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FINAL REPORT

Ubiquitous Eddies of the Eastern Bering Sea and their Coincidence with Concentrations of Larval Pollock

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ABSTRACT

Between 1988 and 1993, 12 satellite-tracked buoys were deployed in four eddies in the southeastern Bering Sea. Our success in finding eddies resulted from placing buoys in high concentrations of pollock larvae. We describe eddies using data from hydrographic surveys, satellite-tracked buoys and moored current meters. Small (<25 km diameter) eddies likely transit along the slope of the Eastern Bering Sea every 45–60 days. In previous studies such small features were not observed because their size fell within typical separation of hydrographic stations and the sea-surface temperature gradients are not resolved by satellite borne infrared imagery. (Keywords: Eddies, larval pollock, Eastern Bering Sea)

INTRODUCTION

Mesoscale features such as eddies can have an important influence on dispersal of ichthyoplankton. Biophysical interactions between early life history stages of fish and eddies are the focus of several recent studies. Interannual variations in recruitment of a number of northwest Atlantic fish stocks appear to be correlated with the number of Gulf Stream features which impinge on the shelf off Newfoundland (Myers and Drinkwater, 1989). Warm core eddies moving near the southern edge of Georges Bank often play an important role in the movement of water on/off shelf, and in transport of organisms including fish larvae (Joyce *et al.*, 1992). In the western Gulf of Alaska, the greatest concentrations of walleye pollock larvae are often found in eddies (Schumacher *et al.*, 1993). These eddies tend to retain larvae on the shelf so that they can be transported to nursery grounds (Hinckley *et al.*, 1991). Furthermore, the first-feeding larvae in these eddies appear to be in better condition than those larvae outside the eddy (Schumacher and Kendall, 1991; Canino *et al.*, 1991). The largest walleye pollock spawning grounds in the Bering Sea lie along the eastern section of the Aleutian Island Arc and over the southeastern shelf between the Alaska Peninsula and the Pribilof Islands (Hinckley, 1987; Shuntov, 1992). Given the extensive abundances of pollock eggs and larvae and the prevalence of eddies (Coachman, 1986: Fig. 15), the potential influence of these features on the early life history stages is great.

Eddies previously observed in the Eastern Bering Sea typically had diameters >75 km (Paluszkiewicz and Niebauer, 1984). An eddy of this size observed in 1978 had a mean current speed of ~25 cm s^{-1}, with maximum speeds as large as 50 cm s^{-1} (Kinder *et al.*, 1980). This eddy translated at a net speed of ~1 cm s^{-1}. While trains of small eddies exist in the Kamchatka Current in the western Bering Sea (Solomon and Ahlnas, 1978), an analogous situation has not been reported for the Bering Slope Current (Kinder *et al.*, 1975) in the Eastern Bering Sea. In this report we present partially concurrent data from hydrographic stations, satellite tracked buoys and moored current meters. We identify and describe the characteristics of four eddies, two smaller than previously reported. Further, we interpret the moored observations to estimate frequency of occurrence of eddies in the Bering Slope Current. Finally, we discuss the association of eddies with patches of larval pollock and possible eddy formation mechanisms.

SETTING

Complex topography dominates the study area (Figure 1). Although the Bering Sea is partially separated from the North Pacific Ocean by the Aleutian Island Arc, exchange of water occurs through 39 passes (Favorite, 1967). In this report we consider those passes between the Alaska Peninsula and 176°W. Over this portion of the Aleutian Arc, Amukta and Yunaska Passes have water depths >300 m, and only Amukta Pass has a substantial cross-sectional area (~20×10^6 m^2; Favorite, 1967). Bathymetry along the north-side of the arc is regular west of 175°W, and highly convoluted eastward. On the west, the geomorphic province north of the arc is characterized by a gentle continental slope lacking V-shaped canyons and an outlying continental borderland formed by the Umnak Plateau (Scholl *et al.*, 1968). This is distinct from the province along the continental shelf between 56°N and 60°N which is characterized by a steep canyon-scarred slope.

While topographic features limit exchange, the Bering Sea is not an isolated, self-contained system (Stabeno and Reed, 1992). Inflow is balanced by outflow through Kamchatka Strait, so that flow in the Bering Sea basin may be aptly described as a convoluted continuation of the North Pacific subarctic gyre (Stabeno and Reed, in press). Both the Kamchatka Current in the western Bering Sea and the Bering Slope Current

Figure 1. A map of the study area (after Scholl *et al.*, 1967). Shown are the locations of current meter moorings over the slope (X) and of a moored platform (+). Note that the bathymetric contour interval is 400 m.

(Kinder *et al.*, 1975; Schumacher and Reed, 1992) in the Eastern Bering Sea are extensions of the Alaskan Stream. Circulation in the present study area is exemplified by complex dynamic topography with eddies (Reed *et al.*, 1988). Satellite-tracked buoy results (Kinder *et al.*, 1980) also clearly show the presence of eddies. The water (Alaskan Stream) that flows through Amukta Pass is generally warmer and less saline than the ambient Bering Sea water. As inferred by these properties, considerable interannual variation exists in transport through Amukta Pass (Schumacher and Reed, 1992).

METHODS

Conductivity, temperature and depth (CTD) casts were taken using a Seabird SBE-9 system to 1500 m or, in lesser depths, to within about 10 m of the bottom. Data were recorded (on disk in a minicomputer) only during the downcasts at lowering rates between 30 and 50 m min^{-1}. To provide field correction offsets, water samples were obtained at various depths, and analyzed for conductivity at all of the CTD stations. Temperatures were measured using reversing thermometers at every fifth station. Conductivity was measured aboard ship using a portable salinometer calibrated with standard seawater. These calibration data confirmed an overall accuracy for the CTD temperature and salinity values of 0.01°C and 0.01 psu, respectively. The data were processed to derive 1-m averages of temperature and salinity, from which density and geopotential anomaly were computed.

During fall 1989 and spring 1990, eight moorings were deployed in the vicinity of the eastern Bering Sea slope (Schumacher and Reed, 1992). Results from two of these moorings are presented in this report. One mooring was taut-wire and the deeper mooring used Kevlar. The instruments were Aanderaa RCM-4 or 7 current meters. The upper instrument was located at approximately 50 m below the surface and had a paddle wheel rotor to limit contamination of the desired signal by surface waves. Current records were first edited for time base and data spikes. To examine mean and low frequency characteristics, the current records were filtered using a cosine squared Lanczos filter with a half power point of 35 h. The resulting series was resampled at 6 hour intervals.

