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Acoustic data collected during and between bottom trawl stations: consistency and common trends

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Abstract: Acoustic data are often collected during bottom trawl surveys. Their use can potentially improve the precision and accuracy of fish abundance estimates if acoustic data collected between trawl stations are consistent with those collected during trawling operations. This question is addressed here through the analysis of 20 bottom trawl surveys (three survey areas and five different survey series) with coincident acoustic measurements during and between trawl stations. Firstly, on-station and underway acoustic data were compared using statistics computed globally over each survey (average vertical profiles, global indices of collocations, and spatial structures) for various combinations of depth layers. Secondly, we focussed on underway acoustic data recorded in the vicinity of stations, distinguishing between data recorded before and after the tows. On-station and underway acoustic data were highly consistent, and no systematic perturbation of the acoustic sign due to the presence of the gear a few hundred metres behind the vessel was observed.

Résumé : On récolte souvent des données acoustiques durant les inventaires faits au chalut de fond. Leur utilisation peut potentiellement améliorer la précision et la justesse des estimations d'abondance des poissons, si les données acoustiques récoltées entre les stations de chalutage sont compatibles avec celles récoltées durant les opérations de pêche. Nous examinons la question en analysant 20 inventaires faits au chalut de fond (trois zones d'inventaire et cinq séries différentes d'inventaires) pour lesquels il existe des mesures acoustiques coïncidentes obtenues dans et entre les stations de chalutage. Nous avons d'abord comparé les données acoustiques obtenues en route et dans les stations à l'aide de statistiques calculées globalement pour chaque inventaire (profils verticaux moyens, indices globaux de collocation et structures spatiales) selon diverses combinaisons de couches de profondeur. Ensuite, nous nous sommes intéressés aux données acoustiques obtenues en route près des stations, en distinguant entre les données enregistrées avant et après le chalutage. Il existe un excellent accord entre les données acoustiques obtenues dans les stations et celles enregistrées en route; on n'observe pas de perturbation systématique du signal acoustique due à la présence des engins de pêche à quelques centaines de mètres derrière le navire.

Abstract

Acoustic data are often collected during bottom trawl surveys. Their use can potentially improve the precision and accuracy of fish abundance estimates if acoustic data collected between trawl stations are consistent with those collected during trawling operations. This question is addressed by the current paper through the analysis of twenty bottom trawl surveys (three survey areas and five different survey series) with coincident acoustic measurements during and between trawl stations. Firstly, on-station and underway acoustic data were compared using statistics computed globally over each survey (average vertical profiles, global indices of collocations and spatial structures) for various combinations of depth layers. Secondly, we focussed on underway acoustic data recorded in the vicinity of stations, distinguishing between data recorded before and after the tows.

On station and underway acoustic data were highly consistent and no systematic perturbation of the acoustic sign due to the presence of the gear few hundreds meters behind the vessel was observed.

Key words

Bottom trawl, acoustic, gear perturbation

Introduction

Bottom trawl surveys are one of the main survey methods used in the assessment of demersal fish stocks around the world (Gunderson 1993). It has recently become possible to carry out combined acoustic and bottom trawl surveys (e.g., in the Barents Sea, Aglen and Nakken 1997; Korsbrekke et al. 2001) or to collect acoustic and trawl data while carrying out a bottom trawl survey (Cachera et al. 1999; Krieger et al. 2001).

In some cases, such as Barents Sea cod (*Gadus morhua* L., Korsbrekke et al. 2001), the acoustic data are used to generate a secondary abundance index from the survey in addition to a trawl catch-rate index. Acoustic observations can also be used to gain additional information on fish availability and distribution away from the trawl station in order to improve the precision and accuracy of the trawl-based estimate. These two approaches were the basis for the EU funded (Framework Programme 5) project CATEFA (Combining Acoustic and Trawl data for Estimating Fish Abundance).

Two hypotheses need to be confirmed to allow this combination of acoustic and trawl survey data. The first is that the fishing gear and the acoustic devices are measuring the same thing. If true it would become possible to derive a relationship between trawl catch and acoustic observations (Krieger et al. 2001; Hjellvik et al. 2003). The second is that acoustic data collected away from the trawl stations is consistent with that collected during the trawling operations. The present paper deals with the second hypothesis.

There is considerable evidence that fish engage in avoidance behaviour to the trawl/vessel combination (Godø et al. 1999; Michalsen 1999; Handegard et al. 2003; Kloser and Horne 2003). Vessel speed is generally low during trawling (e.g. around 3 knots) and, a large and noisy net is being towed. Away from the trawl stations, the survey vessel moves much faster (usually over 10 knots) and without a net. The evidence is mixed as to whether fish also engage in avoidance behaviour under this scenario (Mitson and Knudsen 2003; Fréon and Misund 1999; Fernandes et al. 2000). Different avoidance reactions, and hence availability to the echosounder, could have a significant impact on what is seen on the echogram. In order to use the acoustic data between trawl stations for the purpose of improving trawl survey estimates or of combining the data, we must be sure that the echosounder is seeing the same component of a population during trawling as it does while running between stations. This study uses data from a number of different trawl surveys in the North, Irish and Barents Seas (Fig. 1a). It examines the relationship between on-station and between-station acoustic data at both the local level (i.e., immediately adjacent to the trawl station) and more globally for each survey.

Material and methods

Surveys and data preparation

Bottom trawl data with coincident acoustic measurements from three survey areas and five different survey series were used in this analysis (Table 1).

The International Council for the Exploration of the Sea (ICES) co-ordinates the International Bottom Trawl Surveys (IBTS) in the North Sea. These surveys follow a random design, stratified by ICES rectangle (Fig. 1b). Trawl and acoustic data are only collected during daylight hours. The surveys used in this study were those carried out by the Centre for Environment Fisheries and Aquaculture Science (Cefas) - Lowestoft (2000, 2001 and 2002), the Fisheries Research Services (FRS) - Aberdeen (1999, 2000 and 2002) and the Institut Français de Recherche pour l’Exploitation de la Mer (Ifremer) - Boulogne (2002 and 2003). Each survey comprises between 60 and 80 stations. The North Sea data had the most skewed distributions with many low values and a few extremely high values. In the case of the French data, 65 % of the total back-scattering energy on-station was concentrated in 3 % of the stations.

The Northern Irish Bottom Trawl Surveys (NIBTS) in the Irish Sea. These surveys are mostly small (35 to 45 stations) and follow a random sampling design stratified by depth and substrate (Fig. 1c). Depth varied between 23 and 102 m. Four surveys carried out by Dardni (Department of Agriculture and Rural Development, Northern Ireland) Belfast were available: autumn 1997, spring 2000, autumn 2001 and spring 2002. These surveys tend to encounter much more pelagic fish like herring (*Clupea harengus*) and sprat (*Sprattus sprattus*) than in the North Sea or Barents Sea surveys.

The combined acoustic and bottom trawl surveys for cod (*Gadus morhua*) and haddock *Melanogrammus aeglefinus*) in the Barents Sea – are conducted by the Institute of Marine Research (IMR) Bergen. Sampling follows a regular grid with a haul every 20 n.mi. (Fig. 1d). The number of hauls varied between 200 and 300. Surveys were available from 1997 to 2002.

Simrad EK500 scientific echosounders were used for all surveys, with at least a 38kHz split-beam transducer. The echo-sounder angle was of 7° and its pulse duration was of 1 ms. For this frequency, the efficiency of the TVG is 580 meters (Diner & Marchand, 1995). Since the maximum depth encountered in the different surveys used in this study was between 23 meters (Irish Sea) and 540 meters (Barents Sea), the propagation loss was not a problem. The acoustic back-scattering energies were converted to Nautical Area Scattering Coefficient (NASC; MacLennan *et al.* 2002) and expressed in $m^2 \cdot n.mi^{-2}$. The integration threshold was set at -70dB NASC values were available from trawl stations and between trawl stations. For the on-station NASC, integration was carried out for the whole trawling period. In general, the tow length is fixed within each survey series. NASC values between trawl stations were available at fixed Elementary Sampling Distance Units (ESDU) which differed by survey series: 0.1

n.mi. for IFREMER data, 1 n.mi. for IMR data, and 0.5 n.mi. for the rest of the datasets (Table 1).

Because the ESDUs were smaller than the average tow lengths, between-station NASC values were pooled (regularized) to produce ESDU as close to the average tow lengths as possible for each survey series: 3 n.mi in the Irish Sea, 1 n.mi. in the Barents Sea, and 2 n.mi in the North Sea.

NASC values for each ESDU and trawl station were subdivided into a series of bottom referenced layers (Fig. 2): ten one-meter layers sequentially from the seabed followed by several ten-meters layers. The accuracy of the sounder-detected bottom was verified and corrected where needed. This was achieved using manual or semi-automated procedures in the analysis of the acoustic data. In the latter case, the layer closest to the bottom included a backstep to avoid integrating the seabed. The size of the backstep varied between 10 and 40 cm, depending on the survey series and weather conditions. Acoustic data preparation was carried out using SIMRAD BI500 for the Norwegian data, Movies Plus for the French data and SonarData EchoView 3.1 for all of the other data.

Acoustic signals of obvious and well-defined pelagic fish schools were excluded from the analysis.

Notations

The superscripts indicate whether a parameter refers to on-station (^{o}) or between-station (^{b}) data. For instance, the numbers of samples taken on-station and between-stations are denoted by N^o and N^b. Equations are only given for the on-station data. They are interchangable with between-station data by changing the superscripts.

