

Correcting daylight effect in the estimation of fish abundance using kriging with external drift, with an application to juvenile haddock in North Sea

Jacques Rivoirard and Kai Wieland

ABSTRACT

Kriging with external drift is a geostatistical method, which allows the estimation of a spatial variable when this is driven by a known external parameter. The great flexibility of the method lies in the fact that the response function to this parameter needs only be known up to constants. This is advantageous when the effect of the parameter exists or is postulated, but without being known precisely. A postulated day/night effect on catch rates in trawl survey data can thus be handled, even when the day and night levels are poorly known. Similarly the effect of time of day on catch rates can be handled, supposing for instance that it varies as a cosine but with unknown coefficients. The methods are illustrated on catches of age 1 to 3 haddock in North Sea from the 1st quarter IBTS (International Bottom Trawl Survey) 1983-1997, where daylight effects exist without being precisely known. The results of kriging with external drift are compared to ordinary kriging, IBTS standard indices and ICES assessment, in terms of abundance and mortality coefficients. The level of agreement with ICES assessment was similar for the abundance indices obtained by the different methods. This indicates that the IBTS standard indices are remarkably robust against sampling irregularities. Nonetheless, in particular external drift kriging with time of day resulted in considerable higher in indices than the IBTS standard ones and this was much more pronounced for the 1-group than for age 2 and 3. External drift kriging with day/night indicator but preferably with time of day is capable of compensating successfully for daylight effects and provides a valuable tool for the calculation of survey-based abundance indices.

Jacques Rivoirard, Centre de Géostatistique, Ecole des Mines de Paris, 35 rue Saint-Honoré, F-77305 Fontainebleau-Cedex, France, E-mail: rivoi@cg.ensmp.fr

Kai Wieland, Danish Institute for Fisheries Research, North Sea Center, PO Box 101, DK-9850 Hirtshals, Denmark; present address: Greenland Institute of Natural Resources, PO Box 570, DK-3900 Nuuk, Greenland, E-mail: wieland@natur.gl

INTRODUCTION

Spatial correlation is a common phenomenon in natural populations and among the techniques for describing spatial distributions of marine populations geostatistical tools have shown to be particularly suitable because they explicitly account for spatial correlation (e.g. Rossi et al. 1992). Recent years have seen increasing interest in the application of geostatistics to fisheries survey data (Petitgas 1993, 1996) and several applications have dealt with acoustic survey data (e.g. Maravelias et al. 1996; Simard et al. 1993). In contrast, analyses of bottom trawl survey data using geostatistics are less numerous (e.g. Simard et al. 1992; Stensholt & Sunnanå 1996, Rivoirard et al. 2000).

Differences in catch rates have been observed between day and night for gadoids in the Barents Sea (Aglen et al. 1999; Engås & Soldal 1992) as well as in the North Sea (Ehrich & Gröger 1989; Wieland 1998, Rivoirard 2000b). Hence, diurnal variability in bottom trawl catches affects the quality of the survey indices. This is especially the case if the diurnal effects vary from year to year, e.g. due to alterations of the ratio and changes in the location of day and night hauls. In practice, however, it may be difficult to quantify the response of the catch rates to different daylight levels from the survey data as required for a proper correction (Hjellvik et al. 1999).

The International Bottom Trawl Survey (IBTS), for which Heessen et al. (1997) give a comprehensive description, is a coordinated multi-vessel survey and has been conducted in the North Sea in the 1st quarter of the year since the mid 1960's. Trawling is preferably conducted by day but a substantial number of hauls are taken outside the daylight period due to the problem of achieving full area coverage in the short survey time. The main objective of the IBTS is to provide recruitment estimates and tuning data for ICES (International Council for the Exploration of the Sea) assessments of several commercially important fish stocks. However, standard abundance indices by age group are routinely calculated in a way that does not account for spatial distribution patterns and a possible bias due to differences in catch rates between day and night.

IBTS data have been analyzed previously, using a variety of approaches. For example, IBTS data were used for studying the distribution of individual age groups of cod (Riley & Parnell 1984; Heessen & Daan 1994). Statistical analysis using Generalized Linear Models was performed for herring (Sparholt 1990) and for cod and whiting (Wieland et al. 1998). Geostatistical techniques have been applied to subsets of IBTS data limited to a few years for whiting in the entire North Sea (Wieland 1998) as well as for cod, haddock and whiting in the northwestern North Sea (Fernandes & Rivoirard 1999, Rivoirard et al. 2000). More recently, geostatistics has been used on IBTS data

for age 2 North Sea haddock over 15 years, presenting also a method that allows for including daylight effects without knowing the exact diurnal variation of the catch rates (Wieland & Rivoirard 2000). The present study extends this analysis to ages 1 and 3, allowing also an analysis of mortality.

MATERIAL AND METHODS

IBTS data

The IBTS became standardised in the early 1980's when the French-designed GOV trawl (Chalut à Grande Ouverture Verticale), with a vertical net opening of 5 to 6 m, was adopted as the standard gear. Stratification of the survey has always been based on the grid of ICES statistical rectangles of 1° longitude * 0.5° latitude ($\approx 30 * 30$ n.m., Fig. 1). Two different countries usually fish each rectangle so that at least two hauls are normally made per rectangle with tows conducted by the same vessel in adjacent rectangles being separated by at least 10 n.m. Trawling time is 30 min at a speed of 4 kn. It is recommended that, as far as possible, trawling should be limited to the daylight period, which is defined from 15 min before sunset to 15 min past sunset (ICES 1999a). Abundance indices by species and age group (in numbers per hour trawling) are calculated by averaging within rectangles and then averaging over species-specific standard areas. In the case of haddock the standard area excludes the southern North Sea, where haddock have been almost absent in the past few decades (Knijn et al. 1993), as well as the eastern Skagerrak and the Kattegat (Fig. 1).

For the present study, age-disaggregated catches (in numbers per hour trawling) by haul were obtained for the 1st quarter surveys 1983-1997 from the ICES IBTS Database. Together with the catch data, information on single haul basis, e.g. country, vessel, shooting position, time of day and a day/night code, was received. The domain chosen corresponds to the IBTS standard area for haddock with the exception that the 200 m isobath was taken as the limit in the north and the east and that the entire Skagerrak was excluded due to missing data in 9 of the 15 years (Fig. 1). For this domain, which comprises an area of about 107628 n.m.^2 , about 200 to 300 data points were available in each year.

The number of night hauls in the IBTS varied substantially between years as well as between different parts of the survey area (Fig. 2). In the entire North Sea including the Skagerrak and the Kattegat, the proportion of night hauls was between 11 and 21 %. These numbers did not change very much if the Skagerrak and the Kattegat were excluded. In contrast, the proportion of samples

taken outside the daylight period increased to 14 – 33 % with more than 25 % in 7 out of the 15 years if the southern North Sea was additionally excluded. This indicates that especially in the northern North Sea, which is the main distribution area of haddock and which was used as the domain in our study (Fig. 1), night hauls are a considerable part of the data set. Here it is noteworthy that the hauls were not equally distributed over time of day and that the night hauls were predominantly taken in the early morning and early evening while samples from the middle of the night were relatively rare (Fig. 3).

It had not been possible to establish a quantitative relationship for the response of catches of juvenile haddock to different daylight levels approximated either by time of day or sun elevation from the IBTS data. Nonetheless, ratios of mean night and mean day catches proved for all age groups considered that the average catch rate is usually lower at night than at day (Rivoirard 2000b).

Geostatistical Analysis

A geostatistical analysis usually involves two steps: a) the analysis of spatial structure, e.g. through the calculation and fitting of the variogram; and b) the use of this structure, e.g. in the application of a linear method of spatial prediction known as kriging. Kriging uses the fitted variogram model for weighting the observations taken over an area in order to obtain estimates at any point of this area. These estimates can then be used either locally for mapping or over the whole domain for global estimation. Kriging is optimal in the sense that it is unbiased and it minimises the variance of the estimation error, leading to the so-called kriging variance (e.g. Chilès & Delfiner 1999; Cressie 1993; Matheron 1971). Here, it must be noted that the kriging variance for the whole domain is not the average of the kriging variances of its points.

Variography

A variogram, which is sometimes also called a semivariogram, describes the spatial dependence of data measuring the half variability between data points as a function of their distance.

In the present study, no indication of spatial anisotropy was found and experimental variograms were computed from the sample points as an average over all directions according to Matheron's (1971) classical formula:

$$\gamma^*(h) = 0.5 \frac{1}{N(h)} \sum_{i=1}^{N(h)} (Z(x_i + h) - Z(x_i))^2 \quad (1)$$

where $N(h)$ is the number of experimental pairs $(Z(x_i), Z(x_i + h))$ of data separated by the distance h . Distance intervals with lag increment of 15 n.m. and a tolerance of ± 7.5 n.m. were used. The experimental variograms were normalized by the sample variance in order to avoid possible numerical instability when using squares of high values in the model fitting.

Variogram models, $\gamma(h)$, were fitted with a semi-automatic, weighted-least-squares procedure by minimizing:

$$\sum_{i=1}^H N(h_i) (\gamma(h_i) - \gamma^*(h_i))^2 \quad (2)$$

where H is the number of distance intervals. The variogram models were basically fitted to a maximum distance of 300 n.m. with a two-component structure, a nugget effect and a spherical component:

$$\gamma(h) = \begin{cases} 0, & h = 0 \\ c_n + c_s (1.5 h/r - 0.5 (h/r)^3), & 0 < h \leq r \\ c_n + c_s, & h > r \end{cases} \quad (3)$$

where c_n is the nugget effect representing unresolved small-scale variation and observation error, c_s the amplitude of the spherical component, $c_n + c_s$ the sill of the variogram that represents the maximum level of variability, and r is the range beyond which the data are no longer autocorrelated. Alternatively, variogram models consisting of a nugget effect and a linear component:

$$\gamma(h) = \begin{cases} 0, & h = 0 \\ c_n + c_l * h, & h > 0 \end{cases} \quad (4)$$

where c_l is the amplitude of the linear component, or pure nugget were fitted. The selection of competing variogram models or different maximum distances considered in the model fit was guided by a goodness of fit statistic defined by Fernandes & Rivoirard (1999):

$$gof = \frac{\sum_{i=1}^H w(h_i) (\gamma(h_i) - \gamma^*(h_i))^2}{\sum_{i=1}^H w(h_i) (\gamma^*(h_i))^2} \quad (5)$$

where $w(h_i)$ is the weight taken as the number of pairs at distance interval h_i .

Kriging

There are different types of kriging depending on the spatial structure of the stochastic process $Z(x)$

representing the target variable as a function of location x . Suppose that the process has an expected value, the mean at location x :

$$E[Z(x)] = m(x) \quad (6)$$

and a covariance between two locations x and y :

$$\text{cov}(Z(x), Z(y)) = E[(Z(x) - m(x))(Z(y) - m(y))] = C(x, y) \quad (7)$$

which are known. To be unbiased, the linear regression Z_0^* of $Z_0 = Z(x_0)$ on the $Z_i = Z(x_i)$ is given by:

$$Z_0^* = m(x_0) + \sum \lambda_i (Z_i - m(x_i)) = \sum \lambda_i Z_i + m(x_0) - \sum \lambda_i m(x_i) \quad (8)$$

Minimizing the variance of the error results in a linear system of equations of which the solution gives the optimal weights λ_i . In practice, however, this usually involves too many parameters to be inferred, as $m(x)$ and $C(x, y)$ must be known for any x and y in the domain and hence the model needs to be simplified.

