OCS Study
MMS 2006-052

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Final Technical Summary

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Minerals Management Service
Pacific OCS Region

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Table of Contents

List of Tables

FINAL STUDY REPORT

List of Figures

FINAL TECHNICAL SUMMARY

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STUDY TITLE: Observations of the surface circulation in the eastern Santa Barbara Channel using high frequency radar and Lagrangian drifters.

REPORT TITLE: Do 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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PROJECT MANAGER: Russell J. Schmitt

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KEY WORDS: surface circulation, Lagrangian drifter, Santa Barbara Channel, radar array, radar sites and hardware

BACKGROUND:

Since 1998, Principal Investigator Washburn's research group has been operating an array of HF radars in the Santa Barbara Channel. During the period of this study (25 September 2002 – 30 September 2004; no-cost extension until 30 September 2005), a total of 2-4 radar sites was maintained along the mainland coast of the Channel. The configuration of the array as of 13 June 2006 is shown in Figure 1. Real time data is displayed and archived at http://www.icess.ucsb.edu/iog/realtime/index.php.

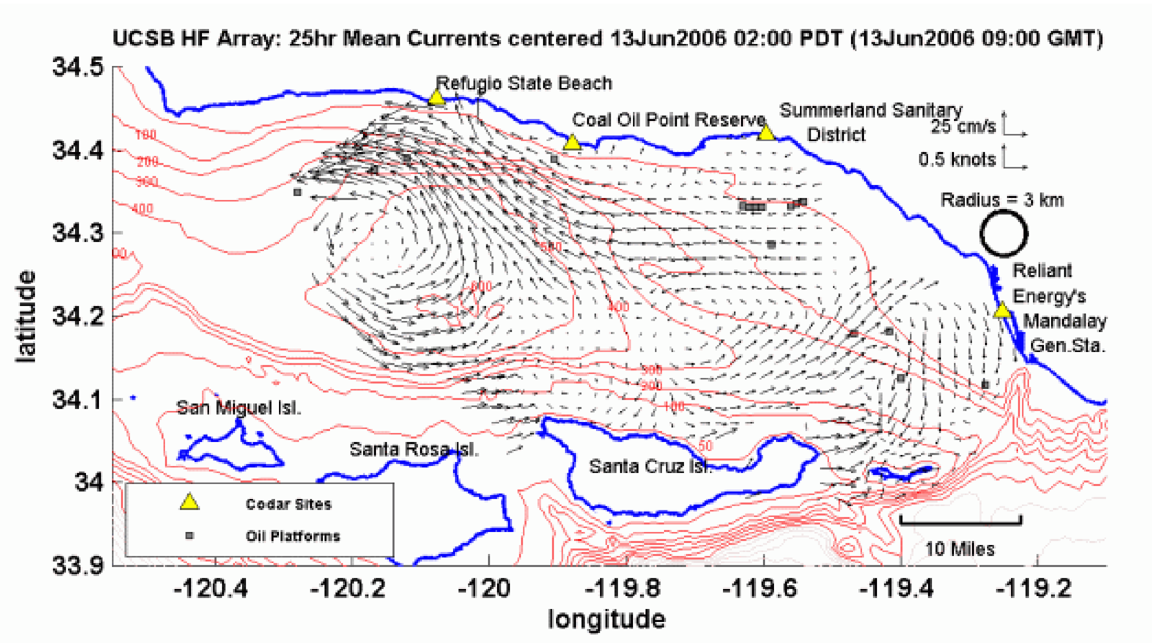


Figure 1. Study area in the Santa Barbara Channel. Black arrows show surface current vectors scaled according to the scale in the upper right-hand corner. Observations are a 25-hr average centerd on 0900 GMT on 13 June 2006. Vectors are spatial averages over circles with radii of 3 km as shown by the circle to the right. HF radar sites are shown with yellow triangles. Oil platforms are squares.

An important new site installed toward the end of this project is at the Summerland Sanitary District plant in Summerland, CA. The site at the Mandalay Generating Station (Mandalay in Figure 1) was also installed during the project, but has not consistently obtained data due to electrical power problems at the site. These power problems have recently been corrected by Reliant Energy, the owner of the site. In April 2006 a new and dedicated circuit was installed to power our equipment. Radar hardware was obtained through grants from the W.M. Keck Foundation and the University of California Marine Council. Two systems were borrowed from NOAA's Environment Technology laboratory in Boulder, Colorado, and a third from Stanford University. Operational support for the radar array has come from a number of agencies including: Minerals Management Service, Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO), University of California Marine Council, and NASA.

Throughout most of this study, each radar system produced time series of radial current components (hereafter referred to as "radials") out to a maximum range of 40-80 km off shore depending on environmental conditions and software version. As discussed by (Emery et al., 2004), the actual range and overall coverage area changes in time. For the 12-13 MHz systems used in this study, radials are obtained as spatial averages over sectors of the sea surface measuring 5 degrees in azimuth by 1.5 km in range. Radials in each sector are computed over 10 minute intervals. Total current velocity vectors are estimated by averaging all radials each hour over circular areas of the sea surface with 3 km radii. The circles are centered on points on a square grid with two km spacing between points. The least square technique described by (Gurgel, 1994) is used to combine radials within the circular areas to estimate the eastward and northward current components at each grid point.

OBJECTIVES:

The original objectives of this project were not fully achieved during the project period because of difficulties encountered in gaining access to suitable HF radar sites in the eastern Santa Barbara Channel. MMS was kept informed of this situation during the project through routine quarterly reporting of progress on the project.

Toward the end of the project, sites were obtained near Summerland, California. A private home owner allowed the short-term installation of a site on his property from 1 May – 1 September 2004. This site supported a MMS-sponsored experiment to examine oceanographic factors leading to settlement of fish larvae on two oil production platforms. This project is an on-going collaboration with the research group of Dr. Milton Love of the Marine Science Institute at UCSB. Later, the Summerland Sanitary District allowed installation of a site on a more permanent basis nearby (about 1 km east); that site began operation in April 2005. Below we describe results of observations obtained with the other radars which addressed important new aspects of the circulation in the Santa Barbara Channel (SBC). Results also address a new method to assess the performance of HF radars for measuring ocean surface currents.

