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DOSIDICUS GIGAS FISHING GROUNDS IN THE EASTERN PACIFIC AS REVEALED BY SATELLITE IMAGERY OF THE LIGHT-FISHING FLEET

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ABSTRACT: *Dosidicus gigas* (the Jumbo flying squid) supports a major fishery in the Eastern Pacific. The commercial fishery consists of a multinational jigging fleet, and the emission of light from these vessels can be observed using satellite-derived imagery obtained by the United States Defence Meteorological Satellite Program - Operational Linescan System (DMSP-OLS). Using a Geographic Information System (GIS), the location of the fleet (derived from DMSP-OLS data) was examined for the region 20ºN to 20ºS; 75 to 100ºW, covering the central part of the species' distribution. Satellite imagery of the light-fishing fleet revealed fishing grounds to be situated off the coast of Peru (2 to 10ºS), with fishing on the high seas observed off both Peru (3 to 18ºS), and Central America (5 to 10ºN). The distribution of the fleet was not associated with bathymetry or proximity to coastal regions, but is likely to be linked to upwelling events in the Eastern Pacific. DMSP-OLS data can be used to provide synoptic imagery of the fleet for time periods from a single day to several years, and enables the study of fleet activity across management and political boundaries.

INTRODUCTION

Dosidicus gigas, the Jumbo flying squid, is widely distributed throughout the Eastern Pacific, occurring in large numbers off the coasts of North and South America. This species has a semi-oceanic pelagic habitat and is distributed from 37–40ºN to 45–47ºS, between California and Southern Chile, extending westwards from the coast to a maximum of 125–140ºW at the equator (Nesis, 1983; Nigmatullin *et al.*, 2001). Over the previous decade, *D. gigas* has become increasingly important in world cephalopod fisheries, and has recently been the subject of a comprehensive review of current knowledge (Rodhouse *et al.*, 2001a). Major fisheries for this species operate off the coasts of Peru (Yamashiro *et al.*, 1998; Taipe *et al.*, 2001), Central America (Ichii *et al.*, 2002), Mexico, and in the Gulf of California, Mexico (Nevárez-Martínez *et al.*, 2000; Morales-Bojórquez *et al.*, 2001). *D. gigas* have traditionally been caught in artisanal fisheries, particularly off Chile, Peru and Mexico (Nesis, 1983; Yamashiro *et al.*, 1998; Nevárez-Martínez *et al.*, 2000; Rocha and Vega, 2003), but since the early 1990s there has been an increase in the number of industrial jigging vessels (largely from East Asia, particularly Japan and Korea), fishing off Peru and Central America, with a resulting increase in squid catches from the Eastern Pacific (Yamashiro *et al.*, 1998; Ichii *et al.*, 2002). These jigging vessels operate at night using powerful lights to attract squid, with a single vessel using up to 300 kW for the production of light (Rodhouse *et al.*, 2001b).

Using remotely sensed data from the United States Defence Meteorological Satellite Program - Operational Linescan System (DMSP-OLS) it is possible to observe the distribution of fishing fleets around the globe by means of the light emitted during fishing operations (Rodhouse *et al.*, 2001b). The distribution of lights can be used to observe the distribution and abundance of squid jiggers, and by inference, the distribution of the exploited squid stocks (Cho *et al.*, 1999; Kiyofuji *et al.*, 2001; Waluda *et al.*, 2002).

This study uses remotely sensed data from DMSP-OLS, along with Geographic Information System (GIS) techniques, to examine the location of the fishing grounds for *D. gigas* in the Eastern Pacific (for the area shown in Figure 1). This covers the central part of the species distribution (Nesis, 1983; Nigmatullin *et al.*, 2001). The fleet is described in terms of large-scale, annual and monthly distributions. In addition, the relationship between fleet location and bathymetry, distance from the coast and proximity to the 200 nautical mile Exclusive Economic Zone (EEZ) are examined.

MATERIALS AND METHODS

Data sources

DMSP-OLS

Lights indicating the distribution of the light-fishing (jigging) fleet in the Eastern Pacific were detected with DMSP-OLS imagery for the region shown in Figure 1. Data comprised daily single-pass visible band images (with a maximum pixel resolution of 2.7km [0.008º]). Each image was georeferenced using algorithms developed by the National Geophysical Data Center (NGDC), Boulder Colorado (Elvidge *et al.*, 1999).

