

RECENT PRE-RECRUIT PACIFIC HAKE (*MERLUCCIUS PRODUCTUS*) OCCURRENCES IN THE NORTHERN CALIFORNIA CURRENT SUGGEST A NORTHWARD EXPANSION OF THEIR SPAWNING AREA

A. JASON PHILLIPS

Cooperative Institute for Marine Resources Studies
Oregon State University
2030 SE Marine Science Drive
Newport, Oregon 97365
Anthony.Phillips@noaa.gov

STEPHEN RALSTON

NOAA Fisheries
Southwest Fisheries Science Center
Fisheries Ecology Division
110 Shaffer Road
Santa Cruz, California 95060

RICHARD D. BRODEUR

NOAA Fisheries
Northwest Fisheries Science Center
Fisheries Ecology Division
2030 SE Marine Science Drive
Newport, Oregon 97365

TOBY D. AUTH

Cooperative Institute for Marine Resources Studies
Oregon State University
2030 SE Marine Science Drive
Newport, Oregon 97365

ROBERT L. EMMETT

NOAA Fisheries
Northwest Fisheries Science Center
Fisheries Ecology Division
2030 SE Marine Science Drive
Newport, Oregon 97365

CARRIE JOHNSON

Cooperative Institute for Marine Resources Studies
Oregon State University
2030 SE Marine Science Drive
Newport, Oregon 97365

VIDAR G. WESPESTAD

Pacific Whiting Conservation Cooperative
4039 21st Avenue West
Seattle, Washington 98199

ABSTRACT

Coastal Pacific hake (*Merluccius productus*) are known to spawn in the southern California Bight from January to March, migrate north during late spring and summer to feed off Oregon, Washington, and British Columbia, and then move back to southern California in the fall. Juvenile Pacific hake nursery areas have been found to occur along the coastal shelf and slope of California, and occasionally into southern Oregon during strong El Niño events. In this paper, we combine information from several studies that captured larval and high abundances of young-of-the-year (YOY) Pacific hake in the northern California Current from 2003–06. These preliminary results suggest that spawning and recruitment of Pacific hake have expanded northward and this will likely have major economic and ecological consequences in the northern California Current (NCC).

INTRODUCTION

There are at least three distinct stocks of Pacific hake (*Merluccius productus*) in the eastern Pacific Ocean: (1) coastal, (2) Puget Sound, and (3) Strait of Georgia (Bailey et al. 1982). The coastal stock ranges from southern California to British Columbia and is the largest of the three stocks. Pacific hake (also known commercially as Pacific whiting) is an important species that supports a major fishery off the west coast of the United States and Canada. The 2005 biomass was estimated to range between 2.5 and 4.0 million metric tons (mt), and since 2000 the annual catch in the non-tribal Pacific hake fishery has averaged about 160,000 mt per year (Helser et al. 2006). Ecologically, Pacific hake represent the largest fish bio-

mass in the northeastern Pacific Ocean (Agostini et al. 2006). It is generally accepted that Pacific hake spawn within the southern California Bight from January to March, migrate north to Oregon, Washington, and British Columbia during the summer to feed, and then move back to southern California in the fall (Bailey and Francis 1985; Ressler et al., in press).

Juvenile Pacific hake (i.e., >31 mm and sexually immature) nursery areas have been identified to be principally along the coastal shelf and slope of California (Bailey and Francis 1985). However, there have been occasional observations of eggs, larvae, and low abundances of YOY Pacific hake in the northern California Current (NCC) off Oregon and Washington prior to 2003. Typically the occurrence of larvae coincided with strong El Niños, such as the 1973, 1983–84, and 1998 events (Richardson et al. 1980; Percy and Schoener 1987; Doyle 1995; Dorn et al. 1999; Doyle et al. 2002). Although there have been occasional documented occurrences of YOY Pacific hake up to 40°N off northern California and off British Columbia (see Discussion), until recently there have not been significant occurrences of Pacific hake reported for Oregon and Washington waters despite intensive sampling of this region (e.g., Brodeur and Percy 1986; Brodeur et al. 2003; Ressler et al., in press).

The NCC is a highly dynamic system that exhibits extreme biological and environmental fluctuations on a variety of time scales (Brodeur et al. 2005). In this paper, we combine information from several studies that suggests that, in general, the distribution of YOY Pacific hake has expanded north in recent years in response to changing ocean conditions. Furthermore, the occur-

rence of larval and YOY Pacific hake in large numbers in the NCC implies that the Pacific hake spawning area may have expanded north. We also discuss the potential effects this northern geographic expansion may have on Pacific hake recruitment and other biological components of the NCC ecosystem.

METHODS

Larval Pacific hake collections

We used previously unpublished data on larval Pacific hake that were collected during three different research surveys in the NCC: (1) the NOAA Fisheries, Newport Hydrographic (NH) Line Biweekly Survey from 1996 to 2004, (2) the NOAA Fisheries, Northwest Fisheries Science Center (NWFS) Stock Assessment Improvement Program (SAIP) Larval/Juvenile Survey from 2004 to 2006, and (3) the Pacific Coast Ocean Observing System (PaCOOS) Survey from 2004 to 2006.

(1) NOAA Fisheries, NH Line Biweekly Survey

NH Line Biweekly Survey samples were collected with a variety of standard ichthyoplankton equipment. Gear ranged in size from 1 m diameter ring to 20 cm diameter bongo nets with 0.200–0.333 mm mesh nets. Samples were taken with vertical and oblique tows from a single transect at 44.65°N from 9–18 km offshore (see Hooff and Peterson 2006 for detailed methods).

(2) NOAA Fisheries, NWFS SAIP Larval/Juvenile Survey

SAIP Larval/Juvenile Survey samples were collected from spring to fall in 2004–06 at stations 5–85 km (typically 10–55 km) offshore ranging from 44.00° to 46.67°N (fig. 1). A 60 cm diameter bongo net with 0.332 mm mesh was fished obliquely from ~100 m depth to the surface (or within 5 m of the bottom at stations <100 m) primarily during the night.

(3) PaCOOS Survey

The PaCOOS Survey sampled the hydrographical and biological conditions of the central and northern California Current during May 2004, 2005, and 2006 at stations 3.5–121 km offshore ranging from approximately 39° to 47°N latitude (fig. 1). A 70 cm diameter bongo with 0.333 mm mesh and a 1 m² Tucker trawl with 0.335 mm mesh were fished obliquely from ~100 m depth to the surface (or within 5 m of the bottom at stations <100 m) during the day and night.

Ichthyoplankton samples collected during all surveys were preserved in a 10% buffered-formalin seawater solution at sea. Fish larvae were sorted under either a dissecting microscope or sorting tray in the lab, identified, enumerated, and measured to the nearest 0.1 mm notochord (NL) or standard (SL) length.

YOY Pacific hake collections

YOY Pacific hake were collected during four different research surveys conducted from May to November over multiple years: (1) the NOAA Fisheries, Southwest Fisheries Science Center (SWFSC) Juvenile Rockfish Survey, (2) the NOAA Fisheries, NWFS SAIP Larval/Juvenile Survey, (3) the NWFS and the Pacific Whiting Conservation Cooperative (PWCC) Survey, and (4) the NOAA Fisheries, Predator Survey. Sampling stations ranged from 4–157 km offshore and 32.72°–48.00°N (fig. 1). Samples were collected by mid-water (30–50 m depth stratum) or surface trawling at night with nets that had codend mesh liners from 3–10 mm. Tow durations were 15–30 min.

(1) NOAA Fisheries, SWFSC Juvenile Rockfish Survey

The NOAA Fisheries SWFSC has conducted a mid-water trawl survey along the central California coast (36.50°–38.33°N) every year since 1983 (1986–2006 data presented). The survey was designed to measure the annual relative abundance of pelagic juvenile rockfishes (*Sebastes* spp.), but also captured YOY Pacific hake (Sakuma et al. 2006). Standardized 15 min midwater trawls with the headrope set at a depth of 30 m were conducted at a series of standard stations with a 9.5 mm mesh liner. The survey was expanded substantially in 2004 to cover a much larger spatial area (i.e., from San Diego to Point Delgada: 32.75°–40.00° N) (fig. 1). During each cruise, the catch was sorted at sea and YOY Pacific hake enumerated. Beginning in 1994, SL (mm) measurements were taken from a subsample of the Pacific hake catch (Sakuma et al. 2006).

A three-way analysis of variance (ANOVA) model (without interaction) was fitted to the SWFSC midwater trawl survey data to summarize the overall spatial and temporal variation in YOY Pacific hake catch rates. The advantage of fitting a simple model to the data, as opposed to calculating individual cell means, is that fewer parameters are estimated (i.e., the main effects only) and missing data are treated in a balanced fashion. Specifically, the fitted ANOVA model was:

$$\log_e(N_{ijk\lambda} + 1) = Y_i + S_j + D_k + E_{ijk\lambda},$$

where $N_{ijk\lambda}$ is the number of YOY Pacific hake caught during a standard 15-minute haul (λ), Y_i is a year effect, S_j is a station effect, D_k is a calendar date effect, and $E_{ijk\lambda}$ is a normal error term. Main effects from the model were summarized as marginal means (Searle et al. 1980) and back-transformed to the arithmetic scale with bias correction (Miller 1984).

