NOTES AND CORRESPONDENCE

Circulation in the Bering Sea Basin Observed by Satellite-Tracked Drifters: 1986–1993*

P. J. STABENO AND R. K. REED

Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, Washington

16 December 1992 and 3 August 1993

ABSTRACT

From 1986 through April 1993, 86 satellite-tracked buoys were deployed in the North Pacific and Bering Sea. Most of the buoys were drogued at 40 m. A composite current pattern is derived using these data. The two principal currents (the Alaskan Stream and Kamchatka Current) are clearly evident. Eddy kinetic–mean kinetic energy ratios are low in the stream and along the western Bering Sea basin. An eastward flowing current occurred along the north flank of the Aleutian Islands; this flow was modified by inflow at the passes. Westward flow occurred north of 56°N; its source was the Bering Slope Current. The Kamchatka Current originated near 175°E along the Russian coast. Numerous eddies and meanders were observed in the Kamchatka Current; eddies were also present on the eastern side of the basin.

1. Introduction

The circulation in the Bering Sea (Fig. 1, a composite of historical flow patterns) has been described as a cyclonic gyre, with a western boundary current (the Kamchatka Current) along the western side of the basin (Favorite et al. 1976; Sayles et al. 1979; Hughes et al. 1974). It is complicated, however, by the strong influence of the Alaskan Stream, which flows through Near Strait and to a lesser extent through other passes (principally Amchitka, Buldir, and Amukta passes). It is generally understood that inflow into the Bering Sea is balanced by outflow through Kamchatka Strait (Hughes et al. 1974), so that flow in the Bering Sea basin may be aptly described as a convoluted continuation of the North Pacific subarctic gyre. This current system has mainly been examined through hydrocast data and to a lesser extent by drifting buoys and current meter moorings.

From 1986 through early spring 1993, 74 buoys were deployed in the Bering Sea and Alaskan Stream by scientists at NOAA's Pacific Marine Environmental Laboratory (Seattle, Washington). In addition, 12 buoys deployed near Kodiak Island (off the Alaska Peninsula; 57°N, ~154°W) eventually entered the stream, with four of these entering the Bering Sea. The buoys were deployed on 11 cruises as part of several projects, and these data form the basis of this paper. Data on the eastern continental shelf are not presented here.

* Contribution Number 1399 from NOAA/Pacific Marine Environmental Laboratory. Fisheries Oceanography Coordinated Investigations Contribution FOCI-B171.

Corresponding author address: Dr. Phyllis J. Stabeno, NOAA/PMEL, NOAA Building No. 3, 7600 Sand Point Way NE, Seattle, WA 98115.

2. Data and methods

Over a period of 8 years, 30 buoy-years of data have been collected (Fig. 2a). From 1986 to 1988 the deployments were done in conjunction with NOAA's Fisheries Oceanography Coordinated Investigations (FOCI); most of the buoys deployed during 1989 and 1990 were part of the Outer Continental Shelf Environmental Assessment Program (OCSEAP), and from 1991 through 1993 deployments were part of Bering Sea FOCI. Prior to 1991, all buoys were deployed in the eastern Bering Sea or northern Gulf of Alaska (Reed and Stabeno 1989; Reed and Stabeno 1990; Stabeno and Reed 1990). In 1991 through 1993, most of the buoys were deployed in the western Bering Sea or in the Alaskan Stream west of Amchitka Pass (Stabeno and Reed 1992; Reed et al. 1993).

The majority of the buoys (95%) were drogued at 40 m, and the others were drogued at 100 m. During 1986–1988, all buoys had "holey sock" drogues, while during 1989–1993 "tristar" drogues were used. Only data from buoys that retained drogues are presented here. The buoys deployed in the last four years had tilt switches, which indicated when the drogue was lost. In earlier years, the loss of the drogue was determined from examination of the relationship between the winds and the buoy trajectory (Stabeno and Reed