Figure 1. Map of the Eastern Pacific. Shaded region indicates area from which Defence Meteorological Satellite Program - Operational Linescan System (DMSP-OLS) data describing the distribution of the *Dosidicus gigas* light-fishing fleet were derived.

Bathymetry

Gridded elevation data at a resolution of 5' by 5' were obtained from the NOAA NDGC (National Geophysical Data Center) TerrainBase Global Terrain Model (http://www.ngdc.noaa.gov/mgg/global/seltopo.html) for the region shown in Figure 1.

Fishery data

Annual catch data were obtained from the FAO (Food and Agriculture Organisation) for fishing areas 77 (East Central Pacific) and 87 (South East Pacific) (Figure 2) for the period 1990 to 2000 (FAO, 2000).

Analyses

Using a Geographic Information System (GIS; Arc/Info version 8.1, ESRI, Environmental Systems Research Institute, Inc.), the distribution of the light-fishing fleet was examined for the region shown in Figure 1.

1. Large-scale distribution patterns 20ºN to 20ºS

Large-scale patterns in fleet distribution were examined by creating a composite image including all satellite passes available from the DMSP-OLS database for 1994, 1996 and 1997 (388 images in total). The location of the fleet was examined in relation to bathymetry, distance from the coast, and proximity to the 200 nautical mile (nm) exclusive economic zone (EEZ).

2. Inter-annual distribution of the light-fishing fleet

Catch data from the Food and Agriculture Organisation (FAO, 2000) were used to examine inter-annual variability in catches of *Dosidicus gigas* in FAO area 77 (East Central Pacific) and 87 (South East Pacific) during the previous decade (1990–2000) (Figure 2). DMSP-OLS data from 1994 and 1996 were compared to examine any variations in fleet distribution in these years, and to compare the distribution of fishing lights with relative catch levels in the two FAO areas.

3. Seasonal movements of the light-fishing fleet in the Peruvian region

The distribution of fishing lights was examined on a monthly basis for the fishery operating off the coast of Peru during 1994, encompassing the region between 0 and 10ºS, 78 and 84ºW.

4. Seasonal movements of the light-fishing fleet in the Central American region

The distribution of fishing lights was examined on a monthly basis for the fishery operating off the coast of Central America during 1996, for the region between 0 and 20ºN, 75 and 100ºW.

RESULTS

1. Large-scale distribution patterns 20ºN to 20ºS

In the northern hemisphere, large concentrations of fishing lights were observed in offshore waters off the coast of Central America, between 5 and 10ºN; 90 and 100ºW. Fishing lights were distributed outside the 200 nautical mile (nm) economic exclusion zone (EEZ), in waters of 3500–4000m depth. In the southern hemisphere, fishing lights were observed off the coast of Peru, between 2 and 10ºS and between 30 to 90nm from the coast, in waters of 200m to 3000m depth.

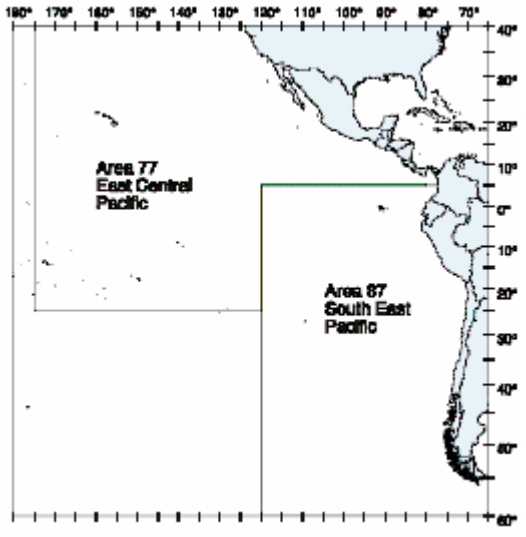

Figure 2. Location of FAO areas 77 (East Central Pacific) and 87 (South East Pacific) from which catch data on *Dosidicus gigas* were obtained.

Additionally, fishing lights were recorded offshore of the EEZ, between 3 and 18ºS, in waters of 3500 to 4500m depth (Figure 3). Offshore lights can also be seen in the Gulf of Mexico, at around 19.5ºN; 92 ºW, which probably indicates a gas flare associated with oil exploration in this region.

