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Lagrangian Measurements in the Kamchatka Current and Oyashio

P. J. STABENO, R. K. REED and J. E. OVERLAND

Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115-0070, U.S.A.

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From 1988 to 1993, 23 satellite-tracked drifting buoys entered the Kamchatka Current. The buoy trajectories showed a well-formed, high-speed current that originated near Shirshov Ridge, and flowed southward through Kamchatka Strait. During some years, the buoys turned eastward at ~50°N, while in other years they were transported as far south as Japan (40°N). Only one buoy entered the Sea of Okhotsk. Eddies were evident in many of the buoy trajectories. Greatest maximum daily velocities (>100 cm s^{-1}) were observed south of Kamchatka Strait, with 50–60 cm s^{-1} being more common.

1. Introduction

The circulation in the Bering Sea basin is a convoluted continuation of the North Pacific subarctic gyre, with inflow of the Alaskan Stream through Near Strait and to a lesser extent through passes farther to the east along the Aleutian Arc (Fig. 1; Stabeno and Reed, 1994). The Kamchatka Current (Verkhunov and Tkachenko, 1992), the southward flowing western boundary current, is the major outflow from the Bering Sea (Takenouti and Ohtani, 1974). South of ~50°N, we call the southward flow the Oyashio in general agreement with Ohtani (1970). There is exchange of water between the Kamchatka Current-Oyashio system and the Okhotsk Sea (Kitani, 1973), but net transports appear to be small (probably $<2 \times 10^6$ m^3 s^{-1}; Kurashina *et al*., 1967). Outflow from the Okhotsk Sea, however, may be important to the formation of North Pacific Intermediate Water (Talley, 1991).

Transport of the Kamchatka Current appears to typically vary between ~6 and 11×10^6 m^3 s^{-1} (Verkhunov and Tkachenko, 1992), although Reid (1973) did report a value of 23×10^6 m^3 s^{-1}. We suspect that much of the variation in transport of the Kamchatka Current in the Bering Sea results from variations of the Alaskan Stream inflow through Near Strait (Reed and Stabeno, 1993). Ohtani (1970) gave Oyashio transports of $5–8 \times 10^6$ m^3 s^{-1}.

From 1988–1993, our laboratory deployed ~120 satellite-tracked drifting buoys in the Bering Sea and the North Pacific, 23 of these entered the Kamchatka Current. The buoys were deployed as part of NOAA's Fisheries Oceanography Coordinated Investigations (FOCI) and Outer Continental Shelf Environmental Assessment Program (OCSEAP). The analyses of the buoy trajectories form the basis of this paper.

2. Data and Methods

Data presented here are from free floating, Argos transmitting, drifting buoys which were drogued at 40 m. During 1988, all buoys had holey sock drogues, while during 1989–1993 tristar drogues were used. Most of the data used here are from drifting buoys deployed in summer of 1991 (13) and late winter of 1993 (6). Only data from buoys which retained their 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 wind and the buoy trajectory (Stabeno and Reed, 1991). An average of 12 satellite fixes were obtained per day, with a standard position error of ~0.2 km.

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 buoy positions were measured at irregular intervals, an Akima spline was applied to the data, which were then resampled at hourly intervals. Centered differences were calculated using the hourly data, and these were used to determine the buoy velocity.

3. Buoy Trajectories

The Kamchatka Current-Oyashio system extends for ~3000 km along the coast from Shirshov Ridge in the north to Hokkaido in the south. For this study, the length of the coast has been divided into four sections (Fig. 1). In Section 1, the shortest section, the coast is oriented east-west. Section 2 is the north-south part of the coast in the Bering Sea. Section 3 extends south of Kamchatka Strait to 50°N, which is considered the northern limit of the Oyashio. The last section extends south from 50°N to Japan (43°N).

