



Timing of juvenile fish settlement at offshore oil platforms coincides with water mass advection into the Santa Barbara Channel, California

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ABSTRACT.—Recent pathways taken by pelagic juvenile fishes to offshore oil platforms were reconstructed from remotely sensed and in situ measurements of currents and hydrography. Juvenile fishes comprised 52.8% (16,952 of 23 species) of all individuals (32,080 juveniles and adults of 35 species) observed during scuba surveys conducted about twice per week at two platforms in the eastern Santa Barbara Channel from May to August 2004. Blacksmith, *Chromis punctipinnis* (Cooper, 1863), and rockfishes (genus *Sebastes*, at least 18 taxa) comprised 95.1% of the recruits. Almost all rockfishes recruited to the deepest part of the platforms surveyed (26 and 31 m), while most blacksmith recruited in shallower waters. The onset of the recruitment season for juvenile rockfishes (genus *Sebastes*, Scorpaenidae) coincided with the advection of a low salinity water mass into the channel from the Southern California Bight. Before arrival of this water mass, water at the platforms resembled upwelled, high salinity water around the Point Conception region at the western channel entrance. Settlement pulses of rockfishes and blacksmith were observed during advective events when salinity decreased in the upper 40 m and currents turned northwestward or intensified in that direction. Two abundant rockfish species [bocaccio, *Sebastes paucispinis* Ayres, 1854, and treefish, *Sebastes serriceps* (Jordan and Gilbert, 1880)] showed synchronous patterns of juvenile settlement between platforms separated by 7 km. Our findings indicate that currents from the bight, rather than from central California, supplied recruits to settlement habitat in the eastern channel and that the spatial scale of connectivity for some fish populations in this region is greater than the channel itself.

Fishes and invertebrates of oil and
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A wide variety of marine organisms have a dispersive phase in their early life histories (e.g., egg, larval, and juvenile stages) lasting for days or months before transforming to a stage that is closely associated with spatially distinct habitats (e.g., coastal reefs, artificial reefs (e.g., offshore oil platforms), deep sea vents, estuaries and bays, islands and offshore banks). Recruitment dynamics, more so than some kind of regulatory process after settlement, may control local population dynamics, particularly for long-lived species that occur at low densities and only occasionally produce large year-classes (Warner and Chesson 1985, Doherty and Williams 1988, Caley et al. 1996, Pineda 2000, Laidig et al. 2007). The degree to which a spatially distinct population receives recruits (defined herein as the young that have left a pelagic existence and have newly settled into demersal habitat) from distant populations or local sources is an important issue in ecology and resource management (Warner and Cowen 2002, Sale et al. 2005, Carr and Syms 2006). In the present study, we directly examined water mass dynamics and ocean current variability to reconstruct a portion of the pelagic history of recently settled juvenile fishes around two platforms in the eastern Santa Barbara Channel—the probable pathways taken by the recruits during the days to weeks before settlement.

Numerical modeling studies suggest that the distribution and transport of prerecruits in the pelagic environment to suitable settlement areas to some extent affect the spatial and temporal variability of recruitment (Roughgarden et al. 1988, Siegel et al. 2003, Byers and Pringle 2006, Cowen et al. 2006, Mitarai et al. 2008, 2009, Watson et al. 2010). Such studies have motivated empirical research focused on identifying the origin of recruits and estimating the relative importance of local and remote sources to population replenishment using genetics and otolith chemistry (e.g., Swearer et al. 1999, Thorrold et al. 2001, Wares et al. 2001, Miller and Shanks 2004, Jones et al. 2005, Selkoe et al. 2006, Ashford et al. 2010, Christie et al. 2010, White et al. 2010, Horne et al. 2013).

Observational studies have shed light on the potential oceanographic processes leading to settlement of recruits to populations residing on open coasts (e.g., Paris and Cowen 2004, Sotka et al. 2004, Woodson et al. 2012). However, few have directly linked hydrographic conditions and circulation to pathways of recruits during their pelagic phase (e.g., Schmitt and Holbrook 2002, Roughan et al. 2005, Shanks 2006, Woodson et al. 2012). A number of studies building upon each other (e.g., Nishimoto 2000, Broitman et al. 2005, Blanchette et al. 2006, Selkoe et al. 2006, Caselle et al. 2010, Gosnell et al. 2014) have linked biodiversity and the genetic structure of recruitment to the dynamic convergence of a cool northern-derived water mass and a warm southern-derived water mass in the Santa Barbara Channel, and surmise that variable recruitment rates are associated with advective currents.

In this study, fish surveys and oceanographic observations were carried out on two oil and gas production platforms (Fig. 1). Such structures are similar to seamounts where juvenile fishes commonly are abundant (Carr et al. 2003, Love et al. 2000, 2003, 2012). The platforms extend vertically through the water column and provide shallow water substrate in the offshore environment with the platform legs serving as structure leading to bottom habitat. Because the jacket habitat, created by the platform structure and encrusting biota, is similar among platforms, the temporal and spatial variability of the recruitment process can be examined without the confounding effect of variable habitat complexity (e.g., low vs high relief substrate, presence vs absence of kelp) that can be problematic in natural reef studies (Pineda

2000, Carr and Syms 2006). Furthermore, shallow water currents in offshore areas can be observed with minimal boundary effects, such as strong vertical shear and near-bottom turbulence caused by interactions with bathymetry that varies among nearshore areas (Shanks 2006).

Species composition and densities of juvenile fishes have been shown to vary tremendously during a recruitment season at a platform, and both vary among platforms, some separated by <10 km (Carr et al. 2003, Love et al. 2003, 2006, 2019a). We surmise that this spatial variability is influenced by the distribution of the prerecruits among different water masses, and the advection of the pelagic larvae and juveniles to settlement areas by ocean current patterns. The specific objectives of this study were to: (1) describe the spatial and temporal variability of settlement of young-of-the-year (YOY) fishes within a recruitment season at two offshore platforms in the eastern Santa Barbara Channel, (2) determine if the timing of recruitment is related to oceanographic variability, and (3) identify the transport pathway(s) that delivered recruits to this settlement habitat.

METHODS

STUDY AREA.—Fish surveys and oceanographic observations were carried out at two platforms, Gail and Gilda, in the eastern Santa Barbara Channel, from 1 May through 30 August, 2004 (Fig. 1A). This period corresponds with the season of much of the fish recruitment in this area (Limbaugh 1955, Love et al. 2002, 2012). Gail (34°10'N, 119°25'W; 224 m depth) and Gilda (34°10'N, 119°25'W; 62 m depth), separated by 7 km, are in an area where ocean currents can vary strongly over a scale of several days, and where fronts and eddies are observed (Winant et al. 1999). Both platforms harbor high densities of YOY rockfishes (Love et al. 2003, 2019a).

The Santa Barbara Channel is a biogeographic transition zone for marine flora and fauna, separating the strong coastal upwelling regime extending from Point Conception to Washington from the warmer subtropical waters of the Southern California Bight (Lynn and Simpson 1987, Blanchette et al. 2006, Horn et al. 2006). The Southern California Bight is the region inshore of the Santa Rosa Ridge and includes the Santa Barbara Channel (Fig. 1B; Bray et al. 1999). Circulation in the channel, which we distinguish from the remaining bight, is complex and variable where a number of distinct water masses of the California Current System converge (Hickey 1993, Harms and Winant 1998, Winant et al. 1999, Nishimoto 2000, Nishimoto and Washburn 2002, Winant et al. 2003, Dever 2004). The circulation in the channel consists primarily of a cyclonic flow that varies in strength through the year. It is strongest spring through fall, and weakest or absent in winter. The cyclonic flow tends to drive westward flow along the northern boundary of the channel and eastward flow along the Channel Islands, the southern boundary. Unidirectional flows spanning the channel toward the east or west occur mostly in the winter, but also intermittently throughout the year. Currents carry a diversity of larval and juvenile fish species into the channel that can recruit to adult habitats (Moser and Watson 2006).

