ANOMALOUS DISTRIBUTIONS OF PELAGIC JUVENILE ROCKFISH ON THE U.S. WEST COAST IN 2005 AND 2006

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ABSTRACT

A combination of midwater trawl surveys of pelagic juvenile rockfish on the U.S. West Coast provide data from 2004 to 2009, which represent the collaborative efforts of the National Marine Fisheries Service Southwest Fisheries Science Center, Northwest Fisheries Science Center, and the Pacific Whiting Conservation Cooperative to survey the waters of the California Current from the U.S.-Mexican border to the Columbia River 33˚–46˚N. We analyze six species of pelagic juvenile rockfish and evaluate the annual stability of their spatial distributions. Our results show that rockfish catches in 2005 and 2006 were shifted away from the core area of the survey, which has been sampled since 1983. In those years there was a bifurcation in their spatial distributions, with some species shifted to the north (*S. entomelas, S. flavidus,* and *S. pinniger*) and some species to the south (*S. jordani and S. paucispinis*). While the geographic distributions of fish in 2005 and 2006 were unusual, total abundance patterns were apparently unrelated to their spatial distributions. By 2007, the distributions of these species had recovered to pre-2005 conditions, especially for northern species. Standardized wind stress anomalies on the West Coast during the months preceding the surveys were evaluated in relation to the anomalous spatial distributions of catch. Results show that significant wind reversals occurred during February of 2005 and 2006, which is the peak of the parturition season.

INTRODUCTION

The National Marine Fisheries Service (NMFS) Southwest Fisheries Science Center (SWFSC) has conducted a midwater trawl survey during May–June since 1983 that is designed to estimate the abundance of pelagic juvenile rockfish (*Sebastes* spp.; Ralston et al. 2013). Prior to 2004 the survey was limited to the central California coast from Carmel to Bodega Bay (lat. 36˚30'–38˚20'N), but in 2004 the latitudinal extent of the survey was expanded 4-fold to encompass the region between the U.S.-Mexican border and Cape Mendocino (lat. 32˚45'–40˚00'N). Moreover, the expanded SWFSC survey was then coupled with a similar midwater trawl survey conducted by the Pacific Whiting Conservation Cooperative (PWCC) and the NMFS Northwest Fisheries Science Center (NWFSC) that was initiated in 2001 (Sakuma et al. 2006). In concert the combined surveys have provided near coastwide coverage in most years since (fig. 1). Catch rate data from the combined surveys are developed into pre-recruit abundance statistics, which are distributed to analysts for use in groundfish stock assessments conducted for the Pacific Fisheries Management Council[1]. Beyond that decidely prosaic function, the survey has developed a broader role in monitoring the overall distribution and abundance of the California Current forage community (e.g., Santora et al. 2011; Wells et al. 2012).

Upon consolidation of the two surveys, a workshop was held to evaluate how the spatial scale of sampling affected inferred recruitment patterns (Hastie and Ralston 2007). Of particular concern was whether data collected solely from the "core" region of the SWFSC survey (lat. 36˚30'–38˚20'N) were informative with respect to impending recruitment to rockfish stocks. Results presented in Field and Ralston 2005 had indicated that rockfish recruitment patterns on the U.S. West Coast were spatially correlated, with 51%–72% of year-to-year recruitment variability shared coastwide, at least for *Sebastes entomelas, S. flavidus*, and *S. goodei*. If survey results from the core survey area could be used to estimate recruitment in stocks with a much broader distribution, the extended time series developed by the SWFSC beginning in 1983 could be utilized in stock assessments.

Here we report results describing the spatial distributions of six species of pelagic juvenile rockfish captured in the combined midwater trawl survey. In particular, we evaluate the temporal stability of their distributions with respect to sampling in the core area only. We also present an analysis of the wind stress field in the months preceding the survey that attempts to explain changes in distributions.

[1] Ralston, S. 2010. Coastwide pre-recruit indices from SWFSC and NWFSC/PWCC midwater trawl surveys (2001–10). Groundfish Analysis Team, Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries, 11 p.

