

Distribution maps and minimum abundance estimates for wintering auks in the Bay of Biscay, based on aerial surveys

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Abstract – The “*Erika*” oil spill has killed more seabirds than any before in Europe: nearly 70 000 guillemots (*Uria aalge*) were found dead or alive on beaches, and many more are thought to have been killed. This unexpectedly high number highlighted how poor our knowledge was on spatial and temporal patterns in seabird distribution in the Bay of Biscay. The purpose of our research project, “*ERIKA-Avion*”, was to fill this gap, providing the first distribution maps and abundance estimates of seabirds wintering in the entire shelf of the Bay of Biscay. In particular, we analysed fine-grained distribution maps for the wintering auks, comparing their areas of highest density with the oil drift area, and proposing for the first time (although preliminarily) minimal abundance estimates for these birds in this area.

Key words: Oil spill / Seabirds / *Uria aalge* / Common guillemot / Distribution / Abundance / Kriging

Résumé – Distribution géographique et estimation d'abondance préliminaire des alcidés en hivernage dans le golfe de Gascogne à partir de suivis effectués par avion. La marée noire de l'« *Erika* » a tué davantage d'oiseaux marins que toutes les précédentes en Europe : presque 70 000 guillemots (*Uria aalge*) ont été retrouvés échoués (morts ou vivants) sur les plages, et il est probable que d'autres guillemots ont été tués. Ce nombre exceptionnellement élevé, inattendu, a révélé à quel point notre connaissance sur la distribution spatiale et temporelle des oiseaux marins dans le golfe de Gascogne était partielle. L'objectif de cette étude est de cartographier entièrement le golfe de Gascogne (100 000 km²) du point de vue de la distribution et des estimations d'abondance des alcidés en hivernage. En particulier, nous analysons la distribution de ces guillemots (produisant des cartes selon une maille de 400 km²), comparons leurs aires de répartition à celles des nappes de pétrole les plus denses, et proposons pour la première fois, bien que de manière préliminaire, des estimations minimales d'abondance pour cette région et ces oiseaux.

1 Introduction

The *Erika* oil spill has been a major ecological disaster for seabirds, unique in the history of oil spills for several reasons. First, the ship sank (on 12 December 1999) nearly 100 km offshore, and freed c. 20 000 tons of fuel which drifted at sea for 15 days (Fig. 1a). Second, the hurricane *Lothar* that occurred on 28–29 December precipitated the oil spill on the coast, which covered nearly 500 km of the French Atlantic coast. Finally, this oil spill killed more seabirds than any before in Europe: nearly 70 000 guillemots (*Uria aalge*) were found dead or alive on beaches (Cadiou et al. 2004). For comparison, the *Exxon-Valdez* oil spill killed c.35 000 birds, though the estimated total of dead birds was 250 000–300 000 (Piatt et al. 1990; Ford et al. 1996).

The number of birds killed was unexpectedly high, and highlighted how poor our knowledge was on spatial and temporal patterns in seabird distribution in the Bay of Biscay. Actually, since 1976, ship-based surveys have been performed from the seashore up to c.100 km off the coast (Hémery et al. 1986; Castège et al. 2004). However, before the *Erika* oil spill, no abundance estimates were made available, and maps were produced only for a small area (5000 km²) in Recorbet (1996, 1998). More recent maps are now available in Castège et al. (2004), nevertheless i) no abundance estimates are advanced, ii) those maps only cover approximately one third of the continental shelf of the Bay of Biscay, and iii) those missed most of the area where the oil spill drifted at sea during 15 days.

The purpose of our research project, “*ERIKA-Avion*”, is to fill those gaps, providing the first distribution maps of seabirds wintering in the entire Bay of Biscay and abundance estimates for major species. In order to estimate abundance, a sampling

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scheme must provide density data (i.e., number of birds/area unit, not just number of birds/time unit). Then, to draw distribution maps, an appropriate geographical scale (i.e., covering entirely the expected distribution area of the birds) must be chosen. In this paper, we use data obtained on auks with aerial surveys to highlight methodological issues related to data collection and analysis, and we provide distribution maps for the wintering auks in the entire Bay of Biscay, comparing their areas of highest density with the oil drift area. Finally, we propose, for the first time although preliminarily, minimal abundance estimates for these birds in this area, following the oil spill.