Satellite tracked buoys with "tristar" drogues centered at a 40 m depth provided Lagrangian measurements. This drogue largely eliminates the influence of wind on buoy movement. Estimates of upper-ocean current were calculated from positions provided through system Argos. Position accuracy has a standard error in an individual location of approximately 0.36 km (Reed and Stabeno, 1990), with an average number of fixes per day of ~16. A spline was applied to the positions obtained from Argos and these unfiltered data are presented herein. Buoy trajectories were used to define the center of an eddy and to estimate translation of the feature.

Ichthyoplankton was sampled by double-oblique tows of 60-cm diameter bongo samplers equipped with 333-micron mesh nets. A pressure sensing device was used to determine maximum sampling depth and to verify that tow trajectories were not biased. Sampled volumes were calculated from mechanical flow meters in the mouth of each net. All samples were preserved in 5% buffered formalin:seawater. During tows conducted in 1993, a Seabird SEACAT SBE 19-01 recording CTD was attached to the cable above the bridle of the bongo net. Using pre-and-post calibrations, we estimate an accuracy of 0.01°C and 0.01 psu.

RESULTS

We examined trajectories of 12 buoys which defined four separate eddies. The mean translation of these eddies (Figure 2), as indicated by the movement of the center of the eddy, was 1 to 5 cm s^{-1}. The maximum daily translation speed of 20 cm s^{-1} occurred in 1992. The other eddies all had maximum daily translation speeds of 10–13 cm s^{-1}. Each of the eddies is discussed in detail below.

A small eddy over the basin, spring 1988: During a cruise whose objective was to collect pollock larvae to define their distribution, two satellite tracked buoys were deployed in a larval patch (rough counts at sea were 50 times greater than those in surrounding tows). Where the buoys were deployed actual counts exceeded 50,000 larvae/10m^2 (Dell'Arciprete, 1992). After deployment the buoys' trajectories indicated an intense, small (~20 km diameter), cyclonic eddy (Figure 3). The eddy translated (Figure 2) at a mean speed of 2 cm s^{-1}, and rotated at 25 cm s^{-1}. The buoys remained in this feature for about 3 weeks. Geopotential topography (Figure 4) indicated a coherent, cyclonic circulation, but no eddy in the vicinity of the buoys. A feature defined by a single station is present north of Unalaska Island. Prior to the buoy results which substantiate the existence of small eddies, we likely would not have contoured around such a point. If this is interpreted as an eddy (not necessarily the one the buoys were later deployed in), then it has a surface expression of 0.02 dyn m and a radius of <15 km. The buoys exited the eddy as a result of strong winds and their attendant currents. After leaving the feature, the buoys moved to the northwest along the continental slope and their paths diverged. They both, however, underwent some "looping" motion (anticyclonic and cyclonic) of short duration before finally exiting the area more than a month after deployment (Reed and Stabeno, 1990).

A large eddy over the basin, spring 1992: During April 1992, four satellite tracked buoys were deployed in a region where rough counts of pollock larvae were 5 to 10 times greater than observed in surrounding waters. These buoys immediately began to describe a large (>40 km) anticyclonic eddy (Figure 5). Two of the buoys transmitted intermittently and are not presented here. The two remaining buoys indicated speeds within the eddy up to 50 cm s^{-1}. For the first 3 weeks, this feature remained relatively stationary and then translated at an average speed on 15 cm s^{-1} for period of 8 days. The buoys remained in this eddy for almost 3 months. Once again, the departure of the buoys from the eddy likely resulted from a deepening of the mixed layer.

On 31 May, the buoys came within 20 km of a moored platform (shown in Figure 1 as a (+), Figure 5). The comparison between currents measured from the platform (at 38 m) and the buoy records indicates that moored speeds were 10–15% greater and within about 15° of the buoy current vectors. This result suggests that the diameter of the eddy was at least 60 km. After the eddy translated, estimates of minimum diameter were >80 km. Currents and salinity time series from the moored platform showed that the eddy extended to a depth of at least 300 m and that isohalines were depressed by >120 m. Using daily averaged currents from low passed filtered observation from 31 May, we computed an average shear between 38 and 302 m of 2.9×10^{-4} s^{-1}. Other estimates based on hydrographic data for a large eddy in this region (Kinder *et al.*, 1980) suggest a shear of similar order of magnitude.

Eddies, spring 1993: During an ichthyoplankton survey in April 1993, six satellite tracked buoys were deployed. Three buoys were deployed over Bering Canyon in a larval patch where rough counts were high (>10 times that found at nearby stations). The other three were deployed in a less well defined larval patch. The trajectories of this latter set

