Fishery dynamics of the California market squid (*Loligo opalescens*), as measured by satellite remote sensing

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Abstract—Novel data on the spatial and temporal distribution of fishing effort and population abundance are presented for the market squid fishery (*Loligo opalescens*) in the Southern California Bight, 1992–2000. Fishing effort was measured by the detection of boat lights by the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS). Visual confirmation of fishing vessels by nocturnal aerial surveys indicated that lights detected by satellites are reliable indicators of fishing effort. Overall, fishing activity was concentrated off the following Channel Islands: Santa Rosa, Santa Cruz, Anacapa, and Santa Catalina. Fishing activity occurred at depths of 100 m or less. Landings, effort, and squid abundance (measured as landings per unit of effort, LPUE) markedly declined during the 1997–98 El Niño; landings and LPUE increased afterwards. Within a fishing season, the location of fishing activity shifted from the northern shores of Santa Rosa and Santa Cruz Islands in October, the typical starting date for squid fishing in the Bight, to the southern shores by March, the typical end of the squid season. Light detection by satellites offers a source of fine-scale spatial and temporal data on fishing effort for the market squid fishery off California, and these data can be integrated with environmental data and fishing logbook data in the development of a management plan.

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The market squid (*Loligo opalescens*) (also known as the opalescent inshore squid, FAO [Roper et al., 1984]) is currently the largest revenue fishery for California (Vojkovich, 1998; CDFG, 2000). The fishery's importance rose steadily in the 1980s and 1990s, in response to increased demand in Asia coupled with declines in other fisheries off the U.S. West Coast. Market squid is a short-lived species (Jackson, 1994; Butler et al., 1999) whose abundance appears to be readily impacted by environmental variability. For example, squid landings plummeted during the 1997–98 El Niño but reached a record high in the following year (CDFG, 2000). Considered an integral component of California's pelagic fishery, the market squid was included in the Coastal Pelagic Species Fishery Management Plan as approved by the Pacific Fisheries Management Council in 1998. In this plan, federal authority is invoked to monitor the fishery to ensure the provisions of the Magnuson-Stevens Fishery Conservation and Management Act of 1996. If a resource is estimated as overfished, the Council is to consider implementing active management measures.

The lack of records of fishing effort, such as vessel logbooks or observer data, hampered initial attempts to formulate a management plan for the market squid. The nature of the fishery, however, suggested an alternative measure of fishing effort: the detection of boat lights by satellites. The market squid is typically harvested on shallow nearshore spawning grounds in the Southern California Bight and Monterey Bay (Vojkovich, 1998). At night, specialized lightboats shine high intensity (c. 30,000 watt) lights on the water, which attract and congregate the squid near the surface. Seiner boats then capture the concentrated squid with purse-seine nets (Vojkovich, 1998). The lights of the fishing boats are detected and recorded by the U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS).

DMSP-OLS satellites continuously orbit the planet, acquiring data on meteorology and, incidentally, nighttime light sources (Croft, 1978; Elvidge et al., 1997, 2001b). Nighttime light detection by satellites has proven useful for various environmental questions, such as identifying the extent of forest fires (Elvidge et al., 2001a) and the effects of urban lighting on sea turtle nest selection and hatchling survivorship (Salmon et al., 2000). Compilation of light data for the global light-fishing squid fleet has contributed to examinations of the fishery's ecosystem impacts (Rodhouse et al., 2001). For local squid fisheries, the locations of boat lights over space and time are particularly valuable in cases where national boundaries pose constraints on the collection of effort data (e.g., *Illex argentinus* in the southwestern Atlantic, Waluda et al., 2002).

In this study, we used boat lights to quantify the spatial and temporal patterns of market squid fishing activity in the Southern California Bight over the period 1992–2000. The bight has come to represent the great majority of squid landings off California (Vojkovich, 1998; Butler et al., 1999; CDFG, 2000). An important component of our study is ground-truthing work that validates the feasibility of using light data as a measure of fishing effort. This estimate for fishing effort enables us to present novel landings-per-unit-of-effort (LPUE) data for the market squid. A companion paper analyzes the light detection properties of the DMSP-OLS satellites over the Southern California Bight (Elvidge et al.[1]).

Materials and methods

Light detection by satellites

The DMSP is a polar orbiting satellite system that acquires daytime and nighttime data during each orbit. The OLS is an oscillating scan radiometer designed for cloud imaging. A full technical description of image acquisition by the DMSP-OLS system, and the subsequent processing of images, appears in a companion paper (Elvidge et al.[1]). Briefly, the DMSP-OLS acquired nighttime data for over 2200 satellite orbits over the Southern California Bight (i.e., 117° to 122° W, 32°30′ to 34°30′N) between 26 April 1992 and 4 April 2001. Four different satellites were employed during this time. Three overlapped in operation dates, producing multiple images for some dates. On all dates, images were acquired between 18:30 and 22:00 Pacific Standard Time (PST), with 20:21 PST being the average time. The satellite images were processed into geo-referenced images of boat lights and clouds. This process involved superimposing a field of grid cells onto the satellite image, which quantified the satellite's "field of view," the extent of detected clouds, and the area available for light detection. Image pixels of lights were taken directly from the satellite image. Pixels were identified as lights by their visible band digital number. The images were subjected to quality-control procedures to correct for atmospheric noise and to eliminate images overly contaminated by solar glare, sunlight, heavy lunar illumination, or those containing missing data. Fixed sources of lights, such as city lights along the southern California coast, the city of Avalon (Santa Catalina Island), off-shore oil platforms, and naval installations, were masked from the light detection algorithm.

