Spatial variability of seabird distribution associated with environmental factors: a case study of marine Important Bird Areas in the Azores

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The spatial structure and distribution at sea of Cory's shearwaters (*Calonectris diomedea borealis*), common terns (*Sterna hirundo*), and roseate terns (*Sterna dougallii*) were analysed in the Azores for various environmental factors: sea surface temperature, chlorophyll *a* concentration, distance to fronts, wind, distance to island shore or tern colonies, distance to seamounts, seabed slope, and depth. Data on seabird sightings were collected by observers on board fishing vessels, 2002–2006. Generalized linear modelling (GLM) explained 43 and 11% of the abundance variability for terns (both species pooled) and Cory's shearwaters, respectively. Variability in seabird abundance was mainly explained by month, wind, distance to shore and/or tern colonies, and distance to seamounts. Variogram modelling indicated that species distribution presented a small-scale spatial structure (i.e. low autocorrelation). Cory's shearwater predictive distribution maps showed widespread distribution patterns of abundance, despite occurring at a greater intensity around the islands and around some seamounts, which are areas of fishery interest. Conversely, terns were essentially concentrated near the shore. The establishment of marine important bird areas should be encouraged close to seabird colonies and around some seamount areas.

Keywords: Azores, geostatistics, marine IBAs, regression models, seabirds, spatial statistics.

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Introduction

It is widely recognized that species distribution varies over space and time as a result of the selection of preferred habitat and environmental conditions (e.g. Ballance *et al.*, 2006). The influence of environmental factors in the at-sea spatial distribution of seabirds has been widely investigated, although most studies have focused on productive continental shelves in subpolar and coastal upwelling systems (see reviews by Hunt and Schneider, 1987; Hunt *et al.*, 1999). Yet, considerably less is known about the habitats of oceanic birds in subtropical and tropical waters, especially in the oceanic realm (for a review, see Ballance and Pitman, 1999). The most common parameters used to explain spatial seabird distribution are water mass types quantified through sea surface temperature (SST) and salinity measurements (Ainley *et al.*, 2005; Hyrenbach *et al.*, 2007), ocean productivity indexed using the concentration of chlorophyll *a* (Chl *a*) as a proxy (e.g. Louzao *et al.*, 2006; Yen *et al.*, 2006), windspeed (e.g. Spear and Ainley, 1998; Suryan *et al.*, 2006), mesoscale features including eddies (e.g. Hyrenbach *et al.*, 2006; Yen *et al.*, 2006) and temperature–salinity fronts (e.g. Begg and Reid, 1997; Ainley *et al.*, 2005), topographic features (e.g. Schneider, 1997; Yen *et al.*, 2004; Morato *et al.*, 2008a), and distance to colonies (e.g. Garthe, 1997; Hyrenbach *et al.*, 2007).

The Azores Archipelago is located in the subtropical Northeast Atlantic, and it represents an ornithological transition between the tropical and temperate waters (Monteiro *et al.*, 1996a). Cory's shearwater (*Calonectris diomedea borealis*) is the most abundant seabird in the area (Table 1), representing the largest concentration of the subspecies *borealis* in the world (Monteiro, 2000; BirdLife International, 2004). The common tern (*Sterna hirundo*) also occurs very frequently in the Azores (Table 1), whereas the population of the roseate tern (*Sterna dougallii*) in the Azores is estimated to be the largest in Europe (Santos *et al.*, 1995; Monteiro, 2000). The global conservation status of these species is of "least concern" (BirdLife International). However, at the European level, the three species are listed in Annex I of the EC Birds Directive, i.e. are considered of conservation concern. The main threats that affect shearwaters and terns in the Azores are related to predation (rats, gulls, etc.), anthropogenic disturbance, changes in vegetation, habitat damage by herbivores, and potential competition for food resources with fisheries (Monteiro *et al.*, 1996a).

Seabird conservation is well advanced in the Azores, where 13 special protection areas (SPAs) have been designated under the EC Birds Directive. However, these are terrestrial SPAs and therefore do not encompass any of the critical coastal and offshore waters such as at-sea feeding or resting areas. Because the Azores archipelago is an important breeding area, chiefly for Cory's shearwaters, proactive measures are necessary to protect these important ecological resources. In particular, information on the

Table 1. Cory's shearwater and tern breeding and feeding characteristics in the Azores (adapted from Monteiro *et al.*, 1996a, b; Neves, 2007).

Species	Breeding sites	Breeding pairs	Period in Azores	Nesting	Main prey
Cory's shearwater	All islands	160 000	Late February until late October	Late May until early June	Small pelagic fish, small squids, crustaceans, and zooplankton (occasionally)
Common tern	All islands	2 805	March – April until late September	Early May until mid-July	Small and juvenile fish
Roseate tern	All islands except Corvo	1 100	March – April until late September	Early May until mid-July	Small and juvenile fish

critical habitats where these seabirds forage and interact with fisheries is essential to identify and delineate potential protected areas.

The main objective of this study is to analyse potential relationships between the spatial structure and distribution of the three seabird species breeding in the Azores (Cory's shearwater and two species of tern) and environmental factors, taking into account seasonal variability along with the development of predictive habitat models. This study is the first that incorporates geostatistical methods. This information will be applied to the identification and delineation of marine Important Bird Areas (IBAs).

Material and methods
Study area
The Azores archipelago is a group of nine volcanic islands and many small islets situated along a 600 km transect surrounded by narrow shelves. The Azorean exclusive economic zone (EEZ) crosses the Mid-Atlantic Ridge in the Northeast Atlantic Ocean and encloses an area of almost 1 million km^2. This study was conducted in a rectangular area of $\sim$226 000 km^2 ($36°39'$ – $39°58'$N and $24°26'$ – $31°26'$W), which includes most of the spatial data existing on seabirds (Figure 1).