DESCRIPTION:

Evaluation of HF radar performance using Lagrangian drifters

In collaboration with Dr. Carter Ohlmann and his research group, comparisons were made between velocity estimates obtained by HF radar and those obtained by arrays of drifters in the SBC. These experiments were moved from the originally-proposed location in the eastern SBC to the central channel when we were unable to secure eastern HF radar sites. Previous comparison (e.g. (Shay et al., 1998; Emery et al., 2004)) focused on comparisons with moored current meters. Because current meters are effectively point measurements in the ocean, they are fundamentally different from current measurements obtained by HF radar. This is due to the fact that radar measurements are inherently averaged in space and time. The hypothesis driving this analysis was that the velocity differences observed between current meters and HF radars result from the different ways the two methods observe the ocean, point measurements versus spatial averages. If spatial averaging is accounted using drifters spread over areas comparable to those over which the radars measure velocity, then differences should be reduced. An experiment was conducted to test this hypothesis.

As part of the test, dense arrays of surface drifters were used to quantify the flow field on time and space scales over which the HF radar observations are measured. Up to 13 drifters were repetitively deployed off Coal Oil Point (COP) in the SBC on 5 days during an 18 month period. The deployments were within coverage of the radars at COP and Refugio (RFG). During each deployment day, a group of drifters was released on a regularly spaced grid within a 2 km x 2 km square. To reduce geometric pointing errors, the deployment square was located such that radial vectors to the COP and RFG radars were nearly perpendicular. As drifters moved from the square they were retrieved and replaced to maintain a broad spatial distribution of observations within the sampling area during the day. This sampling scheme resulted in up to 56 velocity observations distributed over the time (1 hr) and space (1 to 4 km^{-2}) scales from which surface current maps from HF radar are computed. As shown in Figure 2, root-mean-square (rms) differences between HF radar radial velocities and average drifter velocities are mostly 3 to 5 cm s^{-1}, much less than the 9-20 cm s^{-1} typically reported in the literature (e.g. (Shay et al., 1998; Emery et al., 2004)). The reduction over past validation studies employing current meters is due to improved resolution by the drifters of small scale velocity structures that are included in the time- and space-averaged HF radar measurements. Roughly 5 cm s^{-1} of the differences can be attributed to sampling on the differing time and space scales observed by drifters and current meters.

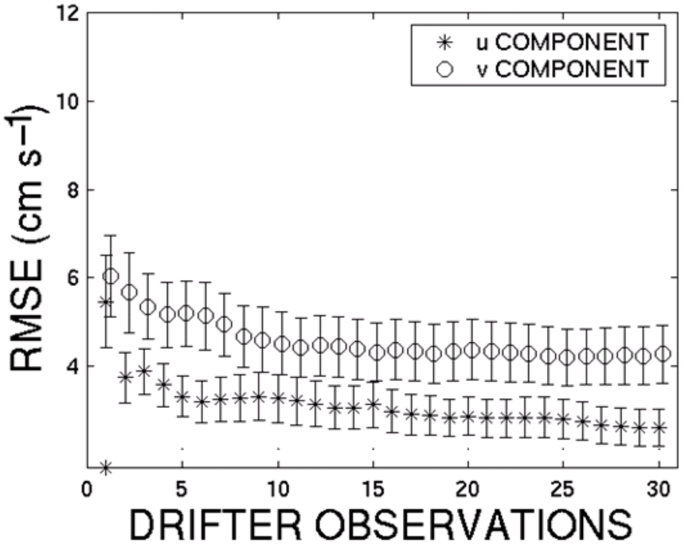


Figure 2. RMS difference between radar and drifter total velocity components for area of Coal Oil Point near Santa Barbara, CA versus number of drifter observations used to compute the drifter mean. HF radar totals are hourly averages within a 2 km square. Drifter velocities are corresponding time and space averages with randomly sub-sampled sets within the square. The u component (*) is east-west and mostly along-shore in the study region. The v component (o) is north-south and mostly across-shore. Error bars show standard error.

Despite generally good agreement, differences can increase strongly with time. In one instance from a HF radar array in San Diego, the difference increased from near zero to more than 20 cm s^{-1} within 2 hr. The rms difference and bias (mean absolute radial speed difference) for that day exceeded 7 and 12 cm s^{-1}, respectively. Overall, however, these observations show that HF radars measure surface currents more accurately than has been inferred based comparisons with current meters. Results of this work are summarized by Ohlmann et al.(submitted to the J. Oceanic and Oceanographic Technology). Results were also presented at the 2006 Ocean Sciences meeting in Honolulu.

Currently, Ohlmann's and Washburn's research groups are examining the capability of the HF radars for predicting current trajectories. The observational approach is to deploy drifters within the observational field of the HF radars over time periods of up to a few days (i.e. before the drifters exit the SBC). As shown in Figure 3, separation distances between actual drifters and pseudo-drifters derived from HF radar observations increase through time. Separation rates are about 0.2 km hr^{-1} in the along shore (x) direction and 0.3-0.4 km hr^{-1} in the cross-shore (y) direction. Data of Figure 3 were obtained from the COP and RFG radars for a location in the central SBC over a time scale of just over 4 hr. Data from other experiments are being examined to evaluate trajectory predictions on scales of about 1 day. A principal goal of this research is to quantify trajectory differences for use in models combining HF radar observations with stochastic models representing unresolved small scale velocity structure. A collaborator on this project, Dr. Arthur Mariano of the Rosentiel School of Marine Sciences at the University of Miami, is an expert on these modeling approaches.

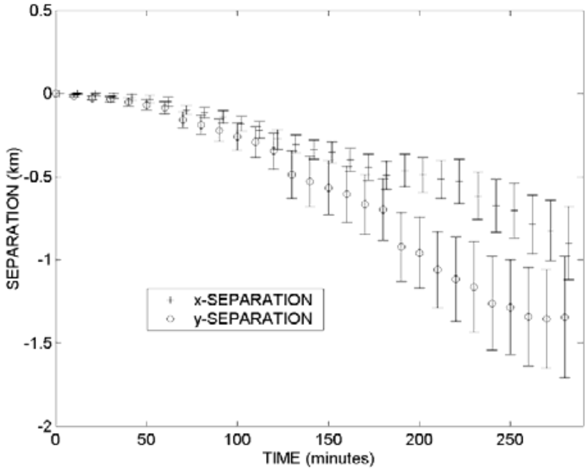


Figure 3. Separation distance between actual drifters and "pseudo-drifters" computed from HF radar time series as a function of time. At time t = 0 the separation distance was zero. The x-separation distance (*) is east-west and mostly along-shore in the study region. The y-separation distance (o) is north-south and mostly across-shore. Error bars show standard error.