Assuming stationarity of the process, the mean is constant, i.e. $m(x) = m$, and the covariance between two points depends only on their separation distance. The estimator, called “simple kriging”, can be written as:

$$Z_0^{\text{SK}} = \sum \lambda_i Z_i + (1 - \sum \lambda_i) m \quad (9)$$

Ordinary kriging, which is the most common type of kriging, is obtained by adding the condition:

$$\sum \lambda_i = 100\% = 1 \quad (10)$$

Then the mean disappears and the estimator:

$$Z_0^{\text{OK}} = \sum \lambda_i Z_i \quad (11)$$

is unbiased whatever the value of the mean, which may be unknown. Moreover ordinary kriging can be shown to require only the more general structural tool, the variogram:

$$\gamma(h) = 0.5 E[Z(x+h) - Z(x)]^2 \quad (12)$$

This tool characterizes an intrinsic process $Z(x)$, defined by increments $Z(x+h) - Z(x)$ having a mean of 0 and a variance depending only on the distance vector h (see equation (1) for the calculation of variogram from the data values in the present study). The kriging weights, which

minimize the variance of the estimation error, are found by solving a system of linear equations using the spatial information given by the variogram:

$$\begin{cases} \sum_j \lambda_j \gamma(x_i - x_j) + \mu = \gamma(x_i - x_0) & \text{whatever } i \\ \sum_i \lambda_i = 1 \end{cases} \quad (13)$$

where μ is a Lagrange parameter constraining the weights to satisfy the condition given in equation (10) (see e.g. Simard et al. 1992 for an application).

Assume now that the mean of the process is not taken as constant, but rather is linearly related to an external variable $f(x)$ known everywhere, e.g.:

$$E[Z(x)] = m(x) = a f(x) + b \quad (14)$$

The linear regression can be written:

$$Z_0^* = \sum \lambda_i Z_i + b (1 - \sum \lambda_i) + a (f_0 - \sum \lambda_i f_i) \quad (15)$$

Adding the conditions on the weights:

$$\sum \lambda_i = 1 \text{ and } \sum \lambda_i f_i = f_0 \quad (16)$$

yields kriging with external drift:

$$Z_0^{\text{ED}} = \sum \lambda_i Z_i \quad (17)$$

which is unbiased whatever the values of a and b . The kriging weights are then obtained by minimizing the variance of the estimation error from:

$$\begin{cases} \sum_j \lambda_j \gamma(x_i - x_j) + \mu_1 + \mu_2 f(x_i) = \gamma(x_i - x_0) & \text{whatever } i \\ \sum_i \lambda_i = 1 \\ \sum_i \lambda_i f(x_i) = f(x_0) \end{cases} \quad (18)$$

where μ_1 and μ_2 are Lagrange parameters constraining the weights to satisfy the two conditions given in equation (16) (see e.g. Chilès & Delfiner 1999 for further details).

In the present paper like in Wieland & Rivoirard (2000), this method of kriging with external drift is used to account of a catch level, either different between day and night, or varying with time of day. Then the mean of the process $Z(x)$ is supposed to vary between day or night, or with time.

In the first case (referred to as external drift kriging with day/night indicator) we have:

$$E[Z(x)] = m(x) = a 1_D(x) + b \quad (19)$$

where $f(x) = 1_D(x)$ is a day/night indicator, equal to 1 by day and to 0 at night. Thus, the mean is supposed to be equal to b at night and to $a + b$ by day, however neither a , nor b nor $a + b$ are assumed to be known. Suppose that we want to estimate the target variable by day, then the conditions imposed on the weights imply firstly that the sum of all weights is 1 and secondly that the sum of day weights is 1. It follows that the estimator is a weighted average of day samples with weights summing to 1 and of night samples with weights summing to 0:

$$Z_0^D = \sum_{\text{day samples}} \lambda_i^D Z_i^D + \sum_{\text{night samples}} \lambda_j^N Z_j^N \quad (20)$$

with:

$$\sum_{\text{day samples}} \lambda_i^D = 1 \quad \text{and} \quad \sum_{\text{night samples}} \lambda_j^N = 0$$

It is then scaled to the day sample values, but with a correction coming from the variations between the night sample values. The level of night values itself or any constant added to them would disappear.

In the second case, referred to as external drift kriging with time of day, we assume that the level of catch varies with sunlight as a cosine function of time:

$$E[Z(x)] = m(x) = a \cos\left(2\pi \frac{t-12}{24}\right) + b \quad (21)$$

but neither a nor b , which are independent of x , are assumed known. The conditions on the weights (eq. 16) become:

$$\sum \lambda_i = 1$$

and

$$\sum \lambda_i \cos\left(2\pi \frac{t_i-12}{24}\right) = \cos\left(2\pi \frac{t_0-12}{24}\right) \quad (22)$$

supposing that we want to estimate the target variable at time t_0 (12:00 in the present case), and so the weights are modulated according to time of samples and time of target.

Mapping and global estimation

For the mapping and the global estimation of abundance a discretisation of 15 n.m. was used in ordinary and the two forms of external drift kriging. This resulted in an estimation grid with 411 nodes in the chosen domain (Fig. 1). All forms of kriging were performed in a unique neighborhood such that all the data values were considered for the estimation of each target point. Hauls at exactly the same location, but at different dates or times, have been moved a little bit to avoid overdetermination in the kriging algorithm. In the absence of nugget effect however, very close hauls may render results unstable, particularly with the external drift method.

Comparison with IBTS standard indices and ICES assessment

IBTS standard indices of age 1 to 3 haddock were taken from ICES 1999b and from previous annual ICES reports on the 1st quarter IBTS. Stock numbers at age were taken from the most recent ICES assessment (ICES CM 2000/ACFM:7). The ICES standard assessment is, however, not strictly independent from the 1st quarter IBTS because the IBTS data are used among data from other fleets for tuning and recruitment estimation. Hence, assessment in which the IBTS was excluded from the tuning fleets but with all other settings identical to the standard assessment were used for comparison.

To prove the effect introduced by the different forms of kriging on the abundance indices for subsequent age groups of the same cohort instantaneous coefficients of total mortality (Z) were calculated using the standard equation for exponential decay:

$$Z = \ln (N_{\text{age, year}} / N_{\text{age}+1, \text{year}+1}) \quad (23)$$

where N is either an abundance index (IBTS standard indices and geostatistical estimates) or the stock number at age (ICES assessment).

RESULTS

Figs. 4a-c show experimental variograms, fitted models, and the corresponding number of pairs of samples including both day and night catches of age 1, 2 and 3 haddock for the years 1983 to 1997. The number of pairs of samples increased rapidly with distance as is typical for omnidirectional

variograms. The highest number of pairs of samples occurred always for distances between 100 and 200 n.m. where most of the variograms reached their maximum level of variability. In some years, satisfactory model fits were only obtained if the maximum distance included was reduced. This was accepted because a good fit near the origin was most critical for further analysis and the remaining distance range was still close to the half of the maximum distance over the domain which can be regarded as the distance of reliability (Journel & Huijbregts 1978). The values of the goodness of fit statistic were reasonable low ranging between 0.4 and 3.7 % (Tab. 1). Nearly all of the resulting variogram models consisted of a nugget, between 0.03 and 0.90, and a spherical component, with a range between 30 and 290 nm.

Age 2 in 1991, with a high proportion of night hauls (Fig. 2) and a low ratio of mean night and mean day catch (0.54), was selected as an example to compare the different forms of kriging in detail. Fig. 5 presents a distributional map of ordinary kriging, of external drift kriging with day/night indicator, and of their difference, as well as a postplot of catch values with distinction between day and night hauls. A distinct maximum of haddock densities originating from 3 large day catches was found east off Orkney Islands. Fig. 6 shows a map of external drift kriging with time of day and of its difference to ordinary kriging. All forms of kriging yielded similar maps of the distribution pattern (Figs. 5A, 5B and 6A), but with local differences. (Fig. 5C, 6B). The difference between ordinary kriging and external drift kriging with day/night indicator was most pronounced in areas where night hauls were relatively isolated, e.g. between 56°00' to 56°30'N and 0° to 2° E (Fig 5D). In external drift kriging with day/night indicator, such night hauls received a positive weight, compared to negative weights for night hauls close to day hauls (Fig. 7B). Day hauls received weights that were positive and higher than in ordinary kriging (Fig. 7A) and the resulting index of mean abundance is 20 % higher than in the case of ordinary kriging. The spatial distribution of weights in external drift kriging with time of day (Fig. 7C) looked largely like this of external drift kriging with day/night indicator, but their modulation with time reduced the contrast between day and night hauls. The effect of time of day was particularly visible in the southern part where essentially day hauls are present and where estimation is higher (Fig. 6B). Globally, external drift kriging with time of day and with day/night indicator differed by less than 2% in this example.

For all three age groups, the relative difference in the global estimation of mean abundance between external drift kriging with day/night indicator and ordinary kriging increased significantly with the proportion of night hauls but with some variation between the years, while a closer and highly significant negative correlation with the ratio of mean night and mean day catch was found

(Figs. 8a-c). A high proportion of night samples, i.e. > 20 %, yielded deviations between the two forms of kriging of more than 15 % only if accompanied by a mean night catch below 80 % of the mean day catch. The relative differences between these two forms of kriging were positive in all years, except in 1986 for age 3 when the largest catch was taken at night close to a day haul and received a negative weight in external drift kriging. On average, the effect of external drift kriging with day/night indicator was higher for the 1-group (12.6 %) than for age 2 (11.4 %) and age 3 (9.5 %). External drift with time of day resulted generally in a further increase in the abundance estimates, which, however, were occasionally below those obtained by ordinary kriging (Tab. 2). This was the case for age 1 in 1994 and for age 3 in 1987 and in 1993, where high catches were taken far away from noon. Again, but even more pronounced, the average relative difference compared to ordinary kriging was highest for the 1-group (20.6 %) and decreased with age (Tab. 2).

In every case the kriging variance of the abundance was observed to be the lowest for ordinary kriging and the highest for external drift kriging with time of day. Because of the different values of the kriged abundance, this resulted in coefficients of variation on the estimates that were on average equal to 11 % for ordinary kriging and for external drift kriging with day/night indicator, and amounted to 13 % for external drift kriging with time of day.

Fig. 9 compares the entire time series of mean abundance estimated by the three different forms of kriging with the IBTS standard index and the most recent ICES assessment for age 1, 2 and 3 haddock. For all age groups the ordinary kriging estimates were very close to the standard indices in most of the years. The estimates obtained by external drift kriging with day/night indicator exceeded substantially the standard indices in a couple of years, in particular for the age 1 and 2 in the 1990's. In the period 1990 to 1997, for example, the difference in the abundance indices between external drift kriging with day/night indicator and the IBTS standard index was between 8.2 and 30.8 % for the 1-group, between 0.4 and 23.6 % for the 2-group and between 5.1 and 28.5 % for the 3-group. On average, external drift kriging with time of day did not result in much higher abundance indices than external drift kriging with day/night indicator. Based on the entire time series its effect compared to the standard indices was much more pronounced for the 1-group (20.7 %) than for age 2 (16.0 %) and age 3 (14.6 %).

Despite of some considerable differences in their level, all the survey based abundance indices revealed similar trends over time, and hence correspondence with assessment results differed only marginally, irrespectively whether the ICES standard assessment or the assessment in which the IBTS had been excluded from the tuning is considered (Tab. 3).

Fig. 10 shows instantaneous coefficients of total annual mortality for age 1 and age 2 haddock calculated from the survey based abundance indices and from ICES assessment for the years 1983 to 1996. The mortality coefficients based on external drift kriging with time of day deviated somewhat from the other abundance indices, which were very similar to each other. In particular for the 1-group, external drift kriging with time of day resulted in mortality coefficients that were higher (0.42 on average) than the other survey based estimates (0.34 – 0.35 on average). All of the survey based mortality coefficients showed much stronger fluctuations than in the ICES assessment. The unrealistic low and frequently negative mortality coefficients for the 1- group obtained from the 1st quarter IBTS indicate that this age group has not reached its maximum catchability at that time of the year. In contrast, the survey based mortality coefficients for the 2-group with average values ranging between 1.16 (ordinary kriging) and 1.19 (external drift kriging with time of day) were close to mean from the ICES assessment of 1.13.

DISCUSSION

Geostatistical techniques were developed to handle estimation problems in spatially autocorrelated data and to use the additional information provided by the spatial structure when computing the estimates. In the present case, the estimates obtained by ordinary kriging, which explicitly accounts for spatial dependency, were close to the IBTS standard index, which ignores any spatial autocorrelation but performs a first averaging at the level of ICES rectangles. This may indicate that the IBTS standard index is relative robust despite the simple way it is calculated and that sampling irregularities were small due to survey stratification. On the other hand, the variograms showed that the amount of small-scale variability represented by the nugget effect and the maximum distance of spatial dependence given by the range of the spherical component varied considerably between years. The differences in the spatial structure might have resulted from the number and location of the hauls in a particular year, but could also be induced by interannual variations in the environment, e.g. changes in the distribution of physical variables such as temperature or biological ones like prey and predators.

