Do oil and gas platforms off California reduce recruitment of bocaccio (*Sebastes paucispinis*) to natural habitat? An analysis based on trajectories derived from high frequency radar

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Abstract

To investigate the possibility that oil platforms might reduce recruitment of rockfishes (*Sebastes* spp.) to natural habitat, we simulated drift trajectories from an existing platform to nearshore habitat using current measurements from high frequency (HF) radars. The trajectories originate at Platform Irene, located west of Point Conception, California, during two recruiting seasons for bocaccio (*Sebastes paucispinis*): May through August, 1999 and 2002. Given that pelagic juvenile bocaccio dwell near the surface, the trajectories estimate transport to habitat. Assuming appropriate shallow water juvenile habitat inshore of the 50 m isobath, results from 1999 and 2002 indicate that 10% and 24% of the trajectories, respectively, represent transport to habitat, while 76% and 69%, crossed the offshore boundary. Remaining trajectories (14% and 7%) exit the coverage area either northward or southward along isobaths. Deployments of actual drifters (with 1 m drogues) from a previous multi-year study provide measurements originating near Platform Irene during May through August. All but a few of the drifters moved offshore, consistent with the HF radar-derived trajectories. These results suggest that most juvenile bocaccio settling on the platform would otherwise have been transported offshore and perished in the platform's absence. However, these results do not account for swimming behavior of juvenile bocaccio about which little is known.

Introduction

The 27 oil and gas platforms off southern and central California have finite economic life spans. Many of these structures have been in place for over 20 years (Love et al., 2003), and it is expected that some of these platforms will be decommissioned in the near future. Because decommissioning may entail full removal of the platform, agencies tasked with determining the best course of action would be assisted by an understanding of the role that platforms play as fish habitat.

The platforms harbor high densities of many species of fishes, although species compositions vary with platform bottom depth (Love et al., 1999a; 1999b; Love et al., 2003). About 35 species of rockfishes (genus *Sebastes*) dominate these assemblages (Love et al., 2003). There are three distinct assemblages around many platforms in the Santa Barbara Channel and off central California: mid-water, bottom, and shell mound. Fishes around platform bottoms tend to be adult and sub-adult individuals. Those on the shell mounds are usually adults of dwarf species or juveniles of larger taxa. The midwater assemblages are composed almost entirely of juvenile fishes. Most of these are rockfishes, predominantly young-of-the-year (YOY), but also one and two-year old individuals. Densities of YOY rockfishes around platforms are usually far higher than those at nearby natural reefs (Love et al., 2003). These observations have raised a concern that platforms may reduce recruitment to natural reefs by functioning as catchments for pelagic juvenile rockfishes (e.g. Krop[1]).

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[1] Krop L. 1997. Environmental user group representative, disposition panel. *In* Proceedings: Public Workshop, Decommissioning and removal of Oil and Gas Facilities Offshore California: Recent Experiences and Future Deepwater Challenges, September 1997 (F. Manago and B. Williamson, eds.), p. 172. MMS OCS Study 98-0023. Coastal Research Center, Marine Science Institute, University of California, Santa Barbara, California. MMS Cooperative Agreement Number 14-35-0001-30761. 269 pp.

To investigate the possibility that an oil platform might reduce recruitment of rockfishes to natural habitat, we simulated drift pathways (hereafter referred to as "trajectories") from an existing platform to nearshore habitat using current measurements from high frequency (HF) radars.

Materials and methods

Modeled species

Because trajectories derived from HF radar approximate transport pathways of near surface water parcels, we chose to model the movements of pelagic juvenile bocaccio (*Sebastes paucispinis)* which dwell near the surface during their time in the plankton. This historically important recreational and commercial fishing target in central and southern California (Love et al., 2002), is also among the shallowest dwelling juveniles (Lenarz et al., 1991; Ross and Larson, 2003).

Off central and northern California, parturition occurs for bocaccio from January to May with a February peak (Love et al., 2002). Off southern California, the species has a reproductive season that spans all year, but most larvae are released from October to July with a January peak. Juvenile bocaccio recruit to inshore waters from February to August off central California, although May through July is the peak season (Love et al., 2002). The trajectory simulation period of May through August was chosen to span this principal recruitment season.