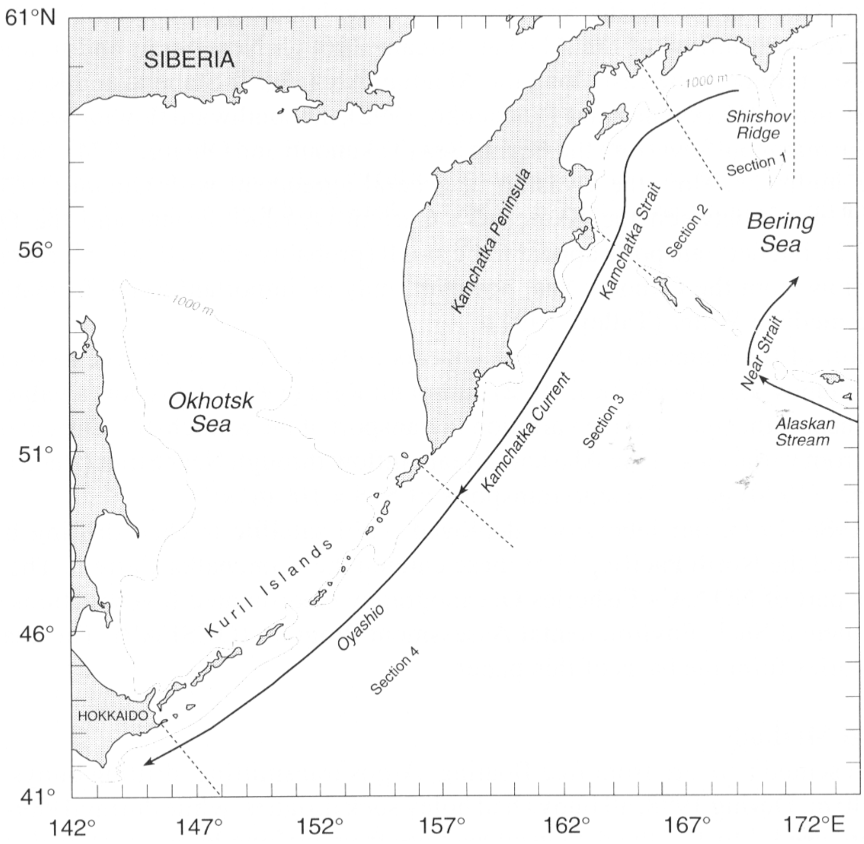

Fig. 1. Map showing selected geographic features and a schematic of circulation along the coast of Russia and Japan. The 1000 m isobath is indicated as a dashed line. Limits of the sections used are also shown.

3.1 Section 1

We begin our examination of the Kamchatka Current at Shirshov Ridge (Fig. 1). East of Shirshov Ridge data were limited, but some information is available. Buoys in the basin (water depth >1000 m), showed weak, generally westward flow, that was rather broad (Stabeno and Reed, 1994). Several buoys, however, provided evidence of a coastal current (water depth <200 m) along the Russian coast in this area. West of Shirshov Ridge the data base is larger, due to buoys deployed near the ridge in 1991 and 1993. Also, buoys from other years were deployed in the eastern Bering Sea and were transported into this section. Maximum daily velocities in this section were typically 30–60 cm s^{-1} (Table 1), but the directions were highly variable (105°–291°T).

3.2 Section 2

On entering Section 2, the buoys turned southward paralleling the coast. Nine of the eleven buoys from Section 1 continued into Section 2. These were augmented by another 8 buoys which were deployed in the section or in the eastern Bering Sea. A quarter of the buoys deployed in 1991 recirculated in the Bering Sea, while all those from other years continued southward through Kamchatka Strait (Table 2). Maximum daily and mean velocities were generally greater in 1993 than in 1991, but the KE′/KE ratios were smaller in 1993. The recirculation and weaker currents in 1991 were not surprising since there was weak inflow into the Bering Sea through Near Strait

