VERTICAL AND HORIZONTAL DISTRIBUTION OF JUVENILE PACIFIC WHITING (*MERLUCCIUS PRODUCTUS*) IN RELATION TO HYDROGRAPHY OFF CALIFORNIA

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ABSTRACT

The vertical and horizontal distributional patterns of young-of-the-year juvenile Pacific whiting, *Merluccius productus*, collected during midwater trawl surveys off California from mid-May through mid-June 1986–95 were examined. Comparison of 1992 MOCNESS tows and depth-stratified midwater trawls indicated that although larvae were most abundant below the mixed layer, juveniles were most abundant in the upper mixed layer. Abundance estimates from the midwater trawl surveys varied from year to year. Large numbers were consistently observed in the Monterey Bay area. The least-squared mean catch per year from a sampling stratum offshore of Monterey Bay was significantly correlated with recruitment to the commercial fishery two years later, suggesting that midwater trawl surveys could provide useful fishery-independent forecasts of year-class strength. Information collected with CTD recorders in 1987–95 indicated that juveniles were significantly less abundant in upwelled water than in non-upwelled water. This could be attributed to advection away from upwelling fronts, a behavioral response to avoid upwelled water, or a general offshore distributional pattern, irrespective of upwelling events. Plots of juvenile abundances and density (σ_t) contours showed substantial catches nearshore during periods of upwelling relaxation, whereas nearshore abundances were greatly reduced during strong upwelling events.

INTRODUCTION

The Pacific whiting[1], *Merluccius productus*, is an abundant, semipelagic species comprising four distinct stocks: Strait of Georgia, Puget Sound, southern Baja California, and coastal (Utter and Hodgins 1971; Vrooman and Paloma 1977; Stauffer 1985; Dorn 1996). The coastal stock is by far the most abundant and most important commercially within the California Current system, with an annual average of 191,925 tons landed off the west coast of the United States and Canada from 1966 through 1995 (Dorn 1996).

Adults migrate south from their summer feeding grounds off the Pacific Northwest to spawn off the coast of California and northern Baja California beginning in autumn (Bailey et al. 1982; Stauffer 1985). The northern and southern boundary of the spawning grounds can shift, depending on prevailing hydrographic conditions. In warmer years (often associated with El Niño events) the distribution shifts towards the north; in colder years it shifts south (Bailey et al. 1982; Dorn 1995). Most spawning occurs between January and March at depths of 130–500 m over the continental slope (Bailey et al. 1982).

Larvae hatch at a size of 2.4 mm notochord length (NL), and transform to the juvenile stage at approximately 30 mm standard length (SL; Matarese et al. 1989). Larval Pacific whiting (less than 30 mm SL) usually remain below the thermocline at depths of 60 m or greater (Ahlstrom 1959; Bailey 1982). However, larger larvae (longer than 12 mm SL) can be found near the surface (Bailey 1982), and early-stage juveniles (longer than 30 mm SL) are quite abundant in the surface layer at night (Lenarz et al. 1991).

Larval survival of Pacific whiting has been shown to be strongly correlated with recruitment success (Bailey and Francis 1985; Hollowed 1992). Bailey et al. (1986) indicated that young-of-the-year juvenile abundance estimated from midwater trawl surveys (Mais 1974) could also be useful in forecasting relative year-class success. Studies have shown that strong recruitment years are infrequent and that these strong year classes dominate the adult population for five to seven years (Bailey and Francis 1985; Francis and Hollowed 1985).

The prevailing hydrographic conditions during the first year of life have been shown to contribute to recruitment success (Bailey 1981; Bailey and Francis 1985; Hollowed 1992). Bailey and Francis (1985) observed that from 1960 to 1977, cold years with strong upwelling always led to poor recruitment of Pacific whiting, and that strong recruitment resulted only from spawning in warmer than average years (although not all warm years led to strong recruitment). Upwelling intensity has been shown to be a factor in the recruitment of other species, such as rockfishes (*Sebastes* spp.) and sanddabs (*Citharichthys* spp.; Ainley et al. 1993; Larson et al. 1994; Sakuma and Larson 1995).

Upwelling off the west coast of the United States is driven by northwesterly winds, which cause the offshore displacement of nearshore coastal waters of the upper

[1][Editors' note: The accepted common name for this species is now Pacific hake, but the name Pacific whiting is still widely used on the West Coast.]

mixed layer (generally 10–50 m, depending on location and time of year; Parrish et al. 1981; Husby and Nelson 1982). This displacement brings cold, nutrient-rich subsurface waters into the upper water column (Simpson 1987). Parrish et al. (1981) designated the region from Cape Blanco, Oregon, to Point Conception, California, as the region of maximal upwelling. This geographic region encompasses a large portion of the northern range occupied by young-of-the-year Pacific whiting (Dark et al. 1980; Bailey et al. 1982; Stauffer 1985).

The incidental collection of young-of-the-year juvenile Pacific whiting in midwater trawl surveys conducted during the upwelling season off central California by the National Marine Fisheries Service (NMFS), Tiburon Laboratory, (Wyllie Echeverria et al. 1990) provided an opportunity to examine spatial distributional patterns and their relation to prevailing hydrographic features such as upwelling fronts. It should be noted that the midwater trawl surveys were initially designed to sample juvenile rockfish, which have a more localized recruitment pattern than Pacific whiting. Therefore, only a small portion of the habitat occupied by the juvenile Pacific whiting population was sampled by these surveys. In this study we examined (1) the spatial and temporal abundance of juvenile Pacific whiting, (2) the vertical distribution of larvae and juveniles, (3) the effect of upwelling on juvenile abundance, and (4) horizontal distributional patterns in relation to specific hydrographic features.

METHODS

Data Collection

Juvenile Pacific whiting (longer than 30 mm SL) were collected aboard the National Oceanic and Atmospheric Administration (NOAA) research vessel *David Starr Jordan*, as part of the NMFS Tiburon Laboratory's annual midwater trawl surveys. A series of standard stations extending from Bodega Bay (38°20'N) to Cypress Point (36°35'N) were sampled at night with a 14 × 14-m modified Cobb trawl with a 12.7-mm stretched mesh codend liner (Wyllie Echeverria et al. 1990). These standard stations were grouped into seven distinct strata: Monterey outside (MO), Monterey inside (MI), shallow south (SS), deep south (DS), Gulf of the Farallones (GF), shallow north (SN), and deep north (DN; figure 1). Stratum designations were based on geographic location and bottom depth; each stratum contained at least five trawl stations.