The Pacific hake length data collected as part of the midwater trawl survey were summarized by: (1) calculating the proportion of fish in 1 mm SL size intervals

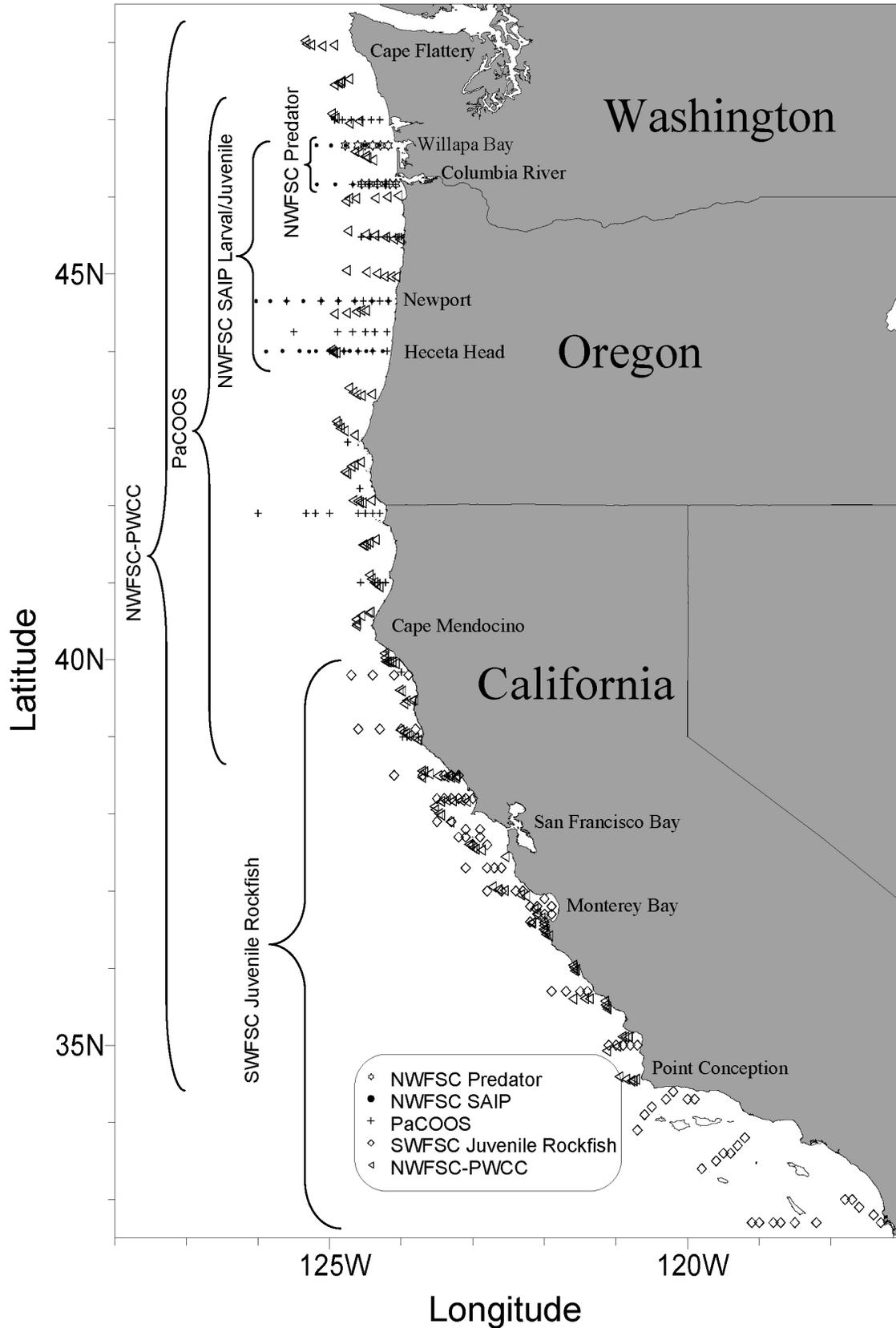


Figure 1. Location of the sampling efforts from the various fish studies along the west coast of the U.S. The NWFSC-PWCC Survey stations varied slightly from year to year. The stations presented are from 2006.

by year and haul, (2) multiplying the proportions by $N_{ijk\lambda}$, (3) summing over all hauls conducted in a year, and (4) expressing the results as annual relative length-frequency distributions.

To illustrate the interaction between year and sampling location on YOY Pacific hake catch rate (fish/trawl), the midwater trawl data were partitioned by year (y) and 1° latitudinal bins (l). The number of observations (n) in each partition was transformed (i.e., $\log_e [N_{yln} + 1]$) and the mean, standard deviation, and standard error calculated for each year-latitudinal combination. These values were then back-transformed with bias correction.

(2) NOAA Fisheries, NWFSC SAIP Larval/Juvenile Survey

In 2004, the NWFSC Fish Ecology Division initiated a study of the ecology of larvae and juvenile fish off central Oregon and Washington. Juvenile fishes were sampled with midwater trawls from summer to fall of 2004–06. Several stations were sampled along four transects off Heceta Head (44.00°N), Newport (44.65°N), the Columbia River (46.16°N), and Willapa Bay (46.67°N) (fig. 1). Stations started approximately 20 km offshore, extending out to about 100 km on each transect.

At each station, either a Nordic 264 rope trawl or a modified Cobb trawl was towed for 15–30 min with the headrope at a depth of 30 m. The Nordic 264 rope trawl had an effective fishing mouth of 12 m high and 28 m wide (336 m^2) using net mensuration equipment (Emmett et al. 2004; 2006), and a 6.1 m long, 3 mm mesh stretched knotless web liner sewn into the cod end. After removing all fish and invertebrates >10 cm in length, the catch was subsampled as follows: samples with a remaining volume of unsorted catch $\leq 0.25\text{ m}^3$ were collected in their entirety, while samples with a remaining volume of unsorted catch $>0.25\text{ m}^3$ were subsampled in the amount of 0.25 m^3 or 20% of the entire sample (whichever was larger). The retained unsorted catches were frozen at sea, and later thawed and sorted in the lab. All YOY Pacific hake were identified, enumerated, and at least 30 randomly chosen individuals were measured to the nearest 1 mm SL.

Midwater trawl methods during the first year of the SAIP project differed slightly from 2005 and 2006. Trawl duration was 30 min for all tows in 2004. For June, August, and September cruises in 2004, only the NH and Heceta Head transects were sampled, and they extended from 8–160 km offshore. A modified Cobb trawl was used in the 2004 July and August cruises, and a Nordic 264 rope trawl was used for all other cruises. The Cobb trawl had an effective fishing mouth area of $\sim 130\text{ m}^2$, which was $\sim 1/3$ that of the Nordic trawl.

Pacific hake densities were determined by multiplying the distance of the tow (as determined by a flowmeter) by the mouth opening of the net, and converting

that to number of Pacific hake $10^6/\text{m}^3$. During the first cruise of 2004 a flowmeter was unavailable, and length of the tow was determined from the vessel's global positioning system.

Pacific hake length-frequency histograms were created for each sampling period based on all individuals measured.

(3) NWFSC-PWCC Survey

The NWFSC-PWCC Survey started in 1999 as a cooperative study between (1) PWCC, (2) NOAA Fisheries, NWFSC Fishery Resource Analysis and Monitoring Division, and (3) NOAA Fisheries, SWFSC Juvenile Rockfish Survey. The NWFSC-PWCC Survey expanded the previously described SWFSC Juvenile Rockfish Survey to more outer shelf stations in order to target YOY Pacific hake. The NWFSC-PWCC Survey conducted in May–June covered an area from 34.50° to 44.50°N from 2001 to 2003, 34.50° to 46.50°N in 2004, and 34.50° to 48.00°N in 2005 and 2006 (fig. 1). A minimum of five stations were sampled across the continental shelf transects at 55.6 km (30 nm) intervals. Juvenile fishes were captured using a midwater trawl identical to that used in the SWFSC Juvenile Rockfish Survey, towed at a target headrope depth of 30 m for 15 min. Detailed methods are described in Sakuma et al. (2006).

To summarize catch distributions, YOY Pacific hake counts were binned into 1° latitude cells, standardized for each cell, and converted into a percentage to remove recruitment variability between years.

(4) NOAA Fisheries, NWFSC Predator Survey

This survey was conducted approximately every 10 days from mid-April through early-August 1998–2006. Twelve sampling stations were located 7–56 km offshore along two transect lines off Willapa Bay and just south of the Columbia River (fig. 1). From 1998 to 1999, surface trawls were 30 min in duration. However, starting in 2000, some hauls were shortened to 15 min because of very large catches of forage fish. A Nordic 264 rope trawl with an 8 mm mesh web liner was towed close to the surface to collect nekton samples. The volume of water fished was calculated as the distance the trawl traveled multiplied by the trawl area (336 m^2).

The first 30 Pacific hake of each class (YOY, subadult, and adult) captured in each haul were measured to SL or total length (TL) (mm). YOY Pacific hake that were measured in TL were converted to SL with the following equation generated from preserved samples:

$$SL = 1.0619 * TL + 2.0747; R^2 = 0.998.$$

To summarize length distributions, measured fish were binned into 10 mm groups. When variable size-classes

TABLE 1
 Abundances (number/10 m²), mean lengths (mm), and sampling station details where larval Pacific hake (*Merluccius productus*) were collected in the central and northern California Current from 1967–2006.

Data are separated between years by solid lines. For gear type, BON 60 = 60-cm diameter bongo net, BON 70 = 70-cm diameter bongo net, 1-m = 1-m diameter ring net, and TT = 1-m² mouth-opening Tucker trawl. The Richardson et al. (1980) abundance data represents the mean for all stations sampled in April 1973.