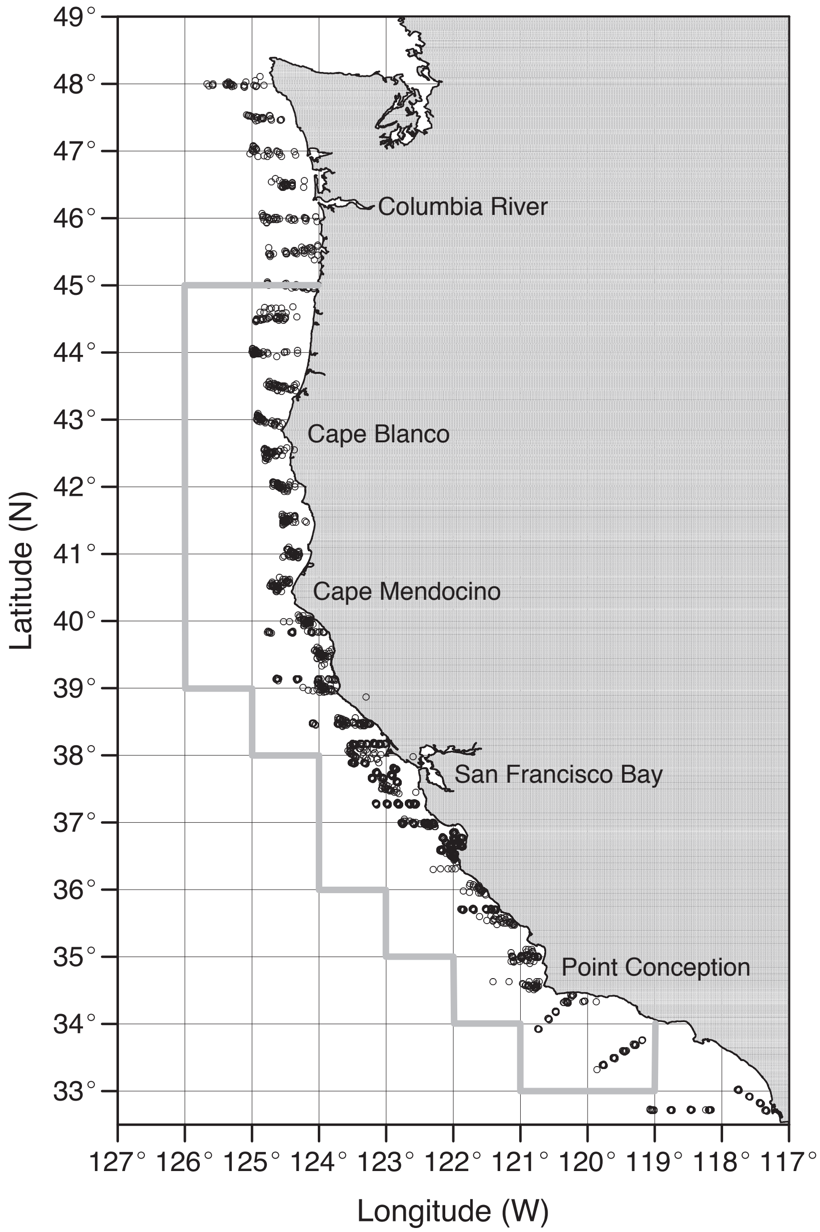

Figure 1. Map of the U.S. West Coast showing the spatial extent of the combined SWFSC-NWFSC pelagic juvenile rockfish midwater trawl survey (2001–09). Trawl sampling stations shown as small open circles; wind stress calculations based on 1° x 1° latitude-longitude cells occurring within the bold gray polygon.

MATERIALS AND METHODS

The combined midwater trawl survey became coastwide in 2004 (Hastie and Ralston 2007) and all sampling has occurred during May–June. However, in recent years (2010–12) survey coverage has been incomplete and comprehensive coastwide data are lacking; we therefore limit our findings to the period 2004–09. Biological sampling is conducted using a standard Cobb midwater trawl fitted with a 26 m headrope and a 9.5 mm (3/8") cod-end liner. Based on net mensuration data obtained with a Simrad ITI system, the height and width of the net when fishing averages 12 m, resulting in a sampled swath of ~144 m^2; a fine-mesh liner retains epipelagic nekton and micronekton. Trawling is conducted only at night due to net avoidance and the target depth for the trawl's headrope is 30 m. Quantitative sampling is obtained by standardizing the amount of trawl warp deployed during a tow to 85 m and using the Simrad ITI sensors to adjust vessel speed in real-time to maintain the depth of the headrope at 30 m. This practice produces a 20° angle of the trawl warp to the sea surface and, as a consequence, a consistent speed through the water. Trawls are further standardized by fishing the net for exactly 15 minutes at the target depth.

Upon completion of a trawl the contents of the cod-end are immediately sorted. All fish, cephalopods, and selected decapod crustaceans are enumerated, and several other key taxa (e.g., euphausiids, jellyfish, etc.) are either counted or estimated by expansion from a subsample. On SWFSC surveys all juvenile rockfishes are identified to species, frozen, and returned to the laboratory. Rockfish samples from the historical NWFSC surveys were immediately frozen and sent to the Fisheries Ecology Division, SWFSC for identification and enumeration following completion of the cruise. A more detailed description of sampling procedures is available in the survey's operations manual.[2]

Given that the absolute scale of latitudinal variation in survey sampling (1700 km) was ~15 times greater than the longitudinal scale (fig. 1), we consider latitude to be of primary importance and limit our analysis to that dimension. Thus, the annual spatial distribution of pelagic juvenile rockfishes in the survey was estimated by rounding the starting latitudinal position of each trawl to the nearest 1° (=111 km), resulting in 14 spatial strata (33°, 34°, …, 46°N). Species-specific catches were summed over all hauls occurring within a latitudinal stratum, and the total annual catch was determined by summing catches over strata. The annual number of hauls occurring within each stratum was also summarized and the annual total calculated. Annual species-specific catch-per-unit-effort (CPUE) statistics were then calculated as the ratio of the total annual catch to the total number of tows.

In addition, for each species, year, and latitudinal stratum, CPUE [fish · tow^{-1}] was calculated and species-specific annual spatial distributions were estimated by normalizing the stratified value to the annual sum, i.e.,

$$P_{s,y,l} = \frac{CPUE_{s,y,l}}{\sum_{l} CPUE_{s,y,l}},$$

where $\boldsymbol{P_{s,y,l}}$ is the proportion of annual CPUE of species $\boldsymbol{s}$ in year $\boldsymbol{y}$ taken in latitudinal stratum $\boldsymbol{l}$ and $\boldsymbol{CPUE_{s,y,l}}$ is the respective catch rate. The weighted average latitude of a species' annual catch was also estimated by computing the scalar (=dot) product of latitude values and the proportions of the total annual CPUE occurring therein.

We evaluated the relationship between winds in the months preceding the midwater trawl survey and the latitudinal distribution of pelagic juvenile rockfish sampled during the survey. For that analysis we queried the global derived monthly Fleet Numerical Meteorology and Oceanography Center wind and Ekman transport data (http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdlasFnWPr.html). In particular, we tabulated wind stress values (τ_x and τ_y [N m^{-2}]) within twenty five 1°×1° cells off the U.S. West Coast (fig. 1) from 1970–2011. Wind stress values are largely proportional to the square of the zonal (east-west) and meridional (north-south) winds, i.e., $\tau_x \propto u^2$ and $\tau_y \propto v^2$ with sign maintained. From those data we calculated the long-term means (μ) and standard deviations (σ) of τ_x and τ_y for all latitude (i), longitude (j), and monthly (k) combinations to establish the seasonal and spatial climatology of the wind stress field on the U.S. West Coast. We also calculated standardized anomalies (Z-scores) of the winds according to:

$$Z_{x,i,j,k,t} = \frac{\tau_{x,i,j,k,t} - \mu_{x,i,j,k}}{\sigma_{x,i,j,k}}$$

where $Z_{x,i,j,k,t}$ is the standardized τ_x anomaly for latitude i, longitude j, month k, in year t, $\tau_{x,i,j,k,t}$ is the zonal wind stress at that place and time, $\mu_{x,i,j,k}$ is the mean zonal wind stress at that place and month, and $\sigma_{x,i,j,k}$ is the standard deviation of the zonal wind stress at that place and month. Standardized anomalies of the meridional wind stress ($Z_{y,i,j,k,t}$) were calculated in a similar manner.

The standardized anomalies were studied to identify statistically extreme wind events in the four months preceding the survey (January–April). For the year in question, the standardized anomalies ($Z_{x,i,j,k,t}$ and $Z_{y,i,j,k,t}$) were averaged over longitude and for each month the results ($\overline{Z}_{x,i,k,t}$ and $\overline{Z}_{y,i,k,t}$) were plotted against latitude (lat. 33.5°–44.5°N). In this analysis longitudinal averaging resulted in a negligible loss of information because the standardized anomalies are highly correlated between adjacent longitudinal cells (r = 0.94 and 0.91 for zonal and meridional scores, respectively). In addition, vector plots that combined zonal and meridional components of wind stress were generated by month and latitude to visualize monthly and latitudinal variation in the wind field.