Standard trawling depth was 30 m, except at nearshore shallow-water stations (bottom depths less than 60 m), where the standard trawling depth was 10 m. At four standard offshore sites (off Cypress Point, Davenport, Pescadero, and Point Reyes), a series of three depth-stratified trawls (depths = 10 m, 30 m, and 100 m) were conducted to examine vertical distributional patterns.

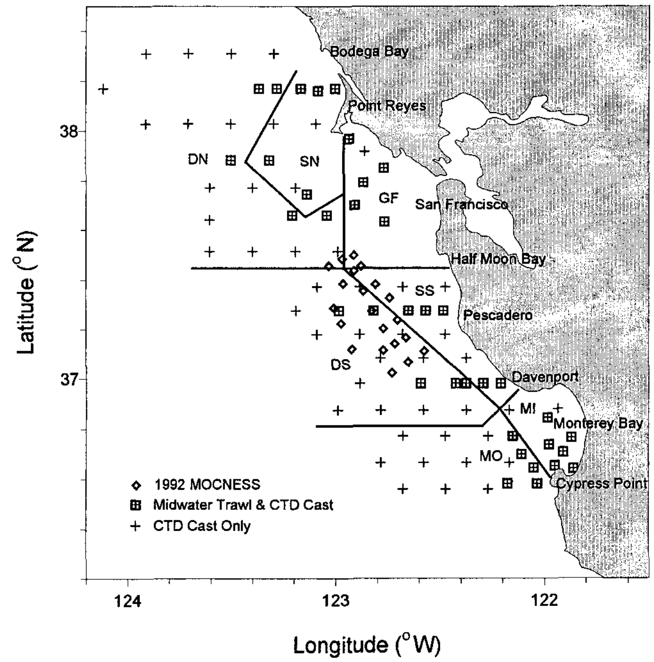

Figure 1. Map of the study area, showing locations of midwater trawl, MOCNESS, and CTD stations, and the strata boundaries (MO = Monterey outside, MI = Monterey inside, SS = shallow south, DS = deep south, GF = Gulf of the Farallones, SN = shallow north, and DN = deep north).

As time permitted, additional depth-stratified trawls were conducted at nonstandard stations. Trawling lasted 15 minutes at depth, and all trawls were completed between the hours of 2100 and 0600.

Stations were sampled from south to north during a 10-day sweep of the survey area. Three replicate sweeps were completed from mid-May through mid-June, 1986–95. Juvenile Pacific whiting were sorted and enumerated at sea.

Beginning in 1987, a conductivity, temperature, and depth (CTD) cast was made at each trawl station during each sweep to obtain temperature, salinity, and seawater density at depth. Additional CTD stations, interspersed between the trawl stations, were sampled during the day and repeated for each sweep. Beginning in 1991, the grid of daytime CTD stations was standardized and extended offshore (figure 1). Specifics of CTD deployment and data processing can be found in Sakuma et al. 1996.

To compare the vertical distribution of juvenile Pacific whiting from the depth-stratified trawls with that of early larvae (smaller than 12 mm SL), a 1.0-m^2 multiple opening/closing net and environmental sensing system (MOCNESS) with 0.505-mm mesh was deployed from the NOAA research vessel *David Starr Jordan* in 1992. Oblique tows were conducted around the clock at 21 stations bordering either side of the continental shelf break (approximately 200 m) between Half Moon Bay (37°30'N) and Davenport (37°00'N) from February 21 to 23. As dictated by bottom depth, up to seven nets were used to sample the following depth bins: 400–300 m, 300–200 m, 200–160 m, 160–120 m, 120–80 m, 80–40 m, and 40–0 m. Samples were preserved in 95% EtOH, and larval Pacific whiting were sorted and enumerated at the NMFS Tiburon Laboratory.

Data Analysis

Catches of juvenile Pacific whiting from the midwater trawl surveys were transformed by $\log_e$(number/trawl+1). Due to changes in the width of the net opening with depth fished, the catches from the depth-stratified trawls were first adjusted as described by Lenarz et al. (1991) and then $\log_e$-transformed. Catches of larval Pacific whiting from the MOCNESS were adjusted to the number/1,000 m^3 water filtered and were then transformed by $\log_e$(number/1,000 m^3 + 1) for comparison with the $\log_e$-transformed catches of juveniles from the midwater trawls. We analyzed only midwater trawl stations at which all three depths had been successfully sampled, and MOCNESS stations where oblique tows were conducted through all seven depth bins. In addition, because the midwater trawls were conducted at night, we analyzed only the nighttime MOCNESS tows for comparison. We applied a two-way ANOVA to both sets of data, using depth and location of each collection as class variables. Tukey's studentized range tests were performed to identify significant differences in the mean catches among the different depths sampled.

In order to examine interannual and geographic variability in the catch of juvenile Pacific whiting, we analyzed only data collected at standard stations. An ANOVA with year and stratum as class variables and a year-stratum interaction was then performed. To evaluate the potential of using midwater trawl abundance data in forecasting year-class strength, we subset the data to include only the stratum (or strata) yielding the largest catches of juvenile Pacific whiting. An ANOVA, with year and sweep as class variables and a year-sweep interaction term, was then performed. The least-squared means (Searle et al. 1980) from these analyses were compared against the recruitment of two-year-old fish, as presented in the most recent Pacific whiting stock assessment (Dorn 1996).

We used CTD data to identify midwater trawls conducted in areas of recent upwelling. Schwing et al. (1991) defined recently upwelled water off central California as having surface temperatures less than 10.5°C and surface salinities greater than 33.6 psu. The combination of low temperature and high salinity in upwelled water leads to high density (σ_t) values. Because the salinity data recorded by the CTD were sometimes erratic at the surface (Sakuma et al. 1996), temperature and salinity values at 30 m were used for this analysis. This also allowed for a more direct comparison of the CTD data with the catches of juvenile Pacific whiting collected at the standard trawl depth of 30 m.

