

Inverse regional responses to climate change and fishing intensity by the recreational rockfish (*Sebastes* spp.) fishery in California

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Abstract: The interactive effects of ocean climate and fishing pressure on nearshore rockfishes (*Sebastes* spp.) were examined using historical commercial passenger fishing vessel catch records from California. Principal component analysis was used to characterize the dominant patterns in catch per unit effort (CPUE) over time (1957–1999) and space (10' latitude × 10' longitude blocks). Ocean climate explained 60% of the variation in CPUE and revealed opposite responses in northern and southern California. In warm El Niño years, CPUE was 4.2 times higher in the north and 1.8 times lower in the south. CPUE responded similarly to low-frequency climate shifts by increasing in the north and decreasing in the south after 1976–1977. Four geographic regions responded as discrete units to environmental forcing and fishing intensity: North, Central, South, and Channel Islands. Over time, annual fish landings declined sharply in the South, with fishing effort remaining stationary and high relative to that in the other regions. In the North, landings and fishing effort remained tightly coupled, with effort an order of magnitude lower than in the South. These findings support a management strategy for nearshore rockfishes in California based on regional responses to ocean climate and fishing intensity.

Résumé : Nous avons examiné les effets interactifs du climat océanique et de la pression de la pêche sur les sébastes (*Sebastes* spp.) de la région côtière en étudiant des données de pêche des années antérieures provenant des bateaux à passagers de pêche commerciale (« Commercial Passenger Fishing Vessels ») de Californie. Une analyse des composantes principales a servi à identifier les principales tendances des captures par unité d'effort (CPUE) dans le temps (1957–1999) et l'espace (des surfaces de 10' latitude × 10' longitude). Le climat océanique explique 60 % de la variation des CPUE; les réactions sont cependant opposées dans le nord et le sud de la Californie. Les années chaudes d'El Niño, les CPUE sont 4,2 fois plus élevés dans le nord et 1,8 fois plus bas dans le sud. Après 1976–1977, les CPUE réagissent de la même façon aux changements climatiques de faible fréquence en croissant dans le nord et en diminuant dans le sud. Quatre régions géographiques réagissent comme des unités indépendantes au forçage environnemental et à l'intensité de la pêche, soit les régions du nord, du centre, du sud et des îles Channel. Au cours des années, les débarquements annuels de poissons ont diminué de façon marquée dans le sud, malgré des efforts de pêche constants et élevés par comparaison aux autres régions. Dans le nord, les débarquements sont restés fortement liés à l'effort de pêche, alors que l'effort est 10 fois moindre que dans le sud. Ces observations appuient la mise en oeuvre d'une stratégie d'aménagement des sébastes côtiers de Californie basée sur leurs réactions régionales au climat océanique et à l'intensité de la pêche.

[Traduit par la Rédaction]

Introduction

Fishing pressure and climate change are primary drivers of interannual variability and long-term declines in many marine populations. While the ecological and socioeconomic

consequences of overfishing are widely documented (Kurlansky 1997; Dayton et al. 1998; Pauly et al. 2002), we are just beginning to understand the confounding effects of interannual and interdecadal climate change (Glantz 1992; Beamish 1995; Bjørnstad and Grenfell 2001). Direct effects

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of climate change on populations arise primarily from changes in sea temperature that can lead to reproductive impairment, recruitment failure, and shifts in distribution (Murawski 1993; Barry et al. 1995; Crawshaw and O'Connor 1996). Indirect effects on population abundances are typically attributed to complex changes in marine productivity and food-web dynamics (Francis and Hare 1994; Roemmich and McGowan 1995; Koslow et al. 2002). In many of these cases, however, obtaining evidence for bottom-up regulation of food webs depends on the quantity and quality of long-term monitoring information and the strength of statistical linkages between environmental and biological time series (Francis and Hare 1994; Koslow et al. 2002). This emphasizes the need to better understand the mechanisms underlying these direct and indirect pathways, as well as how they might interact with fishing pressure to undermine effective management (Hilborn et al. 1995; Dayton et al. 1998).

Many fisheries are severely depleted. Overfishing has occurred, in part, because management strategies did not recognize adverse climatic effects and adjust fishing pressure appropriately (Glantz 1992). This remains a problem even in well-understood systems. In data-poor fisheries, wide disparities in the amount and quality of long-term information will hamper efforts to decipher complex effects of climate change. In recognition of these limitations, as well as inherent uncertainties in forecasting, both fixed and variable management strategies have been proposed to accommodate unforeseen climate changes and their effect on fisheries (Walters and Collie 1988; Walters and Parma 1996; MacCall 2002). The extent to which each of these alternatives ameliorates climatic effects on fisheries depends on the underlying ecology of individual populations. For example, to withstand decadal-scale climate changes, long-lived species may benefit from a conservative fixed strategy that accounts for lower production, while a variable management strategy that more closely tracks environmental conditions appears to better suit short-lived species (MacCall 2002). Optimal management of fishery impacts will thus require strategies tailored to specific cases, raising the bar for investigators to identify key mechanisms of climatic effects (Walters and Collie 1988; Walters and Parma 1996; MacCall 2002).

In the Southern California Bight, it is generally recognized that a positive shift in the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), coupled with frequent El Niño events, severely limited recruitment success in the rockfish (*Sebastes* spp.) fishery complex after 1976–1977. Warmer seas and reduced upwelling during this period are associated with dramatic declines in zooplankton abundance (Roemmich and McGowan 1995) and juvenile rockfish survival (Holbrook et al. 1997; Love et al. 1998a, 1998b). A concurrent weakening of the southward flow of the California Current also reduced larval-supply rates for several of the more commonly fished species near the southern boundaries of their ranges (MacCall 1996; Love et al. 1998a). The effects of climate change on recruitment, combined with intense fishing pressure on adults, probably contributed to declines in rockfish abundances in the Southern California Bight (Love et al. 1998b). Seven deep-water species are now considered overfished and severe fishing restrictions have been implemented (Ralston 2002). Similar signs of overfishing of shallow-water species have also been observed in central California

(Mason 1995, 1998) and are suspected to exist statewide (Karpov et al. 1995). In the past, fishing regulations were implemented statewide, yet the ecology of many species, and socioeconomic characteristics, suggest that the fishery may benefit from management tuned to a finer regional scale. Climatic forcing may also operate at regional scales. Moreover, few studies have explored the historical contributions of fishing and climate changes in a common context or have defined the geographical scales at which regions may respond differently.

