in terms of the consecutive day of the year (Julian Day). A table is provided (Table 1) to convert these numbers to day of the month.

The deficiencies and technical problems associated wih the use of drogued surface buoys have been discussed both in terms of undetected drogue loss during long-term experiments (Richardson, Cheney, and Mantini 1977; Richardson, Wheat, and Bennett 1979) and of the utility of window-shade or parachute drogues in reducing velocity and direction errors due to windage and other slippage effects (Kirwan et al. 1979). Although the small-scale features of circulation are not fully resolved by Lagrangian tracking, it has proved to be an economical and effective method and has found wide acceptance in oceanographic research to determine the broadscale features of ocean circulation.

Shelf/Slope Water Front, Gulf Stream North Wall, and Gulf Stream Ring Positions

The NOAA National Earth Satellite Service (NESS) produces a weekly experimental "Gulf Stream Analysis Chart" series based on thermal IR imagery and showing the position of thermal fronts, shelf, slope, and Gulf Stream water, and warm and cold-core Gulf Stream rings. The NMFS Atlantic Environmental Group (AEG) uses these charts to monitor the position of warm-core rings and the location of the shelf/slope water front and the Gulf Stream north wall along 12 standard bearing lines from selected points from Cape Romain, S. C., to the Gulf of Maine. We have used published data (Hilland 1981; Fitzgerald and Chamberlin 1981) as well as unpublished summaries provided by AEG in an effort to elucidate the relationship of these oceanographic variables to the trajectories of satellite-tracked buoys.

Wind and Wind-Induced Current Regimes

Meteorological data used in this study were obtained from the National Climatic Center in Asheville, N. C., and included daily resultant wind speeds and directions based on three hourly observations (six per day) taken at Nantucket Island during the period of the satellite-tracked buoy experiments (December 1978-December 1979). Wind speed adjustment factors were used to extrapolate Nantucket Island wind values to Georges Bank. The techniques used in determining wind adjustment factors, examples of their application, and the utility of their use are presented and discussed in the Appendix. The adjusted wind data were then converted to wind-driven current values which were estimated to be 1.5 or 3.0% of the wind speed along a wind direction of +15° (Bigelow 1927; Haight 1942; Godshall et al. 1980).

Ichthyoplankton Distribution

The distribution of larval fishes at the time of and subsequent to the satellite-tracked buoy experiments was obtained on plankton surveys conducted in continental shelf waters between Cape Hatteras and Nova Scotia as part of the MARMAP (Marine Resources Monitoring, Assessment, and Prediction) Program of the National Marine Fisheries Service (Sherman 1980). The sampling gear (61-cm bongo nets) and method of tow (double oblique, 1.5-2.0 knot tows, to a maximum depth of 200 m) have been described by Smith and Richardson (1977) and Posgay and Marak (1980). For this study, we have used collections obtained from 0.505-mm mesh nets.

The larval fishes were grouped by 5-mm length classes, and cohorts from contiguous cruises were coupled on a basis of reported growth rates of ca. 0.14-0.25 mm/day for haddock (Walford 1938; Laurence 1974), Atlantic cod (Laurence et al. 1981), Atlantic herring (Boyar et al. 1973; Lough et al. 1980), and redfish (Anderson and Akenhead 1981). We used an all-inclusive growth rate of 5.0 mm/month for all species and developmental stages.

RESULTS

Buoy Trajectories and Residence Times

Experiment I

Six buoys were deployed on Georges Bank during 13-29 December 1978. The tracks of these buoys (Figure 1) have been described in detail by EG&G (1979a). Briefly, all buoys initially followed clockwise trajectories. Three of the buoys (34, 202, and 304) then moved directly off the Bank, across the slope water zone, and were entrained in easterly moving Gulf Stream water. After crossing the shelf break (200-m contour), Buoys 132, 227, and 234 were carried southwesterly in slope water before being retrieved (Buoy 234) or entrained by the Gulf Stream in the vicinity of Cape Hatteras. Daily buoy velocities and temperatures and Nantucket Island wind vectors during the course of this experiment are shown in Figure 2. Marked variations in buoy velocities and abrupt changes in surface temperatures coincided with times when the buoys were moving from one water mass to another.

Estimated residence times for Georges Bank surface waters based on observed buoy trajectories are summarized in Figure 9. Georges Bank was delineated by the 200-m contour to the north, east, and south, and by meridian 71°W. Residence times were based on the time in days for buoys to reach these arbitrary boundaries from various locations along their trajectories. Residence times were least (<5 days) along the eastern and southern edges of Georges Bank and greatest (>30 days) in the Great South Channel area.

Experiment II

Five buoys were deployed on Georges Bank during 23-28 March 1979. Buoy 416, the most southern release (40°56'N, 68°09'W), stopped transmitting 1 day after deployment. A second buoy (332) was retrieved by a fisherman on 21 May 1979. The tracks of the operational buoys (Figure 3) have been described in detail by EG&G (1979b). Buoy 421, deployed off the Northeast Peak, moved rapidly north into the Gulf of Maine. Buoy 405, launched in the Great South Channel, moved northeast and isobath parallel for about 35 days before moving north into the Gulf of Maine. Buoy 510, deployed at the 200-m contour north of Georges

Shoals, completed a counterclockwise loop into the Gulf of Maine before reentering the northern edge of Georges Bank and moving isobath parallel to the east and then south crossing the 200-m contour at approximately 66°W. This buoy then completed two counterclockwise loops before moving east and then north into the Northeast Channel. Buoy 332 moved in a clockwise direction, but remained in the Georges Shoals area and within 60 km of its deployment position before being retrieved 54 days later. As in Experiment I, marked variations in buoy velocity and water temperatures were associated with different water mass regimes.

Daily buoy velocities, temperatures, and Nantucket Island wind vectors during the course of this experiment are shown in Figure 4. The estimate of residence times of Georges Bank surface waters was not particularly instructive as the March deployment was biased to the north and not amenable to such an interpretation.

Experiment III

Five buoys were deployed in the Georges Bank-Great South Channel area during 30 May-2 June 1979. A detailed summary of the tracks followed by these buoys is given by EG&G (1979c). Buoy 556 stopped transmitting on 26 July, Buoy 234 was picked up by a fishing boat on 6 August, and Buoy 620 was retrieved by EG&G on 14 July. The buoy trajectories in this experiment (Figure 5) agree with the generally accepted circulation pattern in that they evidence a clockwise gyre over Georges Bank, a return (northerly) flow along the eastern side, and an outflow (southerly) along the western side of the Great South Channel before turning west around Nantucket Shoals. In addition, the trajectories of Buoy 556 and 433 indicate a westerly drift along the southern side of Georges Bank and across the Great South Channel before turning northwesterly towards Nantucket Shoals and Marthas Vineyard, then westerly along the continental shelf off Southern New England.

Buoy 620, which was deployed on the western side of the Great South Channel, moved south and then west and northwest around Nantucket Shoals before turning southwest to the point of recovery south of Long Island (40°24'N, 72°40'W). Buoy 616, which was released on the east side of the Great South Channel, moved north to approximately 42°N in 30 days and then into the Gulf of Maine where it followed a complex gyral drift pattern with a net northward and then southward flow before turning east and reentering the northern edge of Georges Bank at approximately 66°30'W. Buoy 556, which was launched over north-central Georges Bank, moved southwesterly across Georges Shoals and then westerly parallel to the bathymetry crossing the base of the Great South Channel and then northwesterly onto Nantucket Shoals. Buoy 443, deployed on eastern Georges, moved southwesterly and then westerly to 72°W before turning south and crossing the 200-m contour at which time it moved to the east for approximately 20 days before moving south into slope water. Buoy 234, which was released on Georges Shoals, followed a clockwise path along the 50-m isobath before being retrieved by a fisherman approximately 85 km northeast of its deployment position.

Daily buoy velocities, water temperatures, and Nantucket Island wind vectors during the course of this experiment are shown in Figure 6. Estimated residence times of Georges Bank surface waters based on observed buoy trajectories are summarized in Figure 9. In contrast to Experiment I, residence times were least (<10 days) to the west and northwest of Georges Bank and greatest (approximately 70 days) along the eastern edge of the Bank.

Experiment IV

Four buoys were deployed on Georges Bank during 15-19 August 1979. The tracks of these buoys (Figure 7) have been described in detail by EG&G (1980). Buoy 735, which was deployed at the 100-m contour on the north flank of central Georges, was retrieved on the Northeast Peak by a fisherman on 26 August after having moved east and southeast. Buoy 620, which was deployed on the northwest corner of the Bank, moved similarly to Buoy 735 and then completed a clockwise loop around the Bank, including a counterclockwise excursion into the Gulf of Maine north of the Great South Channel before reentering the Bank and following its original easterly path along the northern edge and exiting the Bank via the Northeast Channel.

Buoy 727, which was deployed on the northeast corner of Georges Shoals (41°47'N, 67°00'W), drifted slowly to the southwest corner of Georges Shoals before moving to the northeast edge of Georges Bank (41°30'N, 68°30'W). Satellite positions were not obtained from Day 278 to Day 291, but apparently Buoy 727 then made a clockwise circuit around Georges Shoals before exiting the continental shelf south of Marthas Vineyard (70°30'W). Buoy 703, which was deployed just south of Georges Shoals (41°00'N, 67°40'W) apparently made a clockwise circuit of the Bank, although estimated buoy positions between Day 250 and Day 260 indicate a direct northeast track across Georges Shoals to the Northeast Peak. From this position, Buoy 703 moved in southwesterly direction and exited the shelf at 67°25'W. Consequent movement was across the slope-water zone and entrainment in the easterly flowing Gulf Stream.

Daily buoy velocities and temperatures and Nantucket Island wind vectors during the course of this experiment are shown in Figure 8. Estimated residence times of Georges Bank surface waters based on observed buoy trajectories are summarized in Figure 9. Residence times were greatest (>100 days) over east central Georges Bank (reflecting the tack of Buoy 727) and least (<5 days) around the periphery of the Bank and along the shelf edge south of Nantucket Shoals.

Effect of Wind on Buoy Trajectories

Visual inspection of buoy and wind velocity stack plots reveals little correlation between buoy movement and Nantucket Island winds. This dissimilarity in wind and current velocity patterns was most apparent during periods when the buoys were in the proximity of the shelf/slope front or entrained in slope or Gulf Stream waters. To further elucidate the relation of wind-driven current to buoy drift, we compare in Figures 10 and 11 progressive vector plots of wind-induced surface currents and buoy trajectories during periods when Buoy 34 was moving in a southerly direction across Georges Bank (Exp. I, 13 December 1978-30 January 1979), and Buoy 405 was moving in a northerly direction from the Great South Channel area into the Gulf of Maine (Exp. II, 31 March-1 June 1979). Wind driven current values were based on predicted Georges Bank winds determined from Nantucket Island wind speed adjustment factors (described in the Appendix) and were estimated to be 1.5% (Exp. I) or 3.0% (Exp. II) of the adjusted wind speed along a wind direction of +15°.

During the first week after release (Exp. I, Day 348-355), Buoy 34 and wind-driven current velocities were well correlated (vector mean buoy velocity - 17.3 cm/sec at 119°, vector mean wind-driven current velocity - 13.3 cm/sec at 120°. After this initial period, there was a marked divergence in the estimated wind-driven current and observed buoy trajectories, with the buoy moving south and southwest and the wind-driven current being directed to the southeast. For the total time period (Day 348, 1978-Day 30, 1979) the vector mean buoy direction and speed were 170° and 5.5 cm/sec while the vector mean wind driven current direction and speed were 125° and 9.5 cm/sec.

The trajectories of Buoy 405 and of the wind-driven current diverged from the time of launching (Exp. II, Day 88) with the buoy initially moving south while the estimated wind-driven current was to the north. Another conspicuous deviation in buoy and wind-driven current movement during this experiment occurred between Day 120 and 131, a period in which the wind-driven current was to the east at an average speed of 20 cm/sec, while the buoy moved to the north at an average speed of 3 cm/sec. For the total time period (Day 88-152), the vector mean buoy direction and speed were 349° and 4.0 cm/sec, while the vector mean wind-driven current direction and speed were 052° and 5.4 cm/sec.

Day (1958) observed on a basis of drift bottle returns and estimated weather map wind velocities that the prevailing circulation in the Gulf of Maine-Georges Bank area may be strongly influenced by winds at all seasons of the year. We conclude, however, that there was no readily discernible or coherent wind effect on buoy movement during the course of the subject experiments.

Buoy Movement in Relation to Thermal Fronts and Warm-Core Ring Positions

Using the data of Hilland (1981) and Fitzgerald and Chamberlin (1981), we plotted the weekly positions of the shelf water front and the Gulf Stream north wall relative to the 200-m isobath for the four most easterly bearing lines during the periods of the four satellite-tracked buoy experiments (Figure 12). The only readily perceivable correlation between thermal fronts and buoy trajectories is that the shelf water front and the Gulf Steam north wall were furthest offshore (especially along the Casco Bay 120° bearing line), during Experiment I at which time all buoys moved rapidly south and off Georges Bank, and were closest to the 200-m isobath during Experiments III and IV when the buoys remained over the continental shelf for the longest time periods.

Comparisons of buoy movement with surface temperature features depicted from satellite IR imagery show that the movement of buoys off the continental shelf was often associated with warm-core ring or Gulf Stream meander activity (e.g., Exp. II, Buoy 510; Exp. IV, Buoys 620, 727, and 703). At other times, however, rapid and direct buoy movement off the shelf was not associated with any apparent warm-core ring activity or fluctuations in the locus of the shelf/slope or Gulf Stream surface temperature fronts (Exp. III, Buoy 433). The fact that surface temperatures measured by the buoys and buoy velocities often changed abruptly indicates that at times the buoys were moving from one water mass to another (across thermal fronts) rather than being entrained within a specific parcel of water.

In Figures 13 and 14 we have plotted the trajectories of Buoys 620 and 703 (Exp. IV) during periods when satellite imagery evidenced marked shelf water entrainment under the influence of warm-core rings 79-G, 79-H, and 79-I. In Figure 13, water mass distributions are based on the "Gulf Stream Analysis Chart" for the period 1-7 November (Day 305-311) and warm-core eddy positions are from Fitzgerald and Chamberlin (1981). Water mass distributions in Figure 14 are from U. S. Naval Oceanographic Experimental "Ocean Frontal Analysis Chart" for the period 21-27 October (Day 294-300). Considering the possible errors involved in buoy positioning and the difficulties encountered in the intrpretation of satellite imagery, there is fairly good correspondence between entrainment features and buoy movement.

Ichthyoplankton Distribution

Data from ichthyoplankton surveys made prior, coincident, and subsequent to the satellite-tracked buoy experiments were used in whole or in part to delineate the distributions of the dominant larval fish species at the time and in the area of buoy deployment and to estimate larval fish dispersion and mortality rates. The cruise numbers and dates were:

Albatross IV 79-03, 28 March-9 April 1979 (Exp. II);

Delaware II 79-04, 11-30 April 1979 (Exp. II);

Delaware II 79-05, 4-29 May 1979 (Exp. II and III);

Belogorsk 79-01, 11 August-2 September 1979 (Exp. IV); and

Albatross IV 79-11, 1-29 October 1979 (Exp. IV).

In Figure 15 we compare the distributions of larval Atlantic cod (*Gadus morhua*) and sand lance (*Ammodytes* sp.) during combined *Albatross IV* Cruise 79-03 and *Delaware II* Cruise 79-04 (109 stations, mid-date: Day 109), and *Delaware II* Cruise 79-05 (130 stations, mid-date: Day 140). As described previously, the 5-mm length classes for each time period were coupled on a basis of growth rates reported in the literature. In this case (31 days between the midpoints of the cruises), we linked successive 5-mm length classes.

Atlantic cod larvae (6-10 mm) were less abundant, but more widely dispersed during Delaware II Cruise 79-05 than 1-5 mm cod larvae during the preceding sampling period. There was no marked transport of larvae from Georges Bank into the Gulf of Maine as indicated by the buoy trajectories during Experiment II. The decrease in average abundance from 8.0/10 m^2 for 1-5 mm larvae during March-April to 3.0/10 m^2 for 6-10 mm larvae during May equates to a mortality rate of 2.0%/day.