Variations in time are generally ignored in the determination of the spatial structure. The abundance or the catch at a fixed location is considered in the model to be constant in time in ordinary kriging, to be constant by day and at night using day/night indicator as external drift, or to follow a perfect cosine curve on time of day using this as external drift. Such behavior in time is

obviously unrealistic, and exactly collocated hauls must be considered as close but spatially distinct hauls. This allows the local behavior in time not to be too closely driven by the theoretical model and removes also the overdetermination in the kriging algorithm, as mentioned in the methodological section, particularly when a nugget effect is present. It may be reasonable to include a nugget component for multi-vessel surveys, using for instance a weighted variogram (Rivoirard, 2000a) instead of the classical estimator (eq. 1). When there is no nugget, the local variations in time are limited, and kriging with external drift, in particular, may be unstable. In our case, however, models without nugget effect corresponded to very short ranges, and taking a pure nugget instead was checked to have nearly no effect on the results.

Several studies conducted in small, well-defined areas have shown that bottom trawl catch rates of juvenile gadoids are lower at night than by day (Aglen et al. 1999; Engås & Soldal 1992; Ehrich & Gröger 1989; Wieland 1998). It has further been demonstrated for haddock that this effect, although decreasing with increasing fish size (Korsbrekke & Nakken 1999), can lead to a serious bias of survey indices up to age 3 (Engås & Soldal 1992). Hjellvik et al. (1999) reported quantitative relationships between catch and time of day as well as between catch and sun elevation for cod in the Barents Sea. While a significant day/night or time effect exists in the IBTS data analyzed in our study, uncertainties on their quantification do not allow a direct rescaling of catches according to day/night or time (Rivoirard 2000b).

Kriging with external drift is a flexible method to estimate a variable, when the drift is driven by another variable with unknown coefficients. In the present study, the drift came either from a day/night indicator, or from time of day, i.e. it was assumed that catches have a different level by day and at night or according to time. However, neither the expected level of day-catches and night-catches nor the level and amplitude of the cosine response function to time needed to be known. The assumption on the temporal variation of catch is thus weak, particularly using the day/night indicator. In this case kriging is scaled on day sample values, and night catches only add a correction depending on their increments and their locations relative to day catches. Compared to the single ordinary kriging from day samples only, this is responsible for local differences, which can be high in the vicinity of night samples. However the estimated abundance over the whole domain is practically the same. This is due to a relatively good coverage of the domain by the day samples. By contrast, using the same method of external drift kriging with day/night indicator to estimate the abundance at night produces results different from ordinary kriging using night samples only. It is noteworthy that the difference between external drift kriging estimating the catch

by day or at noon and ordinary kriging was positive with few exceptions. This means that a day-night effect or a time effect with a night level lower than the day level was corroborated, even for years in which the mean catch at night was higher than the mean catch by day. However, the difference to ordinary kriging increased with the proportion of night hauls and was most pronounced in the years where the ratio between the mean of the night samples and the mean of the day samples was low.

The kriging variance quantifies the variance of the error on the estimation of abundance due to the spatial coverage, as predicted by the geostatistical model. That ordinary kriging variance was lower than external drift kriging variance does not mean that ordinary kriging is a better estimator, but rather that the estimation is less precise if a daylight effect exists. This apparent paradox makes sense. Supposing for instance that the variogram is pure nugget, the weights of night hauls in external drift kriging with day/night indicator (summing to zero and all equal) would be zero. In this case external drift kriging would give the average of the day hauls only, while ordinary kriging would be the average of all hauls. Ignoring a daylight effect if it exists yields a too optimistic precision.

External drift kriging with day/night indicator and with time of day, respectively, did not alter the level of correspondence between the abundance indices and the ICES assessment, as the trend over the years remained unchanged. On the other hand, the correction introduced by external drift kriging was most pronounced for age 1 and its effect decreased rapidly for the two subsequent age groups, in particular when time of day was used as external variable. This is well in accordance with the results of Korsbrekke & Nakken (1999) who reported a strong decrease in the diurnal variation of catch rates with size for haddock in the Barents Sea. The increase in the abundance indices for age 1, however, was not large enough to obtain much more reasonable mortality estimates than from the standard IBTS indices. This indicates that also other factors than daylight effects are involved in the low and varying catchability of the 1-group in the first quarter of the year.

Despite the recommendation of the IBTS Working Group for daytime trawling the proportion of night hauls in the northern North Sea has increased to a high level and several rectangles have frequently been sampled exclusively at night during the 1990's. The estimates of mean abundance obtained by external drift kriging with a day/night indicator as well as with time of day exceeded the IBTS standard values in most of years, in particular in all years since 1990. This was most likely due to a systematic difference in the catch rates due to daylight effects. It would be mandatory that

the proportion of night hauls is kept to a minimum and that sampling of a given rectangle exclusively at night is avoided in future surveys as long as no correction for daylight effects is adopted. External drift kriging as used here re-scales in its own manner night catches to day level and is thus capable of compensating for daylight effects even if a quantitative relationship is not known. It can therefore be regarded as a valuable alternative for the calculation of survey-based abundance indices.

ACKNOWLEDGEMENTS

The European Union provided financial support (DG XIV study N° 97/0009, MIQES – The use of multivariate data for improving the quality of survey-based stock estimation in the North Sea). The assessment data in which the 1st quarter IBTS was removed from the set of tuning fleets were provided by Stuart Reeves, Marine Laboratory Aberdeen. The analysis was carried out with an S-Plus library for geostatistical analysis compiled by Nicolas Bez and Jacques Rivoirard (Centre de Géostatistique Fontainebleau, France).

REFERENCES

- Aglen A, Engås A, Huse I, Michalsen K, Stensholt BK. 1999. How vertical fish distribution may affect survey results. *ICES Journal of Marine Science* 56:345-360.
- Chilès J-P, Delfiner P. 1999. *Geostatistics: Modeling spatial uncertainty*. New York: John Wiley & Sons. 695 p.
- Cressie NAC. 1993. *Statistics for spatial data*. New York: John Wiley & Sons. 900 p.
- Ehrich S, Gröger J. 1989. Diurnal variation in catchability of several fish species in the North Sea. ICES C.M. 1989 / B:39.
- Engås A, Soldal AV. 1992. Diurnal variations in bottom trawl catch rates of cod and haddock and their influence on abundance indices. *ICES Journal of Marine Science* 49: 89-95.
- Fernandes PG, Rivoirard J. 1999. A geostatistical analysis of the spatial distribution and abundance of cod, haddock and whiting in North Scotland. In: Gomez-Hernandez J, Soares A, Froidevaux R, editors. *Geostatistics for Environmental Applications*. Dordrecht: Kluwer Academic Publishers. p. 201-212.
- Heessen H, Daan N. 1994. Cod distribution and temperature in the North Sea. *ICES Marine Science Symposia* 198: 244-253.

- Heessen HJL, Dalskov J, Cook, RM. 1997. The International Bottom Trawl Survey in the North Sea, Skagerrak and Kattegat. ICES CM 1997/Y:31.
- Hjellvik V, Godø OR, Tjøstheim D. 1999. Modelling diurnal variation in bottom trawl catches and potential application in surveys. ICES CM 1999/J:06.
- ICES 1999a. Manual for the International Bottom Trawl Survey - Revision VI. ICES CM 1999/D:2, Addendum 2.
- ICES 1999b. Report of the International Bottom Trawl Survey in the North Sea, Skagerrak and Kattegat in 1998: Quarter 1. ICES CM 1999/D:8.
- Journel AG, Huijbregts CJ. 1978. *Mining geostatistics*. London: Academic Press. 600 p.
- Knijn RJ, Boon TW, Heessen HJL, Hislop JRG. 1993. Atlas of North Sea fishes. *ICES Cooperative Research Report* 194. 268 p.
- Korsbrekke K, Nakken O. 1999. Length and species-dependent diurnal variation of catch rates in the Norwegian Barents Sea bottom-trawl surveys. *ICES Journal of Marine Science* 56:284-291.
- Maravelias CD, Reid DG, Simmonds EJ, Haralabonus J. 1996. Spatial analysis and mapping of acoustic survey data in the presence of high local variability: geostatistical application to North Sea herring (*Clupea harengus*). *Canadian Journal of Fisheries and Aquatic Sciences* 53: 1497-1505.
- Matheron G. 1971. The theory of regionalized variables and its application. *Les cahier du Centre de Morphologie Mathématique* N° 5. Fontainebleau: École Nationale Supérieure des Mines de Paris. 211 p.
- Petitgas P. 1993. Geostatistics for fish stock assessments: a review and an acoustic application. *ICES Journal of Marine Science* 50:285-298.
- Petitgas, P. 1996. Geostatistics and their application to fisheries survey data. In: Megrey BA, Moksness E, editors. *Computers in Fisheries Research*. London: Chapman & Hall. p 113-142.
- Riley RD, Parnell G. 1984. The distribution of young cod. In: Dahl E, Danielssen DS, Moksness E, Solemdal P, editors. The propagation of cod *Gadus morhua* L. *Flødevigen rapportser* 1: 563-580.
- Rivoirard J. 2000a. Weighted variograms. Proceedings of the International Geostatistical Congress, Capetown, South-Africa, April 2000. To be published.
- Rivoirard J. 2000b. Testing the effects of vessel, gear and daylight on catch data from the International Bottom Trawl Survey in the North Sea. ICES CM 2000/K:30.

- Rivoirard J, Simmonds J, Foote KG, Fernandes P, Bez N. 2000. Geostatistics for estimating fish abundance. Oxford: Blackwell Science. 206 p.
- Rossi RE, Mulla DJ, Journel AG, Franz EH. 1992. Geostatistical tools for modeling and interpreting ecological spatial dependence. *Ecological Monographs* 62: 277-314.
- Simard Y, Legendre P, Lavoie G, Marcotte D. 1992. Mapping, estimating biomass and optimizing sampling programs for spatially autocorrelated data: case study of the northern shrimp (*Pandalus borealis*). *Canadian Journal of Fisheries and Aquatic Sciences* 49: 32-45.
- Simard Y, Marcotte D, Bourgault G. 1993. Exploration of geostatistical methods for mapping and estimating acoustic biomass of pelagic fish in the Gulf of St. Lawrence: size of echointegration unit and auxiliary environmental variables. *Aquatic Living Resources* 6: 185-199.
- Sparholt, H. 1990. Using GLM analysis on the IYFS herring data for the North Sea. ICES C.M. 1990/H:6.
- Stensholt B, Sunnanå K. 1996. Spatial distributions of variables in marine environmental and fisheries research; Part I: Geostatistics and autocorrelated environmental and fisheries data. ICES CM 1996/D:16.
- Wieland K. 1998. Spatial distribution pattern generating processes in the International Bottom Trawl Survey in the North Sea. *DFU-rapport* nr. 60-98.
- Wieland K, Foldager L, Holst R, Jarre-Teichmann A. 1998. Spatial distribution and variability of abundance estimates of juvenile (age 1 and 2) whiting and cod in the North Sea. ICES CM 1998/J:7.
- Wieland K, Rivoirard J. 2000. A geostatistical analysis of IBTS data for age 2 North Sea haddock (*Melanogrammus aeglefinus*) considering daylight effects. Submitted to Sarsia.