The NASC values observed at sample i, in layer k, are denoted $s_A^o(i,k)$, $i \in \left[1, N^o\right]$. The longitude and latitude (x_i, y_i) are expressed in decimal degrees. The number and the thickness of the depth layers are denoted by k and t_k as follows:

$$\text{(Eq. 1)}\quad \begin{array}{l} t_1 = 1\text{ m} \quad \text{if no backstep (manual bottom correction)} \\ 0.6\text{ m} \le t_1 \le 0.9\text{ m} \quad \text{if backstep (semi-automatic bottom correction)} \\ t_k = 1\text{ m} \quad \text{for } k = 2,\ldots,10 \\ t_k = 10\text{ m} \quad \text{for } k \ge 11 \end{array}$$

Volumetric Scattering Coefficients, s_V, expressed in m^{-1} are obtained by:

$$\text{(Eq. 2)}\quad s_V^o(i,k) = \frac{s_A^o(i,k)}{t_k}$$

Layers were also integrated and grouped into a bottom and a mid-water layer. In the North Sea and Irish Sea, the bottom layer was defined as the bottom 10 m and the mid-water layer was the layers between 10 and 40 m off the bottom (Fig. 2). Because of the high average depth in the Barents Sea area and the large vertical opening of the trawl, the first 40 meters were regarded as the bottom layer and the mid-water layer was between 40 and 100 m above the bottom:

(Eq. 3) $$s_A^o(i, \mathit{0\text{ - }40}) = \sum_{k=1}^{13} s_A^o(i,k) \quad \mathit{and} \quad s_A^o(i, \mathit{40\text{ - }100}) = \sum_{k=14}^{19} s_A^o(i,k)$$

The sum over all the layers is denoted by $s_A^o(i)$.

Global statistics

Vertical profiles

We computed the average vertical profiles for both on-station and between-station NASC for each survey according to:

(Eq. 4) $$s_V^o(k) = \frac{\sum_{i=1}^{N^o} s_V^o(i,k)}{N^o}$$

This allows for a visual comparison of vertical fish distributions seen on-station and between stations.

Horizontal structures

Global index of Collocation

The match between the two spatial distributions was evaluated using a Global Index of Collocation (GIC; Bez and Rivoirard 2000). This index is based on the centre of mass and inertia of each spatial distribution. The centre of mass for say the on-station bottom layers in a given area ($CoM^{o}_{0\text{-}40}$), was computed as:

(Eq. 5) $$CoM^{o}_{0\text{-}40} = \left(\frac{\sum_{i=1}^{N^o} s_A^o(i, 0\text{ - }40) \cdot x_i}{\sum_{i=1}^{N^o} s_A^o(i, 0\text{ - }40)} \quad , \quad \frac{\sum_{i=1}^{N^o} s_A^o(i, 0\text{ - }40) \cdot y_i}{\sum_{i=1}^{N^o} s_A^o(i, 0\text{ - }40)} \right)$$

with equal weight given to each sample. The centre of mass is a vector of coordinates giving the mean location of the population in terms of longitude and latitude. The inertia

(Eq. 6) $$I^{o}_{0\text{-}40} = \frac{\sum_{i=1}^{N^{o}} s^{o}_{A}(i, 0\text{-}40) \cdot \left((x_i - CoM^{o}_{0\text{-}40})^2 + (y_i - CoM^{o}_{0\text{-}40})^2 \right)}{\sum_{i=1}^{N^{o}} s^{o}_{A}(i, 0\text{-}40)}$$

is expressed in surface units (typically square nautical miles) and quantifies the spatial dispersal of the population. The Global Index of Collocation (GIC) is given by:

(Eq. 7) $$GIC_{0\text{-}40} = 1 - \frac{(CoM^{o}_{0\text{-}40} - CoM^{b}_{0\text{-}40})^2}{(CoM^{o}_{0\text{-}40} - CoM^{b}_{0\text{-}40})^2 + I^{o}_{0\text{-}40} + I^{b}_{0\text{-}40}}$$

It measures the spatial overlap between the on station and between-station populations and ranges from 1 for complete spatial overlap between the two populations to 0 when the two are distinct. Numerically, it decreases quickly with decreasing spatial overlap. This index is analogous to an analysis of variance type of criteria as it compares the mean (square) distance between the centroïds of the two populations, and the mean (square) distance between two individuals taken at random and independently from any of the two populations (Bez, in press).

Variograms

Spatial structures of the vertically integrated NASC values were compared in more detail using variography (e.g. Rivoirard et al. 2000). Because the goal was to compare the spatial structures, and not to estimate biomass, the NASC values were transformed as follows:

(Eq. 8) $\log\left(1+s_A^o(i)\right)$

While this non-linear transformation modifies the spatial structure, it does not preclude comparisons of spatial structures from being made. Zero values remain zero after the transformation but differences between large data values are reduced.

Because the sample sizes of the two sets were significantly different (a few dozen for on-station data and few hundred for between-station), we did not expect the variances to be equal (especially when dealing with skewed data). We therefore compared normalised variograms, i.e. variograms divided by the empirical variance of input data. In two instances, a poor match was observed between the variograms of on-station and between-station data. The impact of extreme values was then investigated by excluding some of the largest data.

Normalised variograms were averaged by surveys series, resulting in one variogram per survey series.

Local statistics : before, during and after trawl

To test for the existence of changes in the acoustic signal due to fish response to trawl gear, we compared records made during trawling with those made just before and after trawling. The objective was to test the null hypothesis (H0) that on-station and nearby between-station NASC values were similar, and more precisely, as similar as two consecutive between-station NASC values that lie outside the stations' areas of influence.

A window of the same order of magnitude of the tow durations was chosen to select between-station data located nearby each trawl station (1 n.mi. for Barents Sea surveys, 2 n.mi. for North Sea surveys and 3 n.mi. for Irish Sea surveys). This window was considered to be small enough to provide local statistics but large enough to include a sufficient number of observations.

Bottom and mid-water layers were summarized by two statistics: a biomass criteria, i.e. the NASC values integrated over the depth layers and, a measure of vertical distribution, i.e. the altitude of the centre of mass (CoM) of the acoustic energy. The null hypothesis H0 to be tested, was that these two criteria were equal on average for observations made before, during and after trawling for both the bottom and mid-water layers.

Comparisons of observations recorded before, during and after the tows were sensitive to possible mixture of a trawl effect and a distance effect. The objective of the test was thus to disentangle how much the observed differences originated from the distance between the observations and from trawl effects respectively. When the spatial distribution of fish is such that any two proximate values are naturally similar (strong spatial structure of the study variable), observations made before, during and after a trawl station must be very similar in order for H0 not to be rejected. On the other hand, if the spatial structure is weak, the average difference between two proximate values is naturally relatively large, and H0 cannot be rejected, even for a relatively large discrepancy between observations made before, during and after trawling. Tests were thus evaluated with regards to the similarity of 1000 randomly selected pairs of successive between-station observations sufficiently far away from trawl stations to preclude a trawl effect. For each survey, the following three differences: *during - before; during – after*; and *random1 – random 2,* were thus considered (the first two being positive when the observations recorded during trawling operations were larger). These differences were considered relative to the mean value of the integrated NASC values and the altitude of the centre of mass of the acoustic energy relatively, both parameters were pooled by survey series. Empirical cumulative density functions (cdf) were thus built for each survey series and for bottom and mid-water layers separately.

Finally, a paired Student test, robust to departure from normality, was used to test if mean differences were equal to zero. Given H0, a large p-value indicates a high likelihood that observed difference are consistent with a zero mean.

Time of day considerations

With the exception of the Barents Sea surveys, all surveys are performed during daylight and no impact of the time of the day is expected. In the Barents Sea however, there is ample evidence that vertical zonation of gadoid fish can vary throughout the day or year (Hjellvik et al. 2002). In the present analysis, this would not be expected to have a major impact. For the pooled analyses, we have combined data for all times of day and equal compensation is expected for both on-station and between-station data as these are homogeneously distributed in time. For the before-during-after studies, each haul is matched to adjacent between-station data taken at same time, thus reducing the impact of diel changes. Finally, surveys are taken at the same time of year (Table 1), thus reducing seasonal effects.

Coordinates transformations

In order to compute true distances between samples, coordinates were transformed to an orthogonal system. A gnomonic projection with a centre at N72°00 E30^{o}00 was used for the Barents Sea data. A transformation based on the cosine of the mean latitude of the coordinates was applied to the North Sea and the Irish Sea data separately.

Results

Vertical profiles

There is a clear and consistent trend in the vertical acoustic profiles across surveys and survey series (Fig. 3, 4 and 5). In general, the mean NASC value is highest in the depth layer closest to the bottom, and decreases approximately exponentially over the next five to nine meters. Above this, the mean NASC is either relatively constant or decreases steadily both for on-station and between-station data. For the Irish Sea (Fig. 5) where a lot of the backscatter can be attributed to fish schools, the above-mentioned trend only appears after dense (pelagic) school echo traces have been excluded from the analyses. If these are retained, they result in a more bell-shaped vertical profile with the maximum energy a few meters above the bottom. The match between on station and between station vertical profiles is nearly perfect for both represented quantiles for the Barents Sea case where the number of stations is large (Fig. 3), but less evident as the number of samples decreases (e.g. Irish Sea; Fig. 5). However, there is no general pattern of on-station or between-station profiles being systematically larger than the other. Similarly, the year-to-year differences in the vertical profiles are consistently reflected in both the on-station and between-station data, regardless of the number of samples.

Global Index of Collocation

The GICs were greater than 0.9 in 75% of the surveys suggesting a strong overall correspondance in the spatial distributions of NASC values between on-station and between-station data (Fig. 6). The GIC was considerably lower (around 0.6) in only two cases where centres of mass of each distribution was far apart each other compared to the respective dispersion of each population (inertia).

No systematic difference in the GIC values was observed between the bottom and mid-water layers. The mid-water GICs were generally smaller than those of the bottom layers (average GICs of 0.91 and 0.93 respectively) but the difference was not statistically significant (Student’s T test: p.value = 0.57).

Variograms

The match between the log-transformed variograms for on-station and between-station data was very good for the Barents Sea surveys (Fig. 7a). For the other survey series (Fig. 7 b-e), a reasonable match was observed. However, in two cases (IBTS from FRS and IFREMER), this was only obtained after respectively 2.5% and 2% of the most extreme values were removed. The between-station data allowed resolution of the small-scale spatial structures that are inaccessible with the on-station data alone and would lead to geostatistical models compounded of a nugget effect that explains around 40 % of the total variability (regardless of survey series) and of a component with autocorrelation limit distance of 200 n.mi for the Barents Sea surveys, and approximately 50 n.mi for the others.

