

# Use of marine sanctuaries by far-ranging predators: commuting flights to the California Current System by breeding Hawaiian albatrosses

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## ABSTRACT

Quantifying the dispersion and habitats of far-ranging seabirds, turtles, and cetaceans is essential to assess whether zoning strategies can help protect upper-trophic marine predators. In this paper, we focus on Black-footed Albatross (*Phoebastria nigripes*) use of three US national marine sanctuaries off central California: Cordell Bank, Gulf of the Farallones, and Monterey Bay. We assessed the significance of these protected areas to albatrosses by: (i) documenting commuting flights between Hawaiian breeding sites and the California Current System (CCS); (ii) quantifying albatross dispersion patterns on the central California continental shelf and slope, and (iii) characterizing albatross habitats within sanctuary waters using concurrent satellite-tracking data and vessel-based sightings. Chick-rearing albatrosses commuted from their colony on Tern Island, Hawaii (23.878°N, 166.288°W), to the CCS (34–48°N) and two of the eight satellite-tracked birds entered the marine sanctuaries. Among the telemetry locations within sanctuary waters, two-thirds (24 of 36) straddled the shelf break and slope (201–2000-m depth), a pattern underscored by a concurrent vessel-based survey in

which 144 Black-footed Albatrosses were sighted. This study illustrates the value of coordinated satellite telemetry and vessel-based surveys to assess the distributions of protected species within existing marine protected areas. More specifically, our results underscore the importance of three central California marine sanctuaries to Hawaiian albatrosses breeding in subtropical waters, approximately 4500 km away.

**Key words:** bathymetry, black-footed albatross, marine protected areas, national marine sanctuaries, *Phoebastria nigripes*, satellite telemetry

## INTRODUCTION

The US National Oceanic and Atmospheric Administration (NOAA) has undertaken a review of the management plan of the national marine sanctuary system, with particular emphasis on the adoption of an ecosystem-level management approach. As part of this broad mandate, existing marine sanctuaries have undertaken a thorough inventory of the biological resources within their waters, as well as an assessment of 'productive habitats' (e.g. seamounts and submarine canyons) adjacent to, but outside of, their boundaries (NCCOS, 2003; NOS, 2003). Analyses of long-term (1985–2002) vessel-based and aerial surveys off central California (39–35°N) have documented marine bird aggregations within the Gulf of the Farallones and Monterey Bay, suggesting that the marine sanctuaries established in these regions encompass the foraging grounds of many resident and transient species (Allen, 1994; NCCOS, 2003). Quantifying the spatial overlap of far-ranging species and existing protected areas is essential to assess the degree to which current zoning can help protect the foraging grounds and movement corridors of pelagic vertebrates, including marine birds, turtles, and cetaceans (Hyrenbach *et al.*, 2000; Anderson *et al.*, 2003).

This paper focuses on the Black-footed Albatross (*Phoebastria nigripes*, hereafter BFAlbatrosses), a seabird listed as 'endangered' by the International Union for the Conservation of Nature because of a projected

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population decline of 60% over the next three generations (56 yr), partly because of longline fisheries bycatch (Croxall and Gales, 1998; Lewison and Crowder, 2003). This species breeds on islands in the central and western North Pacific from late October to mid-June, and ranges from subtropical to subarctic latitudes (McDermon and Morgan, 1993; WPRFMC, 2000). The albatross diet is very broad, including epipelagic fish and squid, neustonic prey (e.g. flying fish eggs and gelatinous zooplankton), carrion, and discards from fishing vessels (Johnson *et al.*, 1993; Gould *et al.*, 1997; WPRFMC, 2000).

BFAI albatrosses are sighted year-round off the west coast of North America, although their numbers increase during the chick-rearing period (February to June) and the post-breeding dispersal stage (July to October) (McHugh, 1955; Briggs *et al.*, 1987). In particular, vessel-based and aerial surveys off central California (39–35°N) during 1985–2002 have documented high albatross densities within the Gulf of the Farallones, the Monterey Bay, and the Cordell Bank National Marine Sanctuaries, particularly during the upwelling season (March to August) (Allen, 1994; NCCOS, 2003).