ESTIMATING THE ABUNDANCE OF RECENTLY SETTLED JUVENILE FISHES.—Fish surveys were conducted at both platforms every 3–4 d following the sampling design and protocols developed to assess fish populations at platforms (Love et al. 2003). Scuba divers surveyed three depths: 5 m at both platforms (herein referred to as the

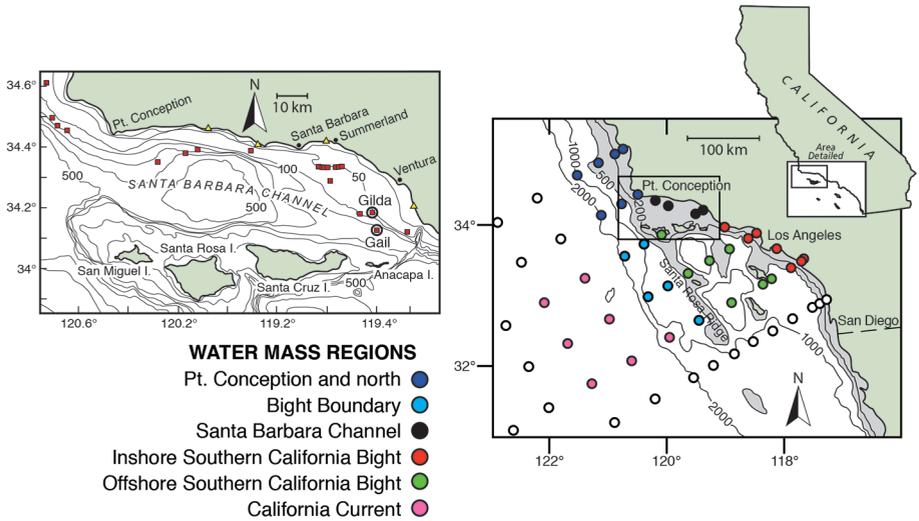


Figure 1. Bathymetric maps of the Santa Barbara Channel and the Southern California Bight with California Cooperative Oceanic Fisheries Investigations (CalCOFI) water mass reference areas. (A) The Channel: triangles show high frequency radar locations; squares show locations of oil and gas production platforms; Platforms Gail and Gilda, the study sites, are circled. (B) Six water mass regions of geographically distinct locations (see inset color code) are designated in the standard station grid (partially mapped) of triennial CalCOFI surveys. Water mass data (potential temperature and salinity (TS) from 0 to 100 m) from the six areas were used as references to identify the sources of water masses observed at the platforms (see Fig. 5).

shallow levels), cross members at 11 m at Gilda and 12 m at Gail (*middle levels*), and cross members at 26 m at Gilda and 31 m at Gail (*deep levels*). Scuba divers visually surveyed fishes along rectangular belt transects (2 m width × 2 m height) that coursed along the perimeter and crossed through the structure bounding a third of the area of the platform at each depth. Scuba divers identified, counted, and estimated the total lengths of all fishes observed with the aid of a ruler on the data recording slate. Observers were trained to estimate the total length of fishes to the nearest centimeter. Our analysis focused on the most abundant YOY fishes observed.

The abundance of recently settled juvenile fishes (herein referred to as *recruits*) for a given period and platform is defined as the increase in number of fishes observed within 2-cm size classes from one survey to the next at a platform. For a given taxon, the number of recruits, R , per survey at time t , is

$$R_t = \sum_{i=s}^m (N_{i(t)} - N_{i(t-1)})$$

where N is the number of fish observed in a 2-cm size class interval i , s is the index identifying the upper limit of a size class [e.g., $s = 4$ for 2–4 cm total length (TL), $s = 6$ for 4–6 cm TL, etc.], and m is the maximum size class index of the fish we defined to be recent settlers. If $(N_{i(t)} - N_{i(t-1)}) < 0$, then this difference is set equal to 0.

We used this approach to distinguish recently settled juveniles from individuals that may have settled during the previous survey. We devised this estimate because we observed a broad size distribution among individuals on the first day of settlement at either platform, and we did not want to limit our approximation of recruits to a single size class of only small individuals. For example, the first settlement event of bocaccio (*see* Table 1 for species names and authorities) was comprised of 6–12 cm YOY. Rockfishes grow about 0.2–0.3 mm d⁻¹ with the notable exception of bocaccio (0.72 mm d⁻¹; Love et al. 1991). An individual bocaccio grows 1 cm in about 2 wk; thus, it is a reasonable assumption that fish would remain in a given size class for the few days between observations and that an increase in abundance from one survey to the next was the arrival of new settlers. Mortality and emigration to deeper, unsurveyed portions of the platform are not factored into the estimate.

To determine the degree of synchrony in settlement patterns at the two platforms, Kendall's correlation coefficient, τ , was used to measure the tendency of concordant changes (i.e., corresponding increases and decreases) in recruit abundance at the two platforms from one paired survey to the next. Kendall's correlation ranked test was conducted using the `cor.test()` function with the method set as "Kendall" (R v3.4.0). We report the value, τ , which ranges from 1 (perfect concordance or synchrony between the two platforms) to -1 (perfect discordance or negative correspondence), and the significance (P value) of τ . Given that strong temporal autocorrelation can affect the P -value, we tested for temporal autocorrelation in our time series of abundance data using the autocorrelation function `acf` in R on the residuals from a linear model of ranked fish counts at the two platforms.

OCEANOGRAPHIC OBSERVATIONS.—Oceanographic data collected by us and others were examined to determine if patterns of settlement were related to ocean circulation. An acoustic Doppler current profiler (ADCP; 600 KHz Workhorse Sentinel by RD Instruments) and a moored conductivity, temperature, depth instrument (herein called a *moored CTD*; SBE37-SMP Microcat by Sea-Bird Electronics, Inc.) were mounted as a package to the southeast leg of each platform: Gilda at 23 m and Gail at 26 m depth. Scuba diving logistics limited the depth of the packages that were deployed a few meters above the deepest level surveyed at the platforms. Approximately every 4 wk, the ADCP and moored CTD were retrieved to upload data, and the instruments were redeployed the following day. The ADCP logged vertical profiles of horizontal currents every 6 min, the moored CTD logged conductivity, temperature, and pressure every 3 min. The ADCP was upward-looking and tilted away from the platform to avoid physical interference by the structure. Processing of the ADCP data accounted for the tilt of the instrument. The depth range profiled was 17.2–24.9 m at Gail (19 bins) and 10.2–22 m at Gilda (29 bins). The bin interval was approximately 0.4 m in the vertical.

We used a SBE 19 CTD with pump (Sea-Bird Electronics, Inc.) to profile the water column within 100 m of the platform on survey dates starting on 10 June. Conductivity, temperature, and pressure were measured to at least 100 m at Gail and to about 60 m (2 m from the bottom) at Gilda. CTD cast and moored CTD data were processed for salinity and potential temperature using the software provided by the manufacturer.

Regional water mass data were obtained from a cruise during 13–28 July, 2004, as part of the California Cooperative Oceanic Fisheries Investigations (CalCOFI;

Table 1. All fishes observed at platforms Gail and Gilda, 1 May through 30 August, 2004. Species are ordered by number of recruits observed.