2. Inter-annual distribution of the light-fishing fleet

Between 1990 and 2000 the fishery for *Dosidicus gigas* exhibited large fluctuations in catches (Figure 4a). In 1994, the majority of catches (99%) were taken in the South East Pacific (FAO area 87, Figure 2, 4b), whereas in 1996, 15% of catches were taken in the South East Pacific, and 85% in the East Central Pacific

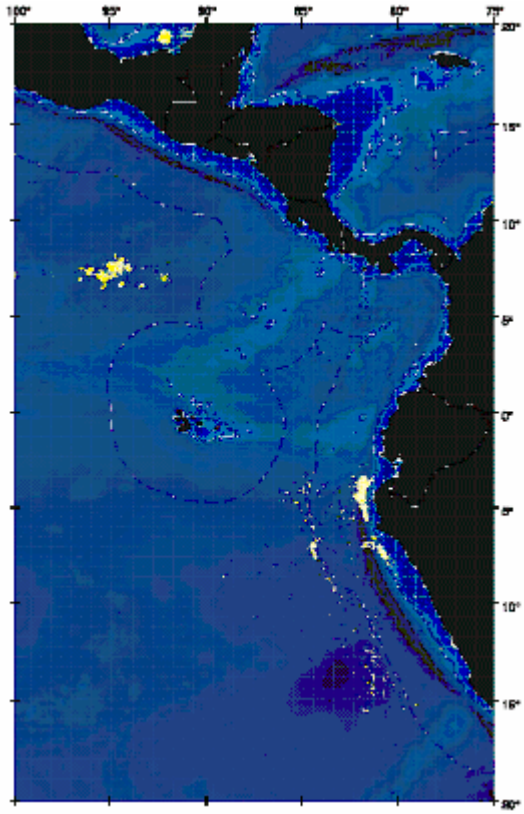

Figure 3. Composite image for 1994, 1996 and 1997 showing the distribution of the *Dosidicus gigas* fleet as derived from DMSP-OLS data. Blue shaded area represents gridded bathymetry data. Solid line indicates 1000m bathymetric contour, dashed line represents 200nm Exclusive Economic Zone (EEZ).

(FAO area 77, Figure 2, 4b). The distribution of fishing lights in these two years follows the pattern observed in the catch data (Figure 4b). In 1994, the fishery was almost exclusively distributed off the coast of Peru (FAO area 87) between 3 and 9ºS, and along the EEZ in high seas waters between 3 and 16ºS. No fishing lights were observed off the coast of Central America during 1994 (Figure 5a). In 1996, squid fishing lights were observed between 3 and 6ºS off the coast of Peru, with a small amount of fishing seen further offshore and on the high seas, close to the EEZ, between 10 and 15°S (Figure 5b). In addition, large concentrations of fishing lights were observed off the coast of Central America (FAO area 77), in high seas waters, between 5 and 10ºN.

3. Seasonal movements of the light-fishing fleet in the Peruvian region

In 1994, fishing lights were seen off the coast of Peru between January and December (Figure 6). Fishing lights occurred between 3 and 9ºS close to the 1000m depth contour in all months except May, and the location of the fleet varied throughout

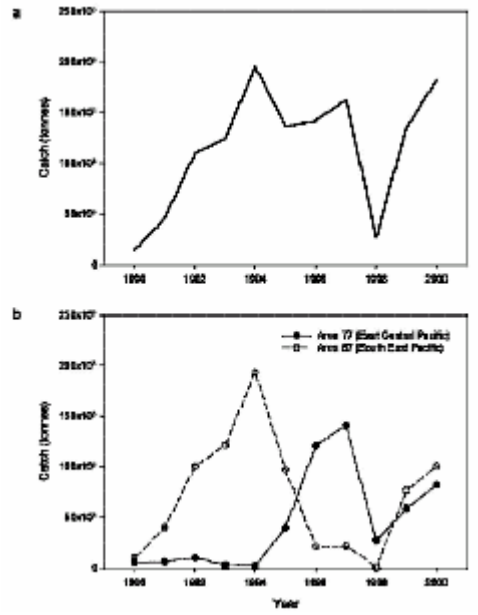

Figure 4. (a) Total catch (tonnes) of *Dosidicus gigas* from the Eastern Pacific (FAO areas 77 and 87) 1990–2000. (b) Catch (tonnes) of squid for the East Central Pacific (FAO area 77; solid line), the South East Pacific (FAO area 87; dotted line). Data from FAO.

