GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L22S08, doi:10.1029/2006GL026614, 2006

Anomalous pelagic nekton abundance, distribution, and apparent recruitment in the northern California Current in 2004 and 2005

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Received 17 April 2006; revised 5 July 2006; accepted 7 July 2006; published 30 September 2006.

[1] Although the California Current has undergone substantial environmental shifts in the past few decades, the summer of 2005 exhibited highly anomalous conditions relative to all previous recorded summers in terms of late initiation of upwelling and the resulting elevated surface temperatures and depressed productivity through July. The response of pelagic nekton to these anomalous conditions was widespread and included onshore and poleward displacement of taxa to new geographic areas, population changes within the normal range, and reduced productivity of early life stages based on larval and juvenile surveys. Some nekton exhibited anomalous distributions in 2004. Many ecologically important species were affected. The response of the nektonic community off California was greater than during El Niño conditions.
Citation: Brodeur, R. D., S. Ralston, R. L. Emmett, M. Trudel, T. D. Auth, and A. J. Phillips (2006), Anomalous pelagic nekton abundance, distribution, and apparent recruitment in the northern California Current in 2004 and 2005, *Geophys. Res. Lett.*, *33*, L22S08, doi:10.1029/2006GL026614.

1. Introduction

[2] The northern California Current Region (CCR) encompasses a highly dynamic eastern boundary current with marked seasonal and interannual fluctuations in along-shelf transport and upwelling intensity. It also has undergone substantial regime shifts, with subsequent effects rippling through all trophic levels [*Peterson and Schwing*, 2003]. There is also substantial interannual variability, imposed, in part, by the northern manifestation of the El Nino-Southern Oscillation (ENSO), which has a periodicity of roughly 3 years [*Lluch-Belda et al.*, 2005].

[3] Pelagic nekton, including juvenile and adult stages of marine fishes and cephalopods, are highly mobile and adept at finding suitable habitat within the range of their physiological needs in this highly fluctuating environment. The coastal pelagic nekton of the CCR is similar to other upwelling eastern boundary current regions in that biomass is dominated by a few species (anchovies, sardines, mackerels, hake), but also unique in the representation of salmon, herring, and smelt species.

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0094-8276/06/2006GL026614$05.00

[4] The nekton of the northern CCR is known through decades of research surveys [*Brodeur and Pearcy*, 1986; *Emmett and Brodeur*, 2000; *Brodeur et al.*, 2003] and a long history of commercial exploitation. Thus, the effects of unusual oceanographic events have been documented over time in terms of anomalous distribution or abundance of nekton [*Hubbs*, 1948; *Pearcy and Schoener*, 1987; *Pearcy*, 2002]. *Lluch-Belda et al.* [2005] reviewed the literature describing the occurrence of allochthonous plankton and nekton of mostly southern origin in the CCR and concluded that their northward movement had a periodicity of about 5 years, thus not coherent with the ENSO cycle.

[5] Conditions in the CCR were highly anomalous in the early summer of 2005, but not related to ENSO. Atmospheric blockage of the jet stream in spring and summer suppressed normal southward along-shore, upwelling-favorable winds, resulting in one of the latest onsets of upwelling on record [*Schwing et al.*, 2006]. Warm and low productivity conditions prevailed until about mid-July. Here we document changes in pelagic nekton and discuss likely mechanisms behind the observed anomalies.

2. Methods

[6] Early life history data are from ichthyoplankton and juvenile fish surveys off Oregon since 1996 [*Auth et al.*, 2005]. Larger juvenile and adult catch data are from pelagic nekton surveys conducted from northern British Columbia to central California. All net tows had the net either at the surface or at midwater [*Brodeur et al.*, 2003, 2005]. Surveys were conducted mainly during the spring-fall period of active upwelling in the CCR. Standard methodology and protocols were used within each sampling regimen so that seasonal and interannual comparisons could be made. Catch per unit effort (CPUE) data for the dominant taxa within the core sampling area of each region were summarized. Off central California, this included the 15 species (including juvenile rockfishes that are the primary target of these surveys) that make up the bulk of the catches each year. Off Oregon and Washington, night and repeat net tows were removed and any stations that were not sampled at least 5 of the 8 years examined were removed, and the remaining data examined for dominant taxa as in work by *Brodeur et al.* [2005]. To compare community structure among years, we used the frequency of occurrence of capture of each species for each year, excluding taxa that occurred in fewer than 10% of the total net tows from all years. Occurrence data were analyzed using a binomial General Linear Model that accounted for year and station effects [*Maunder and Punt*, 2004]. Year effects from the binomial GLM represent the annual estimated probabilities of a positive occurrence of a