Ammodytes sp. were the most abundant larval fishes collected during the initial sampling period, but were found for the most part in areas to the west of buoy deployment during Experiment II. No readily observable pattern of drift is evident from the two sets of distribution data, although one might theorize that the main population of larvae off Southern New England was transported in a southwesterly direction and out of the area of coverage. However, reported average surface current velocities of approximately 4.5 km/day (Bumpus 1973; Hansen 1977; Han and Niedrauer 1981) would not give rise to such an extensive transport. Estimated mortality rates based on the relative abundance of Ammodytes sp. cohorts during the two time periods were:

6-10 mm to 11-15 mm, 3.0%/day;

11-15 mm to 16-20 mm, 3.1%/day; and

16-20 mm to 21-25 mm, 3.1%/day.

Hake (Urophycis sp.), silver hake (Merluccius bilinearis), and redfish (Sebastes sp.) were the dominant and most widely distributed larval fishes collected on Belogorsk Cruise 79-01 and were chosen as candidate species to follow dispersal and estimate mortality rates between Belogorsk Cruise 79-01 (100 stations, mid-date: Day 234) and Albatross IV Cruise 79-11 (106 stations, mid-date: Day 288). On the basis of the 54-day interval between the midpoints of these cruises, we have coupled alternate 5 mm-length classes (Figures 16 and 17).

On Belogorsk Cruise 79-01, Urophycis sp. were found in southwestern Gulf of Maine, along the southern part of Georges Bank, and throughout most of the area sampled in the Middle Atlantic Bight (Figure 16). The bulk of the population was either north or west of the area of buoy deployment in Experiment IV. On Albatross IV Cruise 79-11, no hake larvae were found in the Gulf of Maine and only scattered patches of larvae occurred on southern Georges and in the Middle Atlantic Bight. Buoy trajectories during Experiment IV suggest that larvae found in the southwestern part of the Gulf of Maine and in the Great South Channel during Belogorsk Cruise 79-01 could have been transported in an easterly direction along the northern edge of Georges Bank and out of the area of coverage during Albatross IV Cruise 79-11. Buoy trajectories also suggest that the loss of larvae from southern Georges could be associated with offshore movement (shelf water entrainment). The situation may also account for the loss of larvae in the Middle Atlantic

Bight, but we have no data to support this contention. The decrease in the average abundance of 1-5 mm larvae from 67.1/10 m^2 during *Belogorsk* Cruise 79-01 to 1.6/10 m^2 for 10-15 mm larvae during *Albatross IV* Cruise 79-11 points to a mortality rate of 1.8%/day. On *Belogorsk* Cruise 79-01, the average abundance of 5-10 mm larvae was 7.4/10 m^2 and on *Albatross IV* Cruise 79-11 the average abundance of 15-20 mm larvae was 1.7/10 m^2 which equates to a mortality rate of 1.4%/day.

On *Belogorsk* Cruise 79-01, silver hake larvae were found in the western Gulf of Maine, over Nantucket Shoals, and on southern and western Georges Bank. On *Albatross IV* Cruise 79-11, only a few scattered patches of larvae were found in the Gulf of Maine, on Georges Bank, and off Southern New England. Mortality rates based on the average number of 1-5 mm larvae (18.0/10 m^2) and 6-10 mm larvae (5.3/10 m^2) caught during *Belogorsk* Cruise 79-01, and the average number of 11-15 mm larvae (0.3/10 m^2) and of 16-20 mm larvae (0.3/10 m^2) caught on *Albatross IV* Cruise 79-11, were computed to be 1.8%/day and 1.7%/day, respectively. The shifts in distributions and decrease in abundances between the two time periods were not associated with any obvious residual drift patterns observed during Experiment IV or in previous studies of circulation.

Redfish larvae (1-5 mm and 6-10 mm) were found in appreciable numbers of central and western Gulf of Maine and in the Great South Channel during *Belogorsk* Cruise 79-01, but no larvae (11-15 mm and 16-20 mm) which could be considered the progeny of the same spawnings were found on *Albatross IV* Cruise 79-11. Redfish larvae (5-10 mm) were collected at only two stations in north central Gulf of Maine during this latter cruise. The absence of redfish larvae during *Albatross IV* Cruise 79-11 does not appear to be associated with some form of sampling bias for we have frequently collected redfish larvae of the appropriate size range on ichthyoplankton cruises at this time of the year. In addition, Kelley and Barker (1961), on the basis of mid-water trawl samples, have shown that redfish do not move to the bottom until they are 4.5 months old (approximately 50 mm in length) and that larvae smaller than this occupy the water column above 100 m in depth. Larvae 25 mm and less were found in the upper 20 m of the water column.

It would appear then that the absence of 11-15 mm and 16-20 mm redfish larvae during October 1979 was authentic and not the result of any sampling bias. A mortality rate within the range of 2.0%/day, which is of the same order of magnitude as that estimated for the other species, could account for the complete loss of redfish larvae during this 54-day time period.

In no case have we been able to establish a well-defined link between residual drift and the dispersal of larvae. Estimated mortality rates were similar during periods of low and high residence times of Georges Bank surface waters and in the Gulf of Maine, Georges Bank, and Middle Atlantic Bight. This may be due in part to the fact that sampling during the ichthyoplankton surveys was confined for the most part to continental shelf waters (<200 m) with few samples being obtained in the vicinity of the shelf/slope front where entrainment of shelf water is prevalent. In any event, the loss of larval cohorts observed during these surveys appears to be due to other causes (predation, starvation?) rather than to the transport of larvae to extrinsic environs.

SUMMARY AND CONCLUSIONS

Summary

1. Buoy trajectories substantiate previous evidence of a seasonal development of the Georges Bank gyre and accordingly a gradual increase in surface water residence times from winter to late summer.

2. Once the buoys exited the continental shelf (>200 m) to the south, they remained in slope water or were entrained in the Gulf Stream, while occasionally buoys made brief excursions into the Gulf of Maine before reentering the northern edge of Georges Bank.

3. The shelf/slope front and the Gulf Stream north wall were furthest offshore during Experiment I at which time all buoys moved rapidly south and off Georges Bank, and were closest to the 200-m isobath during Experiments III and IV when the buoys remained over the continental shelf for the longest time periods.

4. Comparisons of buoy, wind, and wind-driven current velocities revealed little correlation between buoy movement and wind. This dissimilarity was most apparent during periods when the buoys were in the proximity of the shelf/slope front or entrained in slope or Gulf Stream waters. The contribution of wind to seasonal circulation appeared to be negligible compared to that of tide, density field, and offshore forcing.

5. The movement of buoys off the continental shelf was often associated with the entrainment of shelf water generated by warm-core rings or Gulf Stream meanders, while at other times rapid and direct buoy movement off the shelf was not associated with any apparent warm-core ring activity or fluctuations in the locus of shelf/slope or Gulf Stream surface temperature fronts. Surface temperatures measured by the buoys and buoy velocities often changed abruptly indicating that at times buoys were moving across thermal fronts rather than being entrained in a specific parcel of water.

6. Shifts in distributions and decreases in numbers of larval fish cohorts were not obviously associated with any pronounced residual drift patterns evidenced by buoy trajectories or in previous studies of circulation. In no case was there sound evidence of a link between residual drift and the transport of larvae. Estimated larval mortality rates were of the same order of magnitude during periods of low and high residence times of Georges Bank surface waters and over Georges Bank as well as in areas to the north and west.

Conclusions

The observed buoy trajectories and estimated surface water residence times presented in this study and the characteristic shelf water entrainment features observed in satellite imagery tend to support the hypothesis that the advection of fish eggs and larvae from the spawning areas on Georges Bank could at times have a significant effect on the dispersal and thus survival of early life history stages and the subsequent abundance of fishes available for commercial and recreational exploitation. The biological data presented, however, do not support this contention in that in no case did advective processes appear to be clearly associated with larval fish mortality estimates. This disparity appears to be due in part to the facts that the two data sets were obtained *in vacuo* and thus caused difficulties in integrating the physical and biological information, that the concentrations of larval fishes occurred for the most part in areas outside the areas of buoy deployment, and that the time intervals between ichthyoplankton surveys were too long to firmly establish cohort linkages.

In the absence of evidence to the contrary, it does not seem unreasonable to assume as the simplest hypothesis, that both early and late pelagic stages of marine fishes drift passively with the current and as a consequence are at times subject to advection from the spawning grounds. Thus it would appear expedient to reexamine this premise in a more detailed and concurrent manner. This approach would involve buoy deployment at the time of ichthyoplankton surveys and in areas of known ichthyoplankton concentrations, restricted coverage to Georges Bank proper and slope water areas to the south during periods of maximum egg production of commercially/recreationally important species such as haddock and cod and minimum residence times of Georges Bank surface waters (February-April), the collection of ancillary hydrographic data to accurately determine water mass distribution and density structure, and intervals between surveys of not more than 2 weeks. In addition to the above, it is requisite that we quantify shelf water entrainment both in terms of volume of water and numbers of organisms (phytoplankton, zooplankton, and ichthyoplankton). This latter project of study is now underway in connection with the National Science Foundation-sponsored interdisciplinary study of warm-core rings in which NMFS is obtaining quantitative information on the vertical structure and the magnitude of the flux of shelf water and contained organisms in the entrainment feature and relating these measurements to surface manifestations as indicated by satellite imagery.

If, after a comprehensive sampling program, we can unequivocally conclude that boreal larval fish species of Georges Bank origin do not occur in entrained shelf water, we will be faced with the more formidable task of explaining why this is so.

ACKNOWLEDGMENTS

We extend special thanks to David Cook, Raytheon Ocean Systems Company, and Daniel Frye, EG&G Environmental Consultants, for generously allowing us to use the edited buoy position and temperature data which are the foundation of this paper. Merton Ingham and other members of the Atlantic Environmental Group facilitated the extraction of meteorological and satellite imagery data. Thomas Plichta compiled the computer summaries of ichthyoplankton abundances and Lianne Armstrong prepared the final figures. Geoffrey Laurence and Wallace Smith critically reviewed earlier drafts of this paper.

LITERATURE CITED

ANDERSON, V. T. and S. A. AKENHEAD.
1981. Distribution and abundance of redfish and cod larvae on Flemish Cap in 1978 and 21979. NAFO Sci. Coun. Studies, No. 1:57-63.

BIGELOW, H. B.
1927. Physical oceanography of the Gulf of Maine. Bull. U. S. Bur. Fish. 40(2):511-1027.

BOYAR, H. C., R. R. MARAK, F. E. PERKINS, and R. A. CLIFFORD.
1973. Seasonal distribution and growth of larval herring (Clupea harengus L.) in the Georges Bank-Gulf of Maine area from 1962 to 1970. J. Cons. int. Explor. Mer 35:36-51.

BUMPUS, D. F.
1973. A description of the circulation of the continental shelf of the east coast of the United States. Progress in Oceanogr. 6:111-157.

1976. A review of the physical oceanography of Georges Bank. Int. Com. Northw. Atl. Fish. Bull. 12:119-134.

BUMPUS, D. F. and L. M. LAUZIER.
1965. Surface circulation on the continental shelf off eastern North America between Newfoundland and Florida. Am. Geograph. Soc., Serial Atlas of the Marine Environment, folio 7.

BUTMAN, B., R. C. BEARDSLEY, B. MAGNELL, J. A. VERMERSCH, R. J. SCHLITZ, R. LIMEBURNER, and M. A. NOBLE.
1982. The mean circulation on Georges Bank. J. Phys. Oceanogr. 12:569-591.

CLARKE, G. L., E. L. PIERCE, and D. F. BUMPUS.
1943. The distribution and reproduction of Sagitta elegans on Georges Bank in relation to hydrographic conditions. Biol. Bull. 85:201-226.

COLTON, J. B., JR.
1961. The distribution of eyed-flounder and lanternfish larvae in the Georges Bank area. Copeia 1961(3):274-279.

COLTON, J. B., JR. and R. R. BYRON.
1977. Gulf of Maine-Georges Bank ichthyoplankton collected on ICNAF larval herring surveys September 1971-February 1974. NOAA Tech. Rep. NMFS SSRF 717:35 p.

COLTON, J. B., JR. and J. M. ST. ONGE.
1974. Distribution of fish eggs and larvae in continental shelf waters, Nova Scotia to Long Island. Am. Geog. Soc. Serial Atlas of the Marine Environment. Folio 23.

COLTON, J. B., JR. and R. F. TEMPLE.
1961. The enigma of Georges Bank spawning. Limnol. Oceanogr. 6:280-291.

DAY, G. G.
1958. Surface circulation in the Gulf of Maine as deduced from drift bottles. U. S. Fish. Wildl. Serv. Fish. Bull. 58:443-472.

DIXON, W. J.
1950. Analysis of extreme values. Ann. Math. Statist. 21:488-506.

DUNCAN, D. B.
1975. "t" tests and intervals for comparisons suggested by the data. Biometrics 31:339-359.

EG&G.
1979a. Appendix A of the Tenth Quarterly Progress Report, NEOCSPOP. EG&G Environmental Consultants, Waltham, MA, May 1979, 32 p.

1979b. Appendix A of the Eleventh Quarterly Progress Report, NEOCSPOP. EG&G Environmental Consultants, Waltham, MA, August 1979, 27 p.

1979c. Appendix A of the Twelfth Quarterly Progress Report, NEOCSPOP. EG&G Environmental Consultants, Waltham, MA, December 1979, 31 p.

1980. Appendix A of the Thirteenth Quarterly Progress Report, NEOCSPOP. EG&G Environmental Consultants, Waltham, MA, July 1980, 30 p.

FITZGERALD, J. L. and J. L. CHAMBERLIN.
1981. Anticyclonic warm core Gulf Stream eddies off the northeastern United States in 1979. Ann. Biol. Cons. int. Explor. Mer 36 36:44-51.

GODSHALL, F. A., R. G. WILLIAMS, J. M. BISHOP, F. EVERDALE and S. W. FEHLER.
1980. A climatological and oceanographic analysis of the Georges Bank region of the outer continental shelf. Final Rep. to the Bureau of Land Management, U. S. Dept. of Comm., NOAA, Washington, D. C., 290 p.

HAIGHT, F. J.
1942. Coastal currents along the Atlantic coast of the United States. U. S. Dept. of Comm., Coast and Geodetic Survey, Spec. Publ. No. 230, 73 p.

HAN, G. and T. NIEDRAUER.
1981. Hydrographic observations and mixing processes in the New York Bight, 1975-1977. Limnol. Oceanogr. 26:1126-1141.

HANSEN, D. V.
1977. Circulation. MESA New York Bight Atlas Monograph 3. New York Sea Grant Institute, Albany, New York, October 1977, 23 p.

HILLAND, J. E.
1981. Variation in the shelf water front position from Georges Bank to Cape Romain in 1979. Ann. Biol. Cons. int. Explor. Mer 36:34-36.

KELLY, G. F. and A. M. BARKER.
1961. Vertical distribution of young redfish in the Gulf of Maine. Rapp. P.-v. Reun. Cons. int. Explor. Mer 150:220-233.

KIRWAN, A. D., JR., G. McNALLY, S. PAZAN, and R. WERT.
1979. Analysis of surface current response to wind. J. Phys. Oceanogr. 9:401-412.

LAURENCE, G. C.
1974. Growth and survival of haddock (*Melanogrammus aeglefinus*) larvae in relation to plankton prey concentration. J. Fish. Res. Board Can. 31:1415-1419.

LAURENCE, G. C., A. S. SMIGIELSKI, T. A. HALAVIK, and B. R. BURNS.
1981. Implications of direct competition between larval cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in laboratory growth and survival studies at different food densities. Rapp. P.-v. Reun. Cons. int. Explor. Mer 178:304-311.

LOUGH, R. G., M. R. PENNINGTON, G. R. BOLZ, and A. S. ROSENBERG.
1980. A growth model for larval herring (*Clupea harengus* L.) in the Georges Bank-Gulf of Maine area based on otolith growth increments. NAFO SCR Doc. 80/IX/131, 16 p.

POSGAY, J. A. and R. R. MARAK.
1980. The MARMAP bongo zooplankton samplers. J. Northw. Atl. Fish. Sci. 1:91-99.

REDFIELD, A. C.
1939. The history of a population of *Limacina retroversa* during its drift across the Gulf of Maine. Biol. Bull. 76(1):26-47.