Small coastal eddies in the Santa Barbara Channel

During this project, small coastal eddies were discovered along the mainland coast of the Santa Barbara Channel using observations from the HF network described above. The eddies frequently occur along the mainland coast of the SBC between Santa Barbara and Pt. Conception. They are 4-15 km in diameter and typically last about 2 days, although some last up to 6 days. Most eddies within the radar coverage area are clockwise with rapid rotation rates; the rates typically equal to about half the earth's rotation rate at the latitude of the SBC. Moored observations over the inner shelf (12 - 15 m water depths) showed that these eddies can occasionally move previously upwelled nutrients on shore. We speculate that these eddies are an important transport mechanism for nutrients and biogenic particles to inner shelf regions and nearshore kelp forests. They would also advect oil and other pollutants toward shore. Figure 4 shows an example a small anti-cyclonic eddy on 30 August 2002 lying offshore, just west of Refugio. This eddy was centered over the 100 m isobath with strong clockwise rotation (blue area). The counter-clockwise pattern southeast of this eddy (red area), only partly resolved by the radar coverage in this figure, is a persistent feature of the SBC circulation (Harms and Winant, 1998; Nishimoto and Washburn 2002; Beckenbach and Washburn, 2004; Dever, 2004). The more frequent occurrence of clockwise eddies suggests that interaction with the bottom is partly responsible for their formation. Further discussion of these eddies is given by (Bassin et al., 2005). This work was also the focus of the Masters Thesis of Ms. Corinne J. Bassin, a graduate student in the UCSB Interdepartmental Program in Marine Science.

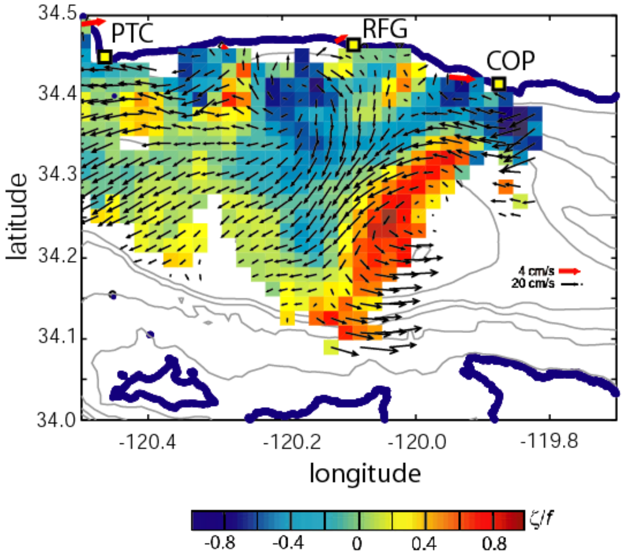


Figure 4. Surface velocity field on 30 August 2002 at 0000 GMT showing small anti-cyclonic eddies (clockwise arrows) south of Coal Oil Point (COP) and southwest of Refugio (RFG). Color contours show rotation rate (i.e. relative vorticity) normalized by the earth's rotation rate *f*. Red regions show strong counter-clockwise rotation and blue areas show strong clockwise rotation. Yellow-filled black squares are HF radar sites at Point Conception (PTC), RFG, and COP. Arrows show velocities based on scale to right. Red arrows are velocities measured at nearshore moorings and black arrows are velocities measured from HF radar.

Delivery of larval bocaccio to oil production platforms in the eastern Santa Barbara Channel:

Another important research activity during the project period has been a collaboration with the research group of Dr. Milton Love of the Marine Science Institute at UCSB. This MMS-funded study is aimed at 1) exploring links between ocean current patterns and the timing of delivery of juvenile rockfishes settling on offshore platforms in the eastern Santa Barbara Channel; and 2) estimating the proportion of these juvenile fishes that, if the platforms did not exist, would have been transported to natural reef habitat. Surface currents in the eastern Santa Barbara Channel were mapped using radar for the first time during this study, and the data are being used to pursue both research objectives.