Data deliveries were irregular during 1992, resulting in gaps in the early part of the time series. For 1992–98, only data collected during the dark half of the lunar cycle were available. To control for lunar illumination throughout the time series, we restricted analysis of fishery data to images for which lunar illumination was less than 0.02 lux (lumens per square meter). Images for analysis were evaluated against additional criteria. For a given image, we calculated the number of total grid cells that were not used for light detection because of glare, missing data, or the masking of known nonboat lights. If the resulting number of grid cells left available for light detection was at least 50% of the original number of cells, we retained the image for analysis. Cloud coverage can obscure light sources[1]; therefore we used only images from nights when clouds covered less than 25% of the grid cells available for light detection. For nights with multiple acceptable images, we averaged the percent cloud coverage and the number of detected light pixels.

Ground-truthing: aerial observations of boat activity

To determine the relationship between detected light pixels and the number of squid fishing vessels on the water, 35 aerial surveys were conducted from 10 June 1999 to 18 May 2000. Each survey took place in a Cessna 337 Skymaster flown at an average altitude of 1160 m above sea level. The path of each survey covered the main areas of squid fishing activity within the Southern California Bight (Fig. 1): from San Diego, over the Channel Islands, to Point Conception, and back down the coastline to San Diego. Each survey took approximately four hours to complete, occurring between 18:00 h and midnight PST. These times encompassed the time that the DMSP-OLS satellites were over the bight. The 35 surveys produced 26 nights of usable data. Survey data were discarded if satellite images were unavailable, if flights were aborted because of weather, or if heavy fog obscured boat visibility. We note that, for this ground-truthing work, we did not restrict our analysis to nights with lunar illumination of less than 0.02 lux. Rather, we used all of the acceptable 26 nights, and quantified lunar illumination as a proportion of the moon's phase, where 0.00 denoted a new moon and 1.00 denoted a full moon.

All vessels on the water were identified by using Fujinon 10×50 gyroscopic binoculars, and the GPS positions of all vessels were recorded. Vessel type was identified as either a nonsquid vessel or as a squid fishing vessel.

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[1] Elvidge, C. D., J. Safran, M. R. Maxwell, K. E. Baugh, A. Henry, and J. R. Hunter. Unpubl. data. Satellite based indices of lightboat fishing effort.