While at-sea survey data provide a broad perspective of BFAI albatross seasonal/interannual occurrence patterns (presence/absence) and population dispersion (areas of aggregation), these observations are strained

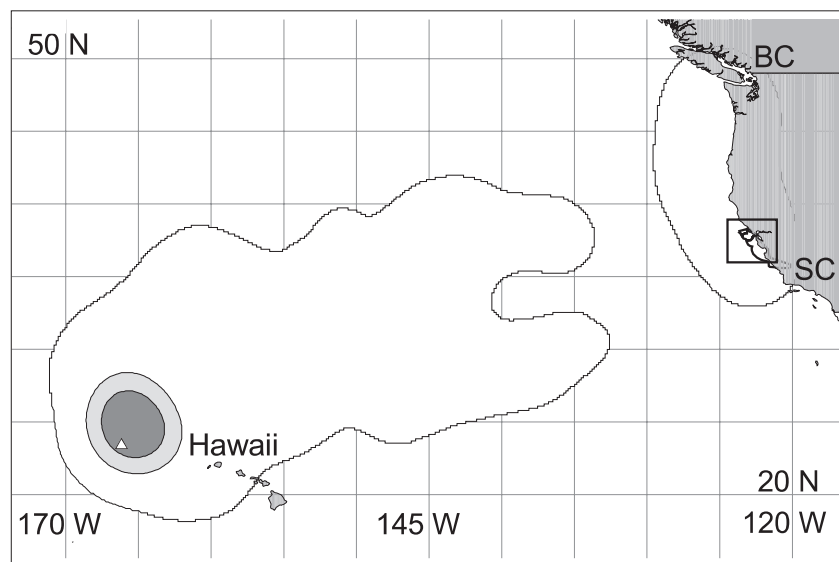
by their limited areal coverage, by the tendency of albatrosses to follow and aggregate at survey vessels, and by the inability to determine the origin, gender, and reproductive status of birds sighted at sea (Briggs *et al.*, 1987; Hyrenbach, 2001). The advent of satellite telemetry has facilitated the study of the movements and habitat use of individual birds over large spatial scales. Telemetry observations during the 1998 chick-rearing period (February to June) revealed that BFAI albatrosses breeding on Tern Island (23.878°N, 166.288°W; French Frigate Shoals, NW Hawaiian Island Chain) repeatedly commuted over 4500 km to the California Current System (CCS) (Fernández *et al.*, 2001; Hyrenbach *et al.*, 2002), including waters of the marine sanctuaries off central California (Fig. 1).

Herein, we assess the degree to which the above sanctuaries encompass BFAI albatross foraging grounds by: (i) documenting commuting flights by breeding birds; (ii) quantifying albatross dispersion on the central California shelf-slope; and (iii) characterizing albatross habitat associations using concurrent satellite-tracking data and vessel-based sightings.

## METHODS

We used two complementary approaches to quantify albatross use of three existing national marine sanctuaries. First, we quantified the fine-scale movements

**Figure 1.** Density contours from kernel estimates of the amount of time satellite-tracked Black-footed Albatrosses spent at sea during the 1998 chick-rearing period (February to June) in relation to three national marine sanctuaries in the central portion of the California Current System (CCS). Densities corresponding to three activity levels are considered: 95% (foraging range, white contour), 50% (focal region, gray contour) and 25% (core area, black contour). The CCS stretches south from British Columbia and begins to diverge offshore south of southern California. The breeding colony (Tern Island; French Frigate Shoals, NW Hawaiian Island Chain) is depicted with a triangle, and the study area off central California is shown in the insert (Fig. 2).



and habitat use of individual birds of known reproductive status and origin using satellite telemetry (Fig. 2a). We then complemented these intensive individual-based observations with a broad-scale description of albatross dispersion and habitat-use, using sightings from a concurrent vessel-based survey (Fig. 2b).

#### Satellite telemetry data

The methods used for collecting and processing telemetry data have been described elsewhere (Fernández *et al.*, 2001; Hyrenbach *et al.*, 2002). Briefly, we used PTT100 (Microwave Telemetry, Columbia, MD, USA) transmitters programmed to operate on a 8 : 24 h on : off duty cycle, and restricted our analyses to 3506 high-quality locations (class A or better) with median positional errors <10 km. We discarded all fixes that required unrealistic flying speeds >80 km h<sup>-1</sup> or were separated by <1 or >8 h. We overlapped these positions with concurrent remote sensing imagery and calculated the amount of time the tracked albatrosses spent over different water masses and bathymetric domains. We then tested for statistical differences across individuals, genders, and periods of the breeding season using generalized linear models. Because we did not detect differences in the habitats (e.g. water temperature, chlorophyll *a* concentration, and water depth) and the searching