Because of the increased depth of the hydrographic comparison, we defined upwelled water as less than or equal to 10.0°C in temperature and greater than 33.7 psu in salinity. A t-test was performed on $\log_e$-transformed abundances in upwelled and non-upwelled water from each individual year and from all years combined (1987–95) to determine if there was a relation between upwelling and juvenile Pacific whiting abundance.

In order to get a general view of the abundance patterns of juvenile Pacific whiting and their relation to hydrographic features, we overlaid catches of juveniles onto contours of seawater density (σ_t) at 30 m for each sweep of each survey year. Density contours were generated from CTD data, postprocessed through Surfer for Windows (1995) with Kriging as the interpolation algorithm. A more complete description of contouring is presented in Sakuma et al. 1996. For the sake of brevity, we will not present an in-depth analysis of each sweep of each year. However, representative plots from the two best recruitment years and one of the worst recruitment years were compared and contrasted.

RESULTS

The ANOVA results from the MOCNESS indicated a significant effect of net depth on larval abundance ($P = 0.0001$, $r^2 = 0.82$). Tukey's studentized range test indicated that larval Pacific whiting were significantly more abundant between 40–160 m than at the shallowest depth (40–0 m) and at the deeper depths (greater than 160 m; $\alpha = 0.05$, df = 24; figure 2).

There was also a significant depth effect on catch rate

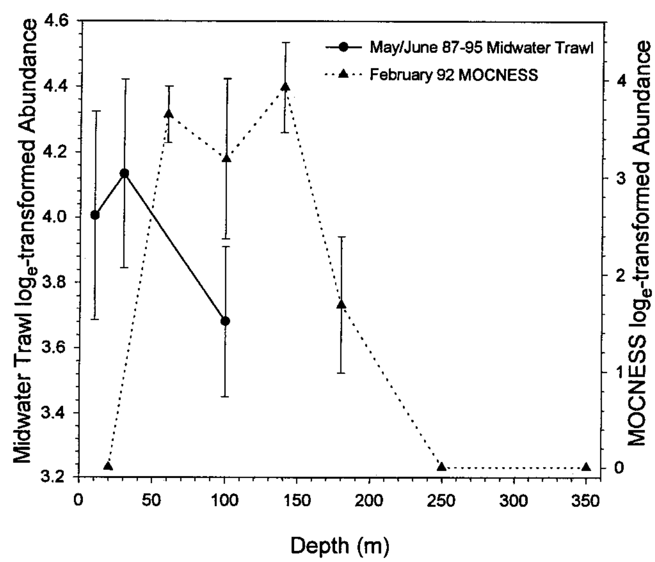

Figure 2. Vertical distribution of Pacific whiting, *Merluccius productus*, larvae (collected by MOCNESS in February 1992) and juveniles (collected by midwater trawl in May/June, 1987–95). Mean abundance at depth and the standard error of the mean are shown.

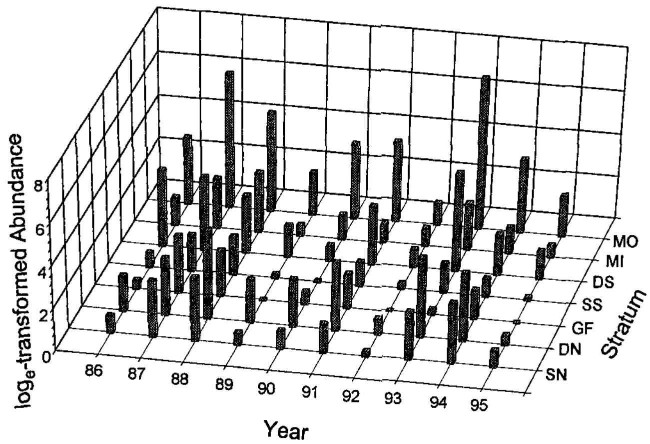

Figure 3. Annual least-squared mean abundance of juvenile Pacific whiting, *Merluccius productus*, collected in midwater trawls at various strata (MO = Monterey outside, MI = Monterey inside, DS = deep south, SS = shallow south, GF = Gulf of the Farallones, DN = deep north, and SN = shallow north), 1986–95.

of juvenile Pacific whiting in the depth-stratified midwater trawls ($P = 0.0427$, $r^2 = 0.86$). Tukey's studentized range test showed that mean catches of juveniles at 100 m were significantly lower than those at 30 m ($\alpha = 0.05$, df = 138; figure 2). These results suggested an ontogenetic vertical shift in distribution, with larvae mostly below the upper mixed layer (the 40–0-m MOCNESS depth bin), and juveniles mostly within the upper water column (figure 2).

Results from the ANOVA used to examine the interannual and geographic variability of juvenile Pacific whiting had an r^2 of 0.40 and showed significant year ($P = 0.0001$) and stratum ($P = 0.0001$) effects, as well as a significant year-stratum interaction ($P = 0.0001$). The least-squared means for year and stratum indicated that abundances were greatest in 1987, 1988, and 1993 and lowest in 1989, 1992, and 1995; the largest catches consistently came from the MO stratum (figure 3). Back-transformation of the least-squared means, with bias correction (Miller 1984), showed that catches within the MO stratum were nearly four times greater than in the stratum with the next highest abundance (figure 4).

Because the largest catches consistently came from the MO stratum (figure 4), an ANOVA using only catches within this stratum was subsequently done; it yielded an r^2 of 0.62 with a significant year effect ($P = 0.0001$) and year-sweep interaction ($P = 0.0003$). Although a comparison of the recruitment index of two-year-old fish presented by Dorn (1996) with the least-square means from the ANOVA using all strata resulted in a nonsignificant ($P = 0.0632$) correlation of 0.68 (figure 5), a comparison with results from the ANOVA using only the MO stratum yielded a significant ($P = 0.012$) correlation of 0.82 (figure 6).