Species	Common name	Total		Recruits	
		Gail	Gilda	Gail	Gilda
<i>Chromis punctipinnis</i> (Cooper, 1863)	Blacksmith	12,069	5,074	5,043	3,440
<i>Sebastes paucispinis</i> Ayres, 1854	Bocaccio	5,817	1,082	4,851	1,046
<i>Oxylebius pictus</i> Gill, 1862 ¹	Painted greenling	156	815	122	567
<i>Sebastes serriceps</i> (Jordan and Gilbert, 1880)	Treefish	531	157	500	156
“Copper complex” ²		5	505	5	505
<i>Sebastes hopkinsi</i> (Cramer, 1895)	Squarespot rockfish	3	400	3	305
<i>Medialuna californiensis</i> (Steindachner, 1878)	Halfmoon	1,485	1,733	39	51
<i>Sebastes entomelas</i> (Jordan and Gilbert, 1880)	Widow rockfish	27	69	27	48
Unidentified <i>Sebastomus</i> ³		1	74		74
<i>Sebastes serranoides/flavidus</i> ⁴	Olive/yellowtail rockfish	29	27	28	24
<i>Sebastes caurinus</i> Richardson, 1844	Copper rockfish	95	19	20	5
Unidentified <i>Gibbonsia</i>	Kelpfish		36		19
<i>Scorpaenichthys marmoratus</i> (Ayres, 1854)	Cabezon	41	145	5	
<i>Sebastes mystinus</i> (Jordan and Gilbert, 1881)	Blue rockfish	15	65	14	1
<i>Phanerodon furcatus</i> Girard, 1854	White seaperch		81		11
<i>Sebastes carnatus</i> (Jordan and Gilbert, 1880)	Gopher rockfish	11	4	4	2
<i>Sebastes dalli</i> (Eigenmann and Beeson, 1894)	Calico rockfish	4	6	2	4
<i>Rhinogobiops nicholsii</i> (Bean, 1882)	Blackeye goby	1	10	1	3
<i>Alloclinus holderi</i> (Lauderbach, 1907)	Island kelpfish		3		3
<i>Sebastes auriculatus</i> Girard, 1854	Brown rockfish	11		2	
<i>Sebastes diploproa</i> (Gilbert, 1890)	Splitnose rockfish	2		2	
<i>Damalichthys vacca</i> Girard, 1855	Pile perch	1	66		2
<i>Sebastes atrovirens</i> (Jordan and Gilbert, 1880)	Kelp rockfish	18	95		1
<i>Sebastes chrysomelas</i> (Jordan and Gilbert, 1881)	Black-and-yellow rockfish	3		1	
<i>Sebastes melanops</i> Girard, 1856	Black rockfish	1	1		1
<i>Brachyistius frenatus</i> Gill, 1862	Kelp perch	1		1	
<i>Sebastes ruberrimus</i> (Cramer, 1895)	Yelloweye rockfish	1		1	
<i>Hexagrammos decagrammus</i> (Pallas, 1810)	Kelp greenling		1		1
<i>Sebastes rastrelliger</i> (Jordan and Gilbert, 1880)	Grass rockfish	117	29		
<i>Sebastes serranoides</i> (Eigenmann and Eigenmann, 1890)	Olive rockfish	38	53		
<i>Mola mola</i> (Linnaeus, 1758)	Mola		3		
Unidentified <i>Syngnathus</i>	Pipefish	1	1		
<i>Anarrhichthys ocellatus</i> Ayres, 1855	Wolf-eel		1		
Unidentified <i>Citharichthys</i>	Sanddab		1		
Unidentified Embiotocidae	Sea perch		1		

¹ This species was not included in the analysis as only one pulse was observed.² Primarily copper rockfish (*Sebastes caurinus* Richardson, 1844) and kelp rockfish (*Sebastes atrovirens* Jordan and Gilbert, 1880), but may also include gopher rockfish, *Sebastes carnatus* (Jordan and Gilbert, 1880), and black-and-yellow rockfish, *Sebastes chrysomelas* (Jordan and Gilbert, 1881).³ Likely primarily rosy rockfish, *Sebastes rosaceus* Girard, 1854.⁴ Juveniles of yellowtail rockfish, *Sebastes flavidus* (Ayres, 1862), and olive rockfish were indistinguishable.

http://www.calcofi.org/newhome/data/data_archives.htm). We used potential temperature and salinity data from the CalCOFI survey and descriptions of large-scale circulation patterns off southern California (Bray et al. 1999) to define regional hydrographic signatures, and to identify the source of the water masses that occupied the platform habitat during our study.

Hourly high-frequency (HF) radar surface current observations provided maps of the surface current field around the platforms and most of the Santa Barbara Channel. Currents that are approximately in the upper 1 m of the water column in the western channel have been continuously mapped since 1998; however, mapping of the eastern channel was initiated for this study with the addition of a radar site at Summerland, California (Fig. 1A). Operational details and data processing for the HF radar array are discussed further by Emery et al. (2004).

The time series of surface current patterns from the HF radar and subsurface currents from the ADCP were used to interpret the near-field flow at the platforms. Time series data from the ADCP, moored CTD, and surface current mapping were low-pass filtered with a $1/36 \text{ hr}^{-1}$ cutoff frequency to suppress tidal variations.

RESULTS

We observed 32,080 fishes of at least 35 species around the two platforms (Table 1). For a list of the scientific names and species authorities of all taxa, see Table 1.

Of these fishes, at least 23 species and 52.8% (16,952) of all individuals were recruits. Almost all of the recruits (95.1%) were either blacksmith or rockfishes (at least 18 taxa). Six species or species complexes (blacksmith, bocaccio, painted greenling, treefish, copper rockfish complex, and squarespot rockfish) comprised the majority of recruits. Most of the rockfish recruits lived near the platform structure, while juvenile blacksmith were not closely associated with the substrate and were typically observed schooling with adult blacksmith.

TIME SERIES OF JUVENILE FISH RECRUITMENT.—We focused our analyses on five of the most abundant “taxa”: bocaccio, treefish, copper rockfish complex, squarespot rockfish, and blacksmith. We did not include painted greenling in this analysis as it only recruited once, a single pulse, to the platforms.

Some synchrony in settlement occurred between platforms and among the four most-commonly observed taxa of juvenile rockfishes. All taxa showed a settlement pulse within 1 wk from 28 June to 6 July. We identify this as the beginning of the rockfish recruitment season. After this time, settlement for all rockfish taxa continued for the rest of the study, herein called the *recruitment period*, as sequences of settlement pulses.

The timing of settlement was synchronized between the two platforms for at least two rockfish species. Bocaccio and treefish occurred at both Gail and Gilda, and clearly exhibited two temporal patterns: the seasonality of recruitment and episodic pulses of settlement within the recruitment period (Fig. 2A–D). The abundances of the copper rockfish complex and squarespot rockfish were too low at Gail to make a comparison.

The major bocaccio recruitment period began on or just before 1 July when hundreds of recruits, 10 cm or less, were found at Gail and Gilda (Fig. 2A, B). Before this date, relatively low levels of settlement occurred between 24 May and 21 June

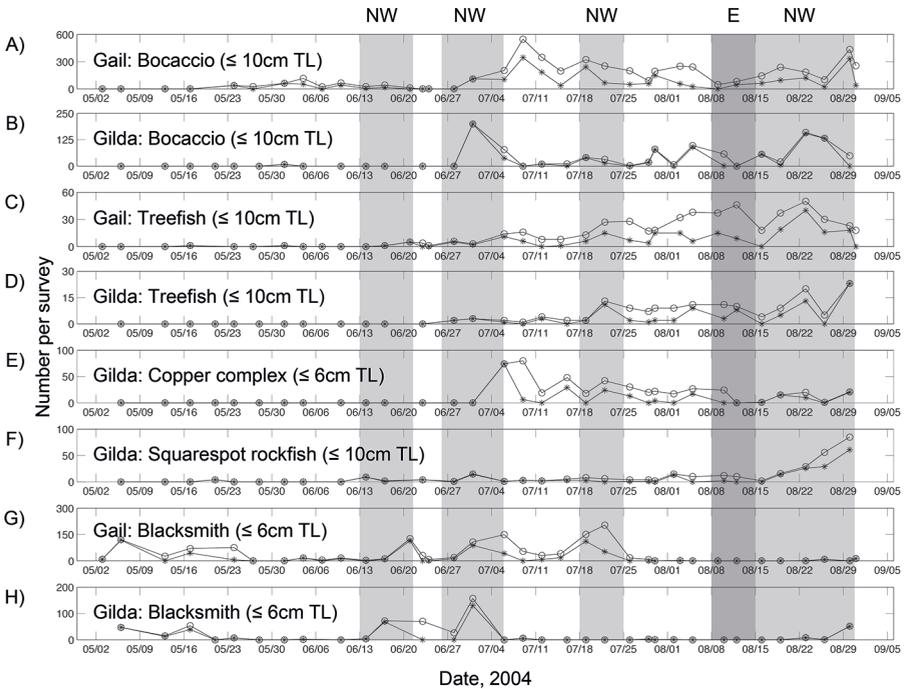


Figure 2. Number of fish observed (\circ ; all sizes] and the number of recruits ($*$) per survey from 3 May through 31 August, 2004, of bocaccio, *Sebastes paucispinis* (size range denoted) at (A) Platform Gail and (B) Platform Gilda; treefish, *Sebastes serriiceps*, at (C) Platform Gail and (D) Platform Gilda; (E) copper-complex rockfishes (genus *Sebastes*) from Platform Gilda; (F) squarespot, *Sebastes hopkinsi*, at Platform Gilda; and blacksmith, *Chromis punctipinnis*, at (G) Platform Gail and (H) Platform Gilda. Note that the abundances of the copper rockfish complex and squarespot rockfish were too low at Gail to make a comparison. Four periods when salinity decreased in the upper 40 m and currents turned northward (NW above blocks) or intensified in that direction are blocked in the time series. A period in the second week of August is blocked when salinity increased and currents turned eastward (E). Blocks designate these five time periods in Figures 3, 4, and 6.