Cruise/Source	Gear	Date	Station	Station depth (m)	Dist. from shore (km)	Latitude (°N)	Longitude (°W)	Number	Abundance (number/10 m ²)	Mean length (mm)
Richardson et al. 1980	BON 70	Apr-73						1	0.3	
Doyle 1992	BON 60	27-Apr-83	G024A	500	60	47.00	125.00	1	7.9	8.5
Doyle 1992	BON 60	4-Apr-84	G118A	3250	94	40.00	125.72	32	213.4	3.5
Doyle 1992	BON 60	2-Apr-84	G104B	1250	57	41.33	124.92	2	13.6	6.1
Doyle 1992	BON 60	2-Apr-84	G105A	2280	53	41.00	124.90	2	12.2	3.1
NOAA NH line	1-m	21-Apr-98	NH10	79	18	44.65	124.30	2	1.6	7.3
NOAA NH line	1-m	12-May-98	NH05	55	9	44.65	124.18	1	0.8	10.5
PaCOOS	TT	06-May-04	PA02	100	14	39.00	123.83	5	13.6	3.9
PaCOOS	TT	06-May-04	KP02	105	4	40.10	124.21	3	9.5	3.3
PaCOOS	TT	05-May-04	FR02	95	7	38.48	123.35	3	8.7	19.9
PaCOOS	TT	06-May-04	PA04	638	27	39.00	123.98	1	5.7	14.1
PaCOOS	TT	08-May-04	CC04	481	33	41.90	124.60	1	2.1	30.0
PaCOOS	TT	08-May-04	CC03	137	24	41.90	124.50	1	2.0	26.0
PaCOOS	TT	09-May-04	NH65	2882	121	44.65	125.60	1	1.8	3.6
PaCOOS	TT	25-May-05	EU02	91	19	41.00	124.30	1	0.7	5.9
SAIP	BON 60	10-Jun-05	NH55	2889	102	44.65	125.36	1	4.0	3.7
PaCOOS	BON 70	09-May-06	NH65	2882	121	44.65	125.60	20	53.0	15.4
PaCOOS	TT	13-May-06	CC07	989	66	41.90	125.00	31	50.7	23.5
PaCOOS	BON 70	09-May-06	NH85	2904	157	44.65	126.05	7	20.5	12.7
PaCOOS	BON 70	09-May-06	CR40	854	75	46.16	124.92	5	16.6	25.8
PaCOOS	BON 70	10-May-06	NH25	300	47	44.65	124.65	3	8.1	22.7
PaCOOS	BON 70	11-May-06	HH04	112	53	44.00	124.80	1	3.5	15.3
PaCOOS	BON 70	11-May-06	HH05	920	69	44.00	125.00	1	3.3	21.0
PaCOOS	TT	10-May-06	NH35	477	66	44.65	124.88	1	2.2	15.4
PaCOOS	TT	10-May-06	NH25	300	47	44.65	124.65	1	2.2	19.8
SAIP	BON 60	16-May-06	WB40	910	71	46.67	124.98	1	2.1	12.4

of Pacific hake were captured, at least 30 of each size-class were measured.

RESULTS

Larval Pacific hake collections

A total of 91 Pacific hake larvae were collected in the three ichthyoplankton surveys conducted in the central and northern California Current region from 1996–2006: 1998 = 3, 2004 = 15, 2005 = 2, and 2006 = 71. Pacific hake larvae were only collected during spring (April–June). Larvae were collected between 39.00°N and 46.67°N. Larval abundances were generally higher offshore (>200 m depth) than nearshore (<200 m depth) (tab. 1), although too few larvae were collected to conduct statistical comparisons.

YOY abundances and distributions

(1) NOAA Fisheries, SWFSC Juvenile Rockfish Survey

Catch rates of YOY Pacific hake observed in the core area of the SWFSC Juvenile Rockfish Survey were

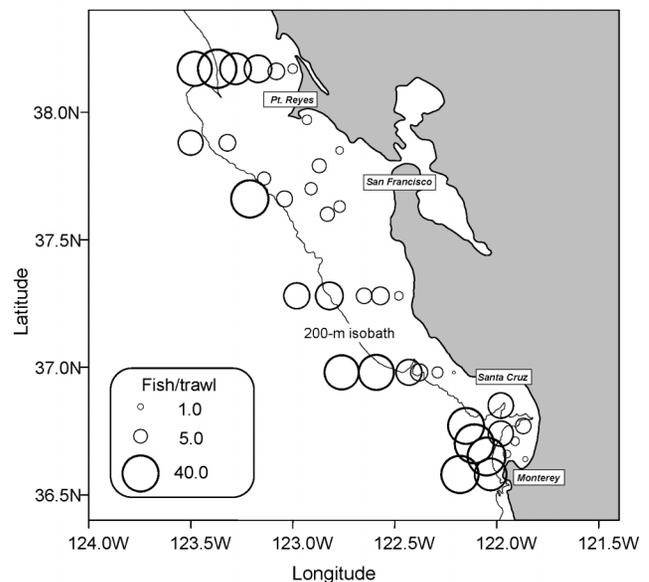


Figure 2. Average catch-per-unit-effort (CPUE; based on ANOVA) of YOY Pacific hake (*Merluccius productus*) by station of NOAA Fisheries, SWFSC Juvenile Rockfish Survey core (central California) stations, 1986–2006.

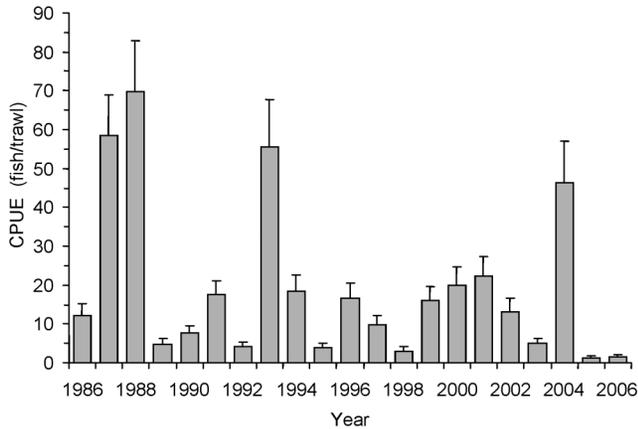


Figure 3. Average catch-per-unit-effort (CPUE; based on ANOVA) of YOY Pacific hake (*Merluccius productus*) by year of NOAA Fisheries, SWFSC Juvenile Rockfish Survey core (central California) stations, 1986–2006 (± 1 standard error).

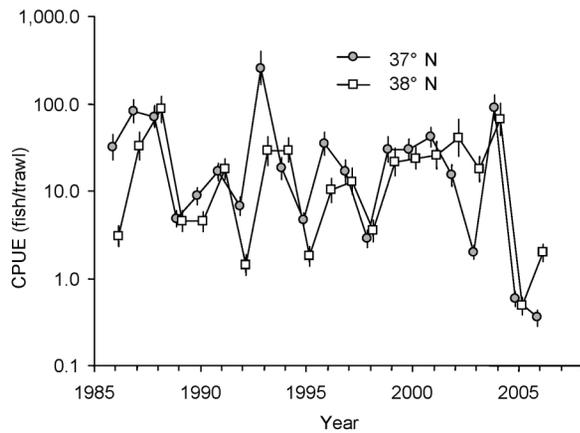


Figure 4. Average catch-per-unit-effort (CPUE; based on means of $\log_e [N + 1]$) of YOY Pacific hake (*Merluccius productus*) by year in 1° latitude bins of NOAA Fisheries, SWFSC Juvenile Rockfish Survey core (central California) stations, 1986–2006 (± 1 standard error).

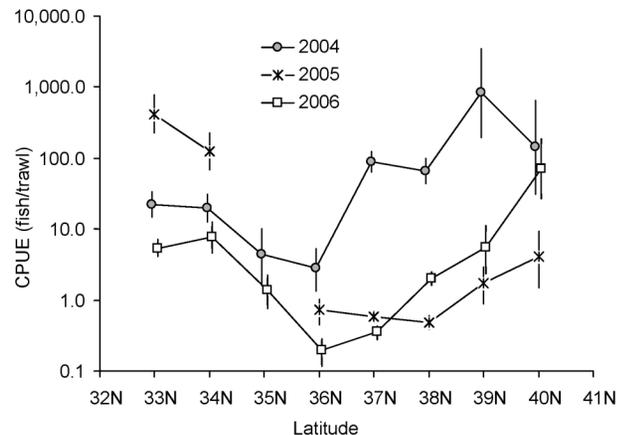


Figure 5. Average catch-per-unit-effort (CPUE; based on means of $\log_e [N + 1]$) of YOY Pacific (*Merluccius productus*) hake by 1° latitude bins from the NOAA Fisheries, SWFSC Juvenile Rockfish Survey expanded coverage area, 2004–06.

strongly affected by bottom depth as shown in the back-transformed station effects from the fitted ANOVA model (fig. 2). Note that catches from stations located at, and seaward of, the continental shelf break (200 m isobath) have historically been much higher than those from stations located on the shelf proper. In addition, elevated catches of YOY Pacific hake were taken regularly in the offshore waters of Monterey Bay.

Interannual catch rates of YOY Pacific hake in the core area of the survey varied markedly (fig. 3). Catch rates in excess of 40 YOY Pacific hake/trawl were observed in 1987, 1988, 1993, and 2004. Conversely, very low catch rates were encountered in many years, including the 1992 and 1998 El Niños, and especially during the 2005 and 2006 surveys (1.2 and 1.4 fish/trawl, respectively). These two most recent surveys produced the lowest YOY Pacific hake catch rates in the entire 21-year time series.

The interaction between year and sample location (i.e., 1° latitudinal bins) within the traditional core area of the SWFSC midwater trawl survey is shown in Figure 4. The figure shows general agreement between the time series of catch rates of YOY Pacific hake observed at 37°N and 38°N, with the exception of 1992–93, when catch rates at 37°N were somewhat higher than at 38°N, and in 2003 and 2006, when the opposite pattern was observed.

Results of the expanded SWFSC Juvenile Rockfish Survey illustrate the geographic extent of YOY Pacific hake catches during the last three years (fig. 5), when survey sampling was conducted from 33° to 40°N. There was large interannual variability in the distribution and abundance of YOY Pacific hake. Catches in the northern portion of the survey area (37°–40°N) in 2004 were >65 fish/trawl and, conversely, were <22 fish/trawl in the southern area. In 2005 however, the opposite pattern was observed, with catches >120 fish/trawl taken south of Point Conception (33°–34°N) and catches <5 fish/trawl taken at all stations to the north. During 2006, catches in the traditional core area of the survey were lower than either to the north or the south.

In addition to fluctuations in catch rate, there was substantial interannual variability in the size composition of YOY Pacific hake (fig. 6). Some years (e.g., 1995, 1998, and 2006) were characterized by an abundance of small fish (20–30 mm), whereas in other years (e.g., 1997, 2002, and 2003) fish were much larger (30–50 mm). Likewise, in some years (e.g., 1994) there was a substantial range in the size of fish caught, whereas in other years (e.g., 2006) the fish were much more uniform in size.