Table 1. Statistics of the 11 drifting buoys in Section 1 (see text). Residence time was the number of days each buoy was in this section. KE′ is the eddy kinetic energy per unit mass (KE′ = $0.5[\sigma_u^2 + \sigma_v^2]$, where σ_u^2 and σ_v^2 are the variances of the u (east) and v (north) velocity components). KE is the kinetic energy of the mean flow per unit mass (KE = $0.5[\bar{u}^2 + \bar{v}^2]$, where $\bar{u}$ and $\bar{v}$ are the mean velocity components). The vector mean velocity (over the residence time) is given in column 4. Daily mean velocities were calculated over each 24-hour period starting at 0000 GMT. The maximum daily mean velocities are listed in column 5. The code for the status of the buoys is as follows: C indicates continued to next section; D indicates loss of drogue or failure to transmit.

Buoy	Entered Kamchatka Current	Residence time (days)	Velocity		KE′/KE	Status
			Mean (cm s^{-1}, °T)	Daily Max. (cm s^{-1}, °T)		
7256	11-26-88	10	23 (268)	47 (291)	1.1	D
7238	8-19-91	30	5 (202)	42 (135)	3.0	C
7166	9-5-91	6	9 (252)	14 (261)	0.2	C
7226	10-23-91	16	17 (265)	56 (105)	1.8	C
7162	11-26-91	6	24 (239)	38 (234)	0.2	C
7236	3-14-92	8	32 (229)	57 (270)	0.8	C
7228	2-20-93	8	22 (225)	56 (199)	0.5	C
7239	2-20-93	7	21 (238)	31 (220)	0.3	C
7161	2-21-93	3	37 (234)	58 (248)	0.2	C
7168	2-27-93	8	13 (236)	54 (237)	9.5	D
7214	2-28-93	11	27 (268)	74 (267)	2.3	C

Table 2. Statistics of the 17 drifting buoys in Section 2. KE′ and KE are as defined in Table 1. The code for the final status of the buoys is as follows: C indicates buoy continued to next section, D indicates loss of drogue or failure to continue transmitting; and E indicates that a large eddy was apparent in the buoy track. The latitude at which the buoy turned eastward and exited the Kamchatka Current is given when appropriate.

Buoy	Entered Kamchatka Current	Residence time (days)	Velocity		KE′/KE	Status
			Mean (cm s^{-1}, °T)	Daily Max. (cm s^{-1}, °T)		
7210	3-20-89	2	12 (202)	13 (228)	0.2	C
7241	8-17-91	4	32 (185)	42 (190)	0.1	57°, E
7243	8-17-91	5	35 (188)	42 (189)	0.1	57°, E
7166	9-11-91	13	29 (199)	46 (192)	0.5	C
7238	9-18-91	37	10 (226)	42 (223)	2.9	C
7160	10-5-91	109	2 (189)	34 (228)	34.7	C, E
7226	11-7-91	6	17 (236)	36 (233)	0.8	D
7162	12-3-91	20	22 (203)	74 (172)	1.1	C
7163	12-3-91	7	19 (177)	81 (201)	3.6	C
7237	4-28-92	22	15 (194)	37 (191)	1.4	C
7161	2-24-93	14	33 (201)	81 (193)	0.7	C
7239	2-27-93	13	34 (201)	82 (177)	0.9	C
7228	2-28-93	14	29 (217)	76 (171)	1.6	C
7221	3-12-93	7	37 (192)	64 (178)	0.1	C
7214	3-14-93	8	52 (195)	86 (174)	0.3	C
7236	3-22-93	13	25 (215)	59 (166)	1.2	C
7164	3-28-93	3	50 (184)	64 (178)	0.1	C

in 1991, resulting in weak flow in the Kamchatka Current (Stabeno and Reed, 1992). By 1992, a more normal inflow had returned to Near Strait and, most likely, higher transport in the Kamchatka Current (Reed and Stabeno, 1993). Typical maximum daily velocities were stronger (40–80 cm s^{-1}; Table 2) here than in Section 1, and the directions were more consistent (200° ± 30°).