at Gail and on one occasion (on 1 June) at Gilda. The time series of bocaccio recruit abundance at the two platforms starting on 24 May were significantly correlated ($\tau = 0.300$, $z = 2.0919$, $P = 0.0365$, $n = 28$). The residual temporal autocorrelation was non-significant. Nearly all juvenile bocaccio occurred at the deep levels as only 1 of 1046 juveniles observed at Gilda and 10 of 4851 juveniles (0.2%) observed at Gail occurred at the middle levels; no bocaccio were observed at the shallow level at either platform.

As with bocaccio, synchronous settlement patterns of treefish recruits (≤ 10 cm) were observed at the platforms. Aside from an occasional sighting of a single recruit, the first pulse of recruits occurred at Gail on 21 June (Fig. 2D). The first recruits at Gilda arrived on 28 June and coincided with a second pulse at Gail (Fig. 2C, D). The time series of recruit abundance at the two platforms were significantly correlated ($\tau = 0.572$, $z = 3.876$, $P = 0.0001$, $n = 29$). The residual temporal autocorrelation was non-significant. All treefish were ≤ 14 cm; 94% at Gail and 99% at Gilda were ≤ 10 cm. Most of the juveniles (≤ 10 cm) were counted at the two deeper levels: 7% and 92% of 500 juveniles were observed at the middle and deep levels at Gail, respectively; 15% and 84% of 156 were observed at Gilda.

The copper rockfish complex and squarespot rockfish recruited in substantial numbers to Gilda (Fig. 2E, F), but not at Gail where only three juveniles of the copper rockfish complex recruited during July and August, and three juvenile squarespot rockfish recruited in late July (data not shown). Like bocaccio and treefish, recruitment of both taxa occurred primarily at the deep level. Of the 479 juveniles of the copper rockfish complex counted at Gilda (≤ 6 cm), 449 (94%) were observed at the deep level. Among the four rockfish taxa, squarespot rockfish tended to settle latest in the recruitment period, primarily in late August. All squarespot rockfish at Gilda occurred at the deep level and ranged in size from 3 to 14 cm. Juveniles (≤ 10 cm) comprised 76% of these fish. While the first occurrence of juvenile squarespot rockfish was on 21 May, recruits were not observed again until 14 June followed by a pulse on 1 July.

Blacksmith, the most abundant nonrockfish species recruiting to the platform, had a settlement pattern that differed both temporally and between platforms when compared to the rockfishes. Juvenile blacksmith (≤ 6 cm) recruited to both platforms when the surveys started at the beginning of May (Fig. 2G, H). In contrast, rockfish recruits were absent until the second week in May. The settlement patterns of the recruits at the two platforms, starting from the beginning of the time series of surveys, were not significantly correlated ($\tau = 0.161$, $z = 1.092$, $P = 0.275$, $n = 31$). Unlike the juvenile rockfishes, blacksmith occurred in the upper water column: at Gail, 51% and 39% of all juvenile blacksmith occurred at the shallow and middle levels, respectively; while at Gilda, these values were 19% and 77%, respectively. Juveniles comprised 11% and adults (>15 cm TL) comprised 50% of all blacksmith observed.

WATER MASS ADVECTION AND JUVENILE FISH RECRUITMENT.—The juvenile rockfish recruitment period was preceded by the arrival of a low salinity water mass to the study area. Time series of salinity, measured near the deep level at both platforms where most of the juvenile rockfishes settled, declined from 33.6 to <33.45 during 1–14 June (Fig. 3, black lines). The salinity from the CTD casts at the depth of the moored CTDs also exhibited this change (Fig. 3, solid circles). Time series of the vertical profiles of salinity and potential temperature from CTD casts (Fig. 4) show that the low salinity values were associated with a mid-depth water mass centered between 15 and 40 m from the surface. Advection of the low salinity water mass is evident in the salinity depth-time contours at both platforms during 10–17 June (Fig. 4A, B). At this time, rockfish recruits were absent, but blacksmith settled in substantial numbers at both platforms. The appearance of salinities <33.4 at both platforms around 27 June–7 July coincided with the beginning of the rockfish recruitment period and another settlement pulse of blacksmith.

During the recruitment period, water properties at the deep survey level, where most juvenile rockfishes settled, resembled waters from the inshore and offshore regions of the Southern California Bight (Figs. 1B, 5). Before the recruitment period, water properties at Gilda and Gail were more saline and resembled upwelled water from the Point Conception region at the western entrance of the channel, and water characteristic of an offshore band extending southwestward from Point Conception along the Santa Rosa Ridge, the boundary of the Southern California Bight (Figs. 1B, 5). Time series of subsurface currents indicate that the low salinity water mass advected into the channel from the bight when currents switched from generally southeast to northwest beginning around 15 June (Fig. 6). These currents had a

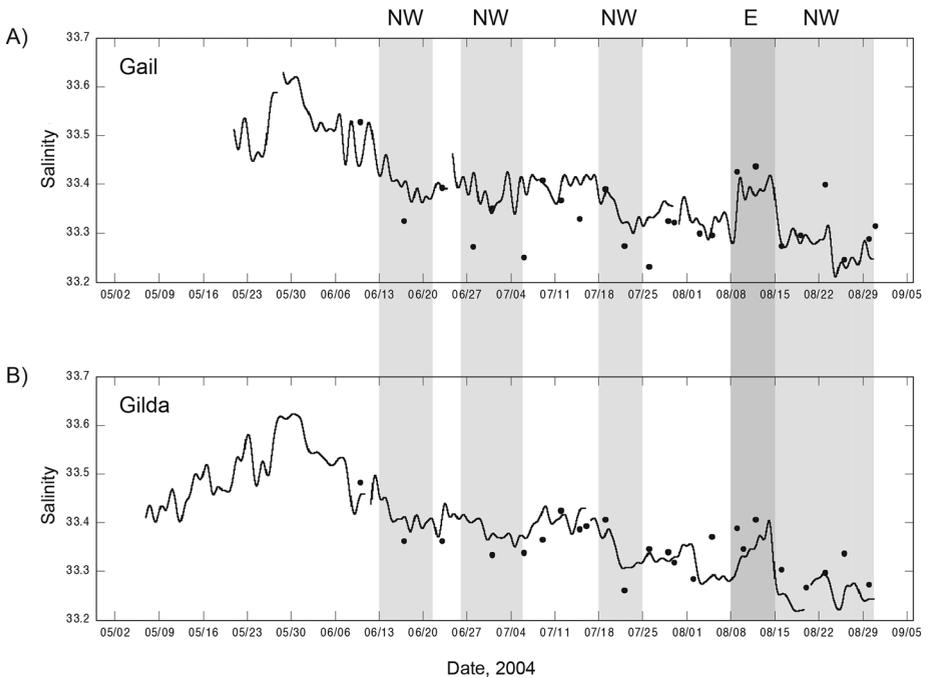


Figure 3. Thirty-six-hr filtered time series of salinity (black line) from a moored conductivity, temperature, depth instrument (CTD) deployed at (A) 26 m depth at Platform Gail and (B) 23 m depth at Platform Gilda. Closed circles are salinity from the CTD casts at the same depths as the moored CTD at each platform. See Figure 2 legend for description of blocked time periods.

westward component typically near 10 cm s^{-1} with a maximum of about 20 cm s^{-1} ; the northward component was somewhat weaker at both platforms.