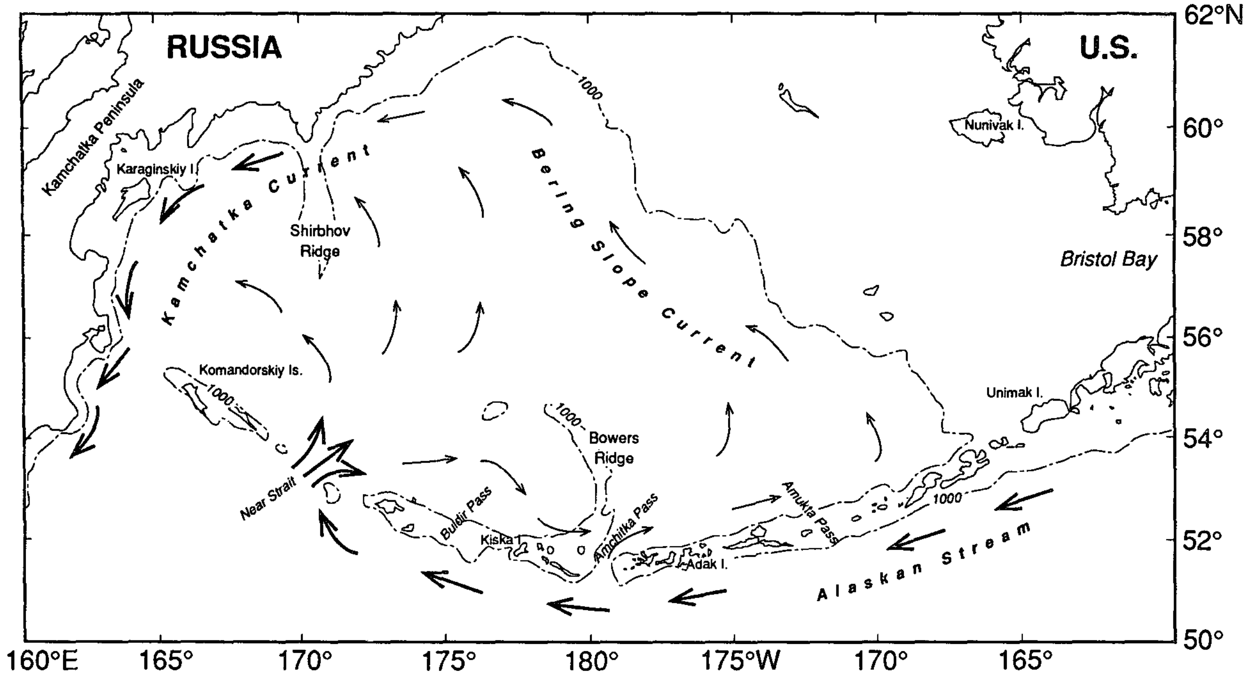

FIG. 1. A schematic of the mean circulation in the Bering Sea [modified from Stabeno and Reed (1992)]. The major currents and topographic features are indicated.

1990). In any case, data from buoys were used for a maximum of 10 months after deployment. An average of 12 satellite fixes were obtained per day, with a standard position error of 0.18 km (Reed and Stabeno 1990).

The data received from the ARGOS system were examined, and obviously erroneous fixes were deleted. Fixes within 10 minutes of each other were averaged together. Since the buoy positions were measured at irregular intervals, a spline was applied to the data, which were then resampled at hourly intervals. (We used an Akima spline, which suppresses wiggles.) Centered differences were calculated using the hourly data, and these were used to determine the buoy velocity. A 25-hour running mean was applied to both the positions and velocities to suppress any tidal or inertial effects.

The mean current velocity was calculated in 1° longitude × 0.5° latitude squares (approximately 50 km × 50 km, Fig. 3) in the Bering Sea basin and south to 47.5°N. Mean velocities were calculated from independent estimates of velocity. Each independent estimate of velocity was the average of the hourly velocity of all buoys within the grid cell during a 5-day period. The integral time scale of velocity (Kundu and Allen 1976) ranged from 2 to 10 days, with a median of ~5 days. A 5-day period began when a buoy entered the grid cell. If there was still at least one buoy in the grid cell after 5 days, another 5-day period began. This method resulted in an average of 51 hourly estimates of velocity in each independent estimate. The velocity variance about each mean was also determined, and the eddy kinetic energy to mean kinetic energy ratios ($KE'/\overline{KE}$) were calculated in grid cells that contained at least three estimates of velocity (Fig. 4). No patterns of $KE'/\overline{KE}$ ratios are shown for the region south of the Bering Sea between 164°E and 170°E; the values were randomly distributed between 0.5 and 50. The number of independent estimates per square are displayed in Fig. 2b.