2 Material and methods

2.1 Study area, transects and seabird counts

As the ship sinking and oil drifting at sea occurred in pelagic waters (c.100 km from the coast, Fig. 1a), we had to investigate seabird distribution at a very large scale. No information was available in 2001 on the location of wintering auks (except in Recorbet 1996), especially on the maximum distance from the coast where auks could be, and if seasonal movements of wintering auks were expected to occur, they were not precisely known. We therefore sampled repeatedly (on a monthly basis) the entire Bay of Biscay, i.e. around 100 000 km², covering the complete shelf area (Fig. 1b). Continental shelf waters are an important habitat for most seabirds, usually more suitable than deeper, oceanic waters, at least for piscivorous seabirds (Stone et al. 1995; Reid et al. 2001; Fauchald et al. 2002).

Traditionally, the methods for conducting at-sea seabird survey are ship-based. Aerial surveys, although first used in the seventies (e.g. Joensen 1968), have become popular only recently with GPS technology (Komdeur et al. 1992; Fox et al. 2003). Aerial surveys are far better aimed at sampling large areas for reduced costs (a plane is able to survey c.10 times more surface than a ship): in our case, we were able to sample 100 000 km² with 5000 km of aerial transects in just 6 days. Two ships would have been required simultaneously every day during one month for achieving the same spatial coverage. Moreover, as a plane moves far faster than the seabirds, there is virtually no bias due to animal movement and/or interactions between counting platform and seabirds (see Spear et al. 1992; Clarke et al. 2003; Lloyd et al. 2003 for discussions on technical problems associated with this particular problem in ship-based methods). Briggs et al. (1985a) compared experimentally ship- and aerial-based surveys, and found that significantly higher mean densities (three to six times) were counted in aerial, than in ship-based surveys (even for auks, presumably the most difficult seabirds to detect). Species level identification was however less in aerial surveys (77–96%) than in ship-based surveys (95–97%). These authors finally concluded that aircraft was best used to obtain population density and distribution (Briggs et al. 1985a), although, as with ship-based surveys, detection coefficients ($g(0)$, that presumably varies among species) are to be evaluated for aerial surveys (e.g. Laake et al. 1997; see below).

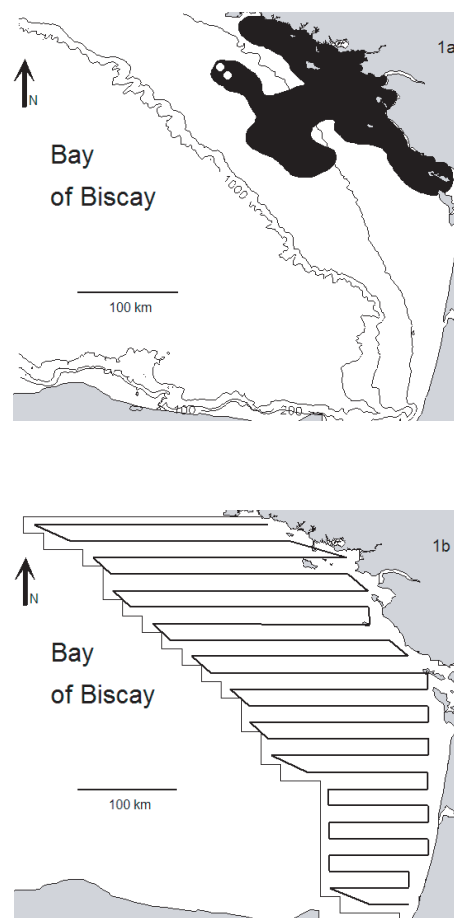


Fig. 1. (a) Map of the study area showing the bathymetry of the Bay of Biscay, the location where the ship sank (white dots) and the extent of oil drift at sea between December 12, 1999 and December 31, 1999 (source: CEDRE); (b) The survey design showing the study area (black line) as well as the transect sampling scheme.