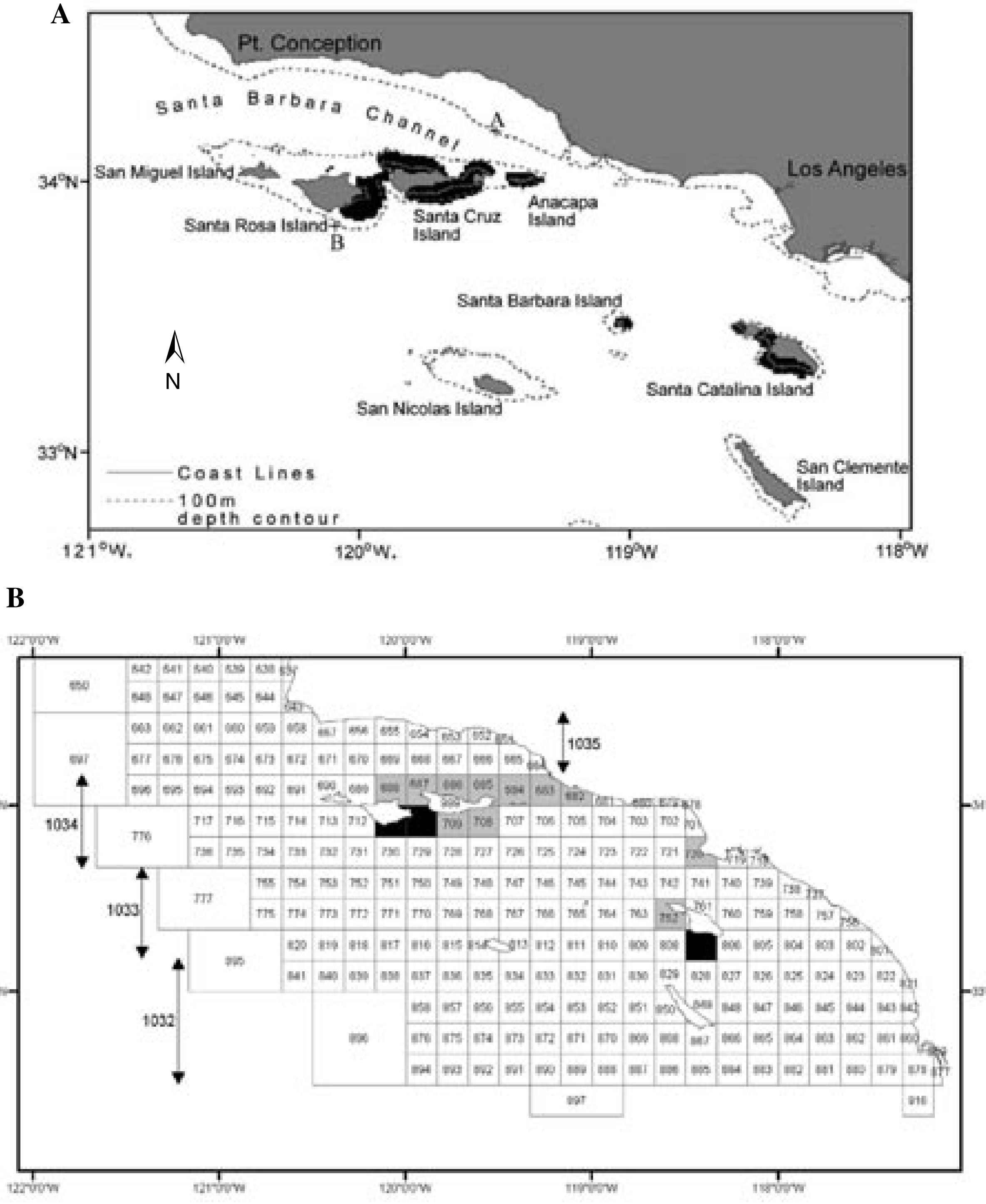

Figure 1

Fishing activity for the market squid in the Southern California Bight, from 26 April 1992 to 28 May 2000. (**A**) Composite satellite image of squid fishing vessel lights (black marks). Permanent sources of lights (e.g., city lights, offshore oil platforms, naval installations) are removed. CalCOFI stations 83.42 ("A"; 34.18°N, 119.51°W) and 83.51 ("B"; 33.88°N, 120.13°W) are indicated. (**B**) Squid landings as reported by California Dept. Fish and Game fishing blocks. Gray: blocks that account for 6.8 million kg (2%) or more of the landings from blocks 651–896. Black: blocks that account for 20.5 million kg (6%) or more. Latitudinal blocks 1032–1035 are indicated. Santa Cruz Island is marked "999" to aid correspondence with A.

Squid fishing vessels could not always be distinguished as light boats or seiners and therefore were recorded as "squid fishing vessels."

The numbers of squid fishing vessels showed large skew in their frequency distribution. These data were transformed by $x' = \log_{10}(x+1)$. Similarly, proportion lunar phase was transformed by $x' = \arcsin(\sqrt{x})$, and detected light pixels were transformed by $x' = \log_{10}(x+1)$ to correct for skew (Zar, 1984). These transformations produced normally distributed data acceptable for regression analysis. With these transformed variables, multiple stepwise regression (forward selection) was performed with the software S-Plus 2000 (MathSoft Inc., Cambridge, MA) to examine the effects of squid fishing vessels and the proportion lunar phase on detected light pixels. Squid fishing vessels and proportion lunar phase showed very little correlation ($r=-0.09$).

Fishery characteristics, 1992–2000

For quantitative analysis of the fishery data, we aggregated the nightly satellite data (i.e., light pixels detected on the water) into calendar quarters, as suggested by the within-year distribution of squid landings in the bight (Butler et al., 1999). To standardize conditions of light detection, we excluded all data after 28 May 2000, because this was the starting date of mandatory shielding of the high intensity lights of the lightboats. This regulation was enforced by California's Department of Fish and Game to reduce light pollution by the lightboats. The shields did not totally obscure the lightboats from detection by the satellites (authors' pers. obs.) but made the emitted light less bright, and, hence, less detectable by the satellites. Thus, our data for fishing effort spanned calendar quarters from Jul–Sep 1992 to Jan–Mar 2000. We included a quarter for analysis if it contained 10 or more nights of acceptable images. By these criteria, we described effort for 24 of the 31 calendar quarters. The mean number of nights per quarter was 26 (range=10–72 nights).

The quantity (kg) and location of landed market squid were recorded by California Department of Fish and Game (CDFG) throughout the 1992–2000 study period and were made available to the authors. During this study period, squid fishing in the bight occurred exclusively at night (Vojkovich, 1998). The squid were landed at port within several hours after being caught; therefore the landings for a given day corresponded to the previous night's effort. Squid fishermen reported the locations of their hauls by CDFG fishing blocks. We defined catch taken from the Southern California Bight as that from blocks 651–896 and 1032–1035 (Fig. 1). Blocks 651–896 are typically 10′ latitude × 10′ longitude and can be used to locate regions of high catch. Blocks 1032–1035 are large latitudinal bands, generally 30' wide, that encompass blocks 651–896. We used blocks 1032–1035 in calculating the total catch in the bight, but not in depicting the location of the catch.

To construct the abundance index of landings per unit of effort (LPUE), we first estimated the number of squid fishing vessels for each night of satellite data, using the regression results of the ground-truthing work (see "Results" section). We then summed the nightly estimated number of vessels for each calendar quarter. For those nights for which we had estimated numbers of vessels, we also summed the landed catch within each calendar quarter. To arrive at LPUE for the quarter, we divided the summed landings by the corresponding summed effort.