3. Mean currents and variability

a. The Alaskan Stream

The Alaskan Stream is the northern boundary current of the Pacific subarctic gyre and extends from the head of the Gulf of Alaska to the western Aleutians (Favorite et al. 1976; Reed 1984; Warren and Owens 1988). It is evident in Figs. 3 and 4 as a narrow, high-speed current, with small $KE'/\overline{KE}$ ratios (generally <1.0) stretching from 165°W to 173°E. Statistics east of 178°W were largely determined from buoys deployed in 1986 and 1987 (Stabeno and Reed 1990), while those to the west are from buoys deployed in 1991 through 1993. Note that the stream turned northwestward near Amchitka Pass (180°), following the bathymetry. At ~176°E the stream separated from the 1000-m isobath and flowed due west. Maximum daily averaged buoy speeds east of 180° were 70–95 cm s^{-1}, while to the west the stream became broader and slower with maximum speeds of 40–65 cm s^{-1}. A decrease in the intensity of the stream would be ex-

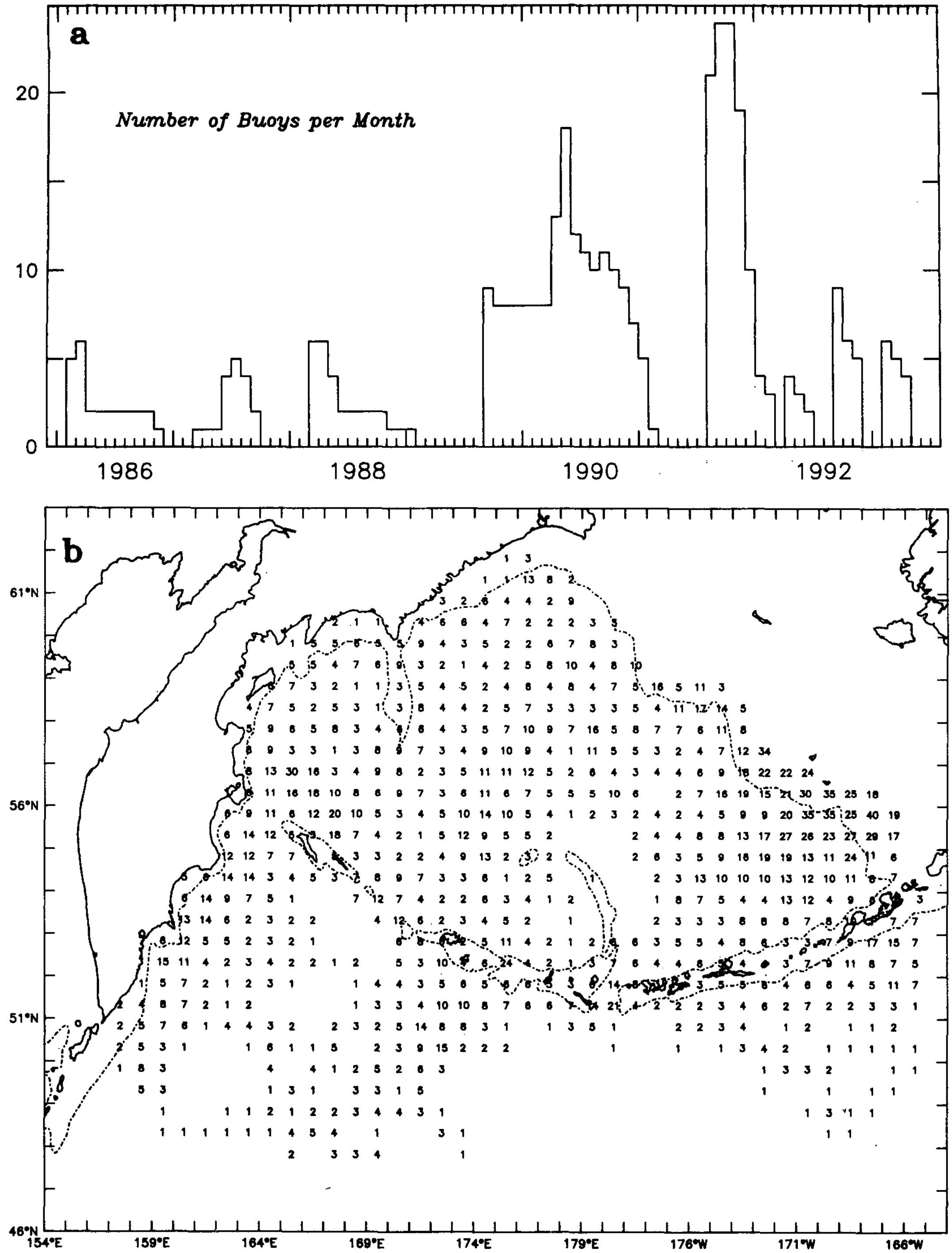

FIG. 2. (a) The number of buoys that retained their drogues and were transmitting each month in the study region. (b) The number of independent estimates per grid cell (~50 × 50 km).

pected west of 180° since the Aleutian Arc turns northward there; thus, the flow is not bounded (Thomson 1972; Favorite et al. 1976). The peak observed speeds are similar to geostrophic speeds from closely spaced hydrocasts (Reed 1984).