In order to cover such a large study area, we used an aircraft, and flew with a twin engine Sesna aircraft. The whole continental shelf of the Bay of Biscay was sampled six times (once a month) between October 2001 and March 2002. On board, two observers (one on each side), equipped with a GPS system and a laptop computer continuously recorded seabirds (and other objects). Speed and altitude of the plane were also recorded every 10 min, as well as sunshine (specifically, glare) and intensity of waves for each transect. We opted for the strip-transect method (Buckland et al. 1993), using a systematic sampling scheme composed of 24 transects perpendicular to the coast, and spaced every 20 km (Fig. 1b). Each transect was c.200 m wide. Transect sampling allows modelling abundance for even rare objects, and is additionally simple in planning and implementation. For these reasons, transect sampling is an attractive spatial sampling technique (Oliver and Webster 1986). Although aerial surveys are often performed at an altitude of 250 feet (78 m) with a speed of 100 knots (185 km h⁻¹; see Briggs et al. 1985b), we preferred to fly at 150 km h⁻¹ and at an altitude of 150 m.

2.2 Statistical analyses

Standardisation of data

Data collected from the aerial surveys takes the form of a discrete variable, the group size which could be mapped on the entire shelf area as raw data (Fig. 2 for data on auks cumulated over the six months). In order to analyse this discrete variable, we first converted group size into density (a continuous variable). Transect data were therefore divided into smaller intervals (“lags”) of varying length. Therefore, the area surveyed per lag was lag length (in km) $\times$ 0.2 km, and auk density per km² was obtained as the cumulated number of auks along the lag/area surveyed. Figure 2 shows raw data, every survey pooled together, with a lag length of 5 km (area surveyed = 1 km²).

Abundance for a given species is usually positively correlated in space, a pattern that results from exogenous (interaction with environment) as well as endogenous (aggregative behaviour) ecological processes (Lichstein et al. 2002). Seabird spatial distribution is well known to be scale-dependent and patchy over a large range of scales (Fauchald et al. 2002). The choice of the lag length was therefore not set a priori, but determined according to the aggregative response of auks. This spatial structure is obtained by using the variogram function. Only when the lag length approaches the scale of the aggregative behaviour of a particular species of seabird is the spatial structure in the data best detected and modelled, as are the estimates of abundance more accurate and robust. Aggregative behaviour of several auk species has already been studied, and values found range between 1 and 10 km (Schneider and Piatt 1986; Mehlum 1999; Davoren et al. 2002, 2003; see also discussion below). We therefore chose to produce variograms, maps and abundance estimates using data at three different spatial scales: lags of 1, 5 and 10 km were successively used in order to best capture and depict the spatial structure of auk distribution.

Spatial statistics

Distribution maps and abundance estimates of auks were generated using density interpolation of values calculated within strips, with the kriging method (Cressie 1993), a method already used to study biological pattern (e.g. Paramo and Roa 2003; Ettema and Yates 2003). This method explicitly takes into account spatial dependence among data: autocorrelation in space leads to false evaluation of the variance of the abundance estimate when using more classical techniques, while the geostatistical approach uses variance spatial structure to provide robust abundance estimates (Rivoirard et al. 2000).

Kriging (i.e. optimal prediction) is a collection of linear regression techniques that takes into account the stochastic dependence (spatial autocorrelation) among the data (Marinoni 2003). It is based on the semivariogram, a function that describes the spatial structure of a random variable by calculating the variance between two locations as a function of distance (h) between them. Estimate of the semivariogram is given by $2\hat{\gamma} = \frac{1}{n(h)} \sum_{s_i-s_j=h} (z(x_i) - z(x_j))^2$, with $\hat{\gamma}$ the semivariance. Using the spatial structure of a random variable $Z(\cdot)$, the

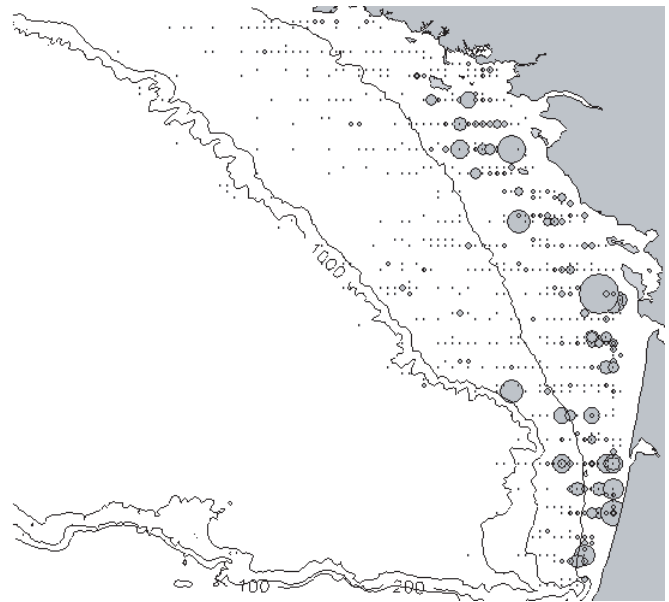


Fig. 2. Raw data showing the distribution of all observations of auks made between October 2001 and March 2002 (dot size proportional to group size). Bathymetry shown (first line = 100 m).