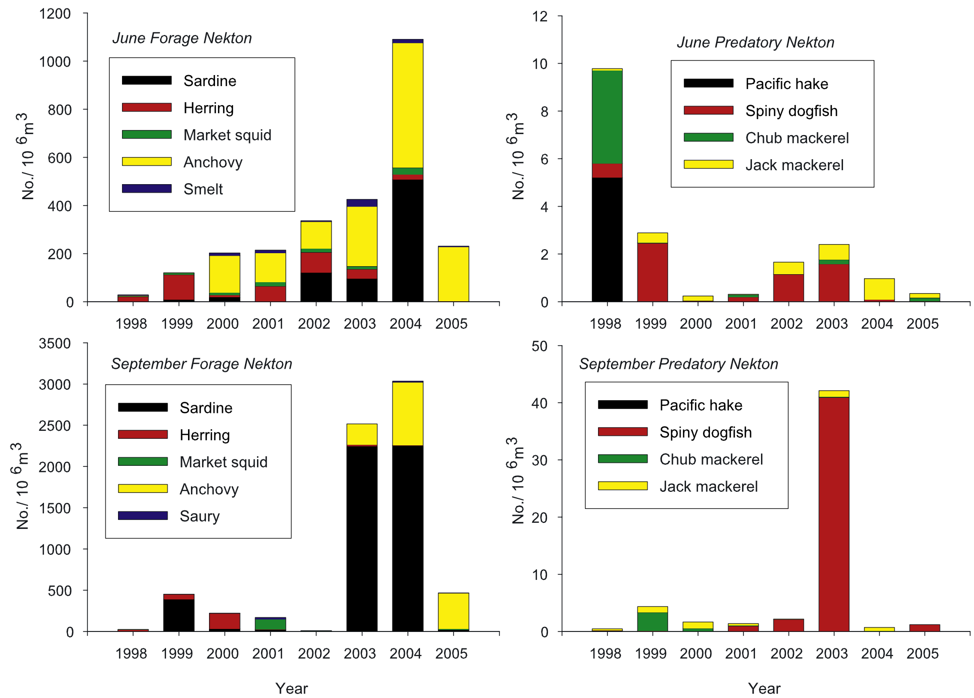

Figure 1. Time series of catches from daytime pelagic trawl surveys along the Washington and Oregon coasts from (top) June and (bottom) September 1998 to 2005 for (left) forage fishes and (right) predatory fishes.

taxon in a tow, accounting for any imbalance in the sampling of stations among years. These estimates were then arcsine-transformed and analyzed using Principal Component Analysis. Scores and loadings for PC1 and PC2 were plotted to reveal interannual variability in the species composition of the surveys.

3. Results

[7] Surveys indicated numerous distributional anomalies in both 2004 and 2005 (see auxiliary material[1]). Of particular note was the occurrence of larval and age-0 stages of both Pacific hake and jack mackerel from Oregon to British Columbia. Although both species occasionally spawn in the northern California Current, their primary spawning area is in the southern California Bight region, an area of low upwelling and high temperatures. However, early life stages of these species were captured in unprecedented numbers in ichthyoplankton and trawl surveys during both years, suggesting that their spawning area has shifted north by ca. 1000 km. Larvae of northern anchovy, which normally spawns in the Columbia River plume, were found at many inshore stations outside the plume, similar to that seen during the strong 1983 El Niño [*Brodeur et al.*, 1985].