3.3 Section 3

Most of the buoys from Section 2 continued southward through Kamchatka Strait (Figs. 2(a) and (b)). These buoys were augmented by one buoy deployed in Kamchatka Strait (Fig. 2(f)), two buoys deployed south of the Aleutian Islands (Fig. 2(c)), and a buoy deployed near Kodiak Island (57°N, 155°W; 7213, Table 3). Thus, part of the transport of the Kamchatka Current south of Kamchatka Strait originated from the portion of the Alaskan Stream which did not enter the Bering Sea. The highest maximum daily velocities were observed in this region, with five buoys measuring speeds >90 cm s^{-1}; the directions were generally toward the southwest (Table 3). There was a marked difference in the trajectories of buoys from 1991, compared to trajectories of buoys from other years. Several of the 1991 buoys turned eastward near 50°N (Figs. 2(c) and (d)) leaving the Kamchatka Current, while the buoys from 1988 and 1993 continued southward.

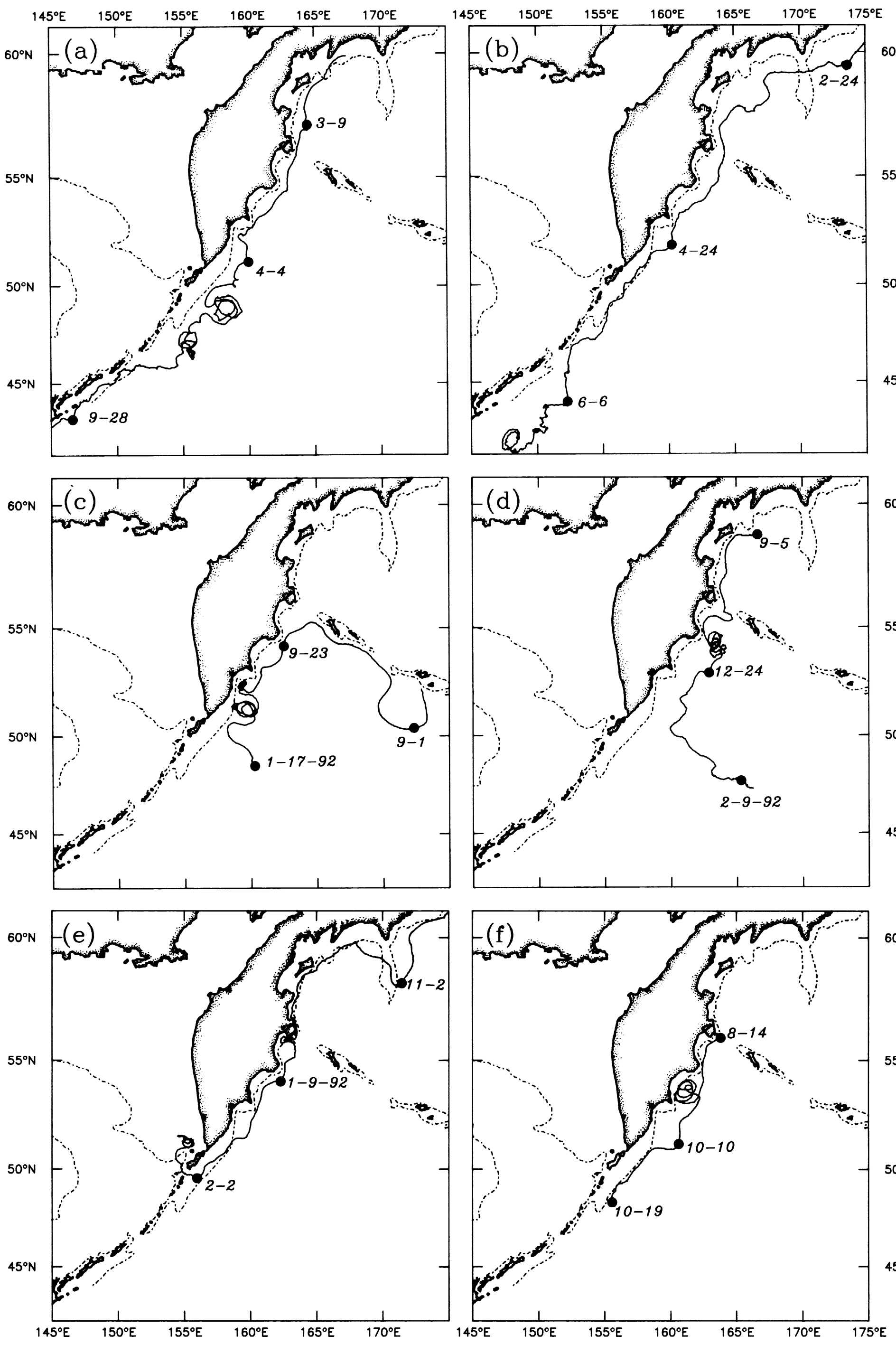

Fig. 2. Selected trajectories of buoys in the Kamchatka Current and Oyashio: (a) buoy 7161, deployed in February 1993; (b) buoy 7236, deployed in September 1992 in the eastern Bering Sea; (c) buoy 0232, deployed southeast of Near Strait in August 1991; (d) buoy 7166, deployed in September 1991; (e) buoy 7162, the only buoy which entered the Okhotsk Sea, deployed in August 1991; (f) buoy 7173, deployed in Kamchatka Strait in August 1991.