The few synoptic CTD grids over a sizable portion of the Alaskan Stream have generally shown conservation of mass (Favorite et al. 1976; Reed 1984); thus, large losses of water east of 178°W are not expected. The two regions of recirculation of the stream east of

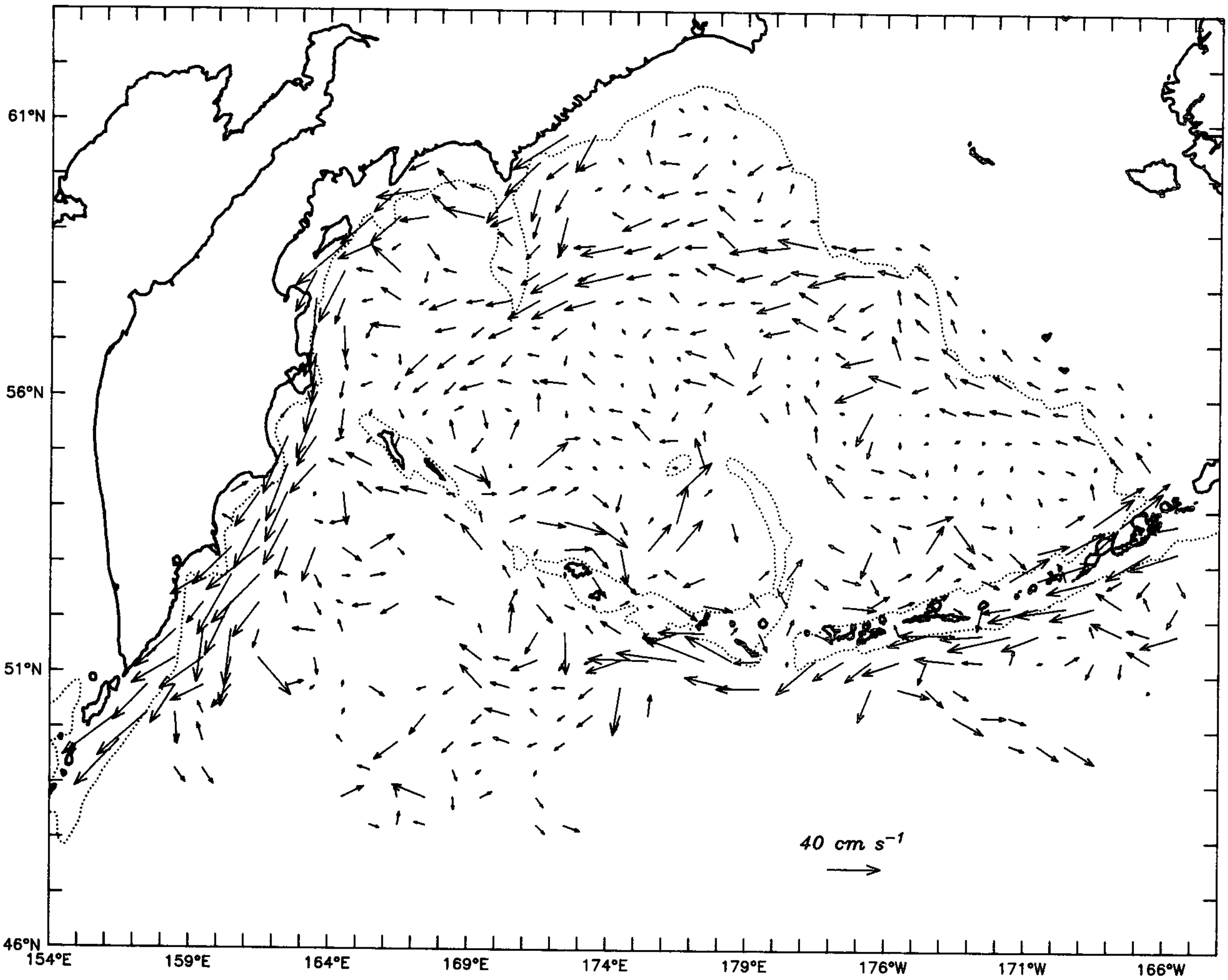

FIG. 3. The mean current velocities interpolated to 1° longitude × 0.5° latitude. A minimum of two independent estimates of velocity were required to determine velocities in each grid cell.