RESULTS

From 2004–09 the combined SWFSC/NWFSC survey completed 1,639 midwater trawls at standard stations on the U.S. West Coast (table 1). Sampling in the 37° and 38°N latitudinal strata has been especially high because this region forms the long-term core area of the SWFSC midwater trawl survey (Ralston et al. 2013). The number of trawls within any particular year × latitude stratum ranged from 6–80 and averaged 20. Among year sampling effort has ranged from 212 to 306 hauls · yr^{-1}.

Six species of winter-spawning rockfish are relatively abundant and are regularly sampled in the combined

[2] Sakuma, K., K. Baltz, J. Field, and S. Ralston. 2012. Operations Manual—Rockfish Recruitment and Ecosystem Assessment Survey Trawling Protocols. Groundfish Analysis Team, Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries, 23 p.

TABLE 1
Distribution of combined SWFSC/NWFSC midwater trawl samples at standard stations by year and latitude.

	Year						
Latitude	2004	2005	2006	2007	2008	2009	Total
33	12	17	19	16	19	10	93
34	13	16	12	12	11	6	70
35	14	11	22	10	9	10	76
36	18	25	23	11	13	14	104
37	70	77	57	80	36	65	385
38	54	47	70	63	29	54	317
39	15	15	21	15	18	16	100
40	12	12	19	19	13	12	87
41	14	12	11	9	12	13	71
42	6	10	10	15	8	14	63
43	12	11	12	11	14	9	69
44	13	10	8	10	7	11	59
45	16	11	13	13	12	12	77
46	14	9	9	12	11	13	68
Total	283	283	306	296	212	259	1,639

TABLE 2
Total catch at standard stations of six abundant pelagic juvenile rockfish (*Sebastes* spp.) taken in midwater trawl samples from 2004–09.

	Year						
Species	2004	2005	2006	2007	2008	2009	Total
S. entomelas	1,973	79	2	41	318	665	3,078
S. flavidus	1,160	28	3	3	91	219	1,504
S. pinniger	472	29	22	128	153	216	1,020
S. goodei	320	20	6	11	36	353	746
S. paucispinis	38	104	7	31	29	51	260
S. jordani	1,334	6,386	328	1,306	464	1,082	10,900
Total	5,297	6,646	368	1,520	1,091	2,586	17,508

midwater trawl survey (Ralston et al. 2013), including *S. entomelas* (widow rockfish), *S. flavidus* (yellowtail rockfish), *S. goodei* (chilipepper), *S. jordani* (shortbelly rockfish), *S. paucispinis* (bocaccio), and *S. pinniger* (canary rockfish). Catches of these species (table 2) demonstrate very high positive interannual covariation within the core survey area (Ralston et al. 2013). For the 2004–09 coastwide data, aggregate annual catches of the six species combined have ranged from 368 to 6,646 fish $\cdot$ yr^{-1}, representing an 18-fold fluctuation in abundance from 2005 to 2006. *Sebastes jordani* is the most abundant of the six species sampled in the survey (N = 10,900) and *S. paucispinis* is the least common (N = 260).

Annual catch rates (CPUE) have fluctuated markedly and are plotted on log-scale in Figure 2. Note that abundances generally declined from 2004 to 2006 and increased thereafter. Positive covariation in abundance among the six species is evident, as has been previously described (Ralston et al. 2013).

The 2004–09 spatial distributions of these six species in the catch are depicted in Figure 3. In the left column of the figure three members of the subgenus *Sebastosomus* are plotted; in the right column three members

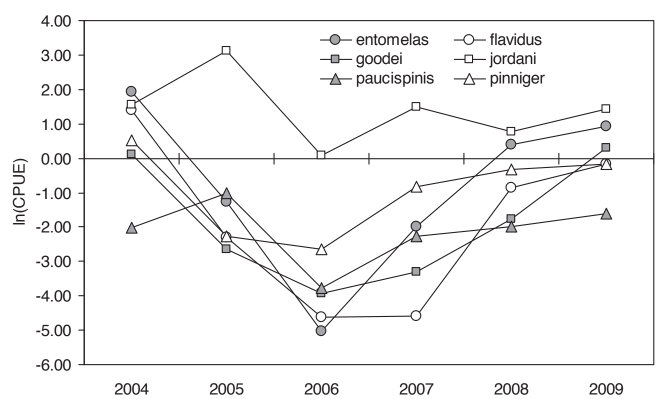

Figure 2. Annual trends in catch-per-unit-effort (CPUE) of pelagic juvenile rockfishes collected in the midwater trawl survey.

of the *Sebastodes* subgenus are shown. For the former group, 2005 and 2006 demonstrated a considerable distributional shift to the north that recovered in 2007 to prior conditions. For the latter group, *S. jordani* and *S. paucispinis* had an analogous shift in distribution to the south in 2005. Curiously, *S. goodei* revealed a strongly bimodal distribution in 2005 and a singularly unimodal distribution in 2006.