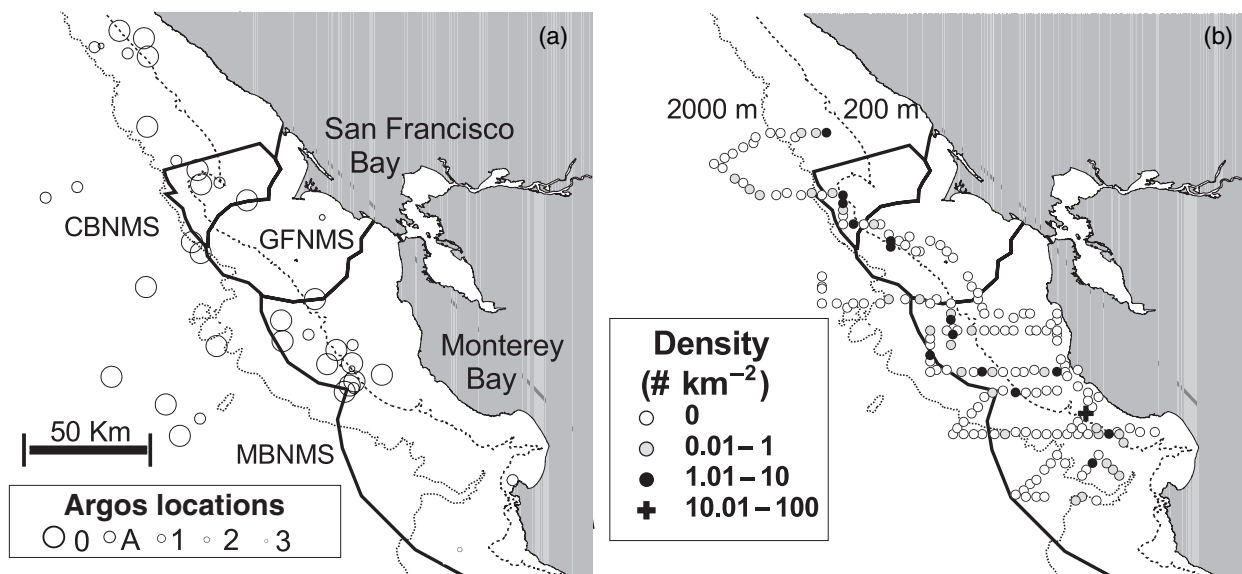
behavior (e.g. flight speed and turning rate) of male and female albatrosses (Hyrenbach *et al.*, 2002), we combined the telemetry data from all birds tracked during the chick-rearing period (19–140 d after their chicks hatched, January to June) of 1998.

We quantified albatross habitat use by calculating the amount of time the satellite-tracked birds spent at sea. We combined the data from all the birds tracked between February and June 1998 (eight individuals tracked during 35 foraging trips and 5855 tracking hours) and used kernel plot estimates to model the foraging range (95% contour), focal region (50% contour) and core areas (25% contour) of the 'time at-sea' distribution (Hyrenbach *et al.*, 2002). We employed the fixed kernel approach with the least-squares cross-validation, and performed the analyses using the Animal Movement ArcView Geographic Information System extension (<http://www.absc.usgs.gov/globa/gistools/>) (Seaman and Powell, 1996; Hooge and Eichenlaub, 1997). Next, we assessed the degree of spatial overlap between the tracked albatrosses and existing national marine sanctuaries, by quantifying the proportion of individuals and foraging trips that ranged within their waters.

#### Environmental data

We used the same environmental variables to characterize albatross habitats, whether they were tracked

**Figure 2.** Black-footed Albatross distribution off central California, as revealed by: (a) satellite telemetry fixes (March 1–June 30, 1998) depicted by circles proportional to the median error of each Argos location quality class: class 3 (0.44 km), class 2 (0.73 km), class 1 (1.53 km), class 0 (5.65 km), and class A (2.95 km) (Fernández *et al.*, 2001); and (b) vessel-based sightings along 15-min survey bins (May 14–19, 1998). Albatross distributions are superimposed on the 200- and 2000-m isobaths and the boundaries of the three national marine sanctuaries considered in this study: Cordell Bank (CBNMS), Gulf of the Farallones (GFNMS), and Monterey Bay (MBNMS).



using satellite telemetry or sighted during the vessel-based survey: (i) sea-surface temperature (SST) ( $^{\circ}\text{C}$ ), (ii) chlorophyll *a* concentration ( $\text{mg Chl } a \text{ m}^{-3}$ ), and (iii) water depth (m).