1941. The effect of the circulation of water on the distribution of the calanoid community in the Gulf of Maine. Biol. Bull. 89(1):86-110.

REDFIELD, A. C. and A. BEALE.
1940. Factors determining the populations of chaetognaths in the Gulf of Maine. Biol. Bull. 79(3):459-487.

RICHARDSON, P. L., R. E. CHENEY and L. A. MANTINI.
1977. Tracking a Gulf Stream ring with a free drifting surface buoy. J. Phys. Oceanogr. 7:580-590.

RICHARDSON, P. L., J. J. WHEAT and D. BENNETT.
1979. Free-drifting buoy trajectories in the Gulf Stream system. Woods Hole Oceanographic Institution Technical Report WHOI-79-4, 159 p.

SHERMAN, K.
1980. MARMAP, a fisheries ecosystem study in the NW Atlantic: Fluctuations in ichthyoplankton-zooplankton components and their potential impact on the system. pp. 9-37. In F. P. Diemer, F. J. Vernberg, and D. Z. Mirkes (eds.) Advanced concepts in ocean measurements for marine biology. Belle W. Baruch Institute for Marine Biology and Coastal Research. University of South Carolina Press.

SMITH, P. E. and S. L. RICHARDSON.
1977. Standard techniques for pelagic fish egg and larvae surveys. FAO Fish. Tech. Paper, No. 175, 100 p.

WALDICHUCK, M.
1963. Drift bottle observation in the Strait of Georgia and its contiguous waters, and off the west coast of Vancouver Island. Fish. Res. Board. Can. MS Rep. Series (Oceanogr. and Limnol.) No. 147, 104 p.

WALFORD, L. A.
1938. Effect on currents on the distribution of the eggs and larvae of the haddock (Melanogrammus aeglefinus) on Georges Bank. Bull. U. S. Bur. Fish. 49(29):1-73.

APPENDIX:

COMPARISON OF WIND REGIMES AT NANTUCKET ISLAND AND GEORGES BANK

Introduction

To determine the feasibility of using wind direction and speed adjustment factors to extrapolate the long time series of Nantucket Island wind observations to Georges Bank, we compare here Nantucket Island (41°15'N, 70°04'W) and Georges Shoal Texas Tower (41°41'N, 67°47'W) wind data during the period April 1958-October 1961, an interval in which hourly wind observations (24/day) were taken at both locations. These data, reduced to daily and monthly resultant (vector mean) wind speeds and directions were obtained from the National Climatic Center in Asheville, N. C.

Wind Regime Comparisons

Nantucket Island and Georges Shoals monthly and annual wind directions and speeds, Georges Shoals/Nantucket Island wind speed ratios, and annual wind speed and direction correlation coefficients and variance ratios are given in Table 2. Zonal and meridional components of monthly resultant wind velocities at the two locations are plotted in Figure 18. Although wind speeds were greater at Georges Shoals, both the high correlation coefficients and the similarity of the wind component cycles substantiate the similarity between wind conditions at the two locations.

Duncan's Multiple Range Test (Duncan 1975) at a level of significance of 0.05 was used to test the significance of the differences in wind speed and direction at the two locations. With one notable exception (April 1959), wind direction at the two locations was from the same sectors during all months and years. In April 1959, the monthly resultant wind at Nantucket Island was from the west (291°) while on Georges Shoals it was from the east (094°). Progressive vector plots of April 1959 daily resultant winds (Figure 19) show that this aberrence was due for the most part to appreciably higher Georges Shoals wind speeds (notably, Days 5-8, 23, 26, 28, and 29) rather than to marked differences in wind direction. Although the April 1959 deviation in wind direction at the two locations appears to be real, a test for outliers (Dixon 1950) indicates that we can omit these values from our computation.

With few exceptions (April and November 1959, and November 1960), monthly wind speeds were greater at Georges Shoals. These wind speed differences were statistically significant in 1961 and for total years. Although there is little reason for considering a wind data variate at one location as dependent on that at another location, we have used linear regression rather than correlation analysis for determining the relation of wind speed and direction values at the two locations since the regression equation allows for simple calculation of adjustment factors. The regression coefficient (1.003) for wind direction (Figure 20) did not differ significantly from unity, while the slope (0.618) of the regression line for wind speed (Figure 21) was appreciably less than unity, further demonstrating the tendency of wind speeds to be greater offshore and for the magnitude of these differences to increase with increasing wind speed.

Discussion

The wind statistics indicate that wind speed, but not wind direction, adjustment factors are required to extrapolate Nantucket Island wind observations to Georges Bank. One of the problems we immediately encounter in attempting to apply such adjustment factors is that our regression equation is based on monthly resultant wind speeds which have a maximum value of 13.4 knots (Georges Shoals, January 1959). Daily resultant wind speeds at both Nantucket Island and Georges Shoals often exceed 15 knots, so that it is necessary to convert daily values to means for protracted time periods (5 days or more) or to assume that the calculated linear relation prevails at higher wind speeds.

To test the applicability of wind speed correction factors, we compared progressive vector plots of daily Nantucket Island, Georges Shoals, and predicted Georges Bank winds for January 1959 and August 1959 (Figure 22). These time periods were selected because Nantucket Island daily wind speeds during these months were for the most part less than 15 knots and in one month (January 1959) the observation point coincided with the regression line while the August 1959 value showed a substantial negative deviation (Georges Bank/Nantucket Island wind speed ratio >2/1).

For January 1959, the predicted Georges Bank wind values closely correspond to those observed at Georges Shoals with a notable improvement in the conformity of wind speeds. For August 1959, however, the adjusted Nantucket Island wind values are more similar to the observed Nantucket Island values than to those observed at Georges Shoals. On the basis of this limited analysis, we feel that for longer time intervals (weekly or monthly resultant winds) that adjustment factors would, in general, improve the quality of wind velocity estimates, but in most cases the variability in daily wind directions and speeds between the two locations preclude the use of adjustment factors for shorter time intervals.

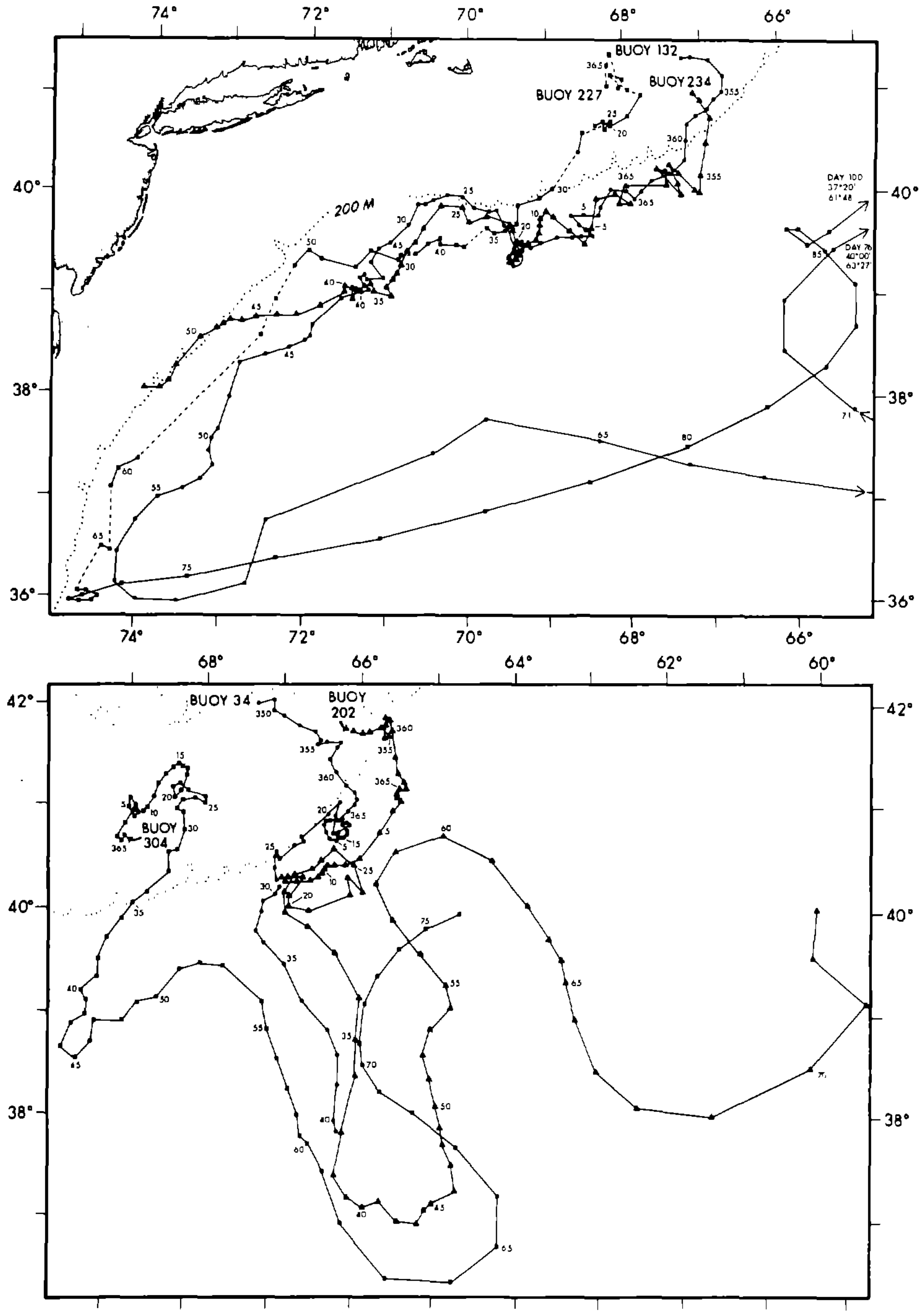


Figure 1. Tracks of buoys deployed during 13-29 December 1978 (Experiment I). Dashed lines indicate missing daily positions.

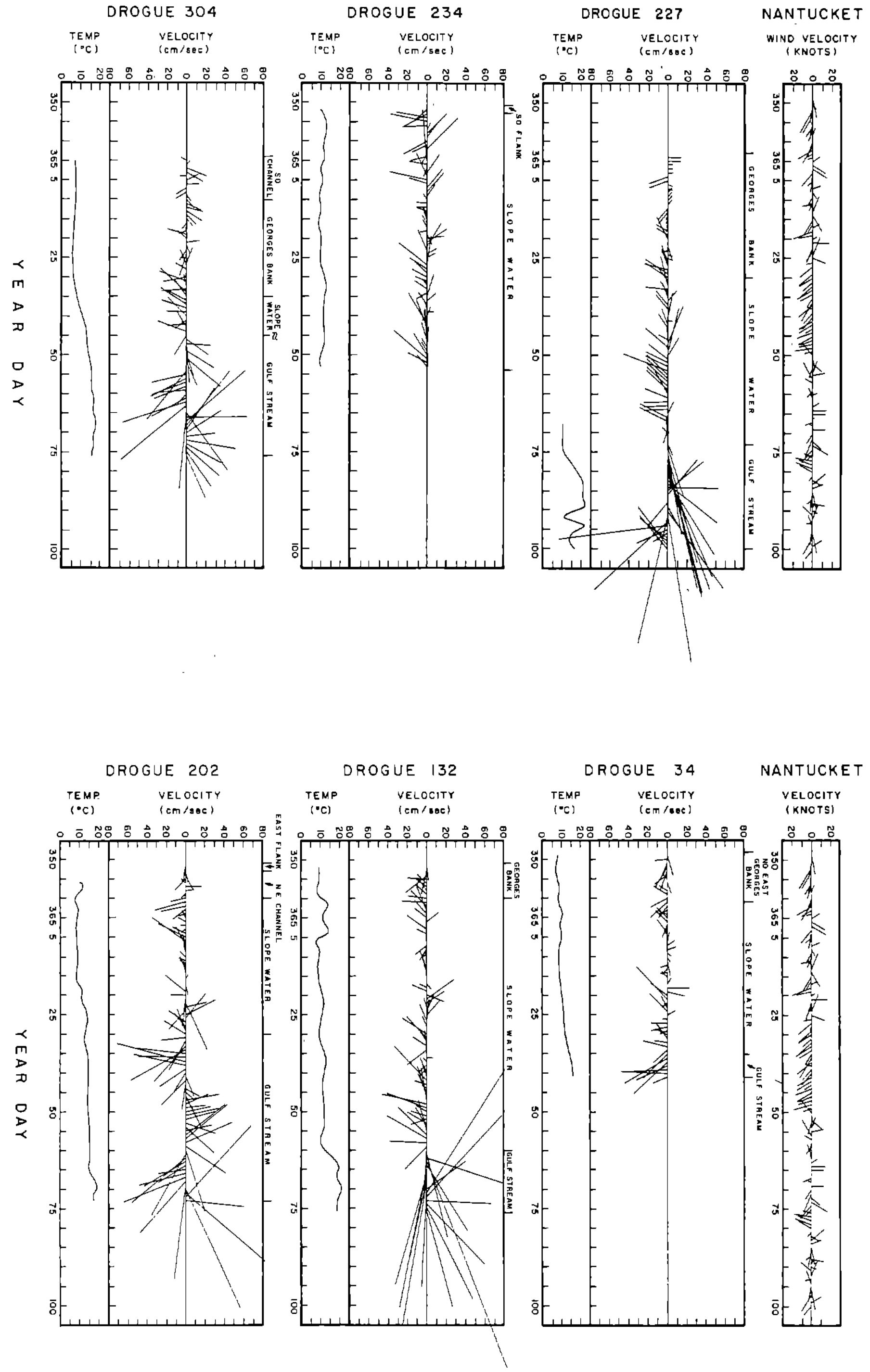


Figure 2. Stackplot of daily Nantucket Island wind vectors and buoy velocity and temperature (Experiment I).

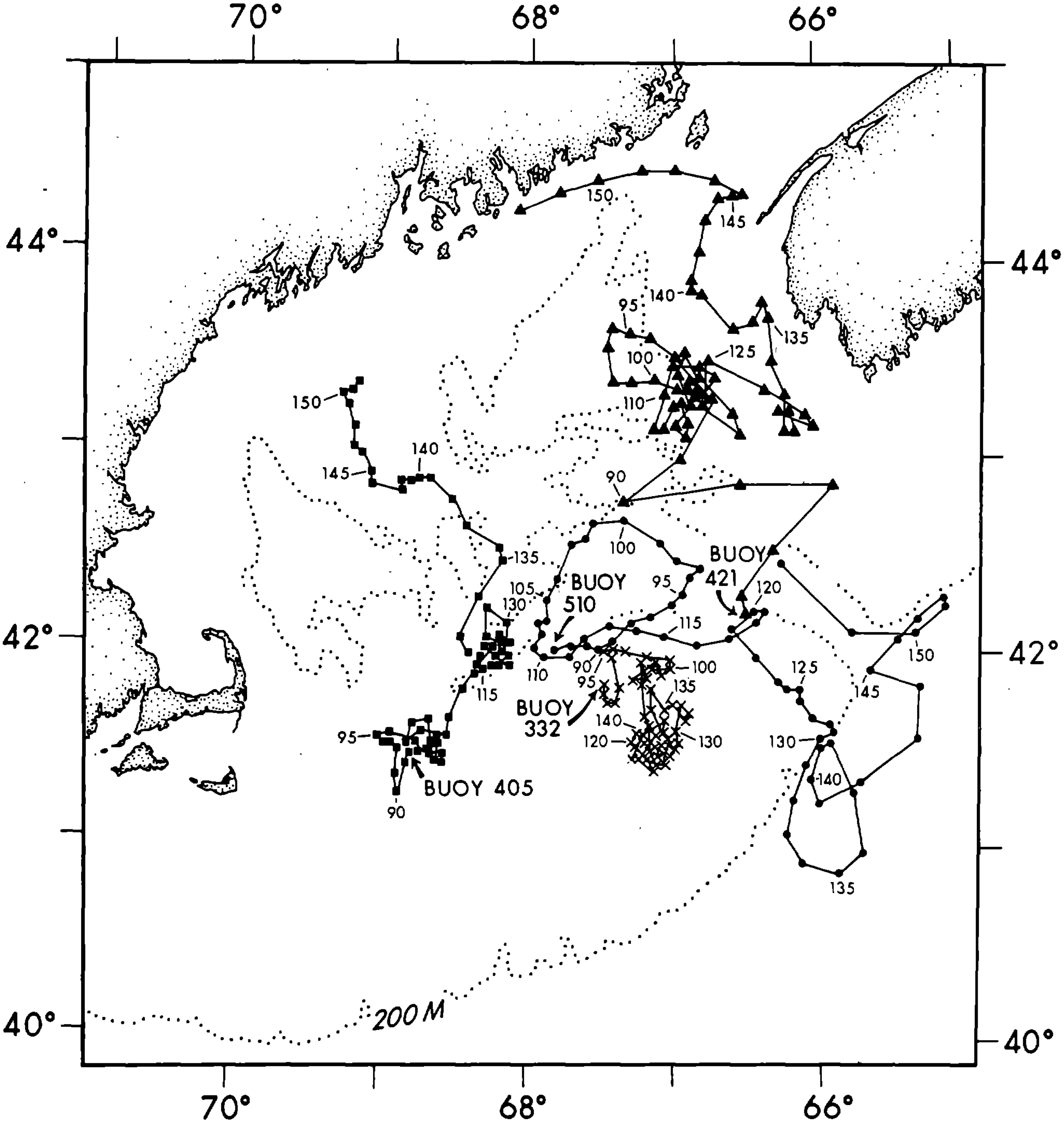


Figure 3. Tracks of buoys deployed during 25-27 March 1979 (Experiment III).