A comparison of Pacific whiting abundance from samples taken in upwelling and non-upwelling areas indicated that juveniles were significantly less abundant in upwelling areas over all years (table 1). Analysis of individual years showed significantly reduced abundance in upwelling areas versus non-upwelling areas in 1988, 1989, and 1990, but no significant differences in abundance in

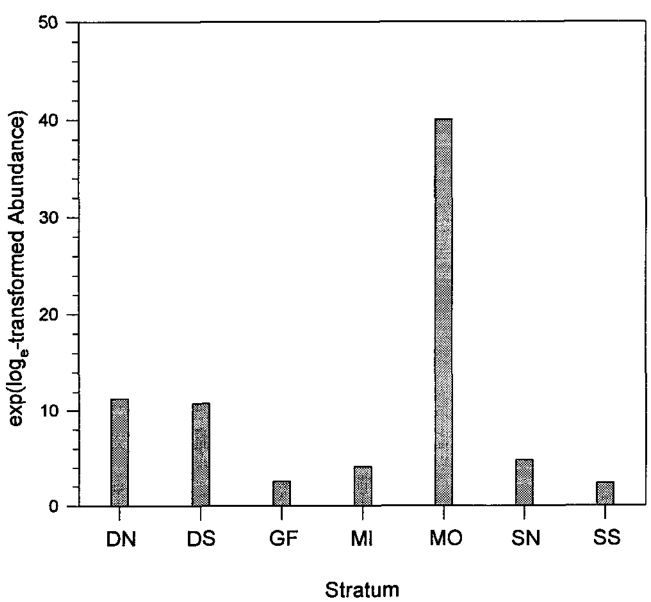

Figure 4. Back-transformed stratum least-squared mean abundance of juvenile Pacific whiting, *Merluccius productus*, over all years combined, 1986–95. Strata designations are: DN = deep north, DS = deep south, GF = Gulf of the Farallones, MI = Monterey inside, MO = Monterey outside, SN = shallow north, and SS = shallow south.

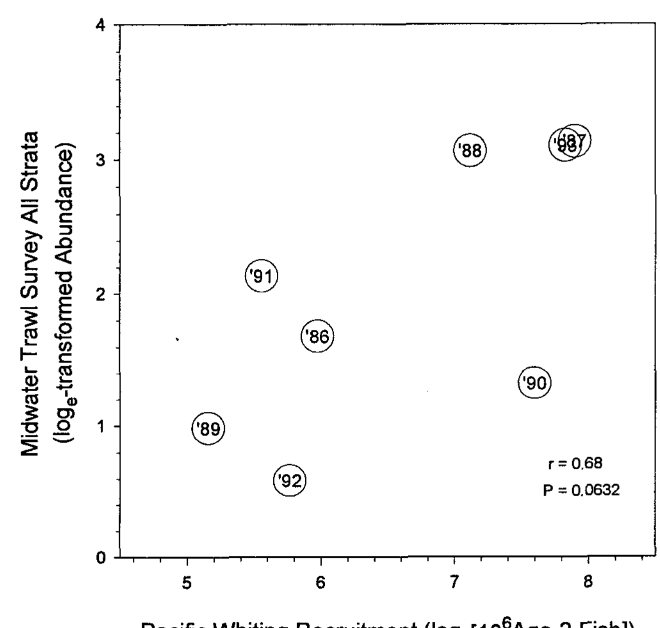

Figure 5. Comparison of the least-square mean abundance of juvenile Pacific whiting, *Merluccius productus*, collected from all strata, with the recruitment index of two-year-old fish presented by Dorn (1996).

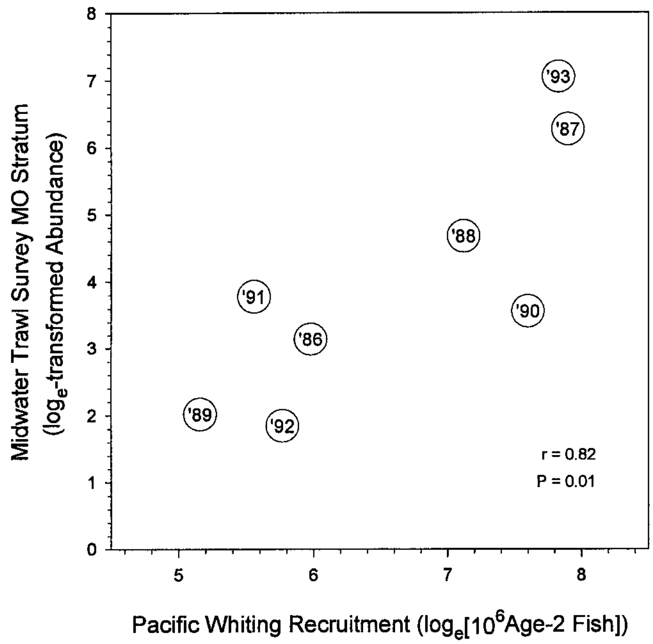

Figure 6. Comparison of the least-square mean abundance of juvenile Pacific whiting, *Merluccius productus*, collected from the Monterey outside (MO) stratum with the recruitment index of two-year-old fish presented by Dorn (1996).

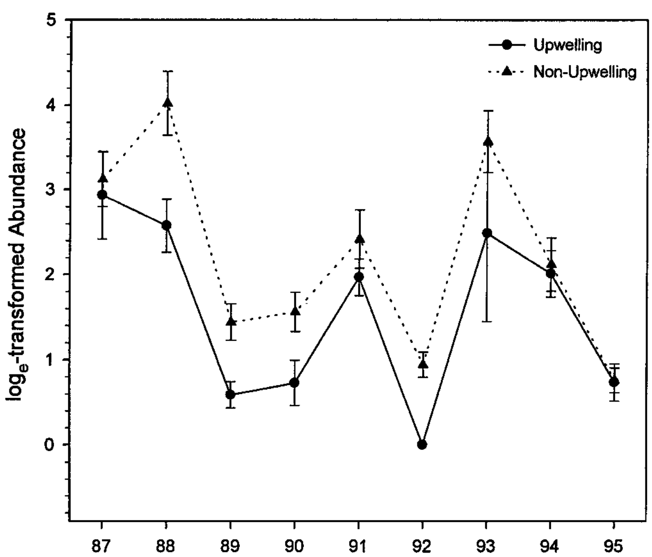

Figure 7. Comparison of juvenile Pacific whiting, *Merluccius productus*, abundance in upwelling areas versus non-upwelling areas. Upwelled water was defined as less than or equal to 10.0°C in temperature and greater than 33.7 psu in salinity at 30-m depth. The mean abundance and the standard error of the mean are shown.