Table 3. Statistics of the 18 drifting buoys that entered the Kamchatka Current (Section 3). KE′ and KE are as defined for Table 1. The code for the status of the buoys is as follows: C indicates continued to next section, D indicates loss of drogue or failure to continue transmitting; G indicates buoy went aground; O indicates buoy entered the Okhotsk Sea; and E that an eddy was apparent in the buoy track. The latitude at which the buoy turned eastward and exited the Kamchatka Current is given when appropriate.

Buoy	Entered Oyashio	Residence time (days)	Velocity		KE′/KE	Status
			Mean (cm s^{-1}, °T)	Daily Max. (cm s^{-1}, °T)		
7210	3-22-89	67	15 (218)	82 (232)	2.8	C
7213	2-15-91	12	39 (217)	77 (220)	0.4	C
7166	9-24-91	102	8 (203)	62 (215)	10.0	50°, E
7171	11-2-91	14	16 (198)	48 (199)	1.1	D
7163	12-10-91	21	41 (212)	106 (244)	0.7	50°
7173	8-14-91	57	16 (213)	71 (225)	5.3	C, E
7238	10-25-91	16	36 (211)	49 (251)	0.3	51°, E
7160	1-23-92	28	31 (217)	72 (214)	0.5	50°
0232	9-18-91	85	9 (218)	65 (230)	14.4	50°, E
7237	6-24-92	66	8 (225)	68 (253)	4.7	G, E
7162	12-22-92	39	25 (215)	83 (199)	1.4	O
7161	3-11-93	27	33 (210)	93 (223)	1.1	C
7239	3-12-93	25	34 (200)	118 (212)	1.8	D
7228	3-14-93	36	25 (212)	92 (217)	2.0	C
7221	3-18-93	25	37 (212)	91 (225)	0.8	C
7214	3-22-93	26	36 (212)	69 (242)	0.2	C, E
7164	3-31-93	34	23 (212)	64 (240)	1.1	C, E
7236	4-4-93	27	35 (218)	69 (180)	0.4	C

In fact, no buoy from 1991 went farther south than ~48°N. It is not known whether the differences in trajectories were caused by interannual variability or by seasonal differences. It has already been mentioned that flow in the Bering Sea was abnormally weak during 1991.