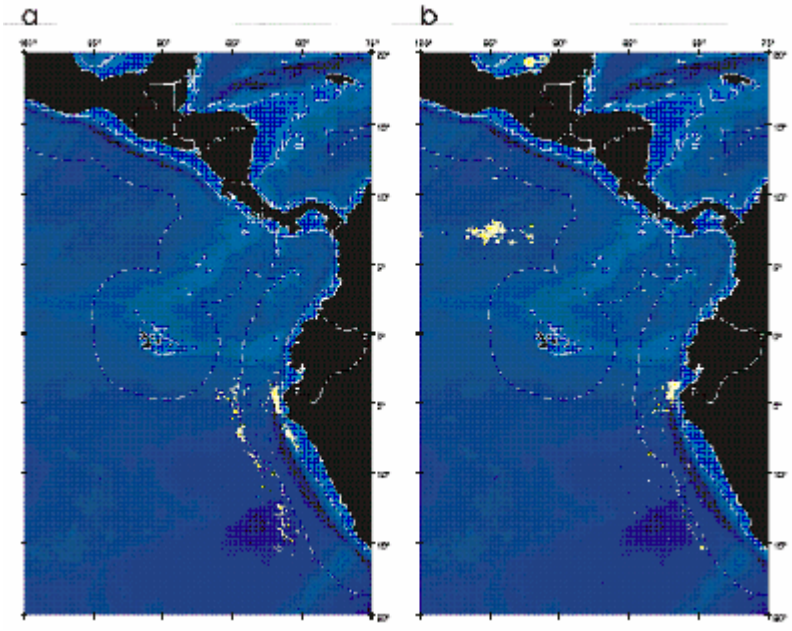

Figure 5. Distribution of the *Dosidicus gigas* fleet (a) 1994 and (b) 1996. Blue shaded area represents gridded bathymetry data. Solid line indicates 1000m bathymetric contour, dashed line represents 200nm Exclusive Economic Zone (EEZ).

the season. In all months except May and July, significant fishing lights were observed between 4 and 6ºS, off the coast of northern Peru, south of the Gulf of Guayaquil. A secondary fishing area centred around 7ºS was observed during the latter part of the season, specifically during June to August, and October to December, suggesting a southward shift of at least part of the fleet as the season progresses.

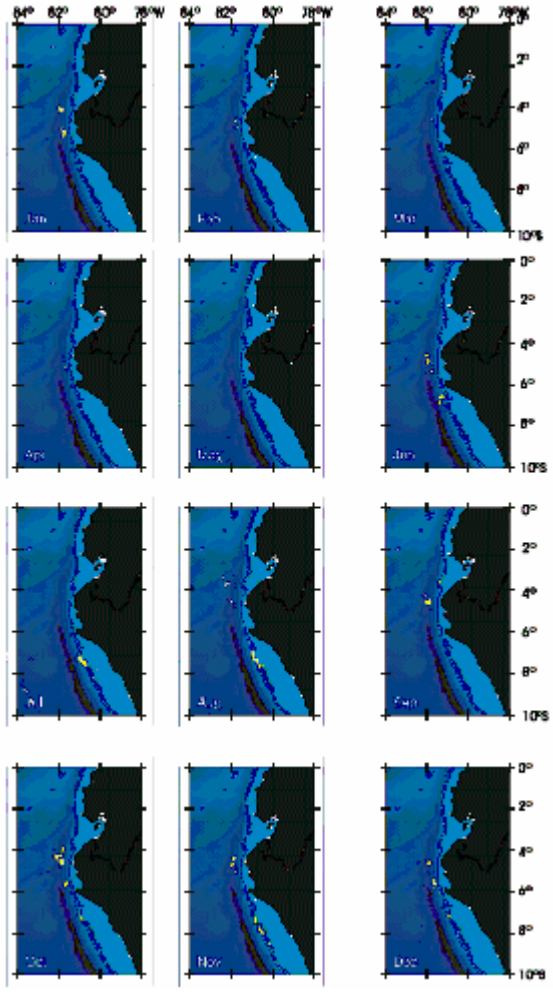

Figure 6. Monthly distribution of the *Dosidicus gigas* fleet operating off the coast of Peru, January to December 1994. Blue shaded area represents gridded bathymetry data. Solid line indicates 1000m bathymetric contour.