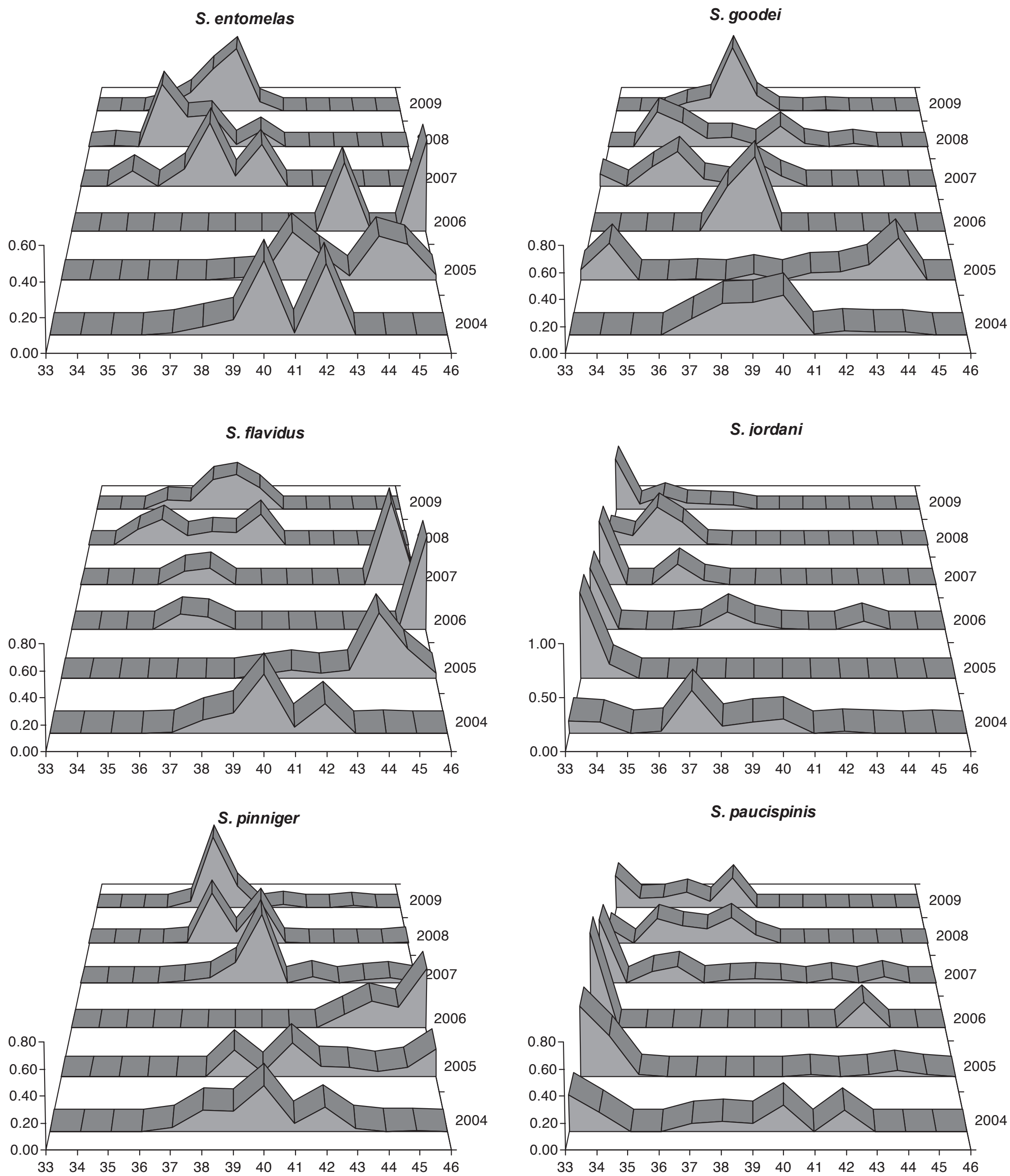

Figure 3. Spatial distributions of normalized CPUE for 6 *Sebastes* spp. from 2004–09. Plotted on the x-axis is latitude, on the y-axis is year, and on the z-axis is the proportion of spatially integrated annual CPUE.

The annual average latitude of CPUE for each of the species is plotted in Figure 4, which shows that in 2005 and 2006 there was an alteration in the spatial distribution of these pelagic juvenile rockfishes. Whereas in the first year of the survey the distribution of all six species was centered in the core area of the survey (37˚–40˚N), in 2005 there was a bifurcation in their spatial distributions, with some species shifted to the north (*S. entomelas*, *S. flavidus*, and *S. pinniger*) and some species shifted to the south (*S. jordani* and *S. paucispinis*). By 2007 the distributions of these species tended to recover to pre-2005 conditions, particularly for the northerly distributed species. *Sebastes goodei* demonstrated little variability in the average latitude of their catch.

To better understand the development of oceanographic conditions that may have led to these anomalous distributions in 2005 and 2006, we examined the climatology and standardized anomalies of zonal and meridional wind stresses in the 4 months preceding the survey. The seasonal and latitudinal climatology of

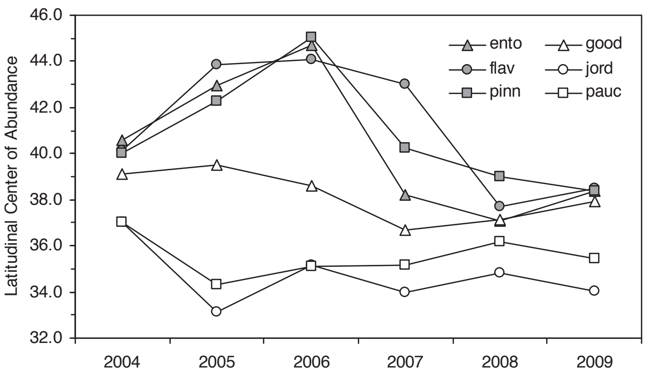

Figure 4. Time series of the average latitudes of survey catches for commonly-sampled juvenile rockfishes taken in the SWFSC-NWFSC midwater trawl survey (legend = first four letters of scientific name).

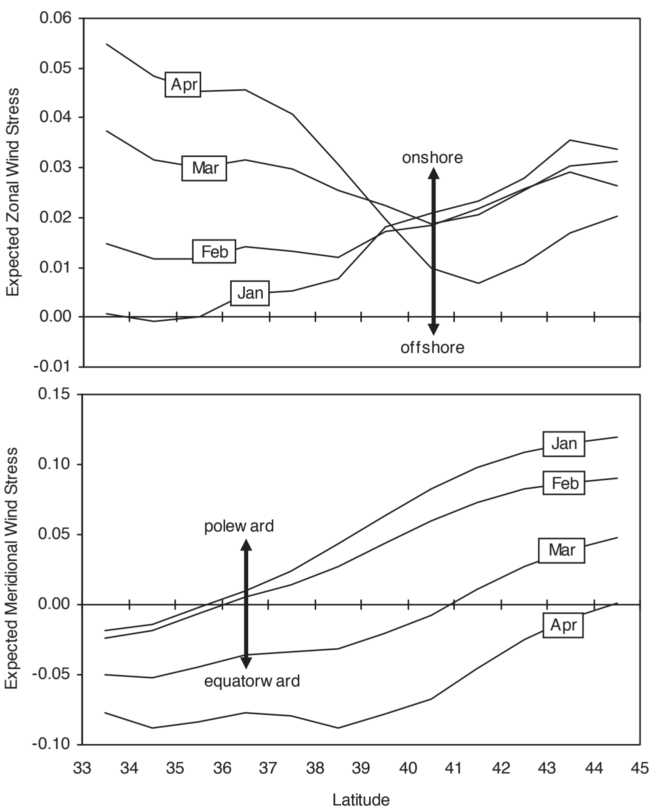

Figure 5. Climatology of wind stresses on the U.S. West Coast in the months preceding the midwater trawl survey (January–April). The upper panel shows zonal (east-west) winds and the lower panel depicts meridional (north-south) winds. Expected wind stresses are based on average values calculated over the period 1970–2011.

expected zonal and meridional wind stresses from January–April are plotted in Figure 5. Note that the spatial expression of zonal wind stresses interacts dramatically with month. In particular, in the south onshore wind stress increases markedly from January through April, whereas in the north onshore wind stress actually tends to decrease, especially in April. Likewise, there is a strong latitudinal gradient in the onset of equatorward meridional winds, which coincides with the spring transition to the upwelling season (Schwing et al. 2006). In the core area of the survey (37°–40°N) winds are generally equatorward in March, whereas in the north (41°–45°N) they are poleward, implying a divergence in the wind field.