We used monthly averages of Pathfinder 4.1 SST from the Advanced Very High Resolution Radiometer (AVHRR), with a spatial resolution of 9 km, to quantify the temperature of the ocean at telemetry locations and along the survey track ([http://www.podaac.jpl.nasa.gov/pub/sea\\_surface\\_temperature/avhrr/pathfinder/data\\_v4.1/](http://www.podaac.jpl.nasa.gov/pub/sea_surface_temperature/avhrr/pathfinder/data_v4.1/)). Because of the potential biases in daytime SST imagery under the variable wind conditions ( $0\text{--}48 \text{ km h}^{-1}$ ) encountered during the May 14–19 cruise, we only used nighttime imagery to estimate SST. Nocturnal AVHRR data tend to underestimate SST by a larger magnitude on average ( $-0.15^{\circ}\text{C}$ ), but this bias is more consistent across low ( $<21 \text{ km h}^{-1}$ ) and high ( $>21 \text{ km h}^{-1}$ ) wind conditions, with mean values of  $-0.12$  and  $-0.18^{\circ}\text{C}$  respectively (Casey and Cornillon, 1999; Casey, 2002). The remotely sensed SST values were significantly correlated with concurrent surface measurements from conductivity–temperature–depth casts taken during the vessel-based survey (Pearson correlation coefficient = 0.740,  $N = 174$ ,  $P < 0.001$ ).

We considered three distinct surface water masses within our study area: upwelling plumes (SST  $< 10.5^{\circ}\text{C}$ ), offshore surface water (SST  $> 13^{\circ}\text{C}$ ), and the fronts separating warm offshore waters from cool recently upwelled water onshore (SST:  $10.5\text{--}13^{\circ}\text{C}$ ) (Schwing *et al.*, 1991; Steger *et al.*, 2000). During the vessel-based survey, we encountered waters of SST ranging from  $11.9$  to  $13.8^{\circ}\text{C}$ .

We derived chlorophyll *a* concentrations from monthly composites of sea-viewing wide field-of-view sensor (SeaWiFS) imagery, with a spatial resolution of 9 km (<http://www.seawifs.gsfc.nasa.gov/SEAWIFS.html>). Within the range of  $0.05\text{--}50 \text{ mg m}^{-3}$ , SeaWiFS estimates are within 35% of global *in situ* chlorophyll *a* concentrations, with the greatest discrepancies for the California Current region in waters having concentrations of  $1\text{--}10 \text{ mg m}^{-3}$ . We discarded chlorophyll *a* values that were beyond the range of SeaWiFS validation, and considered four different productivity regimes: oligotrophic waters with chlorophyll *a*  $< 0.1 \text{ mg m}^{-3}$ ; mesotrophic waters ranging  $0.1\text{--}0.3 \text{ mg m}^{-3}$ ; eutrophic waters between  $0.3\text{--}1 \text{ mg m}^{-3}$ ; and enriched waters having concentrations  $>1 \text{ mg m}^{-3}$  (Hooker and McClain, 2000; Kahru and Mitchell, 2000). During the vessel-based survey, we encountered waters of surface chlorophyll *a* concentrations ranging from  $0.3$  to  $5.1 \text{ mg m}^{-3}$ .

We obtained bathymetric data from NOAA's National Geophysical Data Center ETOPO 5-min gridded elevation data set (NGDC, 1998), with a spatial resolution of approximately 7.3 km at  $38^{\circ}\text{N}$ . Following previous work by Briggs *et al.* (1987), we defined the shelf break as the 200-m isobath and considered three distinct bathymetric domains: pelagic waters (depth  $>2000$  m); the continental slope ( $201\text{--}2000$ -m depth); and the continental shelf (depth  $\leq 200$  m). The vessel-based observations spanned waters between 4 and 3700-m depth.

#### Vessel-based surveys

We surveyed albatross distributions between May 14 and 19, 1998 using standardized techniques (Spear *et al.*, 1992). Two observers (CK, SA), stationed on the flying bridge 10 m above the surface of the water, recorded every albatross that entered an arc of  $90^{\circ}$  extending from the bow to the one side with best visibility (e.g. lowest glare) and out to 300 m from the trackline. Ship-following birds were recorded when they first entered the survey transect, and were ignored thereafter. Continuous albatross counts over 781 km of trackline were summed within 15-min segments (at 10-knot cruising speed: approximately 4.6 km), and were assigned depth and environmental data (SST, chlorophyll *a* concentration) from concurrent satellite imagery.