Environmental data

We used the multivariate ENSO index (MEI) to indicate overall environmental conditions over the course of the 1992–2000 study period. The MEI is a multivariate index that incorporates sea level pressure, surface zonal and meridional wind components, sea surface temperature, surface air temperature, and cloudiness (Wolter and Timlin, 1998). The MEI index is calculated for the tropical Pacific (i.e., between 10°N and 10°S, from Asia to the Americas), and its monthly values appear on the website http://www.cdc.noaa.gov/~kew/MEI/table.html.[2]

Analysis of the location of fishing effort over the course of the traditional squid fishing season in the bight led to an investigation of oceanographic data for waters surrounding Santa Cruz Island in March. Specifically, we examined sea temperature from two sources. First, we obtained sea surface temperature for all satellite nights in March 1993–2000 from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at California Institute of Technology (Pasadena, CA). These data were reported for 18×18 km grids, which were approximately the size of the 10′×10′ fishing blocks. We selected the grid that covered block 686 to represent the northern shore of the island, and that which covered block 708 to represent the southern shore (Fig. 1B). For each year in the 1993–2000 period, we calculated mean March temperature for both blocks.

The second source of sea temperature was the database maintained by the California Cooperative Oceanic Fisheries Investigations (CalCOFI). Since 1950, the CalCOFI program has conducted quarterly survey cruises along transects perpendicular to the southern California coast. This system of transects incorporates 66 geographically fixed stations. At each station, a conductivity-temperature-depth (CTD) instrument is deployed. Details on survey methods appear on the website http://www-mlrg.ucsd.edu/calcofi.html,[3] along with the publicly accessible database. For April 1993–2000, we obtained temperatures at sea surface and at 75 meters depth at two stations (Fig. 1A): 83.42 (northeast of Santa Cruz Island; 34.18°N, 119.51°W) and 83.51 (southwest of Santa Cruz Island; 33.88°N, 120.13°W).

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[2] NOAA-CIRES Climate Diagnostics Center website. [Accessed 3 November 2003.]

[3] California Cooperative Oceanic Fisheries Investigations website. [Accessed 3 November 2003.]

One measurement was made at each station at sea surface and at 75 meters depth during April (n=8 for both depths).

Results

Ground-truthing: aerial observations of boat activity

Nonsquid vessels used weak lights (i.e., much less than 30,000 watts), which did not show in the satellite images. On average, 23 squid fishing vessels were observed each night by the aerial surveys (range=0–64 vessels, n=26 nights). The 20:00-midnight observation period was the peak time for attraction of squid by the light boats. Although the squid vessels did change location during this time, they typically left their lights running to continue searching for squid. The number of squid vessels explained much of the variation in detected light pixels; proportion lunar phase failed to enter the analysis as a significant variable (Table 1). Detected light pixels increased with the number of squid vessels (Fig. 2).

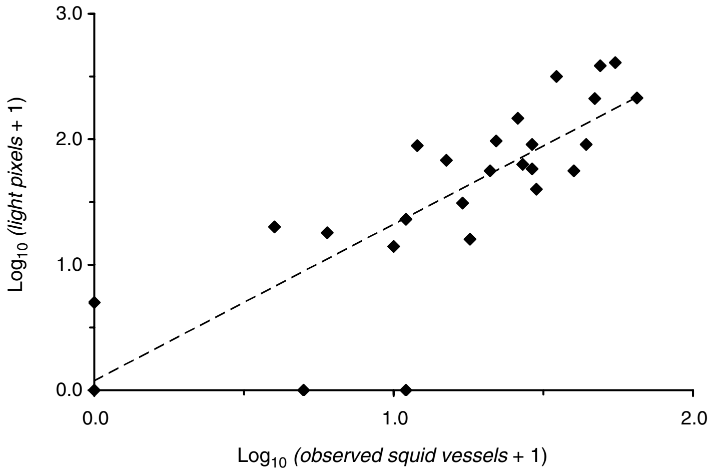

Figure 2

Plot of $\log_{10}$-transformed number of squid vessels and detected light pixels. Regression line taken from the statistics in Table 1.

Table 1

Multiple stepwise (forward selection) regression of detected light pixels on squid fishing vessels (transformed: $x'=\log_{10}(x+1)$ and proportion lunar phase (transformed: $x'=\arcsin(\sqrt{x})$. $r^2=0.64$; ANOVA: $F_{1,24}=42.66$, $P<0.0001$.

Variable	Coefficient ±SE	P
Squid fishing vessels	1.25 ±0.19	<0.0001
INTERCEPT	0.07 ±0.24	>0.75
Proportion lunar phase	not entered	not entered

The regression analysis yields the following simplified equation:

$$\log_{10}(p_t + 1) = 1.25 \times \log_{10}(x_t + 1), \qquad (1)$$

where x_t = observed number of squid vessels; and
p_t = detected light pixels for night t.