To highlight statistically unusual wind conditions in the months preceding the survey we plot zonal ($\overline{Z}_{x,i,k,t}$) and meridional ($\overline{Z}_{y,i,k,t}$) standardized anomalies from 2004–09 in Figures 6 and 7, respectively. These results show that in 2005 strongly negative zonal winds existed during February in the central California region (lat. 37°–40°N), which reversed and became strongly positive by April (lat. 39°–41°N). Similarly, in February negative Z-scores of meridional winds occurred in the northern region (lat. 42°–44°N), which had reversed and become positive by April. Results for 2006 are somewhat different, i.e., relatively weak negative zonal Z-scores occurred in February but strong positive scores in March within the core region of the survey (lat. 37°–40°N). Meridional wind stresses, however, were characterized by strong negative Z-scores in February within the core region, which reversed and became positive in March.

It is useful to visualize the wind field in the months preceding the survey by examining vector plots of the climatology of wind stress and the observed wind stress in 2005 and 2006 (fig. 8). Results from January–March 2005 are presented in the left portion of the figure, whereas analogous results for 2006 are shown on the right. Note that scaling is identical in all six panels and that climatologically expected wind stresses are shown as a bold lines and the observed wind stresses are shown as fine lines with small open square symbols. Observe that by definition expected winds are identical in both years.

A careful examination of Figure 8 illustrates several points: (1) winds in January and March of 2005, although somewhat weaker than expected, were not markedly different in directionality from the climatology, (2) the strongly negative standardized anomalies of zonal winds in February 2005 were due to offshore winds in all areas north of 36°N, a time when onshore winds are expected, (3) at the same time, weak southerly winds occurred north of 36°, when strong northerly winds are expected, (4) winds in January and March 2006 were generally stronger than the climatology but largely similar in direction, (5) as in 2005, February 2006 was characterized by strong southerly winds that were opposite to the climatology north of 36°N.

DISCUSSION

We summarize six years of data from a pre-recruit survey of pelagic juvenile rockfish on the U.S. West Coast. The survey is designed to estimate on an annual basis the abundance of winter-spawning species, which collectively comprise some of the most important rockfish

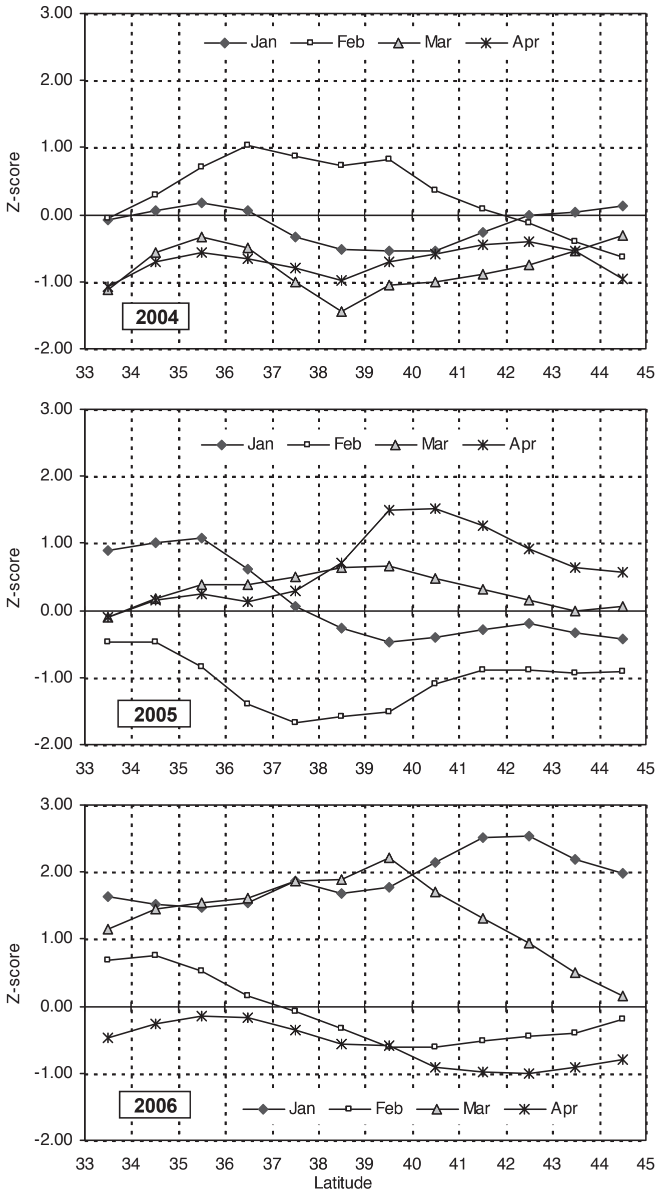

Figure 6. Seasonal and spatial variability in **zonal** wind stress from 2004–06 relative to the climatology. Z-scores are calculated as standardized deviations from the long-term mean (μ) and standard deviation (σ) (see text for further explanation).