Additionally, the observers recorded the wind speed ( $\text{km h}^{-1}$ ) during seabird surveys directly from the vessel's underway environmental data logging system every 15 min. Because wind speed influences albatross activity (e.g. flying versus sitting on the water) and behavior (e.g. flight speeds), changing weather conditions (e.g. storminess) may alter the number of birds sighted within a given area during vessel-based surveys (Spear *et al.*, 1992; Spear and Ainley, 1997; Ainley *et al.*, 2005). To address this potential bias, we included wind speed as an additional explanatory variable in the analysis of the vessel-based survey.

Because albatrosses are attracted to and follow survey vessels and cue on each other's behavior (Nevitt and Veit, 1999; Hyrenbach, 2001), sightings along the survey track are likely related to each other. To address this potential lack of independence in the vessel-based observations, we categorized albatross occurrence (presence/absence) along the survey track instead of analyzing their density within the survey bins ( $\text{birds km}^{-2}$ ). Additionally, before we analyzed albatross-habitat associations, we tested whether the 15-min survey bins were independent sampling units.

We used the sign test to determine whether albatross sightings were temporally autocorrelated, by assessing whether the probabilities of bird presence/absence and absence/presence were equal for subsequent survey bins (Zar, 1984). Under the null hypothesis of no serial autocorrelation (independent albatross sightings along the survey track), the incidence of albatross presence/absence and absence/presence in pairs of consecutive bins should be equal. Conversely, if albatrosses are following the vessel or cueing on each other's behavior, subsequent observations will be dependent on previous sightings. Thus, we would expect the incidence of absence/presence and presence/absence events to differ. We performed this analysis at four distinct temporal scales and discovered that albatross presence was not serially autocorrelated at lags of 10–15 min ( $N = 89$ ,  $P = 0.093$ ), 16–30 min ( $N = 45$ ,  $P = 0.302$ ), 31–60 min ( $N = 65$ ,  $P = 0.824$ ), and 61–120 min ( $N = 272$ ,  $P = 0.289$ ).

Given the independent nature of the vessel-based observations, we analyzed albatross-habitat associations using the 15-min survey bins, which varied in length because of differences in cruising speed and the arrival at hydrographic/trawling stations, as sample units. We restricted our analysis to 178 bins, ranging between 3 and 6 km (0.9–1.8 km<sup>2</sup> of ocean surface area surveyed), which had a complete set of environmental data: water depth, SST, chlorophyll *a* concentration, and wind speed.

#### *Albatross habitats*

To determine which oceanographic variables were related to the presence of albatrosses, we used logistic regression to relate bird occurrence (binary-dependent variable, presence/absence) to four continuous predictor variables: chlorophyll *a* concentration (chl, mg m<sup>-3</sup>), water depth (depth, m), SST (°C), and wind speed (WSP, km h<sup>-1</sup>). Additionally, because the number of kilometers covered during a survey bin may influence the likelihood of encountering an albatross, we included this term in the analysis to avoid potential biases associated with unequal survey effort.

The logistic regression analyses are sensitive to correlations among the explanatory variables (Tabachnick and Fidell, 1996). When we performed a series of Pearson correlations to assess the potential co-variation of the four environmental variables, all six pair-wise comparisons yielded significant results ( $N = 178$ ,  $r$ -critical = 0.145,  $P < 0.05$  for all comparisons). Shallower regions were characterized by cooler waters, higher chlorophyll *a* concentrations, and lower wind speeds. Conversely, warmer, low-chlorophyll *a* waters occurred in the deeper parts of

the study area, where the wind was stronger. Because the habitat variables were correlated, we used a step-wise logistic regression to assemble the best-fit model iteratively, by rejecting/retaining the variables with the lowest/highest explanatory power one at a time.

In addition to analyzing albatross distributions with multivariate statistics, we used generalized additive models, with the logistic link function, to visualize the response of albatross occurrence (presence/absence) to each habitat variable separately (Clarke *et al.*, 2003).