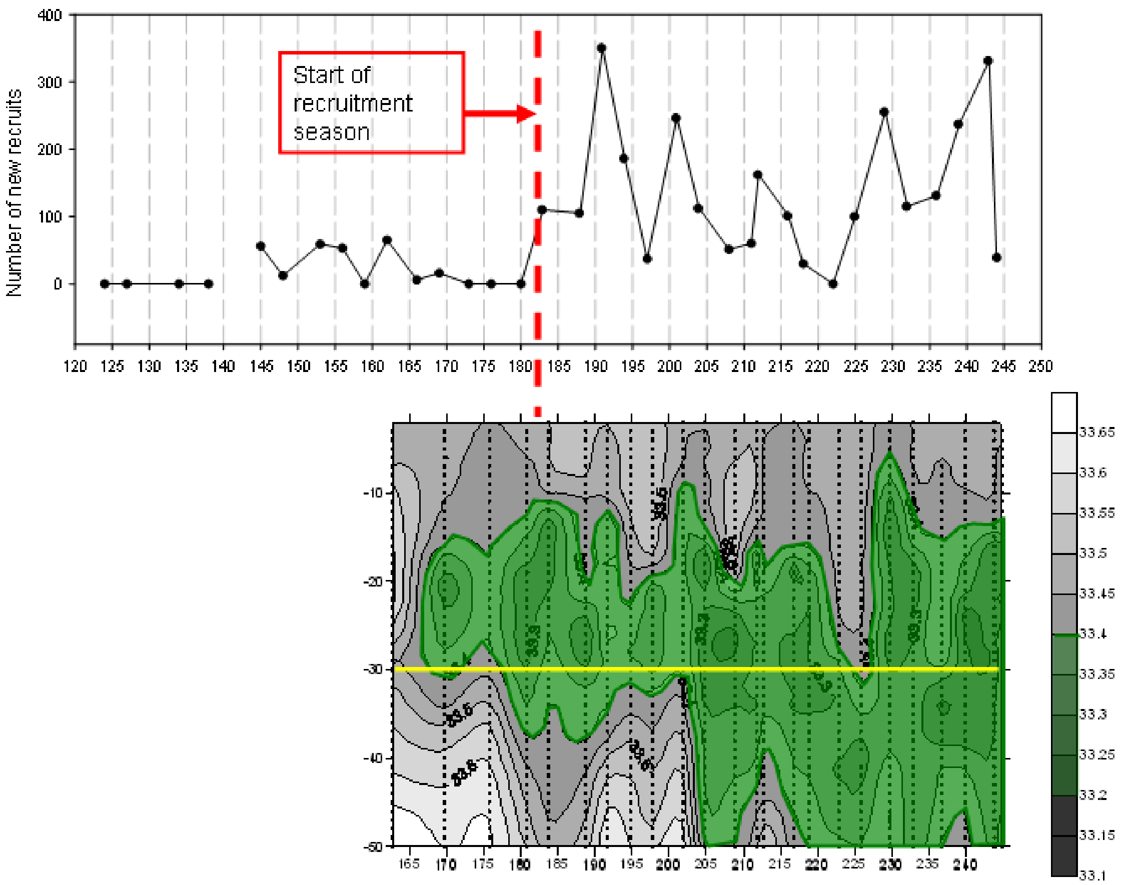
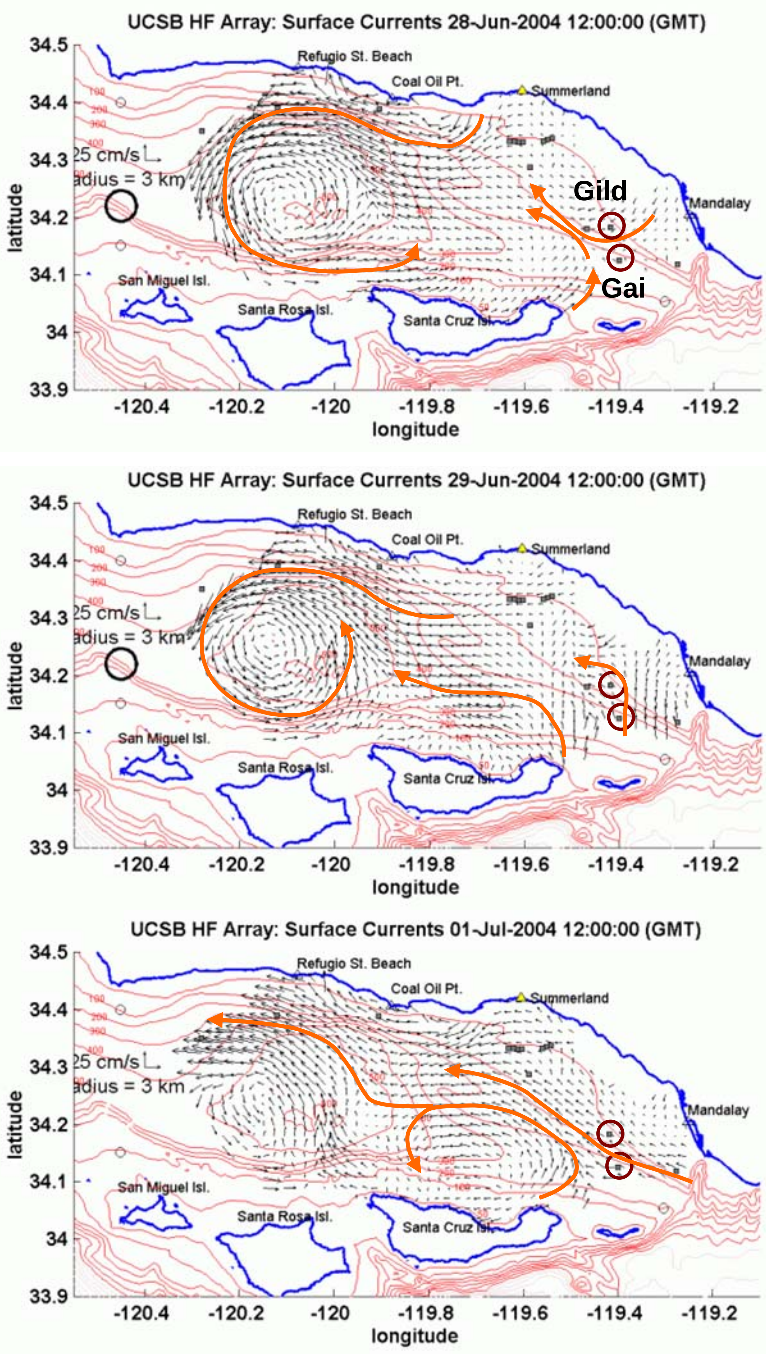


Figure 5. Time series of (upper panel) the number of the number of recently settled juvenile bocaccio and (b) the subsurface salinity structure at 26 m depth at platform Gail.

The field observations of this combined biological and oceanographic study were conducted at two platforms, Gail and Gilda, in the eastern Santa Barbara Channel from May through August 2004. This period corresponded with the season of much of the rockfish recruitment in this area. These two platforms, Gail (in about 230 m depth) and Gilda (about 65 m depth) are in a dynamic area where ocean currents are variable over a scale of several days and where fronts and eddies are observed. Fish settlement was quantified every 3-4 days using SCUBA surveys. Ocean surface currents were measured by the HF radar array of Figure 1 while other oceanographic monitoring was conducted at the platforms. This monitoring included moored acoustic Doppler current profilers (ADCP's) and temperature-salinity (T-S) recording at both platforms. Measurements at platform Gail were made near 30 m depth (yellow line, Figure 5). Vertical profiles of water properties were paired with every SCUBA survey.


UCSB HF Array: Surface Currents 28-Jun-2004 12:00:00 (GMT)

UCSB HF Array: Surface Currents 29-Jun-2004 12:00:00 (GMT)

UCSB HF Array: Surface Currents 01-Jul-2004 12:00:00 (GMT)

June 28 (Day 180)
(Fish survey: No juvenile
bocaccio sighted)

June 29 (Day 181)
(No fish surveys on
days 181 and 182)

July 1 (Day 183)
(Fish survey: 200 juvenile
bocaccio observed at Gilda,
110 juvenile bocaccio at Gail.

Figure 6. Sequence of daily-averaged surface current maps with hand-rendered flow features (curved orange arrows) and abundance of juvenile bocaccio at Platforms Gail and Gilda (gray squares circled in red) during two consecutive fish surveys on 28 June and 1 July, 2004. A recruitment pulse of juvenile bocaccio at the two platforms is associated with the northwestward flow of surface waters from the Southern California Bight through the eastern entrance of the Santa Barbara Channel.

An analysis of the seasonality of recruitment based on the *in situ* physical oceanographic data has been completed. Multiple lines of oceanographic evidence clearly show that the onset of the recruitment season of bocaccio rockfish (*Sebastes paucispinis*) in the eastern Santa Barbara Channel was abrupt and coincided with a change of water masses in June 2004. Bocaccio, presently declared over-fished by the National Marine Fisheries Service, was the most abundant juvenile rockfish observed in this study. Figure 5 shows that a mid-water tongue of low salinity water (highlighted in green) broadened and was centered around the depth where the juvenile bocaccio settled on Platform Gail during the recruitment season. The same water mass phenomenon associated with bocaccio recruitment at Platform Gilda was also evident (data not shown). The temperature-salinity properties observed at the platforms near the depth where the juvenile bocaccio settled were compared with reference samples of water mass sources in the Southern California Current region collected in June 2004 by the California Cooperative Fisheries Investigations (CalCOFI). This comparison showed that waters bringing the larval bocaccio originated east and south of the channel in the Southern California Bight.