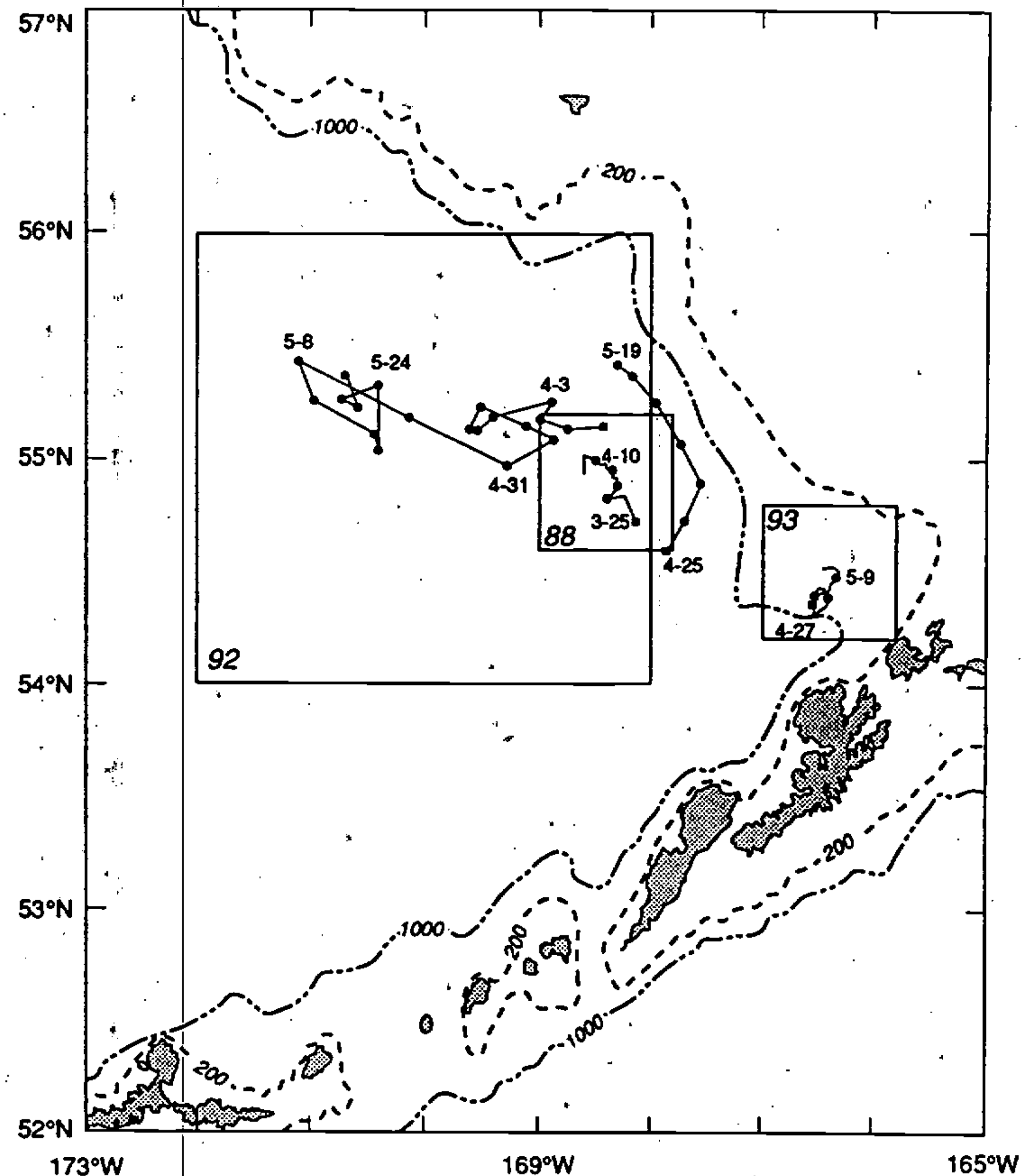

Figure 2. Movement of the center of each of the eddies. A time tick is placed every 4 days. The outline boxes, with the year of the observations indicated (italics), correspond to the areas delineated in Figures 3, 5 and 7.

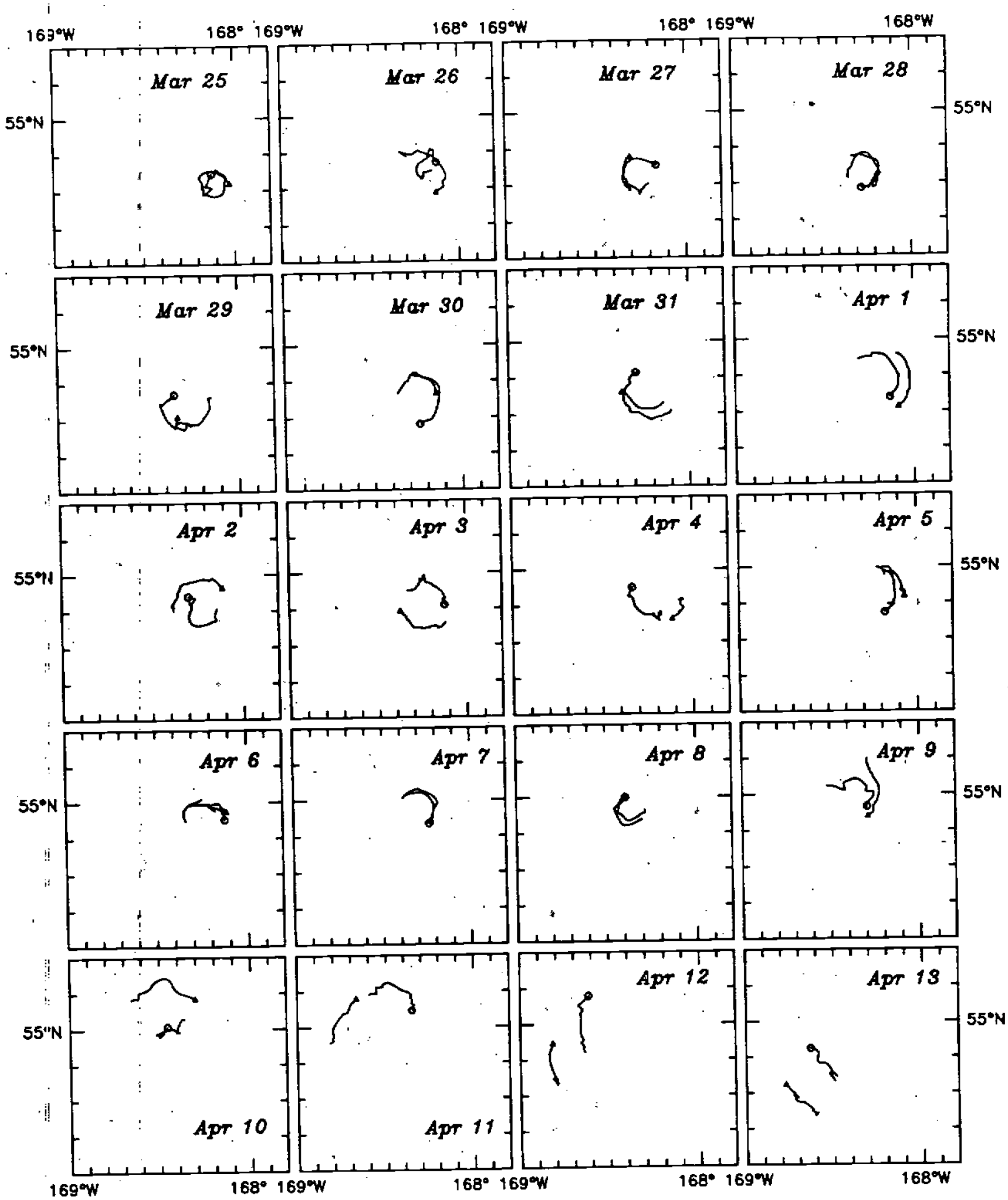

Figure 3. 1988 eddy as described by satellite tracked buoys between 25 March and 13 April 1988. Starting position of each buoy is indicated. Latitude tick marks are 0.1°.