[8] For adult fishes, ocean sunfish, an offshore species rarely found in coastal waters [*Brodeur and Pearcy*, 1986] were collected in high numbers off Oregon during September of 2004 and observed off Vancouver Island during both 2004 and 2005 (see auxiliary material) (Canadian Department of Fisheries and Oceans, State of the Pacific Ocean 2005, available at http://www.pac.dfo-mpo.gc.ca/sci/psarc/OSRs/StateofOceans2005fnl.pdf) (hereinafter DFO website). Similarly, Pacific butterfish, a species of southern origin, were extremely abundant in September 2005. Other noteworthy offshore species captured included Pacific pomfret (*Brama japonicus*), opah (*Lampris guttatus*), and yellowtail (*Seriola lalandi*): all were recorded as far north as British Columbia and southeast Alaska (DFO website). Unusually high numbers of sardines and anchovies were also captured off Southeast Alaska, suggesting a major expansion of their distributional range [*Wing*, 2006].

[9] Perhaps the biggest nekton distributional anomaly in both 2004 and 2005 was the widespread distribution of the Humboldt squid, *Dosidicus gigas*, along the West Coast of North America. This species, normally found off Central and South America [*Nigmatullin et al.*, 2001], was previously reported only as far north as Southern Oregon during the 1997 ENSO event [*Pearcy*, 2002]. These large, voracious predators were common from Oregon through Southeast Alaska during both 2004 and 2005 (see auxiliary material) [*Cosgrove*, 2005; *Wing*, 2006], and were targeted in sport fisheries and found washed up on west coast beaches.

[10] Among the dominant forage fishes from pelagic nekton surveys off Oregon and Washington in June, very high catches of Pacific sardine and northern anchovy were recorded in 2004, but the catches were lower and dominated almost entirely by anchovy in 2005 (Figure 1). Predatory fishes in 2004–05 were dominated by jack and chub mackerel (*Scombrus japonicus*) with almost a complete absence of Pacific hake and spiny dogfish (*Squalus acanthias*) (Figure 1). A substantial drop was recorded for juvenile salmonids and juvenile rockfish (*Sebastes* spp.) in

[1]Auxiliary materiala are available at ftp://ftp.agu.org/apend/gl/2006gl026614.

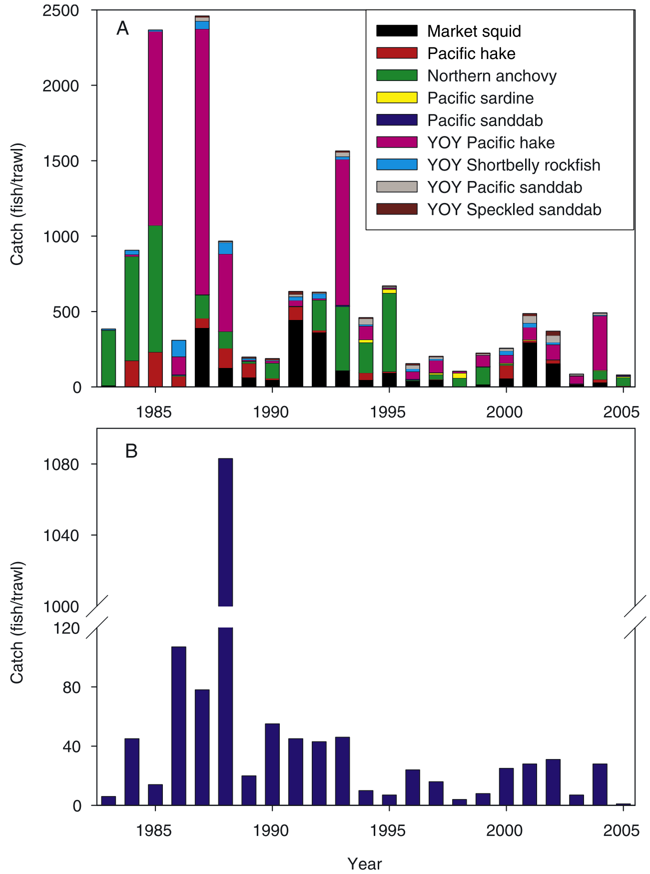

Figure 2. Time series of catches from pelagic trawl surveys along the central California coast from 1983 to 2005 for (a) the dominant nekton species and (b) juvenile rockfishes.

June 2005 [*Auth et al.*, 2005]. During September, there was a change in the forage fish abundances due to a major increase in sardine abundance starting in 2003, although they became relatively unimportant in 2005 (Figure 1). Predator densities were similar among years except for 2003, when large numbers of spiny dogfish occurred.