Correlation before/during/after trawl

Integrated NASC for mid-water layers (Fig. 8a) and for bottom layers (Fig. 8b)

All the cumulative histograms of the relative differences were symetrical with a narrow mode around zero indicating that in half of the cases NASC values were larger during trawling than before and after. Empirical c.d.f. were visually highly consistent for a given survey series; the differences between them being larger between than within survey series. The empirical c.d.f. between the quantiles 25 and 75% were highly consistent. Differences were observed in the distributions' tails only. There was no evidence of the relative differences *during - before* and *during – after* having a systematically higher or lower spread than those obtained for randomly selected data. For bottom layers and for all surveys (Fig. 8b), NASC integrations were on average higher during the tow than before or after. However, these means were not significantly different from 0 in most cases (two p-values out of ten below 0.1). Interestingly, the differences between randomly selected off-station data showed the same symetrical and skewed distributions and were considered equal to 0 for all but two cases as well. The picture was somewhat different for the mid-water layers where the NASC values were alternatively smaller and larger during trawling than before or after. This, however, was rarely statistically significant (two p-values out of ten below 0.1). Here again, the average differences between randomly selected off station data were considered not equal to 0 for two cases.

Differences in altitudes of the centre of mass for mid-water layers (Fig. 9a) and for bottom layers (Fig. 9b)

Differences in altitudes of the centre of mass from NASC values showed weaker tails and weaker modes than the integrated NASC values did resulting in similar medians and means. For the ”bottom” layers (Fig. 2), the majority of the observed differences were less than 1 meter. In only one case (FRS) did the differences *during – before* and *during – after* show empirical distributions shifted towards lower values compared to that of the reference situation. Despite the fact that the mean of the latter was significantly different from zero, this was the sole case where we observed a reduction of the mean heigh of the acoustic energy associated to trawling activities. None of the other cases indicated an impact of trawl presence: average differences were alternatively positive or negative, the proportion of p-values smaller than 0.1 was similar for cases with the trawl and without, and the differences between empirical c.d.f. were larger between survey series than within. Interestingly, the *during – before* and *during – after* trawling differences observed in the Barents Sea surveys were more concentrated around zero than the differences observed where no trawl was in the water: variations in vertical distributions were thus smoothed when the trawl was present.

Discussion

With the final goal to combine acoustic and catch data, which was not considered in this study, we examined the hypothesis that acoustic data collected away from the trawl stations were consistent with those collected during the trawling operations. Rather than examine one survey with a particular format, we chose to study a series of different surveys ranging from the Barents Sea to the North and Irish Seas, to attempt to identify broad trends in this type of data. The major differences between the data sets were the numbers of data points available on-station, and the proportion of stations connected with acoustic transects. The Barents Sea surveys included between 200 and 300 trawl stations per survey, whereas in the North and Irish Seas surveys included between 13 and 80 stations. IBTS data were only taken in daylight hours, with the last station of the day and the first one of the following day not being connected by acoustic transects. As a consequence, relationships between on-station and between-station observations are likely to be more apparent for the Barents Sea than for any of the other surveys.

The first type of analysis was a straightforward global comparison using all the available data, for the pooled NASCs by layers for the on-station and between-station data. The general pattern was broadly consistent across all the surveys. The bulk of the acoustic energy was found in the deepest layers in the water column: the back-scattering energy reduces exponentially as the range from the seabed increases and then stabilises somewhere between 5 m and 10 m off the bottom. More importantly, the pattern is similar for both on-station and between-station data. Where differences occurred, they were not systematic as on-station integrated values could be both greater or less than between-station data. Furthermore, where deviations from the general pattern occurred in a particular survey, they were seen in both on-station and between-station data.

The Global Indices of Collocation (GICs) confirmed the subjective appraisal of the vertical profiles. To help interpretations, GICs were computed for simulated fish distributions (isotropic Gaussian fish density with fish density being set to zero for densities below the 5% quantile). From this simulation, it was concluded that a GIC between 0.6 and 0.8 could be considered as a low value and a threshold of 0.8 might be adopted as a minimum value for a good match (Fig. 10). For the bottom layers, only one survey out of twenty showed a poor match, and this had low station numbers (N^o = 46). Slightly poorer results were obtained for the mid water layers, with three out of the twenty surveys having low GIC values. NASC values were generally much lower in the mid water layers and also much more variable so this outcome is not surprising.

The variograms allowed a more detailed study of the spatial structures associated with the on-station and between-station data. For the Barents Sea data, the relatively high number of stations allowed the generation of good quality variograms for on-station and between-station data. These variograms were highly similar. For the other surveys, the variograms were less well behaved, reflecting the smaller number of samples relative to the sampling area and the large skewness of the data. However, they were also similar, provided that some extreme values were removed in two cases. Variograms were considered relative to their variances; we only compared their shapes. The variance of the between-station data was often larger than the variance of the on-station data because the chances of encountering rare extreme fish concentrations is higher with several thousands samples than with a few dozen or a few hundred samples (Bouleau and Bez, 2005). Still, the strong similarity in the shapes of the variograms, would allow using the spatial structures depicted by the between-station data (rescaled to the on station data variance) to obtain a variogram model usable for the purpose of quantitative estimation. It is worth reiterating here, that the variograms were computed with log-transformed data. This non linear transformation induces bias and the variograms obtained here can not be directly used for estimation purposes. Both the log-transformation and the selection of a certain quantile (97.5 or 98%) of the data, aim to reduce the impact of the extreme data. This is not at odds with the fact that most of the total abundance is explained by a very small proportion of data. As a matter of fact, it is usually agreed that fish data behave like log normal variables. When simulating a lognormal variable, the likelihood of getting an extreme value increases with the number of samples. Therefore, we could not have expected on-station data to sample the tails of the distributions with the same accuracy as the between-station data, the latter being much more numerous than the former. In addition, the impact of few extreme values on empirical variograms is known to be large and not meaningful for the comparative exercise we did in this study. In other words, what made between-station variograms different from the on-station variograms was only the occurrence of extreme rare data. The bulk of the observations had spatial distributions that matched well.

The final step in the analysis, was to examine the relationship between on-station and between-station data in the areas close to each haul. For this comparison we only used the most adjacent between-station data to each haul. However, given the survey protocol, a small but non-zero distance existed between observations made before, during or after trawling. To disentangle how much of the observed differences originated from the distance between the observations and from a possible trawl effect respectively, we bootstrapped between-station data to serve as a reference situation for the comparisons. We found that both before and during trawling data, and during and after trawling data were, with one exception, not more different than two successive randomly selected between-station data (the distributions of their differences are strongly similar). The statistical approach is designed so that under H0, 10% of the p-value are below 0.1. In this study, 25% (10 out of 40) of the p-values obtained when testing on station data with adjacent ones were smaller than 0.1 (6 times for the *during – before* differences and 4 times for the *during – after* differences). Contrary to expectation, this proportion was 35% (7 out of 20) for the so-called reference situations provided by the bootstrapped between-station data. The null hypothesis that the average difference in biomass or in height of the centre of mass for observation made before, during or after trawling was thus acceptable.

Most critically for the purposes of this analysis, the inference supported by all the results is that we see similar energy values on-station and between stations, suggesting that we were observing the same fish assemblages in the two situations. However, there is some evidence in the literature of fish reaction to research vessels during trawling (e.g. Godø et al. 1999; Handegard et al. 2003). Reactions can be both vertical, as in diving, or horizontal, as in moving out of or towards the path of the trawl. We shall distinguish between gear and vessel induced reactions. In the Barents Sea for instance, Handegard et al. (2003) showed that the fish present in the 40 first metres above the sea bed, exhibit a slight diving reaction to the vessel passing and a marked horizontal reaction to the warp. Given the mean depths of the study areas, the distances between the acoustic beam beneath the vessel and the trawl, ranged from 100-200 m for Irish Sea and North Sea to more than 500 m for the Barents Sea (Fig. 11). It is likely though that if the gear does not perturb the fish distribution long in advance (long with regards to the above mentioned distances), on-board mounted echo sounders can only reveal vessel perturbations. In such a case, the only expected perturbation comes from the vessel which is running both between-station and on-station, the two situations are therefore comparable.

We shall also distinguish reactions that lower fish acoustic densities from reactions that increase them. Fish diving would tend to increase fish biomass in the metres above the sea bed. It would also tend to increase tilt angle and hence reduce target strength (MacLennan et al. 1987; McQuinn and Winger 2003; Kloser and Horne 2003). Fish may also move into the acoustic dead zone (Ona and Mitson 1996; Lawson and Rose 1999) and be inaccessible to the echosounder. In the present study, the statistically non-significant but systematic stability or increase of NASC value in the "bottom" layers during trawling is associated neither to a corresponding systematic decrease of NASC values in the "mid-water" layers, nor to a change in height of the mean energy in any of the "bottom" or "mid-water" layers. This suggests that none of the above mentioned gear-avoidance behaviours are operating in the study situations and that the area of influence of gear perturbations are, on average, less than the trawl to vessel distances. This does not suggest that trawl perturbations do not exist, but rather that they can not be observed with on-board mounted echo sounders. In particular, gear perturbations were considered to explain the lack of correlations observed between the acoustic signal and catch data or why the highest correlations between acoustic and trawl catches were obtained after acoustic data were integrated over a greater depth than that of the headline height of the trawl (Bouleau et al. 2003, Hjellvik et al. 2003).

In conclusion, the acoustic data collected between trawl stations were consistent with the acoustic data collected on stations. Overall, there was good agreement between the two data sets while there were some exceptions in some individual survey series. Poor matches could been explained by the sparseness and the skewness of the corresponding data. The Barents Sea case shows what can be achieved for ‘bottom’ layers with a more substantial data set, where in all cases the on-station and between-station data were consistent for all indicators and methods. In this case, the correlation between catch data and on-station acoustics data is high, making it possible to use between-station acoustics to enhance the quality of trawl survey abundance indices.