Table 1. Variogram models for age 1 to 3 haddock, 1st quarter IBTS 1983-1997. Model fit by minimizing the sum of squares weighted by the number of pairs using normalized experimental variograms with a lag of 15 nm and a reference latitude of 58°N (= mean latitude of the domain). Max. dist.: maximum distance considered in the model fitting. GOF: Goodness of fit statistic (see text for definition).

a) age 1

| Year | Model components | Max. dist. (nm) | Nugget effect | Linear component | Spherical component Sill | Range (nm) | GOF (%) |
|------|--------------------|-----------------|---------------|------------------|--------------------------|------------|---------|
| 1983 | nugget + spherical | 300 | 0.88 | - | 0.21 | 267 | 0.40 |
| 1984 | nugget + spherical | 300 | 0.57 | - | 0.51 | 110 | 1.86 |
| 1985 | nugget + spherical | 300 | 0.65 | - | 0.47 | 228 | 0.23 |
| 1986 | nugget + spherical | 285 | 0.68 | - | 0.42 | 128 | 0.97 |
| 1987 | nugget + spherical | 285 | 0.60 | - | 0.58 | 240 | 0.37 |
| 1988 | nugget | 300 | 1.03 | - | - | - | 2.94 |
| 1989 | nugget + spherical | 240 | 0.53 | - | 0.68 | 154 | 0.59 |
| 1990 | spherical | 255 | - | - | 1.07 | 43 | 1.77 |
| 1991 | nugget + spherical | 240 | 0.55 | - | 0.65 | 123 | 1.14 |
| 1992 | nugget + spherical | 300 | 0.62 | - | 0.48 | 166 | 0.60 |
| 1993 | nugget + linear | 300 | 0.70 | 0.0016 | - | - | 0.67 |
| 1994 | nugget + spherical | 255 | 0.60 | - | 0.51 | 74 | 3.67 |
| 1995 | nugget + spherical | 240 | 0.40 | - | 0.47 | 144 | 0.78 |
| 1996 | nugget + spherical | 225 | 0.82 | - | 0.24 | 99 | 1.45 |
| 1997 | nugget + linear | 300 | 0.64 | 0.0024 | - | - | 0.61 |

b) age 2

| Year | Model components | Max. dist. (nm) | Nugget effect | Linear component | Spherical component Sill | Range (nm) | GOF (%) |
|------|--------------------|-----------------|---------------|------------------|--------------------------|------------|---------|
| 1983 | nugget + spherical | 300 | 0.27 | - | 0.72 | 48 | 1.58 |
| 1984 | spherical | 300 | - | - | 1.04 | 31 | 1.19 |
| 1985 | nugget + spherical | 240 | 0.51 | - | 0.63 | 95 | 0.51 |
| 1986 | nugget + spherical | 300 | 0.63 | - | 0.45 | 158 | 0.41 |
| 1987 | nugget + spherical | 300 | 0.65 | - | 0.45 | 197 | 0.76 |
| 1988 | nugget + spherical | 300 | 0.53 | - | 0.58 | 143 | 1.54 |
| 1989 | nugget + spherical | 300 | 0.51 | - | 0.56 | 122 | 0.79 |
| 1990 | spherical | 300 | - | - | 1.05 | 41 | 1.19 |
| 1991 | nugget + spherical | 225 | 0.38 | - | 0.76 | 105 | 1.18 |
| 1992 | nugget + spherical | 300 | 0.72 | - | 0.31 | 95 | 1.83 |
| 1993 | nugget + spherical | 300 | 0.47 | - | 0.54 | 88 | 1.28 |
| 1994 | nugget + spherical | 300 | 0.42 | - | 0.79 | 266 | 1.07 |
| 1995 | nugget + spherical | 300 | 0.61 | - | 0.54 | 250 | 1.00 |
| 1996 | nugget + spherical | 285 | 0.58 | - | 0.54 | 228 | 2.00 |
| 1997 | nugget + spherical | 225 | 0.39 | - | 0.70 | 48 | 2.84 |

c) age 3

| Year | Model components | Max. dist. (nm) | Nugget effect | Linear component | Spherical component Sill | Range (nm) | GOF (%) |
|------|--------------------|-----------------|---------------|------------------|--------------------------|------------|---------|
| 1983 | nugget + spherical | 240 | 0.09 | - | 0.81 | 45 | 0.77 |
| 1984 | nugget + linear | 300 | 0.80 | 0.0012 | - | - | 1.61 |
| 1985 | nugget + spherical | 240 | 0.75 | - | 0.43 | 103 | 1.03 |
| 1986 | nugget + spherical | 225 | 0.80 | - | 0.39 | 99 | 1.48 |
| 1987 | nugget + spherical | 255 | 0.75 | - | 0.26 | 203 | 2.21 |
| 1988 | nugget + spherical | 300 | 0.58 | - | 0.46 | 112 | 0.67 |
| 1989 | nugget + spherical | 300 | 0.43 | - | 0.72 | 188 | 0.98 |
| 1990 | nugget + spherical | 300 | 0.03 | - | 1.01 | 45 | 0.74 |
| 1991 | nugget + spherical | 240 | 0.61 | - | 0.56 | 67 | 1.44 |
| 1992 | nugget + spherical | 300 | 0.70 | - | 0.32 | 92 | 0.90 |
| 1993 | nugget + spherical | 270 | 0.64 | - | 0.33 | 77 | 2.68 |
| 1994 | nugget + spherical | 285 | 0.50 | - | 0.51 | 133 | 1.52 |
| 1995 | nugget + spherical | 300 | 0.08 | - | 1.30 | 289 | 3.49 |
| 1996 | spherical | 300 | - | - | 1.03 | 30 | 1.85 |
| 1997 | nugget + spherical | 300 | 0.74 | - | 0.31 | 153 | 2.26 |

Table 2. Relative difference between indices of mean abundance for age 1 to 3 haddock in the 1st quarter IBTS 1983-1997 estimated by external drift kriging with time of day and ordinary kriging. The relative difference is expressed in respect to external drift kriging, i.e. $(Z_0^{ED} - Z_0^{OK})/Z_0^{ED}$.

| Year | Relative difference (%) | | |
|------|-------------------------|-------|-------|
| | Age 1 | Age 2 | Age 3 |
| 1983 | 29.3 | 18.3 | 7.9 |
| 1984 | 17.9 | 14.3 | 9.0 |
| 1985 | 21.2 | 23.5 | 18.6 |
| 1986 | 26.5 | 12.3 | 4.9 |
| 1987 | 24.6 | 3.7 | -19.6 |
| 1988 | 18.1 | 15.7 | 19.4 |
| 1989 | 19.1 | 7.2 | 15.0 |
| 1990 | 29.7 | 29.6 | 23.9 |
| 1991 | 21.8 | 21.3 | 23.1 |
| 1992 | 26.7 | 6.4 | 4.2 |
| 1993 | 23.4 | 10.8 | -14.5 |
| 1994 | -2.8 | 6.3 | 0.8 |
| 1995 | 18.5 | 16.9 | 22.4 |
| 1996 | 7.6 | 18.2 | 37.2 |
| 1997 | 27.9 | 15.0 | 19.4 |
| Mean | 20.6 | 14.7 | 11.4 |

Table 3. Coefficients of determination (r^2) for the correlation of 1st quarter IBTS abundance indices with ICES assessments of age 1, 2 and 3 haddock, 1983-1997 (*: ICES CM 2000/ACFM:7; **: assessment provided by Stuart Reeves, Marine Laboratory Aberdeen).

| Index | Assessment with IBTS * | | | Assessment without IBTS ** | | |
|-------------------------------|------------------------|-------|-------|----------------------------|-------|-------|
| | Age 1 | Age 2 | Age 3 | Age 1 | Age 2 | Age 3 |
| IBTS standard index | 0.71 | 0.92 | 0.90 | 0.71 | 0.91 | 0.89 |
| Ordinary kriging | 0.74 | 0.90 | 0.91 | 0.73 | 0.90 | 0.91 |
| Day/night as external drift | 0.65 | 0.89 | 0.85 | 0.64 | 0.88 | 0.84 |
| Time of day as external drift | 0.70 | 0.91 | 0.86 | 0.69 | 0.90 | 0.86 |

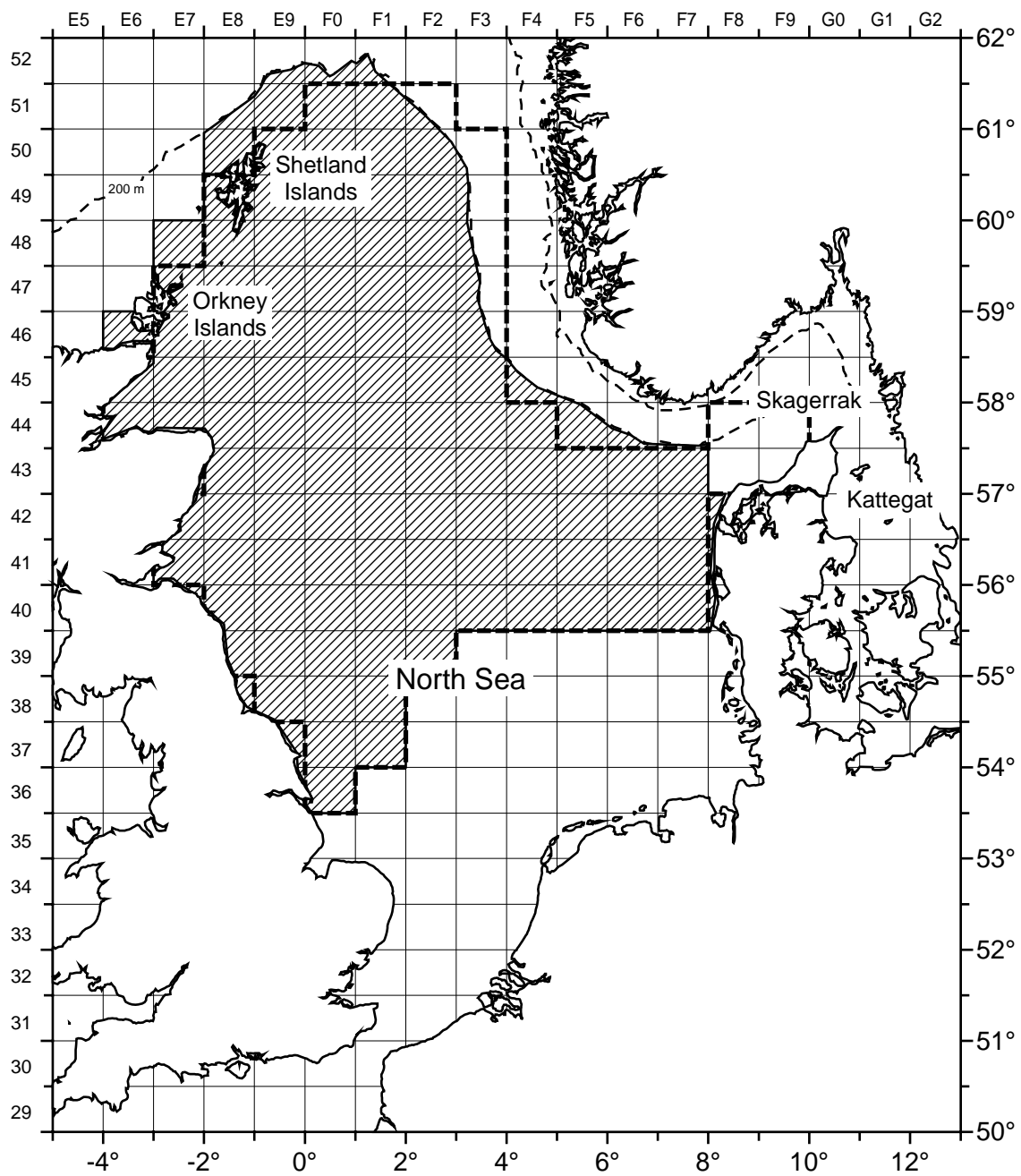


Figure 1. Map of the North Sea with ICES statistical rectangles, the IBTS standard area for haddock (limits indicated by the broken line) and the domain used in the present study (shaded area).