Here we examine simultaneous effects of climate change and fishing intensity in the nearshore recreational fishery for rockfish in California. The nearshore fishery, as defined by the California Department of Fish and Game (<http://www.dfg.ca.gov/mrd/nfmp/index.html>), is composed primarily of 19 shallow-water-dwelling fishes, including 13 of the more than 60 species of rockfishes (genus *Sebastes*) that occur in the eastern Pacific Ocean (Love et al. 2002). We use historical catch records from commercial passenger fishing vessels (CPFV) in concert with environmental data sources to test the working hypothesis that the California nearshore fishery responds in a geographically heterogeneous way to shifts in climate regime. If the null hypothesis (a homogeneous response among regions) is falsified, then management may need to recognize boundaries among regions that have responded as coherent units to climatic forcing and fishing pressure.

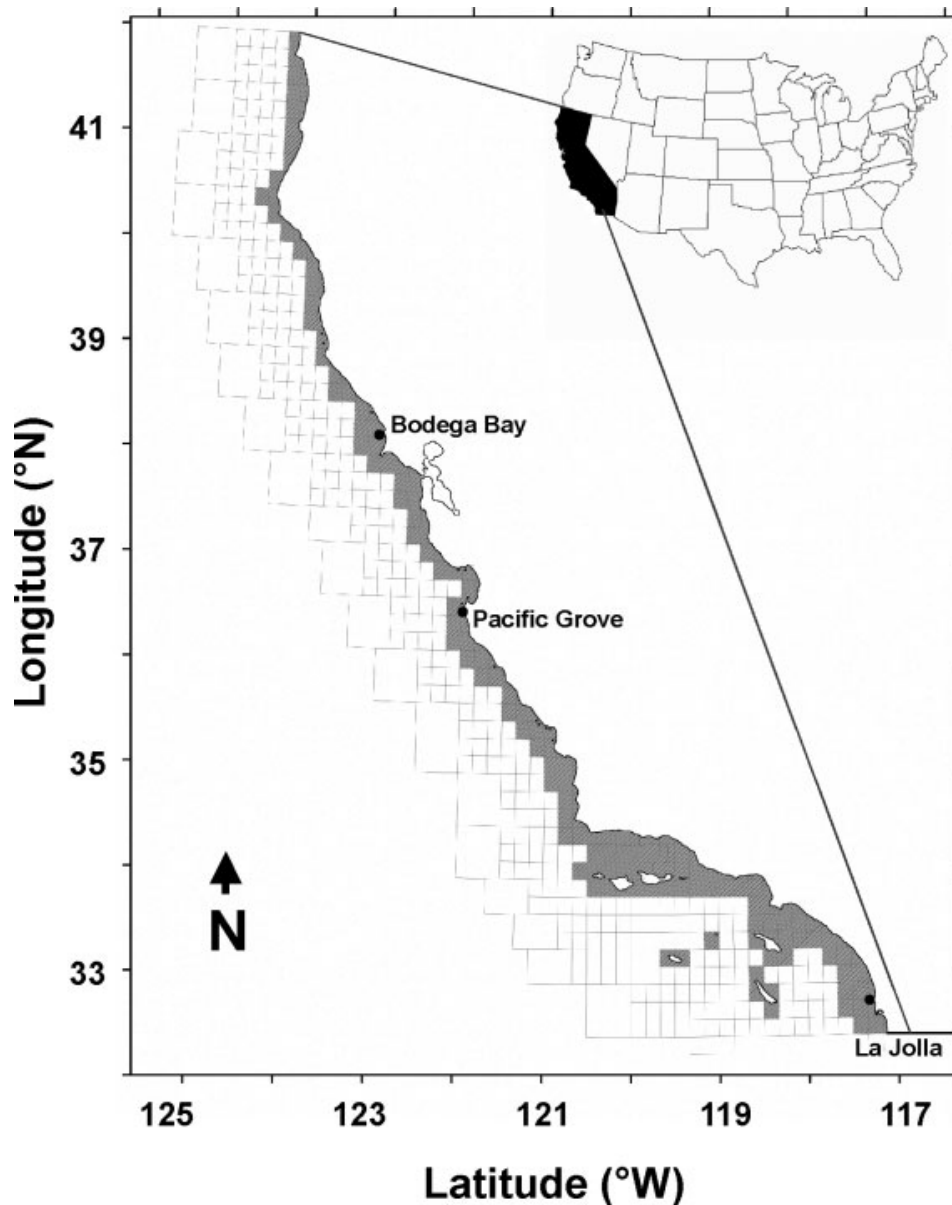
Methods

Data sources

The CPFV logbook records, administered by the California Department of Fish and Game, contain spatially explicit long-term records of fish landings by the California recreational charter boat, or party-boat, fishery. Since 1936, party-boat owners and operators have been required by law to record daily catch and location at which most fishing occurred. Locations are recorded using a grid of geographical blocks, 10' latitude × 10' longitude, encompassing the coastal Pacific Ocean off California (Fig. 1). We used monthly summaries of the CPFV records recently compiled by Hill and Schneider (1999) for 1936–1999 (with only annual summaries available for 1979). The CPFV data are known to contain several sources of reporting bias. These include irregular compliance and problems with accuracy (Karpov et al. 1995; Mason 1995, 1998). Consequently, we began our investigation under the assumption that such inaccuracies will be randomly distributed across the data when summarized at broad taxonomic, temporal, and geographical scales. Accordingly, we were restricted to using a generic rockfish category in our analyses because in most years all rockfish species are recorded as a single taxonomic group, and even when they have been broken out by species, some identifications are incomplete or suspect. In a few recent years and locations, various rockfish were categorized by species, and these records were pooled with the rockfish category.

To help focus our attention on trends in the nearshore fishery, we compiled seasonal and annual summaries of catch per unit effort (CPUE) for the two tiers of blocks closest to the coastline (Fig. 1). We examined data from the entire period 1936–1999; however, we confined multivariate analyses to

Fig. 1. Map of the California coastline showing the spatial grid of blocks (10' latitude \times 10' longitude) used to report landings and effort (angler-hours) by commercial passenger fishing vessels (CPFV). The shaded blocks are those used in analyses for the nearshore component of the rockfish (*Sebastes* spp.) fishery. Also shown are the locations of the shoreline stations recording sea-surface temperatures at Bodega Bay, Pacific Grove, and La Jolla.



the years 1957–1999 because for previous years records are sparse north of Point Conception. Our measure of CPUE consisted of the total number of rockfish caught divided by the number of angler-hours, a measure of effort computed by multiplying the total hours fished by the number of fishers on board (Hill and Schneider 1999). We further refined our effort measure by weighting the total number of angler-hours by the proportion of salmon (*Oncorhynchus* spp.), albacore (*Thunnus alalunga*), white seabass (*Atractoscion nobilis*), and California halibut (*Paralichthys californicus*) in the total catch. Few rockfish are caught when party boats target pelagic or sandy-bottom species. Therefore, this adjusted effort helped to account for annual and seasonal trends in the number of hours spent seeking other

highly prized species that inflate effort with respect to rockfish landings.