Acknowledgement

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Figure 1 Study areas (a) and sampling schemes for (b) the International Bottom Trawl surveys (IBTS), (c) the Northern Irish Bottom Trawl Surveys (NIBTS), and (d) the combined acoustic and bottom trawl surveys for cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea. Solid squares represent stations. Crosses represent between-station recordings. They appear as lines when the density of between stations observations is large.

Figure 2. Bottom-referenced depth layers used for the acoustic integration. The first 10 layers from the bottom have a height of 1 m; the following layers are 10 m in height. Mid-water and bottom layers used for the analysis are represented for the Barents Sea surveys (right) and the North Sea or Irish Sea surveys (left).

Figure 3. Vertical profiles of acoustic backscattering. Barents Sea survey (1997-2002). Representation of the 25% and 75% quantiles of Nautical Area Scattering Coefficient (NASC) values per layer for on-station data (dashed lines) and between-station data (solid lines).The x-axis is the mean NASC value (in $m^2 \cdot n.mi.^{-2}$) per layer. The y-axis is the height of each layer relative to the detected bottom (in meters).

Figure 4. Vertical profiles of acoustic backscattering. International Bottom Trawl surveys (IBTS): (a) Fisheries Research Services (FRS), (b) Environment Fisheries and Aquaculture Science (Cefas) and (c) Institut Français de Recherche pour l’Exploitation de

la Mer (Ifremer). Representation of the 25% and 75% quantiles of Nautical Area Scattering Coefficient (NASC) values per layer for on-station data (dashed lines) and between-station data (solid lines).The x-axis is the mean NASC value (in $m^2{\cdot}n.mi.^{-2}$) per layer. The y-axis is the height of each layer relative to the detected bottom (in meters).

Figure 5 Vertical profiles of acoustic backscattering. Northern Irish Bottom Trawl Surveys (NIBTS) without pelagic data. Representation of the 25% and 75% quantiles of Nautical Area Scattering Coefficient (NASC) values per layer for on-station data (dashed lines) and between-station data (solid lines).The x-axis is the mean NASC value (in $m^2{\cdot}n.mi.^{-2}$) per layer. The y-axis is the height of each layer relative to the detected bottom (in meters).

Figure 6 Histogram of Global Indices of Collocations (GICs) between on-station and between-station spatial distributions of Nautical Area Scattering Coefficient (NASC) values. All surveys combined. Distinction between bottom layers (i.e. $GIC_{0\text{-}40}$ for the Barents Sea surveys and $GIC_{0\text{-}10}$ for the others) and mid-water layers (i.e. $GIC_{40\text{-}100}$ for the Barents Sea surveys and $GIC_{10\text{-}40}$ for the others).

Figure 7 Variograms of log-transformed Nautical Area Scattering Coefficient (NASC). Average of normalised variograms per series of surveys. (a) Barents Sea Surveys 1997-2002. International Bottom Trawl surveys (IBTS): (b) Fisheries Research Services (FRS), (c) Environment Fisheries and Aquaculture Science (Cefas) and (d) Institut Français de Recherche pour l'Exploitation de la Mer (Ifremer). (e) Northern Irish Bottom Trawl

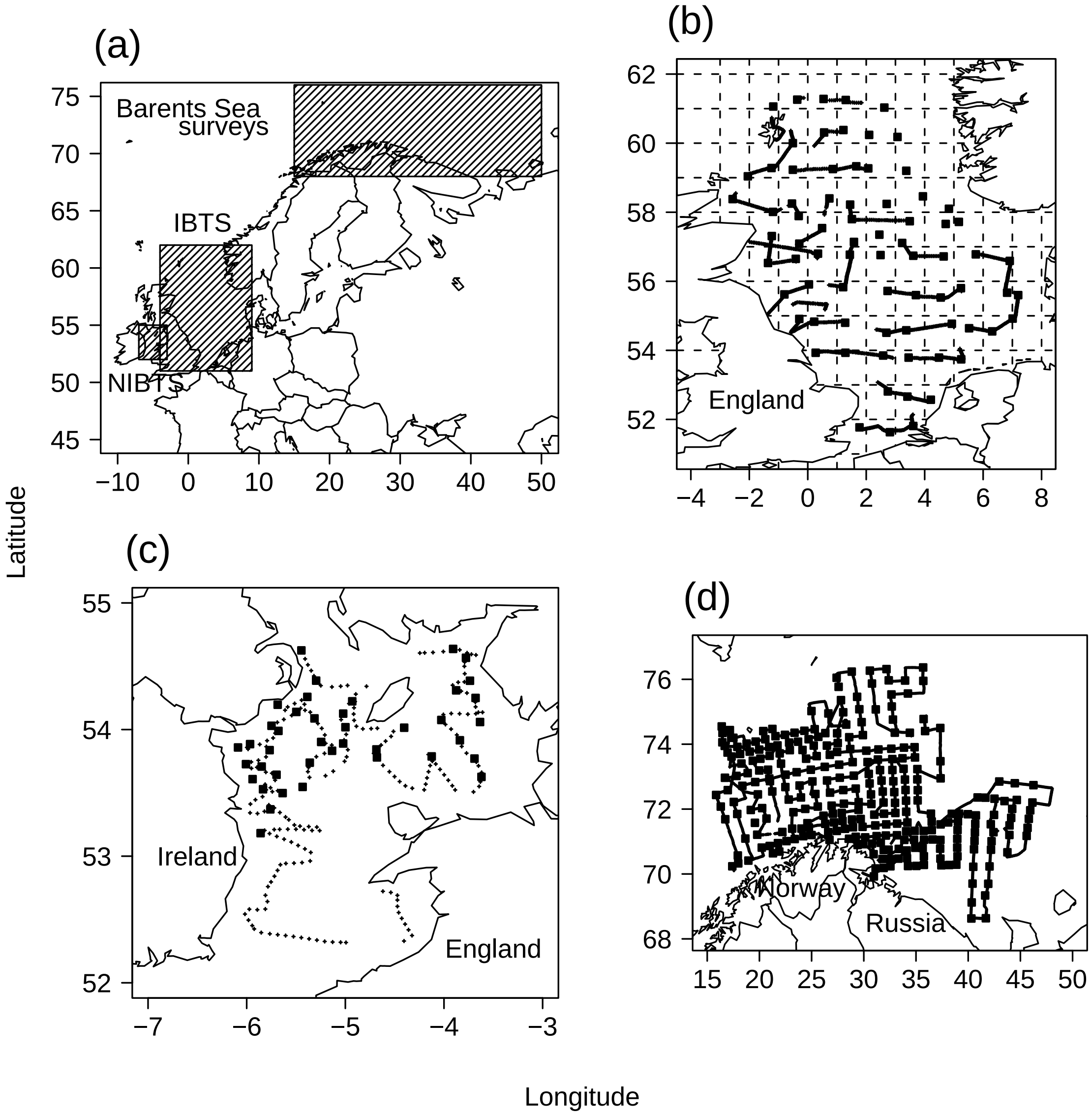
Surveys (NIBTS). Solid lines: between-station variograms. Dashed lines: on-station variograms. Omni directional computations. Distance lags are the ESDU for between-station NASC and the inter stations distance for the on station NASC. The quantile of active data is indicated (98% means that the most extreme 2% of the data was removed).

Figure 8 Difference between the vertically integrated Nautical Area Scattering Coefficient (NASC) observed before, during and after trawling (∇ *during – before* and ∆ *during – after*) and for two randomly selected successive between station observations (☐). The mean difference is indicated by the symbols and cumulative distribution of the differences is indicated by the lines. Each panel represents the pooled data for each survey series. The x-axis represents relative differences of NASC in $m^2 \cdot n.mi.^{-2}$. The y-axis represents the empirical cumulative density function. Distinction is made between mid water layers (a) and bottom layers (b). P-values of the Student tests are indicated: solid symbols represent values smaller than 0.1.