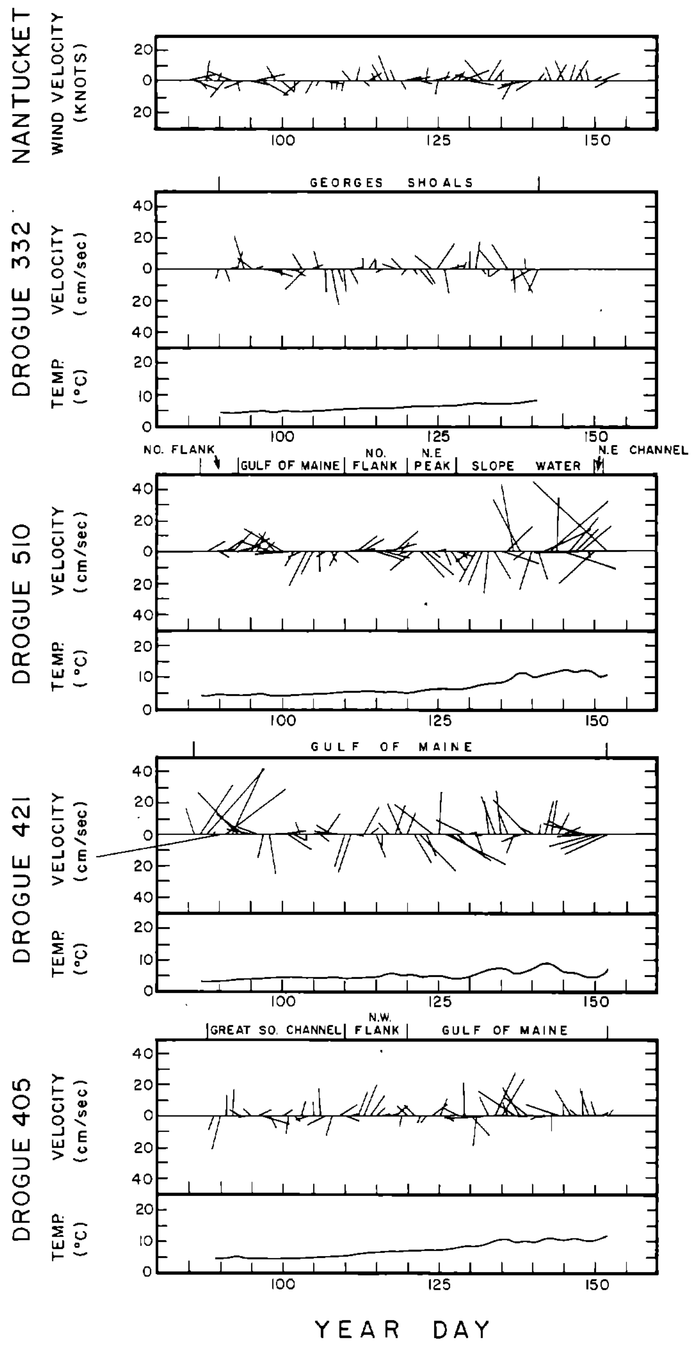


Figure 4. Stackplot of daily Nantucket Island wind vectors and buoy velocity and temperature (Experiment III).

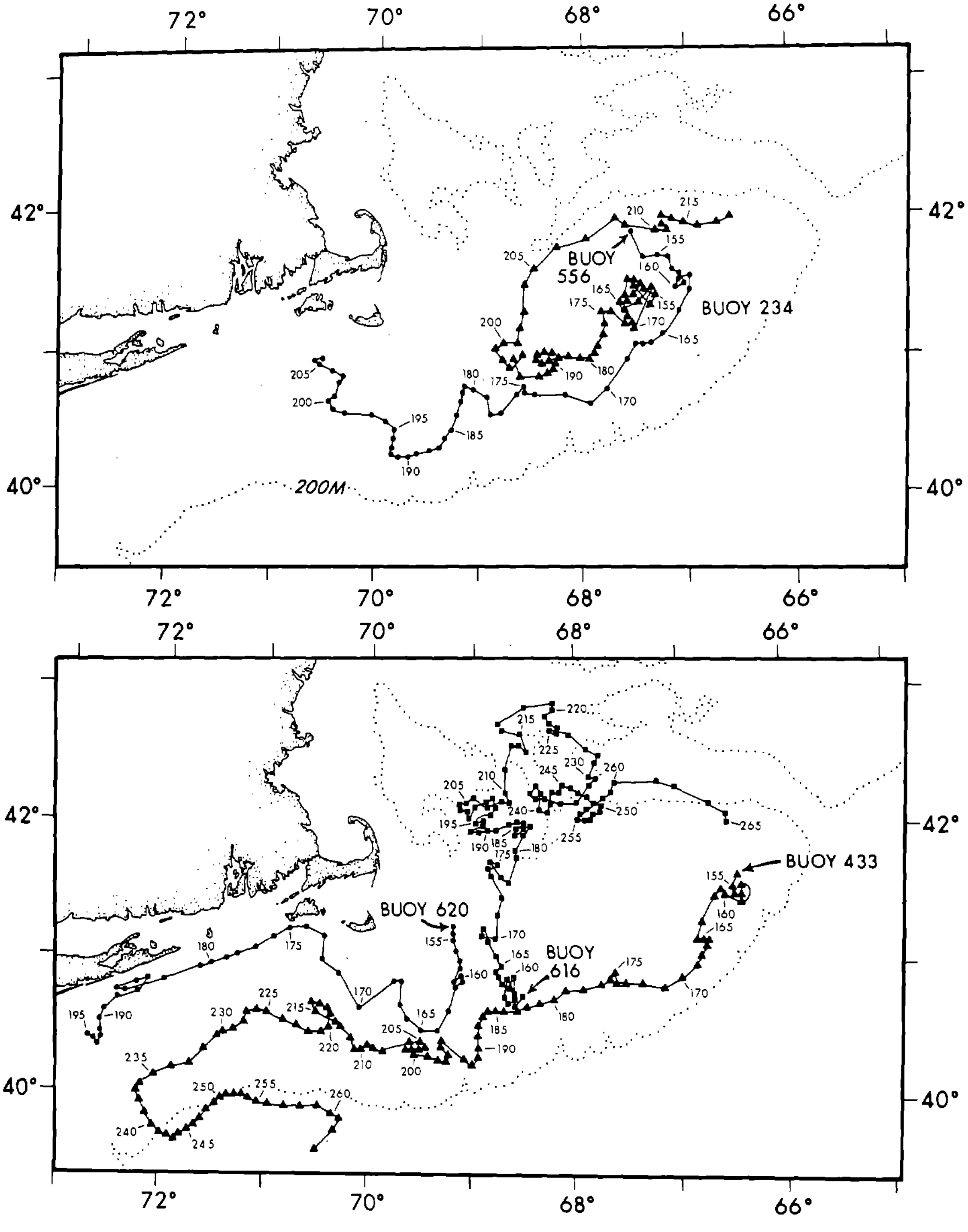


Figure 5. Tracks of buoys deployed during 30 May-2 June 1979 (Experiment III).

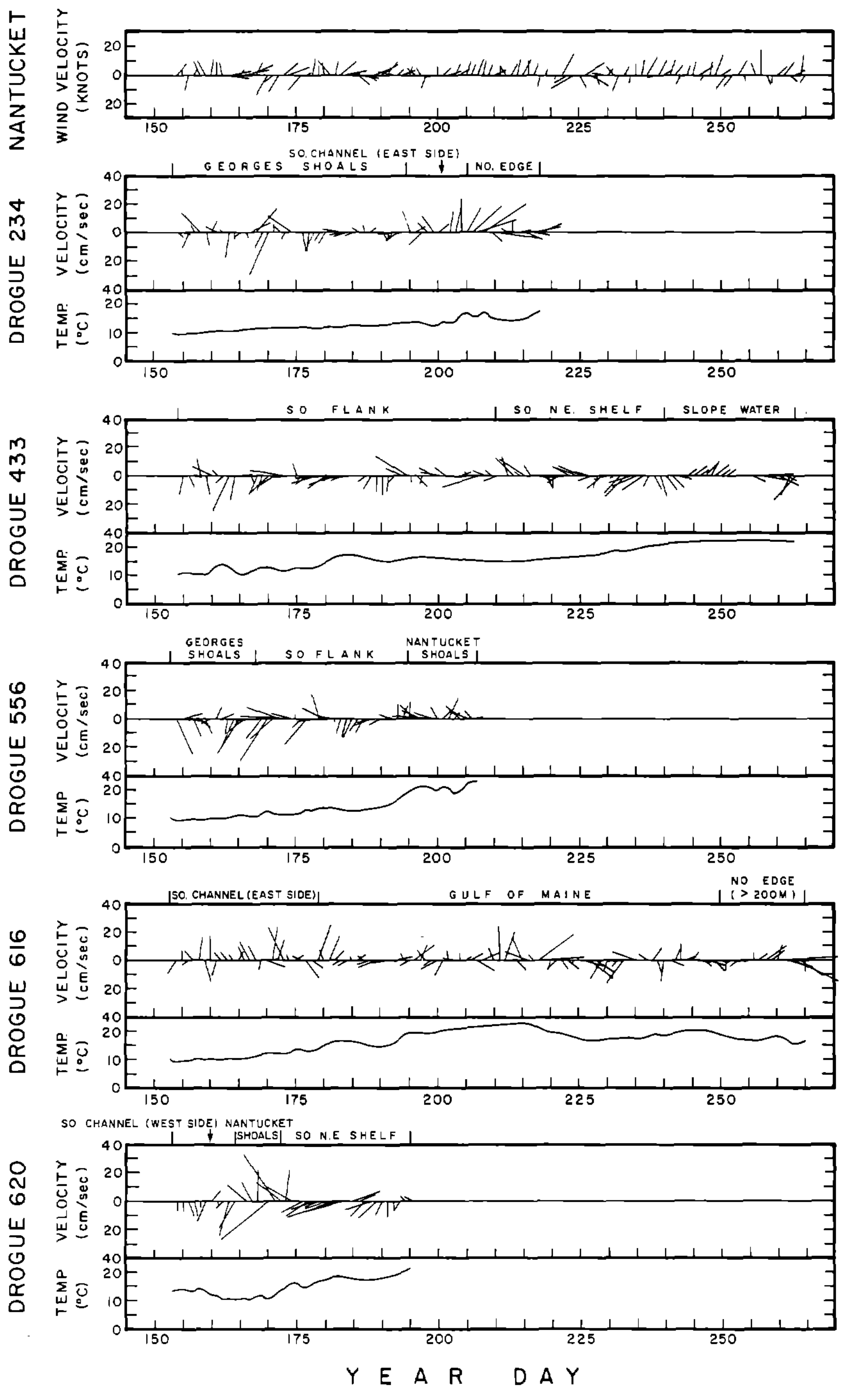


Figure 6. Stackplot of daily Nantucket Island wind vectors and buoy velocity and temperature (Experiment III).

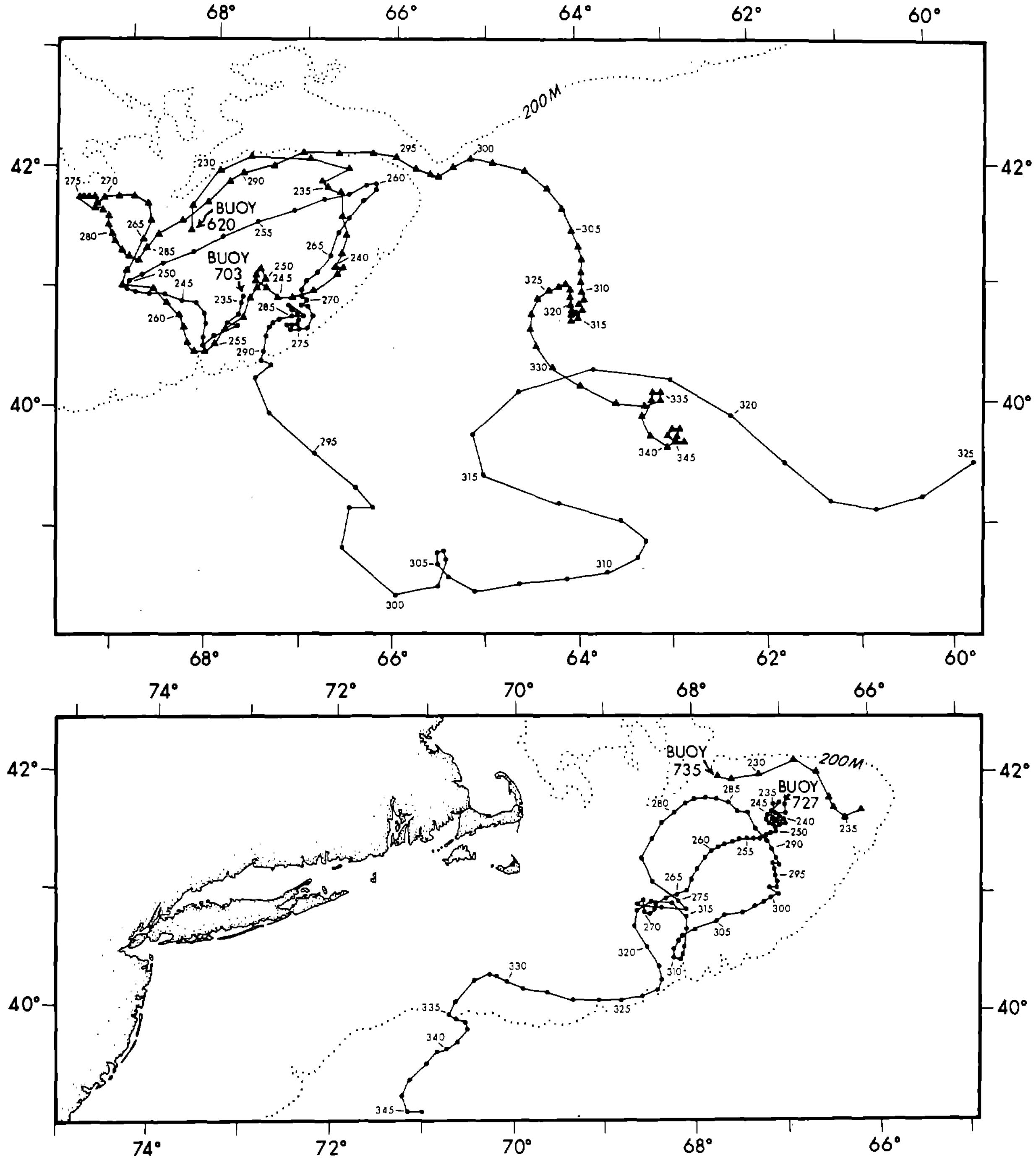


Figure 7. Tracks of buoys deployed during 16-19 August 1979 (Experiment IV).

