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DEPARTMENT OF COMMERCE
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LAGRANGIAN MEASURES OF NEAR-SURFACE WATERS AT THE 106 MILE DUMPSITE

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UNITED STATES DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

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John V. Byrne, Administrator

Office of Marine Pollution Assessment
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Thanks are also due to Lianne Armstrong who drafted the figures and Christine Corey and Gertrude Kavanagh who typed the manuscript.

CONTENTS

LAGRANGIAN MEASURES OF NEAR-SURFACE WATERS AT THE 106 MILE DUMPSITE

James J. Bisagni, NOAA/OMPA

INTRODUCTION

Measurements of advection for near-surface waters at the 106 Mile Dumpsite were conducted during 1979 and 1980 using Lagrangian techniques. A series of drogued, radio direction finding (RDF) buoys operating on either the 6 MHz or 4 MHz band were deployed and tracked at the dumpsite during March 7-17, 1979, and May 8-16, 1979. A third experiment conducted May 8-24, 1980, resulted in a deployment of RDF buoys both at the 106 Mile Site and at a location on the continental shelf some 34 km northwest of the site. Wind data in the vicinity of the 106 Mile Site and continental shelf areas for each experiment were analyzed and used to compute appropriate Ekman layer velocities. Both these wind data and Ekman layer velocities were then compared with the RDF buoy trajectories.

Based on the results of these radio-direction-finding buoy measurements, a long-term advection experiment was planned. Two satellite tracked drifting drogued buoys were deployed near the center of the 106 Mile Dumpsite on September 4, 1980, and tracked until December 31, 1980. These results are compared with the trajectories of 3 satellite tracked drogued buoys deployed in the vicinity of Georges Bank by the Raytheon Environmental Systems Center.

METHODS

Radio-direction-finding (RDF) buoys were located after their release using line-of-bearing measurements from shore-based radio-direction-finding receivers. The receivers were located near Sandy Hook, New Jersey, Cape Henlopen, Delaware, or Ocean City, Maryland. Line-of-bearing (LOB) measurements from two receivers were combined using a great circle triangulation program which produced a mean buoy position and an associated location error. The location error for each mean was an area usually resembling a parallelogram which resulted from the intersection of the mean LOB ± 1 standard deviation from the two shore stations to the buoy. This error area was converted to an equivalent circular area with an equivalent error radius. All buoy positions calculated in this manner from the three RDF experiments are given in Table 1 along with their equivalent error radii.

The satellite-tracked ocean drifting buoys 3020 and 3021 were equipped with Service ARGOS certified platform transmitter terminals (PTT) to allow reliable positional and sea-surface temperature information to be transmitted via TIROS-N satellites to the ARGOS ground station in Toulouse, France. Positional fixes have an error radius of 1 km. The buoys were also equipped with window shade type drogues centered at 10 m depth and a drogue sensor switch that could transmit the status of the drogue via satellite to the ground station.

RADIO DIRECTION FINDING BUOY RESULTS

Buoys released at the 106 Mile Site during the March and May 1979 experiments were deployed by the USCGC Unimak and the NOAA ship Whiting, respectively. Buoys released at both the 106 Mile Site and a shelf site during the May 1980 experiment were deployed by the NOAA ship G. B. Kelez.

The resultant buoy trajectories from these three experiments were quite different.

During the March 1979 experiment (Fig. 1) only one significant positional fix was determined for each of five buoys drogued at 5 m, 10 m, or 30 m depth. These five buoys showed average speeds of 6 to 53 cm/sec (0.1 to 1.0 knots) over a 2- or 3- day period ranging in direction from 274° to 349° true, thus moving shoreward onto the continental shelf. During May 1979 (Fig. 2) buoy reception was better, resulting in up to three statistically significant positional fixes for two of the six buoys, also drogued at 5 m, 10m or 30 m depth. These six buoys showed average speeds of 21 to 118 cm/sec (0.4 to 2.3 knots) over a period from 1 to 8 days ranging in direction from 45° to 71° true. Thus, the movements of the buoys were northeasterly, approximately parallel to the bathymetry, well offshore of the continental shelf. May 1980 (Fig. 3) buoy reception was similar to that of the previous year; a total of six buoys were received, two of which had two significant positional fixes. Four buoys were released at the 106 Mile Dumpsite and were drogued at 10, 20, or 30 m depth, while the remaining two buoys were released from a continental shelf site located at 39°05'N, 72°53'W. These two buoys were drogued at 20 m and 30 m depth. The four buoys released at the 106 Mile Site moved southwest with two buoys moving onto the shelf and showed average speeds of 11 to 21 cm/sec (0.2 to 0.4 knots) ranging in direction from 197° to 266° true. The other two buoys released on the shelf apparently remained on the shelf and behaved similarly with average speeds of 14 and 15 cm/sec (0.3 knots) toward 240° and 226° true, respectively.

Wind data for each experiment period were obtained from two sources. These data were obtained from NOAA Data Buoy 4004 located at 39°N, 70°W and from values derived at 40°N, 73°W and 39°N, 72°W by NOAA/NMFS Pacific Environmental Group through synoptic surface pressure analysis. Daily average wind vectors were determined at each of these three wind stations and their weighted sums plotted as a single station. Continuous vector diagrams of these data are given in Figures 4-6. A mean wind was then determined for each experiment and used for Ekman layer calculations.

Ekman layer velocities are a result of the Ekman spiral solution to the equations of motion for Ekman flow. This shows that for a sufficiently deep ocean, the maximum wind induced current occurs at 0 m depth at 45° to the right of wind stress vector (in the northern hemisphere). Furthermore, the wind induced current decreases rapidly and at higher angles to the right of the wind with increasing depth.

The mean wind vector for each of the three experiments was used to calculate the Ekman velocities for the depths at which the buoys' drogues had been set. This would then allow a comparison to be made between the theoretical wind driven current and the actual buoy trajectory. These comparisons are presented in Table 2 and as vector diagrams (Figs. 7, 10, 12 and 13).

During March 1979 (Fig. 7), the mean wind was toward 95.4°T, i.e., almost due east at 111.7 cm/sec. The calculated Ekman velocities are almost directly opposed to the velocities of the drogued buoys at 5, 10, and 30 m.

A surface Ekman velocity of 26.8 cm/sec at 140°T decreased to 1.8 cm/sec at 295°T for 30 m depth. Buoy trajectories show an increase in velocity with increasing depth from 13 cm/sec at 325°T for 5 m to 47 cm/sec at 277°T for 30 m depth. This difference between the predicted and actual movements of the drogued buoys could be explained by a near-surface Ekman induced offshore flow which would require a deeper onshore return flow. XBT data and satellite-derived sea-surface temperature interpretations from the vicinity (Figs. 8 and 9) at the time of the buoys' deployments have shown a hydrographic regime which is consistent with such a two-layer system. Colder Shelf Water is shown overlying the 106 Mile Dumpsite with the Shelf Water/Slope Water Front located approximately 20 km southeast of the site. Thus, the deeper drogued buoys were possibly responding to the warmer Slope Water flowing in a shoreward layer beneath the near-surface Shelf Water layer. Boicourt (1973) and Boicourt and Hacker (1976) proposed a similar system for the extreme offshore regions of the continental shelf.

During May 1979, the mean wind blew towards 23.4°T at 158.8 cm/sec which resulted in the Ekman velocities shown in Figure 10. The average buoy velocities from this experiment more closely parallel these calculated Ekman values. The average buoy speeds, however, are of considerably greater magnitude. Furthermore, daily speeds of buoys 291, 293, and 295 all exceeded 130 cm/sec at some point. Clearly, Ekman drift by itself cannot explain these very high observed velocities. A more plausible explanation is based on the presence of anticyclonic Gulf Stream ring 79-A which was located east-northeast of the dumpsite based on satellite-derived sea surface temperature data (Fig. 11). The northeasterly directions and speeds of the buoys' trajectories are consistent with a ring located in this position.

Wind-driven currents, however, may have been the factor which initially caused the buoys to move into ring A's geostrophic circulation. XBT data (Fig. 8) and satellite data combine to show that the buoy trajectories lay within Slope Water or surface warmed Slope Water at least until they encountered ring 79-A.

In May 1980, the mean wind blew towards 70°T at 278.7 cm/sec which resulted in the Ekman velocities given in Figures 12 and 13. The wind field was assumed to be uniform at both the 106 Mile Site and the more shallow shelf site where buoys were released. Although the depth of the shelf site was only 96 m, this depth is greater than that required for Ekman calculations to be valid. The average buoy velocities from buoys drogued at 10, 20, or 30 m and deployed at both sites closely parallel the calculated Ekman values at 20 and 30 m depth. This suggests that wind driven currents may have predominated and that these currents were of a similar magnitude and direction at both sites. Satellite-derived data (Fig. 14) shows that buoys 463 and 465 initially remained in Slope Water, but may have crossed the Shelf Water/Slope Water Front onto the shelf and into Shelf Water.

SATELLITE BUOY RESULTS

Figure 15 shows the deployment positions for both satellite-tracked buoys near the center of the 106 Mile Dumpsite and a segment of each trajectory during which the drogues remained intact. These trajectories are only a portion of each buoy's total trajectory which ended on December 31, 1980, when Service ARGOS ceased their tracking efforts. Numbers written alongside the trajectories signify the Julian day number for specific positional fixes beginning with the deployment on September 4 (day 248) and ending with October 12 and 14, 1980 (days 284 and 286). These trajectories were derived from positional fixes, obtained in almost real-time on a daily basis (except weekends) via a telephone link with the French ground station. Multiple positional fixes and data were collected by Service ARGOS daily and later sent fortnightly in printout form to the NOAA Office of Marine Pollution Assessment.

Buoys 3020 and 3021 moved generally to the southwest after an initial movement to the west northwest, never moving inshore of the 100 fm shelf break. The average speeds for buoys 3020 and 3021 along these trajectories between days 248 and 281 were 16 cm/sec (0.3 knots) and 12 cm/sec (0.2 knots), respectively.

Beginning with day 266, both buoys showed a net offshore motion before resuming a net southwesterly drift farther offshore by day 273. This may have been due to both buoys encountering offshore flow around anticyclonic Gulf Stream ring 80-A (not shown) centered near 37°40'N, 73°45'W. Further analysis of the nonreal-time sea-surface temperature and velocity data when combined with derived buoy separation distances could, for example, begin to explain why buoy 3021 began to lag behind 3020 after the possible interaction with ring 80-A. Upon reaching the vicinity of Cape Hatteras, both buoys became entrained in currents from the Gulf Stream.