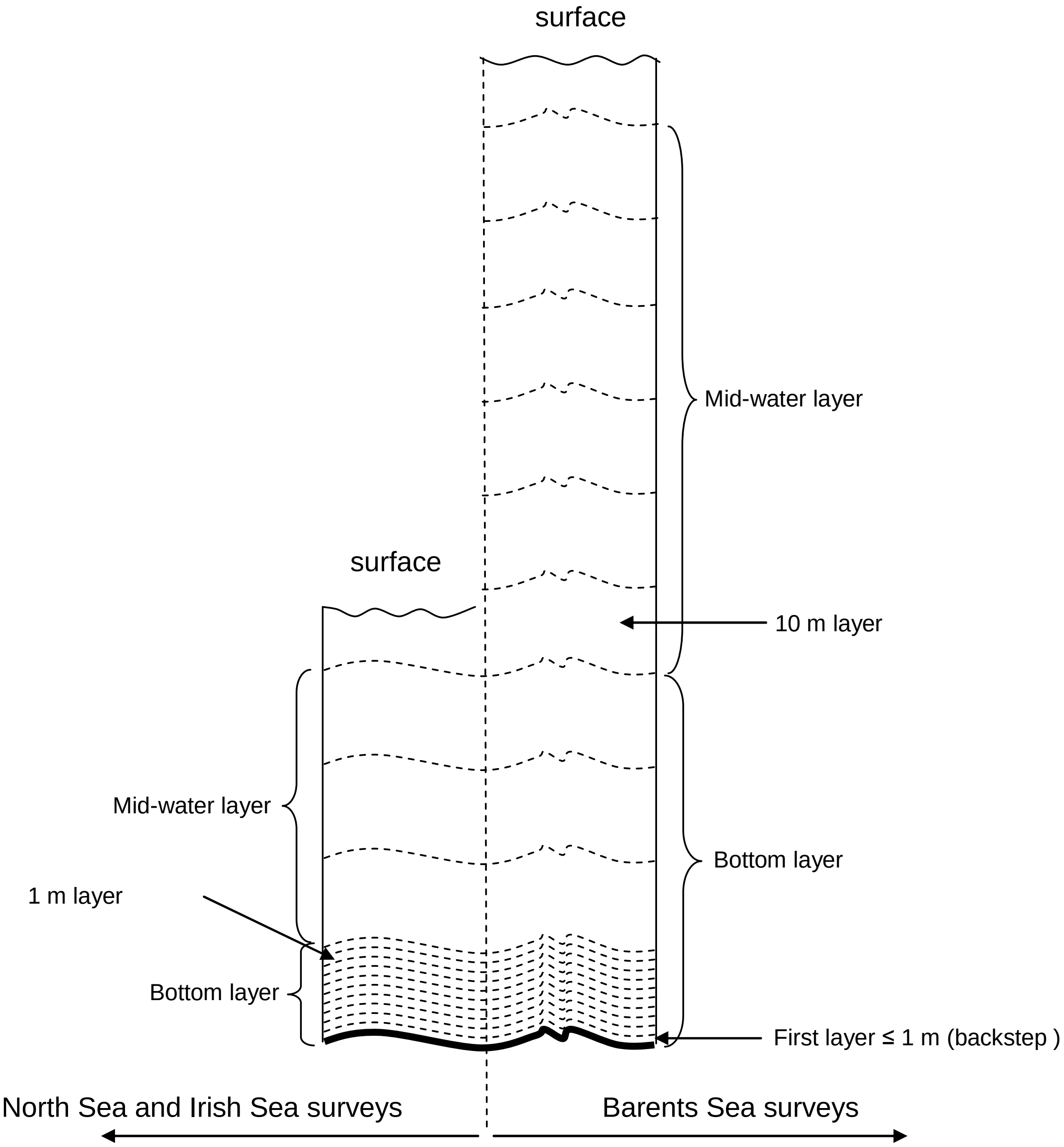
Figure 9 Difference between the altitude of the centre of mass of the Nautical Area Scattering Coefficient (NASC) values observed before, during and after trawling (∇ *during – before* and ∆ *during – after*), and for two randomly selected successive between station observations (☐).The mean difference is indicated by the symbols and cumulative distribution of the differences is indicated by the lines. Each panel represents the pooled data for each survey series. The x-axis represents relative differences of NASC in $m^2 \cdot n.mi.^{-2}$. The y-axis represents the empirical cumulative density function. Distinction is made between mid water layers (a) and bottom layers (b). P-values of the Student tests are indicated: solid symbols represent values smaller than 0.1.

Figure 10 Global Indices of Collocations (GICs) for simulated situations. Fish distributions are considered to be isotropic and distributed according to a Gaussian distribution with fish density being set to zero for densities below the quantile 5%. Two types of fish populations are concerned (patchy or spread). Several possible distances between the centres of mass are concerned.

Figure 11 Scale representation of the observation protocol. North Sea and Irish Sea survey protocols are not distinguished.


(a)
Barents Sea surveys
IBTS
NIBTS
75
70
65
60
55
50
45
−10
0
10
20
30
40
50
(b)
England
62
60
58
56
54
52
−4
−2
0
2
4
6
8
(c)
Ireland
England
55
54
53
52
−7
−6
−5
−4
−3
(d)
Norway
Russia
76
74
72
70
68
15
20
25
30
35
40
45
50
Latitude
Longitude