Bocaccio range from the Alaska Peninsula to central Baja California, and adults are usually found over high relief boulder fields and rocks in 50-250 m of water (Love et al., 2002). The fish most often settle in rocky habitat covered with various algae or in sandy zones with eelgrass. Juvenile bocaccio are commonly found in drifting kelp (Boehlert, 1977; Mitchell and Hunter, 1970) indicating that the fish recruit to natural habitat encountered in offshore surface waters. For this analysis, we assumed that waters from the shallow subtidal to the 50 m isobath represent suitable habitat for juvenile recruits. This choice reflects the lack of information about suitable habitat locations in our study area, and likely overestimates the abundance of such habitat.

Annual scuba surveys and submersible surveys (1995-2001) in the Santa Barbara Channel and Santa Maria Basin regions showed that YOY bocaccio occurred in the upper 35 m around one or more platforms in each year surveyed. Platform Irene (34^{o} 36.62' N, 120^{o} 43.40' W; bottom depth 73 m) was selected for analysis because fish recruited to it each year from 1995-2001 (Love et al., 2001) and it was the site of the highest density of YOY bocaccio observed from submersible surveys during these years (Love et al., 2003). Moreover, during May through August, 1999 and 2002, Platform Irene was also in a region of good HF radar coverage which allowed computation of extensive trajectory ensembles.

Current measurements and trajectory estimation

Near-surface ocean currents were measured hourly using an array of three HF radars (SeaSondes, manufactured by CODAR Ocean Sensors, Ltd. of Los Altos, CA) operating at 12-13 MHz. At these frequencies, the measurement is an average over the upper 1 m of the water column (Stewart and Joy, 1974). The radars were located at Pt. Sal, Pt. Arguello, and Pt. Conception (Fig. 1a). HF radars employ a Doppler technique to measure components of surface currents directed radially from the radar locations over sectors of the sea surface 1.5 km in range and 5^{o} in azimuth. Surface current vectors in an east-north coordinate system were computed on a 2 km grid using the least square technique described by (Gurgel, 1994). In this technique, all radial currents obtained within a 3 km radius around each grid point are combined to estimate the surface current every hour. The 3 km radius limits the spatial resolution of the near-surface current fields. Emery et al. (2004) describe the processing of the HF radar data in more detail. Further discussion on the use of HF radars for measuring near surface currents is given by Paduan and Rosenfeld (1996) and Graber et al. (1997).

Emery et al. (2004) assessed performance of the three HF radars by comparing with in situ current meters at 5 m depth. They found that root-mean-square differences in radial speed measurements between HF radars and current meters ranged from 0.07 – 0.19 m s^{-1}. Recent observations comparing surface currents from HF radars and drifters indicate that differences are substantially reduced if spatial variability in current fields is accounted for (Ohlmann, 2005).

Nominal coverage areas used for computing trajectories lie offshore of Pt. Conception and Pt. Arguello as shown in Fig. 2a for 1999 and Fig. 3a for 2002. These areas are selected to maximize the spatial coverage, while minimizing the inclusion of grid points with low temporal coverage. Variable coverage from individual radars results in differences in coverage between years. Boundaries of nominal coverage areas are oriented along and perpendicular to isobaths. Platform Irene is about 2 km from the inshore boundaries, which lie along the 50 m isobath (Figures 2a and 3a). At times actual radar coverage exceeded nominal coverage boundaries as may be seen by comparing sample computed trajectories (black lines, Fig. 1a) with the 2002 boundary (gray closed curve, Fig. 1a). Coverage in 2000 and 2001 for May through August was inadequate for producing trajectory ensembles around Platform Irene.

A new trajectory was begun at the location of Platform Irene every 4 hours from 1 May through 31 August for 1999 and 2002. Positions along the trajectories were determined by integrating current vectors forward in time using a fourth order Runge-Kutta algorithm.

Trajectories end where they encounter spatial gaps or where they reach the edge of radar coverage.

The number of trajectories reaching the coverage boundaries defined in Figures 2a and 3a, were reduced by gaps in spatial and temporal radar coverage. For example, of the 670 possible trajectories in 2002, 541 (81%) end within the radar coverage area and 129 (19%) intersect the coverage boundary. Changes in spatial coverage on diurnal and longer timescales result from several factors such as broadcast interference, and are a characteristic of HF radars (Paduan and Rosenfeld, 1996). Gaps in the velocity time series are also caused by outages of individual radars. The average durations of these gaps were 4.4±22.3 hr and 5.9±7.9 hr in 1999 and 2002, respectively. Outages of individual radars also produced a few long gaps in the velocity time series for each year across the entire coverage area. In 1999 two long gaps occurred: one from 1800 UTC 28 June through 2000 UTC 22 July, and a second from 2300 UTC 24 July through 2200 UTC 13 August. In 2002 a single long gap occurred from 1700 UTC 16 May through 0100 UTC 21 May. These longer gaps were not filled.