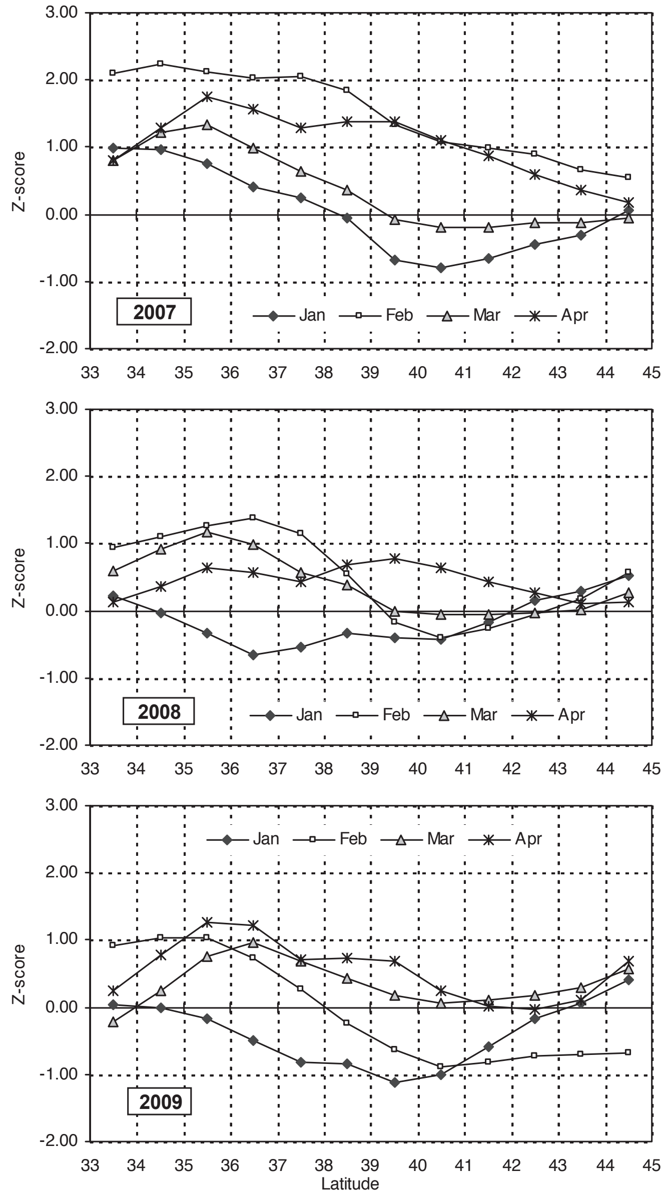

Figure 6 (cont'd). Seasonal and spatial variability in **zonal** wind stress from 2007–09 relative to the climatology.

stocks harvested in commercial and recreational fisheries in California, Oregon, and Washington (PFMC 2008). The parturition season of these species generally extends from December to March, but peaks in January–February (Wyllie-Echeverria 1987; Love et al. 1990; Love et al. 2002) and all exhibit an extended pelagic juvenile stage (Moser and Boehlert 1991) that lasts up to six months (Woodbury and Ralston 1991; Laidig et al. 1991). Previous studies have also indicated that year-class strength is established by the time the survey is conducted in May–June (Ralston and Howard 1995; Ralston et al. 2013). Thus, density-independent mortality during the larval stage is likely responsible for variable fisheries recruitment (Houde 1987, 2008).

Our results show that the spatial distribution of these young-of-the-year *Sebastes* was unusual in 2005 and 2006 (figs. 3 and 4), with some species shifted to the north (e.g., *Sebastosomus*) and others to the south (*Sebastodes*). It is noteworthy that members of the former subgenus tend to have more northerly latitudinal distributions as adults, whereas the latter subgenus is typically southerly in its distribution (Love et al. 2002; Williams and Ralston 2002; Ralston et al. 2013).

Our results reinforce the conclusions of the pre-

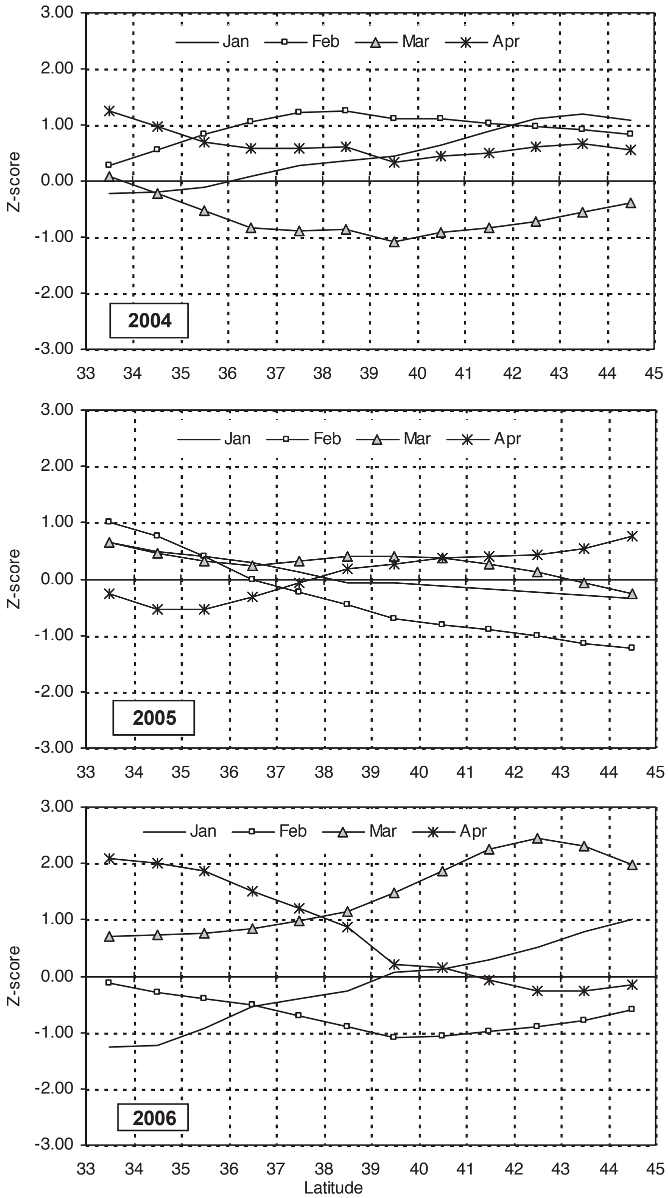

Figure 7. Seasonal and spatial variability in **meridional** wind stress from 2004–06 relative to the climatology. Z-scores are calculated as standardized deviations from the long-term mean (μ) and standard deviation (σ) (see text for further explanation).