We analyzed the CPFV data with several sources of environmental data that served as proxies for climate change. These included sea-surface temperatures (SSTs) and an index for the PDO. SST records from three shoreline stations located at Bodega Bay (Bodega Marine Laboratory), Pacific Grove (Hopkins Marine Laboratory), and La Jolla (Scripps Institute of Oceanography) were used to examine potential high-frequency temporal responses (e.g., El Niño) in different regions in northern, central, and southern California (Fig. 1). The PDO index was used to reflect potential low-frequency temporal responses (e.g., interdecadal) to regional climate change. Missing values in the Pacific Grove temper-

ature records for 3 years (1975–1977) were supplied using temperatures from the Bodega Bay station adjusted upward by the long-term mean difference (2 °C) between these shoreline stations. Most of the SST and PDO index data were obtained over the internet at <http://www-mlrg.ucsd.edu/shoresta/> and <http://tao.atmos.washington.edu/pdo/>.

Statistical analyses

We first explored the CPFV data with graphical methods on an annual and reporting-block basis, and then used principal component analysis (PCA) to summarize dominant patterns among the CPFV records over time (1957–1999) and space (blocks along the coastline). PCA examines patterns of covariance (or correlation) among variables in a matrix, and reduces multivariate data to a few uncorrelated indices, or principal components (Chatfield and Collins 1980). If excessive fishing pressure or extreme climatic events influence rockfish CPUE among years and locations, we might expect this variation to be partitioned among one or more principal components. We devised a tiered approach, using PCA on two forms of CPFV data matrices. For our initial analysis, we constructed a matrix using annual adjusted CPUE for blocks that consistently recorded rockfish landings. The columns of the matrix representing years ($n = 43$) and rows ($n = 70$) were reporting blocks. Then, PCA was computed from a covariance matrix. Because we were interested in uncovering potential causal mechanisms, we rotated selected components in n dimensional space ($n =$ number of components) to identify modes of variation (Jassby 2000). We used the scree test method to select the major axes, defined as those principal components below and at the inflexion point in the slope of a cumulative-variance plot (Chatfield and Collins 1980). Each chosen component was then rotated using the orthogonal (varimax) and oblique (promax) methods. After rotation, we interpreted each mode by examining its factor loadings, or coefficients, which essentially measure the covariance between the original variables and a particular mode. In this case, the coefficients reflect interannual variation in CPUE. We also examined the mode scores, or amplitudes, which measure the relationship of each row element (or reporting block in this case) to each mode.

Because only the dominant mode of variation was readily interpretable, we devised a second PCA analysis in which we transposed and reduced the dimensions of the original matrix to facilitate interpretation of the modes of variation (Jassby et al. 1990; Jassby 2000). This dominant mode responded sharply to climate, therefore we condensed the initial matrix into regional-block groups according to a scheme based on latitudinal trends in CPUE between El Niño and La Niña years. This reduced the spatial dimension of the blocks into four distinct regions (North, Central, South, Channel Islands). We then used the monthly pattern of serial correlation in CPUE as a guide to define seasons (three seasons: January–April; May–August; September–December). This resulted in a 12×42 matrix, where the columns represent the CPUE for each of the three seasons and four regions, and the rows are years. As before, PCA from a covariance matrix was run and a scree graph was used to determine the number of principal components to be rotated using the varimax and promax methods. Now the coefficients associated with each mode would represent patterns of variation among

regions and seasons, and the amplitudes would reflect temporal variation within regions and seasons for each mode.

To associate potential causal mechanisms with the modes of variation derived from the CPFV data, we first used graphical methods to explore the assumptions of various statistical models. We then used least-squares regressions if the assumptions were met by the data. If data did not fit the assumptions of normality and homoscedasticity we used generalized linear regression, and if they contained outliers we used robust regression, an iterative reweighting least squares procedure (Venables and Ripley 1997). Finally, we used multiple regressions to examine additive and interactive effects of environmental variables and fishing pressure. Residuals from model fits were examined for normality and autocorrelation. Significance levels were adjusted for models exhibiting autocorrelation in the residuals using the technique described by Pyper and Peterman (1998) that is robust to moderate levels of nonstationarity in time series. Model fits between ordinary and multiple regressions were evaluated using Akaike's Information Criterion (AIC) that penalizes the log-likelihood of the residual sum of squares according to the number of fitted parameters (Burnham and Anderson 1998). All statistical analyses were performed using the S-PLUS statistical language (Venables and Ripley 1997).

Results

Following the initial PCA a scree plot of cumulative variance indicated that three principal components could be retained for rotation (Fig. 2). These three components explained 81% of the variation in CPUE, with 60% explained by the first component, 11% by the second, and 10% by the third. The results after rotation by the varimax and promax methods were similar, so here we present only the varimax solutions that retain an orthogonal orientation among modes (Chatfield and Collins 1980; Jassby 2000).

The time series of the coefficients for mode 1 reflect a strong climate-induced signal in CPUE (Fig. 3). Large coefficients correspond to El Niño years (e.g., 1983, 1992, 1997), whereas small coefficients correspond to La Niña years (e.g., 1971, 1974–1975) following year-type classifications by the National Oceanic and Atmospheric Administration Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html). In addition, the coefficients increase overall after 1977, suggesting a response to the PDO (Mantua et al. 1997). Regressions using mode 1 as the dependent variable with annual mean SST from each shoreline location and the PDO index as independent variables were significant in all cases except for Pacific Grove (Table 1). This suggests that approximately 60% of the temporal variability in annual CPUE (mode 1) is associated with changes in ocean climate. However, temporal patterns in the coefficients for modes 2 and 3, as well as the mode amplitudes, were not readily interpretable.

Latitudinal trends in annual CPUE between El Niño and La Niña years showed distinct responses to climate change along the California coastline (Fig. 4a). CPUE is, on average, 4.2 times higher in El Niño years than in La Niña years in northern California (where the El Niño years were 1983, 1992, and 1998 and the La Niña years were 1971 and 1974–1975) when the means of three fitted lines are compared us-

Fig. 2. Scree plot from principal components analysis of annual rockfish (*Sebastes* spp.) catch per unit effort (CPUE) from commercial passenger fishing vessel recording blocks along the California coastline. Variances (left-hand axis) are shown with cumulative variance (right-hand axis).