#### *Albatross aggregation*

To quantify the degree of albatross aggregation within different bathymetric domains, we quantified the patchiness of their density (birds km<sup>-2</sup>) across 15-min survey bins using Green's index of dispersion:

$$G_x = [(S^2/X) - 1]/[\Sigma x - 1],$$

where  $S^2$  is the sample variance,  $X$  is the sample mean of bird density, and  $\Sigma x$  represents the sum of bird densities across all sample values.  $G_x$  ranges from 1 for maximum aggregation (patchy distribution: all birds occur in one survey bin), to a small negative number equal to  $-[1/(\Sigma x - 1)]$  for maximum regularity (uniform distribution: all samples yield the same bird density and sample variance equals 0).  $G_x$  is 0 for a random distribution, where the mean equals the variance (Andrew and Mapstone, 1987).

## RESULTS

The satellite-tracked albatrosses ranged from their breeding colony on Tern Island to the CCS, and their foraging range (95% 'time at sea' contour) overlapped with three existing national marine sanctuaries off central California (Fig. 1). In fact, between March 1 and June 30, 1998, two of the eight tracked albatrosses repeatedly entered these sanctuaries (Table 1).

The satellite-tracked birds occupied waters having a broad range of depths (median = 570 m, range = 11–3700 m), SST (median = 12.9°C, range = 12.3–13.8°C) and chlorophyll *a* concentration (median = 1.09 mg m<sup>-3</sup>, range = 0.32–3.67 mg m<sup>-3</sup>) within these sanctuaries. However, most of the satellite fixes (67%, 24/36) straddled the shelf break and the continental slope (201–2000-m depth) (Fig. 2a).

The vessel-based survey revealed that, in spite of being widely dispersed throughout the study area (Fig. 2b), albatrosses were associated with specific bathymetric domains and water masses (Table 2). A total of 144 albatrosses were sighted within 44

**Table 1.** Use of national marine sanctuary waters by satellite-tracked Black-footed Albatrosses breeding on Tern Island, Hawaii, during the 1998 chick-rearing period (February to June).

Sanctuary	Area (km <sup>2</sup> )	% Birds	% Trips
Cordell Bank	1800	25	5.7
Gulf of Farallones	4300	25	5.7
Monterey Bay	18,400	25	11.4
Total	24,500	25	11.4

Sample sizes are eight birds, 35 foraging trips, and 5855 tracking hours.

of the 178 15-min bins surveyed. These birds occupied a broad range of water depths (median = 829 m, range = 44–3612 m), SSTs (median = 13.1°C, range = 12.3–13.7°C), and chlorophyll *a* concentrations (median = 0.99 mg m<sup>-3</sup>, range = 0.35–2.88 mg m<sup>-3</sup>) (Fig. 3). Overall, the probability of albatross presence was significantly higher in shallow waters along the shelf break and the slope (Fig. 3a), characterized by warm SST (Fig. 3b) and low chlorophyll *a* concentrations (Fig. 3c). On the contrary, we did not detect a significant relationship with wind speed, nor a bias associated with the disparity in survey effort (distance surveyed) across the 15-min survey bins (Table 2).

In spite of the broad range of water depths occupied (3568 m), albatross sightings were concentrated in a band extending from onshore of the shelf break (200-m isobath) to the outer continental slope (2000-m

**Table 2.** Results of step-wise logistic regression of albatross occurrence (presence/absence) as a function of water depth (depth), chlorophyll *a* concentration (chl), sea-surface temperature (SST), wind speed (WSP), and the distance (dist) surveyed in each sampling bin.

Parameter	Coefficient	<i>t</i> -statistic	<i>P</i> -value	Effect
Depth	-0.001	-3.810	<0.001	-
Chl	-2.874	-4.044	<0.001	-
SST	+1.901	+2.701	0.007	+
WSP	+0.019	+0.504	0.614	NS
Dist	+0.158	+0.515	0.606	NS

Each variable is coded as having a positive (+) or a negative (-) effect on the probability of encountering Black-footed Albatrosses within a 15-min survey bin. NS denotes a lack of statistical significance. The best-fit model, including depth, chlorophyll *a* concentration, and SST, was highly significant (likelihood ratio = 40.502, *df* = 3, *P*-value <0.001), and correctly assigned albatross presence/absence to 67.9% of the survey bins.

isobath) (Figs 2 and 3a). The albatrosses were most common and widely dispersed (*Gx*: +0.03) over the slope (Table 3). Conversely, these birds were uncommon on the shelf (only 7% of the survey bins contained albatrosses) and were heavily aggregated in the vicinity of the shelf break (*Gx*: +0.82). In fact, over 89% (71/79) of the albatrosses sighted on the shelf were concentrated within one 3-km survey bin north of Monterey Bay (cross-marking on Fig. 2b). BFAlbatrosses were infrequently observed (only present in 14% of the survey bins) within the pelagic domain, where they occurred in uniformly low densities (*Gx*: -0.12).