(2) NOAA Fisheries, NWFSC SAIP Larval/Juvenile Survey

The NWFSC SAIP Larval/Juvenile Survey captured a total of 14,429 YOY Pacific hake from 2004–06 from

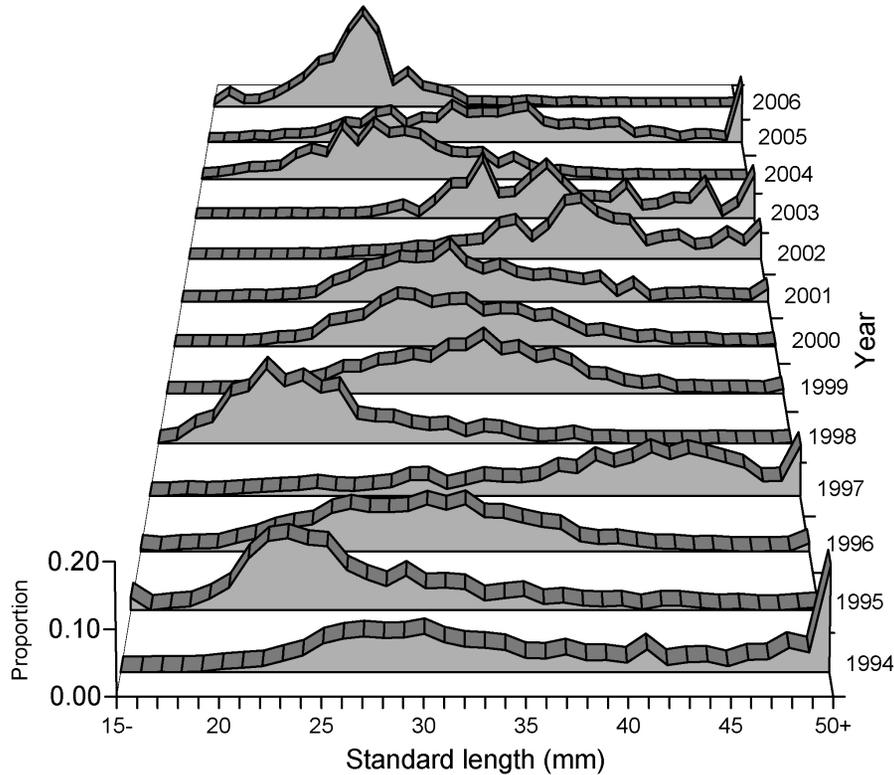


Figure 6. Annual length-frequency distributions of YOY Pacific hake (*Merluccius productus*) captured in the NOAA Fisheries, SWFSC Juvenile Rockfish Survey, 1994–2006.

TABLE 2
 Cruise summaries of NOAA Fisheries NWFSC, Stock Assessment Improvement Program (SAIP) YOY Pacific hake (*Merluccius productus*) captured off Oregon and Washington from 2004–2006. Data are separated between years by solid lines. n = number of tows, and n+ = number of tows that captured YOY hake. For gear types, MCT = modified Cobb Trawl, and NRT = Nordic 264 rope trawl.

Cruise	Trawl type	n	n+	No. caught	Abundance (number/10 ⁶ m ³)	No. measured	Mean SL (mm)	SL S.D. (mm)	±95% C.I. (mm)
Jun-04	MCT	5	3	5262	514.4	90	44.0	5.2	1.1
Aug-04	MCT	13	5	1912	110.9	103	54.7	8.3	1.6
Sep-04	NRT	15	0	0	–	–	–	–	–
Nov-04	NRT	20	0	0	–	–	–	–	–
Jun-05	NRT	21	5	55	2.1	51	42.1	8.6	2.4
Jul-05	NRT	15	4	183	16.6	36	63.2	10.7	3.6
Aug-05	NRT	11	1	1	0.2	1	27.0	–	–
Sep-05	NRT	20	1	2	0.4	2	76.5	–	–
Oct-05	NRT	14	2	2	0.2	2	57.5	–	–
May-06	NRT	4	3	40	3.0	38	24.4	2.3	0.7
Jun-06	NRT	7	6	1079	49.3	147	36.1	5.2	0.8
Aug-06	NRT	18	7	5720	207.7	143	61.4	8.0	1.3
Sep-06	NRT	20	5	173	8.9	101	80.4	9.5	1.9
All cruises		183	42	14429	94.7	714	52.4	17.5	1.3

central Oregon to southern Washington (tab. 2). YOY Pacific hake were captured in 42 of 183 tows with estimated density per tow ranging from 1091.0 fish 10⁶/m³ June 2004 to 0.1 fish 10⁶/m³ October 2005 (fig. 7). Density average per cruise ranged from 0.2 to 514.4 fish 10⁶/m³, and the average density for all tows

was 94.7 fish 10⁶/m³ (tab. 2). For all years, Pacific hake catches were higher nearshore as the season progressed. In 2004, the highest YOY Pacific hake density observed was 65 nm offshore. Although the greatest sampling coverage was in 2005, this year had the lowest densities of YOY Pacific hake (fig. 7).

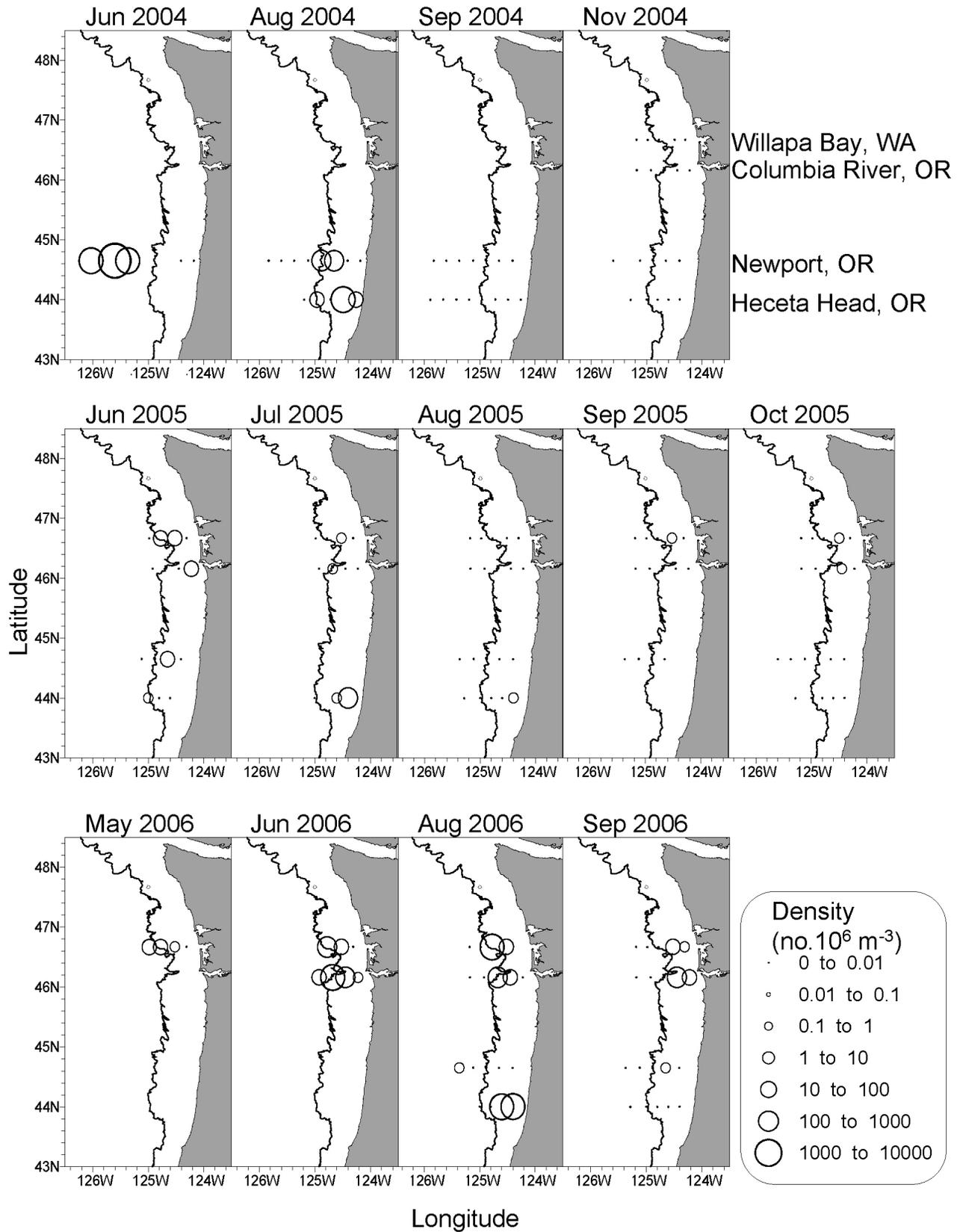


Figure 7. Densities (no. 10⁶/m³) of YOY Pacific hake (*Merluccius productus*) observed during the NOAA Fisheries, NWFS SAIP Larval/Juvenile Survey off Oregon and Washington by cruise. Solid dots indicate no catch and the size of the circles are proportional to the YOY Pacific hake densities, 2004–06.