Seabird data
Data on seabirds were collected during the Azores Fisheries Observers Programme (POPA; www.popaobserver.org). The programme runs with trained observers on board fishing vessels, recording georeferenced data on fishing activities and other relevant information, such as sightings of associated species of cetaceans, seabirds, and sea turtles (Feio *et al.*, 2005; Machete and Santos, 2007; Morato *et al.*, 2008a). Data on seabird sightings
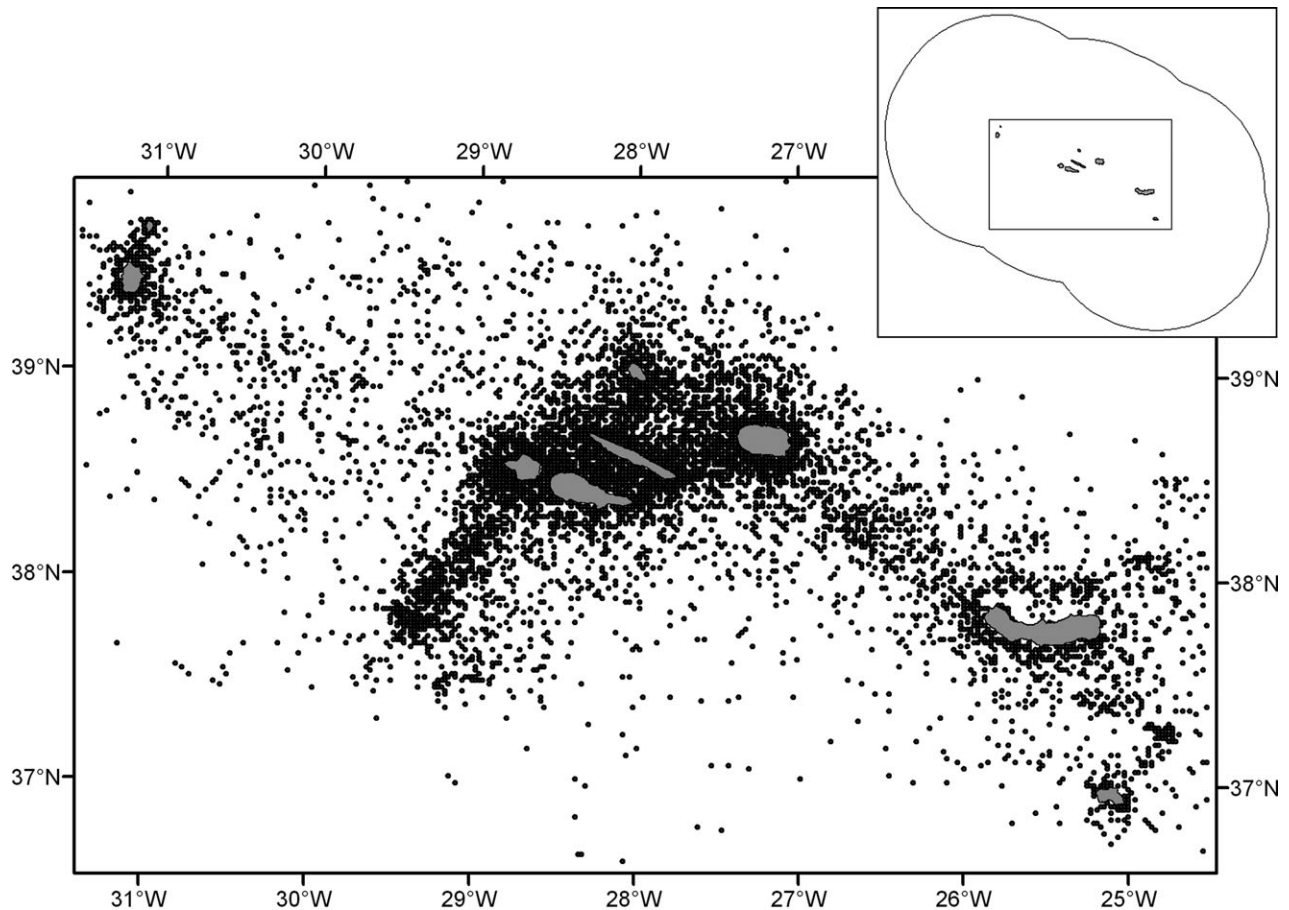
Figure 1. Location of the seabird snapshot counts conducted in the Azores, 2002 – 2006 ($n = 9183$). The outline shape in the inset represents the EEZ of the Azores.

were collected using a snapshot type of methodology, i.e. counting seabirds sighted around the boat (up to 300 m) during six daily fixed periods, separated by 2-h intervals (09:00, 11:00, 13:00, 15:00, 17:00, and 19:00). If no seabirds were observed, a zero count was recorded. Otherwise, seabird sightings were recorded in quantity ranges (shearwaters: 1–10, 11–25, 26–50, 51–100, 101–250, 251–500, 501–1000, and >1000; terns: 1–3, 4–10, 11–25, 26–50, 51–75, 76–100, and >100). These categorical data were converted into continuous variables by assigning the mean value of each class of abundance. We used data collected during 9183 snapshot counts performed from May to October, 2002–2006. During this period, the most frequently observed seabirds were Cory's shearwater, common and roseate terns (pooled), and the yellow-legged gull (*Larus michahellis atlantis*). However, in this study, we will focus on the first three species because of their conservation-concern status.

Environmental data

SST in the Azores was obtained by satellite imagery at the "HAZO" HRPT station (http://oceano.horta.uac.pt/detra/), using the advanced, very high-resolution radiometer (AVHRR) sensor. Chl *a* was obtained using the MODIS sensor of the Aqua satellite (http://oceancolor.gsfc.nasa.gov/). Images were processed at IMAR-DOP/UAç (Figueiredo *et al.*, 2004). Monthly median values of SST and Chl *a* were obtained with a resolution of ~1.2 × 1.2 km, 2002–2006.

Table 2. Monthly survey effort and seabird observations using the snapshot method.

Month	Snapshots	Counts with birds (%)	Mean (± s.d.; individuals per sighting)	
			Shearwaters	**Terns**
May	1 164	84.0	22.7 (± 80.4)	0.4 (± 9.7)
June	2 132	76.6	23.4 (± 61.4)	0.8 (± 5.2)
July	2 271	74.5	37.2 (± 87.7)	2.9 (± 13.1)
August	2 309	87.3	53.8 (± 100.9)	13.9 (± 15.4)
September	1 088	88.3	17.6 (± 67.6)	5.1 (± 14.9)
October	219	88.6	2.0 (± 25.4)	0.2 (± 7.7)

The standard deviation is represented by s.d.

Distances to productivity fronts are defined as discontinuity areas that presented simultaneously values of SST lower and values of Chl *a* higher than their adjacent areas. These distances were estimated using the methodology developed by Valavanis *et al.* (2005) and produced monthly mean grids of productivity fronts with a resolution of 1.852 × 1.852 km.

Information on wind was obtained with a resolution of ~55 × 55 km from QuikSCAT satellite imagery (http://www.ifremer.fr/cersat/en/general/general.htm), processed and distributed by the Centre ERS d'Archivage et de Traitement at IFREMER, Plouzané, France. Wind components (speed, divergence, zonal, and meridional) were subsampled using the inverse distance weighting to produce monthly mean grids of 1.852 × 1.852 km.

Additionally, depth, seabed slope, minimum distance to shore (islands), minimum distance to tern colonies, and minimum distance to large and shallow seamounts were calculated for each cell. Depth was estimated using a bathymetry grid 1.85 × 1.85 km (Lourenço *et al.*, 1998), and the slope angle (in degrees) was calculated with the slope algorithm (in the ArcGIS software, ESRI ArcMap 9.1). The location of large seamounts (>1000 m height) and shallow seamounts (summit up to 300-m depth) was obtained from Morato *et al.* (2008b).

Statistical analysis

Mean monthly values of seabird counts and environmental variables were estimated for each sampled cell of 1.852 × 1.852 km for the period 2002–2006. Pearson correlation coefficients were calculated between all the environmental parameters to test for possible covariation. The same coefficients were also calculated between the mean numbers of seabirds sighted (log transformed) and the mean value of each environmental variable, by cell, to determine potential linear relationships (Dalgaard, 2002).