180° (near 166°W and 175°W, Fig. 3) appeared to be transient events. Although loss of mass to the north is limited by the small cross-sectional area of all the eastern passes, input through these passes can be important to water properties in the eastern Bering Sea (Schumacher and Reed 1992). Generally, flow through any of the passes east of 180° was intermittent. In 1989–1990 flow through Amukta Pass was weak (Schumacher and Reed 1992), resulting in relatively cool waters in the southeast corner of the Bering Sea basin. In 1986–1987, a persistent flow into the Bering Sea through the eastern passes was evident from buoys (Stabeno and Reed 1990). Over a period of 3 months in 1991, buoys were transported southward through Amlia Canyon (173°W).

The easternmost pass through which significant northward transport ($>1 \times 10^6$ m^3 s^{-1}) of stream water occurs is Amchitka Pass. Buoys followed a pattern of inflow (northward) on the east side and outflow (southward) on the west side of the pass. Several buoys remained in the pass for several weeks, while being transported counterclockwise in a large eddy, resulting in the large $KE'/\overline{KE}$ (Fig. 4) in Amchitka Pass. This flow pattern was also evident in CTD sections across Amchitka Pass in summer 1991 (Stabeno and Reed 1992) and 1992 (Reed and Stabeno 1993). Net transport was estimated with data from a single current meter mooring as northward (2–3 $\times$ 10^6 m^3 s^{-1}, Reed 1990), although flow was variable and southward at times. Given the flow patterns prevalent in Amchitka Pass, this estimate may not be reliable.

Farther to the west is Buldir Pass (~175°E). In cross-sectional area, it is smaller than Amchitka Pass but larger than any of the eastern passes. Flow through this pass was intermittent, although the net flow was northeastward (Fig. 3). During 1991, as evident from buoys,

