A digital temperature atlas for the Norwegian Sea

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The first digital temperature atlas for the Norwegian Sea (Nordic Seas/GIN Sea) is described and examples of applications given. The atlas is intended mainly to make historical temperature values available to fisheries oceanographers, fisheries biologists, and stock assessment scientists in a structured, uniform format. It should also be of interest to physical oceanographers, climate researchers, and numerical modellers, and will be of relevance to remote-sensing analyses. The atlas, made freely available for scientific non-commercial purposes, is based on interpolation from 59 496 mainly Norwegian, Faroese, and Icelandic hydrographic stations. It consists of gridded temperature fields for the area 20°W–20°E 60–80°N, with a spatial resolution of 1/2° longitude by 1/3° latitude. It covers the quarters January–March, April–June, July–September, and October–December for each year from 1990 to 2007 at 28 depth levels from 0 to 500 m. Two versions of the atlas were produced, one based solely on actual data and one where cells with "missing" values were filled from World Ocean Atlas 05 climatology. Suggested applications include the mapping of horizontal fields and vertical sections, initiation or verification of numerical models, comparisons with SST values from remote sensing, calculations within any chosen latitude–longitude–depth box, and the estimation of the ambient temperatures fish experience when the atlas is used in conjunction with information on fish distribution.

Keywords: climatology, interpolation, Norwegian Sea, temperature atlas.

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Introduction

Helland-Hansen and Nansen (1909) stated that connections likely exist between fish stocks and variations in the conditions of the environment surrounding them. For some populations, the variability imposed by environmental fluctuations may be minor compared with other factors. On the other hand, stocks located close to the limit of the geographic range of the species tend to be more susceptible to density-independent factors, environmental conditions being important sources of variability in their population parameters (Ottersen, 1996; Planque and Frédou, 1999).

The Norwegian Sea (see Skjoldal, 2004, for a description) harbours two of the largest fish stocks in the world, Norwegian spring-spawning (NSS) herring (*Clupea harengus*) and blue whiting (*Micromesistius poutassou*). In addition, abundant mackerel (*Scomber scombrus*) and horse mackerel (*Trachurus trachurus*) populations spend the summer feeding in the region. These species are at their northernmost extent in the Norwegian Sea. Their main prey in the Norwegian Sea is the calanoid copepod *Calanus finmarchicus*, which is typically confined to Atlantic water masses (Melle *et al.*, 2004). Its spatial distribution and availability to predators is determined by the extension of the water masses and hence sea temperature (and salinity). Further, where the Norwegian Sea meets the coastal waters of Norway, there are rich spawning grounds for NSS herring, Northeast Arctic cod (*Gadus morhua*), saithe (*Pollachius virens*), and haddock (*Melanogrammus aeglefinus*). Sea temperature is an important regulator of recruitment to the herring and cod populations in the region (Ottersen and Stenseth, 2001; Sætre *et al.*, 2002) and is likely an important factor for saithe and haddock too, higher temperatures favouring early survival and growth.

Bogstad *et al.* (1997) demonstrated how stock assessment may be enhanced by employing hydrographic data. To make such information available to stock assessment scientists, observations should be aggregated and analysed using the established connections between environmental and population parameters. A first step required to investigate and exploit such connections was the provision of an archive of gridded temperature data in a suitable format. Bogstad *et al.* (1997) specifically suggest that sea temperature should be used to improve estimates of fish growth and consumption. They underscore the importance of having temperature estimates that reflect, as well as possible, the surroundings in which the fish have lived. They also point to a crucial step towards an operative system for the calculation of such ambient temperatures as the establishment of a digital archive of "true" temperatures, i.e. the actual temperature at a given time and location in the ocean.

The goal of the Norwegian FishExChange (Expected Change in Fisheries in the Barents Sea) project (2007–2010) is to evaluate the effects of climate change in the Barents Sea on the distribution of fish stocks. An aim considered essential in meeting the project's overall objective is the development of a gridded database containing both climate and fish stock parameters. Such a database, or atlas, for the Barents Sea was produced during autumn 2009 and is now being documented (S. L. Johansen, IMR, Bergen, Norway).

Here, the first digital temperature archive for the Norwegian Sea is presented. The main purpose is to make historical temperature values available to fisheries oceanographers, fisheries biologists, and stock assessment scientists in a format suited for their use. However, the temperature atlas should also be of interest within physical oceanographic, climate change, and climate variability research, numerical modelling, and remote-sensing analyses.

No archive of temperature values derived from *in situ* observations covering all seasons and many years has been made for the Norwegian Sea until now. Archives of this nature and quality for areas as large as the Norwegian Sea are unusual anywhere (though see Holbrook and Bindoff, 2000, for a digital atlas of southwest Pacific upper ocean temperatures).

Two versions of the temperature archive were produced, both with a seasonal (3 months) resolution from 1990 to 2007. One is based on the temperature values from the year and season in question with gridpoints remote from any data point given a "missing" value. In the other version, the "missing" values were replaced with the climatological values from World Ocean Atlas 05 (WOA05; Locarnini *et al.*, 2006).