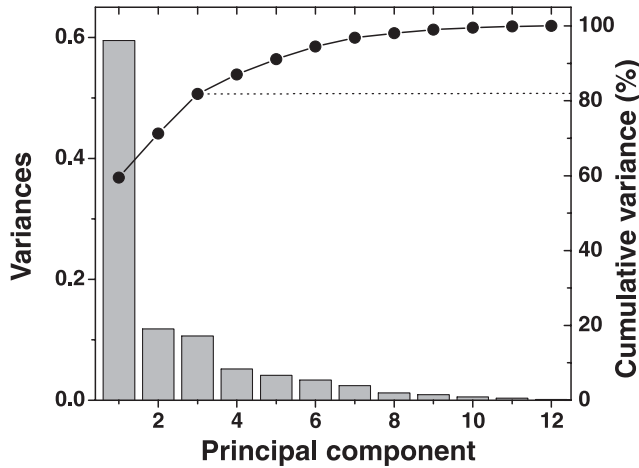
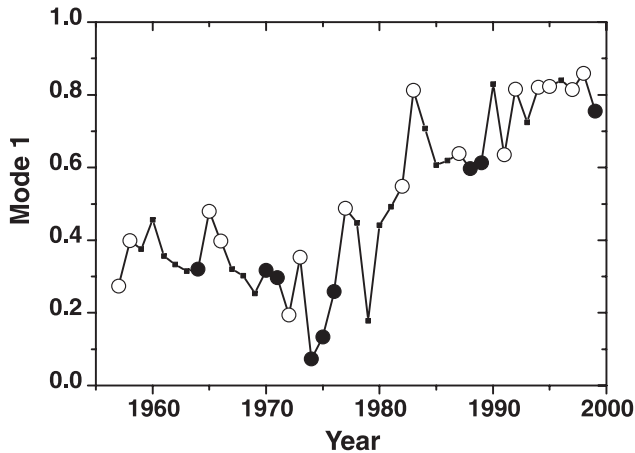


Fig. 3. Time courses of coefficients (loadings) for mode 1 determined from varimax rotation of the first three principal components. Also shown are loadings corresponding to El Niño years (○) and La Niña years (●).



ing local regressions (loess, degree = 1, fraction = 0.5; Cleveland 1993) (Fig. 4b). Conversely, CPUE is, on average, 1.8 times lower in warm-water years relative to cool-water years in southern California (south of Point Conception, recording blocks ≥ 651) (Fig. 4b). Central California (blocks $\geq 454, \leq 643$), ranging from San Francisco Bay in the north to Point Conception in the south, appears to be a region of transition between these opposing patterns, so that the northern boundary fluctuates depending on the signature of particular climatic events (Fig. 4b). For example, during the 1983 El Niño, fishing success remained higher than that observed in cool-water years until Morro Bay (Fig. 4b). Maximum CPUE in the fishery also typically occurs at Morro Bay. Based on the points at which these fitted lines intersect and diverge between cool- and warm-water years, we defined boundaries separating three regional bins to be used in our final PCA analysis (hereinafter North, Central,

Table 1. Regression results for the first principal component (mode 1) of catch per unit effort (CPUE) from commercial passenger fishing vessels versus sea-surface temperature (SST) at shoreline stations, and an index for the Pacific Decadal Oscillation (PDO).

Environmental variable	df*	Mean	SE	P†
SST-recording station				
Bodega Bay	21	0.19	0.06	<0.01
Pacific Grove	21	0.094	0.115	>0.2
La Jolla	11	0.25	0.05	<0.0001
PDO index	11	0.196	0.046	<0.01

*Effective degrees of freedom.

†Adjusted for autocorrelation.

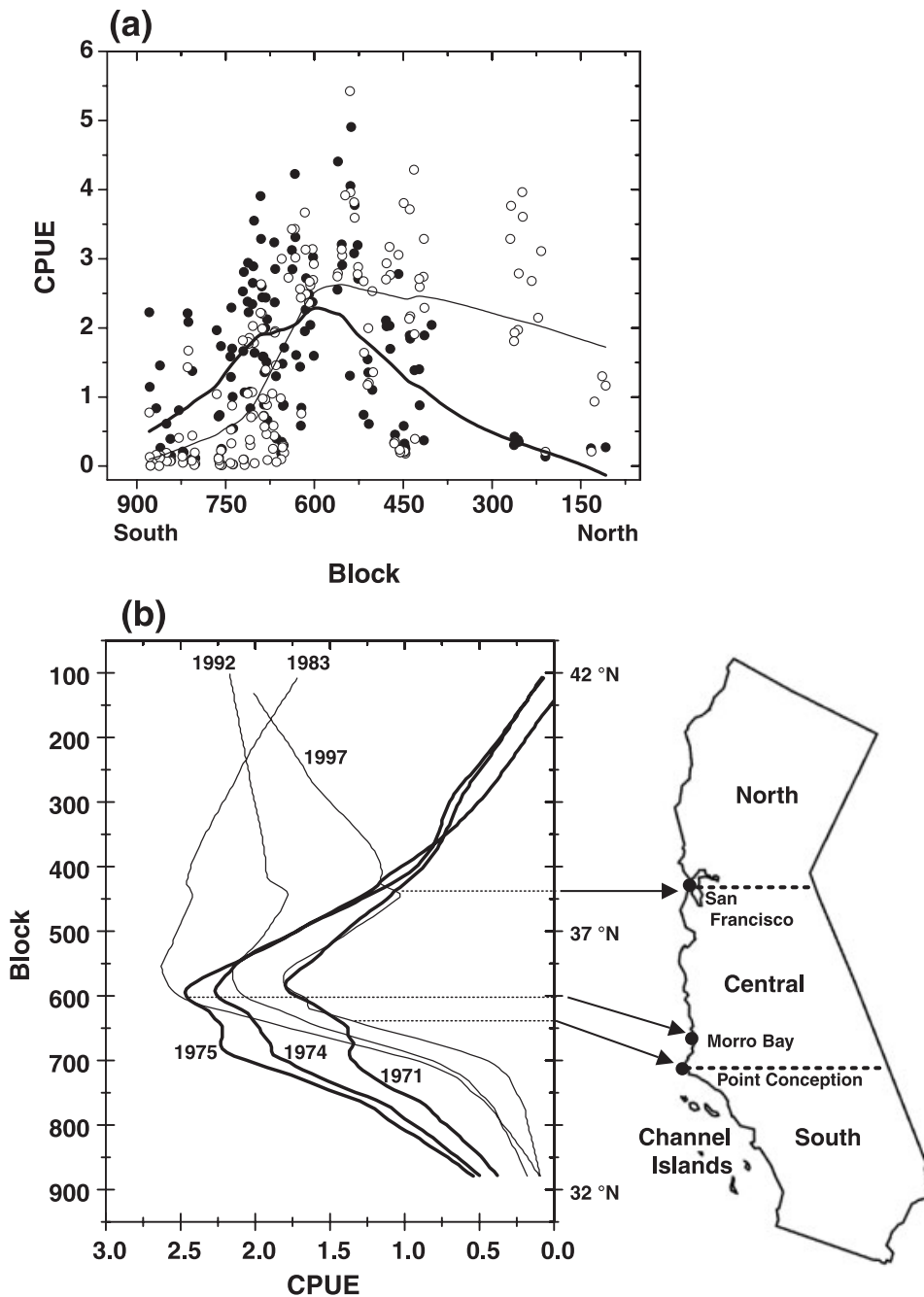
and South). We also defined a fourth regional bin encompassing the Channel Islands to examine potential differences in the response of mainland and island fishing grounds.