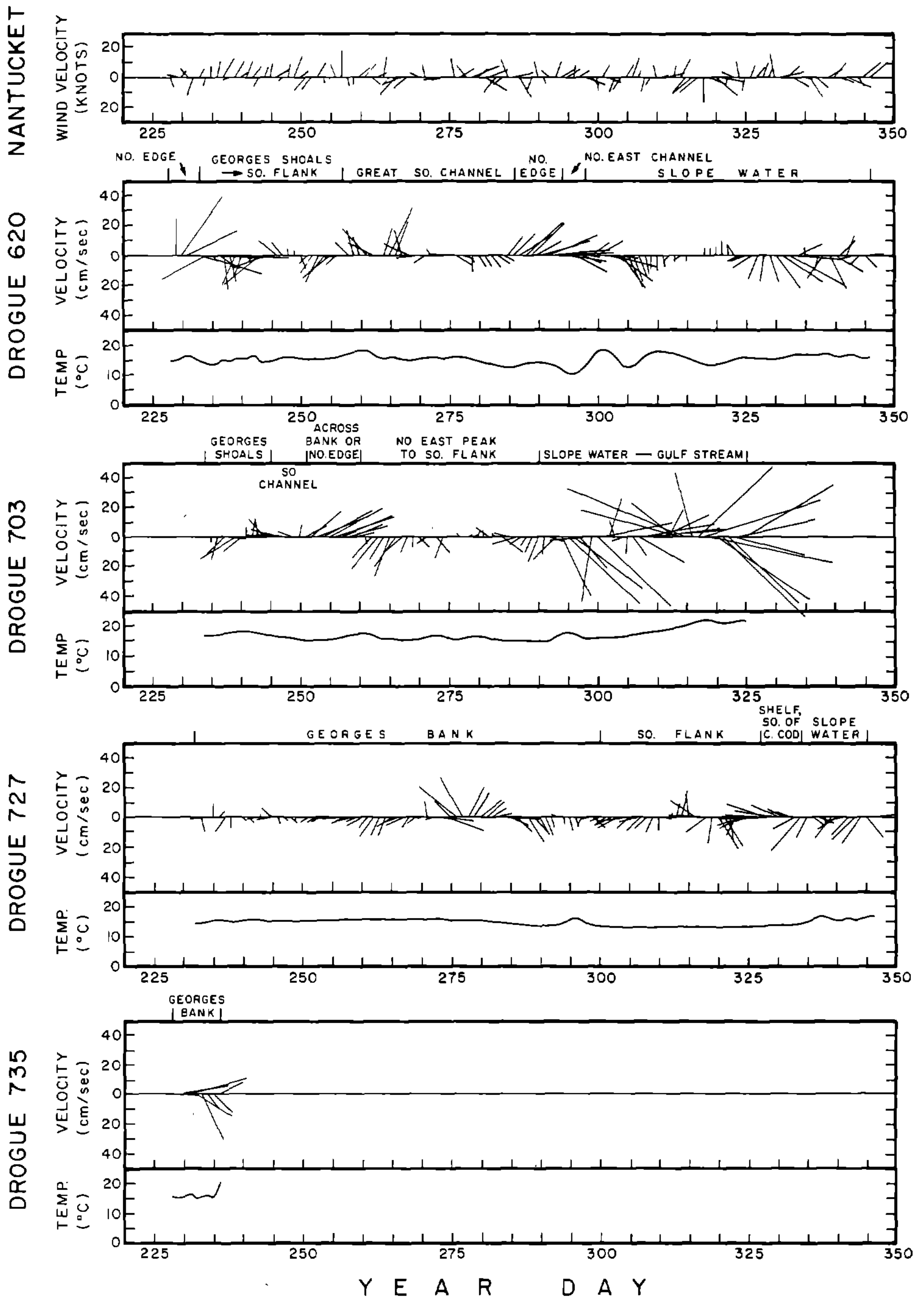


Figure 8. Stackplot of daily Nantucket Island wind vectors and buoy velocity and temperature (Experiment IV).

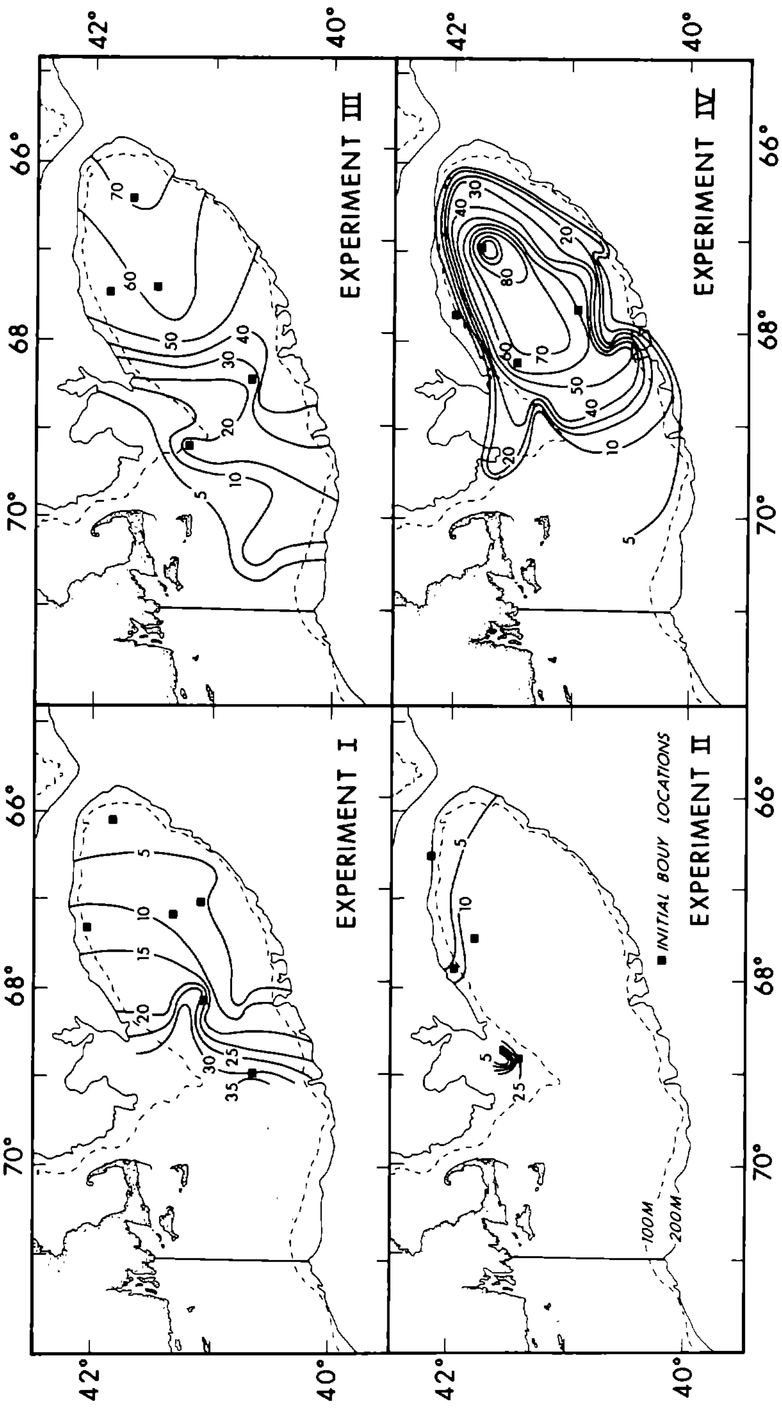


Figure 9. Estimated residence times in days of Georges Bank surface waters.

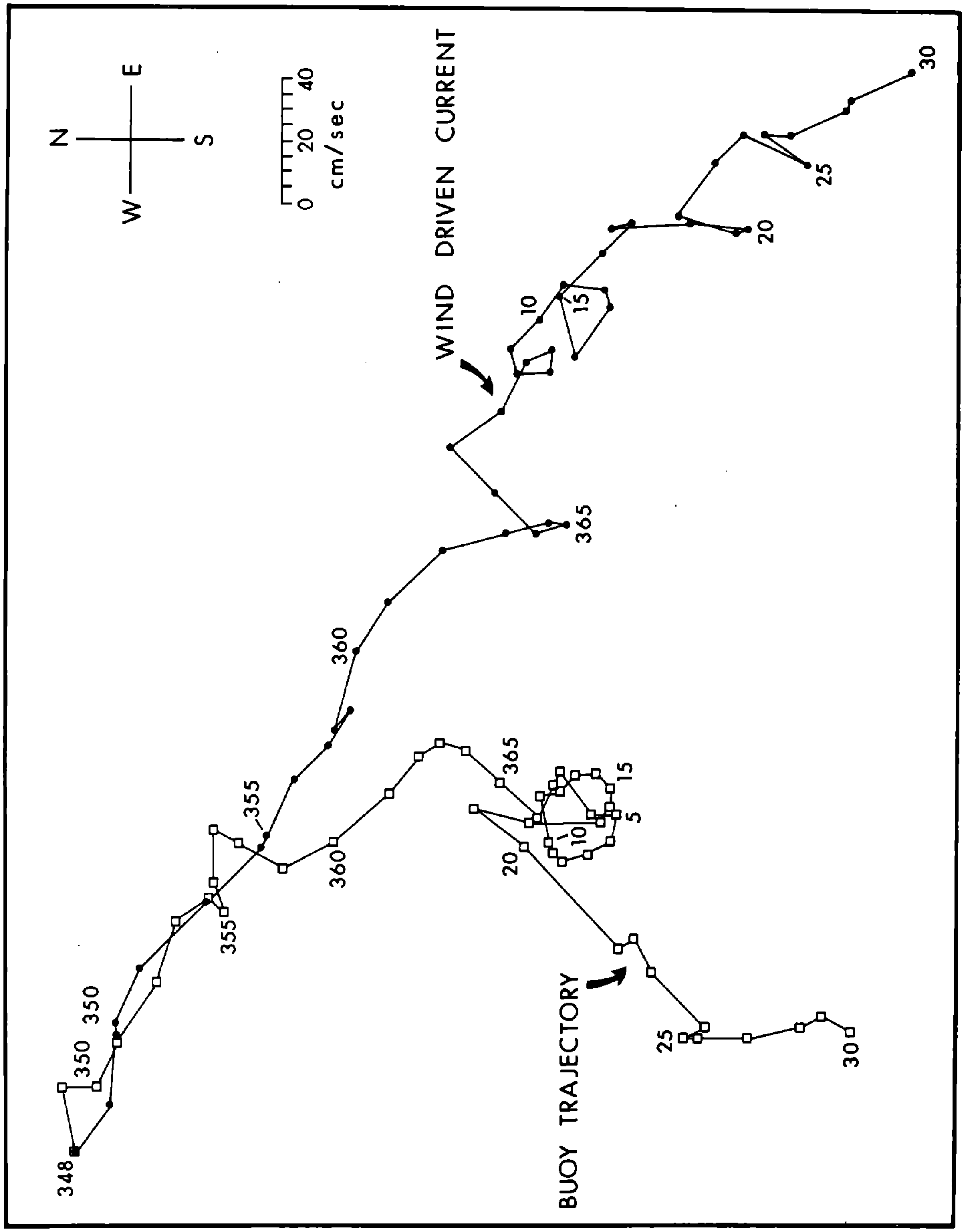


Figure 10. Buoy 34 trajectory and wind-driven-current progressive vector plot, 14 December 1978 (Day 348)-30 January 1979 (Day 30).

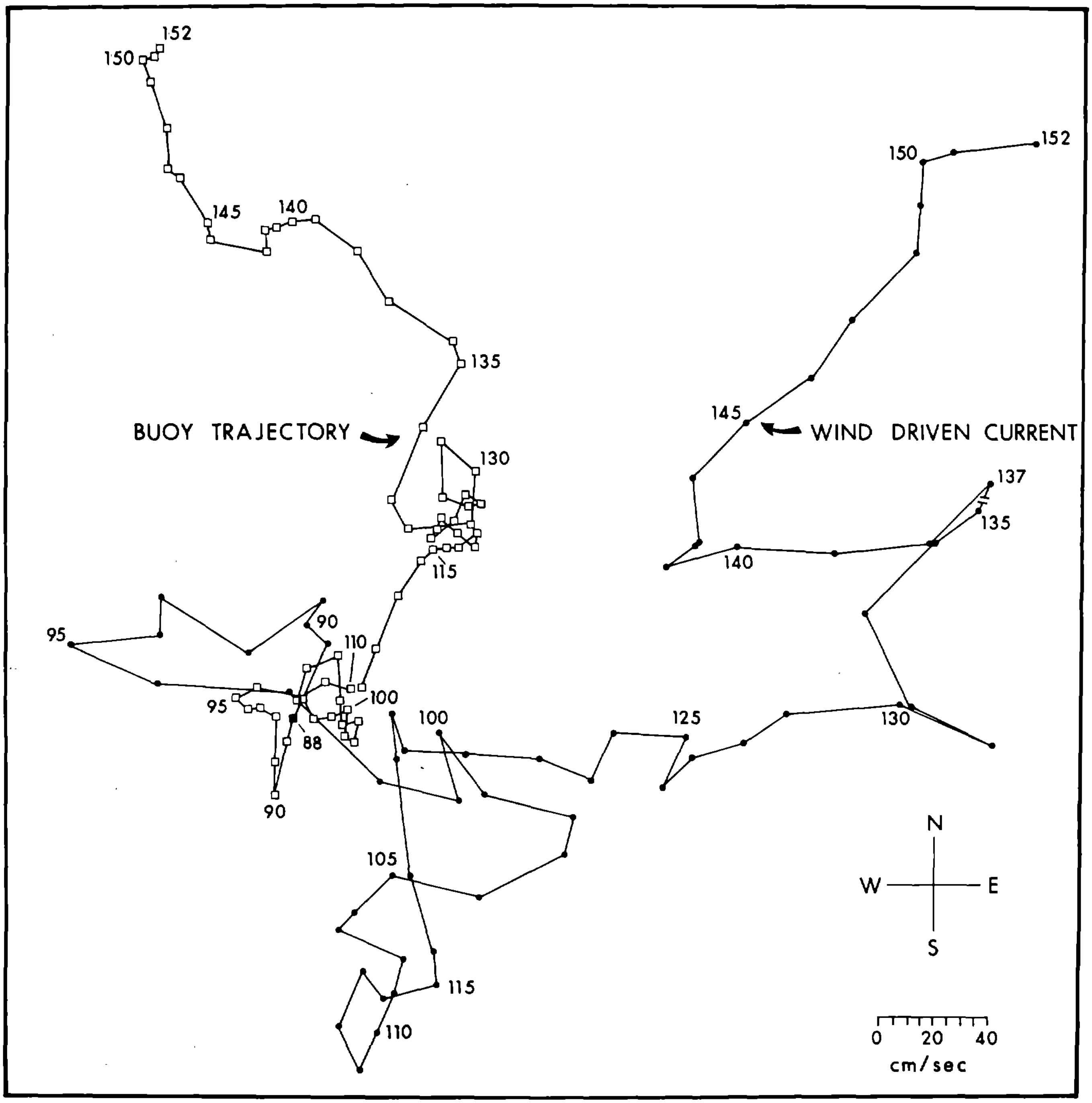


Figure 11. Buoy 405 trajectory and wind-driven-current progressive vector plot, 31 March (Day 88)-1 June (Day 152) 1979.