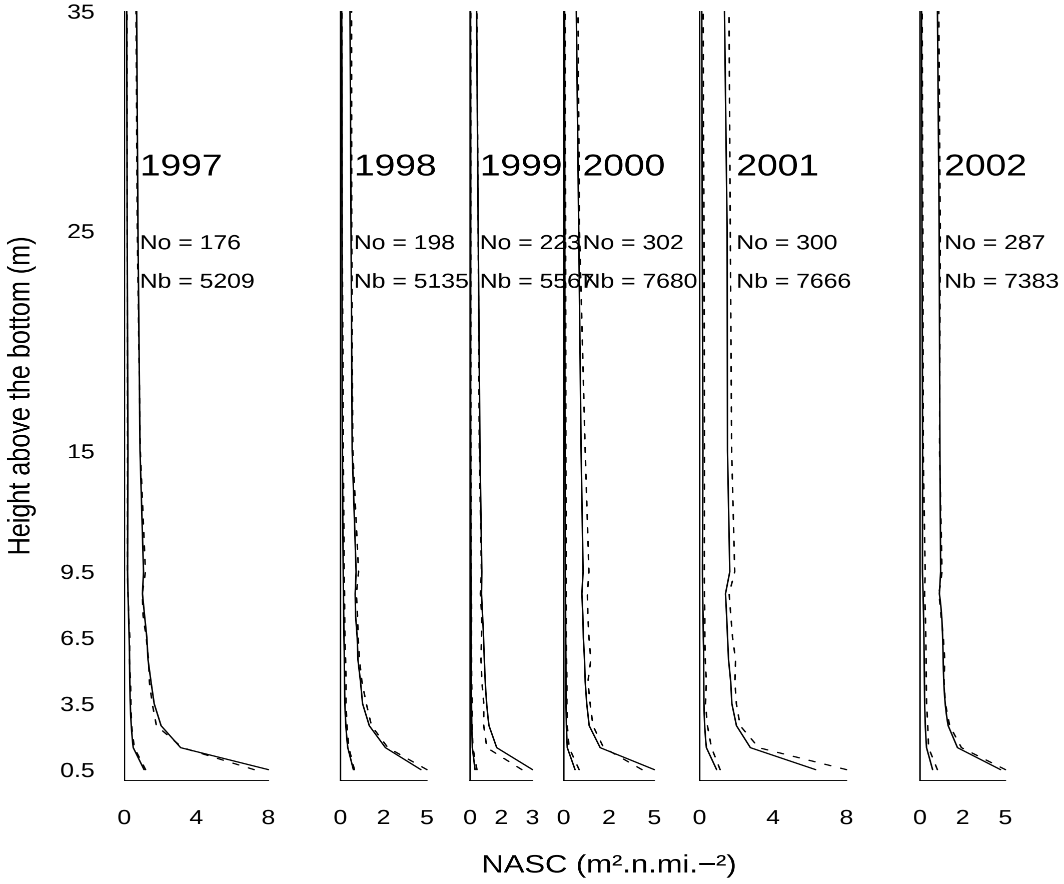
660

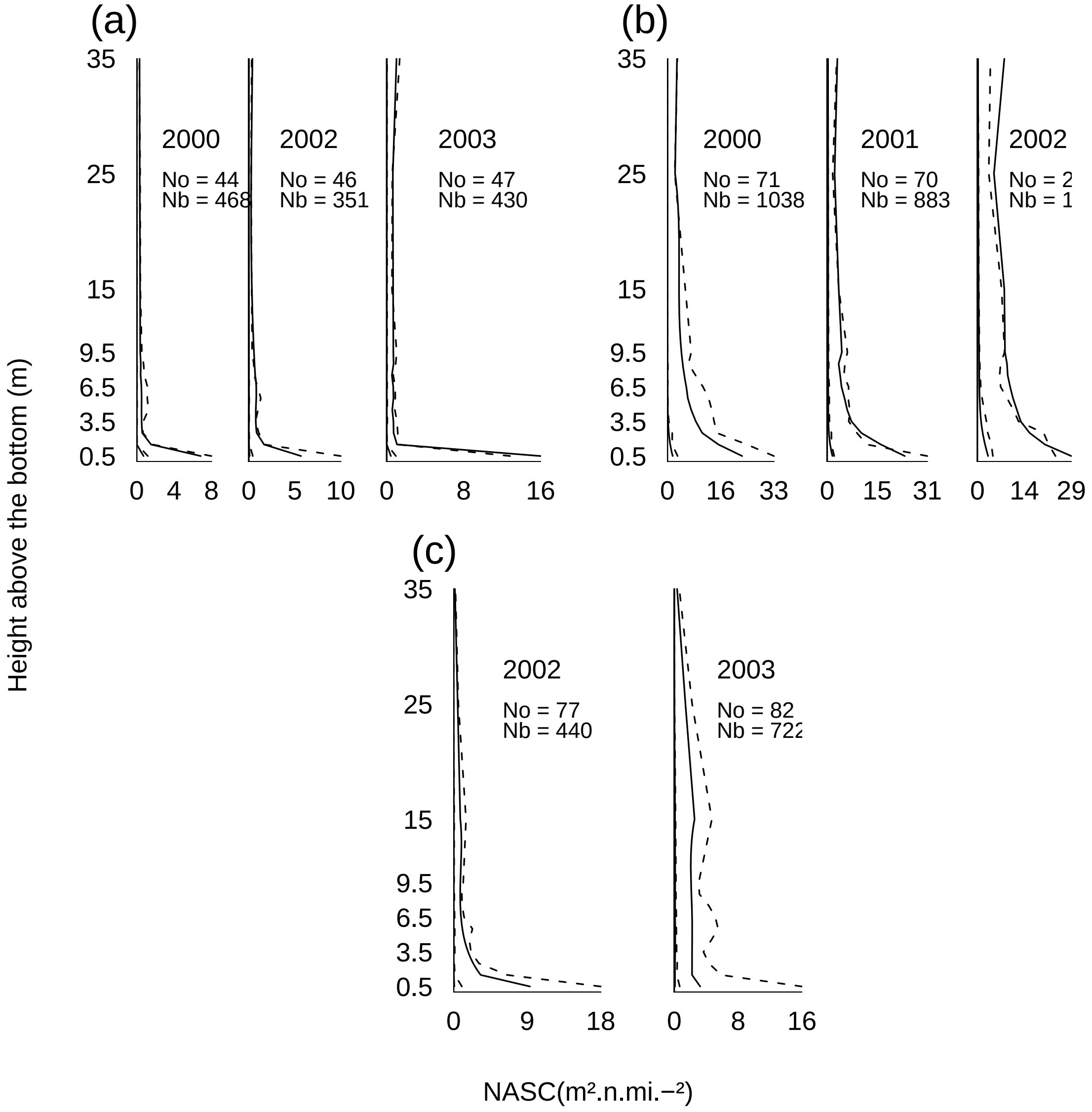


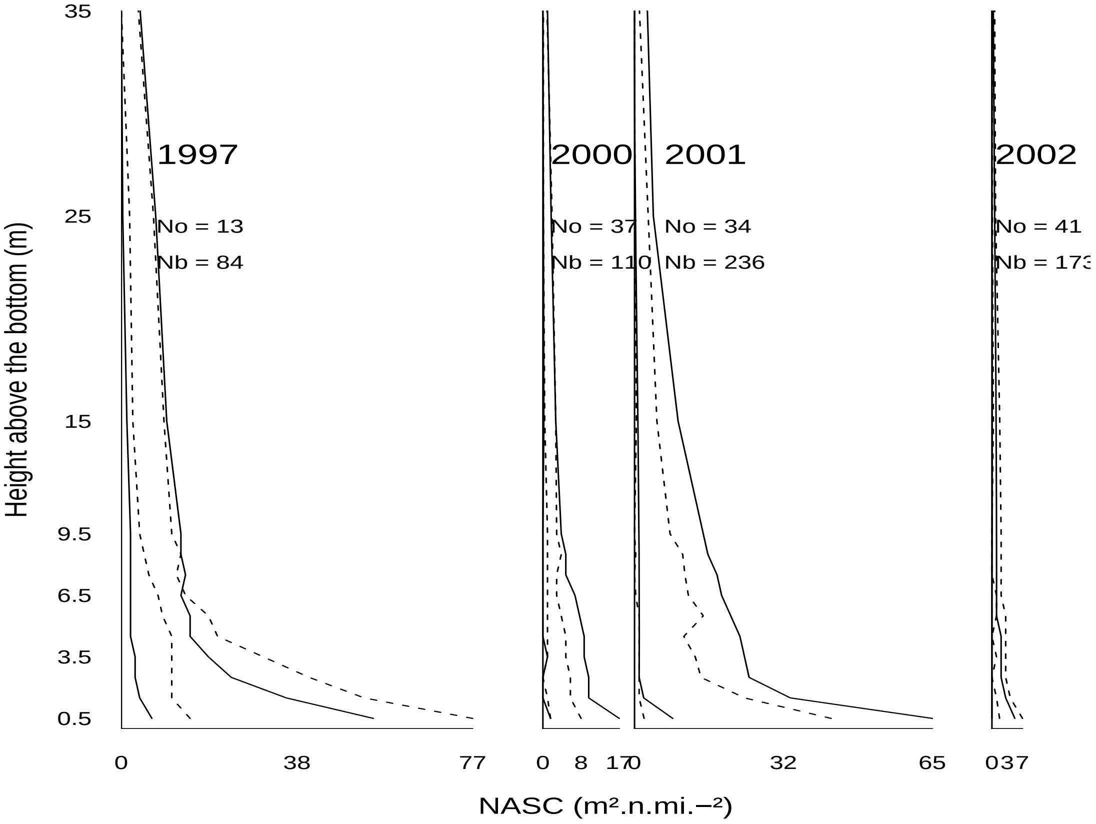
661

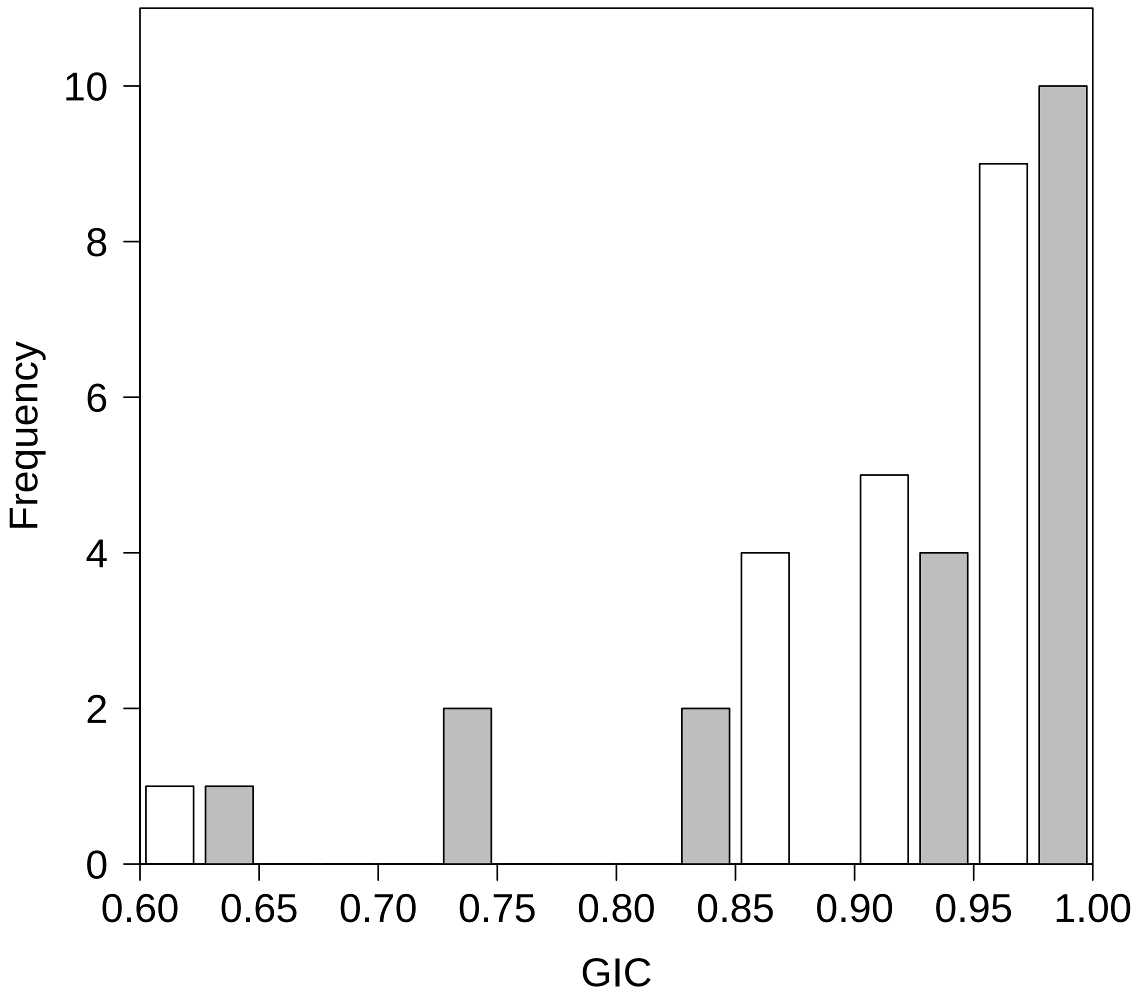
662

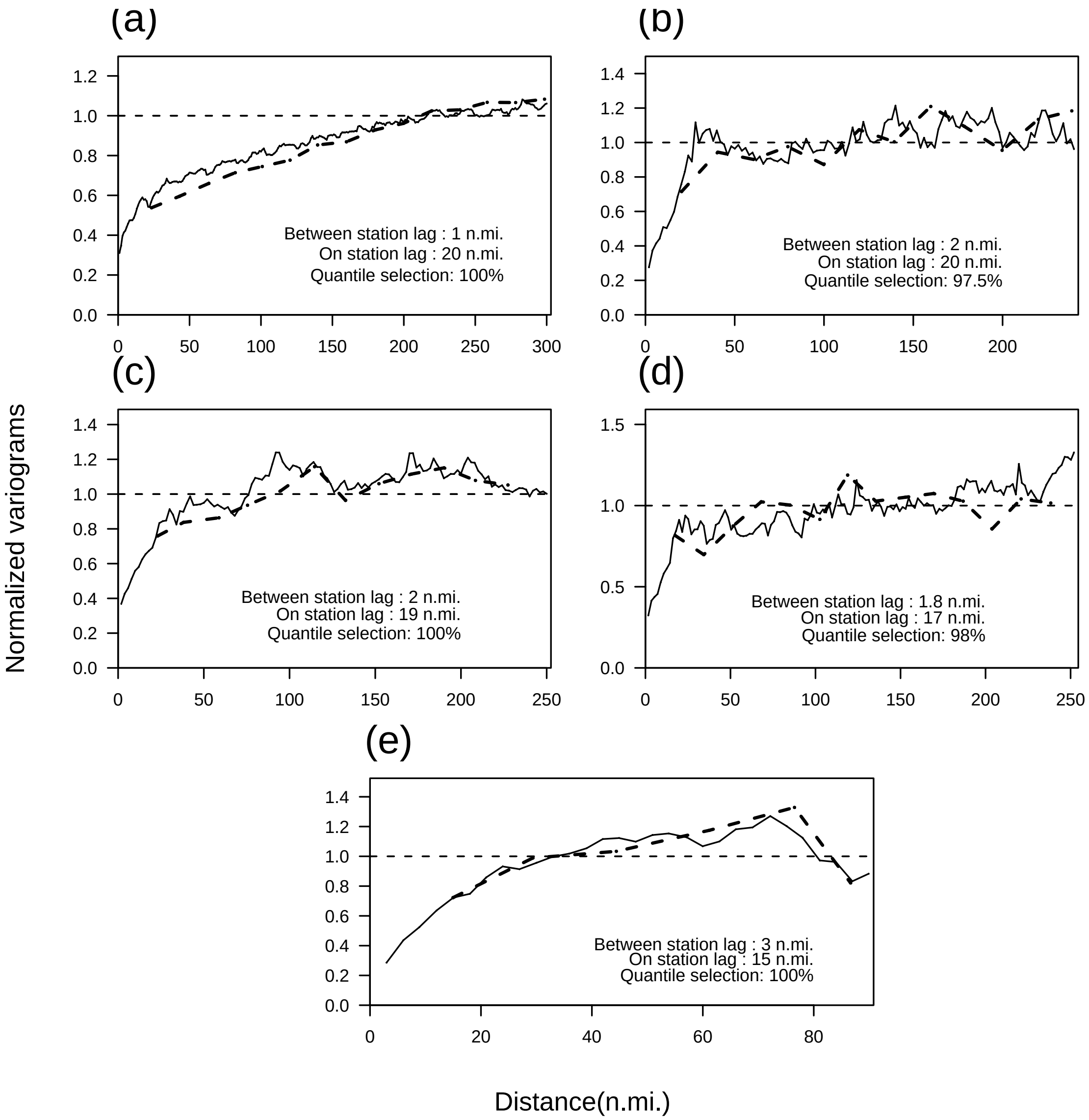
663

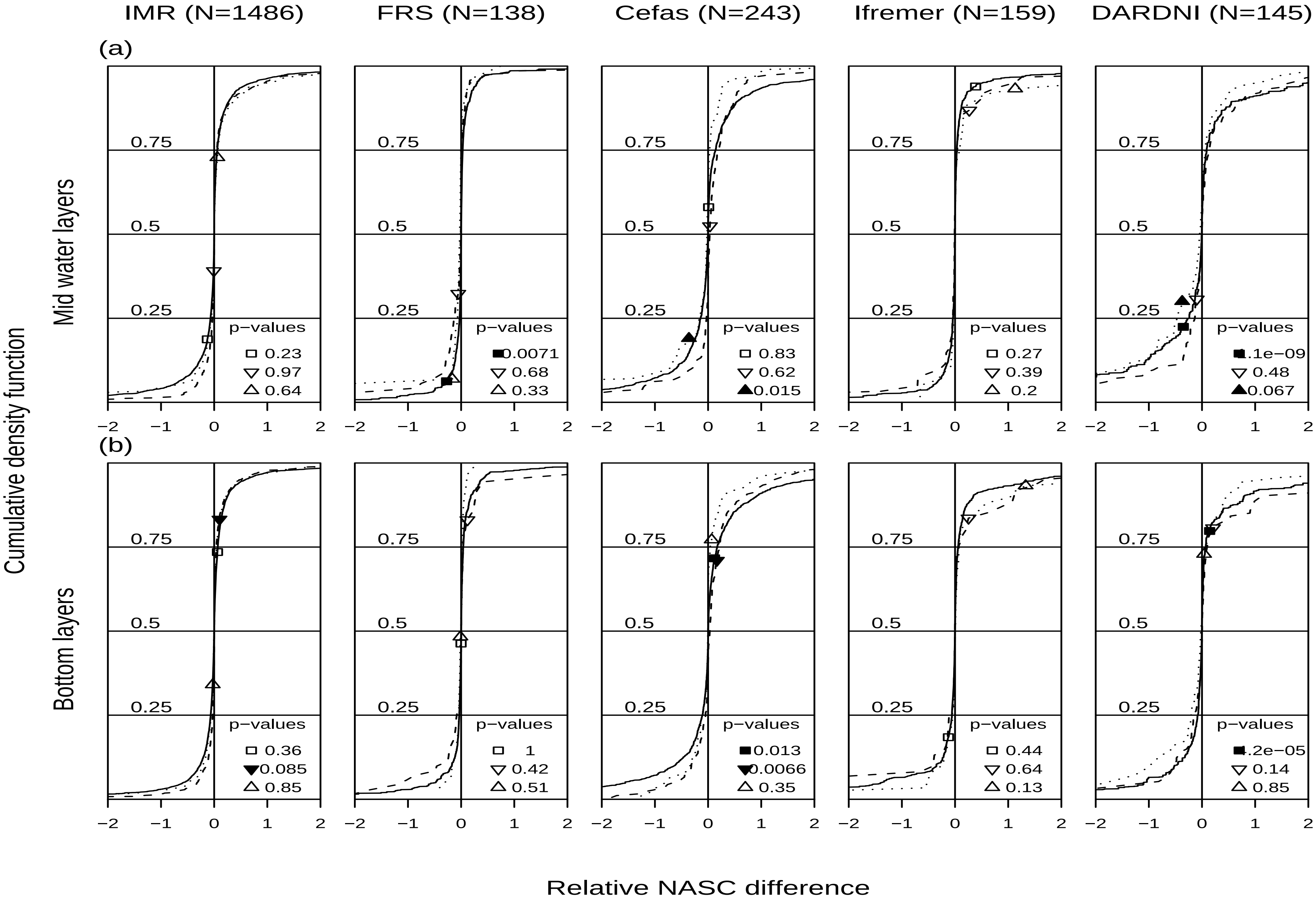

Height above the bottom (m)
35
25
15
9.5
6.5
3.5
0.5
1997
No = 176
Nb = 5209
1998
No = 198
Nb = 5135
1999
No = 223
Nb = 5567
2000
No = 302
Nb = 7680
2001
No = 300
Nb = 7666
2002
No = 287
Nb = 7383
0 4 8
0 2 5
0 2 3
0 2 5
0 4 8
0 2 5
NASC (m².n.mi.⁻²)


(a)
2000