Generalized linear models (GLM) were used to determine if variability in seabird sightings was significantly explained by environmental parameters. Monthly mean values of seabird sightings and environmental data (SST, Chl *a*, distance to fronts, and wind components) by cell were pooled, and "month" was integrated in the GLM as a categorical temporal variable. A quasi-Poisson family of probability distributions was used with the log-link function because of the large number of zero counts (i.e. overdispersion). Seabed slope and distance to shore/
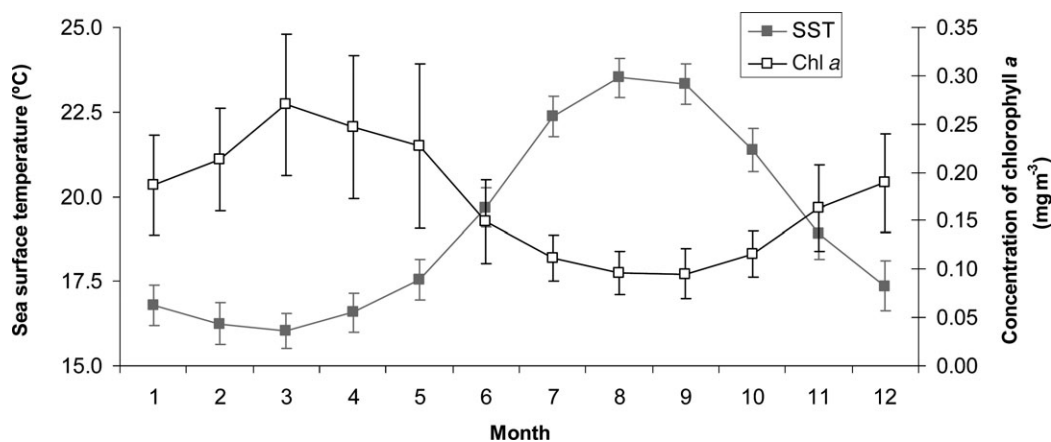
Figure 2. Monthly mean values of the median SST and the median chlorophyll-*a* (Chl *a*) concentration in the sampled area, 2002–2006. Vertical bars indicate standard deviation values. SST missing data: November and December 2004; Chl *a* missing data: January–May 2002.

Table 3. Pearson correlation coefficients calculated between all environmental variables.

Parameter	Depth	Distance shore	Distance seamounts	Distance shallow seamounts	Slope	SST	Chl a	Distance fronts	Wind divergence	Wind meridional	Windspeed	Wind zonal	Distance tern colonies
Depth	**1**												
Distance shore	**0.37**	**1**											
Distance seamounts	**0.08**	**−0.34**	**1**										
Distance shallow seamounts	**0.06**	−0.11	**0.60**	**1**									
Slope	**−0.24**	**−0.28**	−0.01	−0.04	**1**								
SST	**−0.10**	−0.09	**0.14**	**0.26**	**0.10**	**1**							
Chl a	−0.09	0.05	−0.09	**−0.14**	−0.07	**−0.52**	**1**						
Distance fronts	**0.09**	**−0.14**	**0.13**	0.03	**0.03**	**−0.15**	0.01	**1**					
Wind divergence	**−0.07**	**−0.08**	**−0.11**	−0.06	0.02	−0.01	**0.22**	−0.02	**1**				
Wind meridional	−0.02	−0.01	**0.08**	−0.02	−0.03	**−0.21**	**0.24**	**0.18**	**−0.12**	**1**			
Windspeed	**−0.11**	−0.05	−0.06	**−0.11**	0.01	**−0.39**	0.09	0.02	**−0.28**	0.07	**1**		
Wind zonal	0.01	**0.14**	0.03	0.03	**−0.07**	**−0.28**	**0.26**	0.02	**0.05**	**0.12**	**0.39**	**1**	
Distance tern colonies	**0.38**	**1.00**	**−0.34**	**−0.11**	**−0.28**	**−0.10**	0.05	**−0.12**	**−0.09**	−0.01	**−0.04**	**0.14**	**1**

SST, sea surface temperature; chl a, chlorophyll a.
Emboldened values indicate significant correlations (p-value < 0.01).

colonies were log_{10}-transformed to achieve normality. Linear and quadratic relationships between seabird abundance and environmental variables were fitted. All models were built by a forward stepwise selection of variables, adding the significant terms ($\alpha \leq 0.05$) sequentially. Thereafter, non-significant variables were deleted from the final model (Bio, 2000). The final adjustment of the model was made by the analysis of the pseudo-determination coefficient (pseudo-R^2), i.e. the fraction of the total variability explained by the model.

Additionally, to investigate whether or not different parameters might be affecting shearwater abundance close to colonies and off-shore feeding areas, the shearwater sightings data were divided into two datasets: (i) onshore (based on sightings undertaken up to 30 km from shore; $n = 4419$) and offshore (distance to shore ≥ 30 km; $n = 2532$). This break was selected based on the results of the general model that indicated an accentuated decrease in the number of shearwaters $\sim$30 km from shore.

Because the variance caused by autocorrelation cannot be properly quantified by the GLMs, the seabird spatial structure was analysed using geostatistical methods by (i) modelling the spatial structure of the seabirds through the variogram fit and (ii) estimating the seabird distribution through kriging techniques. The residuals were transformed to achieve a constant variance. Standardized Pearson residuals were analysed through the variogram fit to assess spatial autocorrelation (Pebesma, 2004; Pebesma et al., 2005), considering geometric anisotropy and based on the spherical model. The parameters of each model—nugget effect (the discontinuity at the origin), sill (variance of the random field), range (distance beyond which the observations are not correlated), and direction—were determined by an interactive process.

The spatial component was added to the GLM results to yield a prediction of the seabird distribution based on the predictor variables (environmental parameters) and on the part of spatial structure of the seabirds (autocorrelation) to improve the accuracy of seabird numbers estimates. Spatial prediction for the whole study area was performed through block kriging (Pebesma, 2004). The mean error and the percentage of dispersion of the error in relation to sample mean were calculated to compare the observed and predicted values.

Results
Seabird sightings
In all, 9183 snapshot counts were performed during the study period (May–October 2002–2006), with the highest effort June–August (Table 2). Seabirds occurred in more than 80% of all snapshots, with Cory's shearwaters observed in 64% of the snapshots and terns in only 25%. The mean number of seabirds sighted varied among species, with a mean of $\sim$20 shearwaters and three terns observed per snapshot. There were monthly differences in mean seabird numbers, with a peak in August for both taxa (Table 2).

Environmental data
The monthly mean values obtained from the median SST and Chl a images, 2002–2006, varied seasonally (Figure 2). SST around the Azores ranged from 16.0°C to 23.5°C, and near-surface Chl a ranged from 0.1 to 0.3 mg m^{-3}. Comparison of monthly SST and Chl a values revealed an out-of-phase seasonal response, with periods of higher temperatures associated with lower Chl a (Figure 2) showing a significant negative correlation ($r = -0.52$, $p < 0.01$, $n = 6950$; Table 3).

The wind components also varied seasonally (Figure 3). Windspeed ranged from 5 to 10 m s^{-1}. Wind divergence in the region was characterized by positive mean values, indicating an outflow air flux (Figure 3b), except March, which is characterized by a convergence process. The meridional component of the wind indicated that the predominant direction is north–south from April to November, blowing in the opposite direction from December to March (Figure 3c). The positive mean values of zonal wind throughout a year indicated a dominant west–east wind direction (Figure 3d). In general, wind components were negatively correlated with SST and positively correlated with Chl a (all $p < 0.01$). These results indicated that an increase in water turbulence (generated by wind-mixing processes) leads to enhanced phytoplankton standing stocks.