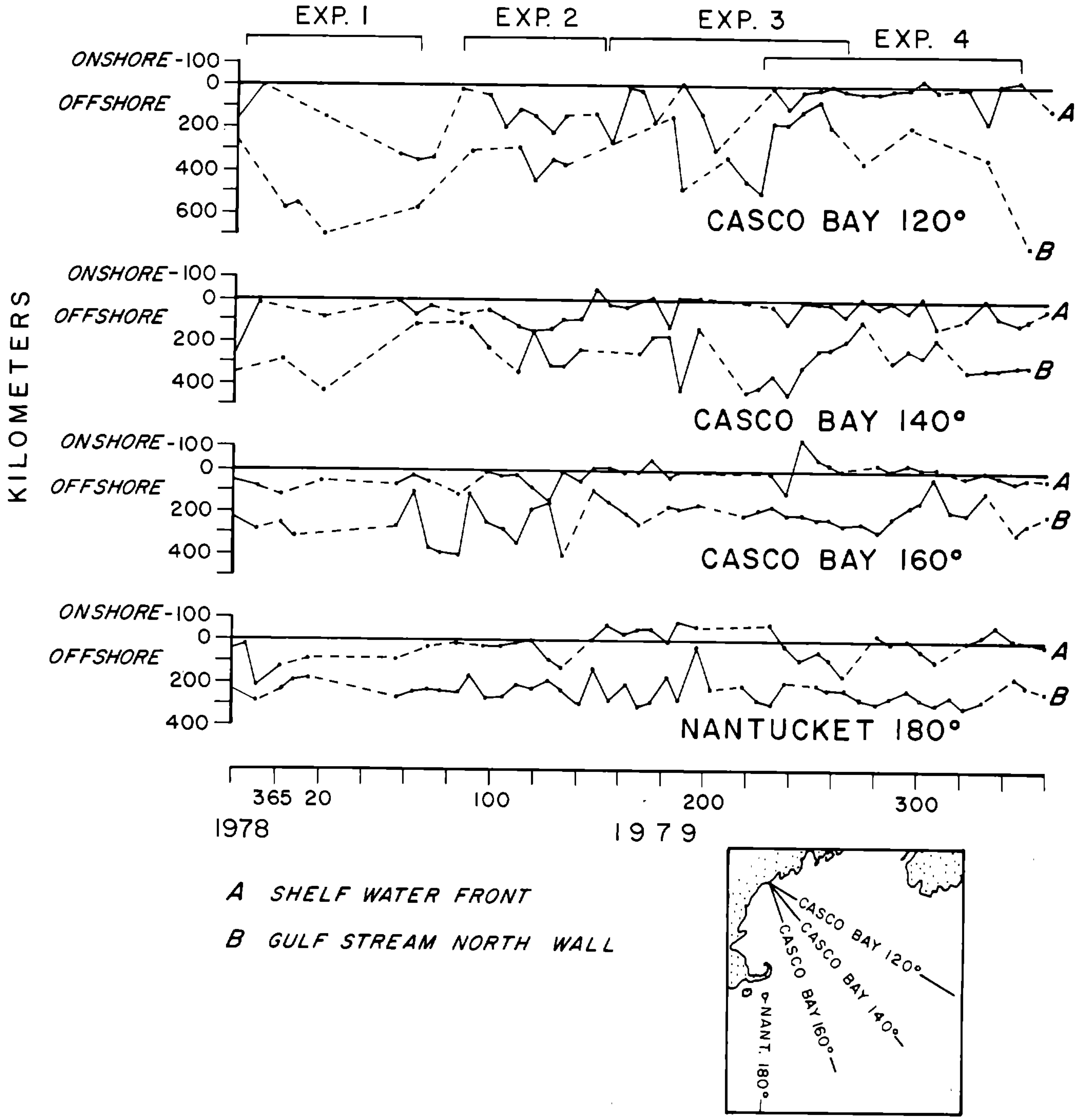


Figure 12. Weekly positions of the shelf water front and the Gulf Stream north wall relative to the 200-m isobath during the period of the four buoy experiments.

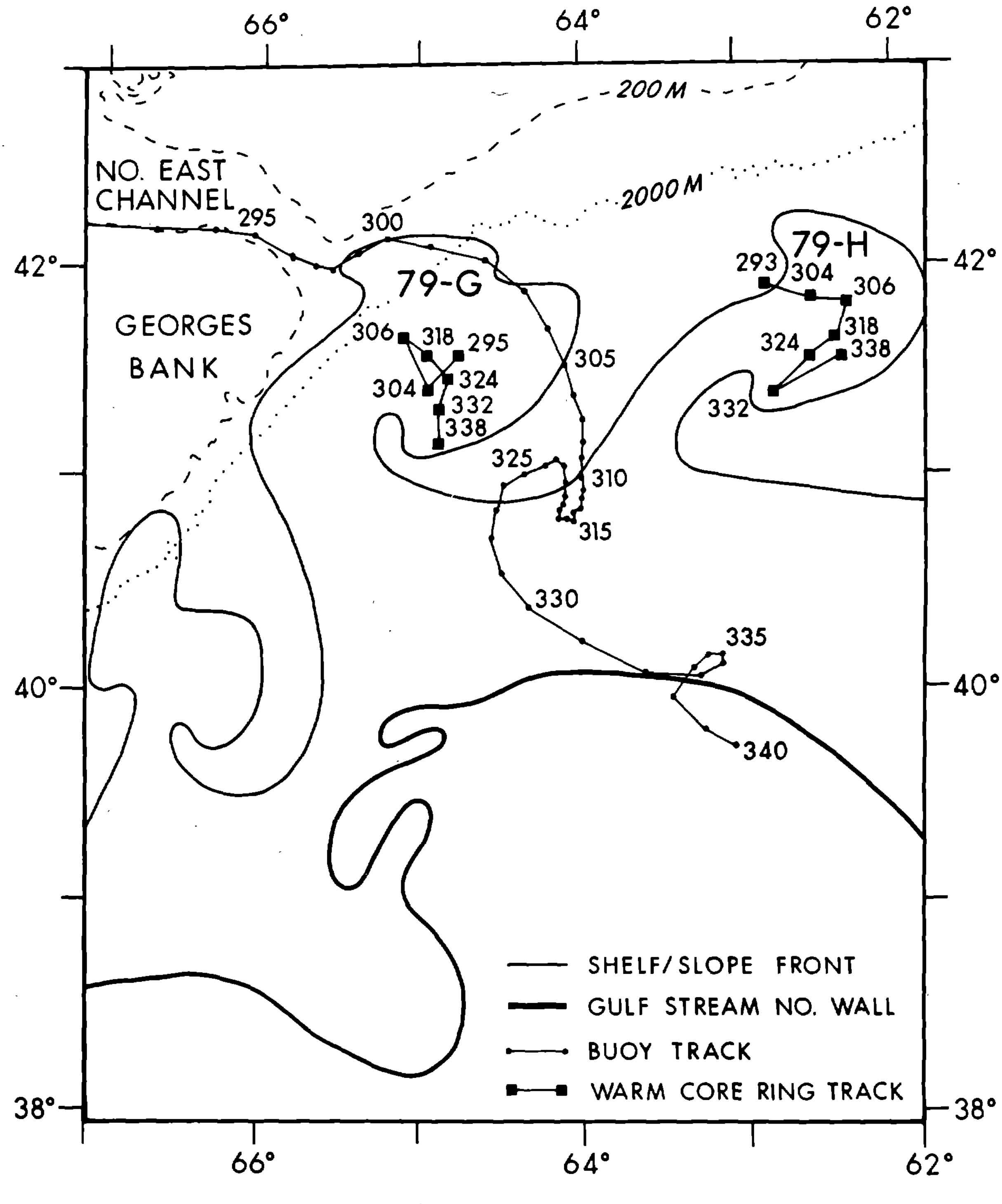


Figure 13. Trajectory of buoy 620 during the period 20 October-6 December 1979 in relation to the location of warm-core rings 79G and 79H and the mean position of thermal fronts as indicated by satellite imagery for the period 1-7 November 1979.

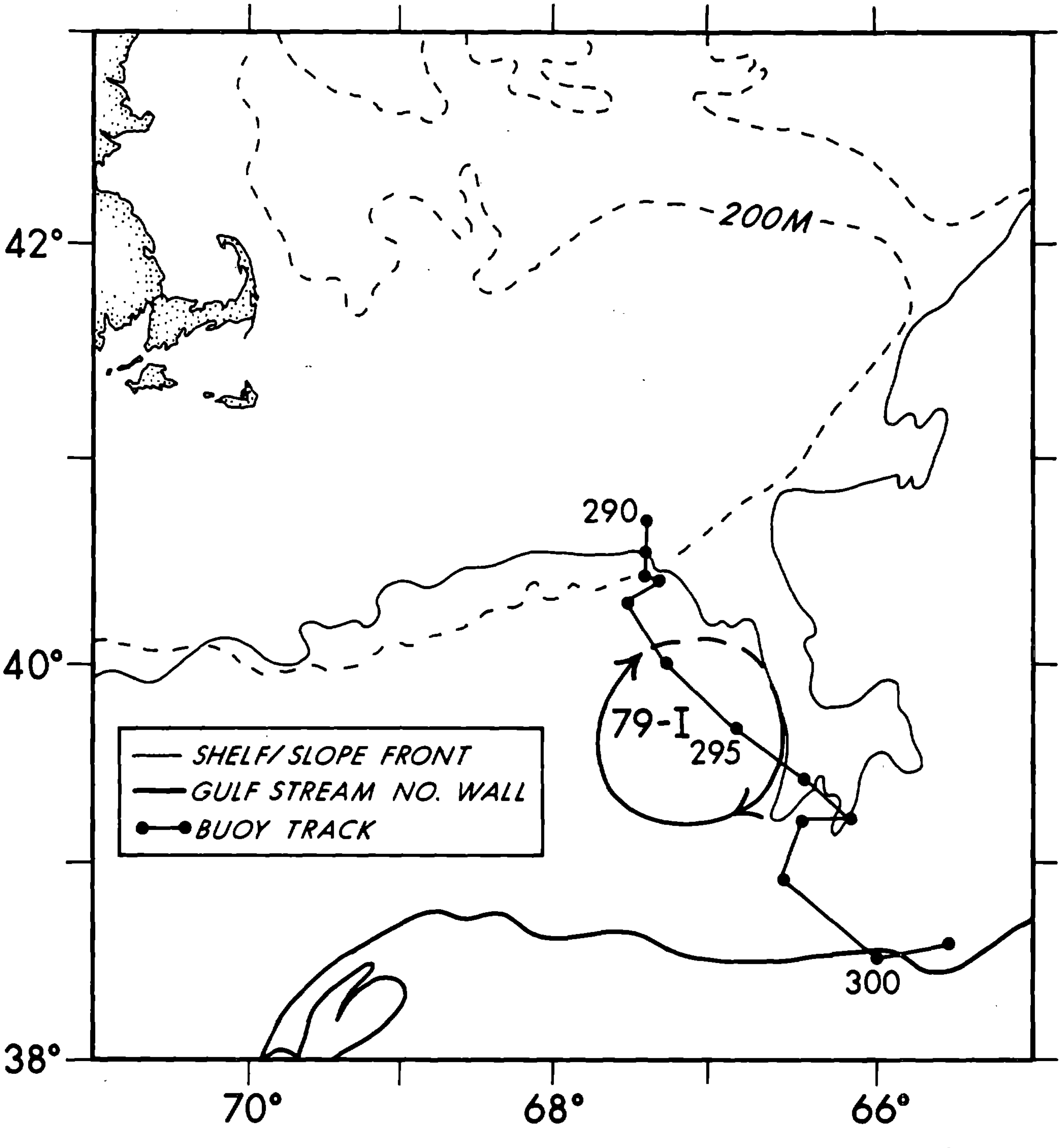


Figure 14. Trajectory of buoy 703 during the period 17-28 October 1979 and the mean position of warm-core ring 79I and the thermal fronts as indicated by satellite imagery for the period 21-27 October 1979.

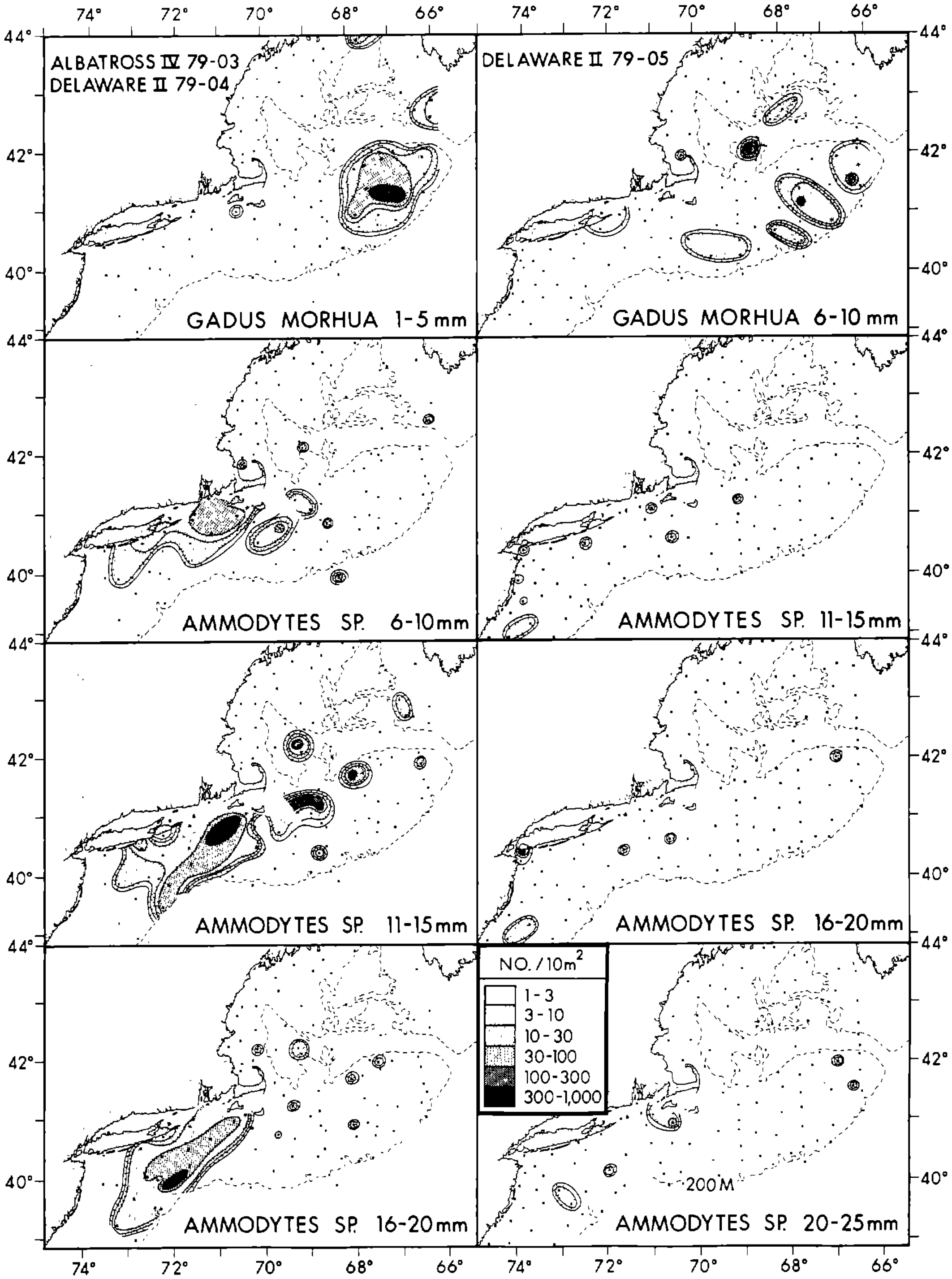


Figure 15. Comparison of the distributions of larval Atlantic cod (Gadus morhua) and sand lance (Ammodytes sp.) during combined Albatross IV Cruise 79-03 and Delaware II Cruise 79-04 (mid-date, Day 109), and Delaware II Cruise 79-05 (mid-date, Day 140).