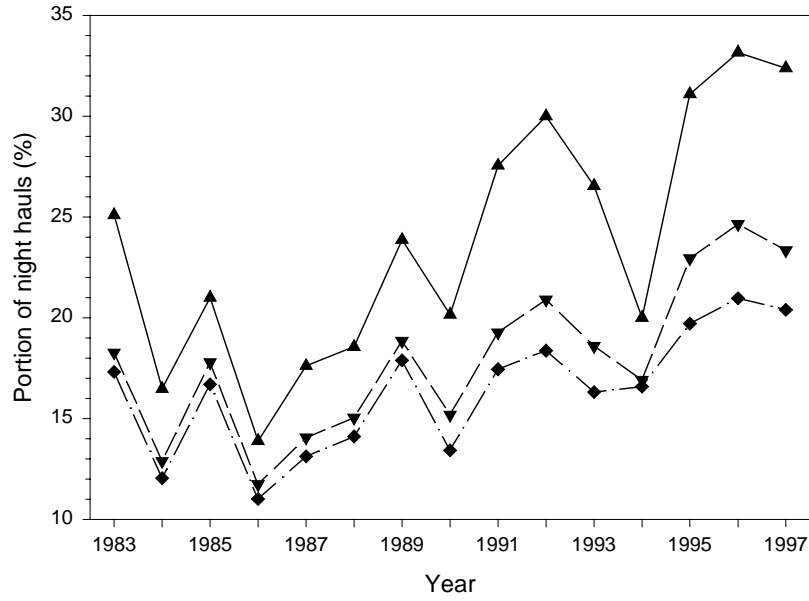


Figure 2. Portion of night hauls in the 1st quarter IBTS 1983-1997 in the entire survey area (diamonds), the North Sea without the Kattegat and the Skagerrak (triangles down) and in the domain used in the present study (triangles up).

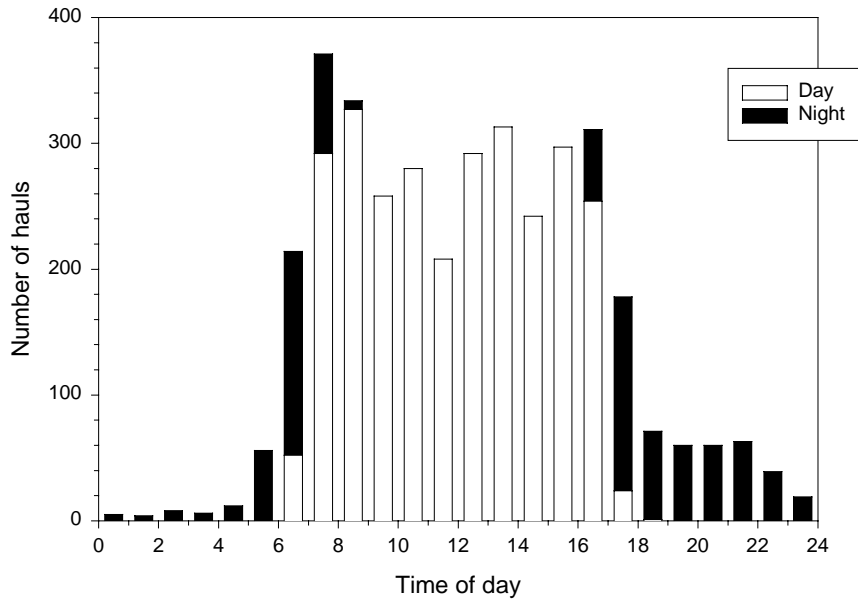


Figure 3. Frequency distribution of day and night hauls in respect of local time of day in the 1st quarter IBTS 1983-1997 for the domain used in the present study (ICES roundfish areas 1 to 4 and 7).

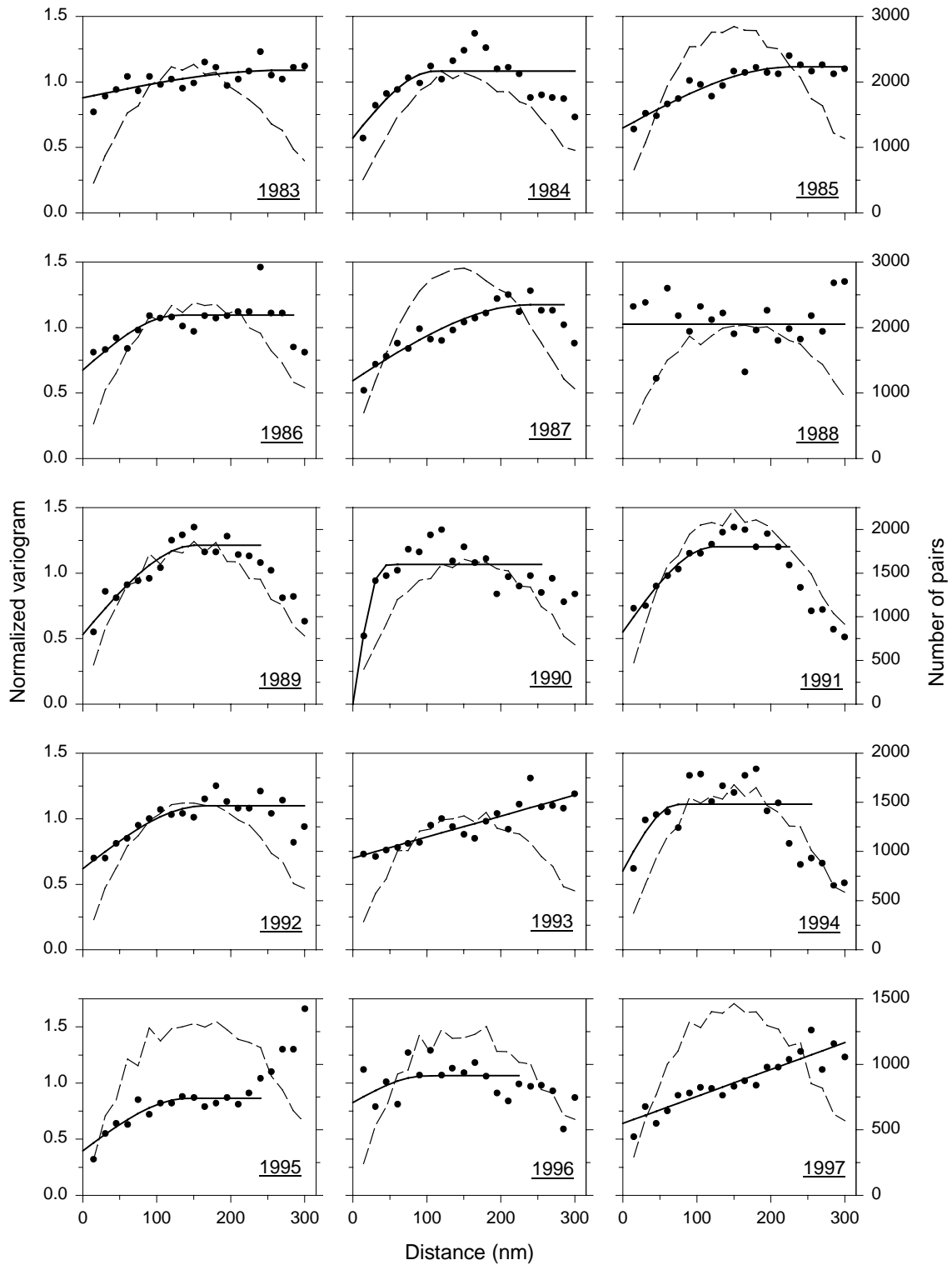


Figure 4a. Omnidirectional normalized variograms for age 1 haddock, 1st quarter IBTS 1983-1997. Solid circles: experimental variogram, dashed lines: number of pairs, solid lines: variogram models fitted by nonlinear least squares weighted by the number of pairs.

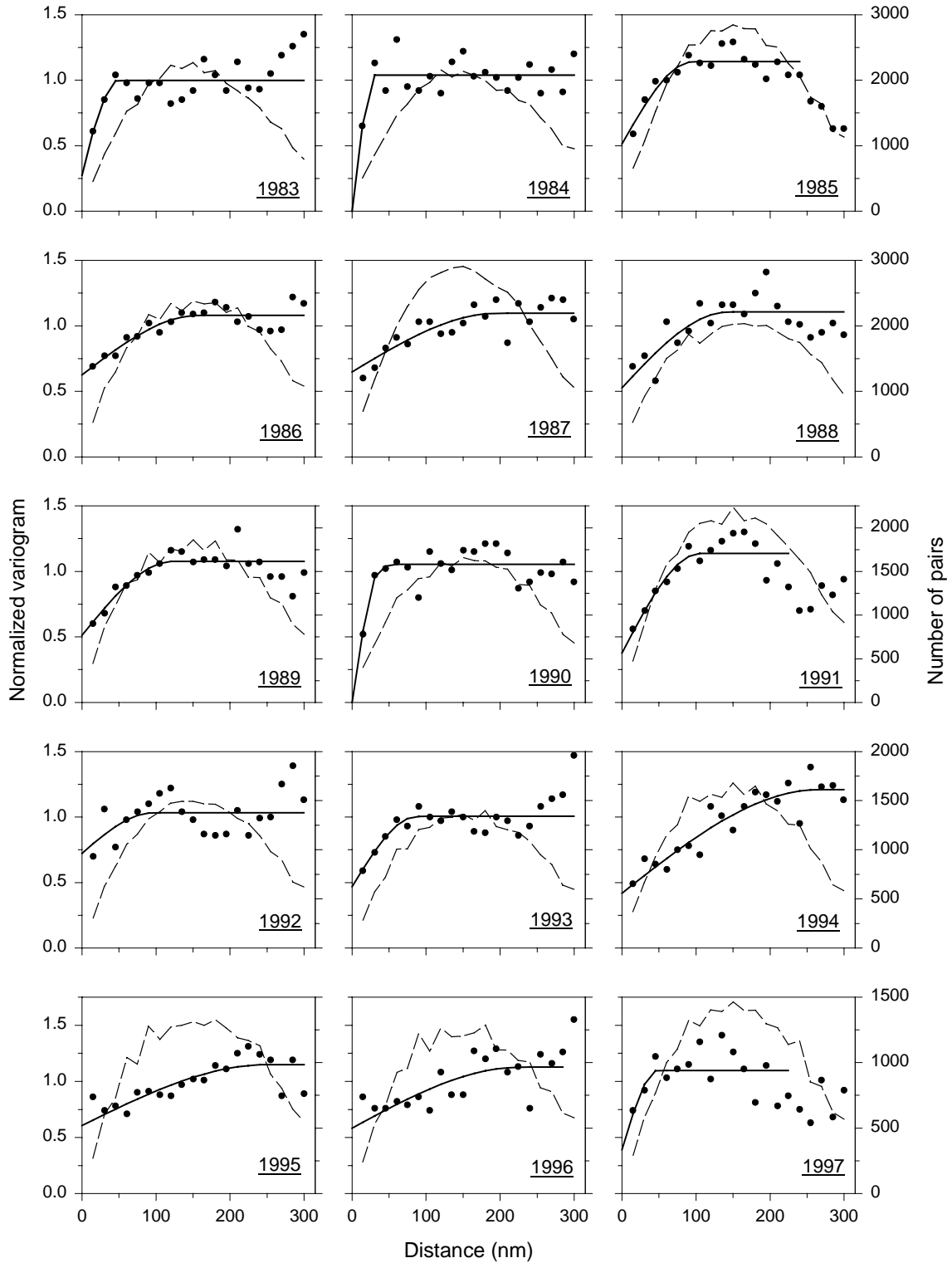


Figure 4b. Omnidirectional normalized variograms for age 2 haddock, 1st quarter IBTS 1983-1997. Solid circles: experimental variogram, dashed lines: number of pairs, solid lines: variogram models fitted by nonlinear least squares weighted by the number of pairs.