Seabird sightings and environmental factors
As a first approach, the Pearson correlation coefficients displayed significant relationships between certain environmental parameters
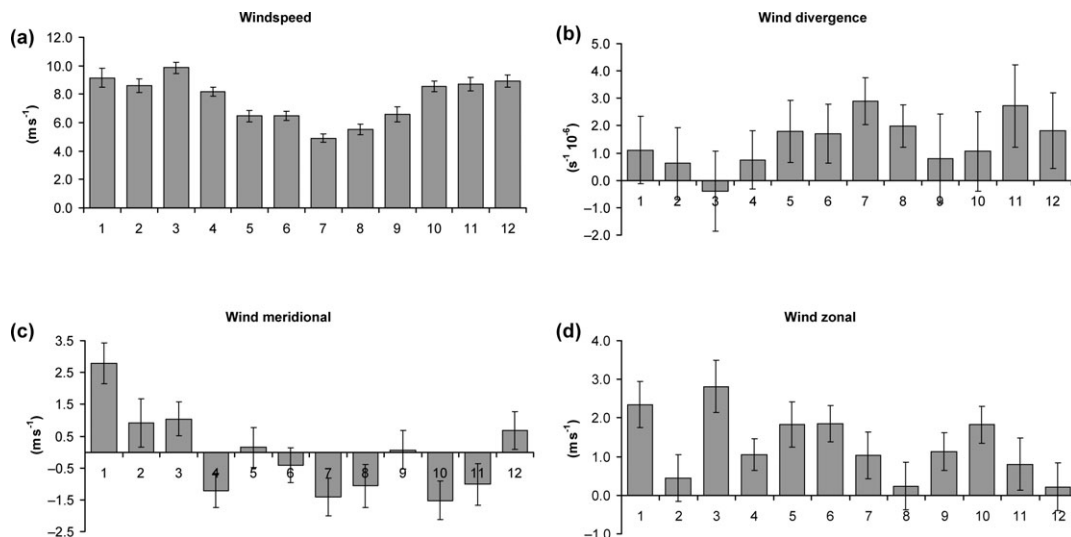
Figure 3. Monthly mean values of the wind components in the Azores: (a) windspeed, (b) wind divergence, (c) meridional windspeed, and (d) zonal windspeed. Vertical bars indicate standard deviation.

Table 4. Pearson correlation coefficients between the mean values of environmental variables and the mean number of shearwaters and terns sighted per snapshot.

Parameter	Shearwaters	Terns
Depth	**−0.27**	**−0.31**
Distance to shore	**−0.20**	**−0.32**
Distance to seamounts	**0.11**	**0.21**
Distance to shallow seamounts	**0.06**	**0.16**
Slope	**0.11**	**0.17**
SST	0.02	**0.28**
Chl a	**0.05**	**−0.12**
Distance to fronts	0.00	−0.03
Wind divergence	**0.04**	−0.02
Wind meridional	0.00	0.00
Windspeed	0.01	0.02
Wind zonal	0.01	**−0.09**
Distance to terns colonies	–	**−0.32**

Emboldened values indicate the significance (p-value < 0.01).

and seabird abundances (Table 4). Both the terns and the shearwaters were negatively correlated with distance to shore and depth, i.e. the number of individuals sighted diminished in deeper offshore waters. The abundance of all seabirds, however, was positively correlated with distance to seamounts and slope. Whereas tern abundance displayed a significant positive correlation with SST values ($r = 0.28, p < 0.01, n = 6952$) and a negative correlation

with Chl a ($r = − 0.12, p < 0.01, n = 6952$), shearwater abundance was only slightly positively correlated with Chl a.

GLM explained 43 and 11% of the abundance variability of terns and shearwaters, respectively (Table 5). The environmental parameters that best explained this variability for all species were month, wind, distance to shore or/and distance to colonies, and distance to seamounts (Figures 4 and 5). The distance to shallow seamounts and windspeed positively (and significantly) affected tern abundance. Terns also showed a significant quadratic relationship with zonal wind (Figure 4). Shearwaters were also less abundant near seamounts and when depth increased. The positive values of meridional wind (direction south–north) and intermediate values of wind intensity (≈ 4–7 m s^{-1}) favoured shearwaters. These seabirds also displayed a quadratic relationship with Chl a concentration, suggesting that shearwater abundance increased until values of Chl $a \approx 0.4$ mg m^{-3} (Figure 5). The correlation coefficients calculated between the observed and predicted distributions from the GLM shearwater and tern models were 0.19 and 0.49, respectively.

There were no great differences in the significant parameters explaining Cory's shearwater distribution between the general model and the two spatially stratified submodels (onshore and offshore). However, the offshore model suggests that shearwaters tended to be slightly more abundant in seamount areas (significant effect). The SST became a significant quadratic parameter with larger numbers of shearwater present between 18°C and 23°C. The pseudo-R^2 values obtained for the onshore and offshore models were 0.09 and 0.12, respectively. Because these two models did not improve the general fit of the model, we

Table 5. Summary of GLM results ($n = 6952$) and percentage of each environmental variable isolated (significance at level $p < 0.05$) to explain the variability of shearwater and tern distribution data.