We used inverse prediction to estimate the number of squid vessels for each satellite night ($\hat{E}_t$) in the 1992–2000 period (Zar, 1984). The estimated number of squid vessels was found by the equation

$$\hat{E}_t = 10^{\log_{10}(p_t+1)/1.25} - 1 = \sqrt[1.25]{p_t + 1} - 1. \qquad (2)$$

The ground sample distance of the satellite data is 2.7 km, which means that multiple squid vessels may potentially fit into one pixel of detected light. This could result in an underestimation of effort. The severity of this problem can be assessed by examining the coefficient of the simple linear regression of log-transformed variables represented by Equation 1. One of four scenarios is possible: 1) boats are not aggregated (coefficient=1), 2) boats are aggregated regardless of the number of boats on the water (coefficient=1), 3) boats are aggregated only when many boats are on the water (coefficient<1), or 4) boats are aggregated only when few boats are on the water (coefficient>1). The coefficient in Equation 1 is 1.25, which fails to significantly differ from 1.00 (t-test for regression coefficient: t = 1.305, $\beta_0 = 1$, df = 24, $P > 0.2$, two-tailed; power < 0.5, retrospectively calculated; Zar, 1984). This result suggests that very little clumping of the boats occurred (scenario 1), or that the degree of clumping was independent of the number of boats on the water (scenario 2). Although the statistical power of this t-test is not high (power<0.5), we conclude that the data provide more support for scenarios 1 and 2 over scenarios 3 and 4. Either scenario, 1 or 2, allows for a comparison of the relative values of estimated effort and LPUE within a time series.

Fishery characteristics, 1992–2000

A composite satellite image of all squid fishing activity in the Southern California Bight during the 1992–2000 study period revealed major concentrations of effort off the Channel Islands, especially Santa Rosa, Santa Cruz, Anacapa, and Santa Catalina (Fig. 1A). Squid fishing occurs close to the island shores and is bounded by the 100-m contour. During the study period, 379.2 billion kg of squid were landed in the bight: 341.2 billion from blocks 651–896 (Fig. 1B), and the remainder from the large blocks 1032–1035. The main areas of fishing activity, as indicated by satellite, are consistent with the blocks of high catch (Fig. 1B). We note that blocks 682 and 720, although areas of high catch, do not appear on the satellite composite because the mainland shore was excluded from light detection. Further, much activity was evident around Santa Barbara Island (block 765). Although this block represented 4.0 million kg (18th out of the 127 blocks), it did not rank highly enough for inclusion in Fig. 1B.

Analysis of temporal trends in the fishery showed peaks in landed catch for the bight in the fall and winter quarters (Oct–Dec and Jan–Mar, respectively; Fig. 3A). There was a near absence of catch during most of 1997–98 (Fig. 3A), which corresponded to the strong El Niño event during this period (Fig. 4). Effort data revealed surges in the Oct–Dec quarters before the 1997–98 El Niño (Fig. 3B). The Oct–Dec quarter of 1998 signalled a resumption of fishing effort following El Niño, but effort levels for 1999 and early 2000 were lower than pre-El Niño levels. Interestingly, squid abundance, as measured by landings per unit of effort (LPUE), showed a rapid increase from the El Niño lows, and squid abundance for 1999–2000 reached the highest values of the time series (Fig. 3C).

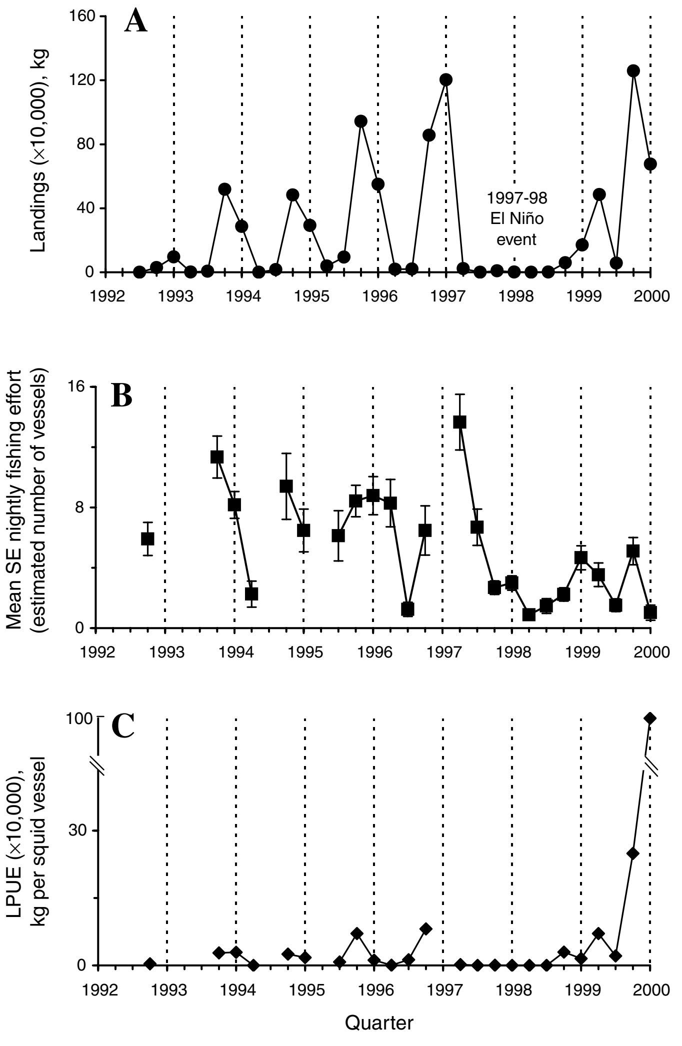

Figure 3

Time series of market squid fishery data in Southern California Bight, by calendar quarter (Jul–Sep 1992 to Jan–Mar 2000). The Jan–Mar quarters are marked by dashed vertical lines. (**A**) Landings are in kg (blocks 651–896, 1032–1035). (**B**) Mean ±SE nightly fishing effort, in estimated number of squid vessels. (**C**) Landings per unit of effort (LPUE): summed landings (kg) on satellite nights were divided by summed effort (estimated number of squid vessels) on the corresponding nights.