Figure 6 shows HF radar current patterns before and during the bocaccio recruitment event to the platforms around day 183 of Figure 5. The significant finding is that the currents delivering juvenile bocaccio recruits to the eastern Santa Barbara Channel platforms were from the Southern California Bight and not from within the channel or north of Point Conception. Presently, we are working toward objectively analyzing the radar data to explain how the spatial and temporal patterns of fish recruitment in the Santa Barbara Channel is linked to current patterns. We will be using the radar data to estimate where recruiting fish would be transported if the platforms were not present by simulating drifter trajectories from the radar data—these results likely will be referenced for platform decommissioning considerations. Preliminary results were presented by Mary Nishimoto at the Ocean Science Meeting in Honolulu, HI in February 2006.

SIGNIFICANT CONCLUSIONS:

1. Validation of HF radar current measurements is significantly improved if comparisons are made with observations on similar time and space scales as used by the radars. Velocity differences between the HF radars and arrays of drifters are 0.03-0.05 m s^{-1}, less than half the typical differences obtained in comparisons with point measurements such as current meters.

2. Surface trajectories can be predicted by HF radars, but predictions depart from actual trajectories measured by drifting buoys. Based on comparisons with surface drifters, differences between predicted and measured trajectories near the coast separate at 0.2-0.4 km hr^{-1}. Separation increased more rapidly in the cross-shore direction compared with the along-shore direction. Improvements in trajectory prediction may result if models of unresolved scales of motion are incorporated.

3. Small eddies often occur near the mainland coast of the Santa Barbara Channel. The eddies are 4-15 km in diameter and typically last about 2 days, although some last up to 6 days. Most eddies within the radar coverage area rotate clockwise. It is likely that the clockwise rotation results from bottom friction near shore.

4. The nearshore eddies are a new transport mechanism for moving nutrients and biogenic particles to inner shelf ecosystems of the Southern California Bight. It is likely that they can rapidly move buoyant pollutants such as oil and stormwater runoff toward shore.

5. Larval bocaccio, an important rockfish species in California waters, can recruit strongly to oil production platforms. Rapid onset of delivery of the larvae onto two platforms in the eastern Santa Barbara Channel (Gail and Gilda) coincided with the arrival of low salinity waters from the Southern California Bight. This suggests that monitoring water masses may be useful in predicting delivery of rockfish larvae.

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FINAL STUDY REPORT

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

Brian M. Emery, Libe Washburn, Milton S. Love, Mary M. Nishimoto,
and J. Carter Ohlmann

Summary

To investigate the possibility that oil platforms may reduce recruitment of rockfishes (*Sebastes* spp.) to natural habitat, we simulated drift pathways (termed "trajectories" in our model) from an existing platform to nearshore habitat using current measurements from high-frequency (HF) radars. The trajectories originated 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. We assume appropriate shallow water juvenile habitat exists inshore of the 50 m isobath. Results from 1999 indicate that 10% of the trajectories represent transport to habitat, while 76% represent transport across the offshore boundary. For 2002, 24% represent transport to habitat, and 69% represent transport across the offshore boundary. Remaining trajectories (14% and 7% for 1999 and 2002 respectively) exit the coverage area either northward or southward along isobaths. Deployments of actual drifters (with 1-m drogues) from a previous multiyear study provided measurements originating near Platform Irene from May through August. All but a few of the drifters moved offshore, as was also shown with the HF radar-derived trajectories. These results indicate that most juvenile bocaccio settling on the platform would otherwise have been transported offshore and perished in the absence of a platform. However, these results do not account for the swimming behavior of juvenile bocaccio, about which little is known.

1. Background

The 27 oil and gas platforms off southern and central California have limited 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, agency personnel tasked with determining the best course of action in regard to the platforms would likely benefit from an understanding of the role that platforms play as fish habitat (Schroeder and Love, 2004).

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 the three distinct assemblages found around many platforms in the Santa Barbara Channel and off central California: the bottom, shell mound, and midwater assemblages. Fishes around platform bottoms tend to be adult and subadult 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. Some of these juvenile fishes are one and two-year old individuals, but most are young-of-the-year (YOY) rockfishes. 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 (e.g., Krop[1]). that platforms may reduce recruitment to natural reefs by functioning as catchments for pelagic juvenile rockfishes**.**

To investigate the possibility that an oil platform may 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.

2. Methods

2.1 Species modeled

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*) that 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 juvenile fishes (Lenarz et al., 1991; Ross and Larson, 2003).

Off central and northern California, parturition for bocaccio occurs from January to May and peaks in February (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, although January is the peak month. 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 from 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 (Mitchell and Hunter, 1970; Boehlert, 1977) 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 represented suitable habitat for juvenile recruits. This choice reflects the lack of information about suitable habitat locations in our study area and likely results in overestimates of the abundance of such habitat.

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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. Mineral Management Service OCS Study 98-0023. Coastal Research Center, Marine Science Institute, Univ. California, Santa Barbara, California, 93106. MMS Cooperative Agreement Number 14-35-0001-30761.

Annual scuba surveys and submersible surveys (1995−2001) in the Santa Barbara Channel and Santa Maria Basin regions showed that YOY bocaccio inhabit the upper 35 m around one or more platforms for each year surveyed. Platform Irene (34°36.62′N, 120 °43.40W; 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, from 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.

2.2 Ocean current measurement and trajectory calculation

Near-surface ocean currents were measured hourly by 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 (Figure 1a).

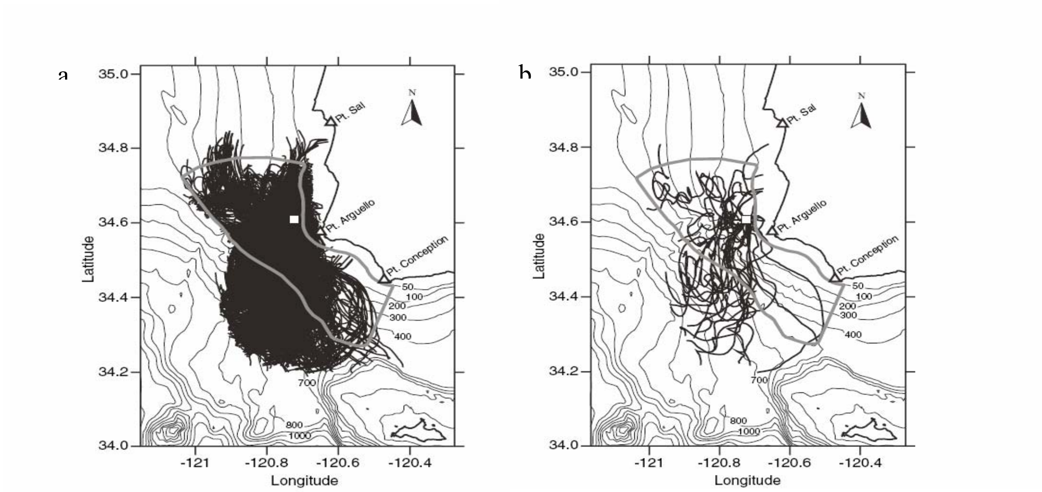

Figure 1. a) Map of study area near Pt. Conception, California, showing trajectories derived from HF radar from 1 May - 31 Aug 2002. Triangles show HF radar locations and the white square shows Platform Irene. Gray curve superimposed on trajectories is the coverage boundary used for 2002. Labeled thin 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.