Raytheon's Environmental Systems Center deployed 3 satellite-tracked ocean drifting buoys (unpublished data) south of Georges Bank on January 23, 1979 (Fig 16). These drogued buoys were tracked via the NIMBUS-G satellites. Usually, only one or possibly two positional fixes were obtained per week using this system. Buoys 0227 and 0234 drifted southwesterly through the 106 Mile Dumpsite with average speeds of 19 cm/sec (0.4 knots) and 14 cm/sec (0.3 knots), respectively. Buoy 0234 was prematurely retrieved on February 20 by a fishing vessel. Buoy 0132 moved initially to the northwest, but later moved southwesterly at 21 cm/sec (0.4 knots) passing just southeast of the dumpsite. After deployment, all three buoys remained offshore of the 100 fm contour. Average speeds for these buoys were slightly higher than those deployed in the NOAA study. Upon reaching the vicinity of Cape Hatteras, the buoys became entrained in the Gulf Stream. The trajectories from both the Raytheon and NOAA studies, however, are remarkably similar despite some small differences.

CONCLUSIONS

Based on these few Lagrangian studies, a slow southwesterly drift of the near-surface water from the 106 Mile Dumpsite seems apparent. This slow, perhaps wind-driven, current was measured to be less than 0.5 knots (25 cm/sec) and is somewhat consistent with Bumpus' (1972) drift bottle data for the shelf region. The drift of waters originally located in the dumpsite to a position located off Cape Hatteras thus requires about one month's time.

Onshore flow of sub-surface Slope Water of close to 1.0 knot from the dumpsite was observed during a period when offshore Ekman flow of surface Shelf Water caused a stratified condition to occur in late winter.

Both types of wind-driven currents appear, however, to be perturbed aperiodically by the swifter geostrophic currents (2.0 knots) associated with anticyclonic Gulf Stream (warm core) rings. Observations from such an episode showed strong northeasterly currents directly opposed to the normally slow southwesterly drift. Waters entrained in such currents could be swiftly advected away from the 106 Mile Dumpsite.

The current regime at the 106 Mile Dumpsite is extremely variable with speeds spanning at least one order of magnitude and widely different current directions. This current variability is attributable to the location of the site itself (i.e., its proximity to strong oceanic density fronts, the movements of which are not well understood) and the seasonal changes in both the near-surface waters and the associated wind regimes.

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Boicourt, W. C. and P. W. Hacker, 1976. Circulation of the Atlantic Continental Shelf of the United States, Cape May to Cape Hatteras. Mem. Soc. Royale des Sciences de Liege, 6° serie, tome X, pp. 187-200.

Bumpus, D. F., 1972. A description of the circulation on the continental shelf of the east coast of the United States. Prog. in Oceanog. 6:111-157.

Table 1

RDF Buoy Positions and Their Associated Equivalent Error Radii as Determined by Great Circle Triangulation from 2 Shore Stations, March and May 1979 and May 1980

March 7-17, 1979 Experiment

Buoy Number	Drogue Depth (m)	Day	Position (Lat., Long.)	Equivalent Error Radius (Km)
264	5	10	38°59'N, 72°17'W	24.7
265	5	10	39°05'N, 72°46'W	16.3
266	30	9	39°01'N, 73°21'W	28.0
267	10	10	38°57'N, 73°07'W	17.0
269	30	9	38°52'N, 73°16'W	16.8

May 8-16, 1979 Experiment

291	5	9	39°02'N, 71°47'W	5.3
291	5	10	39°00'N, 71°33'W	7.5
291	5	11	39°26'N, 70°01'W	12.8
292	5	10	39°00'N, 71°43'W	3.7
293	10	9	39°08'N, 71°28'W	11.9
293	10	10	39°04'N, 71°48'W	4.8
294	10	9	39°13'N, 71°45'W	5.7
295	30	9	39°07'N, 71°49'W	7.1
295	30	15	39°35'N, 71°10'W	11.3
295	30	16	40°01'N, 69°54'W	30.7
296	30	9	39°08'N, 71°38'W	5.1

May 8-23, 1980 Experiment

454	30	23	38°13'N, 74°46'W	2.9
455	10	24	37°51'N, 73°40'W	9.0
463	10	20	38°06'N, 74°04'W	5.9
463	10	23	38°05'N, 74°23'W	5.1
465	30	20	38°05'N, 74°31'W	3.7
468	20	20	38°06'N, 74°12'W	6.0
472	20	16	38°06'N, 72°26'W	7.3
472	20	20	37°30'N, 73°20'W	7.7

Table 2

The Mean Wind and the Average Calculated and Observed Water Velocities During the March 1979, May 1979, and May 1980, RDF Buoy Experiments

March 7-17, 1979 Experiment

Mean Wind	111.7cm/sec at 95° True
Average Buoy Drift at 5 m	13.0 cm/sec at 325° True
Calculated Ekman Drift at 5 m	17.1 cm/sec at 166° True
Average Buoy Drift at 10 m	30.0 cm/sec at 278° True
Calculated Ekman Drift at 10 m	10.9 cm/sec at 192° True
Average Buoy Drift at 30 m	47.0 cm.sec at 277° True
Calculated Ekman Drift at 30 m	1.8 cm/sec at 295° True
Calculated Ekman Drift at 0 m	26.8 cm/sec at 140° True

May 8-16, 1979 Experiment

Mean Wind	158.8 cm/sec at 23° True
Average Buoy Drift at 5 m	64.0 cm/sec at 70° True
Calculated Ekman Drift at 5 m	34.5 cm/sec at 94° True
Average Buoy Drift at 10 m	67.1 cm/sec at 53° True
Calculated Ekman Drift at 10 m	22.0 cm/sec at 120° True
Average Buoy Drift at 30 m	77.5 cm/sec at 57° True
Calculated Ekman Drift at 30 m	3.6 cm/sec at 223° True
Calculated Ekman Drift at 0 m	54.1 cm/sec at 68° True

May 8-23, 1980 Experiment

Mean Wind	278.7 cm/sec at 70° True
Average Buoy Drift at 10 m (DWD 106)	14.7 cm/sec at 237° True
Calculated Ekman Drift at 10 m	67.8 cm/sec at 166° True
Average Buoy Drift at 20 m DWD 106)	17.8 cm/sec at 214° True
Average Buoy Drift at 20 m (Shelf)	14.7 cm/sec at 226° True
Calculated Ekman Drift at 20 m	27.5 cm/sec at 218° True
Average Buoy Drift at 30 m DWD 106)	21.3 cm/sec at 246° True
Average Buoy Drift at 30 m (Shelf)	14.2 cm/sec at 240° True
Calculated Ekman Drift at 30 m	11.2 cm/sec at 270° True
Calculated Ekman Drift at 0 m	166.8 cm/sec at 115° True

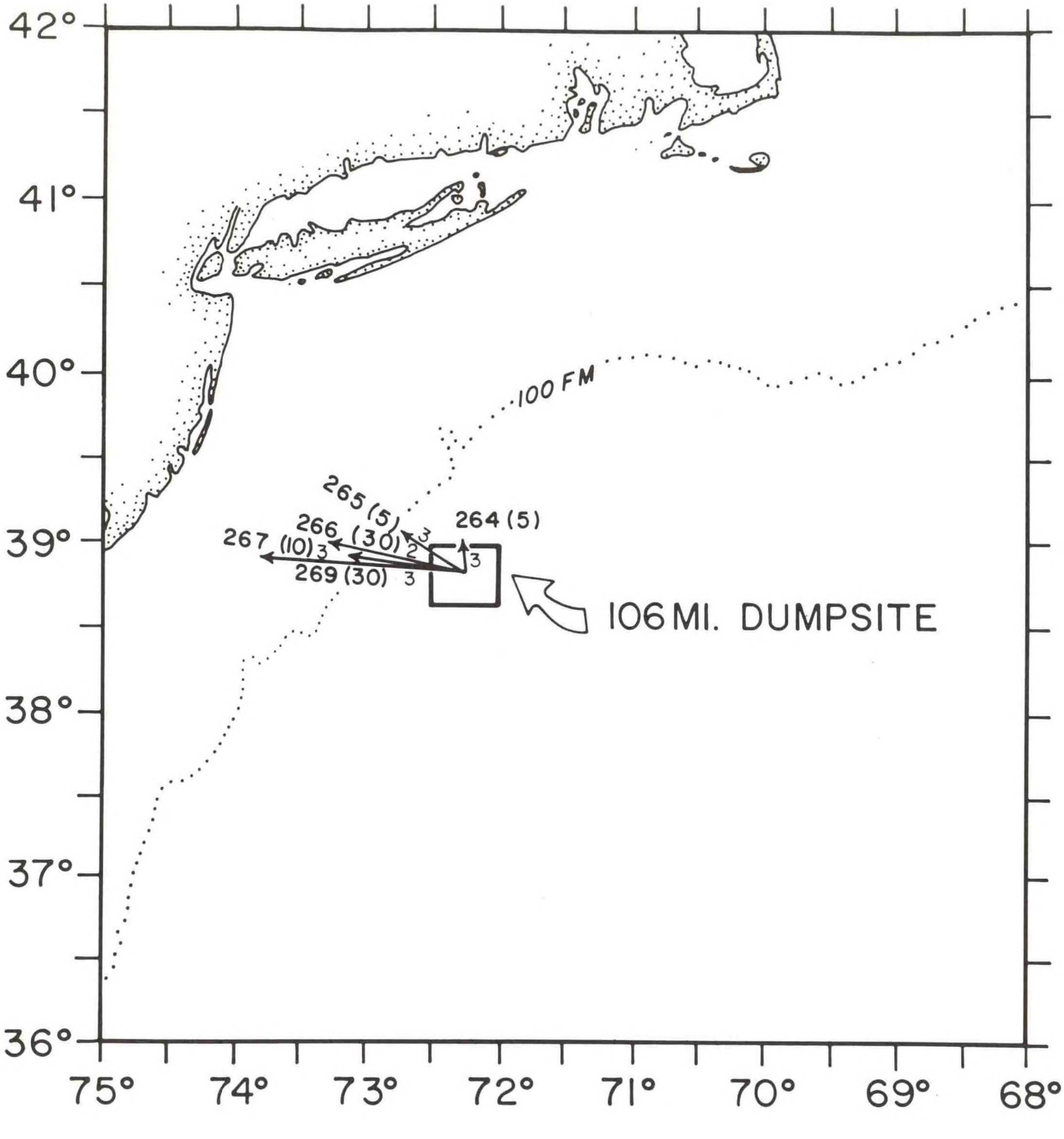

Figure 1. March 7-17, 1979, RDF drogued buoy trajectories for buoys 264, 265, 266, 267, and 269. Drogue depths (m) are given in parentheses. Numbers alongside the arrows indicate the number of days between successive positional fixes.