Parameter	Shearwaters			Parameter	Terns		
	Estimate	Std error	Percentage		Estimate	Std error	Percentage
(Intercept)	3.808	0.190		(Intercept)	0.908	0.301	
log$_{10}$(Shore_dist + 1)	−0.508	0.117	0.87	log$_{10}$(Terns_colonies_dist.)	−1.368	0.210	1.71
Depth	0.000	0.000	1.07	Wind zonal			4.77
Seamounts_dist	0.007	0.001	0.89	poly(W. zonal, 2)1	12.29	2.977	
Month			1.44	poly(W. zonal, 2)2	30.157	2.752	
June	−0.731	0.144		Dist. to shallow seamounts	0.003	0.001	0.57
July	−0.194	0.189		Month			8.92
August	−0.235	0.171		June	−0.178	0.327	
September	−0.606	0.191		July	1.107	0.275	
October	−0.607	0.461		August	1.845	0.261	
Wind meridional	−0.084	0.038	0.22	September	1.264	0.271	
Chl a			0.38	October	−0.576	0.450	
poly(Chl a, 2)1	−10.180	6.493		Distance to shore	−0.017	0.006	0.42
poly(Chl a, 2)2	−31.570	12.590					
Windspeed			0.33				
poly(W_speed, 2)1	0.886	5.755					
poly(W_speed, 2)2	−13.220	5.247					
Null deviance	377 857			Null deviance	56 754		
Residual deviance	335 787			Residual deviance	32 214		
Residual d.f.	6 938			Residual d.f.	6 941		
Pseudo-R^2	0.11			Pseudo-R^2	0.43		
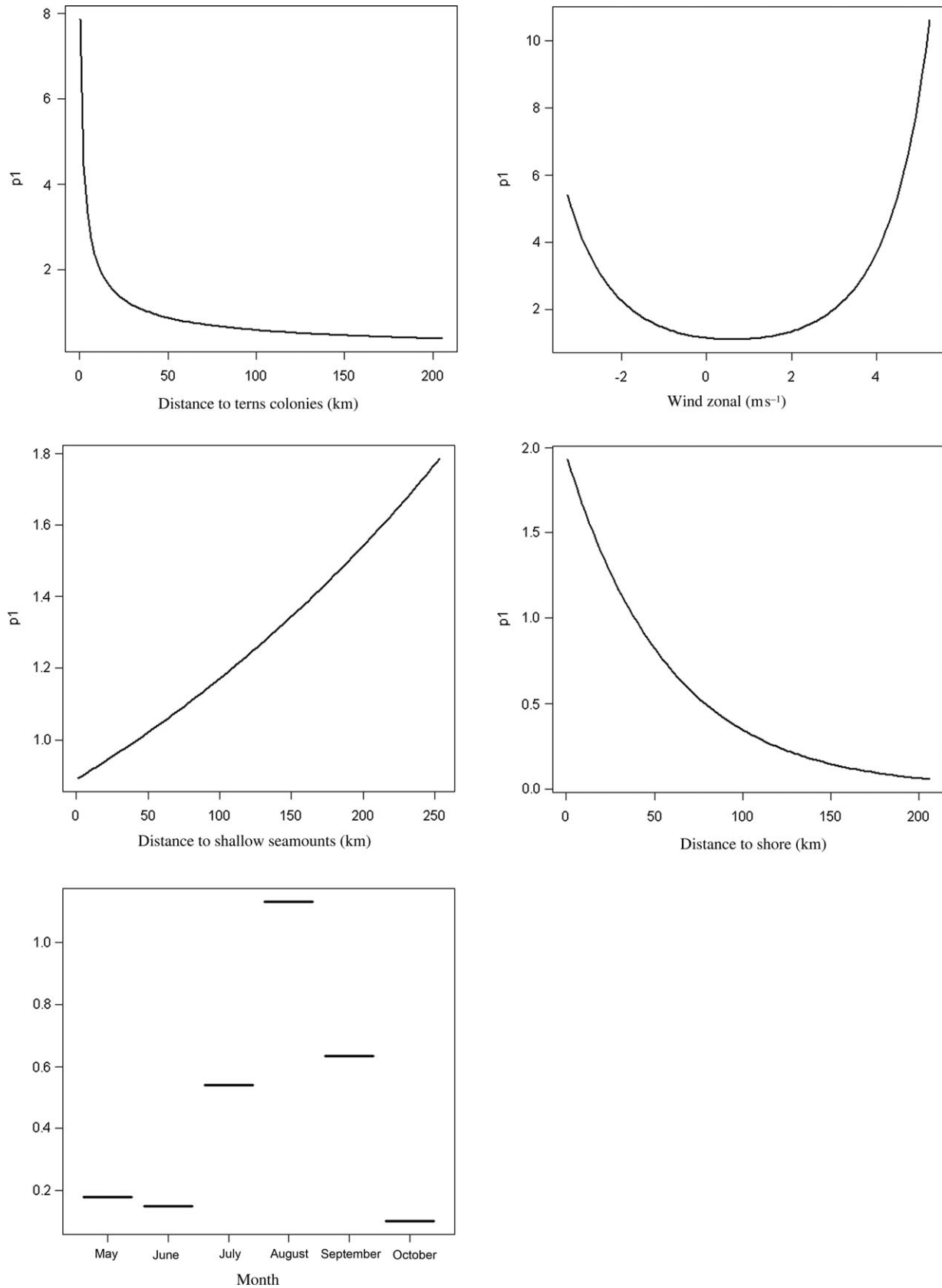
Figure 4. Simulation models of the effect of the significant variables on tern abundance as detected by GLM. Only one variable was simulated at a time by fixing the others variables (p1: mean number of seabirds predicted per grid cell).
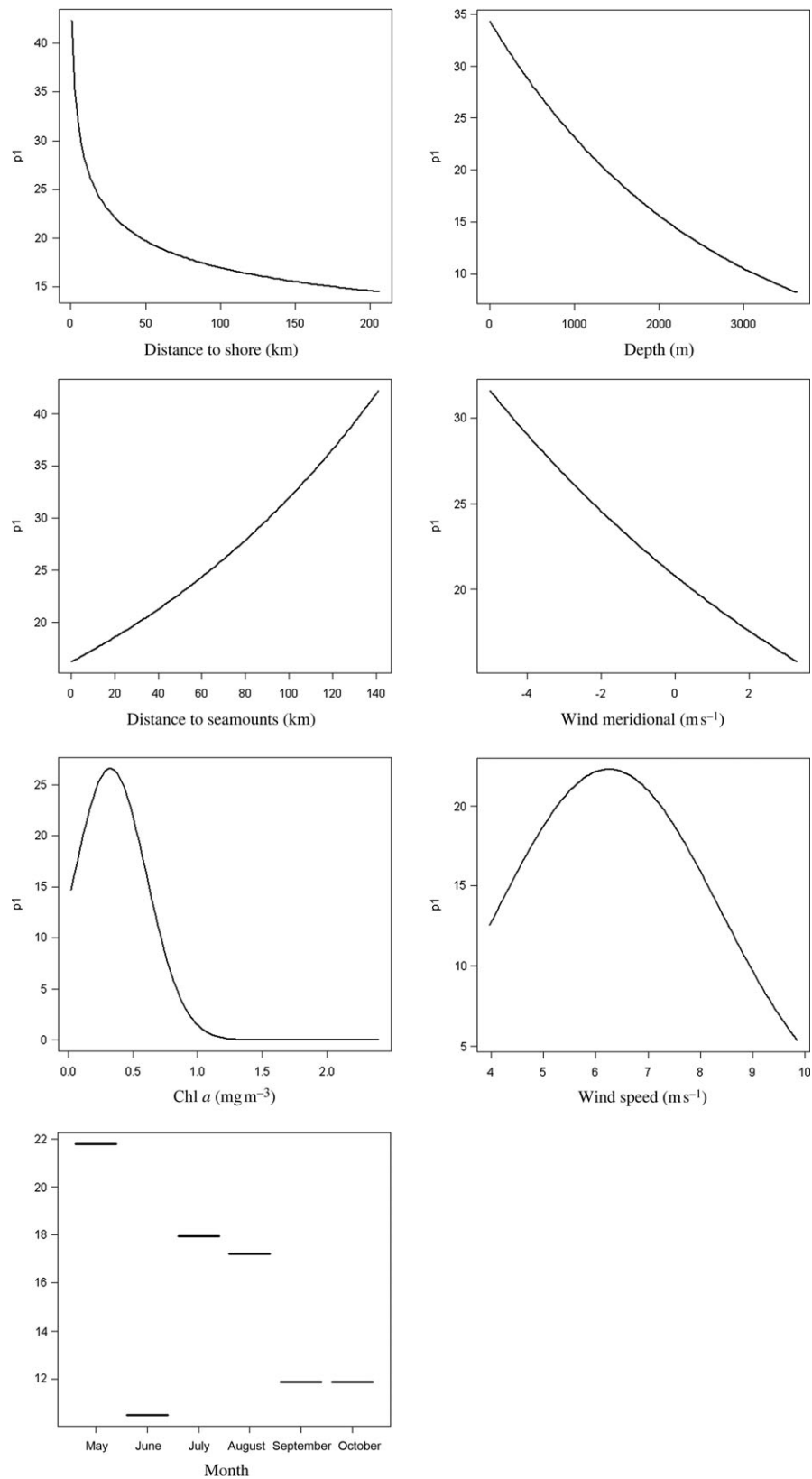
Figure 5. Simulation models of the effect of the significant variables on shearwater abundance, as detected by GLM. Only one variable was simulated at a time by fixing the others variables (p1: mean number of seabirds predicted per grid cell).

resorted to pooling the shearwater data and using the model results from the combined onshore–offshore observations.