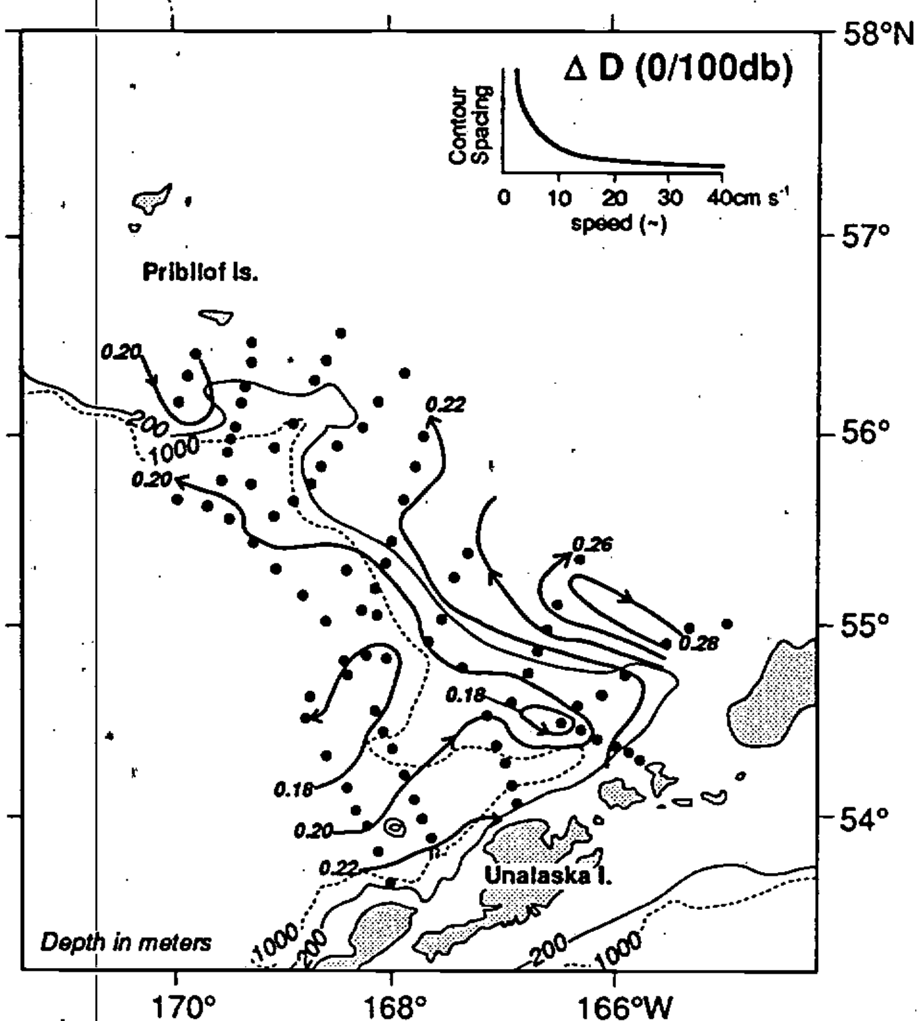

Figure 4. Geopotential topography (0/100 db) during 21 March–4 April 1988.

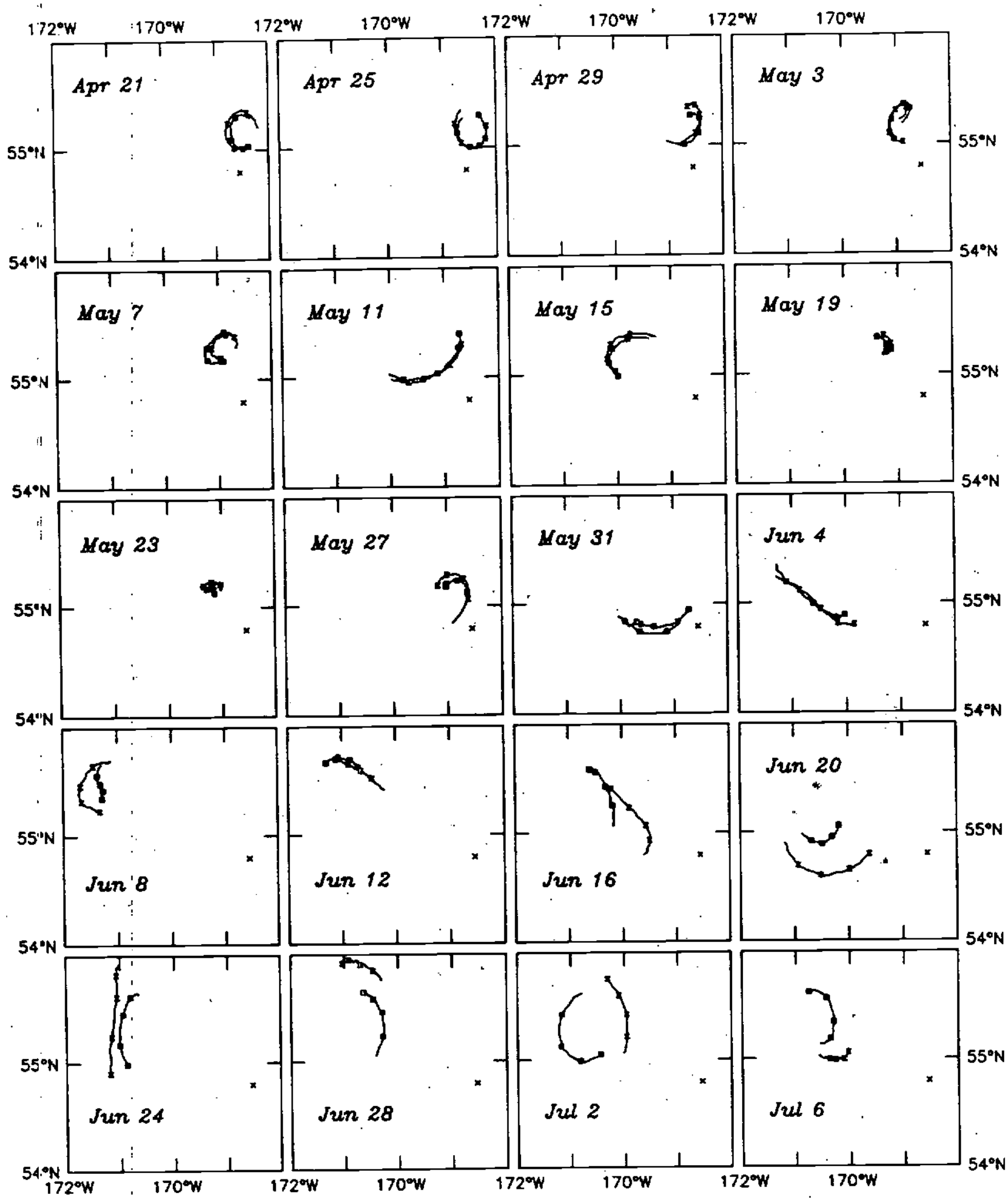

Figure 5. An 80-day period of buoy trajectories from the April 1992 eddy. The X indicates the location of the moored platform, and ticks indicate 1-day periods.