HF radars measure components of surface currents by means of a Doppler technique, at spatial increments of 1.5 km in range and 5º in azimuth from the radar location. Surface current vectors in an east-north coordinate system were computed on a 2-km grid by using the least square technique described by Gurgel (1994). With this technique, all current components obtained within a 3-km radius around each grid point were 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) have described 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 them 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 to 0.19 m/s. Recent observations comparing surface currents from HF radars and drifters have indicated that differences are substantially reduced if spatial variability in current fields is accounted for (Ohlmann, 2005).

The areas used for computing trajectories were offshore of Pt. Conception and Pt. Arguello as shown in Figure 2a for 1999 and Figure 3a for 2002. These areas were selected to maximize the spatial coverage, and to minimize 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 were oriented along and perpendicular to isobaths. Platform Irene is about 2 km from the inshore boundaries, which lie along the 50-m isobath (Figs. 2a and 3a). At times actual radar coverage exceeded nominal coverage boundaries as may be seen by comparing sample computed trajectories (black lines, Figure 1a) with the 2002 boundary (gray closed curve, Figure 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 ended where they encountered spatial gaps or where they reached the edge of radar coverage.

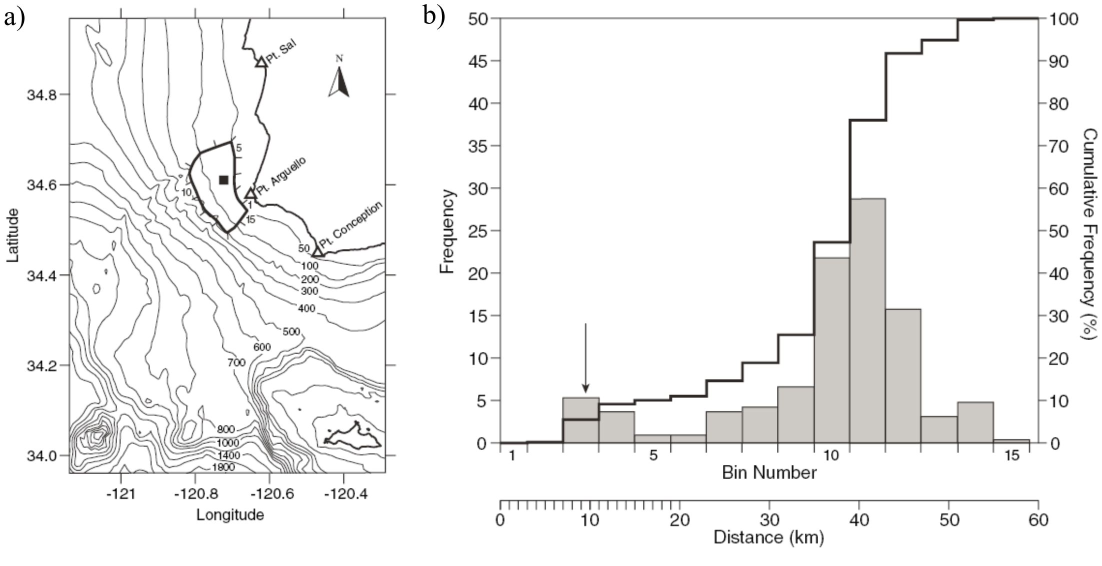

Figure 2. **a)** Coverage boundary for 1 May – 31 August, 1999. Numbers and tick marks around boundary identify bins corresponding to x-axis in panel b. **b)** Histogram (gray bars, left-hand scale) and cumulative frequency (bold line, right-hand scale) show fraction of trajectories (in percent) intersecting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

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%) ended within the radar coverage area and 129 (19%) intersected the coverage boundary. Changes in spatial coverage on diurnal and longer time scales resulted from several factors, such as broadcast interference, and are a characteristic of HF radars (Paduan and Rosenfeld, 1996). Gaps in the velocity time series were also caused by outages of individual radars. The average durations of these gaps were 4.4 ±22.3 h and 5.9 ±7.9 h 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 coordinated universal time (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.

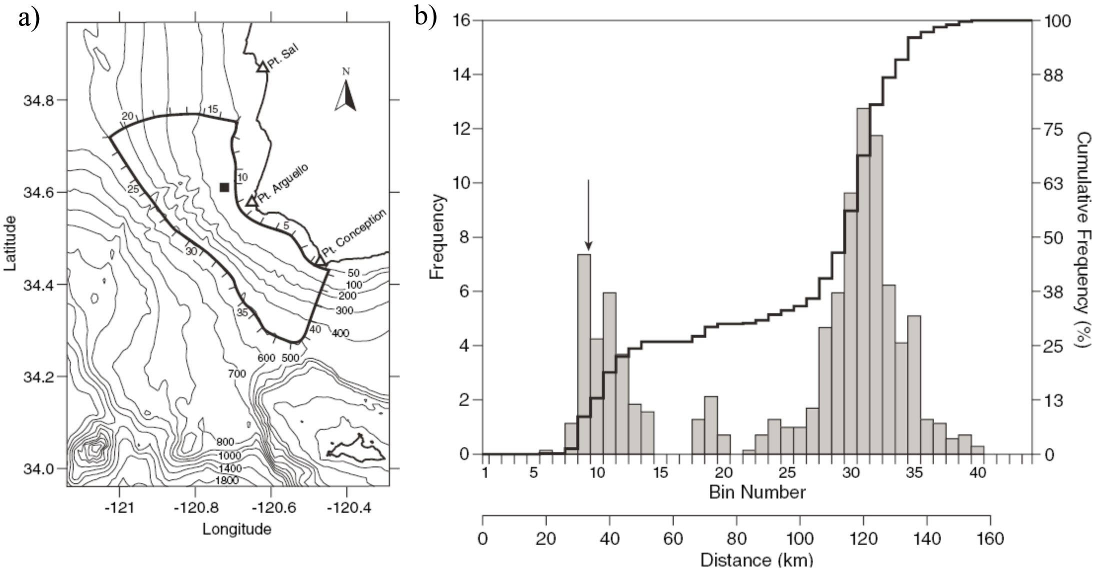

Figure 3. a) Coverage boundary for 1 May – 31 August, 2002. Numbers and tick marks around boundary identify bins corresponding to x-axis in panel b. **b)** Histogram (gray bars, left-hand scale) and cumulative frequency (bold line, right-hand scale) show fraction of trajectories (in percent) intersecting bins around coverage boundary. Panel a shows bin locations. Distance around the coverage boundary (Figure 2a) in kilometers is also shown (bottom scale). Arrow above histogram shows boundary location nearest Platform Irene.