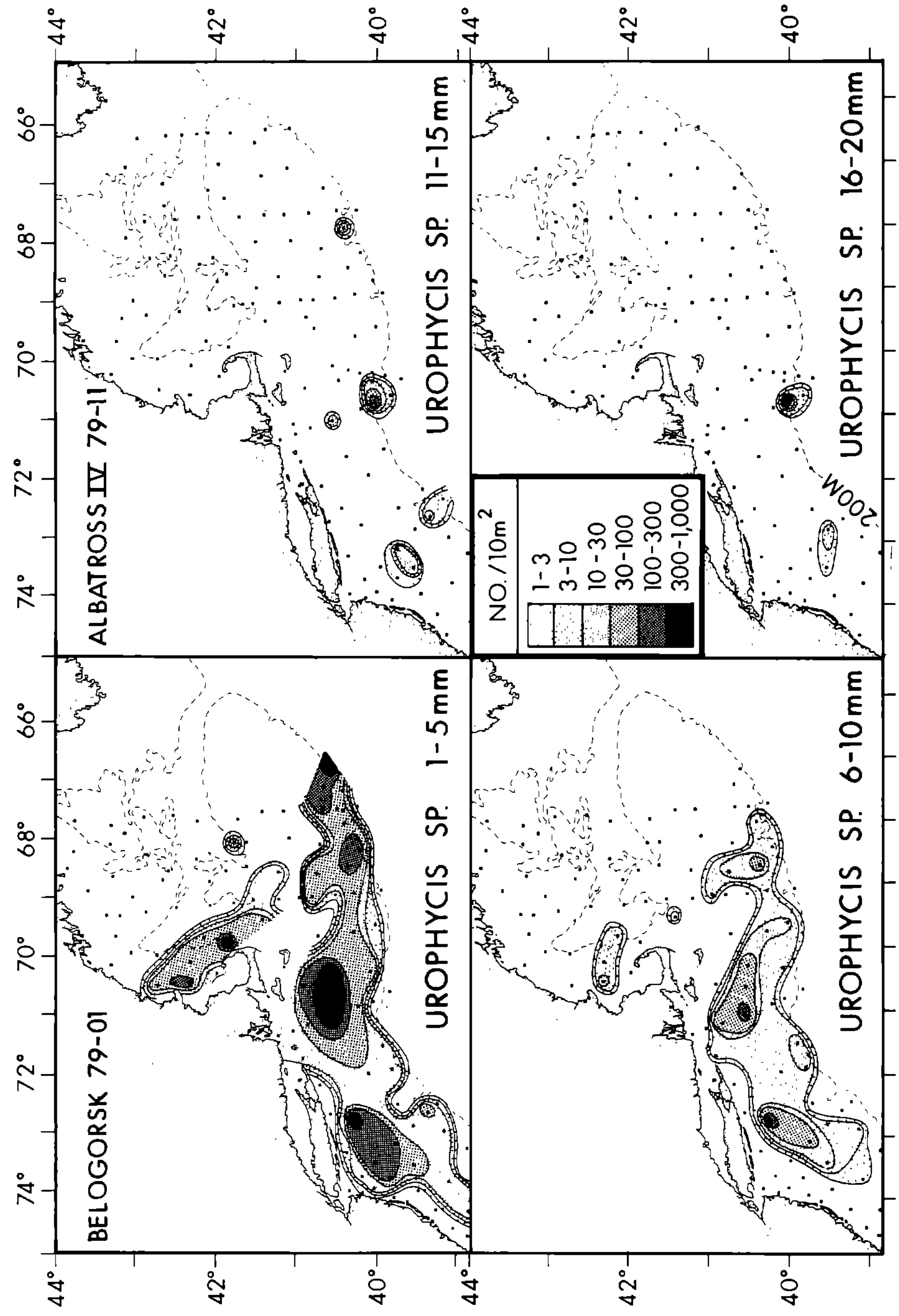


Figure 16. Comparison of the distributions of larval hake (<u>Urophycis</u> sp.) during <u>Belogorsk</u> Cruise 79-01 (mid-date, Day 234) and <u>Albatross IV</u> Cruise 79-11 (mid-date, Day 288).

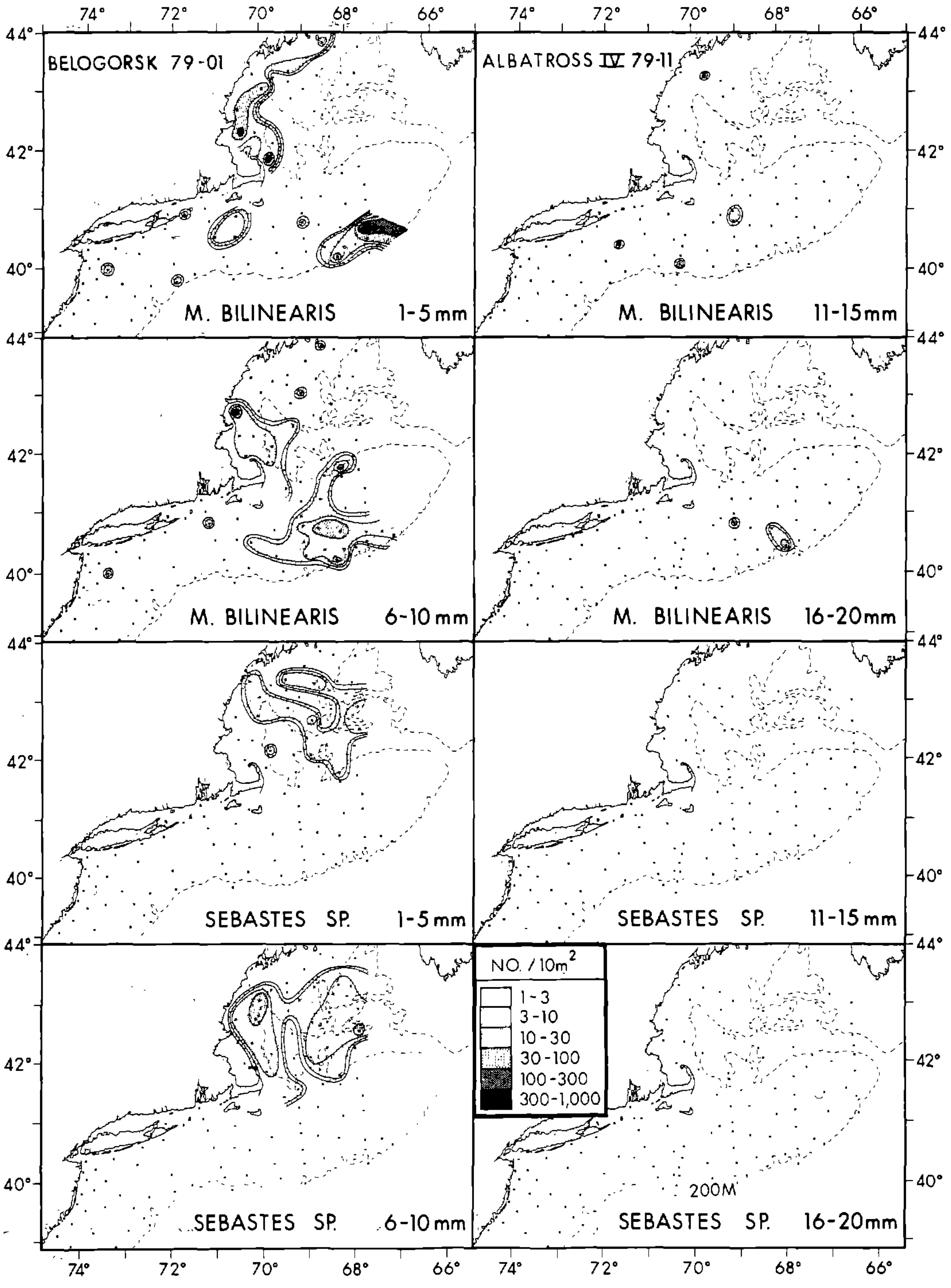


Figure 17. Comparison of the distributions of larval silver hake (Merluccius bilinearis) and redfish (Sebastes sp.) during Belogorsk Cruise 79-01 (mid-date, Day 234) and Albatross IV Cruise 79-11 (mid-date, Day 288).

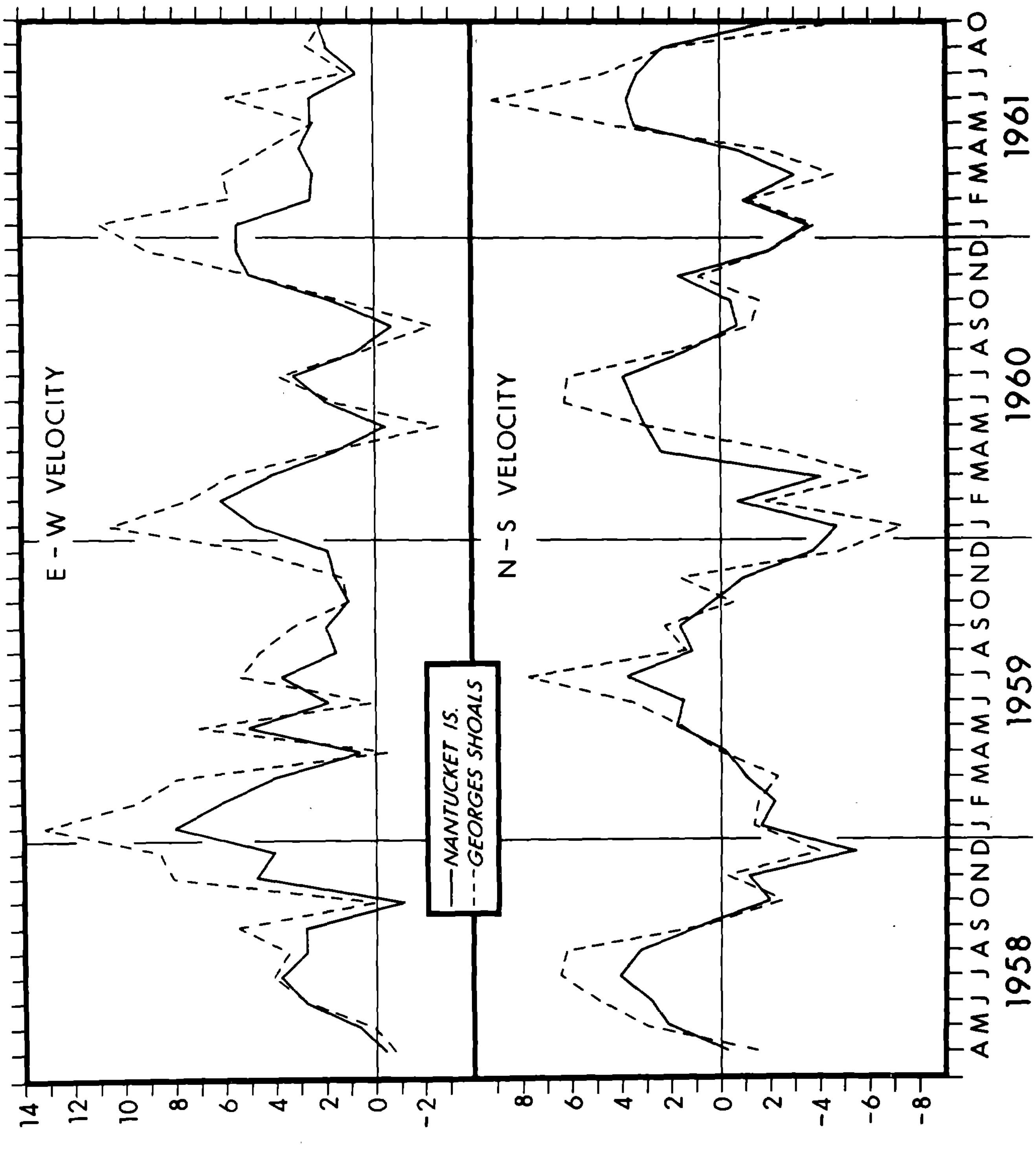


Figure 18. Components of monthly resultant wind velocity at Nantucket Island and Georges Shoals. Positive components are to the east and north.

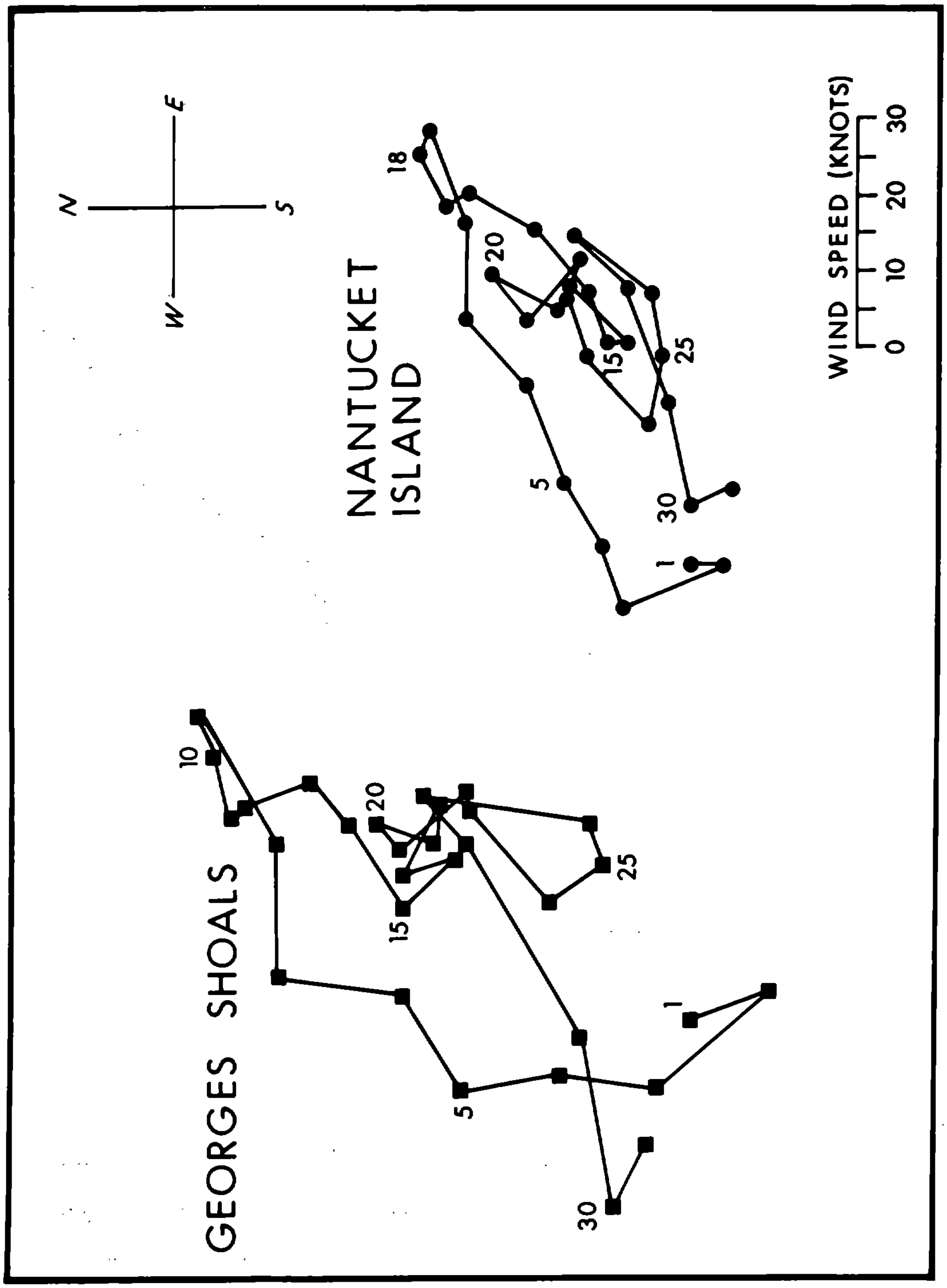


Figure 19. Progressive vector plots of Nantucket Island and Georges Shoals daily resultant winds, April 1951.