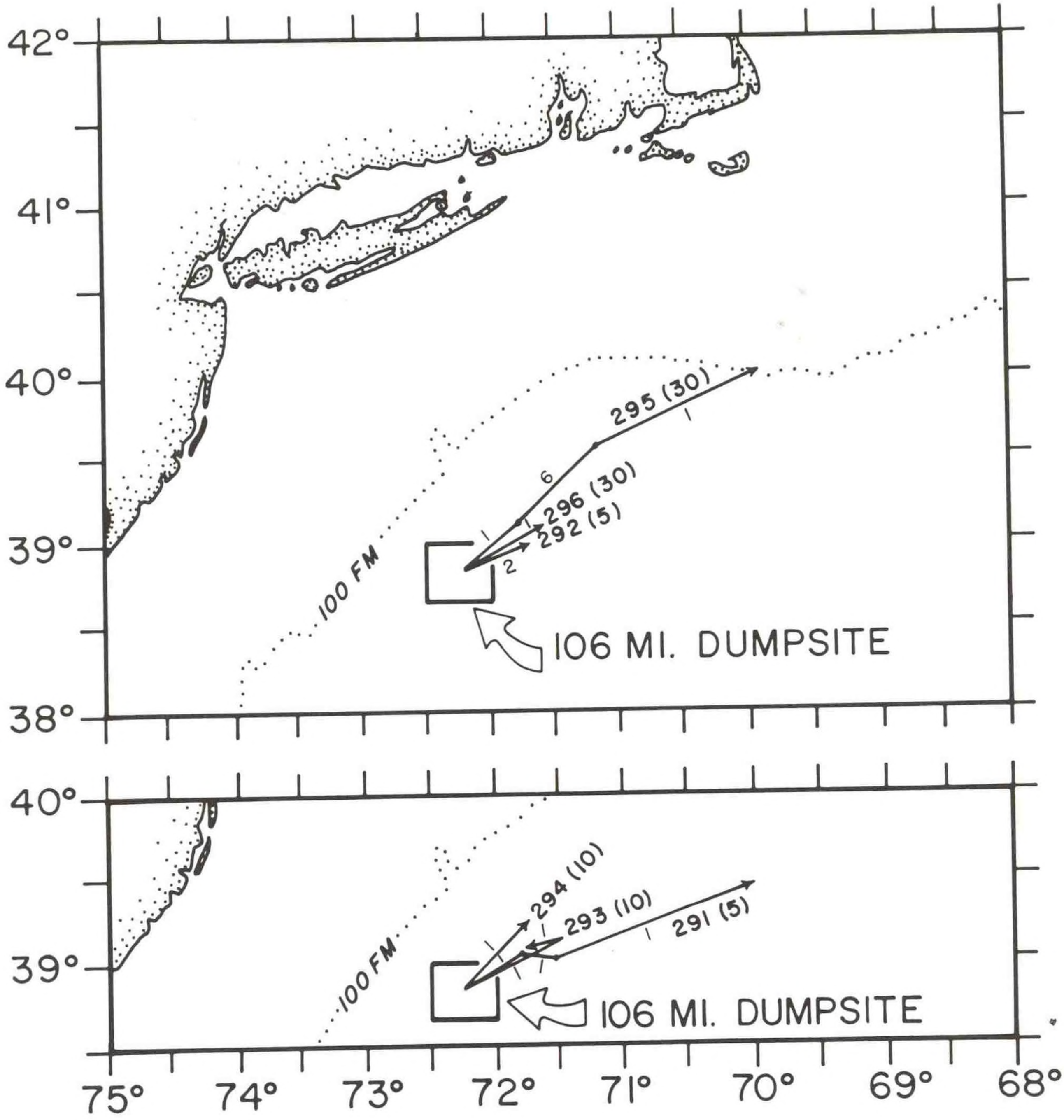

Figure 2. May 9-18, 1979, RDF drogued buoy trajectories for buoys 291 through 296. Drogue depths (m) are given in parentheses. Numbers alongside the arrows indicate the number of days between successive positional fixes.

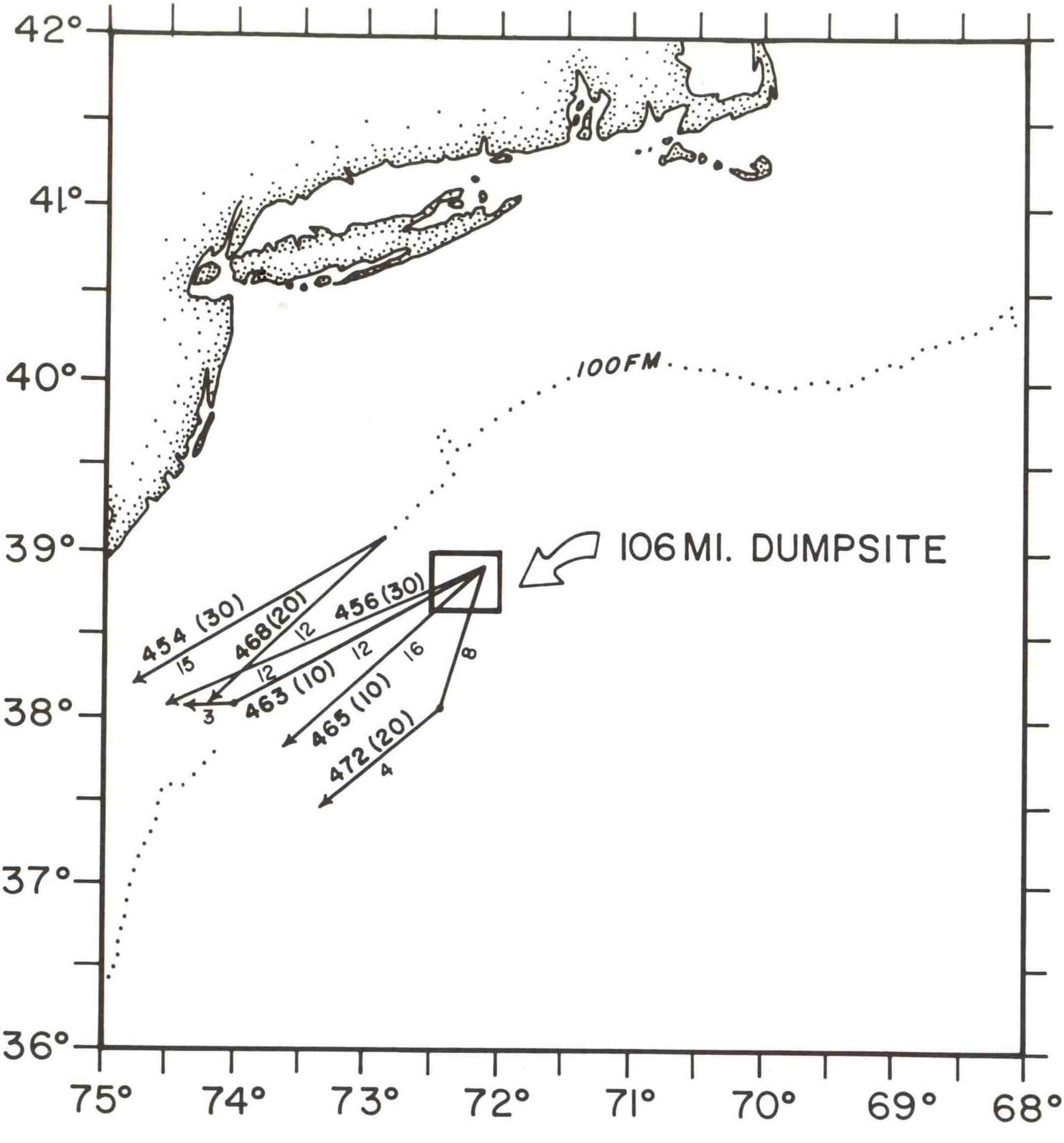

Figure 3. May 8-24, 1980, RDF drogued buoy trajectories for buoys 454, 465, 456, 463, 468 and 472. Drogue depths (m) are given in parentheses. Numbers alongside the arrows indicate the number of days between successive positional fixes.