kriging procedure makes an inference of non-observed values of the variable of interest, i.e. auk density in our case.

In our data, autocorrelation among lags was best detected when using log-transformed values in the form of $L = \ln(1 + Z/b)$, with which semivariograms were estimated. Then, a back-transformation was applied to the model following Guiblin (1995), providing semivariogram estimates and a model for non-transformed data:

$\gamma(h) = [(m + b)^2 + \text{var}(Z)][1 - e^{-(\sigma^2 \gamma_l(h)/\text{var } L)}]$ with $\sigma^2 = \ln[1 + \text{var}Z/(m + b)^2]$, with m the mean of the variable, b a constant that we choose equal to 1, $\text{var } L$ the variance of the log transformed data, and $\gamma_l(h)$ the log-transformed semivariogram estimate.

We used block-kriging (Cressie 1993) for interpolation: a prediction grid composed of blocks had thus to be defined for our study area. Block size was chosen according to our sampling design, such that every block had to be sampled at least once during a monthly survey, a strategy that minimizes variance in kriging abundance estimates. As transects were 20 km apart, block size was fixed at 20 km $\times$ 20 km = 400 km². The number of birds inside each 400 km² block was estimated separately, with a weighted average of the observations inside and around the block. The weights assigned to each sampled value depended on the underlying spatial correlations as obtained with the semivariogram. The resulting system of linear equations yields ($\forall j = 1, \dots, n$):

$$\gamma_{j0} = \sum_{i=1}^n \lambda_i \gamma_{ij} + \mu, \quad (1)$$

with μ the Lagrange parameter, γ_{ij} the semivariogram values among the sampled values, γ_{j0} the semivariogram value between the j_{th} known sample value and the location to estimate, λ_i the weight assigned to the i_{th} sample value, and n the number of samples being considered in the estimate.