(not shown) give evidence of a large (> 80 km) weak cyclonic eddy. This eddy exhibited the greatest mean speed (5 cm s^{-1}) of translation. The buoys, however, ceased circular motion after a couple of weeks.

In contrast, the buoys deployed over the slope to the south showed an intense, small (~25 km diameter) cyclonic eddy which appears in property distributions (Figure 6) and in buoy trajectories (Figure 7). The contours of sea surface temperature show extremely weak horizontal temperature gradients. Contours of dynamic topography had a surface expression of 0.03 dyn m. Although the presence of the eddy is marked in surface salinity (Figure 8), between 40–60 m its signature is not clear. Below this strata, however, the structure of isohalines show that the eddy extended to at least 350 m. The buoys remained in the eddy for 3 weeks. Unlike the other two eddies described earlier, this eddy dissipated after it moved onto the shelf and interacted with shoaling bathymetry.

Small eddies along the slope; 1989–1990: Current measurements were collected between September 1989–September 1990 at four depths over the continental slope at a 995 m water depth. (Schumacher and Reed, 1992). Current vectors (Figure 9) indicate that reversals in the strong northwestward flow occurred 10 times during the 385-day-long record. The records from greater depths (up to 495 m) show similar characteristics. Four of the current reversals persisted for more than 5 days, and the most pronounced event occurred between 16 and 27 May 1990. During this event, there also was a reversal of flow at a mooring located 4 km shoreward of the slope mooring. Water property data from the slope indicated that temperature at 45 and 120 m depths increased by 0.5°C and 0.3°C, respectively. At the same time, salinity at 120 and 255 m decreased by ~0.2 psu. These changes were consistent with the presence of a clockwise rotating eddy. The mean along-slope speed during the passage of the eddy was 28 cm s^{-1} (at 45 m), decreasing to 15 cm s^{-1} at 495 m. Using estimates of translation speeds for eddies in the Bering Sea of 0.5 cm s^{-1} (Kinder *et al.*, 1980) or 1–2 cm s^{-1} from results above, the inferred radius of the present feature was between 5 and 20 km.

DISCUSSION

Eddies have been identified in prior studies using drogue trajectories, hydrographic data and satellite images (Paluszkiewicz and Niebauer, 1984: Table 1). These features had diameters generally > 80 km. Clearly, the station separation used in most hydrographic surveys has undersampled the small eddies. The results we present, however, show that small eddies exist in the Eastern Bering Sea. Analysis of the current records indicate that they passed the mooring locations about every 6 weeks. This is the first estimate suggesting how frequently eddies occur in the Slope Current.

Much speculation has been given to the formation of large eddies in the study region (Kinder *et al.*, 1980). The possible mechanisms include instability in the current which flows eastward along the north side of the Aleutian Arc, spatial variation in wind stress, and interaction of circulation with bathymetric features (i.e., the Umnak Plateau). The mechanisms which can create small eddies include regions of high current shear in open waters (Reed and Stabeno, 1990), and interaction of inflowing Alaskan Stream water with topography of passes in the eastern Aleutian Island Arc. During June 1993, a satellite tracked buoy deployed in the Alaskan Stream near Kodiak Island entered Amukta Pass (Figure 10). This buoy became involved in an anticyclonic eddy. Eddy formation during periods of inflow through this pass are also a feature seen in a numerical model simulation of the North Pacific Ocean and Bering Sea (M. Spillane, pers. communication).