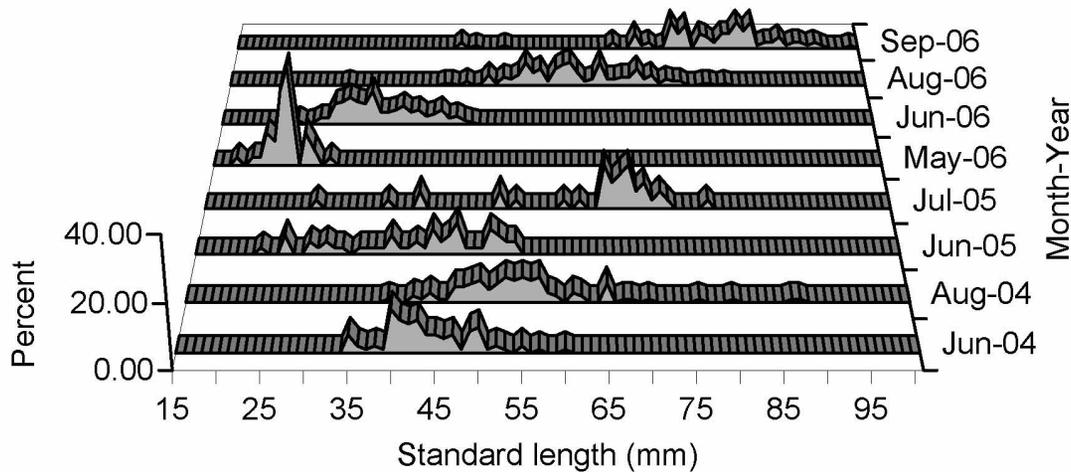


Figure 8. Monthly length-frequency distributions of YOY Pacific hake (*Merluccius productus*) captured in the NOAA Fisheries, NWFSC SAIP Larval/Juvenile Survey off Oregon and Washington, 2004–06.

The YOY Pacific hake captured during the NWFSC SAIP Larval/Juvenile Survey ranged in length from 18–100 mm with an average length of 52.4 mm (fig. 8 and tab. 2). All years showed cohorts of YOY Pacific hake growing throughout the season (fig. 8). In 2004, YOY Pacific hake were present, but sampling was limited to the southern two transects until November, and YOY Pacific hake were not encountered after August. In 2006, there was one dominant size mode and one smaller size mode. The dominant mode was encountered in all cruises, whereas the smaller size mode was represented by a single Pacific hake caught in August (102 km offshore) and four Pacific hake caught in September (46 km offshore) along the NH line, and these were likely spawned late in the season.

(3) NWFSC-PWCC Survey

Catches of YOY Pacific hake by latitude indicated a northward distributional shift from 2001 to 2006 (fig. 9). YOY Pacific hake were caught as far north as 48°N in 2005 and 2006, but prior to 2005, few YOY Pacific hake were captured north of 42°N. In 2005, the largest concentrations of YOY Pacific hake occurred between 45°N and 39°N (i.e., approximately central Oregon to Cape Mendocino, California). The distribution of YOY Pacific hake was similar in 2006, but with more of the fish located in the northern portion of this range. South of Cape Mendocino, YOY Pacific hake were taken in only a few hauls and in low numbers in 2005 and 2006.

(4) NOAA Fisheries, NWFSC Predator Survey

Length-frequency distributions from the NWFSC Predator Survey showed the presence of YOY Pacific hake off northern Oregon and southern Washington beginning in 2004 (fig. 10). A total of 12,039 YOY Pacific

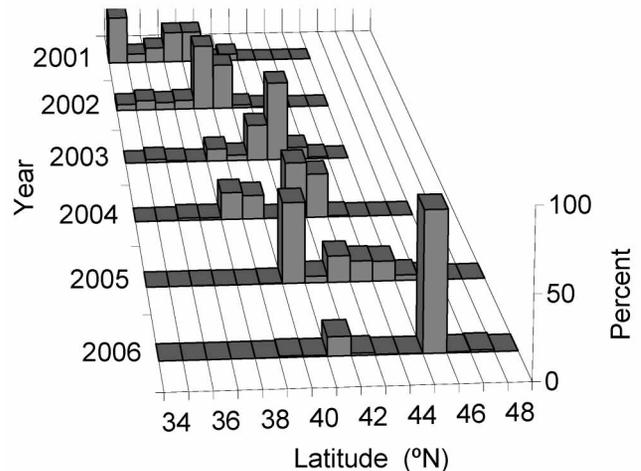


Figure 9. Distribution of YOY Pacific hake (*Merluccius productus*), represented as a percentage of annual catch by 1°-latitude bins, captured in the NWFSC-PWCC Survey, 2001–06. From 2001 to 2003 the survey covered an area from 34.50° to 44.50°N, in 2004 coverage was expanded to 46.50°N, and further expanded to 48.00°N in 2005.

hake (30–113 mm SL) were collected between 2004 and 2006. Adult Pacific hake (generally >300 mm) were collected during all years, and during both 1998 and 1999 some age-1 Pacific hake (140–160 mm) were captured, probably reflecting recruitment during the 1997–98 El Niño event. Age-1 Pacific hake were observed in 2005, but were nearly absent in 2006, indicating that Pacific hake spawned in 2005 may not have successfully recruited that year off Oregon and Washington.

DISCUSSION

Larval Pacific hake collections

Despite relatively intense sampling for fish larvae in the central and northern California Current from 1967

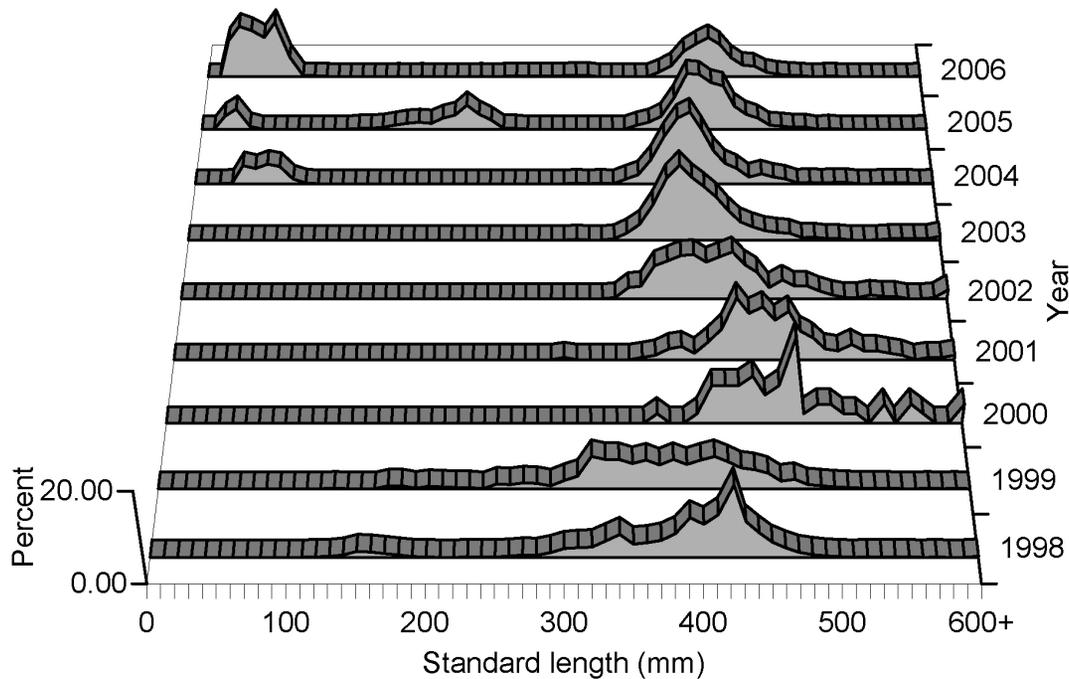


Figure 10. Annual length-frequency distributions of Pacific hake (*Merluccius productus*) captured in the NOAA Fisheries, NWFSC Predator Survey off Oregon and Washington, 1998–2006.

to 2006 (tab. 3; Auth and Brodeur 2006; Auth et al. 2007), Pacific hake larvae have only been collected during years having positive Multivariate El Niño Index (MEI) values (e.g., Doyle 1995). In the last four decades prior to 2004, only 38 larval hake were captured in over 2000 tows. Since 2004, larval Pacific hake were captured in 91 of approximately 300 tows off Oregon during weak El Niño periods, but when ocean conditions were anomalously warm (Peterson et al. 2006; Pierce et al. 2006). The biota was characterized by the presence of numerous southern or offshore fish and zooplankton species (Brodeur et al. 2006; Mackas et al. 2006). Despite not sampling in the correct place or at the appropriate time (deepwater, offshore, and in February and March), we have still captured more larvae since 2004 than had previously been encountered in the area. During 2004–06, larval Pacific hake were collected at increasingly northern locations, with the largest larval Pacific hake numbers ($n = 71$) recorded off the coast of Oregon in 2006. Larval Pacific hake were captured as far north as 45° N during the coast-wide sardine egg survey in 2006 (Lo 2007).

Pacific hake larvae of the size collected were not likely to have migrated from southern California spawning grounds, but likely spawned in northern waters. The mean lengths of larval hake captured during the PaCOOS and SAIP Larval/Juvenile Surveys in 2004–06 were 4.8 mm in 2004, 9.9 mm in 2005, and 20.92 mm in 2006. Using the growth curve from Butler and Nishimoto (1997), we determined that the average ages of the larvae

collected off Oregon were 12 days in 2004, 37 days in 2005, and 72 days in 2006. Agostini et al. (2006) calculated most poleward flow in the California undercurrent waters occupied by Pacific hake to be 0.025–0.075 m/s and Pierce et al. (2000) calculated the overall mean poleward flow in the California undercurrent to be 0.10 m/s in July–August 1995. Larvae 72 days old would have to drift north at a rate of 0.15 m/s, or 13 km/d in a constant heading to travel the 1000 km from the California Bight to Oregon waters. So it is unlikely that drift alone would explain this northern shift in their distribution.

Although larval Pacific hake were collected as close as 4 km from shore, most were found in offshore waters. The mean length of larvae along the NH line during the May 2006 PaCOOS Survey decreased from 22.7 to 12.7 mm SL with increasing distance from shore (tab. 1). This suggests that larval Pacific hake spawned in offshore waters were either actively or passively transported into nearshore waters through ontogeny. Nearshore movement of larval Pacific hake in the north is consistent with oceanographic conditions and findings in the south (Bailey 1981; Grover et al. 2002), and further reduces the likelihood that large larval Pacific hake observed off of Oregon were transported from southern California.