Shorter gaps were filled by interpolation using empirical orthogonal functions (EOF's; (Emery and Thomson, 1998)). EOF's incorporate the underlying spatial structure of all velocity observations from all locations where data exist at a given time. Any velocity component, u say, at grid point j may be expressed as,

$$u_j(t) = \sum_{i=1}^{N} a_i(t)\varphi_{ij} + \bar{u}_j \qquad (1)$$

where t is time, $\bar{u}_j$ is the time average at location j (computed from available data at location j), a_i is the time-varying amplitude function, φ_{ij} is the ith spatial EOF mode at location j, and N is the number of modes. The first seven modes (i.e., N = 7) were used for interpolation and explain

64% (1999) and 56% (2002) of the variance. EOF interpolation increases the number of trajectories reaching the coverage boundary to 99%. As a test, gaps were also filled with linear, spline, and moving average interpolation, but EOF interpolation resulted in the most trajectories reaching the coverage boundaries. Otherwise, results did not depend strongly on the interpolation method.

The fraction of filled data using EOF interpolation compared with the total possible data is 4% in 1999, 12% in 2002, and 14% using the 2002 data for the 1999 coverage boundary. Here the total possible data is the number of grid points within the coverage boundary for either 1999 (45 grid points) or 2002 (291 grid points) multiplied by the number of hours between 1 May and 31 August minus the long gaps discussed above (2952 hrs – 1057 hrs in 1999, 2952 hrs – 104 hrs in 2002). Examples of 25 EOF-filled trajectories that started every 120 hrs and intersected the 2002 coverage boundary are shown in Fig. 1b.

The principal quantity used here to estimate how Platform Irene might affect transport to nearshore habitat is the histogram of points where trajectories cross the boundaries of the coverage areas. To determine this, coverage boundaries are divided into 4 km-long segments, or bins. The first bin of each histogram is less than 4 km since distances around the coverage boundaries are not exactly divisible by 4. Bin numbers increase counter-clockwise around the boundaries starting from 1 in the southeastern corner (Figures 2a and 3a). The smallest numbers identify bins lying along the 50 m isobath.

Results

Trajectories originating at Platform Irene are sufficiently dense to fill in much of the surrounding area. In 2002 for example, EOF-filled trajectories spread over an area of about 20 km in the cross-shore direction by 60 km in the alongshore direction (Fig. 1a). North of Pt. Arguello, several trajectories cross the 50 m isobath and some end very near shore. South of Pt. Arguello, only a few trajectories approach the 50 m isobath. Instead, most turn southward or southwestward and move offshore. A tendency for trajectories to align parallel to isobaths is evident in the northern end of the ensemble, although in other areas such as the southeast many trajectories lie across isobaths.

A histogram of points where trajectories cross the coverage boundary for May-August 1999 exhibits a peak in bin 11 on the offshore side along the 500 m isobath (Fig. 2b, left-hand axis). Table 1 and the cumulative histogram (Fig. 2b, right-hand axis) show that 76% of the trajectories cross the offshore side corresponding to bin numbers 9-13. A second peak occurs in bin 3 and about 10% of trajectories cross the inshore boundary on the 50 m isobath (bins 1-5). The remaining trajectories cross either the northern (9%) or southern (5%) sides of the coverage boundary.

In 2002 the radars covered a substantially larger area (Fig. 3a), including about 50 km of the 50 m isobath, 70 km of the 500 m isobath along the offshore boundary, and a portion of the western entrance of the Santa Barbara Channel. The histogram of coverage boundary crossings for May-August 2002 also exhibits two peaks, one between bins 9-11 along the 50 m isobath and a second in bin 31 along the offshore side of the coverage boundary (Fig 3b). In 2002, 24% of trajectories cross the 50 m isobath (bins 1-13), 69% cross the offshore side (bins 22-39), and the remainder cross the northern side (6%) or the southern side (1%).