Analysis of boat locations along the Channel Islands revealed a shift over the course of the fishing season. Compiling the satellite data to yield composite images in multiyear sets, we found that fishing activity in October consistently included the north shore of Santa Cruz Island (Fig. 5, A,C,E). In contrast, fishing activity in March showed considerable reduction along the north side of Santa Cruz Is., but activity continued along the island's southern shore (Fig. 5, B,D,F). Composite images for December and January were also examined for all of the multiyear sets. December marked a transitional stage from the activity in October to reduction of fishing in March along the northern shores. In all multiyear sets, the December lights along northern Santa Cruz Island were more scattered and less dense than those in October. January images were very similar to those for March. Although data from March 1993–95 indicated little fishing activity, a composite image for January 1993–95 was very similar to that for March 1999–2000: light banks occurred off southern Santa Cruz, southeastern Santa Rosa, and around Anacapa, but were virtually absent from northern Santa Cruz and Santa Rosa.

Water temperatures around Santa Cruz Island did not consistently differ between northern and southern waters. March sea surface temperatures, measured by satellite, were very similar for the island's northern and southern shores (Table 2). April sea surface temperatures, measured at CalCOFI stations, were slightly warmer to the northeast of the island (Table 2). Temperatures at 75 meters, however, were nearly identical for the two CalCOFI stations (Table 2).

Discussion

The satellite images and landings data corroborated spatial and temporal patterns of fishing activity for the market squid. For the period 1992–2000, both data sets indicated intense harvesting along the Channel Islands of Santa Rosa, Santa Cruz, Anacapa, and Santa Catalina. The satellite images captured additional information, such as fishing activity being

Table 2

Water temperature (°C) for the northern and southern waters around Santa Cruz Island, March and April, 1993–2000.

	Northern waters				Southern waters			
Depth (m)	Location	Mean	Min	Max	Location	Mean	Min	Max
March sea surface temperature, as measured by satellite (PO.DAAC data)[1]								
0	Block 686	14.5	12.8	15.7	Block 708	14.7	13.2	15.9
April temperature, measured at CalCOFI stations[2]								
0	Station 83.42	13.6	11.6	16.7	Station 83.51	12.8	11.2	14.5
75	Station 83.42	9.9	9.3	11.2	Station 83.51	10.3	9.3	11.2

[1] Measurements made on multiple nights per month of March (range of measured nights per month of March: 6–26). "Mean" is the overall average of the mean March temperatures; "Min" is the minimum of the mean values, "Max is the maximum, of the mean values.

[2] One measurement made at each station at each depth per month of April (n=8 for both depths).

clearly delimited by the 100-m contour. The landings data, reported by fishing blocks, were much cruder in geographic scale and failed to catch this subtlety.

The ground-truthing work conducted by aerial surveys indicated that detected light pixels are useful in estimating the number of squid vessels in operation. This result is consistent with examination of the fishery for the squid *Illex argentinus* in the southwestern Atlantic, where vessels use powerful lamps to attract the squid to lures (Waluda et al., 2002). In the latter fishery, analysis of images acquired by the DMSP-OLS satellites revealed a good fit between the recorded number of vessels in operation on a given night and the number of light pixels detected (Waluda et al., 2002).

In the present study, the fishery data showed a strong response to the 1997–98 El Niño event, which was one of the strongest events on record (Wolter and Timlin, 1998). Fishing effort and landings tended to peak in the Oct–Dec and Jan–Mar quarters before the 1997–98 El Niño. Both data series dramatically dropped during the 1997–98 El Niño and showed recovery afterwards. Squid abundance, measured as LPUE, also showed a pronounced drop and rapid increase in response to the El Niño. It is interesting to note that another index of market squid abundance, the occurrence of squid beaks in the scat of sea lions, showed similar responses to earlier El Niño events (Lowry and Carretta, 1999). Squid beak occurrence dropped steeply during the strong 1983–84 El Niño, and increased afterwards. Beak occurrence also dipped and rose in response to a milder El Niño in 1992–93. Significantly, Lowry and Carretta (1999) examined southern Channel Islands: Santa Barbara, San Clemente, and San Nicolas. Our present study reflects squid abundance primarily around northern Channel Islands (e.g., Santa Rosa, Santa Cruz, Anacapa). Taken together, these studies may indicate that El Niño exerts a bight-wide influence on squid abundance.