Juvenile Pacific hake collections

Few studies captured YOY Pacific hake north of 40°N in the NCC prior to 2003, and the surveys that did cap-

tured relatively few (tab. 3). The NOAA Fisheries, Alaska Fisheries Science Center (AFSC), Resource Assessment and Conservation Engineering (RACE) Division's triennial bottom trawl survey captured a total of 146 YOY Pacific hake (<100 mm) between 1977 and 2001 north of 40°N. In 2004, the triennial bottom trawl survey (conducted by the NWFSC Fishery Resource Analysis and Monitoring-[FRAM]-Division) captured 3,991 YOY Pacific hake (<100 mm) north of 40°N (M. Wilkins, NOAA Fisheries, AFSC, RACE Division 7600 Sand Point Way N.E. Seattle, Washington 98115 pers. comm., 2007). Between 1977–2001, the NOAA Fisheries, AFSC RACE Division West Coast acoustic survey captured a single YOY Pacific hake north of 40°N (M. Guttormsen, NOAA Fisheries, AFSC, RACE Division 7600 Sand Point Way N.E. Seattle, Washington 98115 pers. comm., 2007). Though not quantified, the Canadian Department of Fisheries and Oceans (DFO) Pacific hake survey from 1984–2006 captured YOY Pacific hake (<8 cm) in 1993, 1994, 1997, and 2006 off of Vancouver Island (G. A. McFarlane, Fisheries and Oceans, Canada, Pacific Biological Station, Nanaimo, BC, V9T 6N7 pers. comm., 2007). During the 1997–98 El Niño event, the NOAA Fisheries NWFSC Predator Survey captured a few age-1 hake but no YOY Pacific hake were caught in these surveys until 2004 (fig. 10).

Our data suggest that a northerly expansion in the spawning location of Pacific hake has occurred in the NCC, especially during 2003–06. Over the last decade, YOY Pacific hake distributions have expanded ~1000 km north. We conclude that it is unlikely this observed expansion was due to increased northerly current transport; this is supported by the findings of several fishery surveys: (1) the yearly occurrence and recruitment of YOY Pacific hake in the NCC captured in the NWFSC SAIP Larval/Juvenile Survey, the NWFSC-PWCC Survey, and the NWFSC Predator Survey starting in 2003; (2) the reduction in the abundance of larvae (≤ 11.75 mm) from 2003 to 2006 in the southern California spawning region (Peterson et al. 2006; Lo 2007); (3) the shoreward rather than northward transport of larvae (PaCOOS and NWFSC SAIP Larval/Juvenile Surveys); and (4) the low abundance of YOY Pacific hake in the NCC prior to 2004 in other surveys (see tab. 3).

The northerly shift of Pacific hake spawning and recruitment is likely related to increased winter/spring temperatures in the NCC. Hollowed (1992), Horne and Smith (1997), and Benson et al. (2002) hypothesized that Pacific hake shift their spawning location north during warm ocean years. Historically, warm years also tend to produce strong year classes, possibly due to relaxed upwelling or expansion of the spawning range (Methot and Dorn 1995; Ressler et al., in press).

YOY Pacific hake (7.5–8.0 mm mean length) were captured by a commercial fishing vessel as far north as Vancouver Island in 2005 (K. Cooke, Fisheries and Oceans, Canada, Pacific Biological Station, Nanaimo, BC, V9T 6N7, pers. comm., 2007). High densities of YOY Pacific hake were also found in the most southern regions of the SWFSC Juvenile Rockfish Survey in the same year (fig. 5), and low densities of YOY Pacific hake were encountered in the areas in between. In the 2006 coast-wide sardine survey, there appeared to be two distinct groups of larval Pacific hake (Lo 2007). The coastal stock may be splitting into two distinct spawning groups or possibly ocean-current patterns are causing a split in distribution. However, a longer time series is needed to confirm either hypothesis.

NCC occurrences of age-1 Pacific hake in 2007

It appears that the 2006 year-class of Pacific hake is successfully recruiting in the NCC based upon recent widespread, high density occurrences not previously reported for this region. Age-1 Pacific hake have been collected from at least central California to Washington. The Predator Survey captured over 8,700 age-1 Pacific hake in a single midwater tow 24 km off of the Columbia River in May 2007. The 2007 NWFSC-PWCC Survey also caught large numbers of age-1 Pacific hake from Monterey Bay to Newport, and a 15-min test tow on light acoustic sign caught 225 kg of age-1 Pacific hake (Wespestad, pers. obs.). Commercial shrimp trawlers have been capturing large numbers of age-1 Pacific hake as bycatch in their trawls and it is negatively affecting the fishery; in some tows the majority of the catch has been age-1 Pacific hake, and the entire tows were discarded. The large catches of age-1 hake in the commercial shrimp fishery have occurred from south of Cape Blanco, Oregon to Destruction Island, Washington (Steve Jones, Oregon Department of Fish and Game, 2040 SE Marine Science Drive, Newport, Oregon 97365 pers. comm., 2007). Thus, the 2006 Pacific hake year class appears to be negatively affecting the commercial shrimp fishery, and will likely affect several other fisheries in the NCC in future years.

Implications for the ecosystem and management

A northerly shift in the spawning and recruitment of Pacific hake will have major implications on the NCC ecosystem. Pacific hake larvae and juvenile survival may increase, and both adults and juveniles will not have to migrate as far to reach their traditional northern feeding grounds and will thus expend less energy migrating. Alternatively, Pacific hake year-class strength may be negatively affected due to: (1) cannibalism (Buckley and Livingston 1997), (2) predation, since YOY Pacific hake will encounter a new suite of predators not experienced off California, and (3) environmental conditions that

TABLE 3

Surveys that captured or were capable of capturing early life-stages of Pacific hake (*Merluccius productus*) collected in the central and northern California Current from 1961–2006. TH = total number of hauls. n = number of larvae or YOY hake collected. For sampling gear, IKT = Isaacs-Kidd trawl, BON = bongo net, TT = Tucker trawl, PRT = Polish rope trawl, MAT = modified anchovy trawl, NRT = Nordic 264 rope trawl, S = surface trawl, MW = midwater trawl, and B = bottom trawl. N/A = data not available.

Survey	Source	Sampling Gear, Mouth opening (m ²)	Mesh size (mm)
Larval surveys			
NOAA Fisheries, NWFSC	Waldron 1972	1-m ring net, 1.0	0.7
School of Oceanography, OSU	Richardson 1973	IKT (MW), 36	0.571
School of Oceanography, OSU	Richardson 1973	0.7-m BON, 0.39	0.571
School of Oceanography, OSU	Richardson 1973	1-m ring net, 0.79	0.571
School of Oceanography, OSU	Mundy 1984	0.2 or 0.7-m BON, 0.03-0.39	0.233–0.571
School of Oceanography, OSU	Richardson & Percy 1977	0.7-m BON, 0.39	0.571
School of Oceanography, OSU	Richardson et al. 1980	0.7-m BON, 0.39	0.571
School of Oceanography, OSU	Lyczkowski-Shultz unpublished ¹	1-m square net, 1.0	0.240
NOAA Fisheries, AFSC	Doyle 1992	0.61-m BON, 0.29	0.505
School of Oceanography, OSU	Boehlert et al. 1985	TT, 0.71	0.505
School of Oceanography, OSU	Brodeur et al. 1985	0.7-m ring net, 0.39	0.333
NOAA NH line	Brodeur et al. unpublished	0.61-m ring or 0.7-m BON, 0.29-0.39	0.333
NOAA Fisheries, NWFSC (BPA)	Brodeur et al. unpublished	1-m ring net, 0.79	0.335
NOAA Fisheries, NWFSC (SAIP)	Auth unpublished	0.61-m BON, 0.29	0.333
PaCOOS	Auth unpublished	TT, 1.0	0.335
PaCOOS	Auth unpublished	0.7-m BON, 0.39	0.571
Juvenile surveys			
Micronekton Surveys, OSU	Brodeur et al. 2003	IKT (MW), N/A	5.0
NOAA Fisheries, NWAFC, RACE Division	Guttormsen unpublished ²	Cobb trawl (MW), 130	32.0
NOAA Fisheries, NWAFC, RACE Division	Guttormsen unpublished ²	Siedlecki bottom trawl, 90	32.0
NOAA Fisheries, AFSC, RACE Division	Weinberg et al. 2002	Poly Nor'Eastern trawl (B), 105	32
NOAA Fisheries, NWAFC, RACE Division	Guttormsen unpublished ²	Norse (MW), 800	46.0
School of Oceanography, OSU	Brodeur & Percy 1986	Purse seine, N/A	32
NOAA Fisheries, NWAFC, RACE Division	Guttormsen unpublished ²	3/4 Norse (MW), NA	32.0
DFO (Hake Surveys)	Saunders & McFarlane 1997: and unpublished.	PRT (MW), 120	9.5
NOAA Fisheries, AFSC, RACE Division	Guttormsen unpublished ²	Alaska diamond (MW), NA	32.0
NOAA Fisheries, SWFSC (Juvenile Rockfish)	Sakuma et al. 2006	MAT (MW), 100	9.5
NOAA Fisheries, AFSC, RACE Division	Guttormsen unpublished ²	Northern gold (MW), NA	32.0
Columbia River Plume salmon survey	Brodeur et al. 2003	NRT (S), 336	3.0
NOAA Fisheries, NWFSC (Predator)	Emmett et al. 2006	NRT (S), 336	3.0
NOAA Fisheries, AFSC, RACE Division	Guttormsen unpublished ²	Nylon Nor' eastern (Bot), 105	32.0
NOAA Fisheries, AFSC, RACE Division	Guttormsen unpublished ²	Marinovich (MW), 37	3.2
NOAA Fisheries, AFSC, RACE Division	Guttormsen unpublished ²	Aleutian wing trawl (MW), 850	4.8
NOAA Fisheries, AFSC, RACE Division	Guttormsen unpublished ²	Methot, 5.3	1.0
NOAA Fisheries, AFSC, RACE Division	Guttormsen unpublished ²	Aleutian wing trawl (MW), 850	32.0
NOAA Fisheries, AFSC, RACE Division	Guttormsen unpublished ²	Poly Nor' eastern (Bot), 130	32.0
NOAA Fisheries, NWFSC (GLOBEC)	Reese & Brodeur 2006	NRT (S), 336	3.0
NWFSC-PWCC	Sakuma et al. 2006	MAT (MW), 100	9.5
NOAA Fisheries, NWFSC (SAIP)	Phillips unpublished	Cobb trawl (MW), 130	3.0
NOAA Fisheries, NWFSC (SAIP)	Phillips unpublished	NRT (MW), 336	3.0

¹Joanne Lyczkowski-Shultz, Gulf Coast Research Laboratory, P.O. Box 7000, Ocean Springs, Mississippi 39564

²M. A. Guttormsen NOAA Fisheries, AFSC, RACE Division 7600 Sand Point Way N.E., Seattle, WA 98115

may not favor larval or YOY Pacific hake survival in the highly advective NCC (Hickey and Banas 2003).