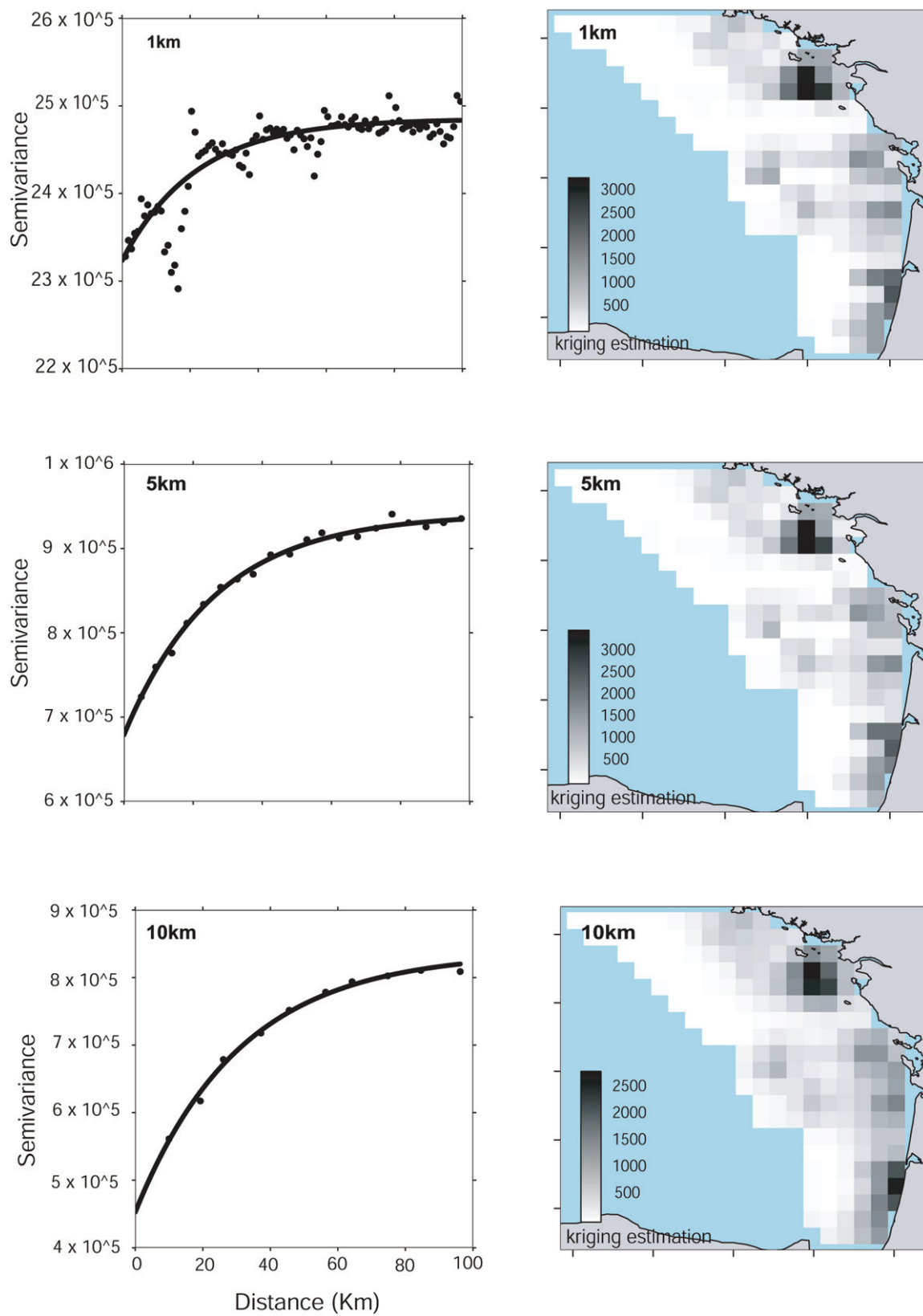


Fig. 3. Effect of lag length (from 1 km to 10 km) on semi-variogram and distribution map obtained using block-kriging (see methods). Data from February 2002 are used as an example.

With the solution of equation (1), the estimated value itself is determined as a weighted average of observed value around, with $z^*(x_0) = \sum_{i=1}^n \lambda_i z(x_i)$, where $z^*(x_0)$ is the estimated value at location x_0 , $z(x_i)$ is the available sample at location x_i , and λ_i is the weight assigned by the structure of the variogram to i_{th} available sample.

The number of neighbour (i.e., number of sampled value used for a block estimation), $z^*(x_0)$ was determined for each map according to the following criteria: the ratio $\frac{E(z^*(x_i))}{E(z(x_i))}$ should converge to 1, such that kriging estimate is equivalent to mean of data, thus preventing from any global bias in the abundance estimate.

3 Results

Our six months survey generated more than 60 000 observations of seabirds, cetaceans, fishing vessels and wastes, of which 2632 were auk observations, totalling 4362 auks. We were unable to distinguish in most cases between Guillemot, Razorbill *Alca torda* and Puffin *Fratercula arctica*, and thus mixed all three species within the general category “auks”. In winter, in this area, the latter two species were however rare for the second and very rare for the third (Recorbet 1996; Cadiou et al. 2004 for mortality rates among auks).

Once data were standardised, semivariograms of auk density showed spatial autocorrelation up to c.50 km, irrespectively of lag lengths (from 1 to 10 km: see Fig. 3 for an example using February data). Spatial autocorrelation was particularly strong until c.20 km, and then declined regularly. Nugget and semi-variance values however, as expected, varied to a much greater extent with lag length (Fig. 3). Block kriging interpolation was then achieved on the distribution of auks during winter. The resulting distribution maps (Fig. 3, lower part) were quite similar to each other except that using larger lags resulted in smoothed distributional patterns.