[11] In the central California region, there has been a long-term trend towards decreasing catches of the dominant species, due largely to reduced catches of young-of-the-year (YOY) Pacific hake and northern anchovy (Figure 2a). Average catch rates during 2003 and 2005 were the lowest for the entire series. Similarly, abundance during 2005 of YOY rockfishes was the lowest of the entire time series: even lower than during the ENSO event of 1998 (Figure 2b).

[12] The PCA for June off Oregon and Washington revealed a similar composition of nekton for 1998–2002, but has been anomalous since 2003 (Figure 3). Beginning in June 2003, a high occurrence of salmonids and other nearshore species resulted in very high positive factor loadings for PC1 (Figure 3). In 2004, high occurrence rates of anchovies and sardines drove the trend toward a high PC2 value, while 2005 shifted back to the lowest PC1 value of the years examined due to the occurrence of many offshore species. The PC scores (Figure 4) for September show that 2004 was more extreme than any other year, due to a high encounter rate of sardine, anchovy, and jack mackerel and low occurrence of all other taxa: the encounter rate of these three species was substantially above the long-term mean in 2004, whereas all other species were well below the mean.

[13] Off central California, the PCA showed that 2005 was the most anomalous year of the entire series, due to increased representation of southern and offshore species, including sardines, northern headlight fish (*Diaphus theta*), and blue lanternfish (*Tarletonbeania crenularis*) (Figure 5). The El Niño years of 1992 and 1998 showed the influence of southern species but not as much as 2005, while 2003 and 2004 were also more strongly influenced by offshore species.

4. Discussion and Conclusions

[14] A substantial number of nekton anomalies were observed during 2004 and especially 2005 in much of the northern CCR. These anomalies fell into three general classes: 1) northward or onshore distributional shifts,

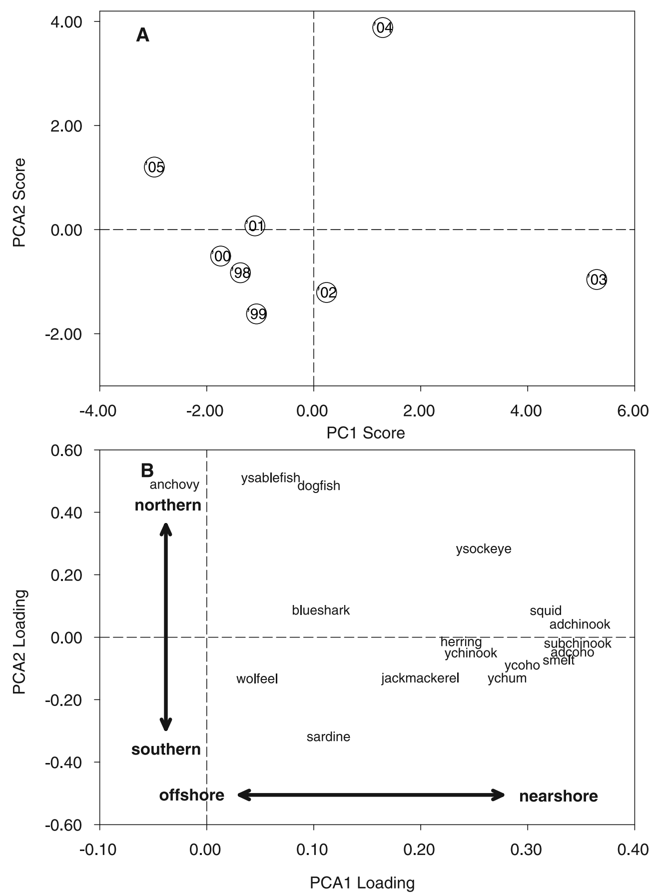

Figure 3. Principal Component Analysis biplot of the 17 most frequently occurring species collected in June trawl surveys off Washington and Oregon showing the first two Principal Components with (a) the factor scores for year and (b) the factor loadings for species. Arrows on the species plot show the main distributional factors associated with each component. Prefixes: y stands for 'yearling', the sub stands for 'subyearling', and the ad stands for 'adult' age classes.