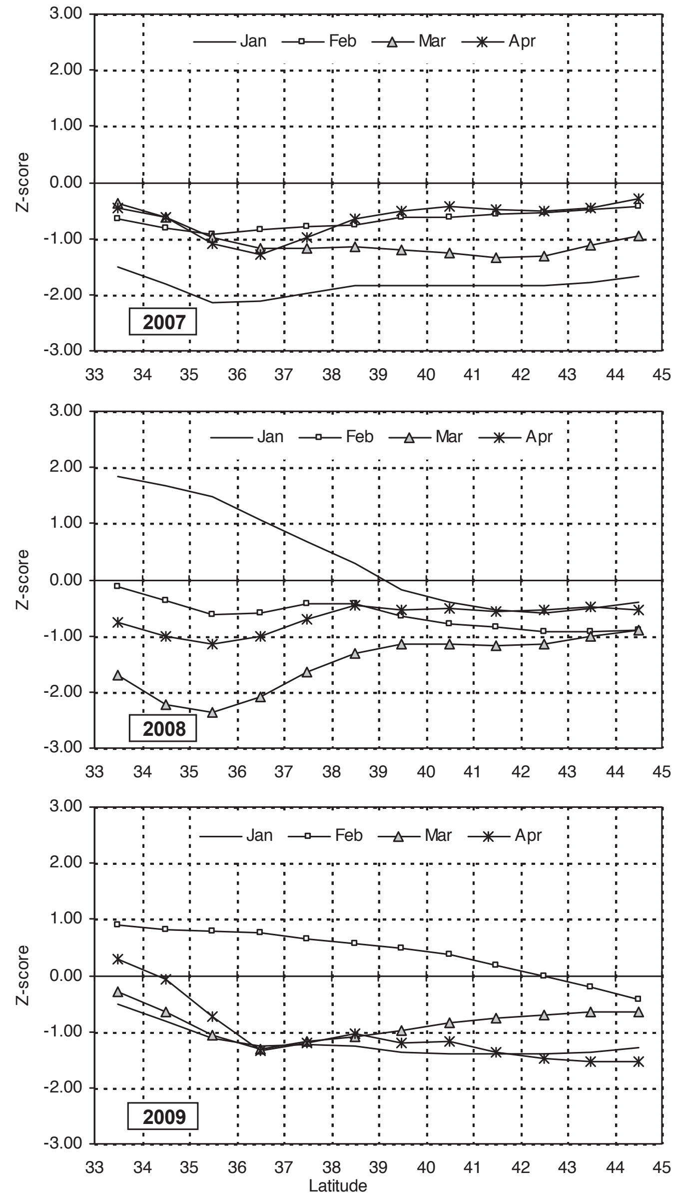

Figure 7 (cont'd). Seasonal and spatial variability in **meridional** wind stress from 2007–06 relative to the climatology.

recruit survey workshop (Hastie and Ralston 2007), which recommended that complete coverage of the U.S. West Coast is required to develop statistically valid indices of abundance for use in stock assessments. Ralston et al. 2013 demonstrated a significant positive correlation between indices of abundance from the "core" survey area and subsequent recruitment to several rockfish stocks. However, the precision of that relationship was low, precluding the incorporation of pre-recruit indices in assessment models derived from samples drawn solely from the core area. Similarly, Field et al. 2010 concluded that for *S. paucispinis*, sampling in the Southern California Bight is needed to develop suitable estimates of pre-recruit abundance.

While the distributions of fish were anomalous in 2005 and 2006, total abundance was apparently unrelated to their spatial distribution. As previously noted, there was an 18-fold fluctuation in the total abundance of pelagic juveniles sampled in the combined survey from 2005 to 2006, corresponding to the maximum and minimum values over the period of study. The maximum, observed in 2005 (N = 6,646), was due to large catches of *S. jordani* in the southern California Bight (table 2, fig. 3). Moreover, assessment models for two of the *Sebas-*

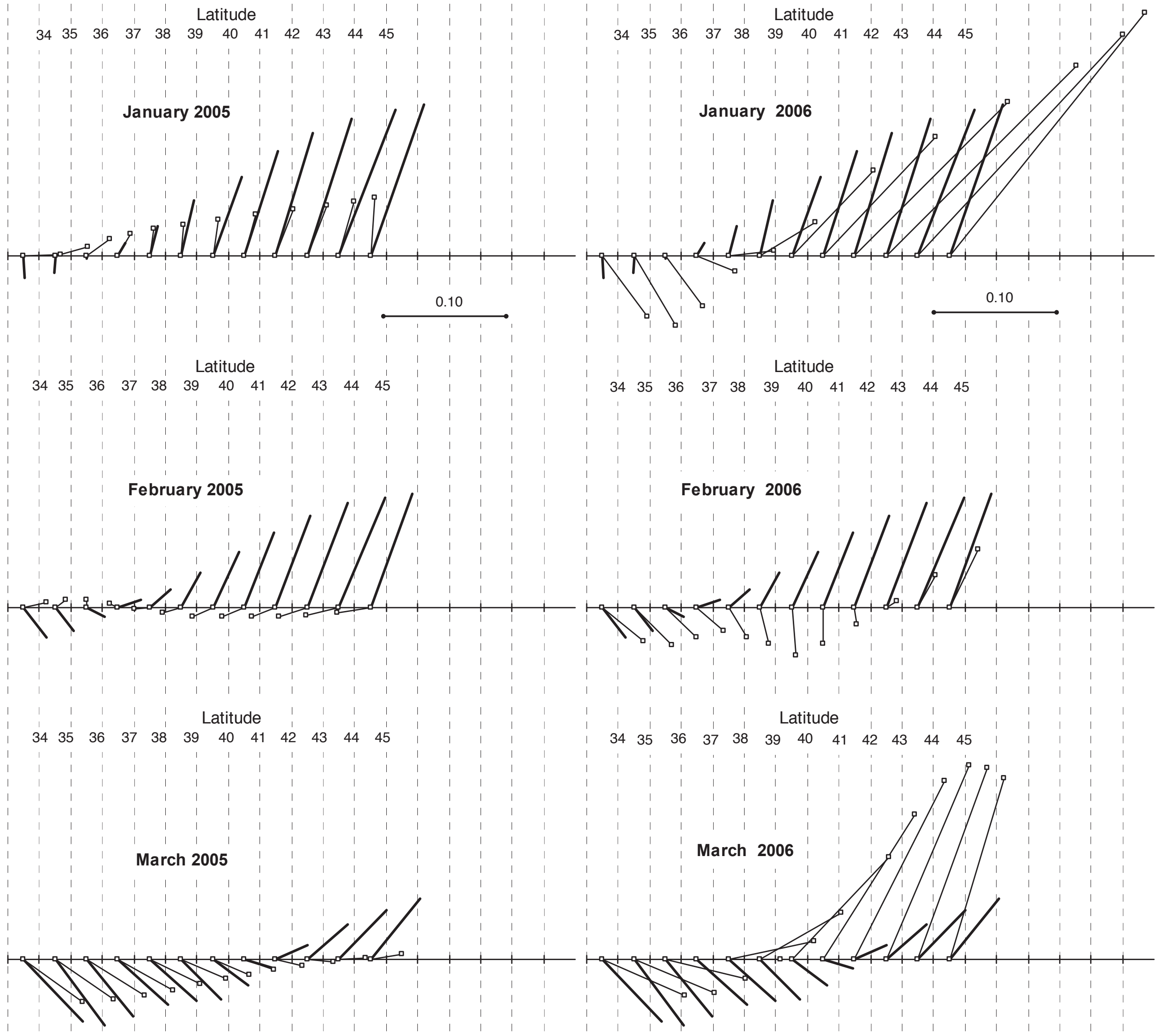

Figure 8. Latitudinal distributions of January–March wind stress vectors during 2005 and 2006 (fine lines with small open squares). Expected wind stress vectors based on climatological means are shown as bolded lines.

todes have been updated (*S. paucisipinis* [Field 2011] and *S. jordani*[3]), which indicate that 2005 and 2006 were relatively strong and weak year-classes, respectively. In contrast, both years appear to be weak for *S. goodei*. Hence, we conclude at this time that the peculiar spatial distributions that we describe would seem to offer little predictive capability vis-à-vis cohort strength. Nonetheless, this result should be investigated further when PFMC stock assessments for *S. entomelas*, *S. flavidus,* and *S. pinniger* are updated and recruitment time series become more reliably estimated.