A scree plot from the PCA analysis using the regional and seasonal matrix showed that the first three principal components again account for about 80% of the variation in CPUE, this time among regions and seasons. The first principal component explains 69% of the variation, with the second and third components explaining only 8% and 6%, respectively. These three components were rotated, and the coefficients of each mode of variation are displayed by region and season in eigenmaps to facilitate interpretation (Fig. 5) (Jassby et al. 1990; Jassby 2000). The coefficients for mode 1 are consistently high across seasons in the South and Channel Islands regions and low in the North region (Fig. 5a). The Central region again transitions between North and South. Mode 2 is the mirror image of mode 1, with the North region now exhibiting the highest coefficients (Fig. 5b). Coefficients for mode 3 show seasonal differences, indicating that patterns in CPUE are similar in the South and Channel Islands regions during winter and early spring and in the North in summer and early fall (Fig. 5c). Overall, the South and Channel Island regions reflect similar patterns of variation.

The amplitude time series confirm that the modes reflect distinct patterns of CPUE in each region (Fig. 5). A time series for CPUE averaged over the South region is nearly identical with that for the coefficients of mode 1 (Fig. 5a). Moreover, mode-2 coefficients clearly reflect temporal variability in North-region CPUE (Fig. 5b), while mode 3 describes Central-region CPUE (Fig. 5c). Mode-1 coefficients and South-region CPUE both appear unimodal, reaching a maximum in 1975 (Fig. 5a). Conversely, the temporal trend for mode 2 and North-region CPUE appears to contain a climate signal, with higher values occurring in 1977, 1983, and 1991–1992 (Fig. 5b). Mode-3 coefficients and Central-region CPUE, however, are highly variable. After adjusting for significant autocorrelation, regressions among environmental variables and trends in regional CPUE are significant at the <0.05 level in all cases except the Central and Channel Islands regions and the PDO index (Table 2). Regressions with regional SST, PDO index, and CPUE are positive in the North and Central regions, whereas they are negative in the South and Channel Islands regions (Table 2).

Patterns shown by time trends in seasonal CPUE are also opposite in the northern and southern regions and are gener-

Fig. 4. (a) Annual CPUE for commercial passenger fishing vessel recording blocks along the California coastline in 1983 (El Niño year; thin line) versus 1974 (La Niña year; thick line), with local regression fits using loess (fraction = 0.5). (b) Loess fits to CPUE between 3 El Niño and La Niña years. Horizontal lines and arrows designate locations along the California coastline of maximum CPUE and key intersection points between trends in El Niño years (1983, 1992, 1997; thin lines) and La Niña years (1971, 1974, 1975; thick lines) used to define regional boundaries.



ally consistent with seasonal differences in SST (Fig. 6a). CPUE is consistently higher from May to December in the North and Central regions, although mean SSTs are only about 1 °C higher than those from January to April (Fig. 6a). In the South and Channel Islands regions, however, this pattern is reversed, with maximum CPUE occurring during the January–April season, when SSTs are about 2.5 °C lower than at other seasons (Fig. 6a). These seasonal patterns are also evident in the coefficients for mode 3 plotted in the eigenmap (Fig. 5c).

Interannual trends in levels of fishing effort and numbers of rockfish landed are distinct in each of the southern regions (Fig. 6b). In the South, CPFV records extend back to 1936, with a gap in reporting during World War II. The annual catch has averaged 463 000 rockfish, yet the trend is sharply bimodal, with a minor peak occurring in 1955 (about 900 000 fish) and a major peak in 1974 (about 1.6 million fish) (Table 3). Clearly, fish landings have plummeted in recent years (Fig. 6b). The trend in fishing effort, however, has remained stationary and high, averaging over 1 million

Fig. 5. Eigenmaps showing space–time magnitudes of coefficients for three modes (*a*, *b*, *c*) determined from varimax rotation of three principal components. Space bins are regions along the California coastline, North (N), Central (C), South (S), and Channel Islands (CI), and time bins are seasons, January–April (S1), May–August (S2), and September–December (S3). Also shown are the time courses in the amplitudes (thick lines) with the mean CPUE (thin lines) from the South (*a*, mode 1), North (*b*, mode 2), and Central (*c*, mode 3) regions.