3.4 Section 4

All nine buoys in Section 4 originated in Section 3 (Table 4). The maximum daily velocities were generally lower (50–80 cm s^{-1}) than observed in Section 3. These velocities were similar to those observed in Section 2. The southward flowing Oyashio was often broader than the Kamchatka Current. Some buoys (Fig. 2(b), for example) were well off-shore, while other buoys remained near the 1000 m isobath (Fig. 2(a)).

3.5 Soya current

Of the four buoys which moved south of 44°N near the 1000 m isobath, one entered the shallow shelf along the east coast of the Kuril Islands. The other three buoys were transported along the 1000 m isobath. Two of these buoys (one in August 1993 and the other almost two

Table 4. Statistics of the 9 drifting buoys in Section 4. KE′ and KE are as defined for Table 1. The code for the status of the buoys is as follows: D indicates loss of drogue or stopped transmitting; E that an eddy was apparent the buoy track in this section. The latitude is given at which a buoy turned eastward and exited the Oyashio when appropriate.

Buoy	Entered Oyashio	Residence time (days)	Velocity		KE′/KE	Status
			Mean (cm s^{-1}, °T)	Daily Max. (cm s^{-1}, °T)		
7210	5-28-89	35	14 (223)	61 (234)	1.9	D
7213	2-27-91	2	13 (210)	25 (178)	1.0	49°
7173	10-10-91	8	16 (231)	53 (218)	0.3	D
7161	4-6-93	179	8 (231)	72 (209)	10.4	D, E
7221	4-12-93	15	34 (225)	100 (211)	1.3	D, E
7214	4-17-93	110	12 (227)	81 (252)	6.7	D
7228	4-19-93	40	22 (213)	81 (238)	2.2	D
7236	5-1-93	77	14 (214)	80 (247)	2.2	D
7164	5-9-93	157	2 (230)	70 (225)	176.5	D, E

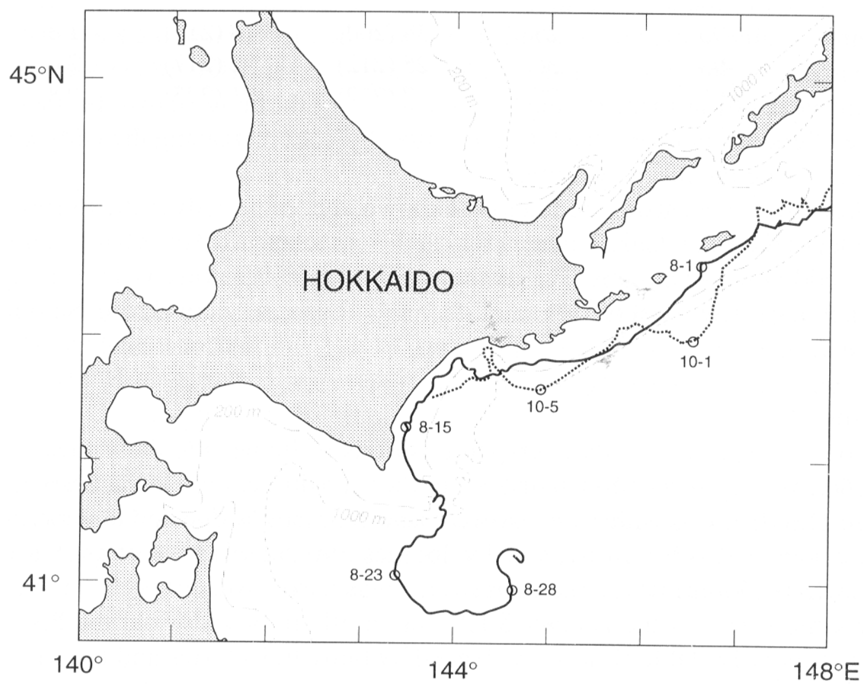

Fig. 3. Trajectories of the two buoys in the Soya Current in 1993.

months later) moved toward the coast and entered an extension of the Soya Current (Fig. 3). The Soya Current originates in Soya Strait, continues along the coast in the southern part of the Okhotsk Sea, is modified along the southern Kuril Islands, and eventually extends along the southeast coast of Hokkaido (Sugimoto, 1990; Bobkov, 1993). It is strongest in late summer (Sugimoto, 1990), which was when the two buoys were in the coastal flow. Maximum daily current velocities in this coastal current were as large as 50–60 cm s^{-1}, but more typically 30–40 cm s^{-1}.