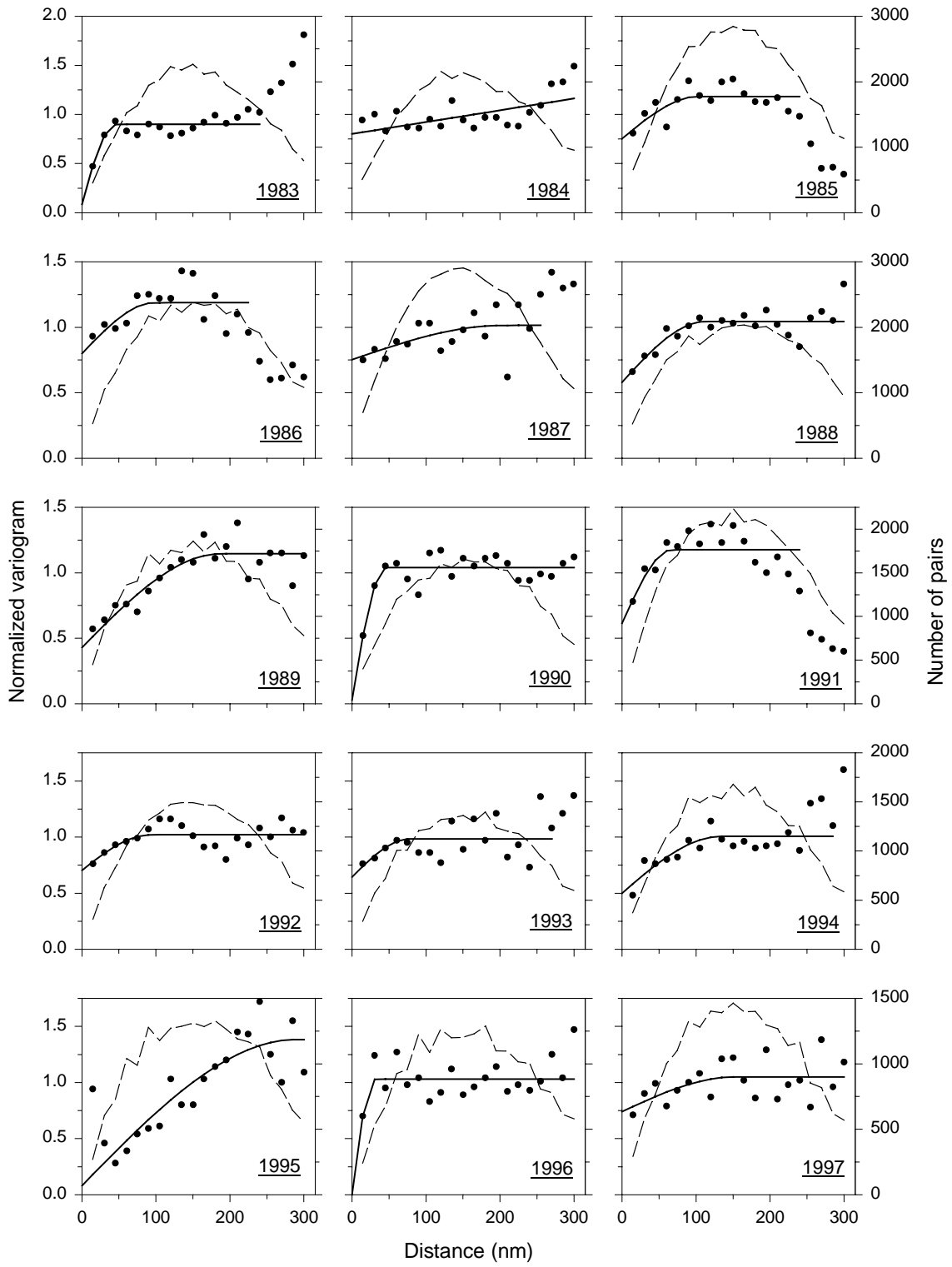


Figure 4c. Omnidirectional normalized variograms for age 3 haddock, 1st quarter IBTS 1983-1997. Solid circles: experimental variogram, dashed lines: number of pairs, solid lines: variogram models fitted by nonlinear least squares weighted by the number of pairs.

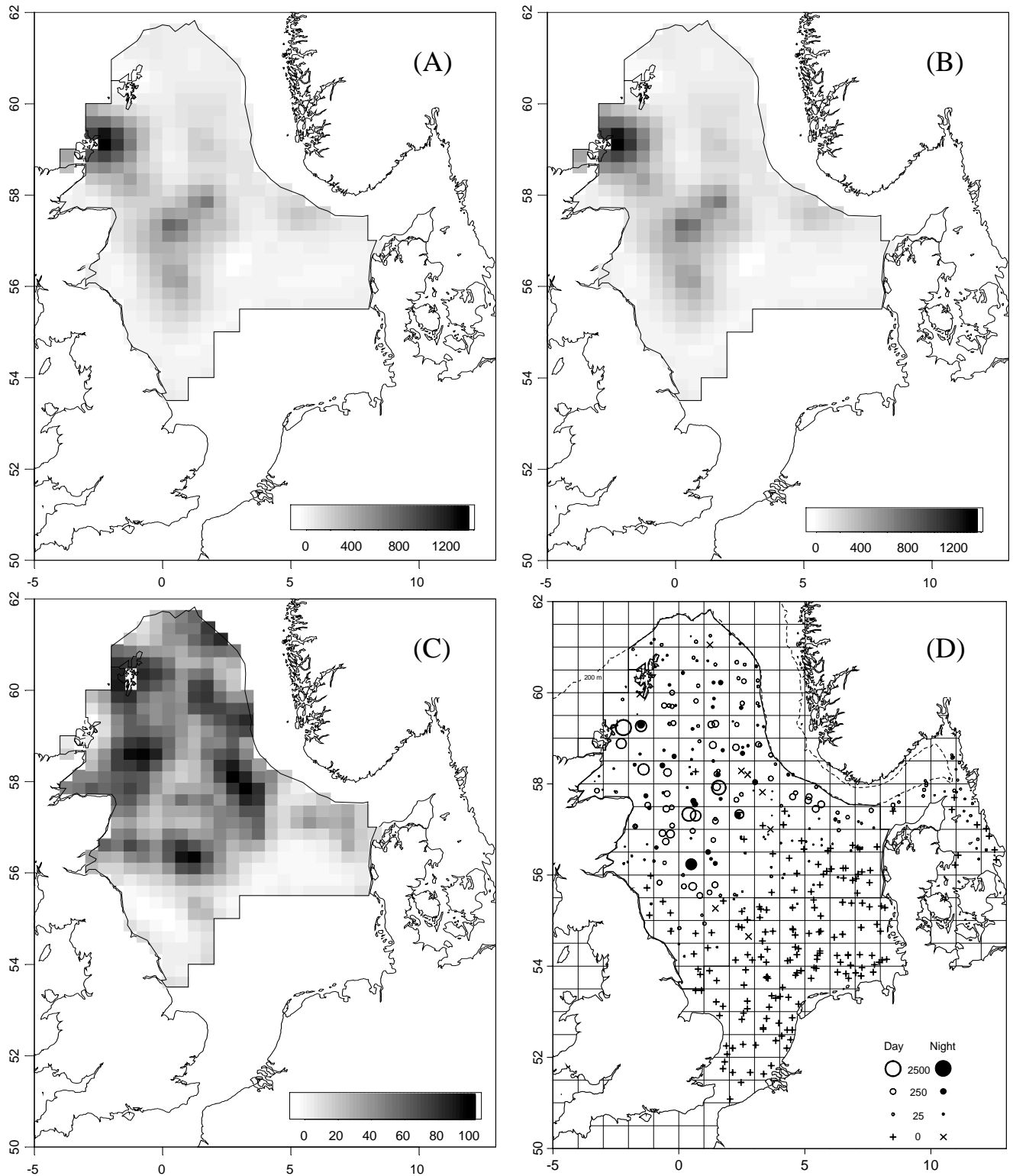


Figure 5. Distribution of age 2 haddock in 1991, 1st quarter IBTS: (A) Ordinary kriging, (B) External drift kriging with day/night indicator, (C) Difference between external drift and ordinary kriging, (D) Location of day and night catches. Grey scale in (A) – (C) refer to numbers per hour trawling, Symbol size in (D) proportional to catch in numbers per hour trawling.

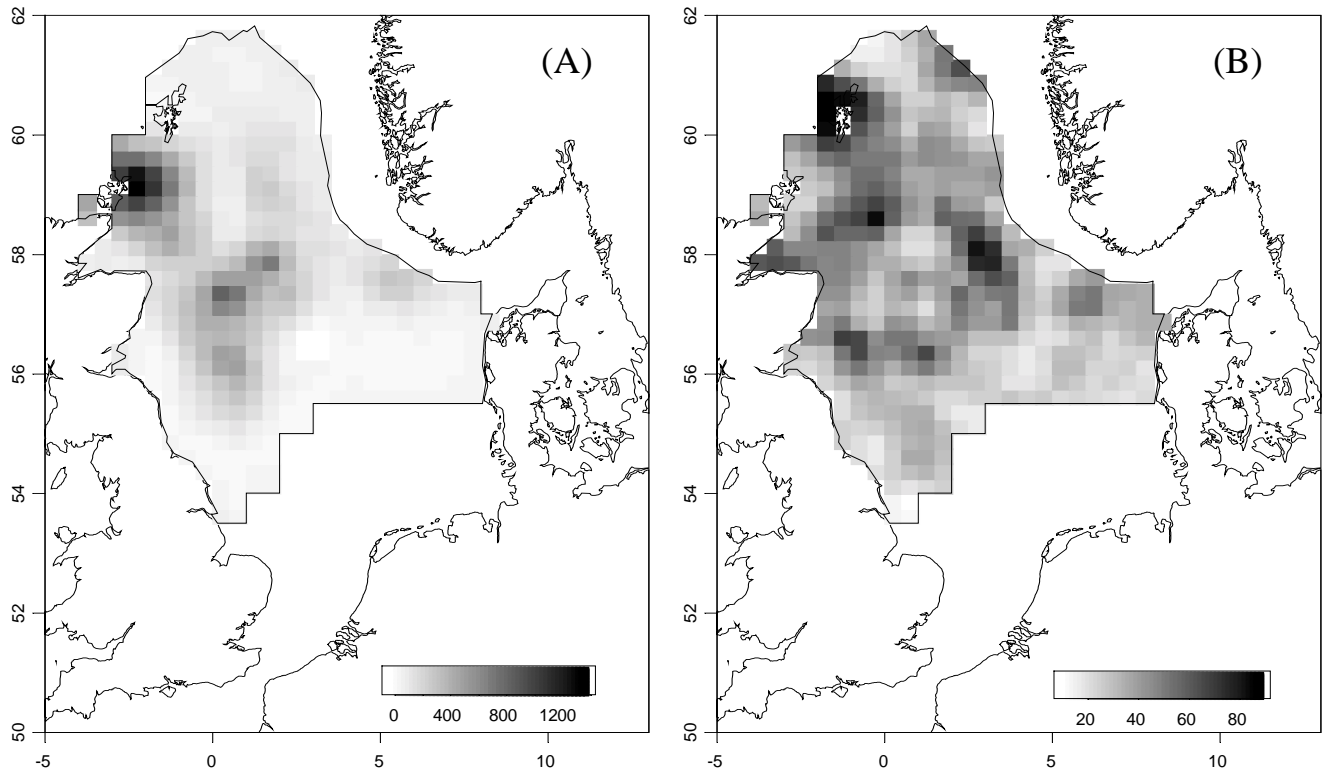


Figure 6. Distribution of age 2 haddock in 1991, 1st quarter IBTS: (A) External drift kriging with time of day, (B) Difference between external drift with time of day and ordinary kriging. Grey scales refer to numbers per hour trawling.