We suggest that a strong El Niño event changes the reproductive conditions for the market squid in the Southern California Bight. With regard to spawning, the spawning population becomes less abundant on the traditional shallow-water spawning grounds. Research on a congener, the South African chokka squid *(Loligo vulgaris reynaudii)*, points to possible environmental influences on spawning for loliginid squid (Roberts and Sauer, 1994). Off South Africa, a strong El Niño can lead to reduced upwelling and increased turbidity. In normal years, upwelling, presumably detected by the squid as an influx of cold water, may trigger spawning behavior (Roberts and Sauer, 1994). In El Niño years off South Africa, reduced upwelling and increased turbidity on the inshore spawning grounds are thought to force the spawners into deeper water, beyond the reach of the fishery (Roberts and Sauer, 1994). In a recent study, catch for the chokka squid increased with strong easterly winds, which caused upwelling, and decreased with increased turbidity (Schön et al., 2002). In the California Current System, upwelling decreases during strong El Niño events (Schwing et al., 2000). Upwelling

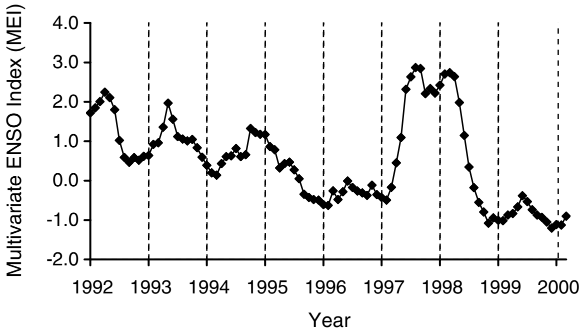

Figure 4

Multivariate ENSO index (MEI) for the tropical Pacific (between 10°N and 10°S), by month. Data were obtained from http://www.cdc.noaa.gov/~kew/MEI/table.html.

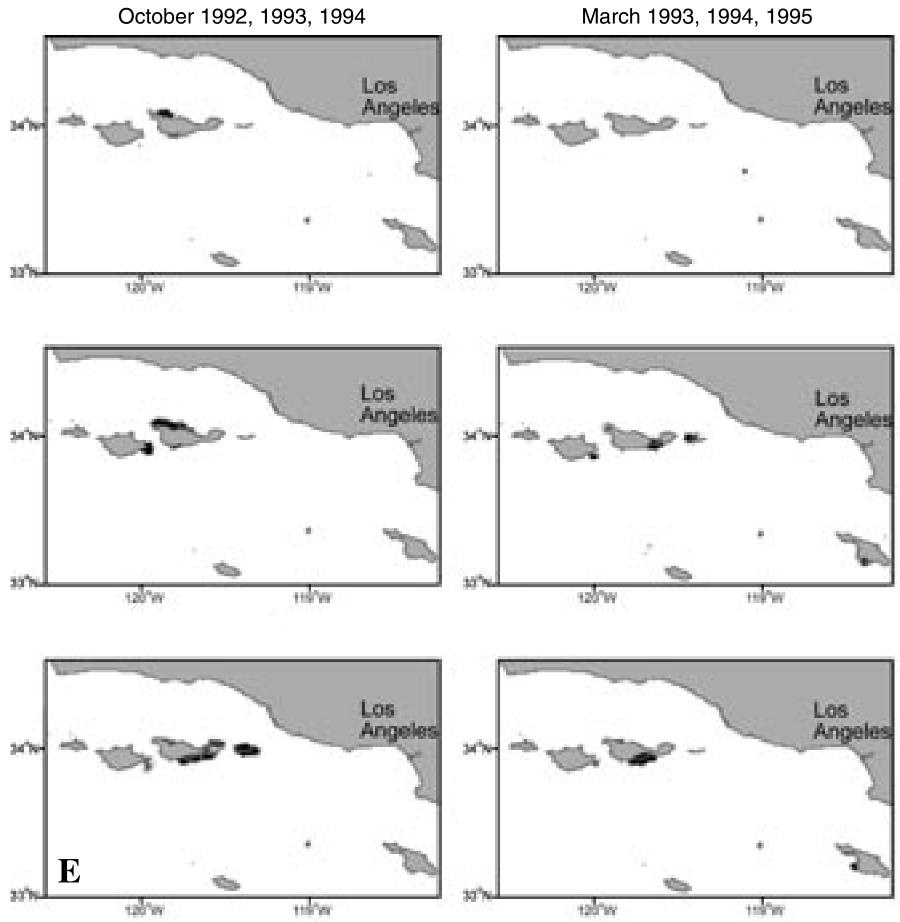

Figure 5

Location of fishing activity, as indicated by black areas, for the early (October) and late (March) parts of the traditional squid fishing season in the Southern California Bight, 1992–2000. For each month, a multiyear composite image is shown. (**A**) October 1992, 1993, 1994. (**B**) March 1993, 1994, 1995. (**C**) October 1995, 1996, 1997. (**D**) March 1996, 1997, 1998. (**E**) October 1998, 1999. (**F**) March 1999, 2000.

in the Southern California Bight was reduced during the 1997–98 El Niño (Hayward, 2000). It is not known how market squid adults respond to changes in water temperature or turbidity, or whether spawning fish shift to other habitats during El Niño events.