4. Seasonal movements of the light-fishing fleet in the Central American region

In 1996, fishing lights were observed off the coast of Central America between September and December (Figure 7), with no fishing lights present during January to August. In September, the fleet was distributed between 5 and 10ºN, occurring in several small clusters between 90 and 95ºW. In October and November the fleet was concentrated over a smaller area, and centred further west at around 95ºW. In December, very few fishing lights remained, with the fleet continuing to move to the west, and a small cluster of lights seen at around 98ºW.

DISCUSSION

Using satellite-derived imagery from DMSP-OLS it is possible to observe the distribution of the light-fishing fleet targeting *Dosidicus gigas* in the Eastern Pacific. The fleet is widely distributed throughout tropical latitudes, with several distinct fishing grounds observed off the coast of Peru, and in high seas areas off Peru and Central America. The distribution of the fleet presented here agrees with previous studies examining the large-scale distribution of *D. gigas* (Nesis, 1983; Nigmatullin *et al.*, 2001) and the smaller scale fishing regions in Peruvian waters (Taipe *et al.*, 2001), and the high seas to both the south (Kuroiwa, 1998) and north of the equator (Ichii *et al.*, 2002).

Within the study area, a number of consistent fishing grounds were seen to exist. It is assumed that the location of fishing lights indicate areas where squid are available to the fishery, and may, by inference, indicate areas of high secondary production and food availability. The distribution of the fleet did not appear to be tied to physical features, such as bathymetry or proximity to the coast. The waters of the Eastern Pacific are very deep, with the continental shelf reaching a maximum distance of 125km from the coast, and sloping steeply into the Peru-Chile trench to depths of 5000 to 6000m (Longhurst, 1998). In this study, the main fishing grounds were situated in waters between 200 and 4500m depth, between 30 and 400nm from the coast, indicating that commercially available quantities of *D. gigas* are

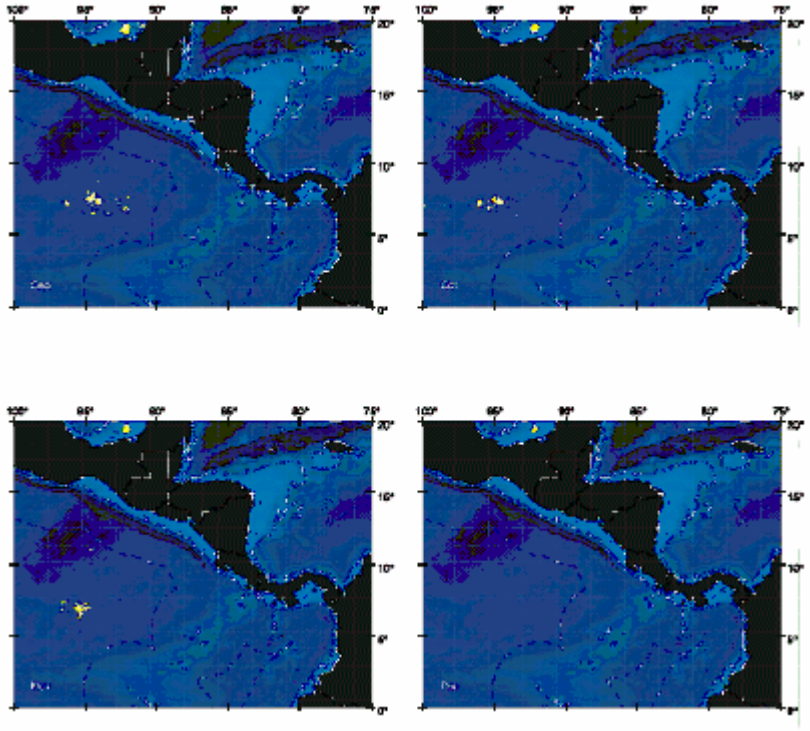

Figure 7. Monthly distribution of the *Dosidicus gigas* fleet operating off the coast of Central America, September to December 1996. Blue shaded area represents gridded bathymetry data. Solid line indicates 1000m bathymetric contour, dashed line represents 200nm Exclusive Economic Zone (EEZ).

widely distributed in the pelagic zone, over deep oceanic waters. This is in agreement with Nigmatullin *et al*. (2001) who found that *D. gigas* were associated with offshore waters in depths of up to 1200m.