The switch in surface current direction was part of an evolving large-scale pattern (Fig. 7). The HF radar maps show strong eastward surface current flow throughout the offshore area of the eastern channel on 10 June. The flow had weakened and turned southward and eastward in the area of Gilda and Gail on 12 June. The surface currents turned predominately poleward by 14 June and they flowed through the eastern entrance and through the gap between Santa Cruz Island and Anacapa Island from the Southern California Bight into the channel. The surface currents continued westward along the isobaths of the mainland coast of the channel.

During the recruitment period, advective events corresponded with settlement pulses. Salinity decreased in the upper 40 m (Figs. 3, 4) and currents turned northwestward or intensified in that direction (Fig. 6) on four occasions: 13–22 June, 26 June–6 July, 18–25 July, and 15–31 August. Settlement pulses of blacksmith were associated with all four events (Fig. 2). Copper rockfish complex settlement peaked during the second event. Settlement pulses were observed among all taxa except squarespot rockfish during the third event. During the second week of August, currents turned strongly eastward in opposition to the westward flow that characterized the four events, salinity abruptly increased in the upper 40 m. The advection of warm, high salinity surface water to the platforms was associated with relatively few new recruits with exception of a small pulse of treefish at Platform Gilda (Figs. 2, 4). After westward currents resumed during the fourth event, salinity

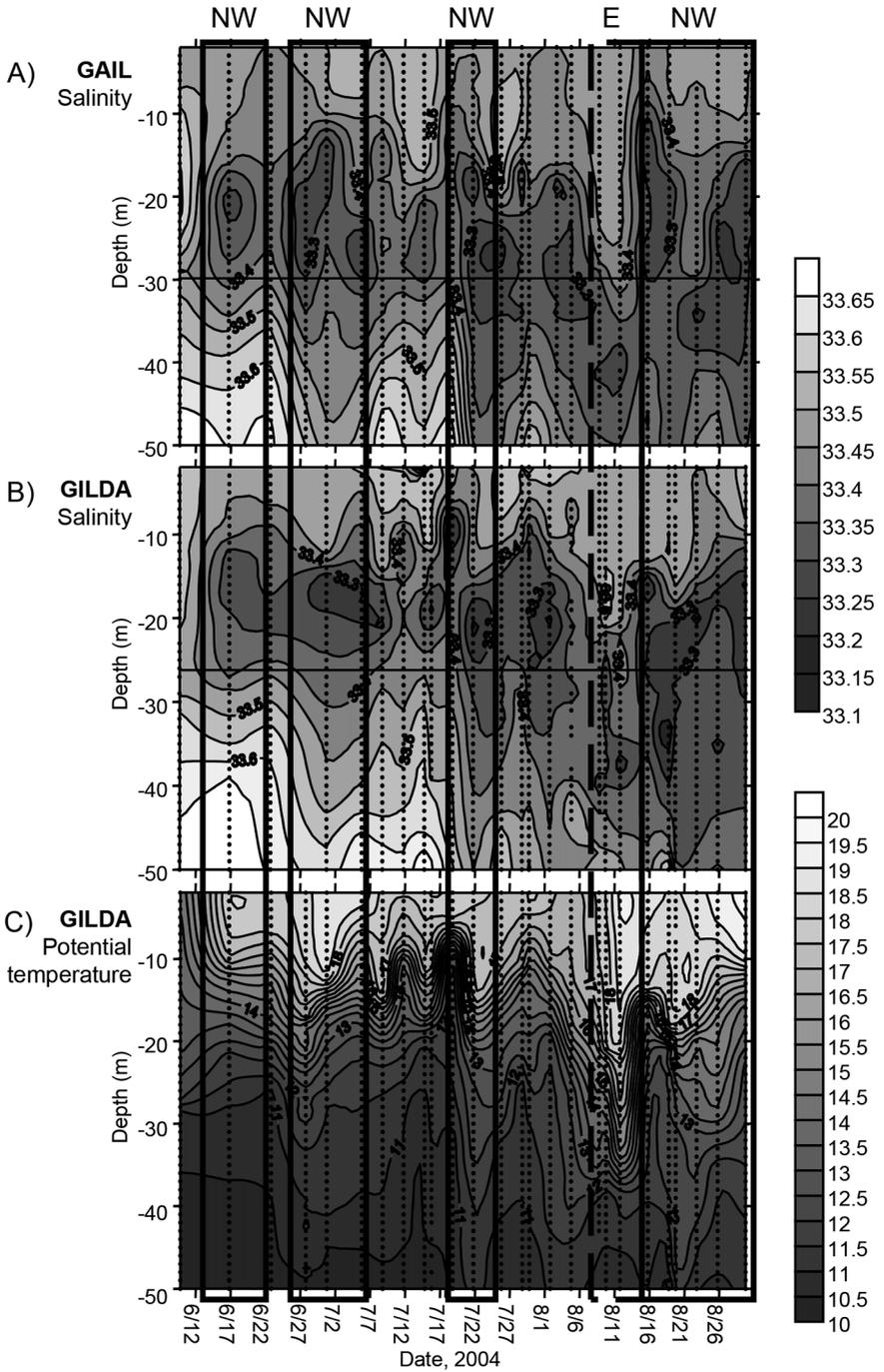


Figure 4. Contoured time series of the vertical profiles of salinity at (A) Platform Gail and (B) Platform Gilda; and (C) potential temperature at Platform Gilda. Black horizontal lines at 30 m and 26 m on the Gail and Gilda plots, respectively, indicate the deepest level surveyed where the majority of the juvenile rockfish recruits were observed. See Figure 2 legend for description of blocked time periods.

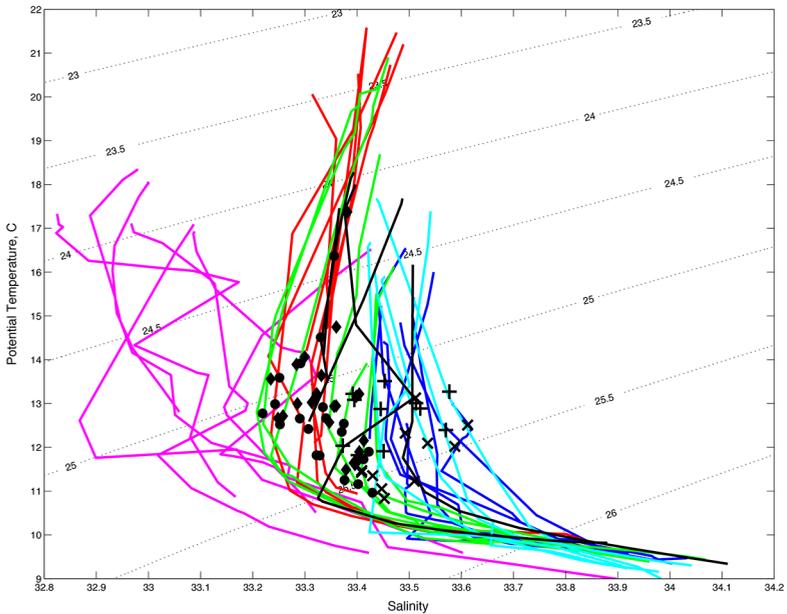


Figure 5. Identification of water mass signatures at the platforms. Temperature-salinity (TS) plots from the six California Cooperative Oceanic Fisheries Investigations reference regions mapped in Figure 1B (TS lines and regions have corresponding color codes) are laid over the mean TS from 24 hrs preceding each survey at Platforms Gilda and Gail before (indicated by \times and $+$, respectively) and after (indicated by \bullet and \blacklozenge , respectively) the nominal onset of the rockfish recruitment season, June 28, 2004.

declined to the lowest values observed during the study and all taxa settled at the platforms in relatively high numbers.