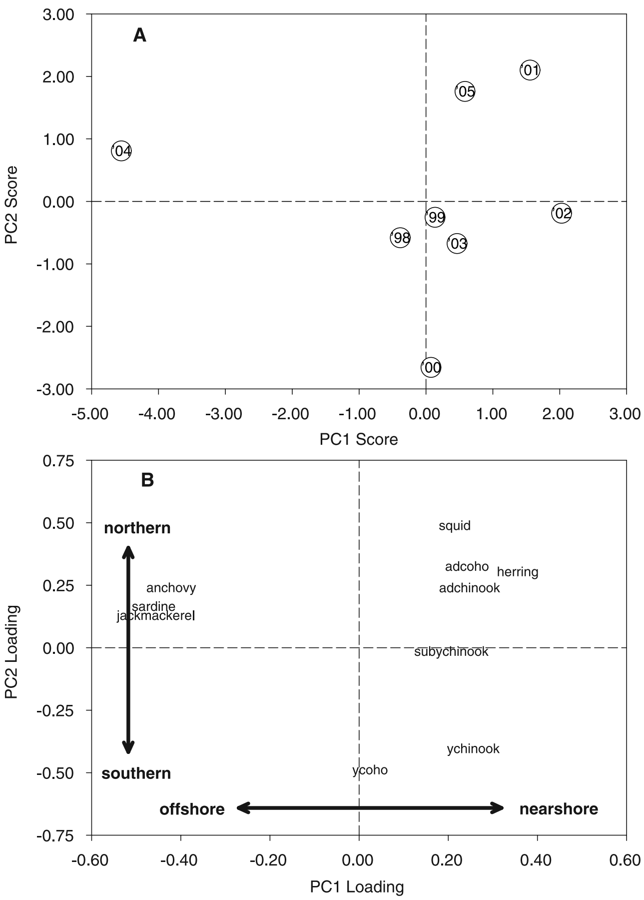

Figure 4. Principal Component Analysis biplot of the 10 most frequently occurring species collected in September trawl surveys off Washington and Oregon showing the first two Principal Components with (a) the factor scores for year and (b) the factor loadings for species. Arrows on the species plot show the main distributional factors associated with each component. Prefixes: y stands for 'yearling', the sub stands for 'subyearling', and the ad stands for 'adult' age classes.

2) abundance changes of dominant species, and 3) recruitment changes related to spawning shifts or lower survival of early life stages. Most of the anomalies are likely to be related to the unusual ocean conditions that started during 2004 [*Goericke et al.*, 2005] but extended up to at least August of 2005 when strong upwelling commenced [*Schwing et al.*, 2006]. A return to a relatively normal nekton community was seen by September of 2005, suggesting much resilience in this community in that many nekton found suitable habitat 'refuges' within their normal range or perhaps migrated to new areas until conditions returned to normal. The relatively warm and vertically-stable ocean conditions during the winter-spring of 2005 created conditions that expanded the spawning habitat of pelagic species such as sardines, anchovies, hake, and jack mackerel well to the north of their normal range. These species were all found north of their usual ranges for all their life history stages, although spawning was still observed in their normal habitat off southern California (N. Lo, SWFSC, La Jolla, personal communication, 2006). Surprisingly, the area south of Point Conception in California, a normal spawning habitat for these species, showed an opposing response to the northern CCR, with above-average phytoplankton [*Thomas and Brickley*, 2006], zooplankton [*Sydeman et al.*, 2006; D. L. Mackas et al., Zooplankton anomalies in the northern California Current system before and during the warm ocean conditions of 2005, submitted to *Geophysical Research Letters*, 2006] and juvenile rockfish catches (S. Ralston, unpublished data, 2005).