## DISCUSSION

Quantifying the spatial and temporal distributions of protected species represents a challenge in assessing conservation benefits of marine zoning (Allen, 1994; Anderson *et al.*, 2003). In this paper, we quantified BFAlbatross habitats and dispersion (patchiness) within the waters of three national marine sanctuaries in the CCS.

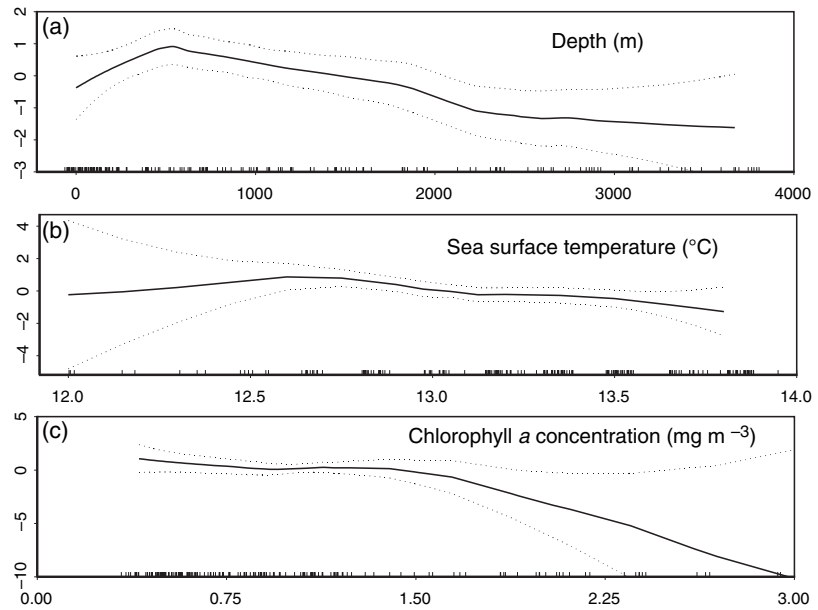
### *Albatross habitats*

The satellite telemetry locations and the vessel-based sightings indicate that BFAlbatrosses occupy warm (median SST: 12.9 and 13.1°C) and low-chlorophyll *a* (median values 1.09 and 0.99 mg m<sup>-3</sup>) waters along the shelf break and the slope during their spring-time (March to June) dispersion off central California. A detailed oceanographic analysis during May to June 2000 documented BFAlbatross aggregations off Oregon, in association with similar water mass characteristics on the seaward side of a coastal upwelling jet (Ainley *et al.*, 2005).

Similarly, the vessel-based albatross sightings were concentrated along the shelf break and adjacent continental slope (Figs 2b and 3a). This distribution pattern was consistent with previous long-term (1985–2002) analyses of vessel-based and aerial albatross sightings off central California (Allen, 1994; NCCOS, 2003). For instance, after averaging the depth at 3149 sightings obtained across seasons and years, the average BFAlbatross distribution was centered on the continental slope, over water 1091 ± 28 (SE) m deep. Additionally, dense albatross concentrations have been previously documented within existing national marine sanctuaries, including Cordell Bank, the northern part of the Gulf of the Farallones, and the Monterey Canyon (NCCOS, 2003).

The step-wise logistic regression revealed that both water depth and chlorophyll *a* concentration were strong predictors of the distribution of vessel-based

**Figure 3.** Generalized additive model results relating Black-footed Albatross occurrence (presence/absence) to environmental conditions during vessel-based surveys off central California (May 14–19, 1998). For each variable, the best-fit loss function (solid line), the 95% confidence intervals (dashed lines), and the distribution of survey effort (vertical ticks) are shown.



**Table 3.** Black-footed Albatross dispersion within three bathymetric domains in the central portion of the California Current (May 14–19, 1998).