To compare results more directly between years, a histogram of crossings was generated from the 2002 trajectories, using the 1999 coverage boundary. The 1999 coverage boundary is completely contained within the 2002 coverage boundary. Using the 2002 trajectories, a peak in the histogram again occurs along the offshore boundary (Fig.4, left-hand scale), this time at bin 12 compared with bin 11 when the 1999 trajectories are used. A second, but much smaller peak occurs along the 50 m isobath at bin 3, consistent with the small peak along the 50 m isobath of Fig. 2b. Table 1 and the cumulative histogram (Fig. 4, right-hand scale) shows that 18% of trajectories cross the 50 m isobath, 66% cross the offshore side of the coverage boundary, and the remainder cross either the northern (7%) or southern (8%) sides.

The time required for trajectories to cross the coverage boundary, defined here as the residence time, varied between years and mainly depended on the size of the coverage area. In 1999 the mean and standard deviation for the residence time are 19 ± 12 hours with a maximum of 86 hours (Table 1). In 2002 they are 47 ± 34 hours with a maximum of 163 hours. When the 2002 trajectories are computed over the 1999 coverage boundary, residence times are comparable to the 1999 values: 22 ± 18 hours with a maximum of 116 hours.

Discussion

Due to limitations in spatial coverage, the HF radar-derived trajectories cannot be used to examine the full range of length and time scales over which actual trajectories might extend. We use a trajectory data set resulting from the release of Argos drifters in the region to examine these scales. Drifters were deployed in the Santa Barbara Channel and Santa Maria Basin at irregular intervals from October 1992 through December 1999 as part of a circulation study conducted by the Scripps Institution of Oceanography (SIO; see Dever et al. (1998) and Winant et al. (2003) for a description of the drifter data set). Drifter positions were obtained up to 6 times per day, typically for 40 days, with a spatial accuracy of about 1 km. Several trajectories ended earlier when the drifters beached.

No drifters were released at Platform Irene although many approached the platform after release elsewhere (130 drifters were deployed to the north of Platform Irene, and 440 were deployed to the south). To approximate trajectories originating at Platform Irene, all drifters released during all seasons for all years, and approaching within 10 km of the platform, were identified. This distance is a compromise between proximity to the platform and ensemble size; 93 trajectories approached within 10 km of Platform Irene (white circle in Fig. 5 is 10 km in radius and is centered on Platform Irene). Of these, 34 were released north and 59 south of Platform Irene. The ensemble of trajectories beginning within 10 km of Platform Irene (gray and black dots, Fig. 5) mainly follows the trend of southward advection by the California Current System, although a smaller number extend northward from the platform with a few reaching Monterey Bay. Four trajectories enter the Santa Barbara Channel.

A further sorting of the ensemble of 93 trajectories approaching within 10 km of Platform Irene to include only those during 1 May - 31 August of all years produces a subset of 21 trajectories (black dots, Fig. 5). Of these, 17 cross the 2002 coverage boundary: 3 on the 50 m isobath, 12 on the offshore boundary, 2 on the northern boundary, and 0 on the southern boundary. Although the ensemble is small, the fraction of drifters crossing the inshore boundary of the 2002 coverage area (18%) is comparable to the fraction of HF radar-derived trajectories doing so (24%) as shown in Table 1. Most trajectories crossing the offshore boundary continue offshore and southward, consistent with advection by the California Current System. Others crossing the offshore boundary extend north of Platform Irene before turning southward or offshore. The two trajectories crossing the northern boundary remain near shore and cross the 50 m isobath north of the platform. None of these 17 trajectories enter the Santa Barbara Channel.

Except for three drifters which beached, all the drifters remained offshore for the duration of Argos data logging.

Trajectories crossing the 50 m isobath tend to do so north of platform Irene, as shown by most of the computed trajectories and three of the SIO drifters (Figures 2b and 3b). This indicates that transport from the platform to shallow water habitat along the mainland coast mostly occurs during times of northward, or poleward, currents. Poleward flow in the region north of Pt. Conception results from weakening or reversal of the prevailing upwelling favorable winds, the so-called "relaxation" flow state described by Dever (2004), Harms and Winant (1998), and Winant et al. (2003). They also describe two other flow states, "upwelling" and "convergent", which produce offshore and equatorward transport near Platform Irene. Together they have a 69% probability of occurring during May-Aug (36% for upwelling and 33%for convergent), while the relaxation state has a 23% probability (Winant et al. (2003), their Table 3). For comparison, 19-30% of trajectories (HF radar-derived plus actual drifters) cross the inshore and northern boundaries, consistent with the relaxation probability and 70-81% cross the offshore and southern boundaries, consistent with the upwelling plus convergent probability.