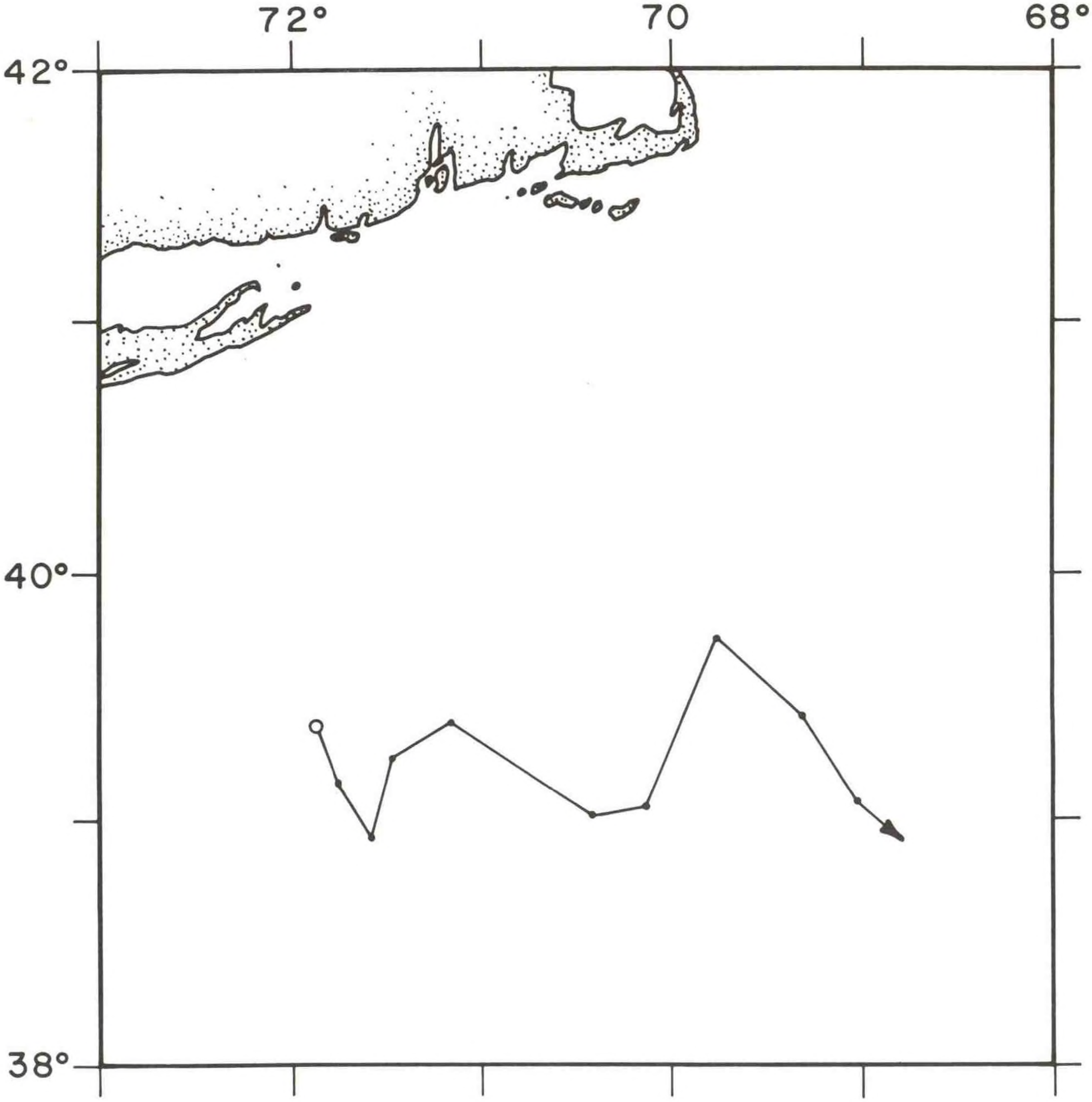

Figure 4. Weighted daily average wind vectors, March 7-17, 1979.

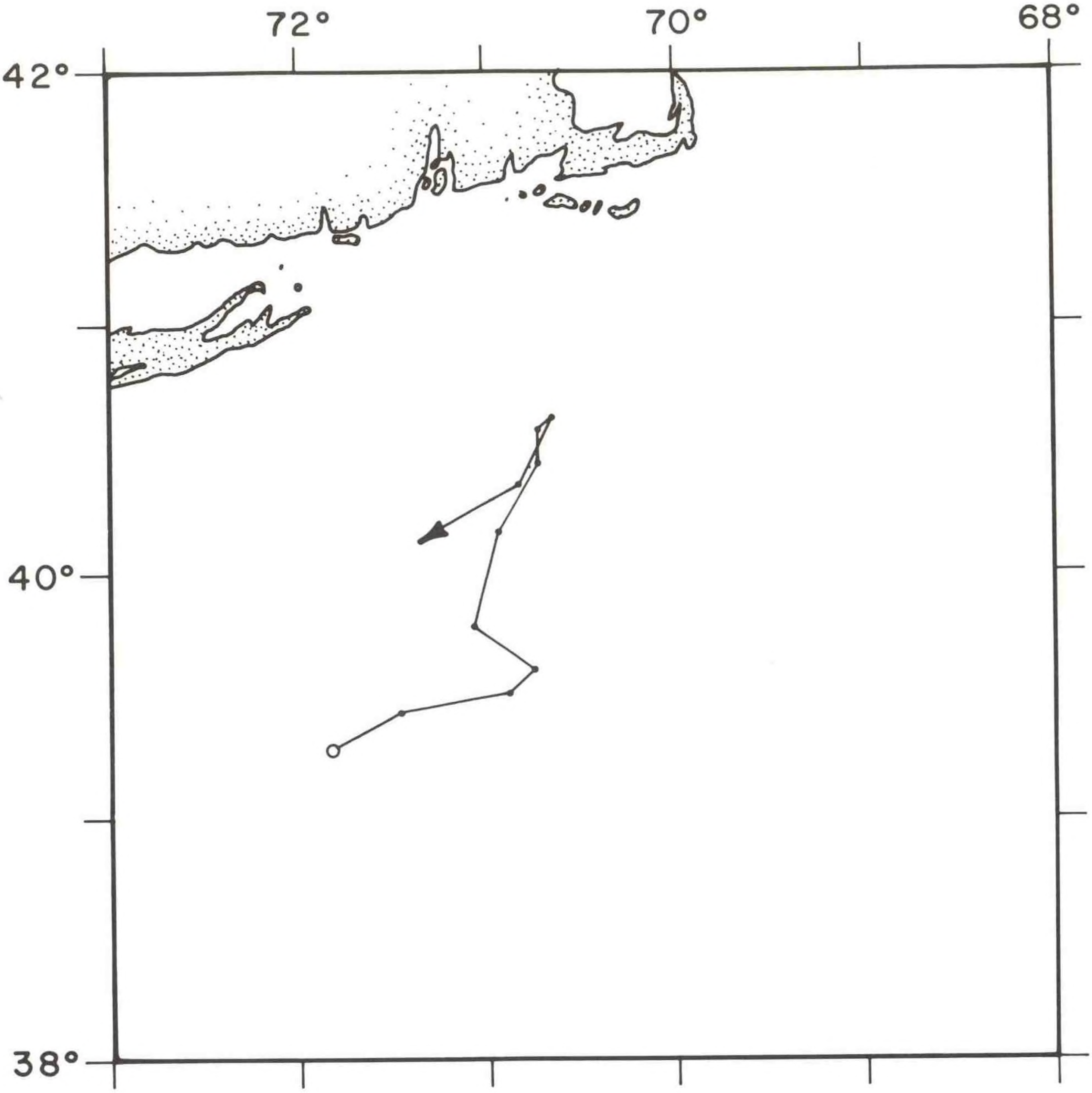

Figure 5. Weighted daily average wind vectors, May 9-18, 1979.

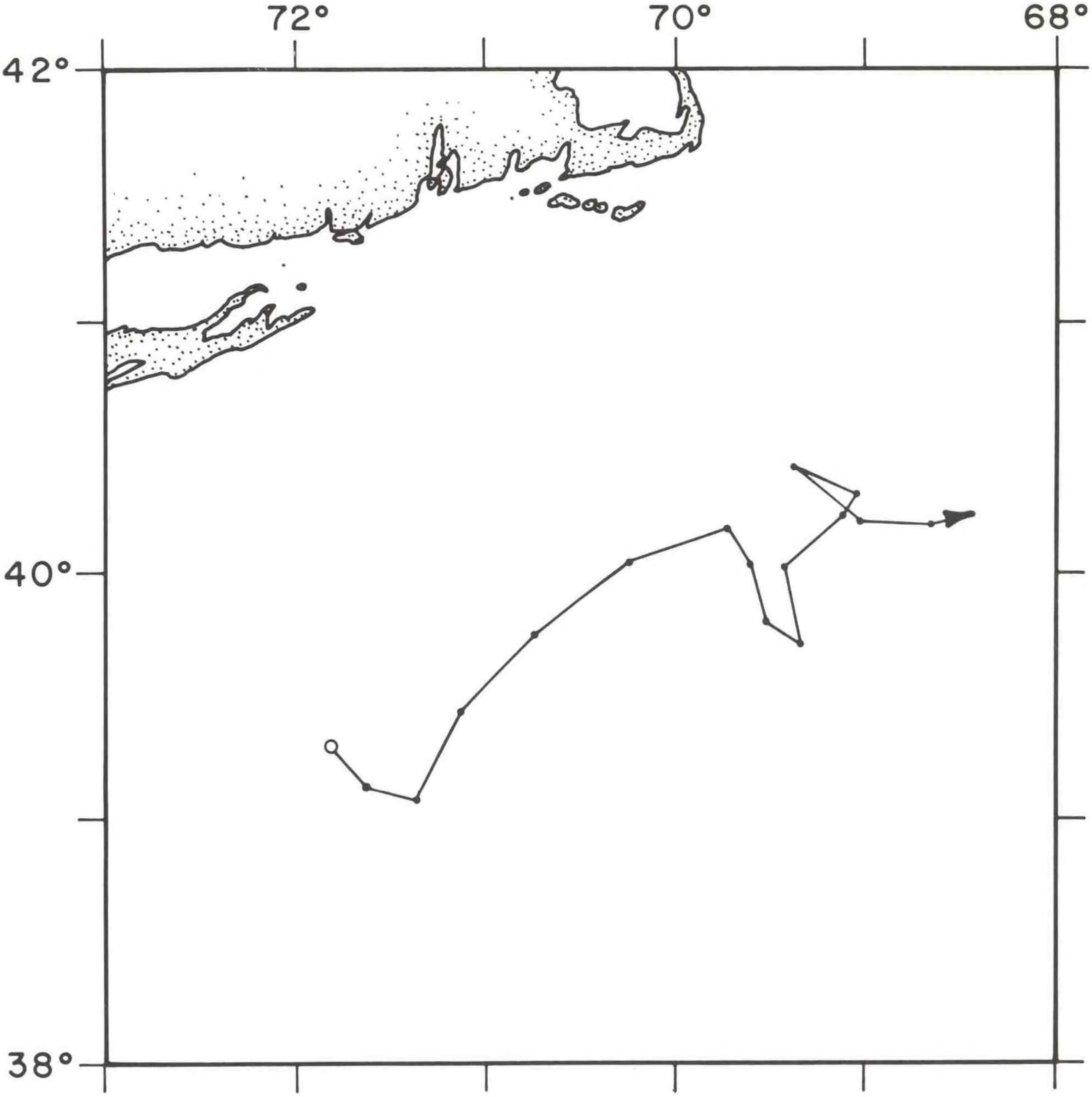

Figure 6. Weighted daily average wind vectors, May 8-24, 1980.