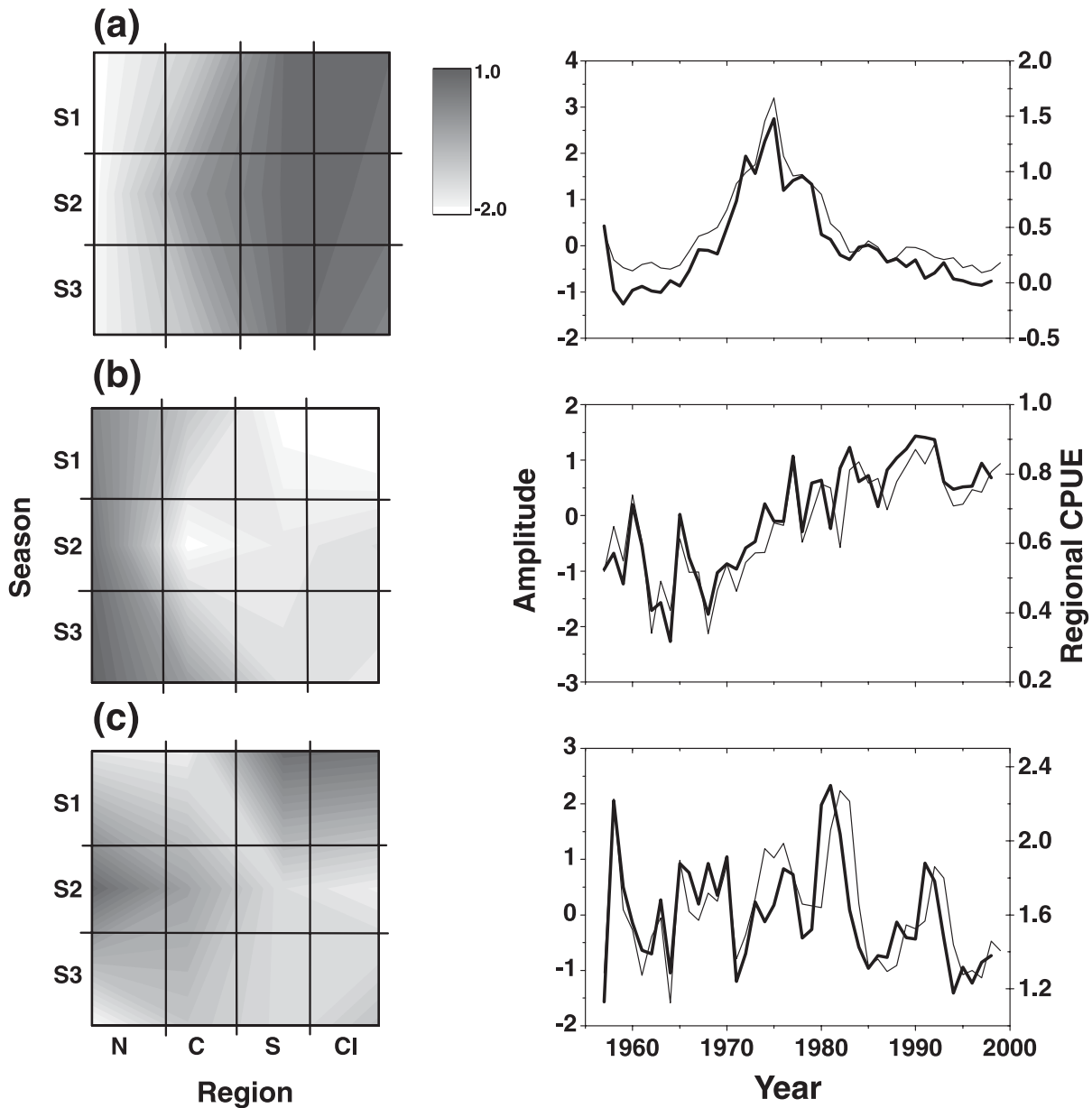


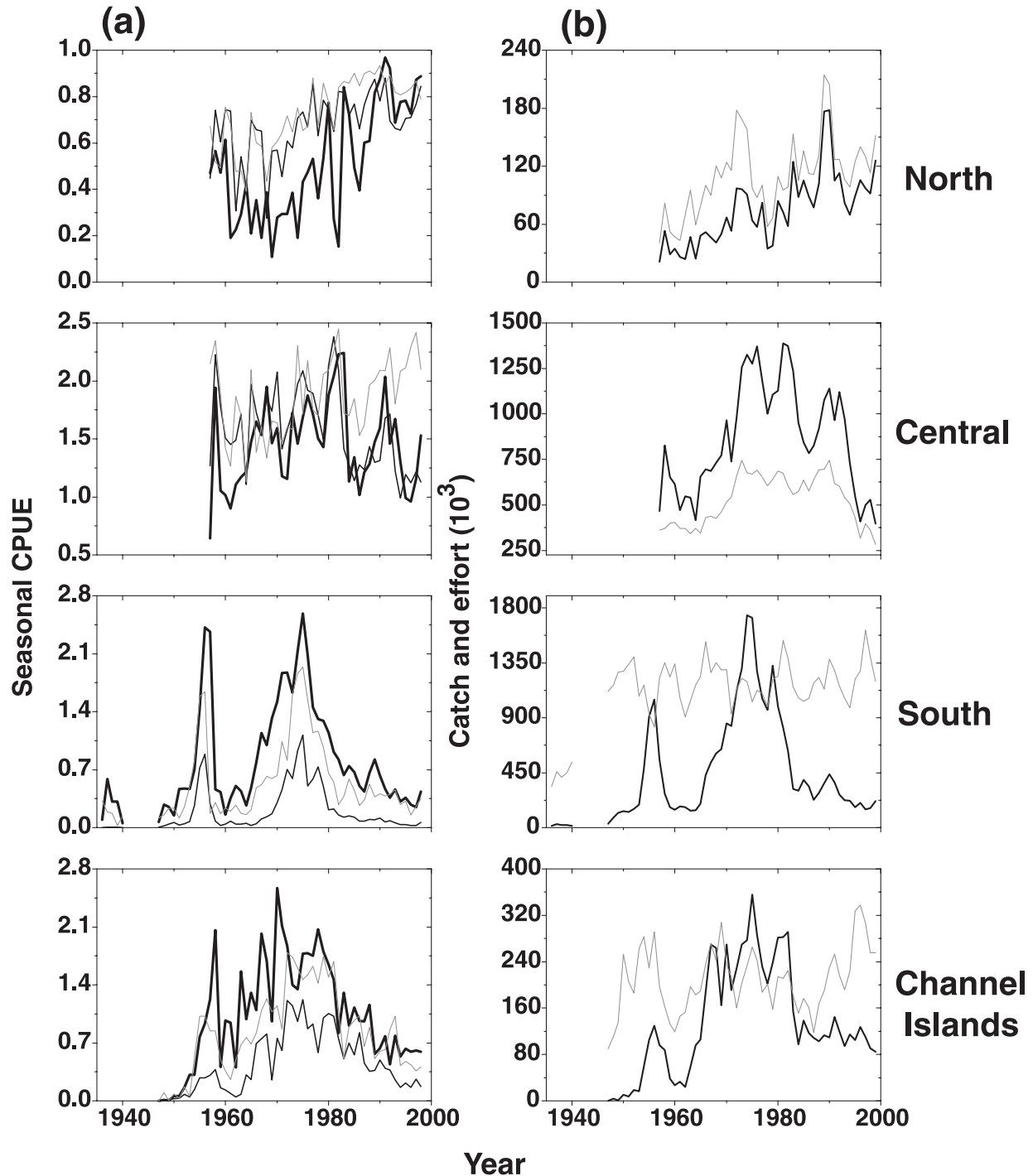
Table 2. Regression results for CPUE from commercial passenger fishing vessels in the North, Central, South, and Channel Islands regions versus SSTs from Bodega Bay (North), Pacific Grove (Central), and La Jolla (South and Channel Islands) shoreline stations and the PDO index.

Region	SST				PDO			
	df*	Mean	SE	<i>P</i> †	df*	Mean	SE	<i>P</i> †
North	22	0.075	0.035	<0.05	12	0.126	0.033	<0.01
Central	32	0.222	0.072	<0.01	28	0.038	0.058	>0.5
South	11	-0.227	0.038	<0.001	11	-0.167	0.056	<0.02
Channel Islands	18	-0.207	0.094	<0.05	18	-0.04	0.08	>0.5

*Effective degrees of freedom.

†Adjusted for autocorrelation.

Fig. 6. (a) Temporal trends in rockfish (*Sebastes* spp.) CPUE among seasons, January–April (thick line), May–August (medium line), and September–December (thin line) and (b) rockfish landings (thick line) and fishing effort (angler-hours; thin line) in four regions along the California coastline.



angler-hours with irregular decadal cycling throughout the history of the fishery (Fig. 6b, Table 3). In addition, fishing effort has averaged about 2 h per kilometre of rockfish habitat as estimated by the extent of shoreline rocky habitat (National Oceanic and Atmospheric Administration 1995). The pattern in the Channel Islands is similar but with far fewer landings and less fishing effort (Table 3). Landings modestly track fishing effort until the late 1980s, but after this, landings decline despite a sharp upturn in fishing effort (Fig. 6b).