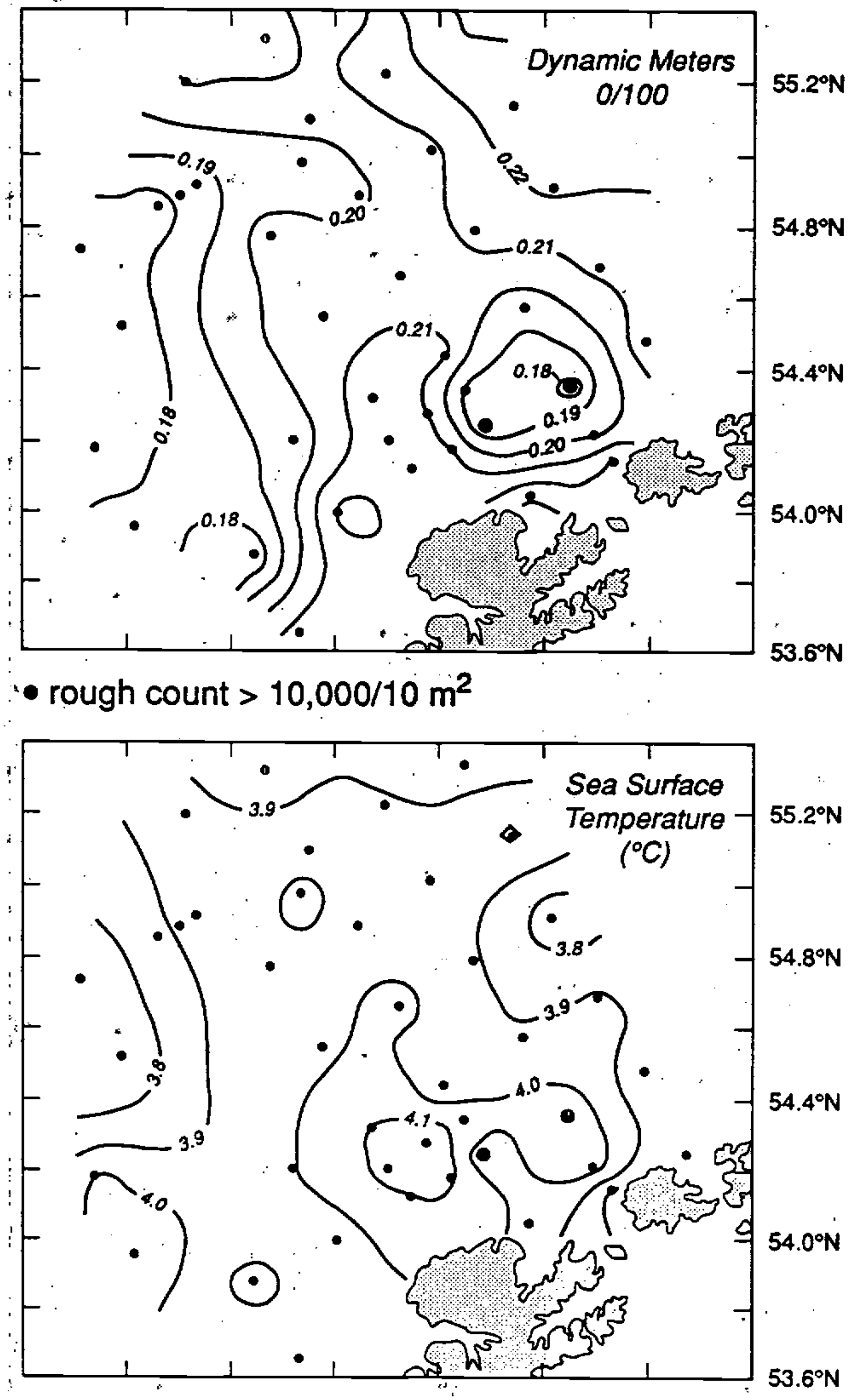

Figure 6. Horizontal distribution of temperature at surface, and dynamic topography (0/100 db) during 15–22 April 1993.

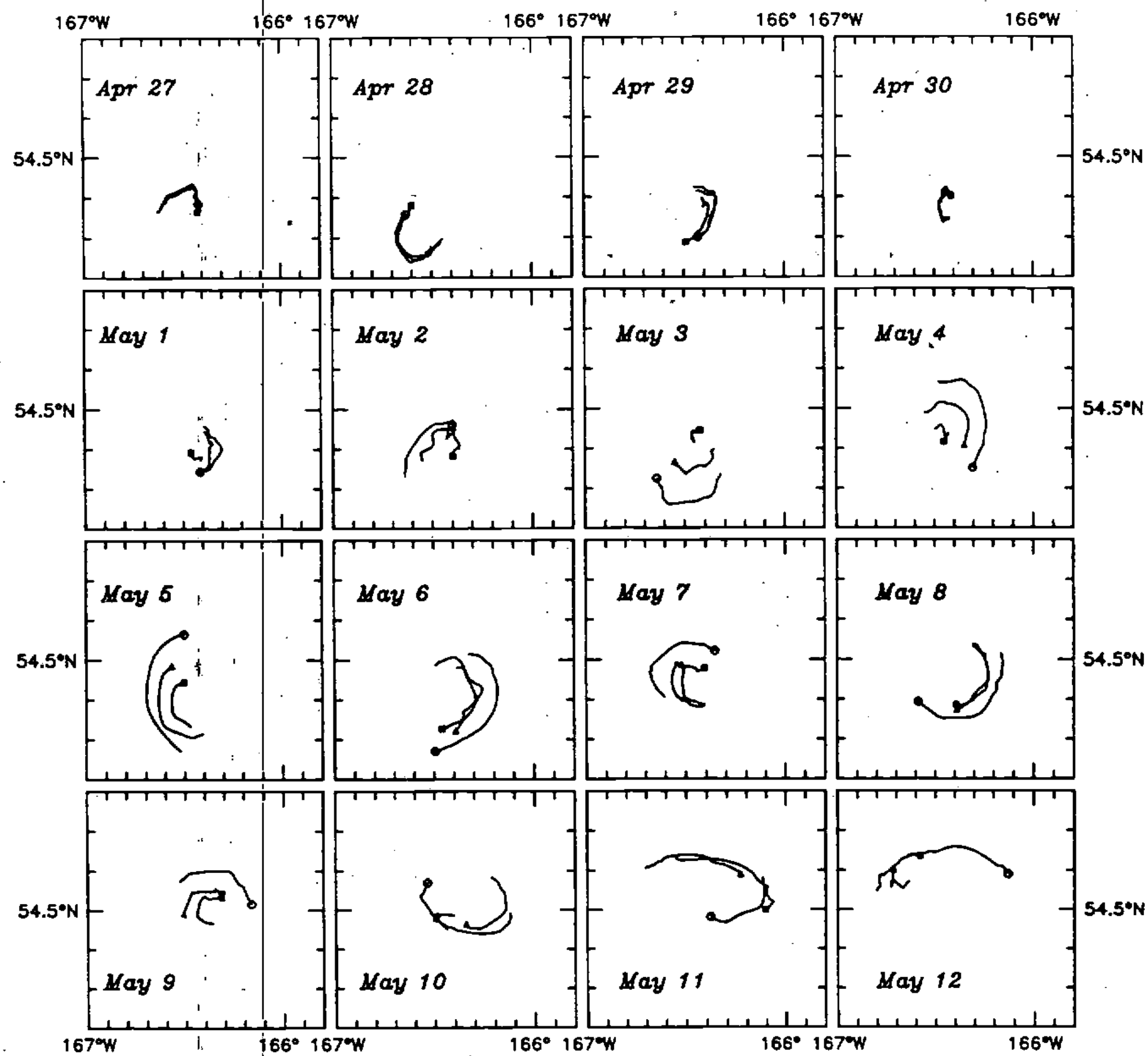

Figure 7. The spring 1993 eddy as described by satellite tracked buoys. Starting position of each buoy is indicated. Latitude tick marks are 0.1°.