1987, 1991, 1993, 1994, and 1995 (table 1 and figure 7). Because only one sample was taken in upwelled water in 1992, an accurate comparison of juvenile abundance in upwelling versus non-upwelling areas was not possible.

Horizontal spatial patterns of juvenile Pacific whiting abundance varied considerably among years and within

TABLE 1
Results of t-tests on Pacific Whiting (*Merluccius productus*) Log_e-transformed Abundances in Upwelled and Non-upwelled Water, 1987–95

Year	N1	N2	t	df	*P*
1987	26	71	−0.2921	95.0	0.7709
1988	71	40	−2.8507	109.0	0.0052
1989	56	47	−3.2284	101.0	0.0017
1990	23	78	−2.3423	58.1	0.0226
1991	73	31	−1.1029	102.0	0.2726
1992	1	93	−0.6643	92.0	0.5082
1993	10	74	−1.0105	82.0	0.3152
1994	57	31	−0.2272	86.0	0.8208
1995	37	55	−0.0656	90.0	0.9479
1987–95	354	520	−2.3770	803.9	0.0177

N1 = the number of samples collected in upwelled water; N2 = the number of samples collected in non-upwelled water. Upwelled water was defined as less than or equal to 10.0°C in temperature and greater than 33.7 psu in salinity at 30-m depth.

years and were, moreover, difficult to characterize. In general, juveniles tended to be distributed in the offshore sections of the sampling area. However, in the Monterey Bay area moderate to large numbers of Pacific whiting were consistently observed both nearshore and offshore. A more in-depth analysis was done on the plots of juvenile abundance and density from the two best recruitment years (1987 and 1993) and one of the worst recruitment years (1989).

During sweep 1 of 1987, following the general pattern observed in all other years, juvenile Pacific whiting were distributed offshore, except for the Monterey Bay area (figure 8). In the Monterey Bay area, where the highest catches occurred, juveniles were numerous both nearshore and offshore. Juveniles were not observed within the upwelling plume off Point Reyes in the northern portion of the sampling area. In sweep 2 of 1987, upwelling intensity off Point Reyes had decreased and juveniles were observed in increased numbers in the northern trawl stations (figure 8). In addition, there appeared to be an onshore encroachment of the frontal zone between offshore California Current water and nearshore coastal water, with large numbers of juvenile Pacific whiting near shore. Furthermore, the highest catches, which came from the Monterey Bay area in sweep 1, were made in the central region of the survey area in sweep 2, indicating a possible northward shift in distribution. In sweep 3 of 1987, conditions off Point Reyes remained relatively the same as in sweep 2, and juvenile abundance apparently continued to shift northward, with the largest catches in the northern trawl stations (figure 8). Although the center of abundance appeared to shift northward during sweeps 2 and 3, moderate numbers of juvenile Pacific whiting were still evident in the Monterey Bay area.

The distributional pattern of Pacific whiting juveniles

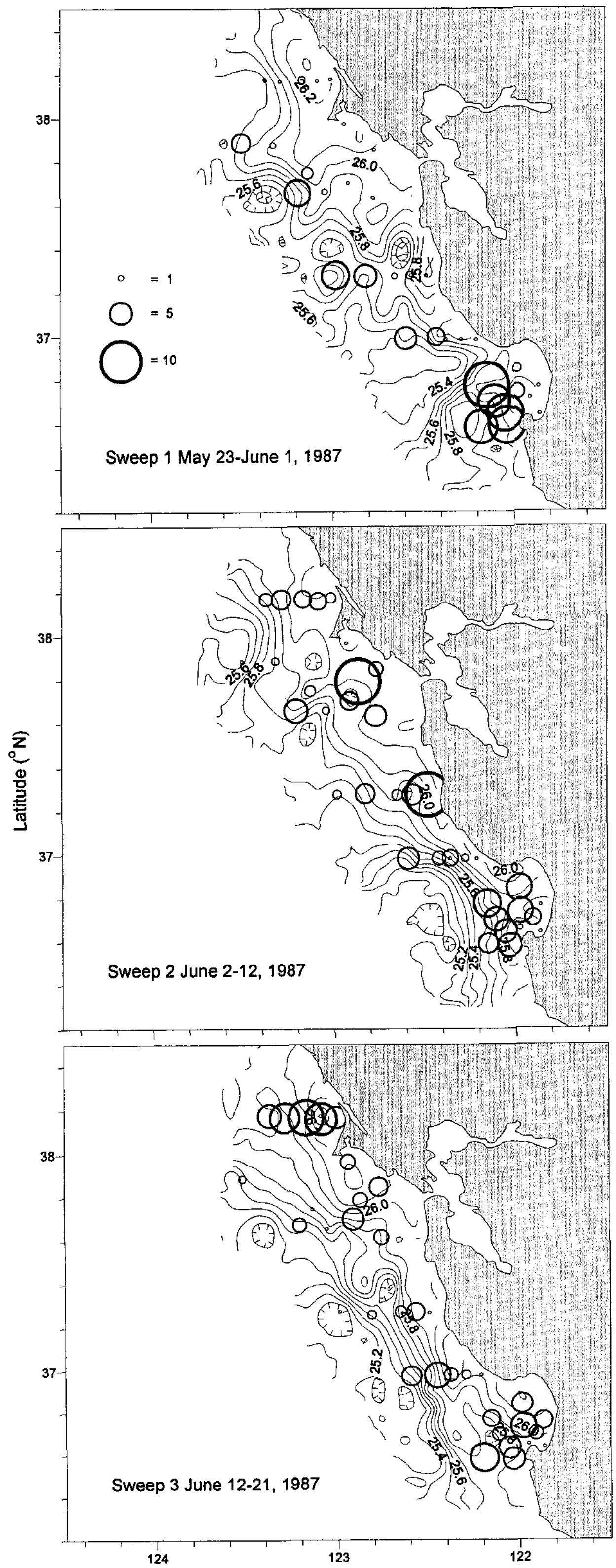

Figure 8. Juvenile Pacific whiting, *Merluccius productus*, abundance overlaid on contours of seawater density (σ_t) at 30 m from the 1987 midwater trawl survey. The size of the circle is proportional to the $\log_e$-transformed abundance. Hachured contour lines represent areas of lower-density water. Contour values greater than 26.0 kg/m^3 indicate upwelling.

in sweep 1 of 1989 appeared similar to that of sweep 1 of 1987, except that catches were much reduced (figure 9). A strong upwelling plume was evident off Point Reyes, and juveniles were distributed offshore. The highest catches came from the Monterey Bay area and off Point Reyes. The moderate numbers of Pacific whiting juveniles in the northern trawl stations were found on the offshore side of the Point Reyes upwelling plume. Upwelling conditions persisted through sweep 2, and juveniles were again distributed offshore, with the largest catches made in the Monterey Bay area (figure 9). During sweep 3 of 1989, upwelling was still evident off Point Reyes, but appeared to have weakened in intensity (figure 9). Juvenile Pacific whiting remained predominately offshore and were still most evident in the Monterey Bay area and off Point Reyes. Latitudinal changes in abundance patterns could not be resolved in 1989 because of the much reduced catch rates.