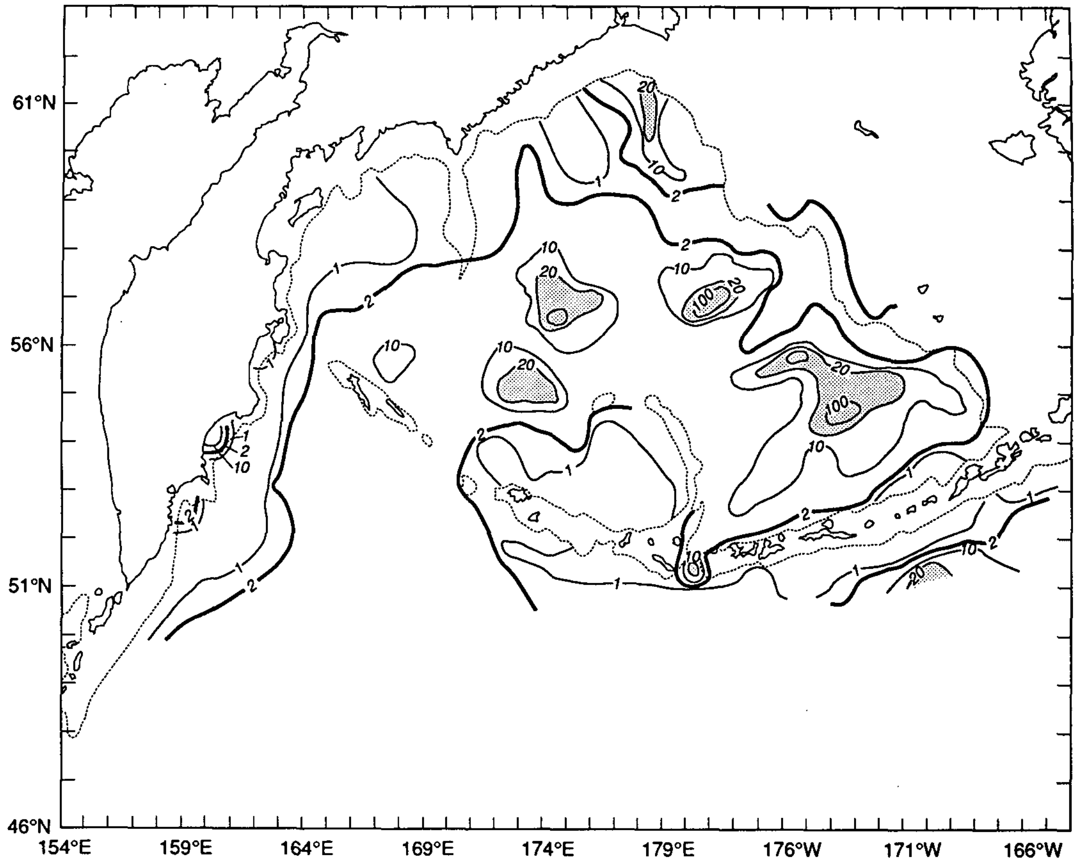

FIG. 4. Ratio of eddy to mean kinetic energy, determined by $(1/N)\sum_{i=1}^{N}\{(u_i-\bar{u})^2+(v_i-\bar{v})^2\}/(\bar{u}^2+\bar{v}^2)$ in each 1° longitude × 0.5° latitude grid, where N is the number of independent estimates (three or more) in each grid, (u_i, v_i) are the measured velocities in a given grid, and $(\bar{u}, \bar{v})$ are the mean velocities.

flow was generally weak and variable. In 1992, it was evident from buoys that flow was to the north and lasted for at least several weeks. This was supported by CTD casts from which transport was estimated at more than 1×10^6 m^3 s^{-1} (Reed and Stabeno 1993).

Historically, transport of the stream water into the Bering Sea through Near Strait has been estimated at $\sim 10 \times 10^6$ m^3 s^{-1} (Favorite 1974). The mean flow into the Bering Sea calculated by our buoy trajectories was variable. In 1991 there was essentially no inflow of stream water (Stabeno and Reed 1992), but in 1992 there was a well-developed northward flow (Reed and Stabeno 1993).

b. The Kamchatka Current

The other major current is the Kamchatka Current, which forms the western boundary current of the Bering Sea gyre. It originated near 175°E and was strongly influenced by the bathymetric feature of Shirshov Ridge, which caused a southward deflection and reduction in speed of the current (Fig. 3). The maximum daily averaged speeds observed in the Bering Sea were in the Kamchatka Current (40–90 cm s^{-1}). Daily averaged velocities as large as 100 cm s^{-1} were measured by buoys in and south of Kamchatka Strait. While maximum velocities were larger than those observed in the stream, the flow was far more variable. Approximately half of the trajectories of buoys in the Kamchatka Current had meanders or eddies; meanders and eddies rarely were observed in the stream east of 173°W. Such features resulted in the mean velocities (Fig. 3) in the Kamchatka Current (10–40 cm s^{-1}) being smaller than those in the Alaskan Stream (20–60 cm s^{-1}).

The major outflow from the Bering Sea was through Kamchatka Strait (Fig. 3). Historically, the Kamchatka Current has also been recognized as the major outflow from the Bering Sea (Hughes et al. 1974). During the period that this dataset was collected, geostrophic transport referenced to 1500 m has ranged from $\sim 6 \times 10^6$ m^3 s^{-1} in 1991 (Stabeno and Reed 1992) to $\sim 12 \times 10^6$ m^3 s^{-1} in 1990 (Verkhunov and Tkachenko 1992).

c. Eddies

Eddies have often been observed in the Bering Sea (Solomon and Ahlnas 1978; Kinder et al. 1980; Paluszkiewicz and Niebauer 1984) and were evident in many of our buoy trajectories. Proposed mechanisms for these eddies include instabilities, wind forcing, and topographic interactions (Kinder et al. 1980). Another source may be strong flows through the eastern passes. An increase in the number of eddies observed in the southeast corner of the Bering Sea occurred when a strong northward flow was permitted through the eastern passes in computer runs of the U.S. Navy layered-ocean model (M. C. Spillane, personnel communication).

On the western side of the Bering Sea basin, several anticyclonic eddies were observed. In the summer of 1991 a set of four buoys showed a meander in the Kamchatka Current being pinched off to form an eddy. This eddy resulted in the high $KE'/\overline{KE}$ ratio (Fig. 4) at 56°N, 168°E, and is fairly representative of the anticyclonic eddies observed in satellite images in 1976–1977 (Solomon and Ahlnas 1978). In three embayments on the Kamchatka Peninsula between 52° and 56°N (Figs. 3 and 4), anticyclonic eddies were evident in the tracks of several of the buoys. They resulted from the interaction of the Kamchatka Current with topographic features and are likely semipermanent since they appeared in trajectories from more than 1 year.