Settlement events were associated with two water mass signatures observed at the platforms during the recruitment period. Larger settlement events of treefish, squarespot rockfish, and copper rockfish complex were associated with warmer, less saline waters ($>12^{\circ}\text{C}$, salinity 33.2–33.35; Fig. 8). These water mass characteristics align with the temperature-salinity (T-S) properties of the inshore Southern California Bight region and indicate waters had advected from the inshore area south of the Santa Barbara Channel (Fig. 5). At other times, relatively cooler, more saline waters ($<12.5^{\circ}\text{C}$, salinity 33.35–33.425) occupying the platforms were similar to waters in the region of the offshore Southern California Bight (Figs. 5, 8). Large pulses of bocaccio recruits occurred when either water mass current aligning with the T-S properties of the inshore or offshore Southern California Bight occurred at the platforms. Northwestward subsurface currents with salinity <33.4 indicate advection from the Southern California Bight rather than from within the channel itself (Figs. 4, 6).

Salinity, rather than temperature, distinguished the two water mass currents from the Southern California Bight that were associated with large rockfish recruitment pulses at the platforms from currents carrying upwelled water from the Point Conception region that delivered relatively few rockfish recruits (Figs. 5, 8). However, the only statistically significant relationship that emerged was a negative correlation between treefish abundance and salinity at Platform Gail (Table 2). Contributing to

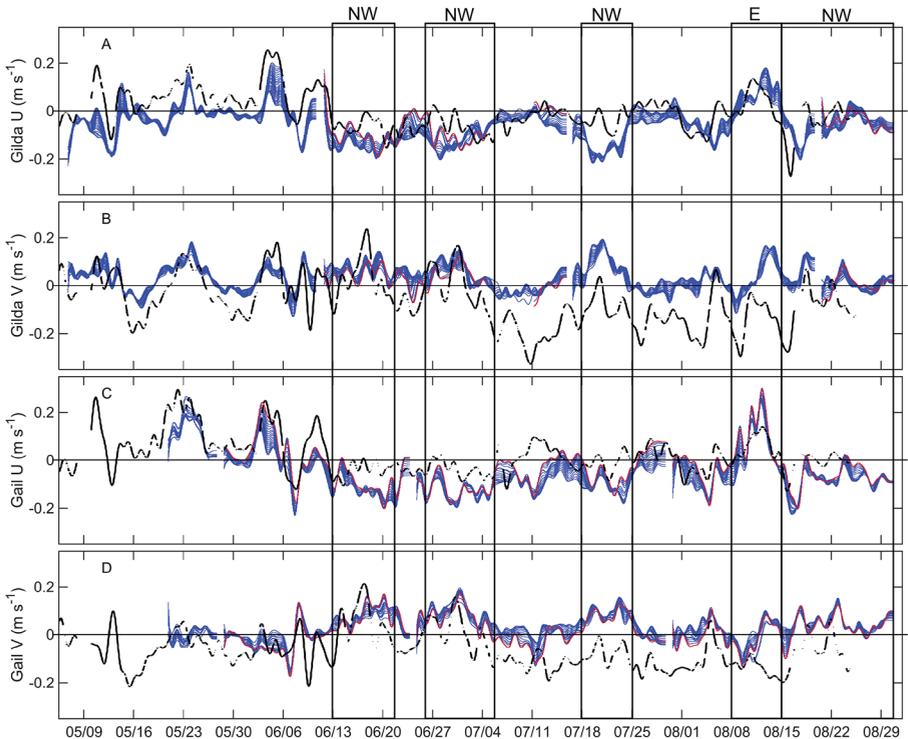


Figure 6. Time series of 36-hr filtered surface and subsurface currents at the platforms. (A) U component (eastward is positive) and (B) V component (northward is positive) of radar-derived surface currents (indicated by black line) and subsurface currents (each blue line represents the mean current within a depth interval with the red line representing the shallowest bin depth interval) from the ADCP deployed at Platform Gilda. (C and D) Same at Platform Gail. The surface current measurements are from the nearest radar mapping grid point to the southeast of each platform. The effective current profile range was 10.2–22 m at Platform Gilda (29 bins) and 17.2–24.9 m from the surface at Platform Gail (19 bins). The bin interval was 0.4 m. See Figure 2 legend for description of blocked time periods.

the weak relationships were that the numbers of recruits observed from survey to survey were highly variable when a particular water mass current was at the platforms (Figs. 2, 8).

DISCUSSION

The water mass change preceding the recruitment period at the platforms was consistent with the seasonal transition from spring to summer oceanographic conditions in the Southern California Bight. Seasonal variations have been observed on the regional scale of the bight (Lynn and Simpson 1987, Bray et al. 1999) as well as in the channel (Harms and Winant 1998, Otero and Siegel 2004). In the spring, equatorward flow predominates throughout the bight at all depths to 500 m. We observed this flow as a predominately eastward current at the platforms during the first portion of our study (Fig. 6). Poleward (i.e., northwestward) alongshore flow develops in the summer and persists through the fall and winter throughout the bight except for the western part of the channel where cyclonic circulation predominates

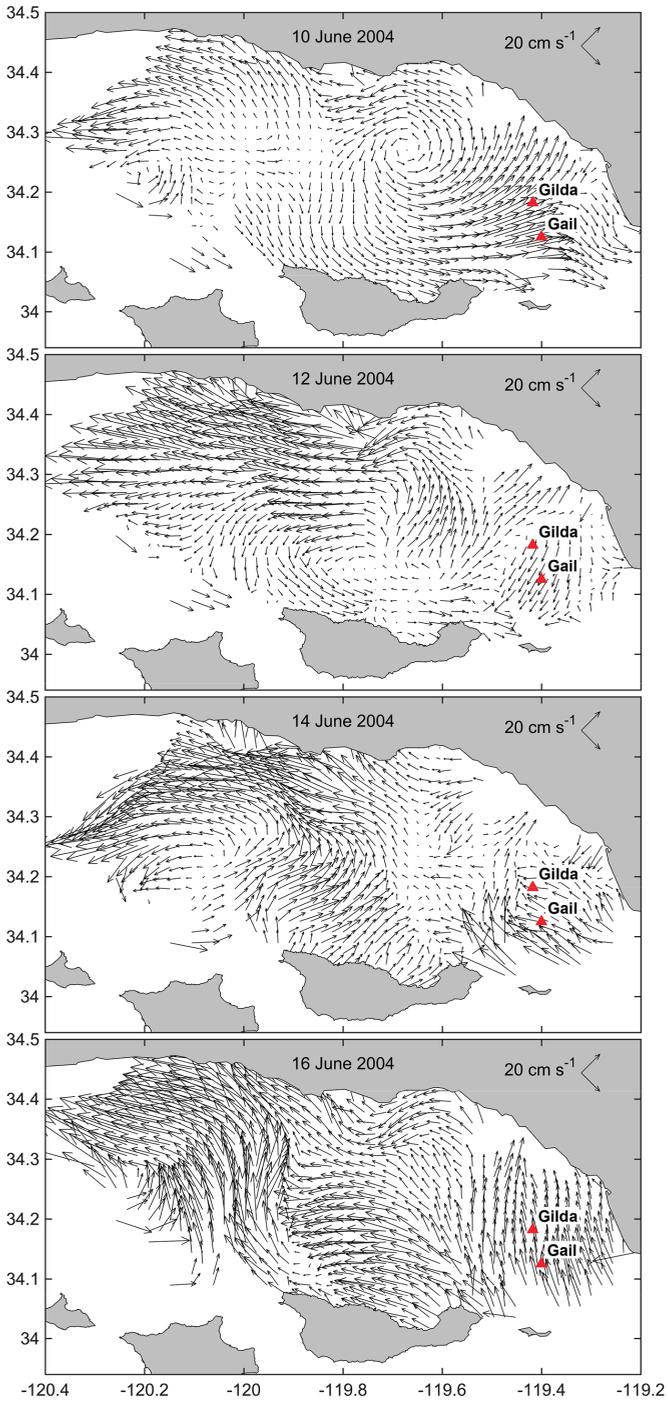


Figure 7. High-frequency radar maps of 25-hr mean surface currents from 10 June, 12 June, 14 June, and 16 June, 2004, show abrupt transition from eastward currents to northwestward currents in the eastern Santa Barbara Channel.