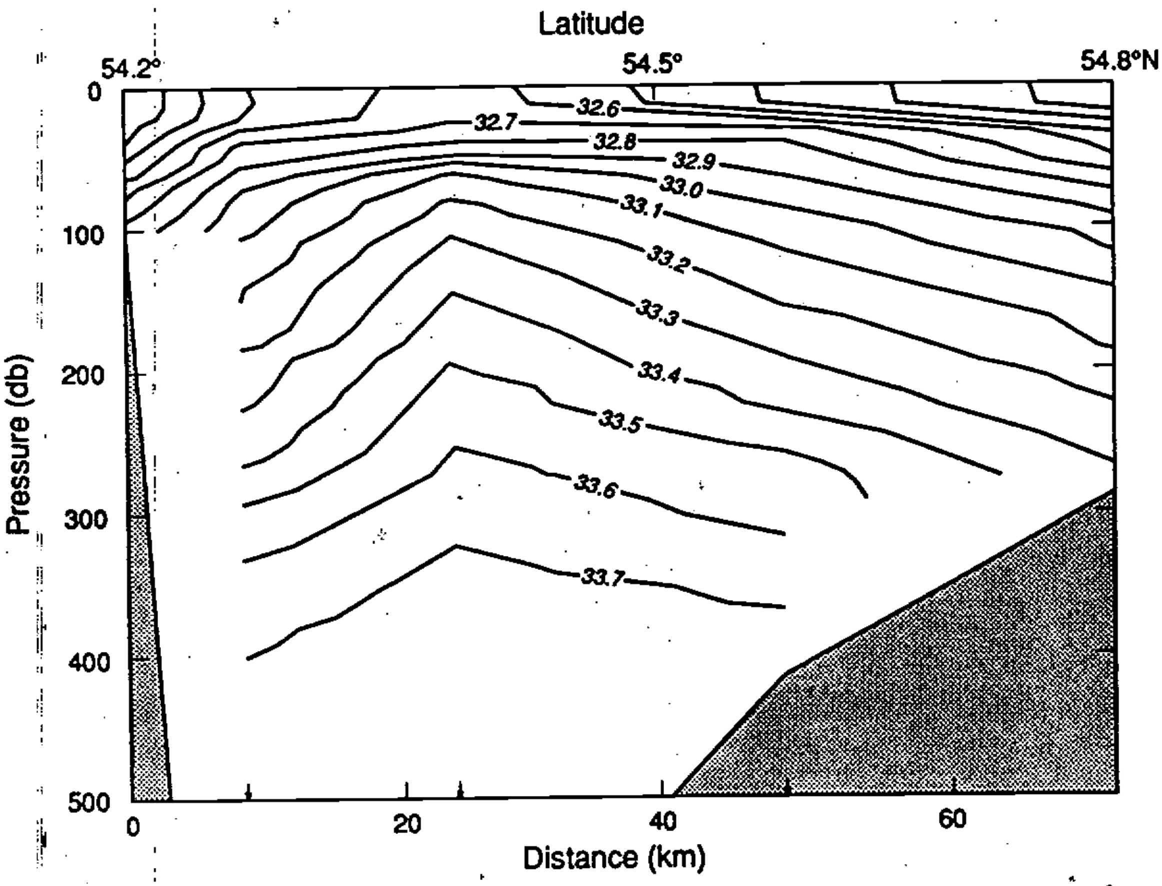

Figure 8. Vertical section salinity in the spring 1993 eddy.

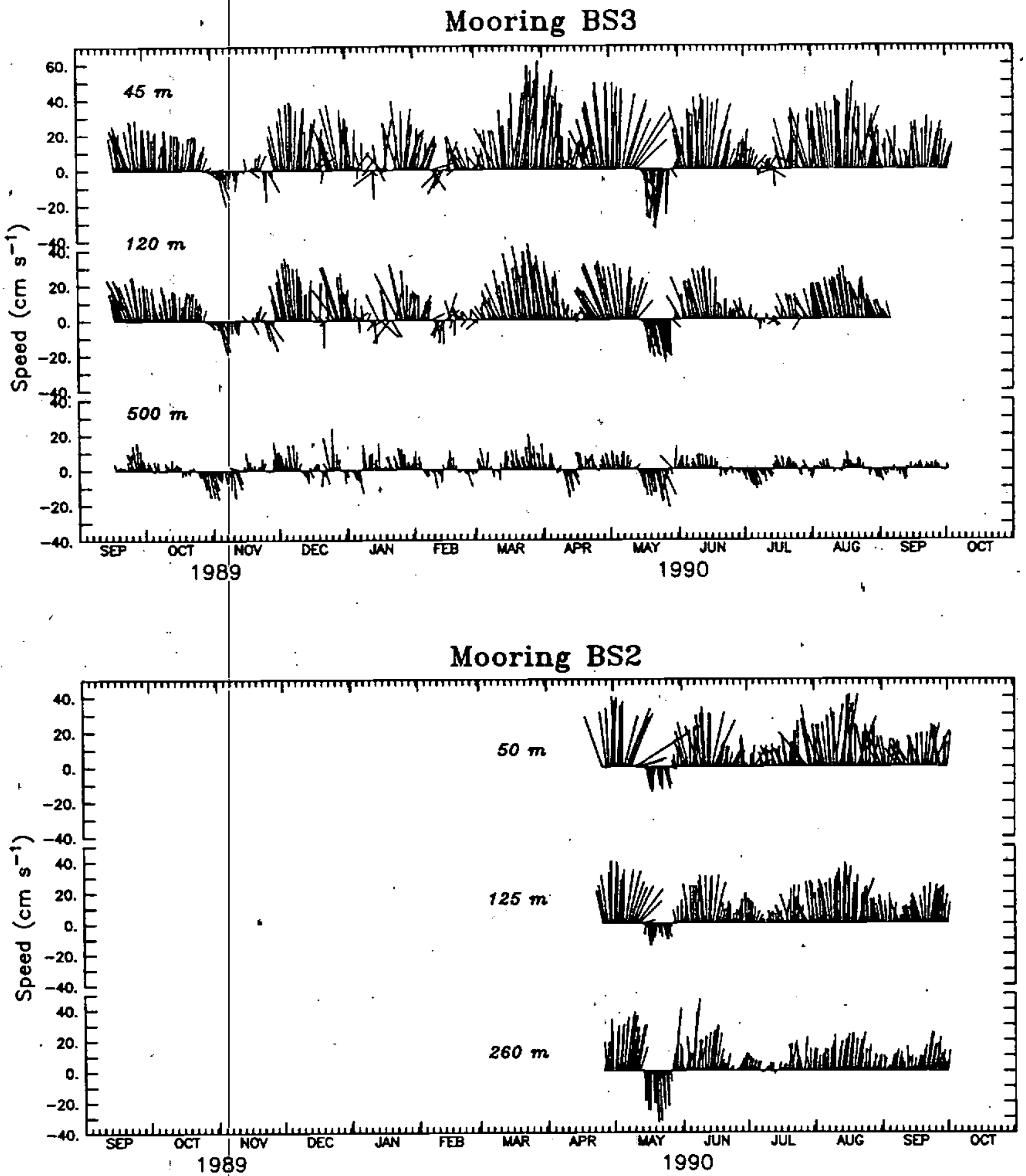

Figure 9. Daily averaged low-pass filtered currents over the slope. Current vectors are aligned with the bathymetry (310°T).