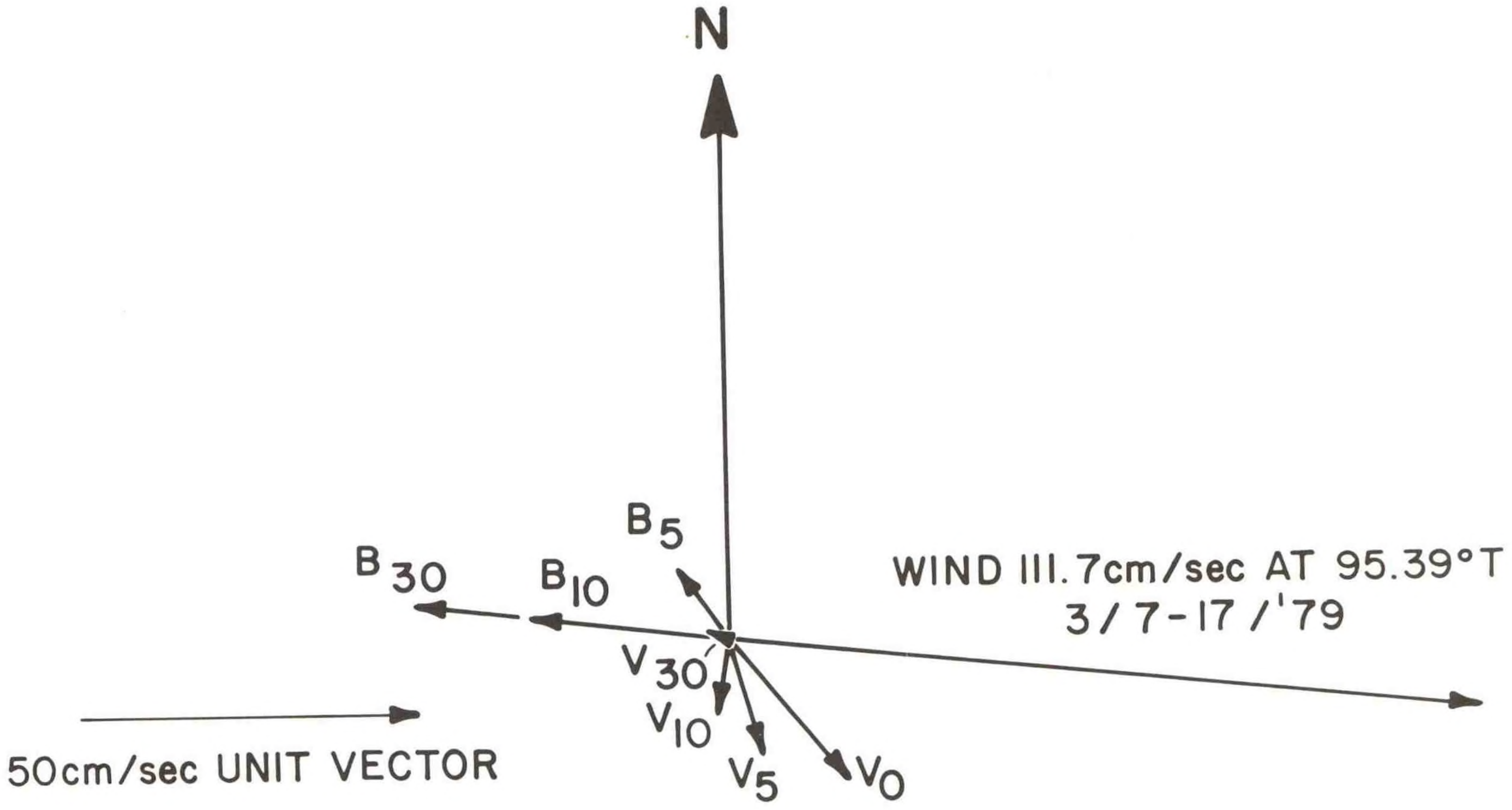

Figure 7. March 1979 mean weighted daily average wind vector, the mean RDF buoy velocities at 5, 10 and 30 m depth (B_5, B_{10}, and B_{30}) and the calculated Ekman velocity vectors at 0, 5, 10 and 30 m depth (V_0, V_5, V_{10}, and V_{30}). Also shown are the direction for true north and a 50 cm/sec unit length vector.

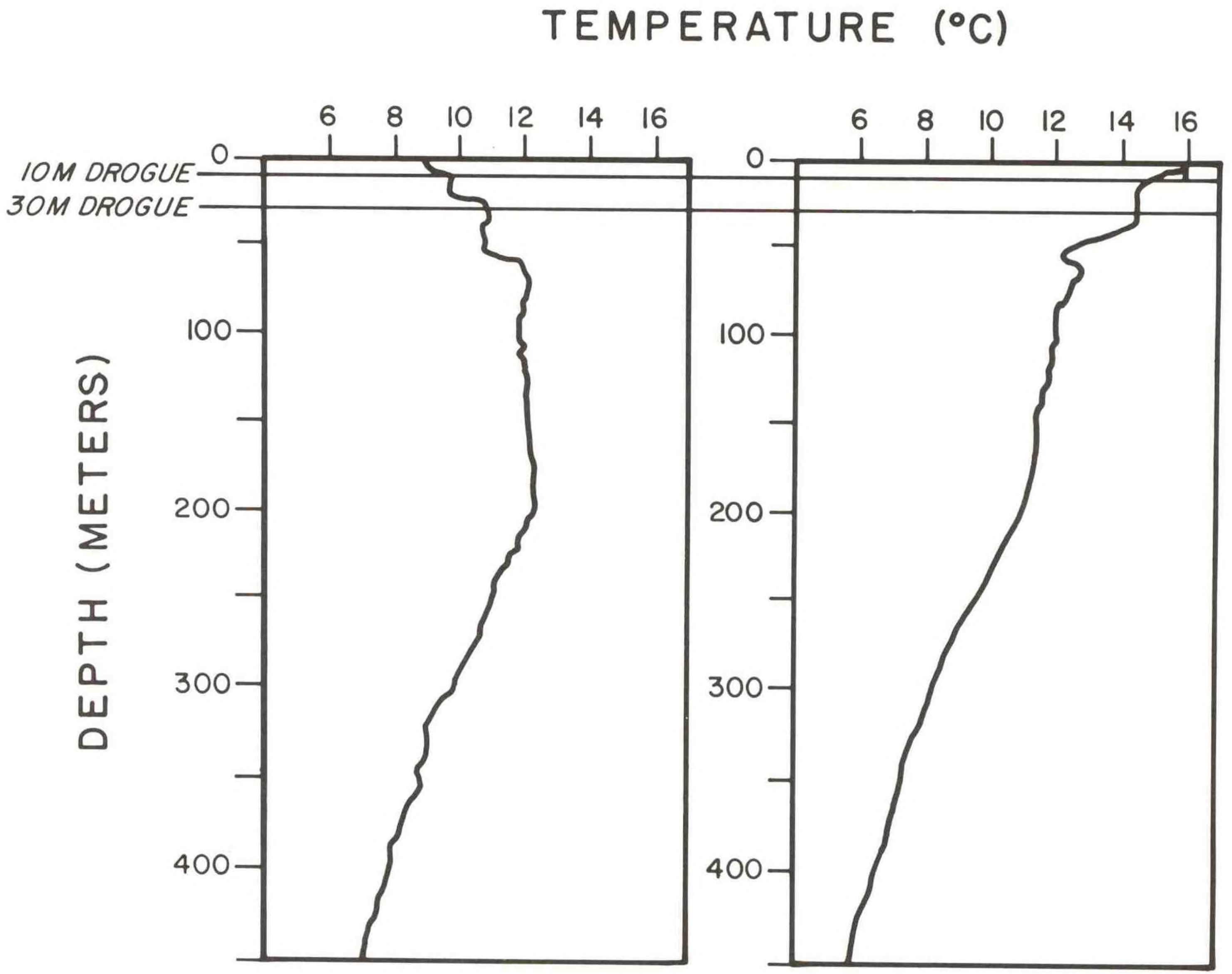

Figure 8. Expendable bathythermograph (XBT) data collected in the vicinity of the RDF buoy deployments during March (A) and May (B) 1979 experiments.