[15] The changes we observed in the distribution and abundance of many of the dominant nektonic species in the CCR will likely have substantial short- and long-term effects on the trophic structure of this ecosystem. The warm temperatures and low plankton production will likely affect the food web in ways similar to those observed during a strong El Niño, leading to longer and less productive food chains [*Brodeur and Pearcy*, 1992]. These changes are likely to affect juvenile stages and recruitment of many species (rockfishes, salmon, sardine) that are dependent on strong upwelling-based production. In addition to these bottom-up changes, the addition of exotic predators can upset the balance of the ecosystem. The ecological impacts

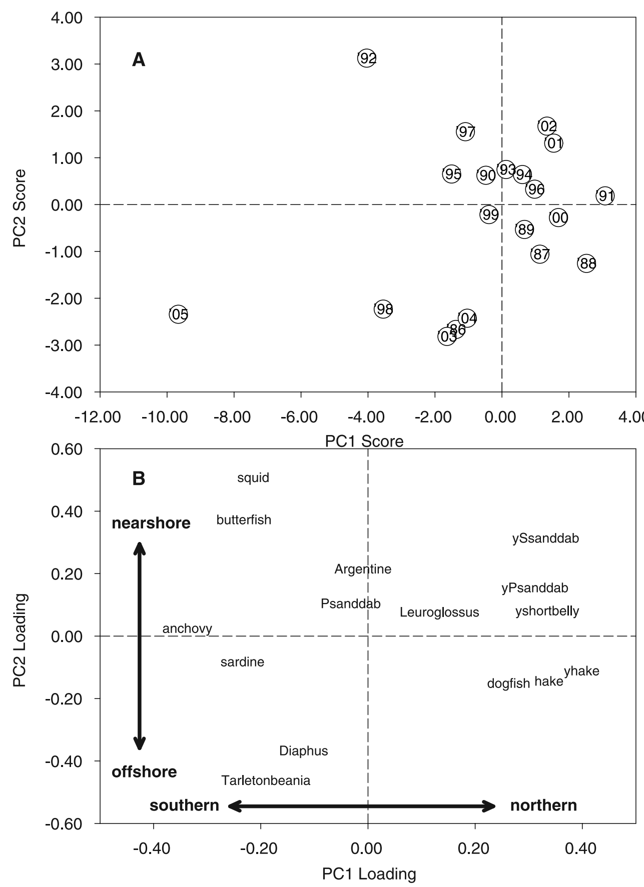

Figure 5. Principal Component Analysis biplot of the 15 most frequently occurring species collected in trawl surveys off central California showing the first two Principal Components with (a) the factor scores for year and (b) the factor loadings for species. Arrows on the species plot show the main distributional factors associated with each component. Prefixes: y stands for 'yearling' and the ad stands for 'adult' age classes.

of Humboldt squid in the northern CCR are unknown at this point, but may be quite considerable depending on their abundance. Humboldt squid have a short life-span (~1 year) and grow quite rapidly to 30–50 kg as adults [*Nigmatullin et al.*, 2001]. As a consequence, they are voracious feeders and have the potential to eat large quantities of fish [*Ehrhardt*, 1991]. In addition, other species not quantitatively sampled in our surveys, such as blue (*Prionace glauca*) and thresher (*Alopias vulpinus*) sharks and albacore tuna (*Thunnus alalunga*), were extremely abundant on the shelf in 2004 and early summer of 2005 and likely became important predators on juvenile rockfishes, salmon, and other forage fish species (R. D. Brodeur, unpublished data, 2005). The lack of small forage species commonly utilized by seabirds and marine mammals was evident, especially in 2005, and may affect the survival of these important predators [*Sydeman et al.*, 2006]. In some cases a net loss in one region was offset by a gain in another region (e.g., sardines moved from Oregon to British Columbia or Southeast Alaska [*Wing*, 2006]), but the overall net effect on the CCR is likely to be negative. These impacts may be amplified over multiple year classes, resulting in long-term effects on the ecosystem and fishery. The 2004–05 anomaly provides information on the manner and scale of the response of nektonic organisms in the northern CCR to extreme environmental perturbations, which, together with existing historical data sets, could further efforts to model future changes in fish stocks based on environmental fluctuations.

[16] **Acknowledgments.** Funding for collection of the data comes from NOAA Fisheries (Stock Assessment Improvement Program, Fisheries and the Environment Initiative), Bonneville Power Administration, and Fisheries and Oceans Canada. We thank our many colleagues who go to sea to help collect samples and Suzan Pool for database assistance. S. McKinnell, D. Reese, W. Pearcy, W. Peterson, and an anonymous reviewer provided helpful comments on earlier versions of the manuscript. This is contribution 307 of the U.S. GLOBEC program.

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