Regressions show that the patterns in rockfish landings are unrelated to fishing effort in the South region; however, after autocorrelation is removed, a similar relationship in the Channel Islands region is close to the 0.05 significance level (Table 4). Multiple regression shows a negative and additive effect of fishing effort and SST on landings in the Channel Islands (Table 4). Both coefficients are significant and the model explains the pattern of landings better than fishing effort alone (lower AIC; Table 4). In the South region, SST by

Table 3. Regional comparisons of key characteristics for the recreational rockfish (*Sebastes* spp.) fishery from commercial passenger fishing vessels.

Characteristic	North region	Central region	South region	Channel Islands region
No. of years	42	42	63	52
Year records begin	1957	1957	1936	1947
Mean effort	110	526	1100	209
Mean effort·km ⁻¹	0.332	1.66	2.061	0.537
Maximum effort*	214 (1989)	746 (1990)	1620 (1997)	338 (1996)
Mean no. of landings	74	863	545	159
Mean no. of landings·km ⁻¹	0.224	2.724	1.021	0.510
Maximum no. of landings*	174 (1990)	1387 (1981)	1741 (1974)	356 (1975)

Note: Effort is the number of adjusted angler-hours (10³). Landings are the total number of rockfish reported for each region (10³). Also shown are effort and landings per kilometre of rockfish habitat estimated from the amount of nearshore rocky habitat.

*The year is shown in parentheses.

itself also has a moderate ($P < 0.04$) negative effect on rockfish landings, as is also implied by comparisons of trends in latitudinal CPUE in warm- versus cool-water years (Fig. 4).

In contrast, patterns of fishing effort and rockfish landings in the North appear to be tightly coupled (Fig. 6b). Since logbook reports began in 1957, landings and effort have generally increased at a rate of about 2%·year⁻¹ (Fig. 6b). Annual landings are highly associated with levels of fishing effort (Table 4); however, the relatively low level of average effort (110 000 angler-hours·year⁻¹) yields only about 75 000 rockfish·year⁻¹ in this region (Table 3). Effort per kilometre of rockfish habitat has also averaged about 6 times lower than in the South region (Table 3). As before, the Central region exhibits trends that are intermediate between those in the North and South. Average annual landings (863 000 rockfish·year⁻¹) exceed that of the South, but with far less effort expended (mean = 526 000 angler-hours·year⁻¹), and about one-half of the effort expended per kilometre of rockfish habitat (Table 3). However, landings per kilometre of nearshore rockfish habitat have averaged about 2 times those in the South (Table 3). The trend in landings is similar to those in the southern regions; however, levels of fishing effort have also declined over the last decade (Fig. 6b), such that effort and landings are strongly associated, as in the North region (Table 4). Nevertheless, multiple regressions with fishing effort and either SST or the PDO index (the choice of variable to include was determined using the results in Table 2) show a strong positive and additive influence of ocean climate and fishing effort on numbers of rockfish landed (Table 4).

Discussion

Nearshore rockfish landings in northern and southern California respond to ocean climate in opposite ways. In the North, warmer ocean conditions increase the rate of fishing success relative to that in cool-water periods, whereas in the South, lower ocean temperatures increase CPUE. The Central coast appears to be a region of transition between these opposing patterns of climate-dependent fishing success. This response is apparent at both annual and seasonal time scales. These regions, as defined by the fishery response to climate, show dramatic differences in the potential impact of the fishery on rockfish landings, and share a southern boundary with the well-documented biogeographical division at Point

Conception (Briggs 1974). Throughout the fishery record (1957–1999), rockfish landings closely track levels of fishing effort in the North, in contrast to the South, where landings were independent of fishing effort and remained an order of magnitude higher than in the North. This is also reflected by about 6 times more effort being expended per estimated kilometre of nearshore rockfish habitat in the South region. Such intense fishing effort may be partially responsible for the dramatic decline of landings in the South after the mid-1970s. In this respect as well, the Central region appears to be transitional. However, a higher number of landings per kilometre of nearshore rockfish habitat may imply that the Central region is more productive than the South. These results are consistent with previous findings showing declines in CPFV landings in the Southern California Bight, and in rockfish body lengths in the Monterey Bay area (Central region) (Mason 1998; Love et al. 1998b). Furthermore, our results show that fishing intensity and climate have an additive effect on rockfish landings in all regions except the South, where high effort may dominate the trends.

Regional responses by rockfish CPUE to climate change may be due to processes acting on fish foraging success, metabolic rates, and (or) appetites. This appears to be a unique mechanism involving both direct and indirect pathways of effect. Typically, climatic effects on fisheries are attributed to either direct effects on reproductive failure and physical effects on larval survival or indirect “bottom-up” effects on recruitment due to constraints on food-web productivity (Glantz 1992; Beamish 1995). These effects often exhibit time lags and do not manifest themselves until years later. Here we show how small changes (1–2 °C) in seasonal and annual mean temperatures exert immediate pronounced effects on rockfish CPUE at seasonal and annual scales. Similar adjustments in mean temperatures are sufficient to produce major changes in fish distribution and migration patterns (Crawshaw and O’Connor 1996). For example, increases of about 1 °C are associated with latitudinal shifts in distribution for 12 species in the western North Atlantic (Murawski 1993), as well as with earlier emigration dates for pink salmon (*Oncorhynchus gorbuscha*) from the Fraser River estuary (Henderson et al. 1995).

Responses to temperature combined with impacts from fishing suggest opposite scenarios for historical trends in different regions. In the North, lower food production and higher metabolic activity in warmer water may result in fish being hungrier and more active, rendering them more vulnerable to

Table 4. Regression results for rockfish (*Sebastes* spp.) catch by commercial passenger fishing vessels versus adjusted fishing effort (angler-hours), SST, and PDO index by region in California.

Region	No. of terms	Independent variable	df*	Mean	SE	P [†]	AIC
North	1	Effort	15	0.837	0.062	<0.001	959.3
	2	Effort	23	0.839	0.053	<0.001	947.1
		PDO			11.23	2.835	<0.01
Central	1	Effort	9	1.903	0.166	<0.001	1149.2
	2	Effort	24	1.913	0.154	<0.001	1143.9
		SST			103.2	37.91	<0.01
South	1	Effort	13	-0.305	0.437	>0.3	1244.8
	1	SST	11	-303.6	83.29	<0.04	1233.2
Channel Islands	1	Effort	13	0.528	0.244	>0.05	1100.4
	2	Effort	24	0.585	0.223	<0.05	1093.2
		SST		-502.1	162.2	<0.02	

Note: La Jolla SST was used with the fishery data in the Channel Islands region. Akaike's information criterion (AIC) was used to compare model fits.

*Effective degrees of freedom.