Others have noted unusual conditions on the West Coast during the two years in question. In particular, Lindley et al. 2009 describe the failure of the 2004 and 2005 brood years of Sacramento River fall Chinook salmon, which precipitated unprecedented closures of California and Oregon ocean salmon fisheries in 2008 and 2009. In their evaluation of the potential causes of the brood year failures, Lindley et al. concluded that ocean conditions in the spring of 2005 and 2006, i.e., during outmigration from San Francisco Bay into the Gulf of the Farallons (lat. 37°–38°N), were responsible for the demise of those two cohorts. In particular, feeding conditions for juvenile salmon in those years were apparently very poor due to an absence of appropriate foods, which includes pelagic juvenile rockfish (Mills et al. 2007; Thompson et al. 2012; Thayer et al. in press). Likewise, there was a similar dearth of krill in the Gulf

[3] John Field, personal communication, SWFSC Santa Cruz, March 2013.

of the Farallons during May–June of 2005 and 2006 (Santora et al. 2011; Wells et al. 2012).

The general state of the California Current during these two years, including a characterization of both physical and biological conditions, is discussed in detail in Petersen et al. 2006 and Goericke et al. 2007. Both reports concluded that delayed upwelling, especially in the northern portion of the California Current, led to a delay in the production cycle (Schwing et al. 2006), with concomitant effects on the biological communities that depend on the seasonal availability of food resources (Takahasi et al. 2012; Thompson et al. 2012). Other studies highlighting anomalous conditions during this period include Dorman et al. 2011, who argue that advection of krill north of Cape Mendocino in 2005 led to their starvation; and Brodeur et al. 2006, who reported an anomalous species composition in the nekton community of the northern California Current. With regard to the central California forage community, results presented in Bjorkstedt et al. 2012 (figs. 23 and 24), also show that the community composition of the micronekton sampled by the SWFSC midwater trawl survey in the core area during 2005 and 2006 was extreme, being dominated by an offshore pelagic assemblage indicative of El Niño-like conditions.

The general consensus within the research community is that delayed upwelling, as described by Schwing et al. 2006, was responsible for these various events (Peterson et al. 2006; Goericke et al. 2007). It is worth pointing out, however, that Schwing et al. measured annual variation in upwelling relative to the regional climatologic mean date when cumulative upwelling becomes positive, a statistic that depends strongly on latitude (fig. 5). For example, reference calendar dates at the "start" of the upwelling season from their Figure 1 are: January 15th at 36˚N, March 1st at 39˚N, and March 25th at 42˚N. While relative temporal comparisons like this have some value, it may be more meaningful to undertake absolute temporal comparisons when considering the phenology of upwelling relative to the spawning season of exploited rockfish.

As an alternative, if at all locations one calculates cumulative upwelling statistics from a January 1st start date, cumulative upwelling during the "winter" mode (Black et al. 2011) in 2005 was actually greater than the climatology in the north (39˚ and 42˚N), whereas it was less than the climatology in the south (33˚ and 36˚N). The implication of this observation is that contemporaneous spatial variation in coastal upwelling during February–April of 2005 was greatly reduced, which we hypothesize influenced the subsequent spatial distribution of pelagic juveniles.

Because upwelling is largely driven by meridional winds, this alternative view of conditions in 2005 can be seen in Figure 7. Note for example that in 2005 there exists a substantial latitudinal gradient in February Z-scores, with negative values in the north and positive values in the south. Results presented in Figure 8 show that normal spatial variation in the wind field, as observed in the climatology, was altogether absent. Moreover, February 2005 zonal winds in central California were also quite unusual (fig. 6), being offshore from 36˚ to 45˚N (fig. 8). A consideration of the winds in 2006 reveals similarities and differences relative to 2005. Perhaps most similar is that February 2006 also showed a very divergent pattern relative to the climatology (figs. 6, 7, and 8). Meridional winds were southerly from 36˚ to 42˚N, when typically they are northerly. However, unlike 2005, January and March winds show greater spatial variability than would be expected based on the climatology.

February is a key month in the reproductive phenology of these species because that is when the annual production and accumulation of larvae is greatest (MacGregor 1986; Wyllie-Echeverria 1987; Love et al. 1990; Love et al. 2002; Ralston et al. 2003). *Sebastes* larvae are, moreover, vertically distributed in the mixed layer, primarily shallower than 50 m (Ralston et al. 2003; Auth et al. 2007). Consequently they are susceptible to advection due to the effects of surface wind stress. Under normal conditions, represented by the climatology, February winds north of 36˚N are poleward and onshore (fig. 6). Such winds would tend to maintain larvae on the continental shelf, due to the direct effect of the zonal wind stress and onshore Ekman transport (downwelling) arising from the meridional wind stress.

In the central California region, we conjecture that the anomalous wind stress fields that occurred in February 2005 and 2006 (fig. 8), which zonally and meridionally were opposite in direction from expectation, transported the larvae of winter-spawning *Sebastes* offshore into poleward flowing winter currents (Petersen et al. 2010; Dorman et al. 2011). Under this hypothesis, the dearth of pelagic juveniles in the core region of the survey during May–June of those two years was due to unusual advective processes during the larval period. In fact, the incidence of statistically extreme oceanographic conditions in the California Current, such as the wind stress events depicted in Figures 6 and 7, would seem to be increasing in frequency (Sydeman et al. in press). Those authors presented evidence suggesting that increasing variance in the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008) has resulted in a cascade of biological impacts on California populations of krill, juvenile rockfish, salmon, and seabirds, explaining in part the failure of the 2004–05 brood years of Sacramento River fall Chinook salmon (Lindley et al. 2009; Wells et al. 2012; Thayer et al. in press).

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