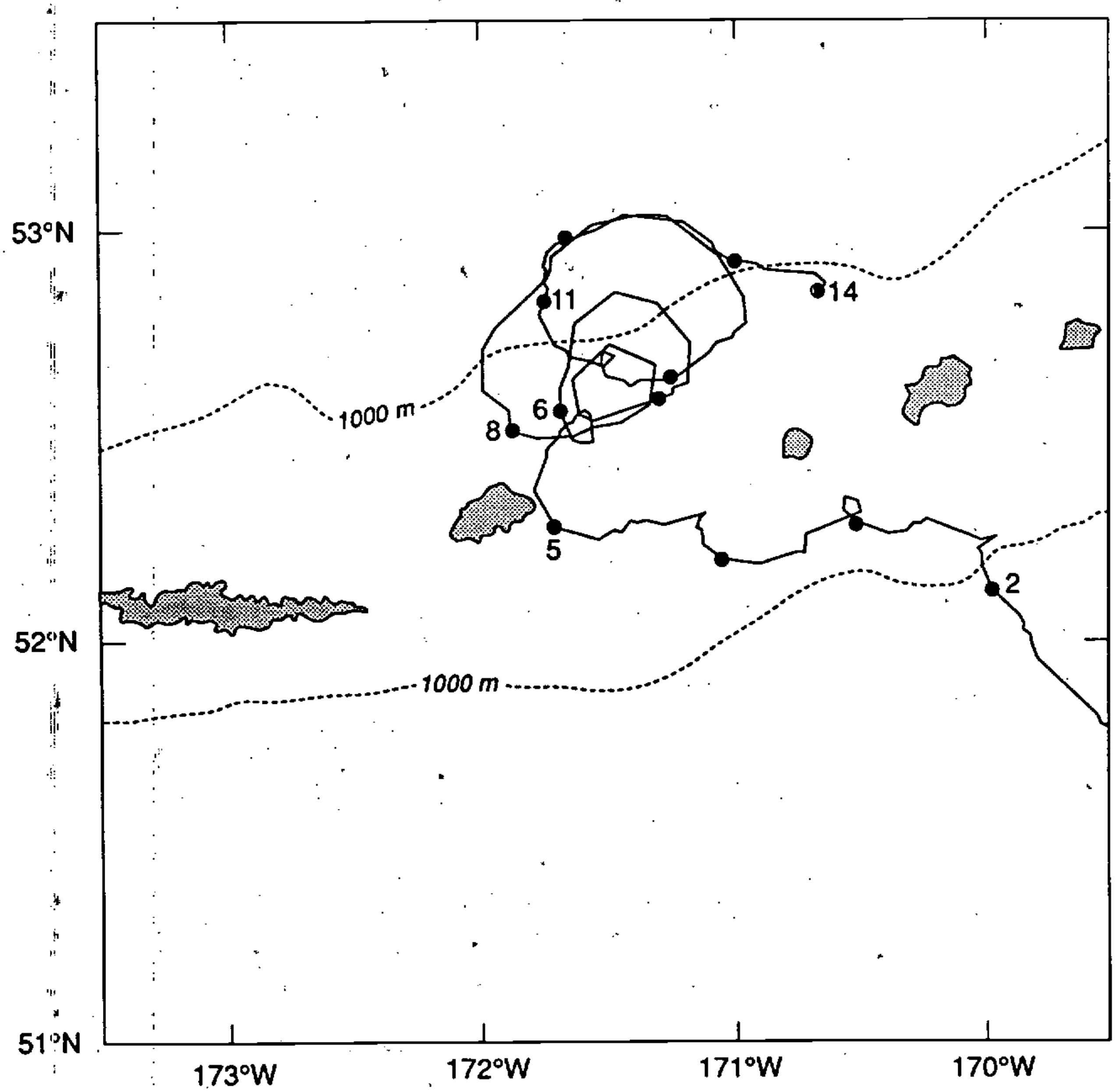

Figure 10. Trajectory of a satellite tracked buoy going through Amukta Pass indicating formation of an eddy. Daily ticks are indicated by circles. All data are from July 1993.

Small eddies can be important to early life history stages of walleye pollock. Results from studies of larval pollock and the physical environment in the Gulf of Alaska show that high concentrations of pollock larvae and eddies tend to coincide (Schumacher *et al.*, 1993), and that early larvae within an eddy were in better condition (Canino *et al.*, 1991; Bograd *et al.*, submitted). Between 1986 and 1993, 45 satellite-tracked buoys have been deployed in support of studies of pollock and their environment. In three of these years, four regions of high rough counts of pollock larvae were found and buoys deployed in them. In all cases, the trajectories of the buoys defined eddies. Likewise, the 33 buoys which were not deployed in a patch never indicated the presence of eddies. Clearly, there is an association of pollock larvae and eddies in the Eastern Bering Sea.

The next steps in our understanding the influence of eddies on survival of larval pollock is to contrast conditions within and outside of an eddy, and to assess potential influence on the larval population by determining how many eddies exist. To conduct a census of eddies in the Eastern Bering Sea is a challenge. Unlike Shelikof Strait (Bograd *et al.*, submitted), it is not possible to capture all the eddies with a line of moored current meters. Satellite infrared imagery is severely limited by cloud cover. Furthermore, observations collected during 1993 showed weak gradients existed in sea surface temperature, hence such eddies are not resolved in A Very High Resolution Radiometer (AVHRR) imagery. Although synthetic aperture radar (SAR) has been used to detect eddies (Schumacher *et al.*, 1991), the present temporal and spatial coverage in the eastern Bering Sea is limited. Formation of eddies by inflow of Alaskan Stream waters through Amukta Pass could provide a site to make a census of eddies. Furthermore, interannual variations in the volume of Alaskan Stream flow into the southeastern Bering Sea affects both production of eddies and water properties (Schumacher and Reed, 1992) over a depth range where pollock spawn and larva reside.

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