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

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

where t = time;

$\bar{u}_j$ = the time average at location j (computed from available data at location j);

a_i = the time-varying amplitude function;

φ_{ij} = the ith spatial EOF mode at location j; and

N = the number of modes.

The first seven modes (i.e., N=7) were used for interpolation and explained 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 with EOF interpolation compared with the total possible data was 4% in 1999, 12% in 2002, and 14% with the 2002 data for the 1999 coverage boundary. Here the total possible data were 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 hours – 1057 hours in 1999, 2952 hours – 104 hours in 2002). Examples of 25 EOF-filled trajectories that started every 120 hours and intersected the 2002 coverage boundary are shown in Figure 1b.

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

3. Results

Trajectories originating at Platform Irene were 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 (Figure 1a). North of Pt. Arguello, several trajectories crossed the 50-m isobath and some ended very near shore. South of Pt. Arguello, only a few trajectories approached the 50-m isobath. Instead, most turned southward or southwestward and moved offshore. A tendency for trajectories to align parallel to isobaths was evident in the northern end of the ensemble, although in other areas, such as the southeast, many trajectories lay across isobaths.

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

Table 1. Statistics for computed trajectories and SIO drifters.

Year	Coverage boundary	Total trajectories	Trajectories intersecting coverage boundary	Trajectories intersecting inshore boundary (%) (50 m isobath)	Trajectories intersecting offshore boundary (%)	Trajectories intersecting northern boundary (%)	Trajectories intersecting southern boundary (%)	Mean residence time in coverage area (± 1 std. dev.) (hr)	Maximum residence time in coverage area (hr)
1999	1999	590	546	10	76	9	5	19 (± 12)	86
2002	2002	716	706	24	69	6	1	47 (± 34)	163
2002	1999	716	712	18	66	7	8	22 (± 18)	116
SIO drifters	2002	21	17	18	71	12	0	38 (± 21)	79

In 2002 the radars covered a substantially larger area (Figure 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 exhibited 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 crossed the 50-m isobath (bins 1−13), 69% crossed the offshore side (bins 22−39), and the remainder crossed the northern side (6%) or the southern side (1%).

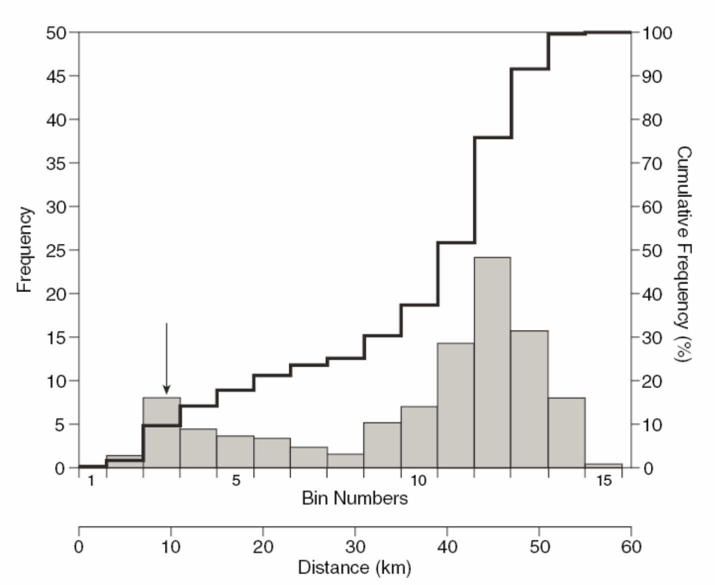

Figure 4. Histogram (gray bars, left-hand scale) and cumulative frequency (bold line, right hand scale) showing percent of 2002 trajectories intersecting bins from 1999 coverage boundary. Bottom scale shows distance around the coverage boundary in kilometers. Arrow above histogram shows boundary location nearest Platform Irene.

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 was completely contained within the 2002 coverage boundary. With the 2002 trajectories, a peak in the histogram again occurred along the offshore boundary (Figure 4, left-hand scale), this time at bin 12 compared with bin 11 when the 1999 trajectories were used. A second, but much smaller peak occurred along the 50-m isobath at bin 3, consistent with the small peak along the 50-m isobath of Figure 2b. Table 1 and the cumulative histogram (Figure 4, right-hand scale) showed that 18% of trajectories crossed the 50-m isobath, 66% crossed the offshore side of the coverage boundary, and the remainder crossed either the northern (7%) or southern (8%) sides.

The time required for trajectories to cross the coverage boundary, defined in our study 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 was 19 ±12 hours, and the maximum was 86 hours (Table 1). In 2002 they were 47 ±34 hours and the maximum was 163 hours. When the 2002 trajectories were computed over the 1999 coverage boundary, residence times were comparable to the 1999 values: 22 ±18 hours and a maximum of 116 hours.

4. Discussion

Because of limitations in spatial coverage, the HF radar-derived trajectories could not be used to examine the full range of length and time scales over which actual trajectories may extend. We used 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 [1998] and Winant et al. [2003] for a description of the drifter data set). Drifter positions were obtained up to six times per day, typically for 40 days, and had a spatial accuracy of about 1 km. Several trajectories ended earlier when the drifters beached.