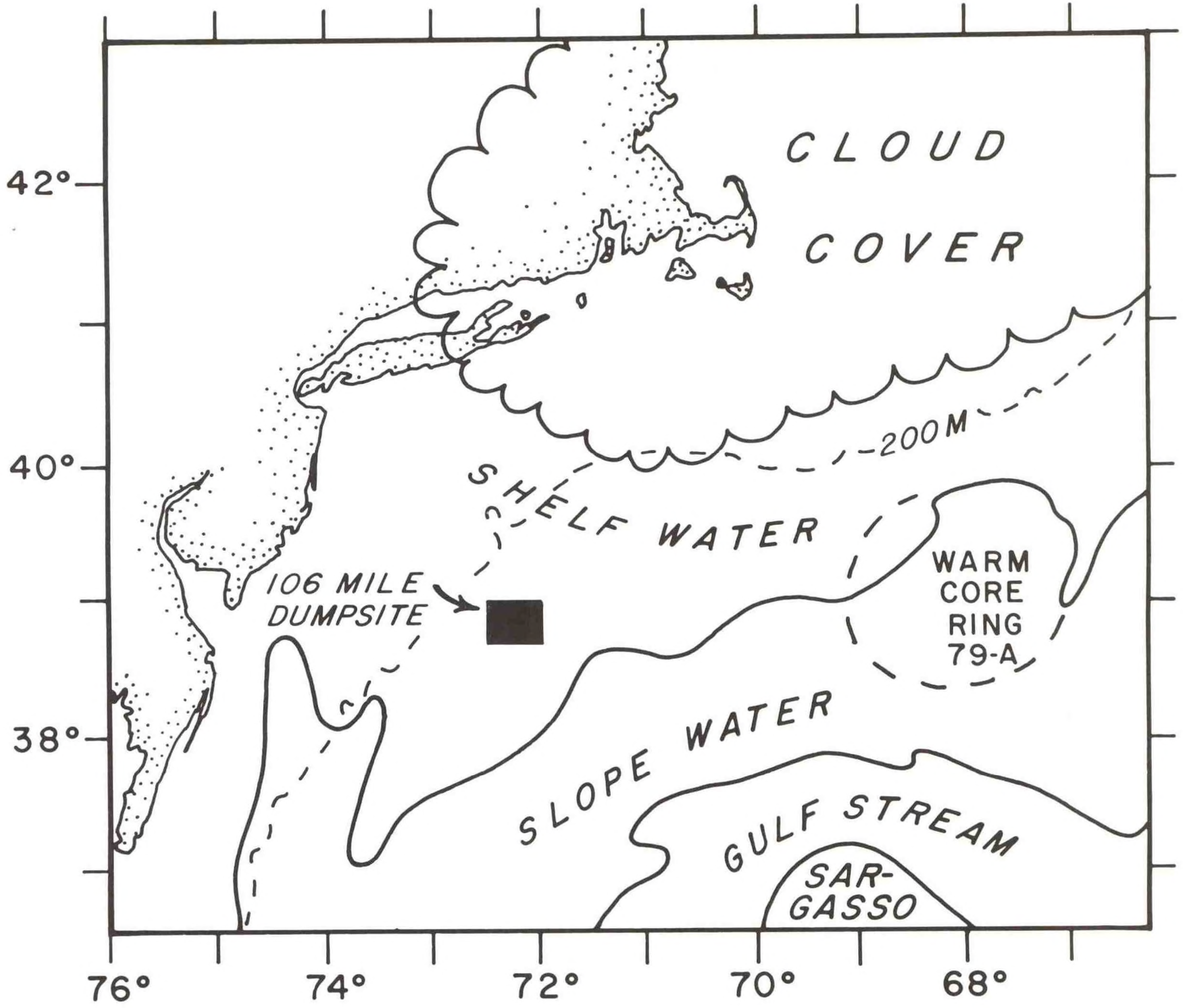

Figure 9. NAVOCEANO satellite derived Experimental Ocean Frontal Analysis March 4-10, 1979. (Modified by Atlantic Environmental Group NMFS/NOAA, Narragansett, RI).

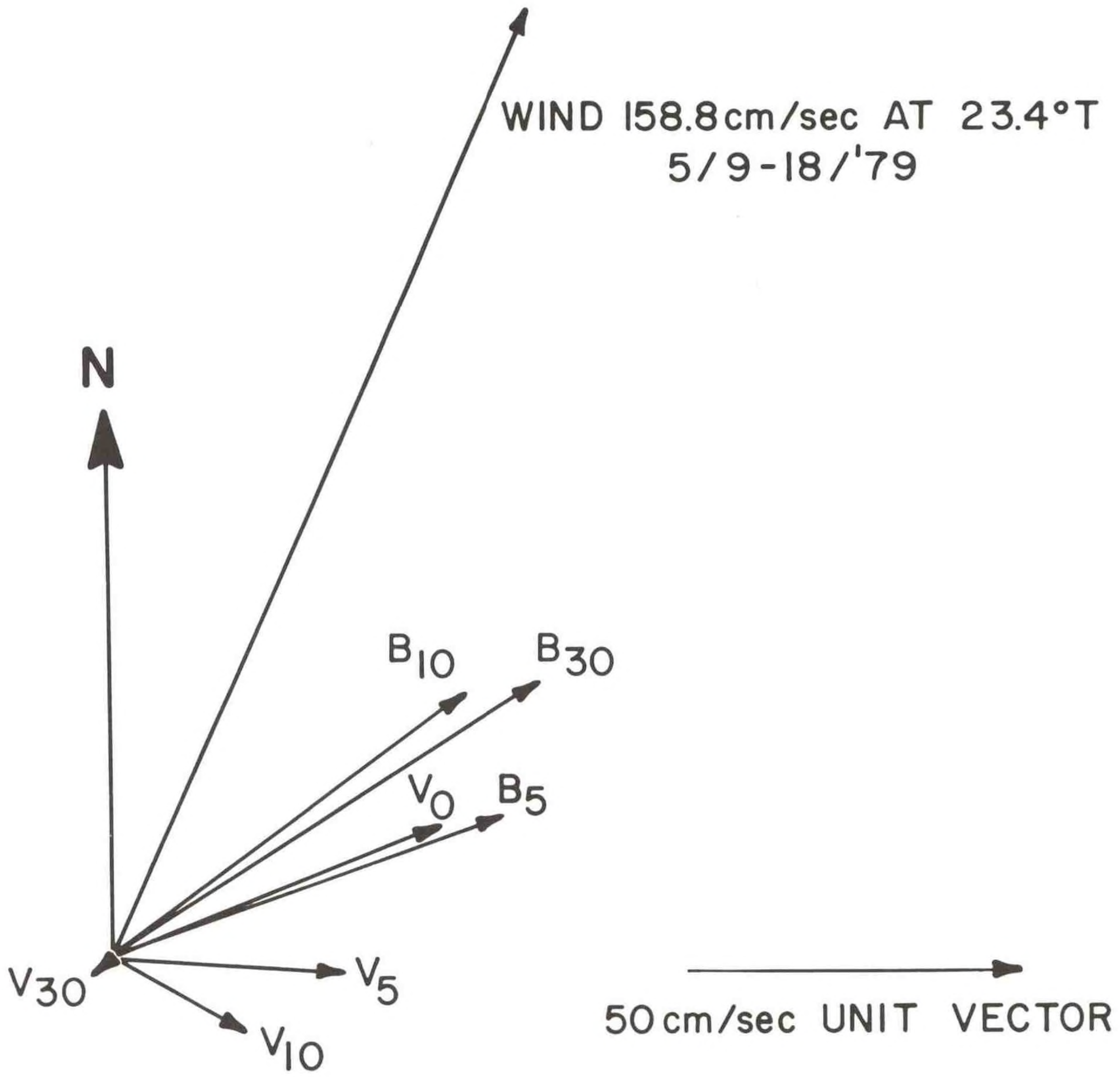

Figure 10. May 1979 mean weighted daily average wind vector, the mean RDF buoy velocities at 5, 10 and 30 m depth (B_5, B_{10}, and B_{30}) and the calculated Ekman velocity vectors at 0, 5, 10 and 30 m depth (V_0, V_5, V_{10}, and V_{30}). Also shown are the direction for true north and a 50 cm/sec unit length vector.

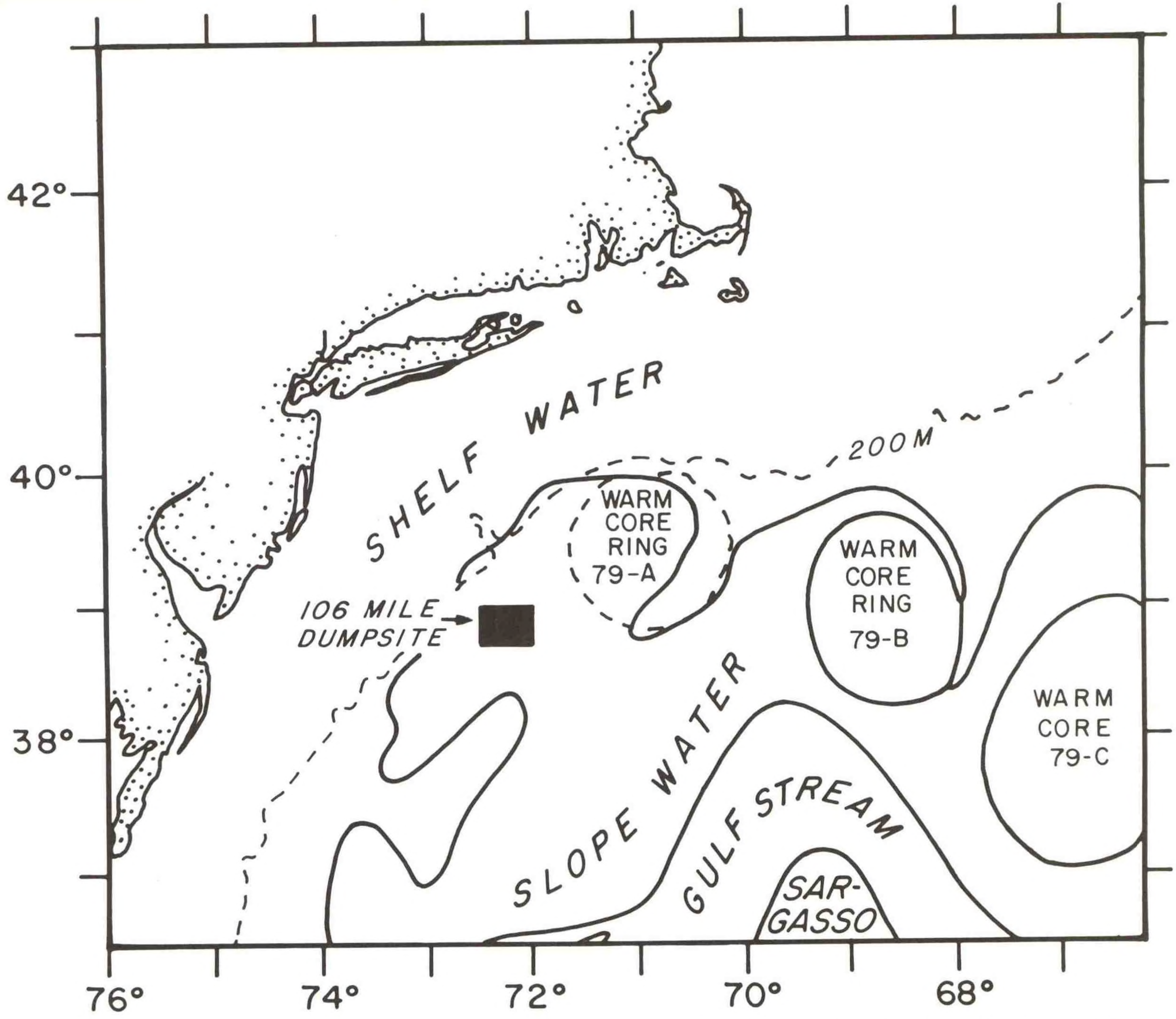

Figure 11. NAVOCEANO satellite derived Experimental Ocean Frontal Analysis May 6-12, 1979, (Modified by Atlantic Environmental Group NMFS/NOAA, Narragansett, RI).