West of Bowers Ridge a large (~200 km) and energetic (velocities ~30–40 cm s^{-1}) eddy is apparent (Fig. 3). Buoys were deflected around the feature, with none being entrained into the center. This feature was present for several months in 1991, but its long-term persistence is unknown. It helps explain, however, the high geostrophic transport observed there (Reed et al. 1993).

d. Slope flow

In the Bering Sea, eastward flow occurred along the northern flank of the Aleutian Islands (Fig. 3). The eastward flow began north of the Komandorskiy Islands (Fig. 1), the flow broadened as it crossed Near Strait, and it was deflected northward by the eddy west of Bowers Ridge. Some of the buoys continued northward, while most returned to the north flank of the Aleutian Islands. The total eastward transport was modified by flow through Amchitka and Amukta passes.

Embedded within this flow was a narrow (~20 km) slope flow that was best documented and appears strongest between 174°W and 167°W. Five buoys over a period of 4 years were transported northeastward along the 1000-m isobath at speeds between 20 and 40 cm s^{-1}. Buoys outside this narrow band showed less organized, more variable flow patterns.

The eastward flow along the Aleutian Islands turned northwestward shoreward of 1000 m and formed the Bering Slope Current (Kinder et al. 1975; Schumacher and Reed 1992), which is evident along the 1000-m isobath (Fig. 3). This flow was strongest and most persistent south of ~58°N. North of 58°N the slope current was very weak, and some reversals occurred. Hence there was little evidence for an inflow of eastern slope waters to the Kamchatka Current north of 59°N. Seaward of the slope current, the flow was quite variable (Fig. 4).

e. Westward flow

The slope current along the eastern boundary of the Bering Sea is the source of the westward flow across the basin (Royer and Emery 1984), which originated at the two areas along the slope where the 1000-m isobath is oriented east–west (~56°N and ~58.5°N; Fig. 3). At the southern source (~56°N), the flow bifurcated with a majority forming a small subgyre in the southeast corner of the basin. The flow in the center of this feature was highly variable with many eddylike features. At the northern source (~58.5°N), the flow moved westward across the basin with much of it joining the Kamchatka Current. The buoys that did not enter the Kamchatka Current recirculated within the Bering Sea. As buoys started westward across the basin, individual trajectories were smooth with little evidence of eddies, but they became more variable toward the center of the basin (Fig. 4).

4. Discussion

Because of the lack of direct current measurements in the region, circulation maps of the flow in the deep Bering Sea have largely been inferred from geostrophic calculations (Hughes et al. 1974; Sayles et al. 1979). There was general agreement that flow was cyclonic with the major inflow through Near Strait and outflow through Kamchatka Strait (as shown in Fig. 1). The flow within the Bering Sea basin, however, varied considerably among the different circulation patterns. None showed the strong eastward flow along the north slope of the Aleutian Islands, probably because the spacing between stations was too large. The Bering Slope Current (BSC) was shown as continuous to the northernmost corner where it turned to form the Kamchatka Current. The westward separations of the BSC at 56°N and 58.5°N are not evident in any of the circulation maps. Speeds in the Kamchatka Current were also underestimated.

Many of the details evident in Fig. 3 agree with results of the U.S. Navy layered-ocean model (Overland et al. 1994). The influence of Bowers Ridge and Shirshov Ridge on upper-layer currents, and the eddy activity west of Bowers Ridge, are evident in model runs. There is a marked similarity between the data and the model in the origin (at ~56°N and 58.5°N) of westward flow across the center of the basin. The eastward flow along the northern flank of the Aleutian Islands is also evident in model runs.

There are also some major differences. The model results do not show strong meanders of the Kamchatka

Current. The fact that the narrow, consistent flows along the 1000-m isobath are not evident in the model results is expected since the model may not resolve the slope well. The strong annual transport variation observed in the model is difficult to detect because of the irregular spacing of the buoys in time. This variation needs to be addressed with moored instruments. The year-long current moorings on the eastern slope, however, showed no pronounced seasonal cycle to the flow (Schumacher and Reed 1992), nor do observations in the Alaskan Stream (Reed 1984).

Strong variability of inflow through the passes was evident in the data. The time scales on which this occurred varied from a few weeks to a year. Although the total transport through the smaller passes is limited by small cross-sectional areas, the effects are important to creation of eddies, to eastward transport north of the Aleutian Islands, and to water mass properties. The major inflow to the Bering Sea occurs through Near Strait and Amchitka Pass, with the only strong outflow occurring through Kamchatka Strait. The narrowness and stability of the Alaskan Stream, the source of inflow to the Bering Sea, is striking.