No = 44
Nb = 468
2002
No = 46
Nb = 351
2003
No = 47
Nb = 430
0 4 8
0 5 10
0 8 16
(b)
2000
No = 71
Nb = 1038
2001
No = 70
Nb = 883
2002
No = 2
Nb = 1
0 16 33
0 15 31
0 14 29
(c)
2002
No = 77
Nb = 440
2003
No = 82
Nb = 72
0 9 18
0 8 16
35
25
15
9.5
6.5
3.5
0.5
Height above the bottom (m)
NASC(m².n.mi.⁻²)

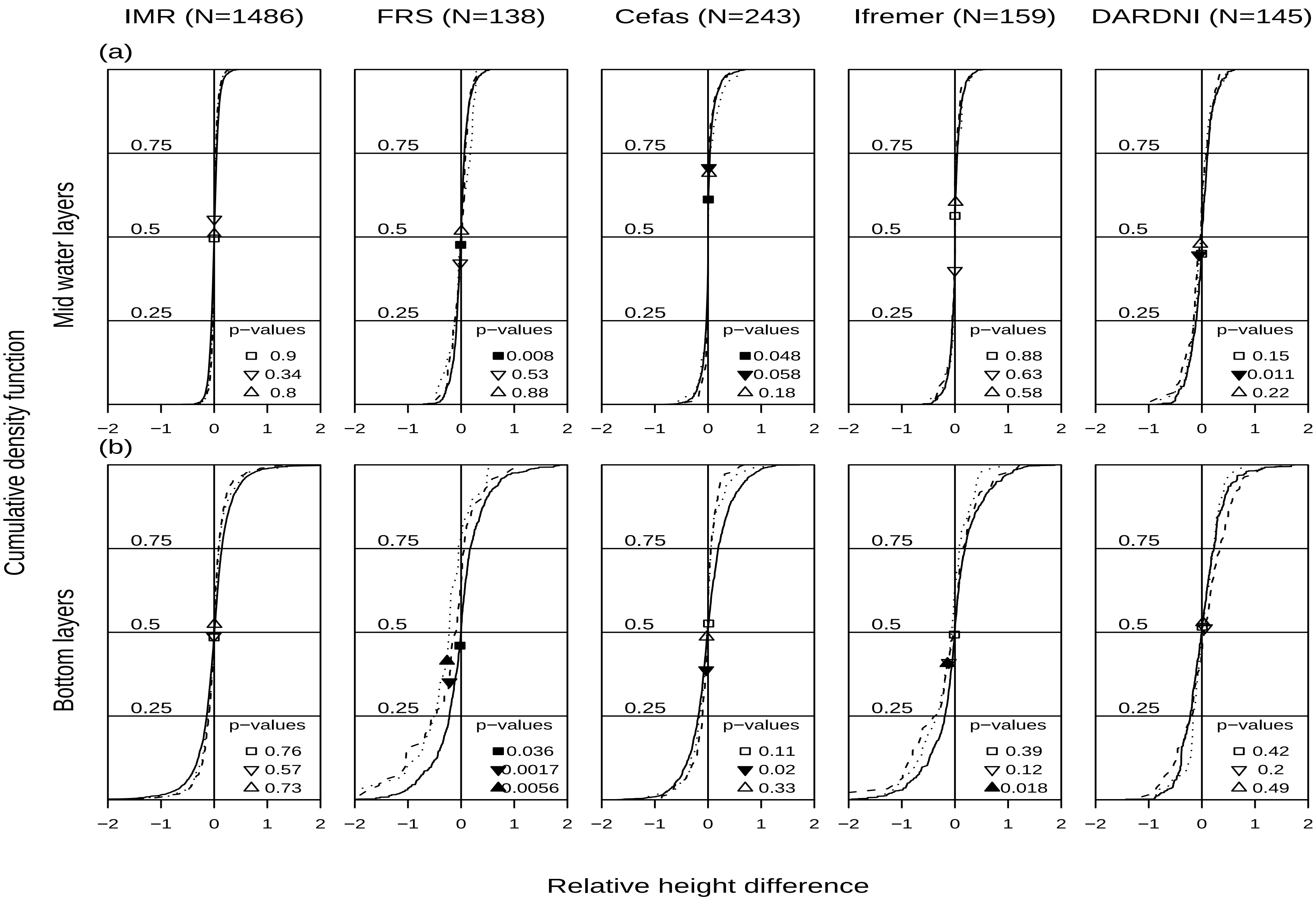

1997
No = 13
Nb = 84
2000
No = 37
Nb = 110
2001
No = 34
Nb = 236
2002
No = 41
Nb = 173
Height above the bottom (m)
35
25
15
9.5
6.5
3.5
0.5
0
38
77
0
8
17
0
32
65
0
3
7
NASC (m².n.mi.⁻²)