The trajectories can also be used to estimate recruit survivorship, based on the time required for transport to habitat. Recruit survivorship is estimated from a simple exponential decay model,

$$P(t) = P_o e^{-mt} \qquad (3)$$

where m is mortality (0.02 or 0.06 day^{-1}, Ralston[2]), P is population at time t, and P_o is the initial population. Here, P_o represents the population of juvenile bocaccio which recruited at Platform Irene, and survivorship estimates are used to predict their survival in the absence of the platform.

[2] Ralston, S., 2004. Personal commun. NOAA National Marine Fisheries Service, 110 Shaffer Road, Santa Cruz, CA 95060

In 1999 and 2002, trajectories to habitat from Platform Irene cross the 50 m isobath within 19-47 hours (Table 1), indicating high survivorship for bocaccio of 96-98%. In contrast, offshore and southward drifter trajectories from the SIO drifter data suggest much lower survivorship. Pelagic juvenile bocaccio transported by these flows would be carried southward by the California Current and remain far from the mainland and the Northern Channel Islands (Fig. 5) for at least 40 days, the nominal time the drifters were tracked. Survivorship after 40 days along these trajectories ranges from 9-45%.

It is possible that juvenile bocaccio spend time away from near surface waters during their planktonic larval phase so their trajectories may depend on deeper currents. Previous observations in the study region show strong correlation between near surface and deeper flows suggesting that inferences from surface trajectories apply to deeper trajectories. Dever (2004), Harms and Winant (1998), and Winant et al. (2003) generally found high correlation between moored currents at 5 and 45 m depth with flow speed decreasing with depth. They also found that poleward flow at 45 m occurs during the convergent and relaxation states, and equatorward flow occurs during the upwelling state. Therefore, during relaxation and upwelling states, currents at 45 m likely have similar directions, but lower speeds compared with surface currents. During the convergent state, currents at 45 m are opposite surface currents suggesting that surface currents represent deeper currents only to some shallower depth.

This trajectory analysis assumes that juvenile bocaccio effectively behave as passive particles. This was done for two reasons: 1) it represents a lower bound on their range of possible swimming behaviors; 2) little is known about the actual swimming behavior of bocaccio in the open ocean, so meaningfully accounting for its effects is problematic. These results do not assume that juvenile bocaccio do not swim; rather, the results assume they swim randomly such that their effective transport is similar to that for passive particles. The other behavioral limit of rapid, consistently directional swimming behavior would likely alter the fraction of bocaccio encountering shallow habitats versus being advected offshore. Flume experiments using visual cues for directional orientation demonstrate that the late pelagic stage of coral reef fish can swim up to ~100 km in 8 days (Stobutzki and Bellwood, 1997), so behavioral modification of trajectories could be very important. Larval and pelagic juvenile fish may possess swimming and sensory abilities to overcome passive drift in currents; however, some kind of external reference is necessary for fish to detect and respond to the direction of a current. In a review of the behavior of larval and juvenile fish in the pelagic environment, Leis and McCormick (2002) point out that it is yet to be demonstrated that these early stages in offshore "blue water" can effectively modify current-driven trajectories by orienting to cues from settlement habitat located at a scale greater than several kilometers away. A variety of near-field stimuli, such as light and temperature gradients, sound, and visible prey affect swimming behavior. Clearly more research is needed to evaluate the effects of swimming behavior of temperate reef fishes, such as bocaccio, for modeling their dispersal. We speculate, however, that the assumption of passive dispersal will remain an important lower bound on constraining effects of swimming behavior.

Smoothing and interpolation in the processing of the HF radar velocity data limit the spatial resolution of current fluctuations to scales of ~6 km, the diameter of circles used to compute velocity vectors. Velocity structures smaller than this scale are not resolved, but may be important in determining trajectories. For example, Helbig and Pepin (2002) found that errors in modeling the spatial distributions of fish eggs in an embayment increased as spatial resolution of a circulation model decreased. Assuming effects of unresolved velocity structures on smaller scales act as a diffusive process, we speculate that incorporating diffusion would cause spreading of points where trajectories intersect boundaries in histograms such as in Figures 2b, 3b, and Figure 4. In this case, peaks in the histogram would decrease as diffusion spreads boundary intersections to adjacent bins. Velocity statistics at scales of order a few km and smaller in our study area, however, are not available for incorporating the effects of diffusion into the trajectories. Results from actual drifters, which do contain velocity structure unresolved by the HF radars, are not very different from HF-radar-derived trajectory results (Table 1) suggesting effects of unresolved variance are not large. It may also be that for predicting settlement to habitat, trajectory improvements gained through the incorporation of smaller scale flow features might be offset by assumptions of swimming behavior and habitat location.