Potential impacts of increased numbers of juvenile Pacific hake in the NCC ecosystem will vary. Pacific hake juveniles may compete for prey with other commercially important species, such as juvenile salmon and rockfish. Adult Pacific hake become increasingly piscivorous with age, and may prey upon juvenile salmon and forage fishes, thus reducing their abundances (Livingston

1983; Livingston and Bailey 1985; Emmett and Krutzikowsky, in press).

Ultimately, if the distance that Pacific hake migrate south to spawn is reduced, it is likely that a larger percentage of the coastal stock of the Pacific hake population will spend more time in Canadian waters. Presently, the American Pacific hake fishery is the largest single-species fishery off the west coast of the U.S., and the U.S. and Canada coordinate to define the annual total

TABLE 3 (continued)

Surveys that captured or were capable of capturing early life-stages of Pacific hake (*Merluccius productus*) collected in the central and northern California Current from 1961–2006. TH = total number of hauls. n = number of larvae or YOY hake collected. For sampling gear, IKT = Isaacs-Kidd trawl, BON = bongo net, TT = Tucker trawl, PRT = Polish rope trawl, MAT = modified anchovy trawl, NRT = Nordic 264 rope trawl, S = surface trawl, MW = midwater trawl, and B = bottom trawl. N/A = data not available.

Years of sampling	Season of sampling	Total cruises	Latitude range (°N)	Area or depth coverage offshore (km or m)	TH	n	Years of capture
Larval surveys							
1967	April to May	2	42–51	Nearshore–550 km	88	0	
1969	May to October	6	42–46	Nearshore–>100 km	127	0	
1969	May to October	6	42–46	Nearshore–>100 km	62	0	
1969	May to October	6	42–46	Nearshore–>100 km	99	0	
1969–1972	Biweekly	74	44.67	2–18 km	273	0	
1971–1972	Monthly	18	44.65	2–111 km	287	0	
1972–1975	March & April	6	43–46	2–56 km	306	1	1973
1977–1978	November to June	10	44.65	5–10 km	25	0	
1980–1987	Mostly Spring	10	42–46	2–46 km	1086	37	1983, 1984
1982	April–July	5	44.67	9–18 km	6	0	
1983	April to September	11	44.67	6–18 km	39	0	
1996–2006	Biweekly	159	44.67	9–18 km	261	3	1998
1999–2004	Biweekly (typically spring and summer)	47	46.16	20–30 km	85	0	
2004–2006	Spring to Fall	9	44–46.67	5–75 (typically 10–55) km	138	1	2005
2004–2006	May	3	38.48–47	4–121 km	106	49	2004–2006
2004–2006	Spring to Fall	5	44–46.67	5–85 (typically 10–55) km	76	38	2006
Juvenile surveys							
1961–1969	Monthly	175	42.1–46.4	28–165 km	623	0	
1977	July to September	1	34.10–49.75	75 m to > 1,500 m	116	0	
1977	August to September	1	39.07–48.22	75 m to > 1,500 m	65	0	
1977–2004	Summer	10	34.5–49.5	55–500 m	5215	18645	1977–2004
1979–1980	August to September	2	37.22–49.32	75 m to > 1,500 m	107	81	1980
1979–1984	June to September	15	43–48.33	6–56 km	843	0	
1980–1986	July	3	36.98–48.99	75 m to > 1,500 m	48	0	
1984–2006	July & August	35	48–50.5	Nearshore–>100 km	N/A	N/A	1993–94, 1997, 2004, 2006
1986–1989	July	2	37.00–49.13	75 m to > 1,500 m	46	0	
1986–2006	Spring	24	32.75–45.0	Nearshore–140 km	2241	530513	1986–2006
1989–1992	July to August	2	34.83–51.49	75 m to > 1,500 m	78	0	
1998–2006	May to September	26	44–47	Across shelf	1259	0	
1998–2006	April to August	85	46.16–46.67	7–56 km	941	12039	2004–2006
1992–1995	July to August	2	35.78–51.06	75 m to > 1,500 m	52	0	
1992–2001	July to August	3	42.30–54.82	75 m to > 1,500 m	6	0	
1995	July	1	32.53–37.80	75 m to > 1,500 m	17	318	1995
1995–2001	July	3	34.79–55.00	75 m to > 1,500 m	103	0	
1995–2001	June to September	3	37.14–54.83	75 m to > 1,500 m	237	0	
1995–2001	June to September	3	36.30–54.57	75 m to > 1,500 m	38	5	1998
2000, 2002	June & August	4	42–22.67	2–70 km	343	0	
2001–2006	Spring	6	34.5–48	Across shelf	782	237764	2001–2006
2004	July to August	2	44–44.67	5–85 km	18	7174	2004–2006
2004–2006	Spring to Fall	11	44–46.67	5–85 (typically 10–55) km	165	7255	2004–2006

¹Joanne Lyzcykowski-Shultz, Gulf Coast Research Laboratory, P.O. Box 7000, Ocean Springs, Mississippi 39564

²M. A. Guttormsen NOAA Fisheries, AFSC, RACE Division 7600 Sand Point Way N.E. Seattle, WA 98115

allowable catch (TAC). Under this agreement, 26.12% of the TAC is allocated to Canada (Helser et al. 2006). A more northerly spawning Pacific hake population may result in more Pacific hake in Canadian waters (Benson et al. 2002), thus affecting the proportion of the population available to the U.S.

It is too soon to ascertain whether this northward shift in the occurrence of larvae and YOY Pacific hake represents a permanent life-history feature in the Cali-

fornia Current, or is a short-term response to warming ocean conditions. Similar northerly shifts in fish distributions have been observed in other systems such as the U.S. East Coast (Murawski 1993), the North Sea (Perry et al. 2005), and the Mediterranean Sea (Sabatés et al. 2006). Detailed studies of the effects of fish distributional shifts on other ecosystem components are clearly warranted in order to manage these systems properly.

ACKNOWLEDGMENTS

We wish to thank all the scientists and crews of the research and fishing vessels that participated in the cruises and the processing of samples in the laboratory. Miriam Doyle of the Alaska Fisheries Science Center provided unpublished data on earlier ichthyoplankton collections. Gordon (Sandy) McFarlane of the Department of Fisheries and Oceans, Canada, provided unpublished data from the DFO hake survey. Martin Dorn, Mark Wilkins, Chris Wilson, and Mike Guttormsen of the Alaska Fisheries Science Center provided unpublished data from the AFSC triennial bottom trawl survey and AFSC triennial acoustic survey. Patrick Ressler and Ed Casillas of NOAA Fisheries, Seattle, and the anonymous reviewers provided useful comments on this manuscript. Funding for the collection and analysis of the data comes from the NOAA NWFSC and SWFSC, SAIP, PWCC, and the Bonneville Power Administration (BPA).