Bathymetric domain	Depth range (m)	Number of birds	Number of bins	Proportion (% present)	Mean density $\pm$ SD (birds km <sup>-2</sup> )	Gx index
Shelf	$\leq 200$	79	57	0.07	1.05 $\pm$ 7.14	+0.82
Slope	201–2000	59	77	0.44	0.60 $\pm$ 1.16	+0.03
Pelagic	>2000	6	44	0.14	0.10 $\pm$ 0.06	-0.12

For each bathymetric domain, the total number of birds sighted, the total number and the proportion of 15-min survey bins containing birds, the mean density, and the patchiness (Green's index of dispersion, Gx) of albatrosses are shown.

sightings, with SST also having a significant influence on BFAlbatross dispersion (Table 3). We could not determine whether albatross distributions were driven by bathymetry or by hydrography, because the best-fit model included one static (water depth) and two dynamic (chlorophyll *a* concentration, SST) habitat variables. Furthermore, chlorophyll *a* concentration ( $r = -0.585$ ) and SST ( $r = +0.288$ ) are strongly correlated with seafloor depth in the study area, with warmer and clearer waters found over the continental slope and the shelf break, offshore of the coastal upwelling plumes (Schwing *et al.*, 1991; Steger *et al.*, 2000). Off Oregon, where this species also occurs near the shelf break, it is associated with physical (hydrographic) and biological (acoustic prey biomass) features, which are influenced by the underlying topography (Ainley *et al.*, 2005).

Our study took place just as one of the strongest El Niño events in more than 50 yr was waning, during a

period of unusually weak upwelling, a depressed thermocline, and low ocean productivity in the CCS. At this time, high chlorophyll *a* concentrations and fish egg distributions were confined to a narrow band (approximately 50-km wide) nearshore, suggesting that coastal upwelling was reduced (Lynn *et al.*, 1998; Ralston *et al.*, 1999). In accord with these hydrographic patterns, oceanic species would be expected to shift their distributions. Consequently, the results of our analyses should be interpreted with caution because albatrosses may have moved onshore during the spring of 1998.

#### Marine zoning for albatross conservation

Although both static and dynamic habitats may influence albatross distributions off central California, we focus our discussion of potential marine zoning strategies on seafloor depth. In principle, marine protected area designs based on geographically fixed features are much more conducive to implementation

and enforcement, as their boundaries are defined by the extent of isobaths on a map (e.g. seamounts and submarine canyons). Furthermore, there exists a precedent for marine zoning based on water depth in this region. A fishery closure of waters <40 fathoms (73 m) deep has been implemented to mitigate seabird and cetacean bycatch in coastal gillnets off central California (Forney *et al.*, 2001). Nevertheless, it is essential to acknowledge that topographic features often strongly influence hydrographic features in the CCS (e.g. Batchelder *et al.*, 2002).

Our results suggest that marine zoning could be used to protect spring-time (March to June) albatross foraging grounds off central California. More specifically, an albatross sanctuary would have to encompass the shelf break and the slope, with a buffer extending shorewards to contain high-use areas along the northern edge of Monterey Canyon (Fig. 2b). Our results also show that albatrosses aggregate along the continental slope, as revealed by satellite-tracking (67%, 24/36 of telemetry locations occurred in this region, Fig. 2a) and vessel-based observations (birds present in 44% of the survey bins from the slope, Fig. 2b). Moreover, because albatrosses are widely dispersed throughout the slope (Table 3), this entire bathymetric domain would have to be protected from potential impacts associated with fisheries bycatch and oil spills (Johnson *et al.*, 1993; WPRFMC, 2000; Lewison and Crowder, 2003).

In addition to Monterey Canyon and Cordell Bank, we have documented other areas of BFAlbatross use beyond sanctuary boundaries. In particular, the vessel-based sightings and the telemetry data revealed albatross aggregations on the slope north of the Cordell Bank NMS (Fig. 2a, b). These observations suggest that the northward expansion of the existing sanctuaries would afford this species with enhanced protection.

While the existing national marine sanctuaries encompass large expanses of the continental shelf and slope off central California, they currently provide little protection to albatrosses foraging within these waters, aside from mitigating impacts associated with oil drilling and dumping from vessels. In the future, marine zoning strategies for albatross conservation may seek to regulate pelagic longline and gill-net fisheries within the high-use foraging grounds of these species (Gilman, 2001). To the extent that existing marine sanctuaries may serve as a catalyst for future conservation actions, it is imperative that they encompass the foraging grounds and migration corridors of protected seabirds, turtles, and cetaceans (Hyrenbach *et al.*, 2000).

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