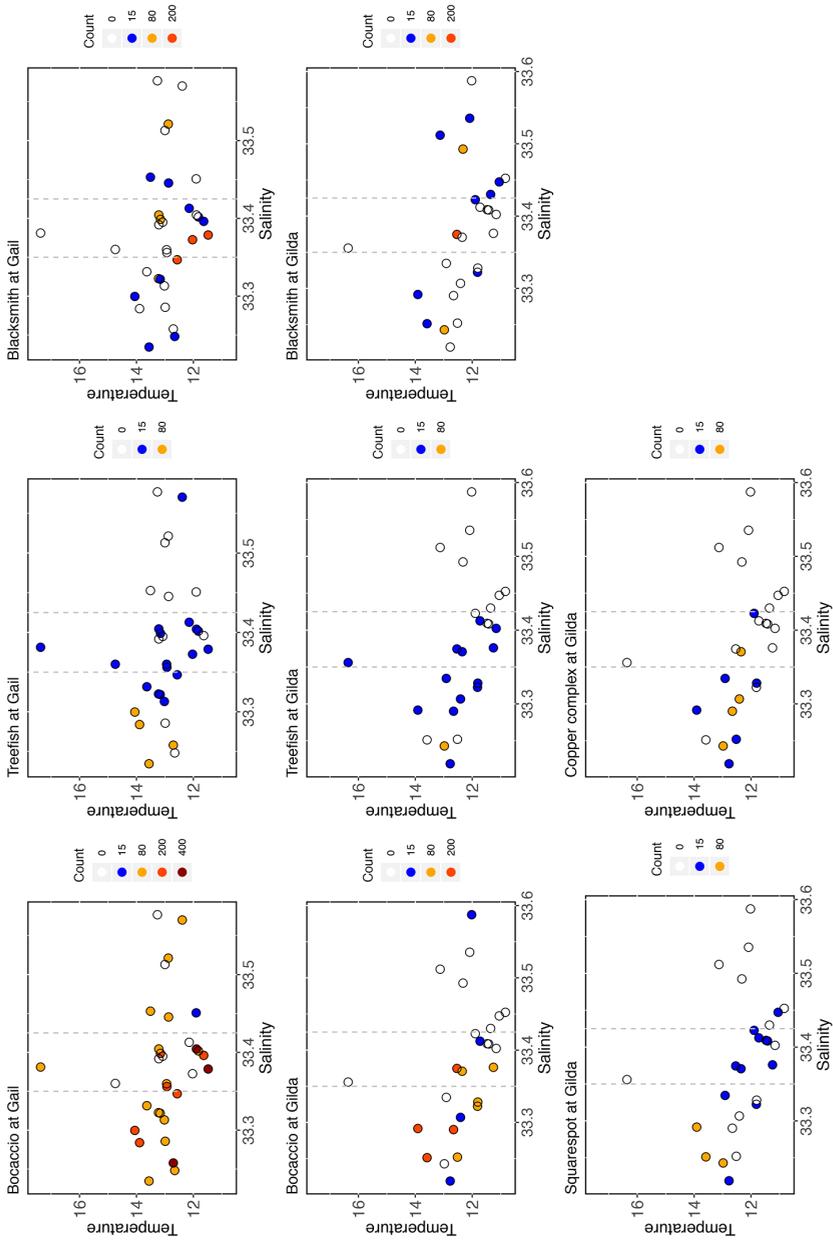


Figure 8. Number of recruits per survey in relation to water mass signatures at Platforms Gilda and Gail. The number of recruits are color coded to the scale indicated. The water mass signature is the mean temperature-salinity (TS) from 24 hrs preceding each survey at a platform. These signatures also are plotted in Figure 5 in relation to TS plots from the six California Cooperative Oceanic Fisheries Investigations reference regions mapped in Figure 1B.

Table 2. Pearson's product-moment correlation, r , between the number of recruits observed and salinity or temperature at platforms Gail ($df = 30$) and Gilda ($df = 24$). * indicates statistical significance at a Bonferroni adjusted alpha level of 0.0031 per test (0.05/16).

Species	Platform Gail			Platform Gilda		
	r	t	P	r	t	P
Salinity						
Bocaccio	-0.238	-1.344	0.189	-0.393	-2.092	0.047
Treefish	-0.530	-3.425	0.002*	-0.535	-3.099	0.005
Blacksmith	-0.060	-0.331	0.743	0.011	0.052	0.959
Copper rockfish complex				-0.283	-1.444	0.162
Squarespot rockfish				-0.484	-2.712	0.012
Temperature						
Bocaccio	-0.266	-1.509	0.142	0.259	1.311	0.202
Treefish	0.360	2.115	0.043	0.442	2.412	0.024
Blacksmith	-0.326	-1.890	0.068	0.002	0.008	0.994
Copper rockfish complex				0.112	0.554	0.585
Squarespot rockfish				0.274	1.398	0.175

(Bray et al. 1999). The core of the poleward flow shoals through the late summer from about 100 m in July to the surface in early October. The low salinity water mass that delivered recruits to the platforms from the bight may have been associated with this phenomenon since the timing and flow direction are consistent. Our results concur with findings from a larval tracking simulation from offshore platforms in an ocean circulation model by Nishimoto et al. (2019). They demonstrated that, from spring to summer, the potential for larval subsidies from the bight to the channel increases.

Some level of larval import from outside an area may be required to sustain local populations, and the importance of these remote subsidies vs local recruitment is expected to vary among biophysical systems (Sponaugle et al. 2002, Carr and Syms 2006). Shanks (2009) showed that dispersal distance typically increases with pelagic larval duration (PLD); coastal species with relatively long PLD (e.g., ≥ 30 d) are expected to disperse on the scale of 100 km unless the eggs and larvae are able to stay at or near the bottom to avoid offshore advection. We note that the PLD of rockfishes ranges from 3 to 6 mo (Love et al. 2002) and of blacksmith for about 1 mo (Wellington and Victor 1989). Long-distance dispersers are more likely to subsidize remote sources than species with PLD on the order of several days. Cowen et al. (2006) cautioned that dispersal distance can be substantially reduced by retention and they used an eddy-resolving biophysical model to show that typical larval dispersal distances were on scales of 10–100 km for a variety of reef fish species in the Caribbean Sea. We infer from our study that the scale of connectivity is at the upper end of this range for at least some rockfish species in the Santa Barbara Channel.

Various lines of evidence suggest that populations from the Southern California Bight provide greater contributions than from central California to some fish populations in the Santa Barbara Channel. Matala et al. (2004) found that bocaccio populations in the channel were genetically indistinguishable from coastal populations in the bight (Santa Monica Bay) and off northern Baja California. Furthermore, these three coastal populations south of Point Conception formed a group that genetically differed from populations north of Point Conception and from Tanner Bank, an offshore ridge south of the channel that is in the path of the

California Current. Oceanography may shape the genetic structure of the population; we found that water mass properties at the platforms during the recruitment period indicate that poleward currents carried bocaccio recruits to platforms Gilda and Gail in the channel from the Southern California Bight and offshore Southern California Bight regions. A question arises as to whether recruits carried by currents from either north of Point Conception or from the Santa Rosa Ridge region where Tanner Bank is located—and arrived early before the nominal start of the recruitment period as our findings indicate—provide a significant genetic contribution to the population in the channel (Figs. 1B, 5, 8).