†Adjusted for autocorrelation.

a set hook, thus increasing CPUE seasonally as well as during El Niños. Lower somatic and gonadal indices also have been reported for blue rockfish (*Sebastes mystinus*) in central California during these warm-water periods (Ven Tresca et al. 1995). Fishing in the North, however, may have been sustainable, perhaps related to lower overall effort due to a smaller human population and restricted access along a rugged shoreline, as well as frequently inhospitable ocean conditions. Sustainable fishing may also have occurred even though higher fishing effort was applied during warm-water years, when successful fishing may have increased the popularity of the fishery. In addition, lower ocean temperatures during years of average ocean conditions may have acted to dampen the rate at which fish were caught relative to other regions. Thus, the strong positive relationship between fishing effort, ocean temperature, and rockfish landings indicate that the fishery in the North, with more stable landings and CPUE, may have been sustainable at the regional scale over time. At smaller spatial scales, however, local depletions may have occurred, especially near fishing ports.

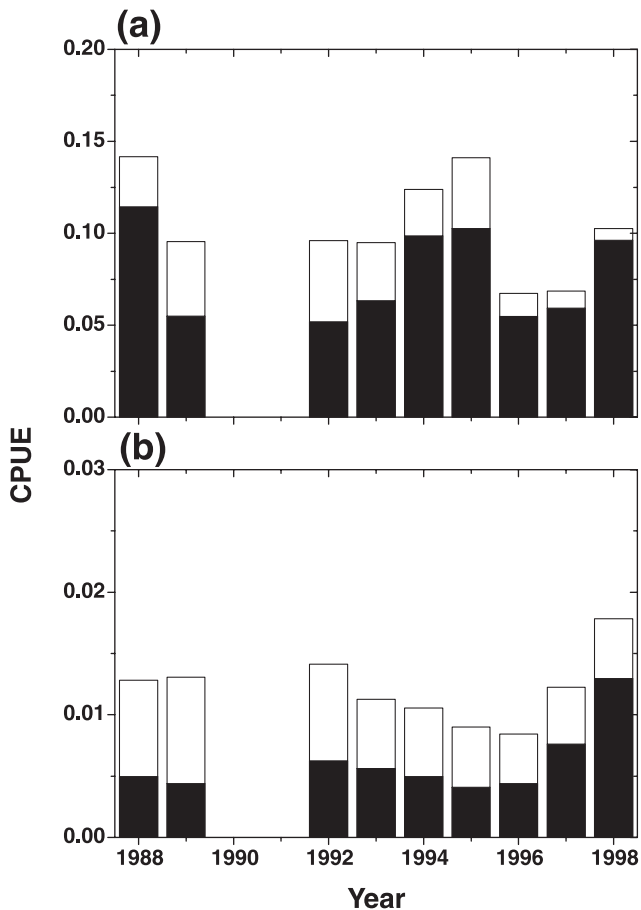
Conversely, in the South, warm-water effects on fish physiology may have dampened fishing success, but prolonged and intense effort may have overridden the temperature signal. SST during El Niños may approach unfavorable levels, such that nearshore species either decrease activity levels or move offshore to cooler water at depth, decreasing nearshore CPUE. Intense fishing during the initial stages of the fishery in the South region resulted in increased landings as is common in many fisheries. However, peak landings in 1974–1976 coincided with the well-documented shift in the PDO, which may have also reduced larval-supply rates (MacCall 1996). Subsequently, however, with no adjustment in fishing effort, landings may have declined as a consequence in the adverse climatic conditions (Love et al. 1998b). The dramatic collapse in landings, as well as reports of declines in fish body lengths and the proportion of adults in the catch (Love et al. 1998b), are indications that the South region may have been overfished.

Additional factors may have also contributed to the patterns observed in the CPFV data records. We have consid-

ered several confounding factors. First, although we attempted to emphasize the nearshore component of the fishery by confining our analyses to reporting blocks near the coastline, deeper water species were included in the generic rockfish category. The California Department of Fish and Game monitored rockfish catch on board CPFV vessels in the Central and North regions from 1987 to 1998, accompanying an average of 224 fishing trips each year (excluding 1987, 1990, and 1991, when fewer than half this number were monitored). Species identified in the catch show that proportions of nearshore rockfish varied regionally and among years, composing, on average, 75% in the North but only 45% in the Central-region reporting blocks used in our study (Fig. 7). Second, changes in fishing regulations and technological improvements throughout the historical record may also have influenced our results. The daily limit for rockfish per angler was 15 throughout most of the 43-year record; before 1971 it was 20 fish, and in 1999 it was lowered to 10 fish. Fishing technology, however, improved considerably over time, especially with the advent of hydroacoustics. These developments undoubtedly improved effectiveness, and impart a positive weighting on effort over time. Finally, other components of the nearshore fishery, such as private skiffs and the new commercial live-fish fishery, are not included in this analysis. The live-fish fishery includes nearshore rockfish species, California sheephead (*Semicossyphus pulcher*), cabezon (*Scorpaenichthys marmoratus*), and California scorpionfish (*Scorpaena guttata*) (Rogers-Bennett 2002), and appears to be approximately one-third the size of the recreational CPFV fishery, taking an average of 1.6 million fish each year since about 1990. In the future, our results will be compared with information from other components of the fishery.

Regional responses of rockfish landings to climate change and fishing effort provide an opportunity to tailor management strategies for the recreational fishery. Currently, our ability to manage the nearshore fishery (<http://www.dfg.ca.gov/mrd/nfmp/index.html>) is severely constrained by the daunting and costly task of developing detailed stock assessments with limited data for 19 individual species. Given the

Fig. 7. CPUE for nearshore (solid bars) versus offshore (open bars) rockfish (*Sebastes*) species from commercial passenger fishing vessels in (a) the North and (b) Central regions. Rockfish identifications were conducted by onboard observers from the California Department of Fish and Game.



difficulties in using traditional management strategies based on virgin biomass, the regional responses to fishing pressure and climate described here may provide a framework for establishing a set of management procedures (Butterworth et al. 1997). Rules based on these regional responses may be devised to adjust total allowable catch, as opposed to setting a conservative fixed management strategy for the fishery statewide (Walters and Parma 1996; MacCall 2002). For example, we can now begin to identify excessive fishing pressure from levels in the South region (mean = 1.1 million angler-hours) that were unsustainable relative to fishing pressure in the North region (mean = 110 000 angler-hours), where the fishery appears sustainable. Moreover, rapidly evolving technology allows better monitoring of the progress of developing El Niños, providing a sentinel that permits managers to fine-tune fishing levels in near real-time, thus allowing for climatic effects on fish vulnerability. While no one can be certain how rockfish populations will respond to future fishing pressure and climate changes, the historical record suggests that cooler environmental conditions such as those occurring since 1999 (Durazo et al. 2001) may be beneficial to nearshore populations, particularly if rebuilding

plans consider potential increases in southern fishing success that may occur as a result.

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