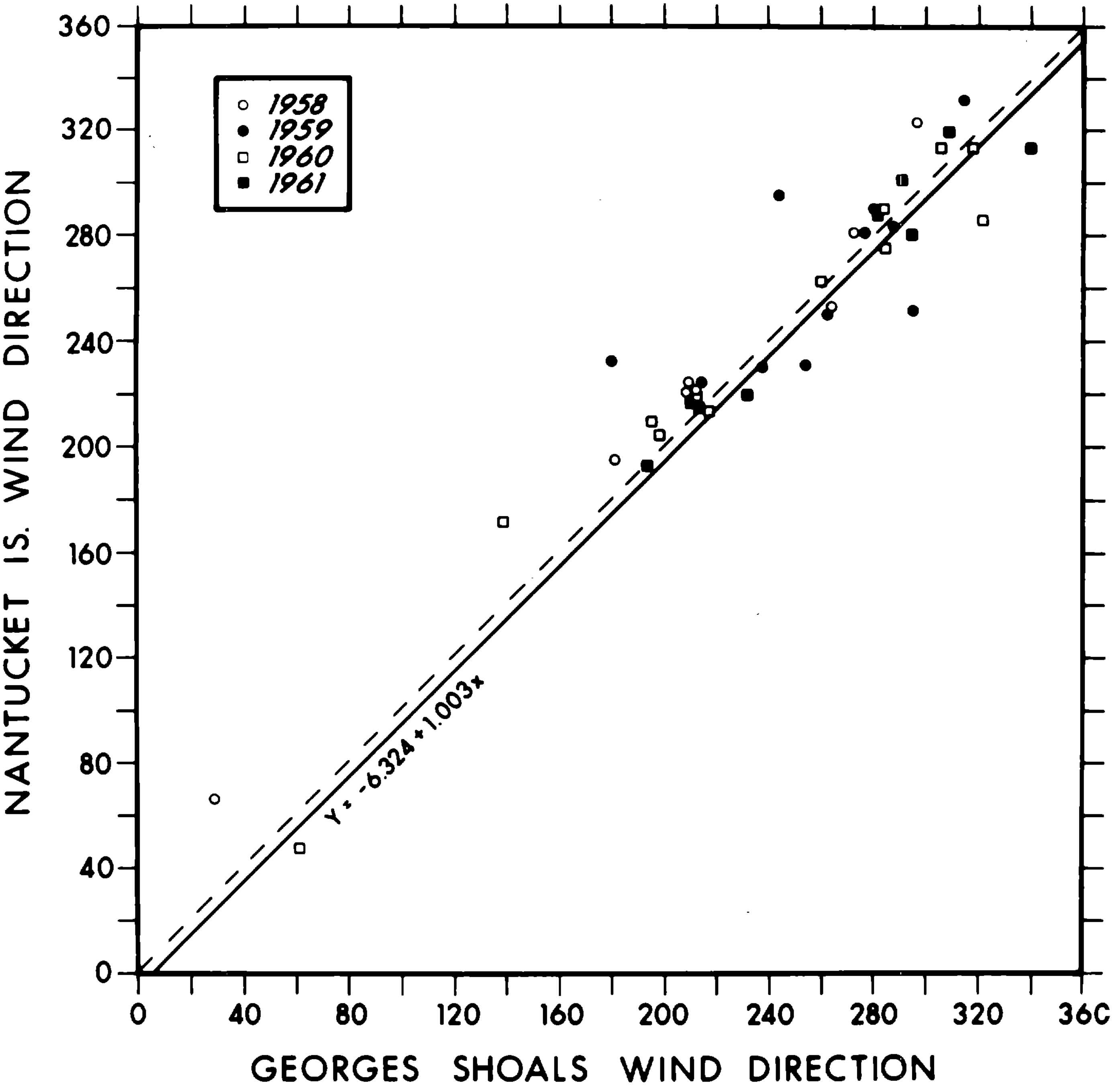


Figure 20. Comparison of Nantucket Island and Georges Shoals wind directions. Dashed line has a slope of unity.

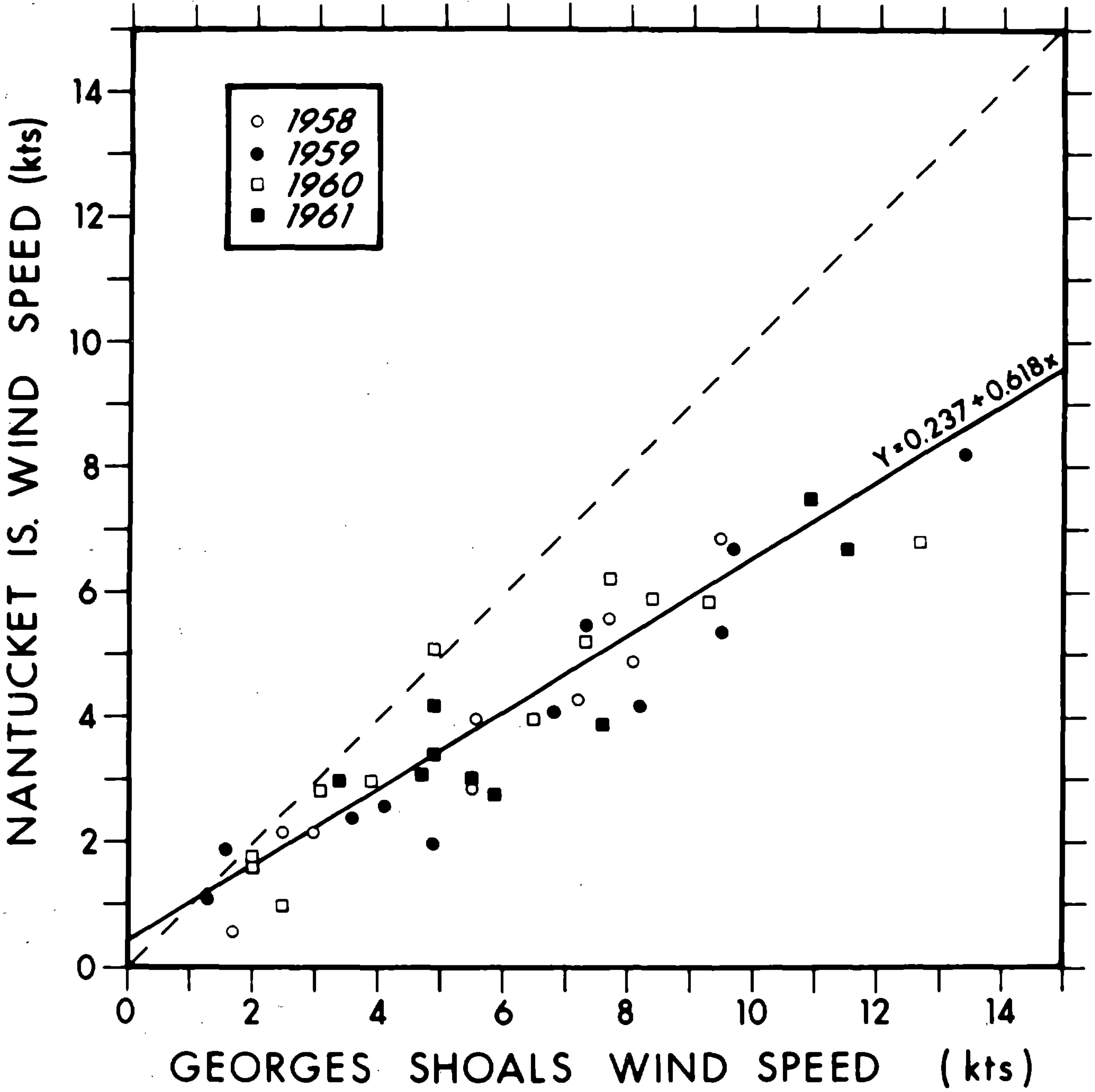
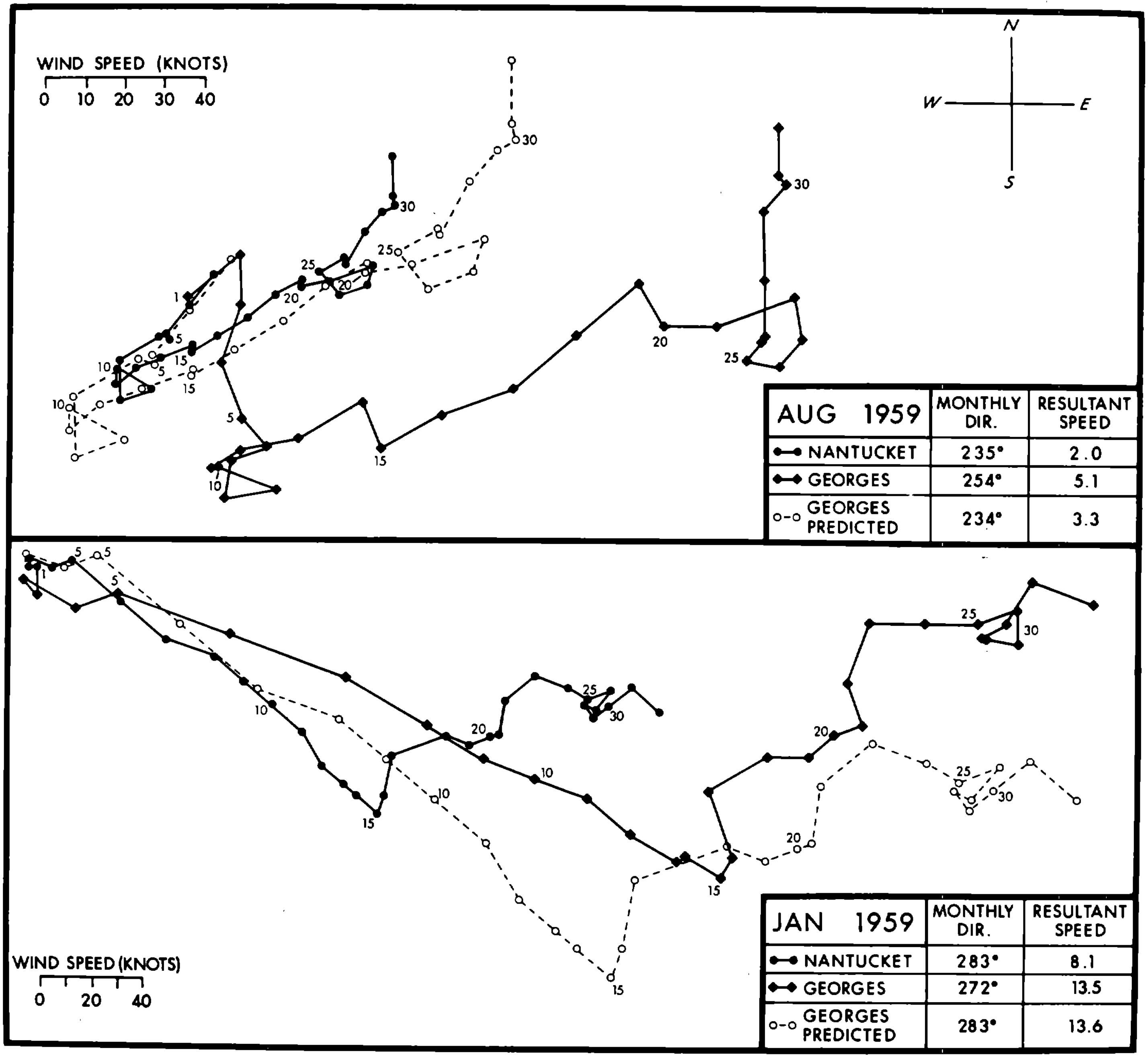


Figure 21. Comparison of Nantucket Island and Georges Shoals wind speeds. Dashed line has a slope of unity.



AUG 1959	MONTHLY DIR.	RESULTANT SPEED
●—● NANTUCKET	235°	2.0
◆—◆ GEORGES	254°	5.1
○-○ GEORGES PREDICTED	234°	3.3

JAN 1959	MONTHLY DIR.	RESULTANT SPEED
●—● NANTUCKET	283°	8.1
◆—◆ GEORGES	272°	13.5
○-○ GEORGES PREDICTED	283°	13.6

Figure 22. Comparison of progressive vector plots of daily Nantucket Island, Georges Shoals, and predicted Georges Bank winds, Janaury 1959 and August 1959.

Table 1. The consecutive number of each day of the year.

Day of month	Jan.	Feb.[a]	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Day of Month
1	1	32	60	91	121	152	182	213	244	274	305	335	1
2	2	33	61	92	122	153	183	214	245	275	306	336	2
3	3	34	62	93	123	154	184	215	246	276	307	337	3
4	4	35	63	94	124	155	185	216	247	277	308	338	4
5	5	36	64	95	125	156	186	217	248	278	309	339	5
6	6	37	65	96	126	157	187	218	249	279	310	340	6
7	7	38	66	97	127	158	188	219	250	280	311	341	7
8	8	39	67	98	128	159	189	220	251	281	312	342	8
9	9	40	68	99	129	160	190	221	252	282	313	343	9
10	10	41	69	100	130	161	191	222	253	283	314	344	10
11	11	42	70	101	131	162	192	223	254	284	315	345	11
12	12	43	71	102	132	163	193	224	255	285	316	346	12
13	13	44	72	103	133	164	194	225	256	286	317	347	13
14	14	45	73	104	134	165	195	226	257	287	318	348	14
15	15	46	74	105	135	166	196	227	258	288	319	349	15
16	16	47	75	106	136	167	197	228	259	289	320	350	16
17	17	48	76	107	137	168	198	229	260	290	321	351	17
18	18	49	77	108	138	169	199	230	261	291	322	352	18
19	19	50	78	109	139	170	200	231	262	292	323	353	19
20	20	51	79	110	140	171	201	232	263	293	324	354	20
21	21	52	80	111	141	172	202	233	264	294	325	355	21
22	22	53	81	112	142	173	203	234	265	295	326	356	22
23	23	54	82	113	143	174	204	235	266	296	327	357	23
24	24	55	83	114	144	175	205	236	267	297	328	358	24
25	25	56	84	115	145	176	206	237	268	298	329	359	25
26	26	57	85	116	146	177	207	238	269	299	330	360	26
27	27	58	86	117	147	178	208	239	270	300	331	361	27
28	28	59	87	118	148	179	209	240	271	301	332	362	28
29	29	*	88	119	149	180	210	241	272	302	333	363	29
30	30		89	120	150	181	211	242	273	303	334	364	30
31	31		90		151		212	243		304		365	31

[a] In leap years, after 28 February, add 1 to the tabulated number.

Table 2. Monthly and annual wind statistics for Nantucket Island and Georges Shoals, 1958-61.

		Nantucket Island		Georges Shoals		Georges-Nantucket wind speed ratio	Nantucket vs. Georges Shoals			
							Variance ratio[a]		Correlation coefficient[a]	
Year	Month	Direction (from)	Speed (knots)	Direction (from)	Speed (knots)		Direction	Speed	Direction	Speed
1958	April	066°	0.6	029°	1.7	1.8				
	May	196°	2.2	181°	3.0	1.4				
	June	225°	4.0	209°	5.6	1.4				
	July	222°	5.6	212°	7.7	1.4				
	August	221°	4.3	208°	7.2	1.7				
	September	254°	2.9	263°	5.5	1.9				
	October	029°	2.2	360°	2.5	1.1				
	November	282°	4.9	272°	8.1	1.7				
	December	324°	6.9	296°	9.5	1.4				
	Total	258°	2.2	250°	3.8	1.3	0.28	2.91	0.98	0.96
1959	January	282°	8.2	276°	13.4	1.6				
	February	290°	6.7	279°	9.7	1.4				
	March	284°	4.2	287°	8.2	2.0				
	April	291°	0.6	094°	0.6	1.0				
	May	251°	5.5	262°	7.3	1.3				
	June	233°	2.4	180°	3.6	1.5				
	July	225°	5.4	214°	9.5	1.8				
	August	232°	2.0	254°	4.9	2.5				
	September	231°	2.6	237°	4.1	1.6				
	October	253°	1.1	295°	1.3	1.2				
	November	296°	1.9	243°	1.6	0.8				
	December	332°	4.1	314°	6.8	1.7				
	Total	264°	3.2	263°	4.9	1.5	0.16	2.75	0.69	0.96
1960	January	314°	6.8	305°	12.7	1.9				
	February	276°	6.2	284°	7.7	1.2				
	March	314°	5.9	317°	8.4	1.4				
	April	214°	2.9	217°	3.1	1.1				
	May	172°	3.0	138°	3.9	1.3				
	June	210°	4.0	195°	6.5	1.3				
	July	220°	5.2	212°	7.3	1.4				
	August	205°	1.6	198°	2.0	1.3				
	September	047°	1.0	061°	2.5	2.5				
	October	287°	1.8	321°	2.0	1.1				
	November	263°	5.1	260°	4.9	1.0				
	December	290°	5.9	283°	9.3	1.6				
	Total	266°	2.8	262°	3.5	1.3	0.00	2.37	0.97	0.91
1961	January	302°	6.7	290°	11.5	1.7				
	February	289°	2.8	281°	5.9	2.1				
	March	320°	3.9	308°	7.6	1.9				
	April	281°	3.1	294°	4.7	1.5				
	May	217°	4.2	210°	4.9	1.2				
	June	215°	7.5	213°	10.9	1.5				
	July	193°	3.4	193°	4.9	1.4				
	August	220°	3.0	231°	3.4	1.1				
	October	314°	3.0	339°	5.5	1.8				
	Total	261°	2.4	265°	4.6	1.9	0.00	4.72[b]	0.96	0.90
Total		265°	2.7	262°	4.2	1.6	0.04	12.38[b]	0.96	0.93

---

[a] Values at 0.05 level of significance.

[b] Significant.