During sweep 1 of 1993, upwelling was not evident off Point Reyes, but a strong frontal density gradient was apparent (figure 10). While the largest catches of Pacific whiting juveniles were made in the Monterey Bay area, moderate numbers were also caught in the northern trawl stations within the frontal region and throughout the central region. Although there was no evidence of recent upwelling, juveniles still showed a more offshore distribution. Upwelling was again absent in sweep 2 of 1993, and a strong frontal gradient was again evident off Point Reyes, with moderate numbers of juveniles in the northern trawl stations (figure 10). An additional front was observed offshore of San Francisco, south to Davenport, and an onshore distribution of juveniles in the Pescadero region seems to have been associated with this feature. Once again, the greatest abundances occurred in the Monterey Bay area.

During sweep 3 of 1993, strong upwelling-favorable winds at the end of the sweep reduced sampling effort in the northern portion of the survey area, particularly off Point Reyes. Because of high winds, only three of the five trawl stations were sampled, and many of the CTD stations were canceled. Therefore, contours of seawater density in the area off Point Reyes for sweep 3 are incomplete (figure 10). In the three trawl stations off Point Reyes that we were able to sample, catches of juveniles were small relative to catches in this region during the first two sweeps (figure 10). Prior to the last two days, wind conditions during sweep 3 had been similar to those observed in sweep 2. Elevated catches in sweep 3 appeared to be associated with two frontal gradients, one off San Francisco and the other off Pescadero and Monterey Bay. The large catch of Pacific whiting juveniles offshore of Davenport was associated with an eddylike feature evident within the frontal gradient (figure 10).

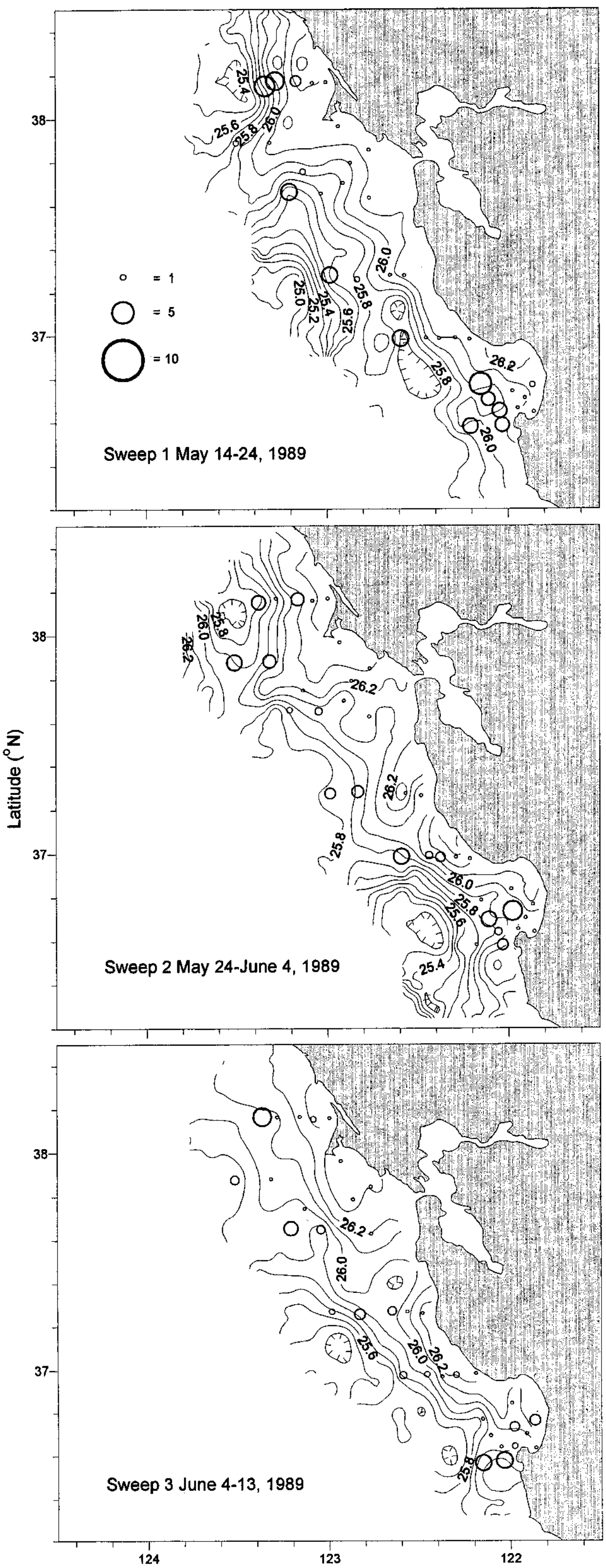

Figure 9. Juvenile Pacific whiting, *Merluccius productus*, abundance overlaid on contours of seawater density (σ_t) at 30 m from the 1989 midwater trawl survey. The size of the circle is proportional to the $\log_e$-transformed abundance. Hachured contour lines represent areas of lower-density water. Contour values greater than 26.0 kg/m^3 indicate upwelling.