Questions and issues have arisen in the decommissioning process about the regional importance of platform fish assemblages (Schroeder and Love, 2004). For example, does removing a platform impact the bocaccio population? Based on our annual research submersible surveys (detailed in Love et al., 2003) conducted in 1997, 1998, 1999, and 2001, estimates of YOY bocaccio at Platform Irene ranged from 61 (2001) to 41,000 (1999) (Lenarz[3]). YOY bocaccio abundances can be even higher than those observed at Platform Irene. We have recently estimated that, during 2003, Platform Grace, located in the Santa Barbara Channel, harbored over 300,000 YOY bocaccio (Lenarz[3]). Under even the most conservative parameters, this would translate into many thousands of adults (MacCall[4]). In addition, there is evidence that some of the bocaccio that recruit to platforms as YOYs migrate, and thus seed, natural reefs. Fish tagged at Platform A, located off Summerland, CA in the Santa Barbara Channel, were later recovered over natural reefs over 100 km to the north and south of that platform (Hartmann, 1987). In

[3] Lenarz, W. 2004. Personal commun. PO 251, Kentfield, CA, 94914-0251
[4] MacCall, A. 2004. Personal commun. NOAA National Marine Fisheries Service, 110 Shaffer Road, Santa Cruz, CA 95060

another study, recruiting bocaccio became resident on a deep-water platform and formed the highest density of adult fish observed in the Southern California Bight (Love et al., 2003). Thus, bocaccio that recruit as YOYs to a platform may benefit natural reefs either through emigration to these reefs or through increased larval production.

Conclusion

Observations of evolving surface current patterns obtained by HF radar are used to estimate dispersal pathways for juvenile bocaccio in the vicinity of Platform Irene, an oil production platform off the central California coast. Results indicate that most of YOY bocaccio settling around Platform Irene would not survive in the platform's absence. Instead, prevailing currents would likely advect them offshore with very low probability of survival. While it is possible that some individuals would encounter acceptable nursery habitat on offshore banks or islands, it is likely that most would perish. Thus, the presence of Platform Irene almost certainly increases survivorship of young bocaccio in the Point Conception – Point Arguello region.

These results indicate that knowledge of regional ocean circulation patterns is essential for evaluating the effects of oil production platforms, or other artificial habitats, on dispersal pathways of juvenile fishes. Platform location, local current patterns, and natural habitat distribution determine the balance between settlement at a specific platform and settlement on natural habitat. The approach used here based on trajectory analysis from observations of evolving current patterns using HF radar, can provide insights into this balance. Additional research on small-scale circulations features unresolved by the radars and on swimming behavior of juvenile rockfishes will sharpen these insights.

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Figure captions

Figure 1. a) Map of study area near Pt. Conception, California, showing trajectories derived from HF radar from 1 May - 31 Aug 2002. Triangles show HF radar locations and the white square shows Platform Irene. Gray curve superimposed on trajectories is the coverage boundary used for 2002. Labeled thin black lines are bathymetric contours. **b)** Solid black lines are 25 sample trajectories which intersect the coverage boundary. Gray curve is the same as in panel a. The trajectories in panels a and b were created from velocity time series that were interpolated with EOFs.

Figure 2. **a)** Coverage boundary for 1 May – 31 August, 1999. Numbers and tick marks around boundary identify bins corresponding to x-axis in panel b. **b)** Histogram (gray bars, left-hand scale) and cumulative frequency (bold line, right-hand scale) show fraction of trajectories (in percent) intersecting bins around coverage boundary. Panel a shows bin locations. Distance around the coverage boundary (Fig. 2a) in kilometers is also shown (bottom scale). Arrow above histogram shows boundary location nearest Platform Irene.

Figure 3. As in Figure 2, but for 2002.

Figure 4. As in Figure 2, but for coverage boundary of 1999 and histograms computed using trajectories of 2002.

Figure 5. Trajectories of all drifters deployed by the Scripps Institution of Oceanography at various times from October 1992 through December 1999 after passing within 10 km of Platform Irene (gray dots). Also shown are all drifters after passing within 10 km of Platform Irene for only the time period 1 May to 31 August for all years (black dots). White circle is centered on Platform Irene with and has a radius of 10 km.