Residual spatial prediction

Variogram models for the residuals of shearwater and tern abundance revealed low spatial autocorrelation patterns. The parameters of the variogram models obtained were similar for both species: a range of around 4 km, a principal direction of 135° (southeast–northwest), and an anisotropy factor of 0.5. The partial sill for the terns ranged between 0.3 and 1.0, and the nugget effect varied between 0.05 and 0.20. Similarly, the partial sill values for shearwaters varied between 0.4 and 1.0, and the nugget effect ranged between 0.10 and 0.20 (Table 6). In general, the results indicated that species distribution had a small-scale spatial structure, i.e. low autocorrelation. Therefore, it is expected that seabird distributions should vary considerably between neighbouring cells. The correlation coefficients between the observed and predicted data for shearwaters and terns were 0.97 and 0.91, respectively, and the dispersion errors were low for both species (Table 6). Overall, the shearwaters had a wide distribution pattern of abundance in the whole sampled area, despite occurring with higher intensity around the islands and at some seamounts (e.g. Princesa Alice) from June on (Figure 6). Conversely, the terns were essentially concentrated within 5 km of shore, with a wider spatial distribution in August (Figure 6).

Discussion

Understanding the patterns of seabird distribution at sea is crucial to the definition of marine IBAs. Most aspects of the spatial planning of seabird conservation are based on protection of breeding areas. Little attention has been given to the evaluation of feeding and resting areas, both around island coasts and offshore, where fisheries and seabirds may be in conflict.

The spatial distributions of shearwaters and terns at sea in the Azores depended mainly on the monthly variability (seasonal patterns), distance to colonies/shore (onshore–offshore patterns), distance to seamounts, and wind components. The month effect may represent a seasonal factor indirectly related to prey availability and breeding phenology, which affects seabird distributions and behaviour. Spatial distribution of seabirds is highly dependent on the breeding phase and tends to be concentrated in areas where prey abundance is particularly enhanced (Wilson *et al.*, 2002).

Between May and October, the incubation and chick-rearing period for both species (Monteiro *et al.*, 1996a, b), seabirds were expected to be concentrated close to their breeding colonies. In fact, shearwaters used the coastal-zones as evening resting areas when returning to their colonies (Monteiro *et al.*, 1996a). Modelling results confirmed this association with nearshore waters, whereas both the distance to shore and the water depth have a negative effect on their at-sea abundance. This pattern has been documented in the Indian Ocean, where seabirds respond to small-scale onshore–offshore gradients with higher densities within the shelf-slope regions around breeding islands than in deeper oceanic waters (Hyrenbach *et al.*, 2007).

Wind components were also significantly correlated with seabird abundance and helped to explain part of the variance observed in the best-fit models. The terns were more abundant when winds were weak, whereas the shearwaters preferred winds of intermediate intensity and with a north–south direction. Many seabirds respond to changes in wind direction and intensity (Shealer, 2002), often travelling with the prevailing winds and thus benefiting from substantial energy savings (Weimerskirch *et al.*, 2000; González-Solís *et al.*, 2007). Shearwaters obtain more efficiency in situations of moderate wind because their flight is characterized by hover periods.

Morato *et al.* (2008a) reported more Cory's shearwaters, but not terns, around seamounts. Our study confirms the lack of association between terns and seamounts, because they were observed mostly near the shore. On the other hand, associations between shearwaters and seamounts were only significant in the offshore domain (distances to shore ≥30 km). The results from the general model masked this relationship, because the best-fit model was strongly influenced by the distance to shore/colonies.

In general, environmental parameters better explained the variance of our models for tern spatial distribution (43%) than for the shearwater distribution (11%), although the former includes two species. The roseate tern has a more restricted distribution than the common tern; however, these species show similar distribution patterns, occurring together in the same colonies. The Cory's shearwater model fit was noticeably lower. However, in this case, the study area did not encompass the whole range of spatial distribution of this species, although it covered, by far, all the terns' foraging area range. Shearwater adults used a dual foraging strategy that involved repeated alternation of short and long foraging trips, up to 1800 km from the nest. These trips can last

Table 6. Variogram parameters (sill and nugget effect) and summary of the predicted values from the model fitting.

Seabird	Month	*n*	Mean sample	Mean predicted	Nugget	Sill	Mean error	Dispersion error (%)
Shearwater	May	1 002	21.97	22.51	0.1	0.7	0.53	2.43
	June	1 686	10.70	10.89	0.2	1.0	0.18	1.72
	July	1 992	17.83	18.08	0.2	0.8	0.26	1.44
	August	1 430	24.04	24.47	0.2	0.9	0.43	1.78
	September	678	16.12	16.21	0.1	0.4	0.08	0.52
	October	163	10.45	10.59	0.1	0.5	0.14	1.33
Terns	May	1 002	0.40	0.41	0.1	0.6	0.01	1.94
	June	1 686	0.32	0.33	0.2	0.7	0.01	2.60
	July	1 992	1.14	1.16	0.2	0.9	0.03	2.40
	August	1 430	5.45	5.66	0.2	0.7	0.21	3.79
	September	678	4.17	4.37	0.2	1.0	0.20	4.83
	October	163	1.18	1.25	0.05	0.3	0.07	5.85
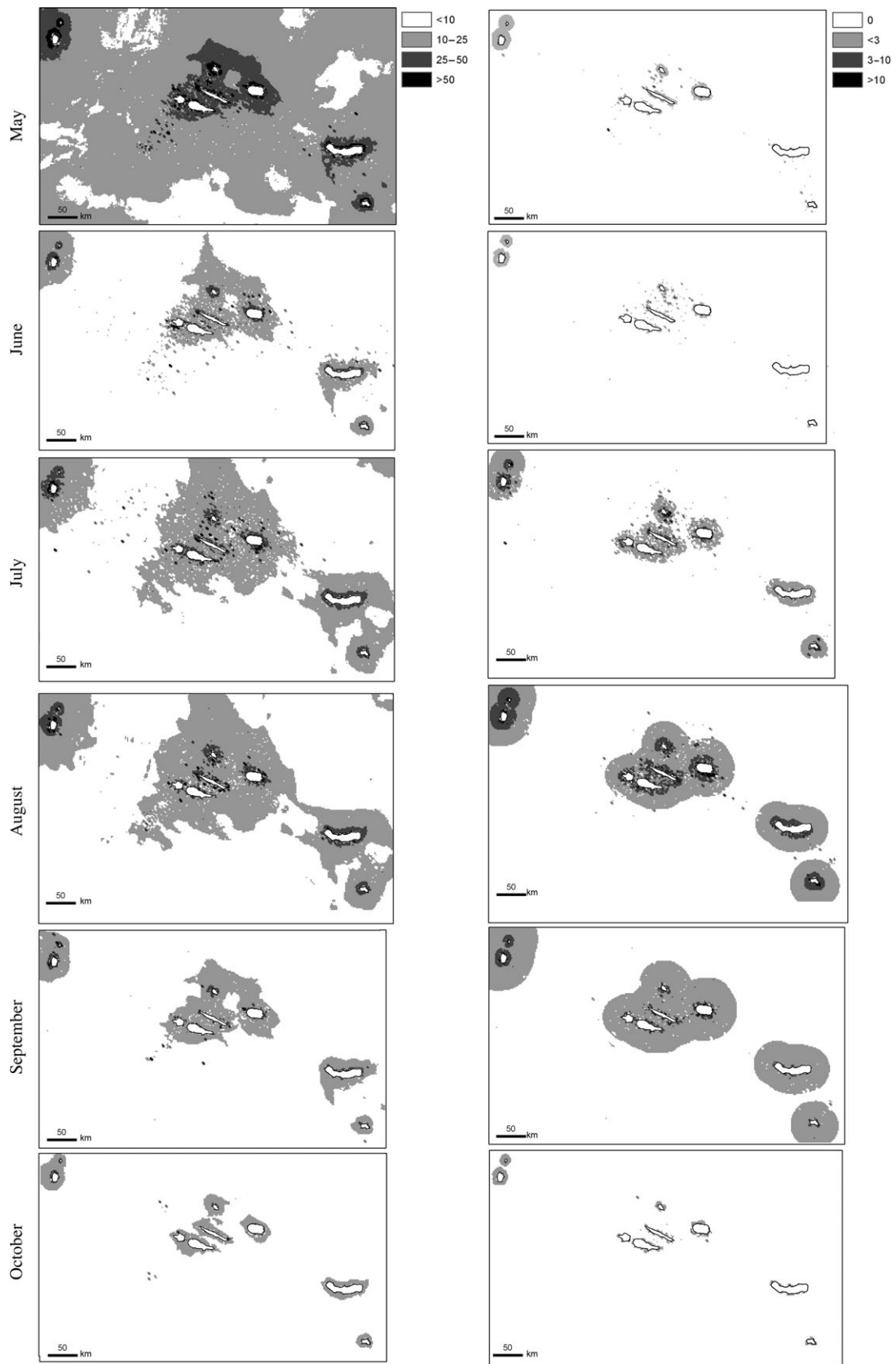
Figure 6. Predicted monthly distributions of shearwaters (left) and terns (right) in the Azores (1.852 × 1.852 km block mean).