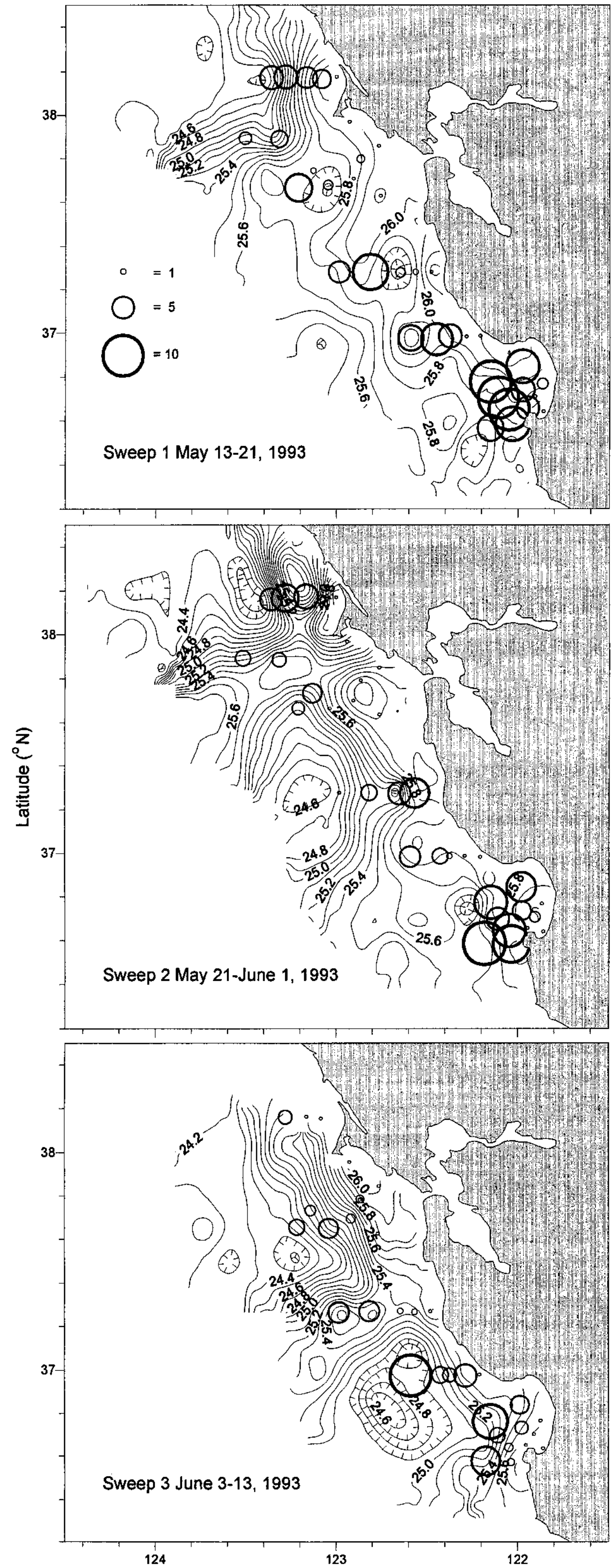

Figure 10. Juvenile Pacific whiting, *Merluccius productus*, abundance overlaid on contours of seawater density (σ_t) at 30 m from the 1993 midwater trawl survey. The size of the circle is proportional to the $\log_e$-transformed abundance. Hachured contour lines represent areas of lower-density water. Contour values greater than 26.0 kg/m^3 indicate upwelling.

DISCUSSION

Juvenile Pacific whiting were most abundant within the upper mixed layer; larvae were more abundant at depths presumably well below the mixed layer (figure 2). These results were consistent with the vertical distribution of larvae and juveniles reported by Ahlstrom (1959), Bailey (1982), and Lenarz et al. (1991). Such ontogenetic shifts in distribution are not uncommon and have been observed in other species, including shortbelly rockfish (*Sebastes jordani*; Lenarz et al. 1991), walleye pollock (*Theragra chalcogramma*; Sogard and Olla 1993), and Pacific and speckled sanddabs (*Citharichthys sordidus* and *C. stigmaeus*; Sakuma and Larson 1995). Although the relatively deep distribution of Pacific whiting larvae reduces the likelihood of offshore advection by upwelling (Smith 1995), the occurrence of juveniles within the upper water column would seem to leave them quite susceptible to such movements.

It should be noted that the vertical distribution of young-of-the-year juvenile Pacific whiting reported in this study resulted from collections made at night; daytime distributions could be quite different. Daytime midwater trawls conducted by the NMFS Tiburon Laboratory in May–June of 1988 at the same locations as the standard nighttime trawls yielded significantly lower catches of juvenile Pacific whiting (NMFS Tiburon Laboratory, unpublished data). Low catches during the day could have resulted from juveniles' ability to avoid the net, a more dispersed distribution, a deeper distribution than the standard trawl depth of 30 m, or a combination of these factors. Sogard and Olla (1996) observed that juvenile walleye pollock were more active and widely dispersed throughout the water column during the day, whereas at night they moved into the upper water column and became less active. Koeller et al. (1986) reported that young-of-the-year silver hake (*Merluccius bilinearis*) 20–30 mm long were distributed on the bottom during the day and migrated up into the water column at night.

Catch rates of juvenile Pacific whiting in the midwater trawl survey varied considerably among years, as well as between specific geographic regions (figure 3). The lack of a significant correlation between the year-effect from the ANOVA that incorporated all strata and the recruitment of two-year-old fish to the commercial fishery (Dorn 1996) was primarily due to the lack of correlation of the years 1988 and 1990 (figure 5). Dorn (1996) indicated that 1990 was a moderate year class, slightly better than that of 1988. In contrast, the midwater trawl surveys indicated that 1988 was one of the better years, whereas 1990 was relatively poor (figures 3 and 5). However, the midwater trawl survey data indicate that 1988 was a good year only because juvenile Pacific whiting were caught in moderate numbers in all strata (figure 3).