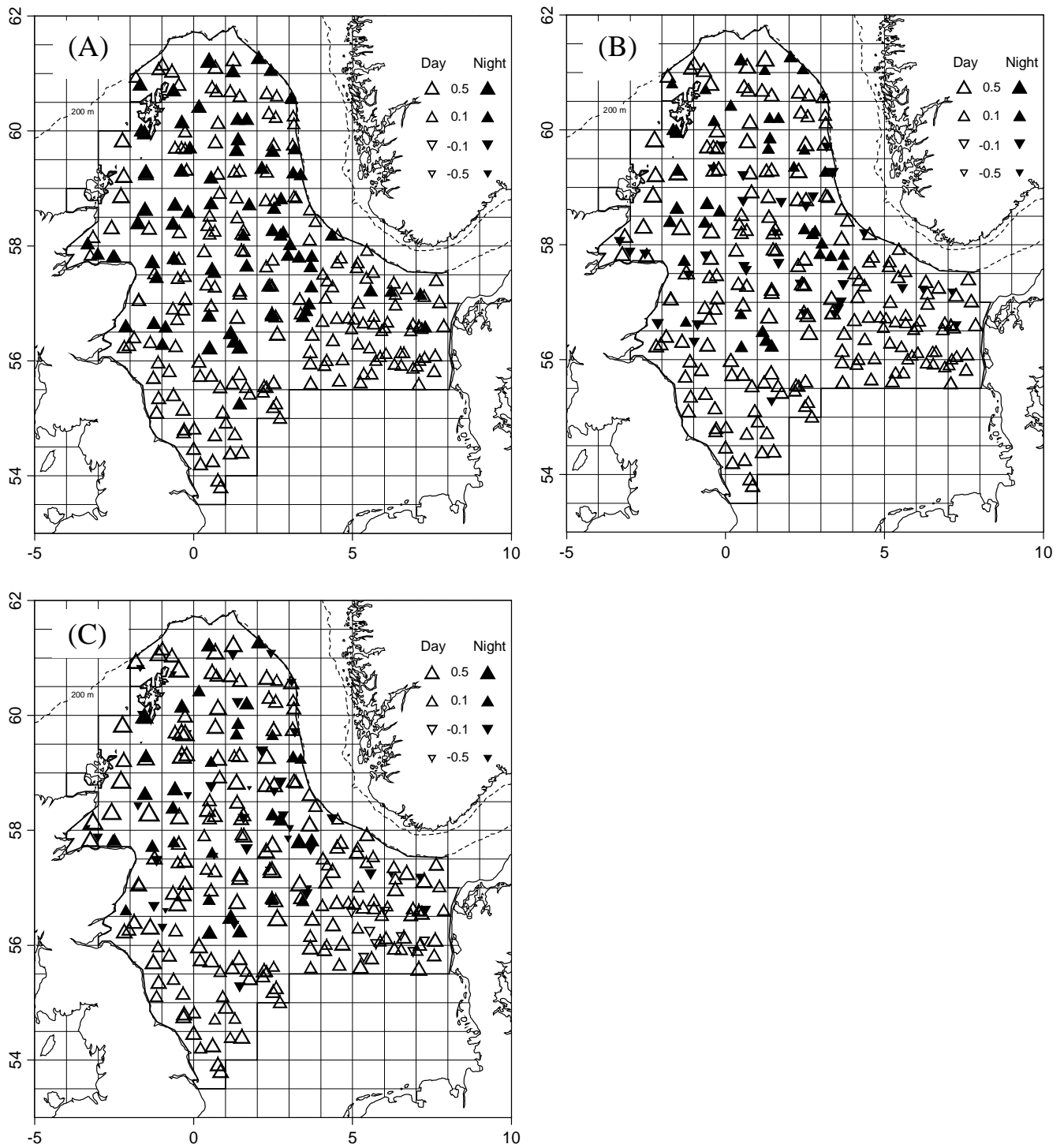


Figure 7. Kriging weights (in %) used for mapping and global estimation of abundance of age 2 haddock, 1st quarter IBTS 1991: (A) Ordinary kriging, (B) External drift kriging with day/night indicator, (C) External drift kriging with time of day.

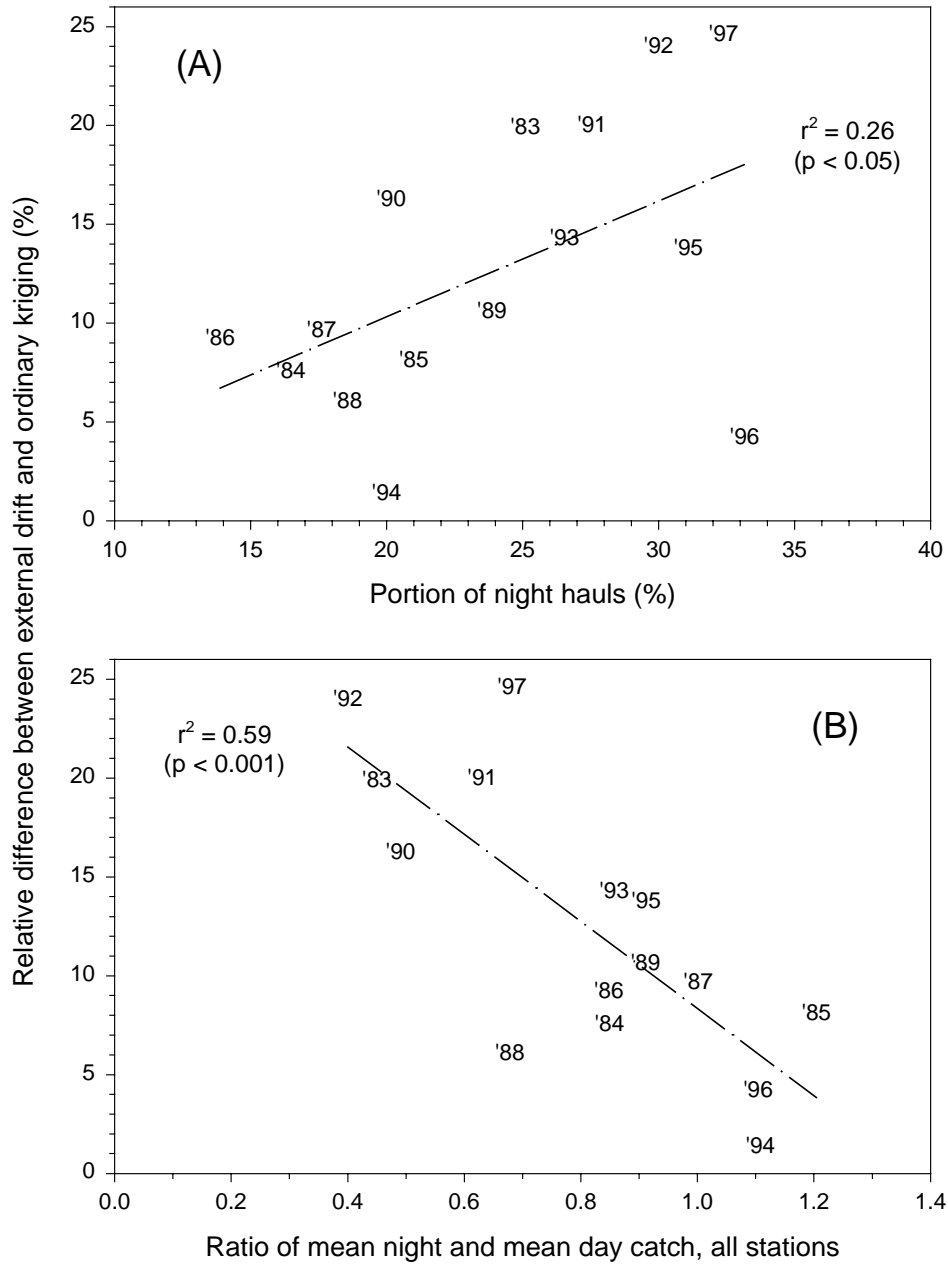


Figure 8a. Relative differences between mean abundance of age 1 haddock in the 1st quarter IBTS 1983-1997 estimated by ordinary kriging and external drift kriging with day/night indicator. The relative difference is expressed in respect to external drift kriging, i.e. $(Z_0^{ED} - Z_0^{OK})/Z_0^{ED}$. (A) Relative difference plotted versus the portion of night hauls and (B) versus the ratio of mean night and day catch rates from all stations in the domain.

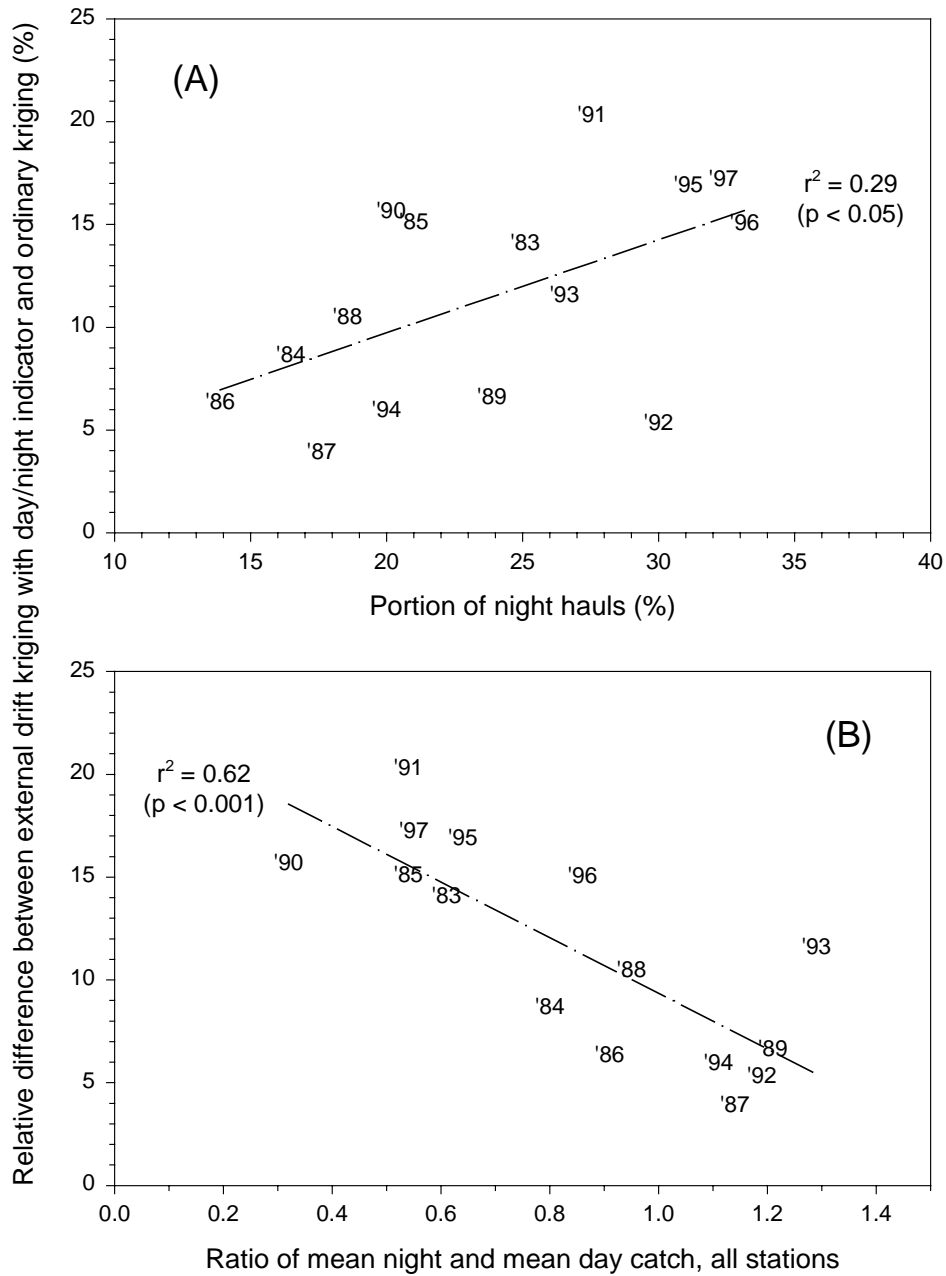


Figure 8b. Relative differences between mean abundance of age 2 haddock in the 1st quarter IBTS 1983-1997 estimated by ordinary kriging and external drift kriging with day/night indicator. The relative difference is expressed in respect to external drift kriging, i.e. $(Z_0^{ED} - Z_0^{OK})/Z_0^{ED}$. (A) Relative difference plotted versus the portion of night hauls and (B) versus the ratio of mean night and day catch rates from all stations in the domain.