for several days (mean 9 d; $\pm$ 2.7 s.d.) and occurred in areas of higher productivity north of the Azores EEZ, whereas short trips were evenly distributed around breeding colonies (Magalhães *et al.*, 2008). However, the variance explained by this type of model is within common values for such studies. For example, Louzao *et al.* (2006) used a similar approach to characterize the presence or absence of the Balearic shearwater (*Puffinus mauritanicus*) and developed a model explaining 21% of the observed variability. Another reason for the low variability explained by the GLM might be related to data collection, because our sampling was not spatially random but was heavily influenced by the behaviour of the tuna fishing fleet. Usually, the tuna fleet tends to operate around the islands and in some well-known seamounts (e.g. Princesa Alice). Additionally, the data do not include seabird behaviour, which could also enhance the effect of colony location because birds travelling between the colonies and foraging areas would be seen more often close to the colony. Hence, to understand the behaviour and distribution of the Cory's shearwater at sea better, it would be necessary to widen the investigation to include their whole geographic distribution range, by additionally compiling data on seabird distribution and behaviour during the entire period that they are present in the Azores, including the post-breeding winter dispersal from breeding colonies. In particular, movement data collected with geolocation data loggers may be a good complement to traditional census and could furnish detailed information on the offshore foraging areas.

In summary, the geostatistical methods used in this study, incorporating environmental parameters, contributed to a better understanding of the spatial at-sea distribution of Cory's shearwater and tern populations in the Azores coastal and offshore regions. The predictive maps that result from this study are an important tool for defining marine IBAs in the Azores. Monthly maps (May–October) of predicted shearwater and tern distribution in the Azores were produced. Terns appeared mostly concentrated within 5 km of shore, with a broad distribution in August when most tern chicks have fledged (Monteiro *et al.*, 1996b), resulting in a wider tern foraging range. Cory's shearwaters were evenly distributed in the whole study area, although they occurred in larger numbers around the islands from June on, coinciding with the egg-laying and incubation period (Monteiro *et al.*, 1996b). The results of this study (Figure 6) revealed higher concentrations of shearwaters and/or terns in Corvo, Flores, the north and west coasts of Faial, the northwest shore of Pico, the east and west extremes of São Jorge, Graciosa, the east coast of Terceira, São Miguel (Ilhéu de Vila Franca), and Santa Maria. These data will be compared with recent census data and datalogger information to help define the future coastal IBAs. The areas around the seamounts (Princesa Alice, Formigas, and Dollabarat; Figure 6) were also preferred areas of Cory's shearwater occurrence. These seamounts should be considered as potential offshore IBAs.

Our findings demonstrate that, at an archipelago level, the waters surrounding breeding colonies are the most relevant in terms of seabird concentrations. However, these areas were excluded from the Natura 2000 SPAs that were declared for the application of the Birds Directive (79/409/ECC). In particular, these areas pose potential conflicts between seabird protection and fisheries. Small pelagic fish, such as jack mackerel (*Trachurus picturatus*) and young black-spot sea bream (*Pagellus bogaraveo*), are caught seasonally close to shore by the Azorean tuna fleet to be used as live bait. The shore areas are also where greater abundances of shearwaters and terns are found during the breeding season. Therefore, marine protected areas encompassing the waters surrounding seabird breeding areas should be encouraged, at least during the breeding season or when the pursuit of commercial fisheries for small pelagic fish may overlap temporally with dense concentrations of resting or foraging seabirds. However, to improve the spatial and temporal definition of MPAs, further studies are certainly required, e.g. to quantify the spatial overlap between live-bait fishing and seabird distributions, to infer potential competition strategies for the same resources (e.g. species and size classes targeted), or to evaluate possible negative impacts on seabirds populations (e.g. lowered reproductive success).

References

Ainley, D. G., Spear, L. B., Tynan, C. T., Barth, J. A., Pierce, S. D., Ford, R. G., and Cowles, T. J. 2005. Physical and biological variables affecting seabird distributions during the upwelling season of the northern California Current. Deep Sea Research II, 52: 123–143.

Ballance, L. T., and Pitman, R. L. 1999. Foraging ecology of tropical seabirds. *In* Proceedings of the 22nd International Ornithological Congress, Durban, pp. 2057–2071. Ed. by N. Adams, and R. Slotow. BirdLife South Africa, Johannesburg.

Ballance, L. T., Pitman, R. L., and Fiedler, P. C. 2006. Oceanographic influences on seabirds and cetaceans of the eastern tropical Pacific: a review. Progress in Oceanography, 69: 360–390.

Begg, G. S., and Reid, J. B. 1997. Spatial variation in seabird density at a shallow sea tidal mixing front in the Irish Sea. ICES Journal of Marine Science, 54: 552–565.

Bio, A. M. F. 2000. Does vegetation suit our models? Data and model assumptions and the assessment of species distribution in space. Nederlandse Geografische Studies 265. Utrecht.

BirdLife International. 2004. Birds in Europe: Population Estimates, Trends and Conservation Status. BirdLife International, BirdLife Conservation Series, 12. Cambridge, UK. 374 pp.

Dalgaard, P. 2002. Introductory Statistics with R. Springer-Verlag, New York. 267 pp.

Feio, R., Dias, L., and Machete, M. 2005. Manual do Observador. Séries internas do DOP. 88 pp. www.popaobserver.org.