Acknowledgments. The field work and initial data preparation were supported by NOAA's Coastal Ocean Program, Fisheries Oceanography Coordinated Investigations, and the Outer Continental Shelf Environmental Assessment Program of NOAA and the Minerals Management Service of the Interior Department.

REFERENCES

Favorite, F., 1974: Flow into the Bering Sea through Aleutian Island passes. *Oceanography of the Bering Sea,* D. W. Hood and E. J. Kelley, Eds., Occasional Publication No. 2, Institute of Marine Science, University of Alaska, Fairbanks, 3–37.

——, A. J. Dodimead, and K. Nasu, 1976: Oceanography of the subarctic Pacific region, 1960–1971. Int. North Pacific Fisheries Commission Bull., No. 33, 187 pp.

Hughes, F. W., L. K. Coachman, and K. Aagaard, 1974: Transport and water exchange in the western Bering Sea. *Oceanography of the Bering Sea,* D. W. Hood and E. J. Kelley, Eds., Occasional Publication No. 2, Institute of Marine Science, University of Alaska, Fairbanks, 59–98.

Kinder, T. H., L. K. Coachman, and J. A. Galt, 1975: The Bering slope current system. *J. Phys. Oceanogr.,* **5,** 231–244.

——, J. D. Schumacher, and D. V. Hansen, 1980: Observations of a baroclinic eddy: An example of mesoscale variability in the Bering Sea. *J. Phys. Oceanogr.,* **10,** 1228–1245.

Kundu, P. K., and J. S. Allen, 1976: Some three-dimensional characteristics of low-frequency current fluctuations near the Oregon coast. *J. Phys. Oceanogr.,* **6,** 181–199.

Overland, J. E., M. C. Spillane, H. E. Hurlburt, and A. J. Wallcraft, 1994: A numerical study of the circulation of the Bering Sea basin and exchange with the North Pacific Ocean. *J. Phys. Oceanogr.,* **24,** 736–758.

Paluszkiewicz, T., and H. J. Niebauer, 1984: Satellite observations of circulation in the eastern Bering Sea. *J. Geophys. Res.,* **89,** 3663–3678.

Reed, R. K., 1984: Flow of the Alaskan Stream and its variations. *Deep-Sea Res.,* **31,** 369–386.

——, 1990: A year-long observation of water exchange between the North Pacific and the Bering Sea. *Limnol. Oceanogr.,* **35,** 1604–1609.

——, and P. J. Stabeno, 1989: Circulation and property distributions in the central Bering Sea, Spring 1988. NOAA Tech. Rep. ERL 439-PMEL 39, 13 pp.

——, and ——, 1990: Flow trajectories in the Bering Sea: Evidence for chaos. *Geophys. Res. Lett.,* **17,** 2141–2144.

——, and ——, 1993: The recent return of the Alaskan Stream to Near Strait. *J. Mar. Res.,* **51,** 515–527.

——, G. V. Khen, P. J. Stabeno, and A. V. Verkhunov, 1993: Water properties and flow over the deep Bering Sea basin, summer 1991. *Deep-Sea Res.,* in press.

Royer, T. C., and W. J. Emery, 1984: Circulation in the Bering Sea, 1982–1983, based on satellite-tracked drifter observations. *J. Phys. Oceanogr.,* **14,** 1914–1920.

Sayles, M. A., K. Aagaard, and L. K. Coachman, 1979: *Oceanographic Atlas of the Bering Sea Basin.* University of Washington Press, 158 pp.

Schumacher, J. D., and R. K. Reed, 1992: Characteristics of currents over the continental slope of the eastern Bering Sea. *J. Geophys. Res.,* **97,** 9423–9433.

Solomon, H., and K. Ahlnas, 1978: Eddies in the Kamchatka Current. *Deep-Sea Res.,* **25,** 403–410.

Stabeno, P. J., and R. K. Reed, 1990: Recent Lagrangian measurements along the Alaskan Stream. *Deep-Sea Res.,* **38,** 289–296.

——, and ——, 1992: A major circulation anomaly in the western Bering Sea. *Geophys. Res. Lett.,* **19,** 1671–1674.

Thomson, R. E., 1972: On the Alaskan Stream. *J. Phys. Oceanogr.,* **2,** 365–371.

Verkhunov, A. V., and Y. Y. Tkachenko, 1992: Recent observations of variability in the western Bering Sea current system. *J. Geophys. Res.,* **97,** 14 369–14 376.

Warren, B. A., and W. B. Owens, 1988: Deep currents in the central subarctic Pacific Ocean. *J. Phys. Oceanogr.,* **18,** 529–551.