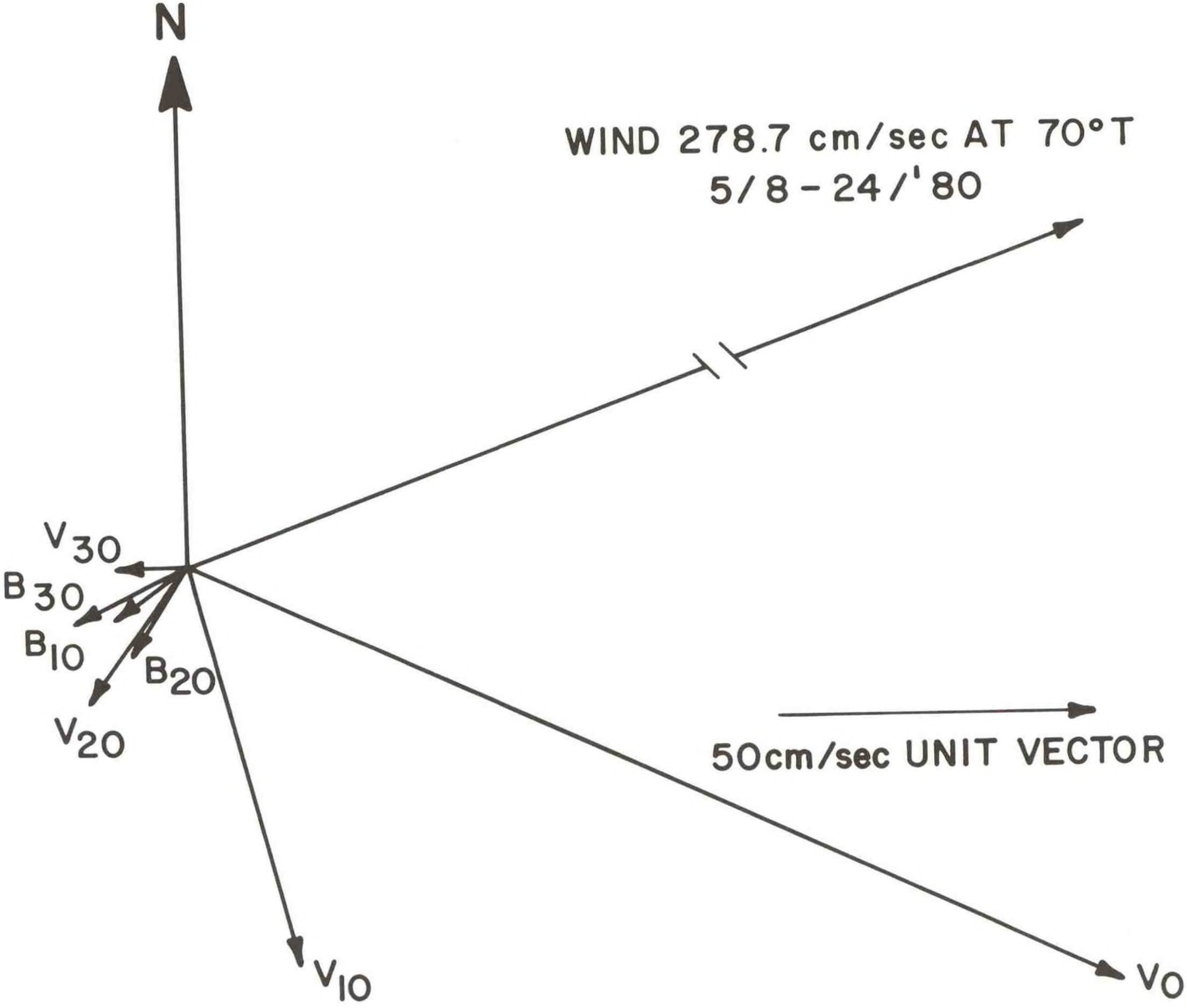

Figure 12. May 1980 mean weighted daily average wind vector, the mean RDF buoy velocities from the 106 Mile Dumpsite at 10, 20 and 30 m depth (B_{10}, B_{20}, and B_{30}) and the calculated Ekman velocity vectors at 0, 5, 10 and 30 m depth (V_0, V_{10}, V_{20}, and V_{30}). Also shown are the direction for true north and a 50 cm/sec unit length vector.

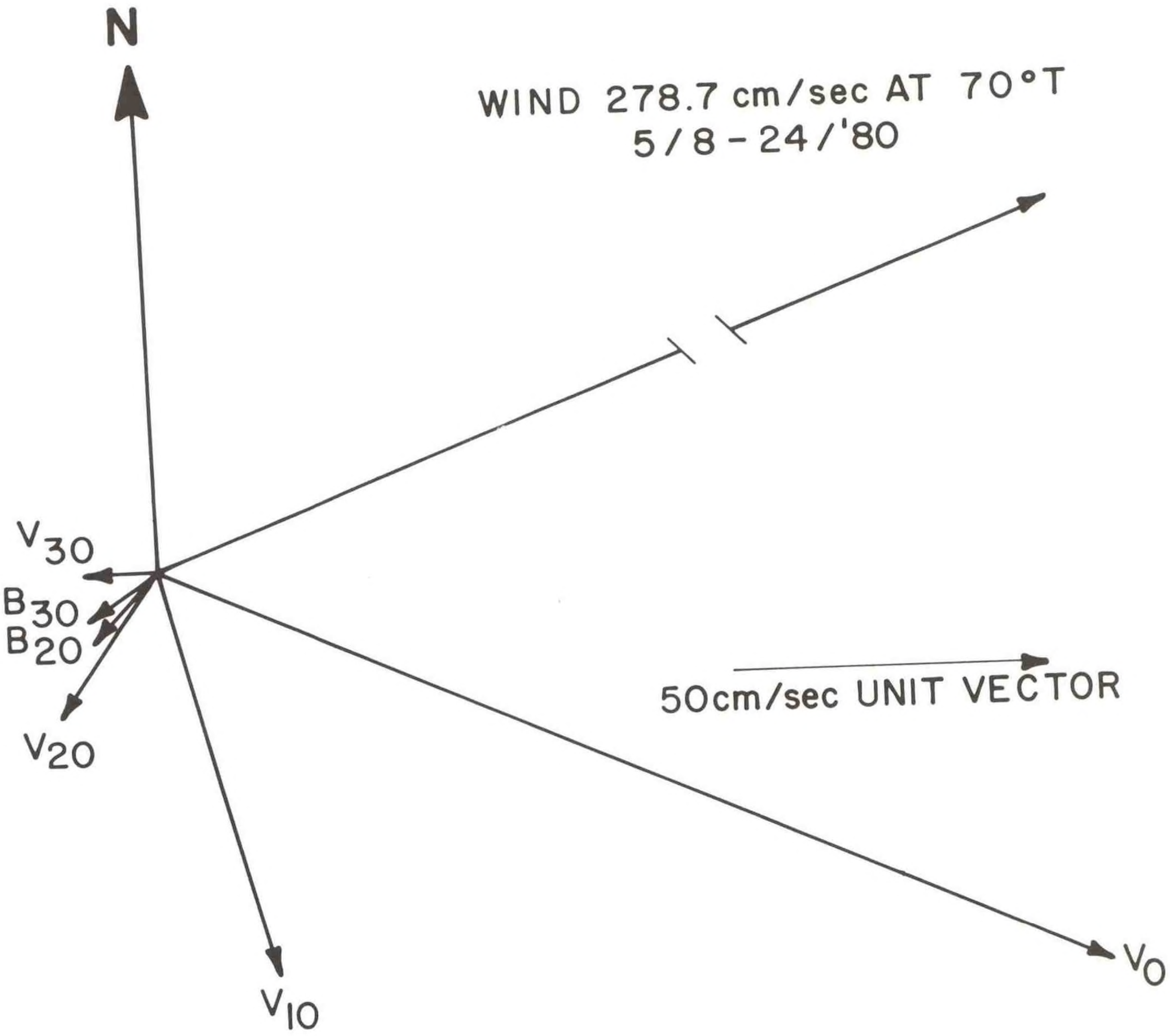

Figure 13. May 1980 mean weighted daily average wind vector, the mean RDF buoy velocities from the continental shelf site (39°05'N, 72°53'W) at 20 and 30 m depth (B_{20} and B_{30}) and the calculated Ekman velocity vectors at 0, 20 and 30 m depth (V_0, V_{20} and V_{30})/ Also shown are the direction for true north and a 50 cm/sec unit length vector.