LITERATURE CITED

- Auth, T. D., and R. D. Brodeur. 2006. Distribution and community structure of ichthyoplankton off the coast of Oregon, USA, in 2000 and 2002. *Mar. Ecol. Prog. Ser.* 319:199–213.
- Auth, T. D., R. D. Brodeur, and K. M. Fisher. 2007. Diel variation in vertical distribution of an offshore ichthyoplankton community off the Oregon coast. *Fish. Bull., U.S.* 105:313–326.
- Agostini, V. N., R. C. Francis, A. B. Hollowed, S. D. Pierce, C. Wilson, and A. N. Hendrix. 2006. The relationship between Pacific hake (*Merluccius productus*) distribution and poleward subsurface flow in the California Current system. *Can. J. Fish. Aquat. Sci.* 63:2648–2659.
- Bailey, K. M. 1981. Larval transport and recruitment of Pacific hake *Merluccius productus*. *Mar. Ecol. Prog. Ser.* 6:1–9.
- Bailey, K. M., R. C. Francis, and P. R. Stevens. 1982. The life history and fishery of Pacific whiting, *Merluccius productus*. *Calif. Coop. Oceanic Fish. Invest. Rep.* 23:81–98.
- Bailey, K. M., and R. C. Francis. 1985. Recruitment of Pacific whiting, *Merluccius productus*, and the ocean environment. *Mar. Fish. Rev.* 47:8–15.
- Benson, A. J., G. A. McFarlane, S. E. Allen, and J. F. Dower. 2002. Changes in Pacific hake (*Merluccius productus*) migration patterns and juvenile growth related to the 1989 regime shift. *Can. J. Fish. Aquat. Sci.* 59:1669–1679.
- Boehlert, G. W., D. M. Gadomski, and B. C. Mundy. 1985. Vertical distribution of ichthyoplankton off the Oregon coast in spring and summer months. *Fish. Bull., U.S.* 83:611–621.
- Brodeur, R. D., D. M. Gadomski, W. G. Pearcy, H. P. Batchelder, and C. B. Miller. 1985. Abundance and distribution of ichthyoplankton in the upwelling zone off Oregon during anomalous El Niño conditions. *Est. Coast. Shelf Sci.* 21:365–378.
- Brodeur, R. D., and W. G. Pearcy. 1986. Distribution and relative abundance of pelagic non-salmonid nekton off Oregon and Washington, 1979–1984. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 46. 85 pp.
- Brodeur, R. D., W. G. Pearcy, and S. Ralston. 2003. Abundance and distribution patterns of nekton and micronekton in the Northern California Current Transition Zone. *J. Oceanogr.* 59:515–534.
- Brodeur, R. D., J. P. Fisher, R. L. Emmett, C. A. Morgan, and E. Casillas. 2005. Species composition and community structure of pelagic nekton off Oregon and Washington under variable oceanographic conditions. *Mar. Ecol. Prog. Ser.* 298:41–57.
- Brodeur, R. D., S. Ralston, R. L. Emmett, M. Trudel, T. D. Auth, and A. J. Phillips. 2006. Recent trends and anomalies in pelagic nekton abundance, distribution, and apparent recruitment in the northeast Pacific Ocean. *Geophys. Res. Lett.* 33, L22S08, doi:10.1029/2006GL026614.
- Buckley, T. W., and P. A. Livingston. 1997. Geographic variation in the diet of Pacific hake, with a note on cannibalism. *Calif. Coop. Oceanic Fish. Invest. Rep.* 38:53–62.
- Butler, J. L., and R. N. Nishimoto. 1997. Growth and cohort dynamics of Pacific hake larvae. *Calif. Coop. Oceanic Fish. Invest. Rep.* 38:63–68.
- Dorn, M. W., M. W. Saunders, C. D. Wilson, M. A. Guttormsen, K. Cooke, R. Kieser, and M. E. Wilkins. 1999. Status of the coastal Pacific hake/whiting stock in U.S. and Canada in 1998. Canadian Stock Assessment Secretariat Research Document. 99/90.
- Doyle, M. J. 1992. Patterns in distribution and abundance of ichthyoplankton off Washington, Oregon, and northern California (1980–1987). *Alaska Fish. Sci. Cent. Proc. Rep.* 92–14.
- Doyle, M. J. 1995. The El Niño of 1983 as reflected in the ichthyoplankton off Washington, Oregon, and northern California. *Can. Spec. Publ. Fish. Aquat. Sci.* 121:161–180.
- Doyle, M. J., K. L. Mier, M. S. Busby, and R. D. Brodeur. 2002. Regional variation in springtime ichthyoplankton assemblages of the northeast Pacific Ocean. *Prog. Oceanogr.* 53:247–281.
- Emmett, R. L., R. D. Brodeur, and P. M. Orton. 2004. The vertical distribution of juvenile salmon and associated fishes in the Columbia River plume. *Fish. Oceanogr.* 13: 392–402.
- Emmett, R. L., G. K. Krutzikowsky, and P. Bentley. 2006. Abundance and distribution of pelagic piscivorous fishes in the Columbia River plume during spring/early summer 1998–2003: relationship to oceanographic conditions, forage fishes, and juvenile salmonids. *Prog. Oceanogr.* 68:1–26.
- Emmett, R. L., and G. K. Krutzikowsky. In Press. Nocturnal feeding by Pacific hake (*Merluccius productus*) and jack mackerel (*Trachurus symmetricus*) off the mouth of the Columbia River, 1999–2004: implications for juvenile salmon predation. *Trans. Am. Fish. Soc.*
- Grover, J. J., T. W. Buckley, and D. Woodbury. 2002. Effects of the 1997–1998 El Niño on early-juvenile Pacific hake *Merluccius productus*: age, growth, abundance, and diet in coastal nursery habitats. *Mar. Ecol. Prog. Ser.* 240:235–247.
- Hesler, T. E., I. J. Stewart, G. W. Fleischer, and S. Martell. 2006. Stock Assessment of Pacific Hake (Whiting) in U.S. and Canadian Waters in 2006. www.pcouncil.org
- Hickey, B., and N. S. Banas. 2003. Oceanography of the U.S. Pacific Northwest Coastal Ocean and Estuaries with Application to Coastal Ecology. *Estuaries* 26: 1010–1031.
- Horne, J. K., and P. E. Smith. 1997. Space and time scales in Pacific hake recruitment processes: latitudinal variation over annual cycles. *Calif. Coop. Oceanic Fish. Invest. Rep.* 38:90–102.
- Hooff, R. C., and W. T. Peterson. 2006. Copepod biodiversity as an indicator of changes in ocean and climate conditions of the northern California current ecosystem. *Limnol. Oceanogr.* 51:2607–2620.
- Hollowed, A. B. 1992. Spatial and temporal distributions of Pacific hake, *Merluccius productus*, larvae and estimates of survival during early life stages. *Calif. Coop. Oceanic Fish. Invest. Rep.* 33:100–123.
- Livingston, P. A. 1983. Food habits of Pacific whiting, *Merluccius productus*, off the west coast of North America, 1967 and 1980. *Fish. Bull., U.S.* 81:629–636.
- Livingston, P. A., and K. M. Bailey. 1985. Trophic role of Pacific whiting, *Merluccius productus*. *Mar. Fish. Rev.* 47:16–22.
- Lo, N. C. 2007. Daily larval production of Pacific hake (*Merluccius productus*) off California in 1951–2006. *Calif. Coop. Oceanic Fish. Invest. Rep.* 48. pp.
- Mackas, D. L., W. T. Peterson, M. D. Ohman, and B. E. Lavaniegos. 2006. Zooplankton anomalies in the northern California Current system before and during the warm ocean conditions of 2005. *Geophys. Res. Lett.* 33, L22S07, doi:10.1029/2006GL27930.
- Method, R. D., and M. W. Dorn. 1995. Biology and fisheries of North Pacific hake (*M. productus*). In *Hake: Biology, Fisheries, and Markets*, J. Alheit and T. J. Pitcher, eds. London, UK: Chapman and Hall. pp. 389–414.
- Miller, D. M. 1984. Reducing transformation bias in curve fitting. *Amer. Stat.* 38:124–126.
- Mundy, B. C. 1984. Yearly variation in the abundance and distribution of fish larvae in the coastal upwelling zone off Yaquina Head, Oregon, from June 1969–August 1972. MSc thesis, Oregon State University, Corvallis.
- Murawski, S. A. 1993. Climate change and marine fish distributions: forecasting from historical analogy. *Trans. Am. Fish. Soc.* 122:647–658.
- Pearcy, W. G., and A. Schoener. 1987. Changes in the marine biota coincident with the 1982–1983 El Niño in the northeastern subarctic Pacific Ocean. *J. Geophys. Res.* 92 (C13):14417–14428.

- Perry, A. L., P. J. Low, J. R. Ellis, and J. D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. *Science* 308:1912–1915.
- Peterson, W. T., R. Emmett, R. Goericke, E. Venrick, A. Mantyla, S. J. Bograd, F. B. Schwing, R. Hewitt, N. Lo, W. Watson, J. Barlow, M. Lowry, S. Ralston, K. A. Forney, B. E. Lavaniegos, W. J. Sydeman, D. Hyrenbach, R. W. Bradley, P. Warzybok, F. Chavez, K. Hunter, S. Benson, M. Weise, and J. Harvey. 2006. The state of the California Current, 2005–2006: warm in the north, cool in the south. *Calif. Coop. Oceanic Fish. Invest. Rep.* 47:30–74.
- Pierce, S. D., R. L. Smith, P. M. Kosro, J. A. Barth, and C. D. Wilson. 2000. Continuity of the poleward undercurrent along the eastern boundary of the mid-latitude North Pacific. *Deep-Sea Res. II*, 52:89–108.
- Pierce, S. D., J. A. Barth, R. E. Thomas, and G. W. Fleischer. 2006. Anomalously warm July 2005 in the northern California Current: historical context and the significance of cumulative wind stress. *Geophys. Res. Lett.*, 33, L22S04, doi:10.1029/2006GL027149.
- Reese, D. C., and R. D. Brodeur. 2006. Identifying and characterizing biological hot spots in the Northern California Current. *Deep-Sea Res. II*. 53:291–314.
- Ressler, P. H., J. A. Holmes, G. W. Fleischer, R. E. Thomas, and K. C. Cooke. 2007. Pacific hake, (*Merluccius productus*) autecology: a timely review. *Mar. Fish. Rev.* 69.
- Richardson, S. L. 1973. Abundance and distribution of larval fishes in waters off Oregon, May–October 1969, with special emphasis on the northern anchovy, *Engraulis mordax*. *Fish. Bull.*, U.S. 71:697–711.
- Richardson, S. L., and W. G. Pearcy. 1977. Coastal and oceanic larvae in an area of upwelling off Yaquina Bay, Oregon. *Fish. Bull.*, U.S. 75:125–145.
- Richardson, S. L., J. L. Laroche, and M. D. Richardson. 1980. Larval fish assemblages and associations in the North-east Pacific Ocean along the Oregon coast, winter-spring 1972–1975. *Est. Coast. Mar. Sci.* 11:671–699.
- Sabatés, A., P. Martín, J. Lloret, and V. Raya. 2006. Sea warming and fish distribution: the case of the small pelagic fish, *Sardinella aurita*, in the western Mediterranean. *Glob. Change Biol.* 12:2209–2219.
- Sakuma, K. M., S. Ralston, and V. G. Weststad. 2006. Interannual and spatial variation in the distribution of young-of-the-year rockfish (*Sebastes* spp.): expanding and coordinating the survey sampling frame. *Calif. Coop. Oceanic Fish. Invest. Rep.* 47:127–139.
- Saunders, M. W., and G. A. McFarlane. 1997. Observations on the spawning distribution and biology of offshore Pacific hake (*Merluccius productus*). *Calif. Coop. Oceanic Fish. Invest. Rep.* 38:147–157.
- Searle, S. R., F. M. Speed, and G. A. Milliken. 1980. Population marginal means in the linear model: an alternative to least squares means. *Amer. Stat.* 34(4):216–221.
- Weinberg K. L., M. E. Wilkins, F. R. Shaw, and M. Zimmermann. 2002. The 2001 Pacific west coast bottom survey of groundfish resources: estimates of distribution, abundance, and length and age composition. U.S. Dep. Comm., NOAA Tech. Memo. NOAA-NMFS-AFSC-TM 128. 140 pp.
- Waldron, K. D. 1972. Fish larvae collected from the northeastern Pacific Ocean and Puget Sound during April and May 1967. NOAA Tech. Rep. NMFS SSR F-663. 16 pp.