We found evidence for a wide seasonal distribution pattern (Fig. 4), together with varying abundance according to location and month. We used intermediate lag length for the analysis of seasonal distribution, i.e. 5 km. To our knowledge, these are the first available seasonal maps of wintering auk distribution over the entire Bay of Biscay (although obtained only for the winter 2001–2002). The peak abundance in winter 2001–2002 was obtained in February for the entire shelf, and our first and preliminary minimal abundance estimates for this month are between 94 000 (lag of 1 km, 44 neighbours) and 102 000 auks (lag of 10 km, 50 neighbours). This is the first estimate of abundance ever proposed for this area of the western palearctic for auks, although this abundance estimate is currently not corrected by undetected birds (either diving at the time the aircraft flew over them, or missed by the observer), and thus it must be taken with care and viewed as strictly minimal.

Interestingly, auks were mainly present close to the coast, avoiding more pelagic waters (Fig. 4, lower right). However, rather high numbers of wintering auks could occur up to 100 km from the coast, probably in relation to the particular bathymetry of the Bay of Biscay (Fig. 2), where water depth of less than 80 m can occur as far as 200 km from the seashore. The northernmost area of high abundance fits precisely the

area where oil drift occurred during 14 days after the ship sank, and we suggest that hurricane *Lothar* accentuated bird mortality by pushing tons of oil over thousands of km² at sea within a few hours, possibly collecting numerous auks that were concentrated by the storm especially close to the seashore. This may partly explain why the number of birds killed was so high.

4 Discussion

Recent advance in technical instrumentation (e.g. GPS technology) has allowed a massive increase in the use of aerial transect for investigating distribution and abundance of seabirds and marine mammals at a large scale (Briggs et al. 1985a; Yoshida et al. 1998). This sampling methodology, used together with statistical tools recently made available, such as distance sampling (Buckland et al. 2001) and geostatistics (e.g. van der Meer and Leopold 1995), offer promising perspectives in terms of modelling and predictive approaches by using covariates in order to optimize prediction sensitivity (see Estrada-Pena 1999 for a geostatistical approach using satellite imagery). Marine physical parameters are known to affect seabird behaviour and distribution (Begg and Reid 1997; Daunt et al. 2003), therefore oceanographic factors can spatially structure the community (e.g. Carl Schoch and Dethier 1996), and geostatistics can further be used to characterize interactions between animals or between animals and vessels (Jelinski et al. 2002).

Our aircraft sampling method and geostatistical analysis have provided the first published distribution maps of wintering auks at the geographical scale of the entire shelf of the Bay of Biscay. The winter distribution of auks suggests a strong bathymetrical preference, between 30 and 100 m, a depth that is already known to be the usual diving depth of these birds (Burger and Simpson 1986; Mehlum et al. 1998). Within the Bay of Biscay, three particular areas hold most of the wintering auks: two are in front of large estuaries (Gironde and Loire), and a further is to the south of these, just south of the Arcachon Basin (that is, to some extent, a large estuary). Apart from these three concentration areas, a high number of isolated birds was also observed as far as 200 km from the coast, suggesting that auks are able to exploit a vast area over the continental shelf, and not just coastal areas as is often stated.

We found spatial autocorrelation in auks up to 50 km. Spatial scales at which correlations were found previously between common or other murre species and their prey vary from 0.25–15 km for auks in general (Schneider and Piatt 1986), 3–8.75 km (Schneider and Piatt 1986), 3 km (Fauchald et al. 2000), 0.4–4 km (Davoren et al. 2002), and 4–5 km (Davoren et al. 2003) in common murre, and 2–4 km in Brunnich's Guillemot (Mehlum et al. 1999). These values are all lower than the spatial autocorrelation detected in this study. It is possible that spatial aggregation due to prey is within the range 1–10 km for auks, but that other processes (social, hydrological?) lead to farther aggregation, up to 50 km as detected in our study.

Auk abundance was highest in January and February, with around 100 000 birds estimated each month. Fewer birds (around 50 000) were counted in other months. Again we should stress that these numbers must be viewed as minimal