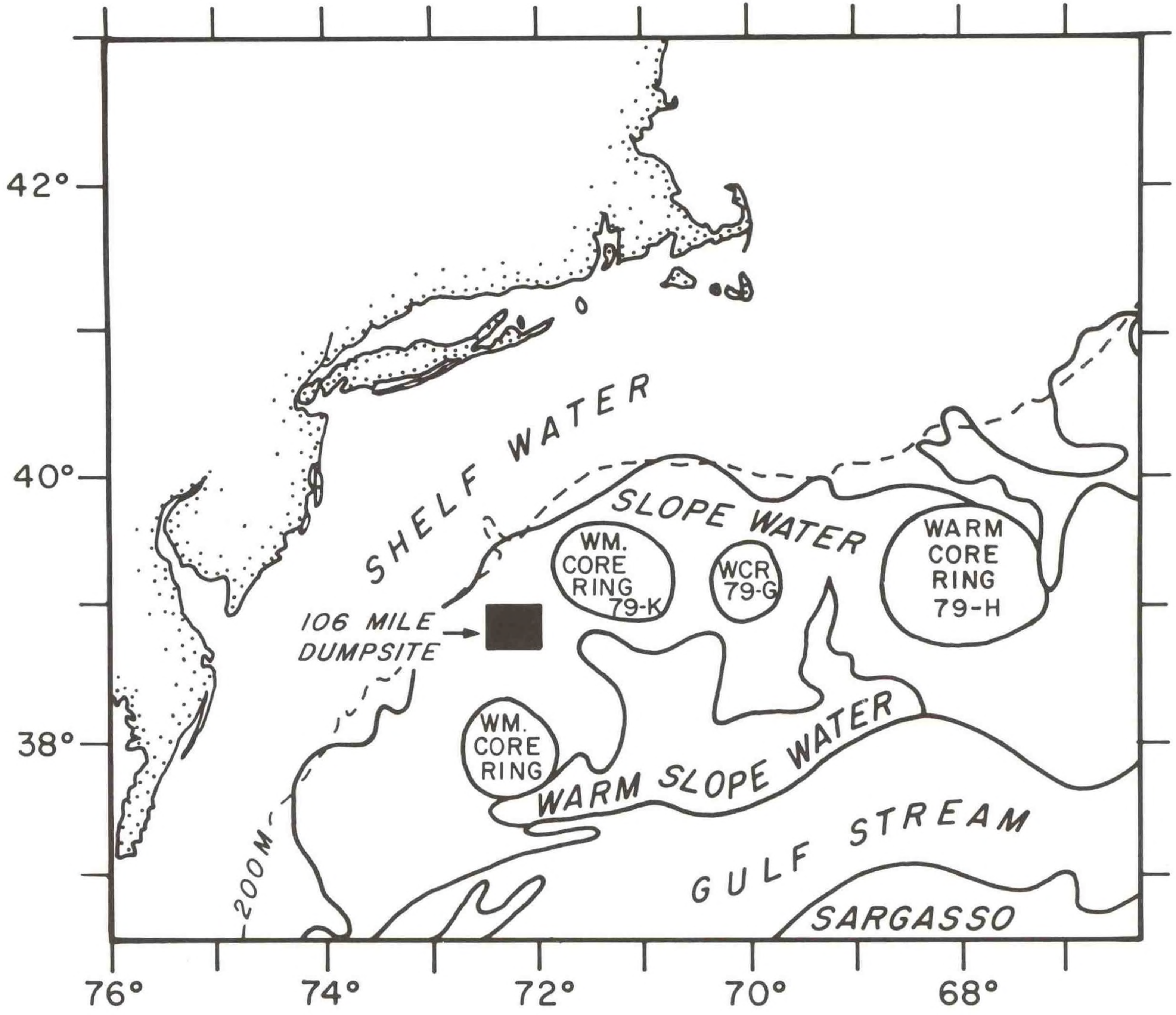

Figure 14. NOAA/NESS satellite derived Gulf Stream Analysis May 8, 1980. (Modified by Atlantic Environmental Group NMFS/NOAA, Narragansett, RI).

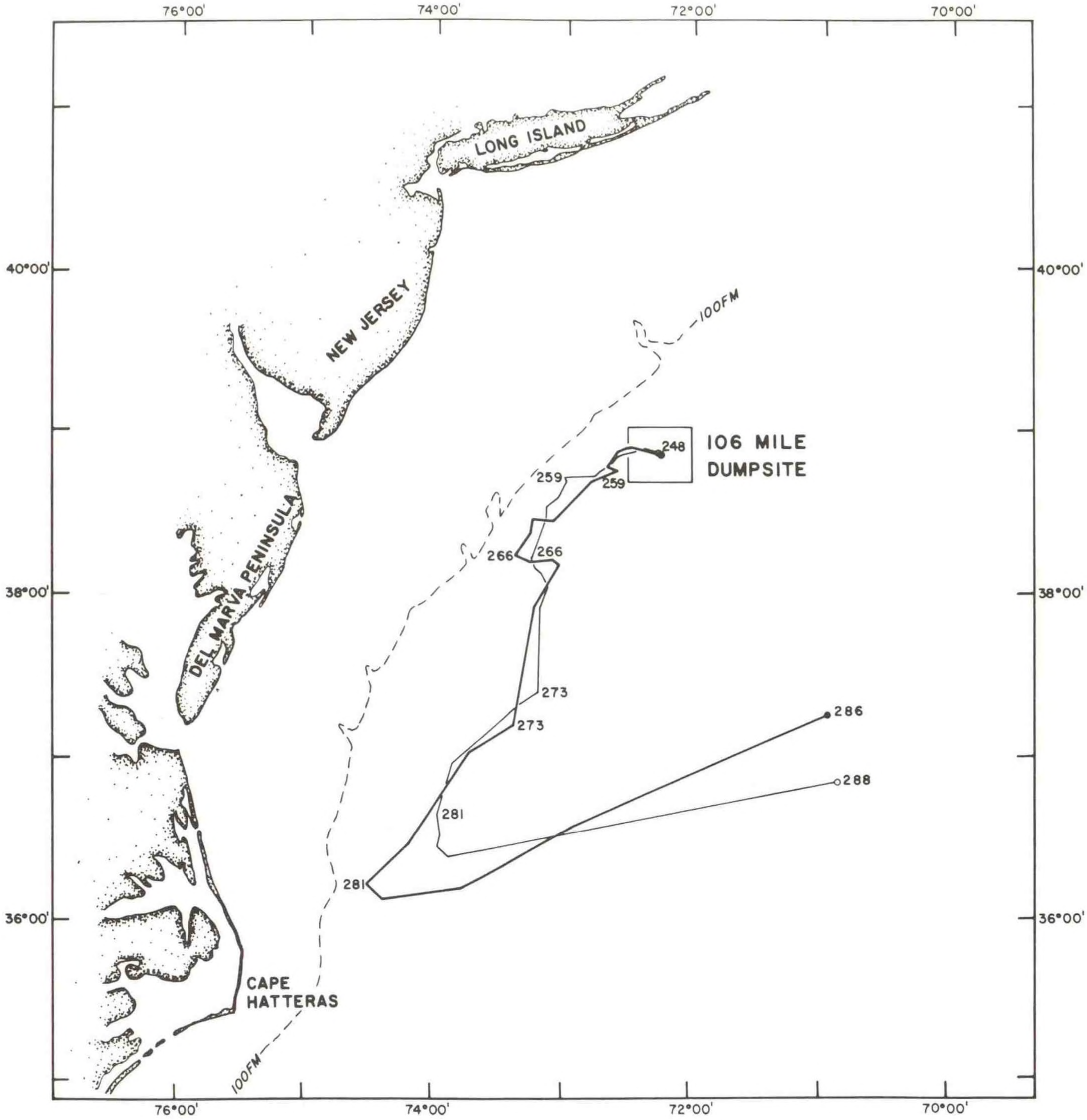

Figure 15. The deployment positions and trajectories of satellite tracked drogued buoys 3020 (solid circle) and 3021 (open circle) from the September through December 1980 NOAA study. Numbers alongside the trajectories indicate Julian days.

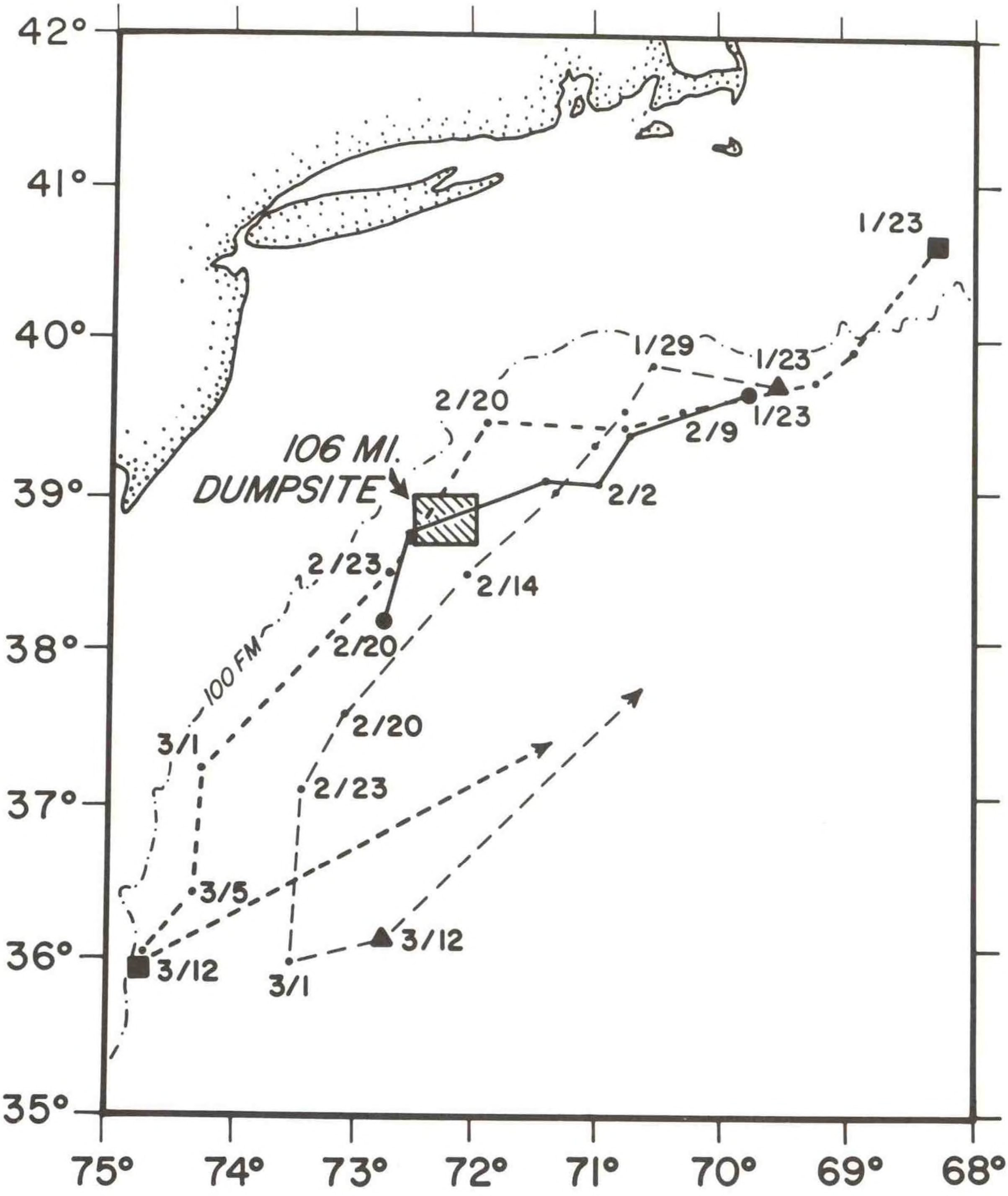

Figure 16. The deployment positions and trajectories of satellite tracked drogued buoys 0227 (squares), 0234 (circles) and 0132 (triangles) from the January through March 1979 Raytheon study. Dates are indicated along each trajectory.