The location of the 200nm exclusive economic zone (EEZ), marking the limits between national and international waters, was observed to support large numbers of fishing vessels in the Eastern Pacific. This is a similar pattern to that observed in the fishery for *I. argentinus* in the Southwest Atlantic (Waluda *et al.*, 2002). The use of DMSP-OLS in locating the light-fishing fleet is of particular value in examining the existence of fishing on the high seas, an area for which traditional fisheries data are rarely available. The occurrence of fishing vessels operating outside the Peruvian EEZ, south of the equator, appears to correspond with the numbers of vessels operating within Peruvian waters, for example high levels of fishing lights were observed in both regions during 1994, but not during 1996, when the presence of fishing lights was reduced in both regions. Fishing lights to the north of the equator occurred exclusively in high seas waters, corresponding with fishing grounds described by Ichii *et al*. (2002). This suggests that squid are widely distributed off the coastal margins of Peru, Ecuador and Central America, inhabiting both coastal and offshore waters.

Data on squid catches from the Eastern Pacific suggest shifts in the distribution of *D. gigas* stocks during 1990 to 2000, with higher catches made in the South East Pacific in all years except 1996 to 1998, during which an increase in catches was observed in the East Central Pacific (FAO, 2000). Although a large part of this catch can be attributed to the fishery operating off Mexico and in the Gulf of California (Morales-Bojórquez *et al.*, 2001), it appears that fishing in the high seas off Central America follows this trend (this study, Ichii *et al*., 2002), with the fleet operating in this region in

1996 (also 1997; Ichii *et al.,* 2002) but not 1994. Using data from DMSP it is possible to quantify levels of fishing on the high seas (Waluda *et al.*, 2002), but this has not yet been done for the fishery for *D. gigas*. The fleet operating in Pacific waters off Mexico and within the Gulf of California (north of 20ºN) clearly supports an important fishery, with catches of up to 40,000 tonnes made annually during 1977 to 1995, peaking at 140,000 tonnes during 1997 (Morales-Bojórquez *et al.*, 2001). However, as the majority of fishing in this region is done by artisanal vessels (pangas) which fish using low wattage lights (which are unlikely to be detectable using remotely sensed data), the region was not examined in this study.

Although the fleet exhibits seasonal changes in distribution in both the northern and southern hemisphere fisheries, it does not appear to follow a systematic pattern of migration, as is seen in the winter-spawning population of *Illex argentinus* exploited in the Southwest Atlantic (Haimovici *et al.*, 1998; Waluda *et al.*, 2002), or the fishery for *I. illecebrosus* in the Northwest Atlantic (Rowell and Trites, 1985). The distribution of each of these species is tied to the strong western boundary currents of the Brazil Current and Gulf Stream respectively, and large-scale migrations are an integral part of the species life cycle (O'Dor, 1992), whereas *D. gigas* is associated with a much less dynamic eastern boundary current upwelling system (Anderson and Rodhouse, 2001). It is likely that the distribution of *D. gigas* as shown by the distribution of the light-fishing fleet may relate to the occurrence of regions or 'cells' of upwelling (Thomas *et al.*, 1994; Longhurst, 1998) which may explain the clusters of lights observed in the DMSP-OLS images in both Peruvian and Central American regions. These upwelling regions may in turn support the production of small mesopelagic fish species (particularly myctophids) that inhabit these areas, and which constitute a large part of the diet of *D. gigas* (Nigmatullin *et al.*, 2001).

We conclude that on the basis of the distribution of the light-fishing fleet, the distribution of *D. gigas* in the Eastern Pacific does not appear to be influenced by bathymetry or proximity to coastal regions, however, variability in upwelling may be a critical factor. A reduction or effective failure in upwelling may cause a reduction in the population, or at least reduce the availability of squid stocks to the commercial fishery, for example during the El Niño event of 1998. Further work will examine the influence of upwelling strength on the abundance of squid and the distribution of the fishery, and examine potential links between squid distribution, upwelling cells, primary and secondary production in the Eastern Pacific upwelling system.

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