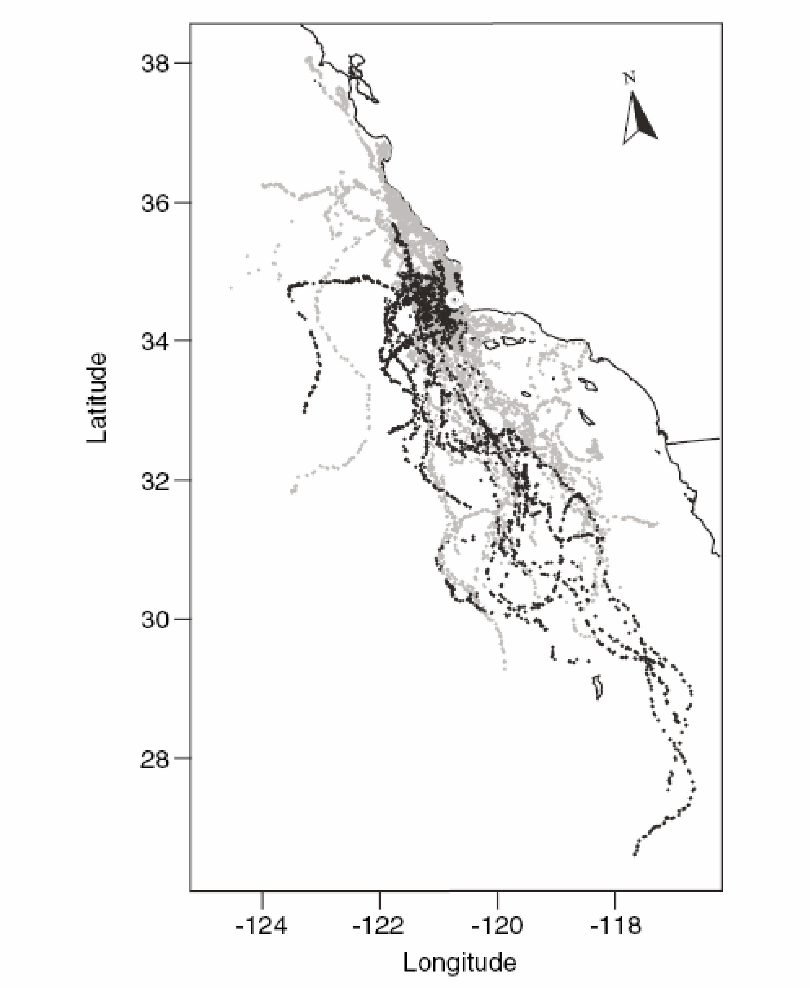

Figure 5. Trajectories of all drifters deployed by the Scripps Institution of Oceanography at various times from October 1992 through December 1999 after passing within 10 km of Platform Irene (gray dots). Also shown are all drifters after passing within 10 km of Platform Irene for only the time period 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.

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 Figure 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, Figure 5) mainly followed the trend of southward advection by the California Current System, although a smaller number extended northward from the platform and a few reached Monterey Bay. Four trajectories entered 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 produced a subset of 21 trajectories (black dots, Figure 5). Of these, 17 crossed 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 was small, the fraction of drifters crossing the inshore boundary of the 2002 coverage area (18%) was comparable to the fraction of HF radar-derived trajectories that did so (24%), as shown in Table 1. Most trajectories crossing the offshore boundary continued offshore and southward, consistent with advection by the California Current System. Others crossing the offshore boundary extended north of Platform Irene before turning southward or offshore. The two trajectories crossing the northern boundary remained near shore and crossed the 50-m isobath north of the platform. None of these 17 trajectories entered the Santa Barbara Channel. Except for three drifters that beached, all the drifters remained offshore for the duration of Argos data logging.

Trajectories crossing the 50-m isobath tended to do so north of platform Irene, as shown by most of the computed trajectories and three of the SIO drifters (Figs. 2b and 3b). This movement indicates that transport from the platform to shallow water habitat along the mainland coast mostly occurred 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 described two other flow states, "upwelling" and "convergent," which produce offshore and equatorward transport near Platform Irene. Together these flow states have a 69% probability of occurring during May−Aug (36% for upwelling and 33% for convergent), whereas the relaxation state has a 23% probability of occurring (Winant et al. [2003], their Table 3). For comparison, 19−30% of trajectories (HF radar-derived plus actual drifters) crossed the inshore and northern boundaries, consistent with the relaxation probability and 70−81% crossed the offshore and southern boundaries, consistent with the upwelling plus convergent probability.

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

$$P(t) = P_0 e^{-mt}, \tag{3}$$

where m = mortality (0.02 or 0.06/day, Ralston[2]);
P = population at time t; and
P_0 = the initial population.

Here, P_0 represents the population of juvenile bocaccio that recruited at Platform Irene, and survival estimates are used to predict their survival in the absence of the platform. In 1999 and 2002, trajectories to habitat from Platform Irene crossed the 50-m isobath within 19−47 hours (Table 1), indicating a high percentage of survival for bocaccio (96−98%). In contrast, offshore and southward drifter trajectories from the SIO drifter data indicated much lower survival. Pelagic juvenile bocaccio transported by these flows would be carried southward by the

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

California Current and remain far from the mainland and the Northern Channel Islands (Figure 5) for at least 40 days, the nominal time the drifters were tracked. Survival after 40 days along these trajectories ranged from 9−45%.

It is possible that juvenile bocaccio spend time away from near surface waters during their planktonic larval phase and therefore their trajectories may depend on deeper currents. Previous observations in the study region show strong correlation between near surface and deeper flows, indicating 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, indicating that surface currents represent deeper currents only to some shallower depth.

We assumed in this trajectory analysis that juvenile bocaccio effectively behave like passive particles. We made this assumption for two reasons: 1) this assumption allowed us to focus on the lower bound of their range of possible swimming behaviors; and 2) such an assumption also eliminated the need to account for their actual swimming behavior in the open ocean, about which little is known. We do not assume that juvenile bocaccio do not swim; rather, we assume that they swim randomly such that their effective transport is similar to that of passive particles. The other behavioral limit of rapid, consistently directional swimming behavior would likely alter the fraction of bocaccio encountering shallow habitats versus the fraction being advected offshore. Flume experiments with visual cues for directional orientation demonstrate that coral reef fish in the late pelagic stage can swim up to ~100 km in 8 days (Stobutzki and Bellwood, 1997); therefore 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) pointed out that it is yet to be demonstrated that these early-stage fish 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, in order to model 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 where trajectories intersect coverage boundaries. In this case, peaks in the histograms (such as in Figures 2b, 3b, and 4) would decrease as diffusion spreads boundary intersections to adjacent bins. Velocity statistics at scales of order of 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), indicating that effects of unresolved variance are not large. For predicting settlement to habitat, trajectory improvements gained through the incorporation of smaller scale flow features may 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 removal of 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 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.

5. 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 absence of the platform. Instead, prevailing currents would likely advect them offshore where they would have a very low probability of survival. Although 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 the survival of young bocaccio in the Point Conception–Point Arguello region.

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[3] Lenarz, W. 2004. Personal commun. P.O. Box 251, Kentfield, CA, 94914-0251

[4] MacCall, A. 2004. Personal commun. NOAA National Marine Fisheries Service, 110 Shaffer Road, Santa Cruz, CA 95060

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 in this study, an analysis of trajectories derived from HF radar current measurements, 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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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.