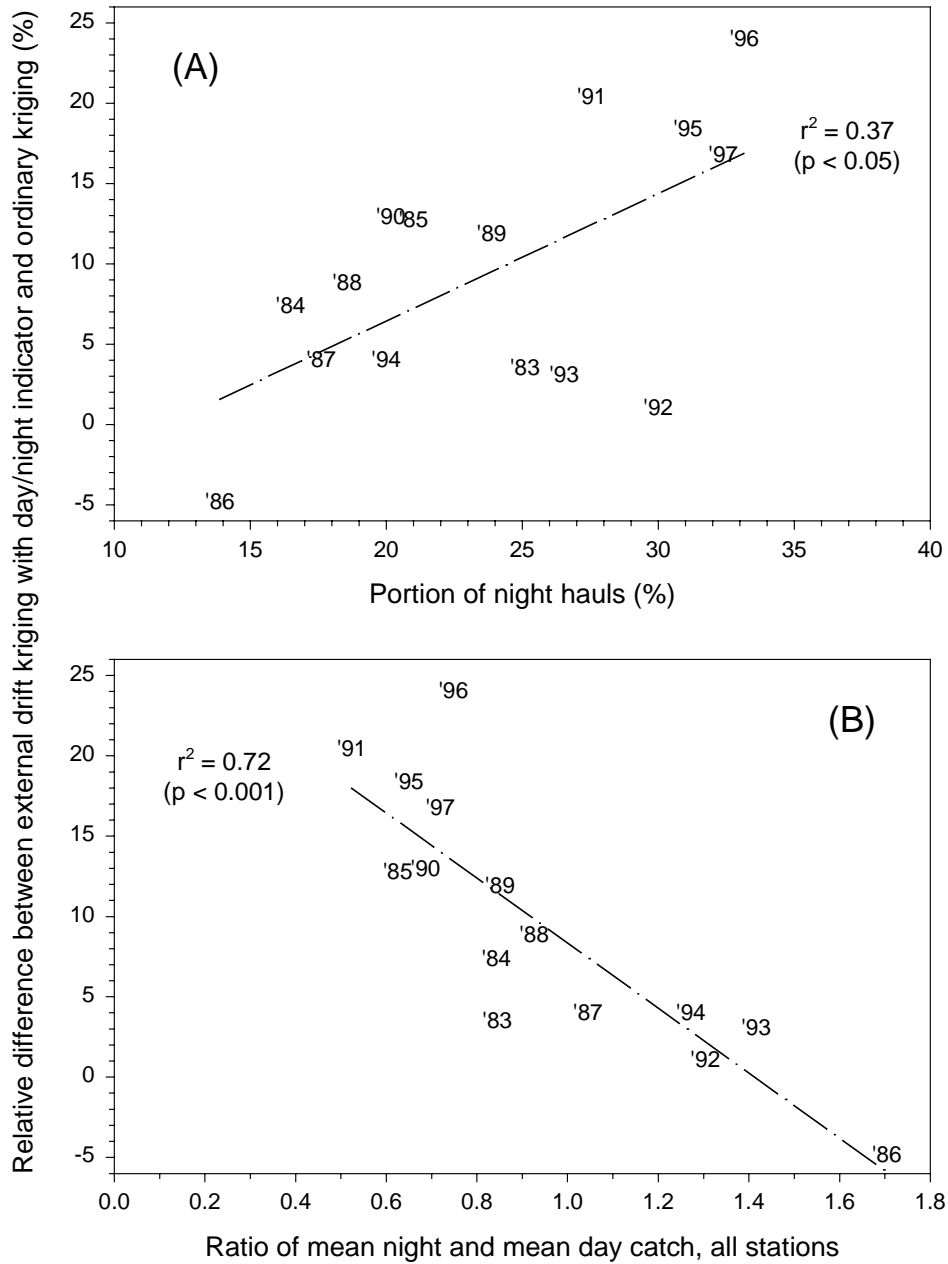


Figure 8c. Relative differences between mean abundance of age 3 haddock in the 1st quarter IBTS 1983-1997 estimated by ordinary kriging and external drift kriging with day/night indicator. The relative difference is expressed in respect to external drift kriging, i.e. $(Z_0^{ED} - Z_0^{OK})/Z_0^{ED}$. (A) Relative difference plotted versus the portion of night hauls and (B) versus the ratio of mean night and day catch rates from all stations in the domain.

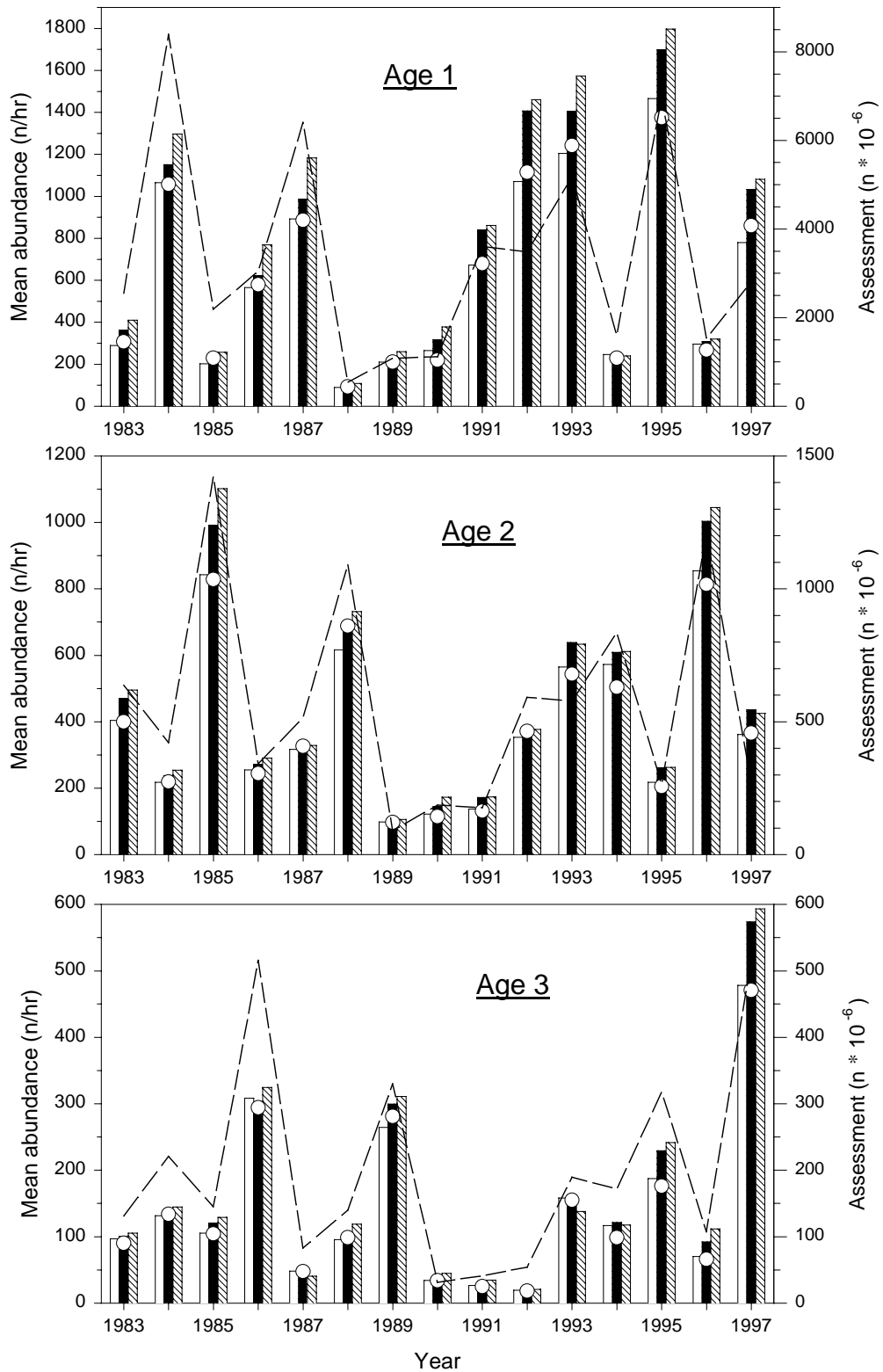


Figure 9. Times series of abundance indices for age 1 to 3 haddock, 1st quarter IBTS 1983-1997, estimated by ordinary kriging (open bars), by external drift kriging with day/night indicator (solid bars) and by external drift kriging with time of day (shaded bars). The IBTS standard index (open circles, source: ICES 1999b) and the most recent ICES assessment (dashed line, source: ICES 2000) are given for comparison.

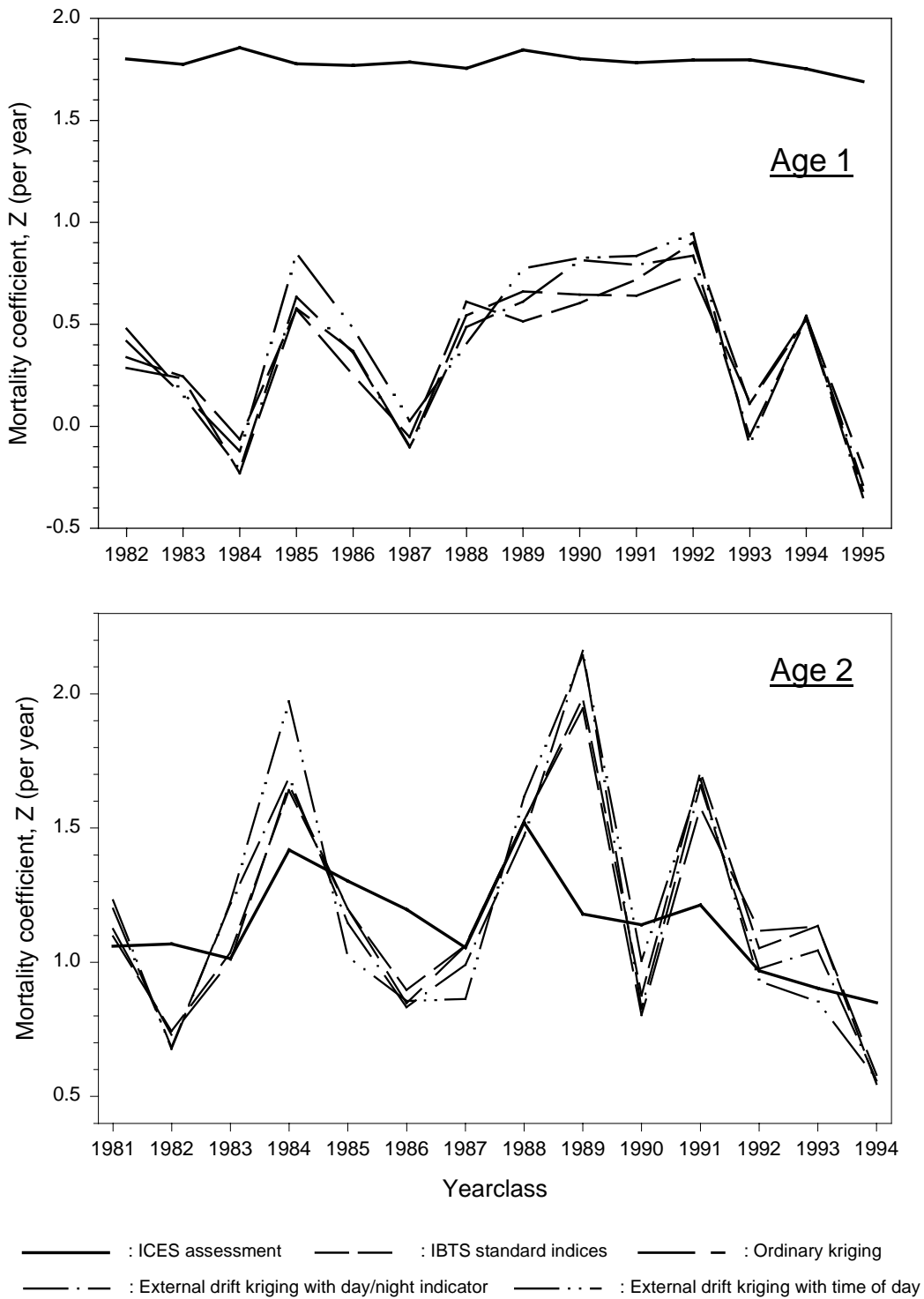


Figure 10. Coefficients of total mortality for haddock age 1 (yearclasses 1982-1995) and age 2 (yearclasses 1981-1994) based on ICES assessment, IBTS standard indices and abundance indices obtained by ordinary kriging, external drift kriging with day/night indicator and external drift kriging with time of day.