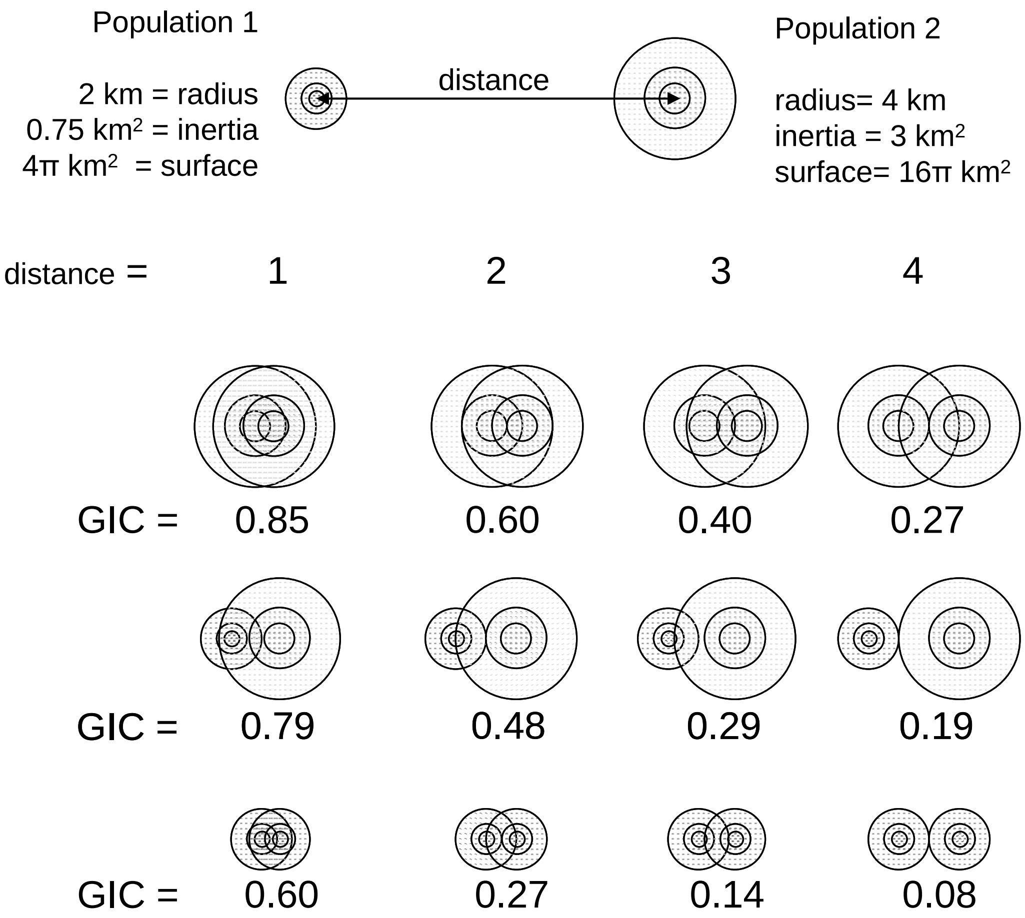

Frequency
0
2
4
6
8
10
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
GIC


(a)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
300
Between station lag : 1 n.mi.
On station lag : 20 n.mi.
Quantile selection: 100%
(b)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
Between station lag : 2 n.mi.
On station lag : 20 n.mi.
Quantile selection: 97.5%
(c)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
Between station lag : 2 n.mi.
On station lag : 19 n.mi.
Quantile selection: 100%
(d)
1.5
1.0
0.5
0.0
0
50
100
150
200
250
Between station lag : 1.8 n.mi.
On station lag : 17 n.mi.
Quantile selection: 98%
(e)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
Between station lag : 3 n.mi.
On station lag : 15 n.mi.
Quantile selection: 100%
Normalized variograms
Distance(n.mi.)



IMR (N=1486)
FRS (N=138)
Cefas (N=243)
Ifremer (N=159)
DARDNI (N=145)
(a)
(b)
Mid water layers
Bottom layers
Cumulative density function
Relative NASC difference
0.75
0.5
0.25
−2 −1 0 1 2
p−values
□ 0.23 ▽ 0.97 △ 0.64
■ 0.0071 ▽ 0.68 △ 0.33
□ 0.83 ▽ 0.62 ▲ 0.015
□ 0.27 ▽ 0.39 △ 0.2
■ .1e−09 ▽ 0.48 ▲ 0.067
□ 0.36 ▼ 0.085 △ 0.85
□ 1 ▽ 0.42 △ 0.51
■ 0.013 ▼ 0.0066 △ 0.35
□ 0.44 ▽ 0.64 △ 0.13
■ .2e−05 ▽ 0.14 △ 0.85


IMR (N=1486)
FRS (N=138)
Cefas (N=243)
Ifremer (N=159)
DARDNI (N=145)
(a)
(b)
Cumulative density function
Mid water layers
Bottom layers
0.75
0.5
0.25
−2 −1 0 1 2
p−values
□ 0.9
▽ 0.34
△ 0.8
■ 0.008
▽ 0.53
△ 0.88
■ 0.048
▼ 0.058
△ 0.18
□ 0.88
▽ 0.63
△ 0.58
□ 0.15
▼ 0.011
△ 0.22
□ 0.76
▽ 0.57
△ 0.73
■ 0.036
▼ 0.0017
▲ 0.0056
□ 0.11
▼ 0.02
△ 0.33
□ 0.39
▽ 0.12
▲ 0.018
□ 0.42
▽ 0.2
△ 0.49
Relative height difference


Population 1
2 km = radius
0.75 km² = inertia
4π km² = surface
distance
Population 2
radius= 4 km
inertia = 3 km²
surface= 16π km²
distance = 1 2 3 4
GIC = 0.85 0.60 0.40 0.27
GIC = 0.79 0.48 0.29 0.19
GIC = 0.60 0.27 0.14 0.08

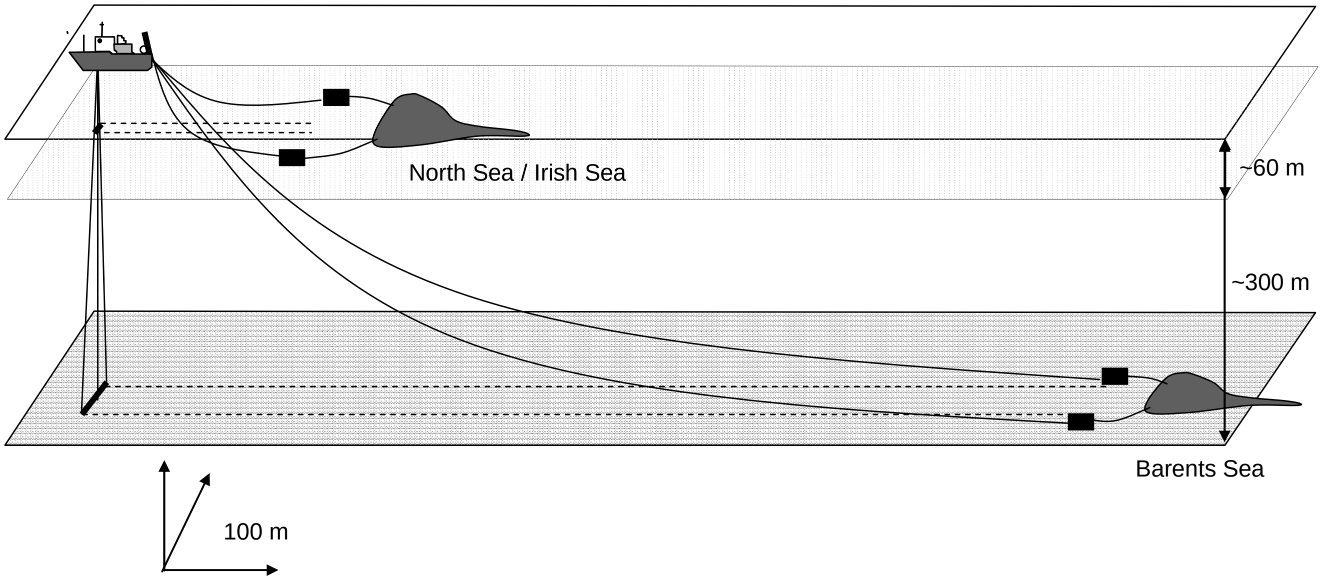

North Sea / Irish Sea
~60 m
~300 m
Barents Sea
100 m

Table 1. Main characteristics of the various surveys used in the analyses. ESDU : Elementary Sampling Distance Unit

Area	Source Survey series	year	month	Number of stations	Mean towed distance (n.mi.)	Original ESDU (in n.mi.)	Number of between station data (after regularization)	Height used to split vertical profiles	depth range (m)	GIC ”bottom” layers	GIC ”midwater” layers
Barents Sea	IMR	1997	02- 03	176	1.50	1	5209	40	143 – 699	0.98	0.95
	IMR	1998	02	198	1.53	1	5135	40	63 – 720	0.9	0.85
	IMR	1999	01- 02	223	1.49	1	5567	40	104 – 480	0.99	0.97
	IMR	2000	01- 02	302	1.42	1	7680	40	58 – 550	0.98	0.99
	IMR	2001	01- 03	300	1.49	1	7666	40	55 – 487	0.97	0.96
	IMR	2002	01- 03	287	1.44	1	7383	40	63 – 542	0.98	0.98
North Sea	FRS	2000	01- 02	44	1.8	0.5	468	10	45 – 150	0.6	1
	FRS	2002	01- 02	46	2.01	0.5	351	10	48 – 144	0.89	0.74
	FRS	2003	01- 02	47	1.98	0.5	430	10	49 – 150	0.9	0.98
	Cefas	2000	08 - 09	71	1.98	0.5	1038	10	24 – 178	0.99	0.99
	Cefas	2001	08 - 09	70	2.01	0.5	883	10	24 – 211	0.99	0.84
	Cefas	2002	02	23	1.98	0.5	1140	10	24 – 84	0.93	0.97
	Ifremer	2002	02	77	1.83	0.1	440	10	9 – 88	0.9	0.95
	Ifremer	2003	02	82	1.89	0.1	722	10	14 – 90	0.93	0.75
Irish Sea	DARDNI	1997	10	13	3.00	0.5	84	10	25 – 103	0.98	0.91
	DARDNI	2000	3	37	2.90	0.5	110	10	26 – 106	0.99	0.95
	DARDNI	2001	10	34	2.70	0.5	236	10	23 – 90	0.94	0.99
	DARDNI	2002	3	41	2.85	0.5	173	10	24 – 102	0.93	0.98