A strong El Niño event can also alter feeding and developmental conditions for squid. During the 1997-98 El Niño, macrozooplankton abundance substantially decreased in the Southern California Bight and off Baja California (Lynn et al., 1998; Hayward, 2000; Lavaniegos et al., 2002). Food availability affects growth rates of loligind squid (Jackson and Moltschaniwskyj, 2001). Recently, Jackson and Domeier (2003) indicated lower growth rates for the market squid in the Southern California Bight during the 1997–98 El Niño.

In the present study, fishing effort following the 1997–98 El Niño was generally below pre-El Niño levels. The subsequent high levels of catch in late 1999 and early 2000 may indicate that squid were in great abundance, thereby requiring less overall catch effort to meet market demand. A strong La Niña succeeded the 1997–98 El Niño (Lynn and Bograd, 2002; Schwing et al., 2002), with strong upwelling and high macrozooplankton abundance in the Southern California Bight by spring 1999 (Schwing et al., 2000; Hayward, 2000). Indeed, the high LPUE in the present study in late 1999 and early 2000 points to increased squid abundance in response to a more productive environment. Alternatively, one could argue that increased fishing efficiency, not increased squid abundance, resulted in high LPUE. One manifestation of higher fishing efficiency could be a contracted fishing range, where especially productive pockets are identified and targeted. An overall comparison of fishing location in October and March before and after El Niño did not support this explanation: the total spatial extent of fishing activity was not greatly reduced in post-El Niño October or March. A noticeable concentration of fishing effort off the southern shore of Santa Cruz Island was evident in the post-El Niño period, however. The landings data may indicate that this southern shore, represented by blocks 708 and 709, was indeed productive. In the pre-El Niño period (1992–96), blocks 708 and 709 represented 3% of the landings in the bight. In the post-El Niño period (1999 to early 2000), these two blocks came to represent 12% of the landings.

The spatial distribution of fishing activity appears to shift over the course of the squid fishing season. In the Southern California Bight, October and March mark the traditional beginning and end of the squid fishing season, respectively (Butler et al., 1999). In the present study, fishing activity along the Santa Rosa and Santa Cruz Islands moved largely to the southern shores by March, leaving the northern shores relatively unfished. This spatial shift may reflect change in local squid habitat or changes in the fishermen's behavior. As a rough indicator of habitat quality, water temperature did not consistently differ between the northern and southern waters around Santa Cruz Island in March and April, both at sea surface and at 75 meters depth. Wind conditions, on the other hand, change considerably from October to March. The northern shores of Santa Rosa and Santa Cruz lie on the rim of the Santa Barbara Channel. Wind speed and wind stress are relatively low through the channel in the fall and early winter but increase significantly in March to remain high throughout the spring and summer (Winant and Dorman, 1997; Harms and Winant, 1998; Dorman and Winant, 2000). It remains unresolved whether the high winds in the Channel in March and April create ocean-floor turbulence and turbidity that discourage squid spawning (cf., Roberts and Sauer, 1994), or whether fishermen simply eschew the rocky Channel in favor of the southern shores of the islands.

Although satellite remote sensing can generate a "neutral party" record of fishing effort, we note three caveats associated with satellite data. First, large stationary sources of light, such as coastal cities, must be excluded when quantifying fishing vessel activity. The exclusion of urban light sources can result in underestimating effort, because boats that work near large light sources can be excluded from analysis. We were concerned that an underestimation of effort along the mainland coast would explain this study's post-El Niño increase in LPUE. Landings data, however, may indicate that effort in coastal blocks actually declined after the 1997–98 El Niño. Coastal blocks accounted for 19% of the landings in the pre-El Niño years (1992–96), dropping to 11% of landings in the post-El Niño years (1999 to early 2000).

Second, the spatial resolution of the satellite images may be large enough to allow multiple boats to fit into one "pixel" of detected light. Thus, effort may be underestimated. Analysis of the ground-truthing flyovers, however, did not indicate a strong interaction between boat aggregation and nightly fleet size. Boats may have indeed aggregated over the course of our study, but our analysis indicates that such aggregation was independent of nightly fleet size. In this case, the absolute values of estimated effort and LPUE would be underestimated across all dates. The relative values of effort and LPUE, however, will be only slightly affected within a time series; therefore we place confidence in our examinations of the temporal patterns of the effort-based data. A third caveat is specific to the present study. The ground-truthing work occurred during a period of relatively low fishing effort (1999–2000). Future fly-overs during periods of greater effort will be useful in corroborating our observed relationship between fly-over and satellite data.

The present study demonstrates that light detection by satellite remote sensing is useful for examining temporal and spatial patterns of fishing effort and population abundance, as measured by LPUE. Light detection by satellite has certain drawbacks, but these are not insurmountable. Importantly, geo-referenced satellite images provide an independent source of fishing effort, which can be feasibly integrated with environmental data through GIS analysis. With regard to market squid off California, satellite data can help provide fine-scale data on fishing location for this fishery's ongoing management efforts[4,5] (see also Mangel et al., 2002). Although mandatory shielding of the boat lights went into effect in May 2000, these lights are still detectable by the satellites (authors' pers. obs.). Recently, effort logbooks have become mandatory for squid fishermen off California. This requirement points to a unique opportunity to collect and corroborate fishery-dependent and independent measures of fishing effort.

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