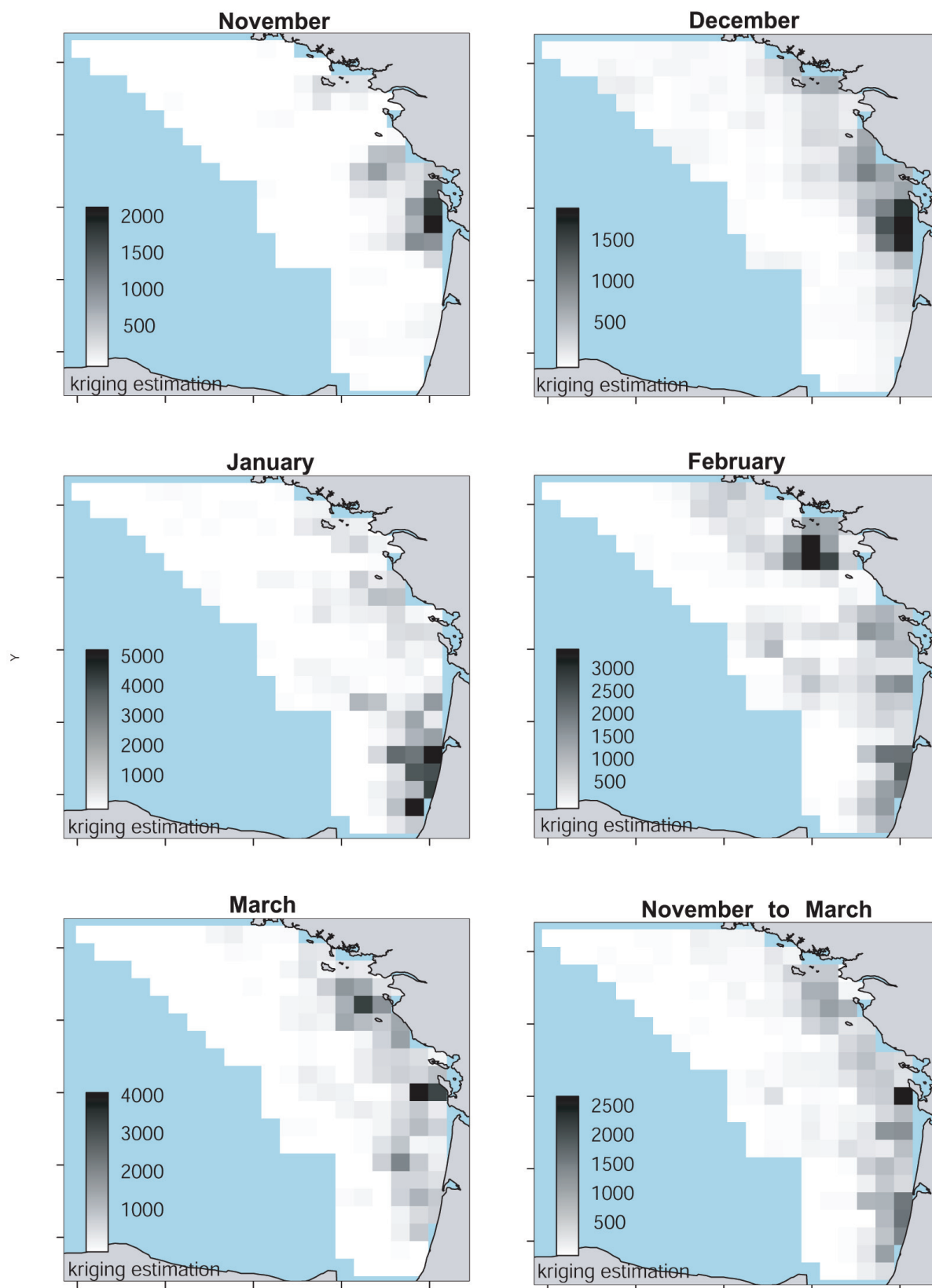


Fig. 4. Distribution and abundance of auks in the Bay of Biscay according to month, from November to March. The right-lower map considers all data cumulated from November to March.

estimates. Moreover, we do not know anything about seasonal turnover rates, and it is clearly possible that in terms of numbers of individuals frequenting the Bay of Biscay during winter, the figure could be much over 100 000 birds. This is nevertheless an interesting figure to compare with the estimate of Guillemots killed by the *Erika* oil spill (varying from 70 000 to 125 000, Cadiou et al. 2004). The orders of magnitude are similar, and may suggest that the oil spill could have killed the entire wintering population of guillemots in the northern half of the Bay of Biscay that year. However, this has to remain speculative until we evaluate experimentally the detection probability of auks along the aerial transect (Quang and Becker 1996 for analytical procedures using log-linear modelling approach), and assess the potential effects of additional factors (meteorological conditions, proportion of auks diving when the aircraft pass over the transect etc.).

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