3.6 Inflow to the Okhotsk Sea

Although an earlier view was that the Oyashio is a combination of water from the Kamchatka Current and the Okhotsk Sea, Ohtani (1970) concluded that it is mainly of Kamchatka Current origin. From the buoy trajectories presented here, there is little evidence that there is a large influx of near surface (<50 m) waters from the Oyashio into the Okhotsk Sea. Of the 14 buoys that were transported along the Kuril Islands, only one entered the Sea of Okhotsk (Fig. 2(e)). It has been reported that warm water enters the Okhotsk Sea through these northern passes (Kitani, 1973). Any outflow from the Okhotsk Sea is more difficult to detect with this data set.

4. Eddies

A common feature in buoy trajectories is the presence of eddies, and the trajectories presented here were no exception. (An eddy is identified here as a feature around which a buoy rotates at least twice.) A total of 12 eddies (11 anti-cyclonic) were observed in the buoy trajectories, only one of which was in the Bering Sea. The eddies were often stationary and evenly distributed between Kamchatka Strait and 42°N, ranging in size from ~20 km near the coast to >150 km. Three sizable embayments south of 56°N in the east coast of the Kamchatka Peninsula (Fig. 1) appeared to be preferential sites for eddies (Figs. 2(c) and (f)). Eddies were most common in 1991 during weak inflow to the Bering Sea, when 60% of the buoys showed evidence of eddies. The presence of eddies increases the KE′/KE ratios, by both increasing the eddy kinetic energy (KE′) and decreasing the mean velocities.

While the source of most of the eddies is unknown, the single eddy in the Bering Sea resulted from a meander of the Kamchatka Current, which then pinched off. Three buoys remained in this anti-cyclonic eddy for 1–2 months. The diameter of this eddy (50 km) was fairly representative of the anti-cyclonic eddies observed in satellite images of the western Bering Sea (Solomon and Ahlnas, 1978).

5. Discussion

At 149 of the over 5000 daily averaged positions of buoys, the daily mean velocity was greater than 60 cm s^{-1} (Fig. 4). More than 95% of these positions were in the Kamchatka Current and Oyashio. The flow was widest and slowest near Shirshov Ridge and downstream of 50°N. The highest velocities (~15 daily averaged velocities >90 cm s^{-1}) were consistently found just south of Kamchatka Strait, where the current also was narrowest.

The Alaskan Stream is the westward-flowing, northern boundary of the Pacific subarctic gyre. It is a particularly stable flow as evidenced by buoy trajectories and moorings (Reed and Stabeno, 1989; Stabeno and Reed, 1991). Eddies are rarely observed in the stream, and the ratios of eddy kinetic to mean kinetic energy are generally less than 1.0 (Stabeno and Reed, 1991). Conversely, in the Kamchatka Current eddies were common, and about half the KE′/KE ratios were >1.0 (Tables 1–3). The ratios in the Oyashio were even larger, where only 1 in 9 were <1.0

Fig. 4. The daily mean positions of buoys with daily average velocities >60 cm s^{-1}.

(Table 4). The presence of eddies resulted in smaller mean velocities in the Kamchatka Current and Oyashio, than were measured in the Alaskan Stream. Perhaps a more telling parameter for comparing current velocities is the maximum daily velocity, which is not influenced by eddies. Maximum daily velocities in Sections 2 and 4 were comparable to those measured in the Alaskan Stream. Section 3, however, had velocities that exceeded any measured in the stream, and Section 1 had values that were less than in the stream.

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