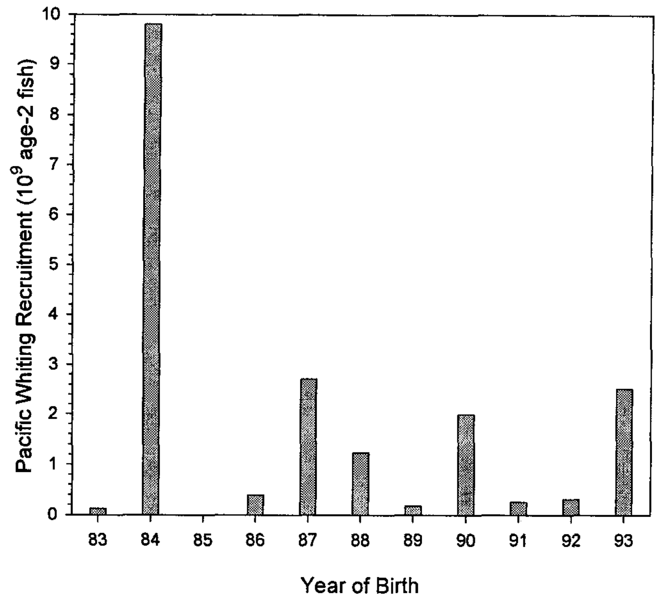

Figure 11. Recruitment index of two-year-old Pacific whiting, *Merluccius productus*, from 1983 through 1993, presented by Dorn (1996).

It could be argued that successful recruitment might depend on the survival of large localized aggregations of juveniles, rather than on the widespread occurrence of moderate-sized schools. A much better correlation with Dorn's (1996) results was produced by focusing on the MO stratum, where juvenile Pacific whiting persistently occurred (figure 6). This result, and the fact that strong recruitment years dominate the adult population for several years (Bailey and Francis 1985; Francis and Hollowed 1985), would seem to imply that the persistence of large schools of juveniles, as observed in the MO stratum, is important to year-class success.

It should be noted, however, that even the best year classes observed in this study do not compare on as great a scale as the dominant year class observed in 1984 (Dorn 1996; figure 11). Although the NMFS Tiburon Laboratory's midwater trawl surveys began in 1983, the current standardized set of stations was not incorporated until 1986 (Wyllie Echeverria 1990), and young-of-the-year juveniles were not routinely differentiated from adults until 1985. Therefore, a comparison of the 1984 midwater trawl data with Dorn's (1996) results is not possible. In addition, the midwater trawl survey focused on only a small portion of the juvenile Pacific whiting habitat. Latitudinal shifts in the spawning distribution, as reported by Bailey et al. (1982) and Dorn (1995), could greatly confound the estimation of year-class success in a study with limited geographic coverage.

Each year the largest catches of Pacific whiting juveniles came from the MO stratum (figure 3). This persistence could be caused by convergence due to localized hydrographic features (e.g., a mesoscale eddy);

a behavioral response to the abundance of predators or prey; or a combination of both factors.

Acoustic Doppler current profiler (ADCP) data showed evidence of an eddylike circulation pattern off Monterey Bay at 15–63 m during sweep 3 of 1994, at 95–111 m during sweep 2 of 1995, and at 15–63 m during sweep 3 of 1995 (Sakuma et al. 1995, 1996). Unfortunately, ADCP data prior to 1994 are unavailable, so an eddylike feature off Monterey Bay in other years cannot be verified. But the occurrence of a mesoscale eddy off Monterey Bay in both 1994 and 1995 (Sakuma et al. 1995, 1996) would seem to indicate that this might be a recurrent, predictable feature.

Mesoscale eddies might not necessarily entrain juvenile Pacific whiting, but may concentrate less mobile zooplankton and other food items within the Monterey Bay area. Huntley et al. (1995) observed enhanced zooplankton abundance associated with a mesoscale eddy located 185 km offshore of Monterey Bay in June 1993. Hayward and Mantyla (1990) observed increased primary production and phytoplankton biomass as a result of the combined effects of a coastal upwelling jet and a mesoscale eddy off Cape Mendocino in May 1987. The large numbers of juvenile Pacific whiting in the Monterey Bay area could result from an active response to increased prey availability, rather than from passive transport driven by hydrography. But passive transport due to prevailing currents probably has some effect on the distribution of juveniles, particularly smaller individuals, whose swimming abilities are less well developed.

Averaged over the years 1987–95, juvenile Pacific whiting were significantly less abundant in upwelled water than in non-upwelled water, although within any particular year, differences were not always evident (e.g., 1987, 1994, and 1995; table 1 and figure 7). Decreased abundance in upwelled water could result from the advection of juveniles away from upwelling fronts, a behavioral response to avoid upwelled water, or a general offshore distributional pattern that is independent of coastal upwelling events.

Juvenile Pacific whiting could migrate deeper into the water column and therefore appear to be absent in areas of recent upwelling. Changes in the vertical migration patterns of some species of larval and juvenile fish have been reported coincident with changes in the vertical thermal structure (Neilson and Perry 1990). But thermal stratification weakens during upwelling and would be more likely to cause juveniles to migrate into the upper water column rather than to constrain them to deeper depths.

The occurrence of moderate to large numbers of juveniles near the coast of Point Reyes during upwelling relaxation, and the absence of juveniles in this same region during periods of strong upwelling, as observed in 1987 and 1993, would suggest that these juveniles were subject to advection (figures 8, 10). Similarly, the offshore distribution of juvenile Pacific whiting in 1989 could have been due to advection as a result of the strong upwelling during that year (figure 9). Bailey et al. (1982) reported that the distance of Pacific whiting larvae offshore was positively correlated with upwelling indices. Offshore transport due to upwelling has been observed in small pelagic juvenile rockfish and in early pelagic metamorphic stages of sanddabs, although the same patterns were not evident in large pelagic juvenile rockfish and late pelagic metamorphic-stage sanddabs (Larson et al. 1994; Sakuma and Larson 1995). It is likely that Pacific whiting's susceptibility to offshore advection due to upwelling also depends on size or developmental stage.

In summary, we have shown that Pacific whiting appear to undergo a shift in vertical distribution, as evidenced by the absence of larvae in the upper mixed layer and the presence of large numbers of juveniles in this region (figure 2). These juveniles' presence in the upper water column may make them susceptible to advection by upwelling, as evidenced by their distribution offshore during upwelling episodes and nearshore during upwelling relaxation (figures 8–10). In the area off Monterey Bay juveniles are consistently observed in substantial numbers (figures 3, 8–10). This may be attributed to the episodic occurrence of a mesoscale eddy in this region, which might entrain juveniles or aggregate prey.

From this study, we conclude that data about juvenile abundance gathered from midwater trawl surveys could be a useful source of fishery-independent information for forecasting year-class strength.

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