The genetic structure of some species of *Pteropodus*, a subgenus of *Sebastes* that typically resides in shallower areas than adult bocaccio and includes the copper rockfish complex (Li et al. 2006), also are consistent with the division of central and southern California oceanographic regimes (e.g., grass rockfish, Buonaccorsi et al. 2004; brown rockfish, Buonaccorsi et al. 2005). We found that large pulses of copper rockfish complex and treefish, another nearshore reef species, occurred at the platforms when water mass characteristics at the platform were that of the inshore Southern California Bight region and not that of the region far offshore in the bight (Figs. 1B, 5, 8). In addition to the seasonal prevailing coastal poleward flow during the recruitment season, oceanographic barriers to exchange or differential sources of mortality between inshore and offshore waters could contribute to large-scale genetic structure.

The delivery of young fishes from coastal areas north of Point Conception into the channel may be restricted by persistent upwelling at the headland that may function as a hydrographic barrier to dispersal along the coast. The mean current along the California coast is equatorward during spring and early summer when larvae and juveniles are in the pelagic environment. However, upwelling at Point Conception would advect larvae from central California offshore (Winant et al. 2003, Dever 2004). Real and simulated surface drifter trajectories starting off Point Conception indicate that transport in offshore waters is southward with wind-induced upwelling and advection into the channel unlikely (Emery et al. 2006). Pelagic stages of nearshore demersal invertebrates and fishes, including larval and juvenile rockfishes, are rare in newly upwelled water (Wing et al. 1998, Nishimoto 2000).

Studies from coral reef systems indicate that larval retention can affect local population abundance (e.g., Swearer et al. 1999, Jones et al. 2005). We cannot eliminate the possibility that larval sources from the channel contributed to recruitment because the fish species in our study have a long planktonic period, and we could not reconstruct transport pathways from natal origin to juvenile settlement habitat. However, our results indicate that most juvenile rockfish recruits were transported into the channel by currents from the bight. Previous circulation studies suggest short retention times within the channel compared with the pelagic larval and juvenile duration of rockfishes and blacksmith (*but see* Simons et al. 2015), demonstrating retention within a persistent eddy circulation in the channel. In general, the residence time for drifters in the channel was on the order of 1–3 wk; however, a third of the drifters released ran aground on the channel mainland or islands (Dever et al. 1998, Winant et al. 1999). During the spring and early summer, the drifters exited the channel through the passes separating the islands. If larvae are dispersed (*but see* Fisher 2005, Leis et al. 2006) by the typical mean current speeds observed in the channel of 0.2 m s^{-1} (Dever et al. 1998, Winant et al. 2003), then

they would move 100 km in 12 d, a scale comparable to the length of the channel. Therefore, some combination of behavioral and physical mechanisms would have to operate throughout the pelagic phase to retain the recruits or return them to the channel.

Eddies occur year-round throughout the Southern California Bight and in the Santa Barbara Channel (DiGiacomo and Holt 2001, Dong et al. 2009), and complex interactions of eddies, filaments, and fronts in the eddy field may be important in the connectivity scheme linking local and remote populations. More early-stage larvae have been found within eddies than outside eddies in the bight (Taylor et al. 2004). In the Santa Barbara Channel, higher densities of pelagic juvenile rockfishes were observed in a persistent cyclonic eddy than in surrounding waters. Simons et al. (2015) demonstrated that this eddy accumulated and retained passive particles simulating fish larvae and other plankton; the pelagic juvenile fishes could either have developed in the eddy or been attracted to concentrated prey in the feature. Harrison et al. (2013) demonstrated that eddies coalesce forming filaments that bring together and concentrate larvae into discrete packets, potentially of many ages and source regions. Our observation of a broad size range in each settlement event is consistent with their model.

In the present study, settlement was synchronous between the two platforms separated by 7 km, and the rate of settlement typically increased and then decreased over two or three surveys. When a particular water mass current was at a platform, the number of recruits arriving to the platform was highly variable; for example, from 0 to 400 individuals (Fig. 8). Based on recruitment pulses persisting 1–6 d and the transport of recruits in a current speed of 0.1 m s^{-1} (8 km d^{-1}), we estimate that the patch size of pelagic juveniles is roughly 8–48 km. DiGiacomo and Holt (2001) observed that all eddy diameters in the Southern California Bight were $<50 \text{ km}$ and 50% ranged from 5 to 20 km. The synchrony in settlement pulses at the two platforms separated by 7 km may reflect the scale of patch size of the presettlers, possibly a remnant effect of eddy retention during the pelagic early life history of the recruits.

Shanks and Eckert (2005) hypothesized that coastal fish species have evolved a long planktonic period in combination with other life history traits, particularly the timing of spawning or the release of larvae, to exploit the spatial and temporal variability of the oceanographic setting and improve the odds of offspring returning to settle, “not necessarily near their parents, but in the parental population.” An important consideration is the spatial scale of the parental population in question. We argue that the scale of the parental populations of the recruits observed in this study extend beyond the Santa Barbara Channel. Our study provides empirical evidence that ocean circulation directly influences recruitment: an advecting water mass from the Southern California Bight supplied juvenile recruits to settlement habitat in the eastern Santa Barbara Channel.

Synchrony in the interannual variation of abundance among multiple species has been observed during both the pelagic phase in offshore waters and during recruitment to nearshore reefs in central California. Ralston et al. (2013) showed that interannual fluctuations in the prerecruit indices of 10 rockfish species are strongly coherent across a time series of 28 yrs. These findings are consistent with Laidig et al. (2007), who described interannual covariation in the summer settlement of three rockfish species in central California kelp forest habitats. Ralston et al. (2013) were able to detect differences in the spatial distribution of northern vs southern species

within the survey region offshore central California due to variation in the geographic distribution of spawning adults and the timing of spawning. Both Ralston et al. (2013) and Laidig et al. (2007) associated poleward and equatorward flow anomalies with recruitment variability. Although our surveys were conducted within a single season and in a small geographic area in the Santa Barbara Channel, our results similarly show temporal synchrony of settlement events at two platforms and differences in abundance related to water mass currents from the inshore and offshore regions of the Southern California Bight (inferred remote sources of larvae) during the recruitment period.

We surmise that remote sources subsidized local fish populations in the eastern Santa Barbara Channel given the broad spatial scale of ocean currents over the course of the weeks to months long pelagic early life history of the species we observed. However, we do not discount the potential for recruitment from local sources. Larvae originating from adult populations residing in the Santa Barbara Channel, including natural reefs and platforms, might be retained within the channel throughout the pelagic phase preceding recruitment or have a circuitous route offshore and back again. The degree to which local and remote sources contribute to a spatially defined population of interest has been elucidated in previous studies from the reconstruction of transport pathways from natal origin to juvenile settlement habitat coupled with the analysis of genetic structure or chemical-based signatures from otoliths for example (Kool et al. 2013).

In the interest of California public policy decision making, the connectivity of offshore oil platforms to distant sources of recruits, that then utilize the structures as a nursery or resident habitat, could be considered an “environmental benefit” of platforms. The State of California is mandated to evaluate the environmental benefits provided by platforms, all 27 located in southern California, to determine whether any, on a case-by-case basis when decommissioned, will be removed or partially left in place as part of a “Rigs-to-Reefs” program (California Marine Resources Legacy Act 2010). Some species that recruit to a platform remain at the structure as mature adults if the platform has enough complex structure at midwater depths or its base for shelter (e.g., gap between a horizontal crossmember and the substrate) and is located within the preferred depth range (Love and York 2006, Lowe et al. 2009, 2019b, Martin and Lowe 2010). For example, Love et al. (2006) tracked the growth of a dominant year class of bocaccio across 5 yrs from the juvenile stage to mature adults residing at Platform Gail. Aspects of population dynamics of resident fishes at platforms might be similar to that of coral reef systems dominated by species that recruit to spatially distinct habitat where they take up permanent residence (e.g., Swearer et al. 1999, Jones et al. 2005). In contrast, individuals that recruit to platform structures may eventually leave the platform as older juveniles or subadults; some may move into deeper, preferred habitat (Hartmann 1987, Love et al. 2003). Studies such as Love et al. (2006) can estimate the contribution of this “spillover” of fishes that utilize the platform as nursery habitat and then make their ontogenetic migration to populations at near and distant demersal habitats.

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