Figueiredo, M., Martins, A., Castellanos, P., Mendonça, A., Macedo, L., Rodrigues, M., Lafon, V., et al. 2004. HAZO: a software package for automated AVHRR and SeaWiFS acquisition and processing. Arquivos do DOP, Série Relatórios Internos, 3/2004. 92 pp.

Garthe, S. 1997. Influence of hydrography, fishing activity, and colony location on summer seabird distribution in the south-eastern North Sea. ICES Journal of Marine Science, 54: 566–577.

González-Solís, J., Croxall, J. P., Oro, D., and Ruiz, X. 2007. Trans-equatorial migration and mixing in the wintering areas of a pelagic seabird. Frontiers in Ecology and the Environment, 5: 297–301.

Hunt, G. L., Mehlum, F., Russell, R. W., Irons, D., Decker, M. B., and Becker, P. H. 1999. Physical processes, prey abundance, and the foraging ecology of seabirds. In Proceedings of the 22nd International Ornithological Congress, Durban, pp. 2040–2056. Ed. by N. Adams, and R. Slotow. BirdLife South Africa, Johannesburg.

Hunt, G. L., and Schneider, D. C. 1987. Scale dependent processes in the physical and biological environment of seabirds. In The Feeding Ecology of Seabirds and their Role in Marine Ecosystems, pp. 7–41. Ed. by J. P. Croxall. Cambridge University Press, Cambridge. 416 pp.

Hyrenbach, K. D., Veit, R. R., Weimerskirch, H., and Hunt, G. L. 2006. Seabird associations with mesoscale eddies: the subtropical Indian Ocean. Marine Ecology Progress Series, 324: 271–279.

Hyrenbach, K. D., Veit, R. R., Weimerskirch, H., Metzl, N., and Hunt, G. L. 2007. Community structure across a large-scale ocean productivity gradient: marine bird assemblages of the southern Indian Ocean. Deep Sea Research I, 54: 1129–1145.

Lourenço, N., Miranda, J. M., Luis, J. F., Ribeiro, A., Mendes Vítor, L. A., Madeira, J., et al. 1998. Morpho-tectonic analysis of the Azores volcanic plateau from a new bathymetric compilation of the area. Marine Geophysical Researches, 20: 141–156.

Louzao, M., Hyrenbach, K. D., Arcos, J. M., Abelló, P., de Sola, L. G., and Oro, D. 2006. Oceanographic habitat of an endangered Mediterranean procellariiform: implications for marine protected areas. Ecological Applications, 16: 1683–1695.

Machete, M., and Santos, R. S. 2007. Azores Fisheries Observer Program (POPA): a case study of the multidisciplinary use of observer data. In Proceedings of the 5th International Fisheries Observer Conference, Victoria, British Columbia, Canada, 15–18 May 2007, pp. 114–116. Ed. by T. A. McVea, and S. J. Kennelly. NSW Department of Primary Industries, Cronulla Fisheries Research Centre of Excellence, Cronulla, Australia. 412 pp.

Magalhães, M. S., Santos, R. S., and Hamer, K. C. 2008. Dual-foraging of Cory's shearwaters in the Azores: feeding locations, behaviour at-sea and implications for food provisioning of chicks. Marine Ecology Progress Series, 359: 283–293.

Monteiro, L. R. 2000. The Azores. In Important Bird Areas in Europe: Priority Sites for Conservation. 2: Southern Europe, pp. 463–472. Ed. by M. F. Heath, and M. I. Evans. BirdLife International BirdLife Conservation Series, 8. Cambridge, UK. 791 pp.

Monteiro, L. R., Ramos, J. A., and Furness, R. W. 1996a. Past and present status and conservation of the seabirds breeding in the Azores Archipelago. Biological Conservation, 78: 319–328.

Monteiro, L. R., Ramos, J. A., Furness, R. W., and Del Nevo, A. J. 1996b. Movements, morphology, breeding, molt, diet and feeding of seabirds in the Azores. Colonial Waterbirds, 19: 82–97.

Morato, T., Machete, M., Kitchingman, A., Tempera, F., Lai, S., Menezes, G., Pitcher, T. J., et al. 2008b. Abundance and distribution of seamounts in the Azores. Marine Ecology Progress Series, 357: 17–21.

Morato, T., Varkey, D. A., Dâmaso, C., Machete, M., Santos, M., Prieto, R., Santos, R. S., et al. 2008a. Evidence of seamount effect on aggregating visitors. Marine Ecology Progress Series, 357: 23–32.

Neves, V. 2007. Azores 2007 Tern Census. Arquivos do DOP, Série Estudos, 4/2007. 21 pp.

Pebesma, E. J. 2004. Multivariate geostatistics in S: the gstat package. Computers and Geosciences, 30: 683–691.

Pebesma, E. J., Duin, R. N. M., and Burrough, P. A. 2005. Mapping sea bird densities over the North Sea: spatially aggregated estimates and temporal changes. Environmetrics, 16: 573–587.

Santos, R. S., Hawkins, S. J., Monteiro, L. R., Alves, M., and Isidro, E. J. 1995. Marine research, resources and conservation in the Azores. Aquatic Conservation. Marine and Freshwater Ecosystems, 5: 311–354.

Schneider, D. C. 1997. Habitat selection by marine birds in relation to water depth. Ibis, 139: 175–178.

Shealer, D. A. 2002. Foraging behaviour and food of seabirds. In Biology of Marine Birds, pp. 137–178. Ed. by E. A. Schreiber, and J. Burger. CRC Press, Boca Raton, FL. 744 pp.

Spear, L. B., and Ainley, D. G. 1998. Morphological differences relative to ecological segregation in petrels (family: Procellariidae) of the Southern Ocean and Tropical Pacific. Auk, 115: 1017–1033.

Suryan, R. M., Sato, F., Balogh, G. R., Hyrenbach, K. D., Sievert, P. R., and Ozaki, K. 2006. Foraging destinations and marine habitat use of short-tailed albatrosses. A multi-scale approach using first-passage time analysis. Deep Sea Research II, 53: 370–386.

Valavanis, V. D., Katara, I., and Palialexis, A. 2005. Marine GIS: identification of mesoscale oceanic thermal fronts. International Journal of Geographical Information Science, 19: 1131–1147.

Weimerskirch, H., Guionnet, T., Martin, J., Shaffer, S. A., and Costa, D. P. 2000. Fast and fuel efficient? Optimal use of wind by flying albatrosses. Proceedings of the Royal Society of London, Series B, 267: 1869–1874.

Wilson, R. P., Grémillet, D., Syder, J., Kierspel, M. A. M., Garthe, S., Weimerskirch, H., Schafer-Neth, C., et al. 2002. Remote-sensing systems and seabirds: their use, abuse and potential for measuring marine environmental variables. Marine Ecology Progress Series, 228: 241–261.

Yen, P. P. W., Sydeman, W. J., Bograd, S. J., and Hyrenbach, K. D. 2006. Spring-time distributions of migratory marine birds in the southern California Current: oceanic eddy associations and coastal habitat hotspots over 17 years. Deep Sea Research II, 53: 399–418.

Yen, P. P. W., Sydeman, W. J., and Hyrenbach, K. 2004. Marine bird and cetacean associations with bathymetric habitats and shallow-water topographies: implications for trophic transfer and conservation. Journal of Marine Systems, 50: 79–99.