It is stressed that this product is not (i) a climatology; although one of the main points of the archive is to capture the differences between years, a climatology, to the contrary, accumulates all data for a given region and season across the years, so representing averaged characteristic values rather than time-variant *in situ* values. Nor is it (ii) output from a model of any kind. It is based only on the *in situ* measurements and as straightforward an interpolation scheme as possible. The idea is to make it as objective as possible, independent of specific model parameterizations.

Although the archive is directed towards fisheries-related applications, it will also have its more direct oceanographic use. Using temperature fields for the Barents Sea during autumn of the years 1970–2000, Ingvaldsen *et al.* (2003) concluded that three established fixed sections are reasonably representative of the Atlantic domain in the Barents Sea, at least during that season. Their approach was to construct maps of spatial correlation between temperature fields and sections. The archive described here may be used in a similar manner, e.g. to calculate the various temporal and spatial statistics, including temperature mean and variability within regions, spatial variability as a function of distance, decorrelation radii, and variability within different frequency ranges.

The archive further makes temperature values easily available for modelling purposes. Numerical hydrodynamic ocean models are typically initiated by temperature and salinity fields derived from the actual measurements. Frequently, climatological means are used for this purpose (e.g. Locarnini *et al.*, 2006, for the global WOA05; Engedahl *et al.*, 1998, for the Nordic Seas; Damm, 1989, for the North Sea), but often values more directly representative for a particular year and season or month are better suited. In addition to model initiation, the temperature atlas presented here should be useful for validating model output.

Material and methods

The data

The atlas is based on 59 496 stations where vertical profiles have been obtained using conductivity–temperature–depth (CTD) instruments or, in a few cases, Nansen bottles (Figure 1). The atlas covers the period 1990–2007 and is compiled from a variety of sources. The initial dataset used was from the NISE (Norwegian Iceland Seas Experiment; Nilsen *et al.*, 2006) project. The data made available to the atlas through NISE originated from the International Council for the Exploration of the Sea's (ICES) Oceanographic Database (www.ices.dk), the Institute of Marine Research, Norway (IMR, www.imr.no), the Faroese Fisheries Laboratory (FFL, www.frs.fo), and the World Ocean Database 2005 (WOD05, http://www.nodc.noaa.gov/OC5/WOD05/pr_wod05.html; Boyer *et al.*, 2006). A significant number of additional stations was also included from IMR, FFL, WOD05, and the Marine Research Institute (MRI), Iceland (www.hafro.is). Most of the stations were sampled using CTDs and data were available with a vertical resolution of 1–5 decibar (m). For stations sampled using Nansen bottles, data were available at standard oceanographic depths.

The temperature data on which the archive is based are unevenly distributed in both space and time. The annual number of stations in the region has varied from year to year, without any obvious systematic trend, although there was outstandingly good effort in 1990 (Figure 2). The number of stations is typically highest in spring and summer, giving the best coverage in the second (April–June) and third (July–September) quarters (Figures 2 and 3). There were, for example, 2375 stations in the second quarter of 1990, more than ten times that of the 321 stations in the fourth quarter of 2005. Spatially, there is a general pattern of more stations in the east and south than in the west and north (Figures 1, 3, and 4).

Data handling was with Ocean Data View (ODV) software (Schlitzer, 2006; http://odv.awi.de), several FORTRAN programs developed by the author and, to a lesser degree, SAS (SAS Publishing, 2004; www.sas.com). ODV was also used for visualization and some calculations.

All data were gathered from trustworthy databases and were subjected to the quality-checking routines of the respective institutions (e.g. see http://www.ices.dk/Ocean/odmsoft/index.htm for an overview of ICES procedures). Also, as only the period from 1990 is covered, some technical and methodological problems that could apply to older data are not an issue. No thorough quality-control routines were deemed necessary *a priori*. Unfortunately, during the process a significant number of stations was identified with erroneous format. The most common forms of error were (i) stations with depths repeated with different temperature values, (ii) stations that started again at low depths (either with the same or different values), and (iii) data lines with non-numerical temperature values. In each of these cases, there was no way to determine the correct values, so either the full station or part of it was deleted from the dataset.

When accumulating data from several sources, overlap between the different datasets is expected. As the different databases typically use different protocols for identifying sources of data origin, countries, cruises, and stations, identifying duplicate stations may be complicated. In such cases, substantial overlap especially between the ICES, IMR, and WOD05 datasets had to be dealt with. It was not possible to identify and remove duplicates automatically, so a semi-manual approach was employed.

Climatological "fill-in" temperature values

One of the two versions of the temperature archive described here also includes climatological values from WOA05. This is a rigorously updated version of what is arguably the most well known of all hydrographic climatological archives, which originated as Levitus (1982). These climatological fields of temperature, salinity, and other parameters cover the world oceans on a $1^\circ \times 1^\circ$ spherical grid at standard levels down to 5500 m. The fields of WOA05 are monthly for the upper 1500 m, and seasonal below that depth. The archive was made by an objective analysis scheme (Cressman, 1951) applied to data from the WOD05 (Boyer *et al.*, 2006). The recent WOA21c climatology (Chang *et al.*, 2009) was not available when the work presented here was prepared.

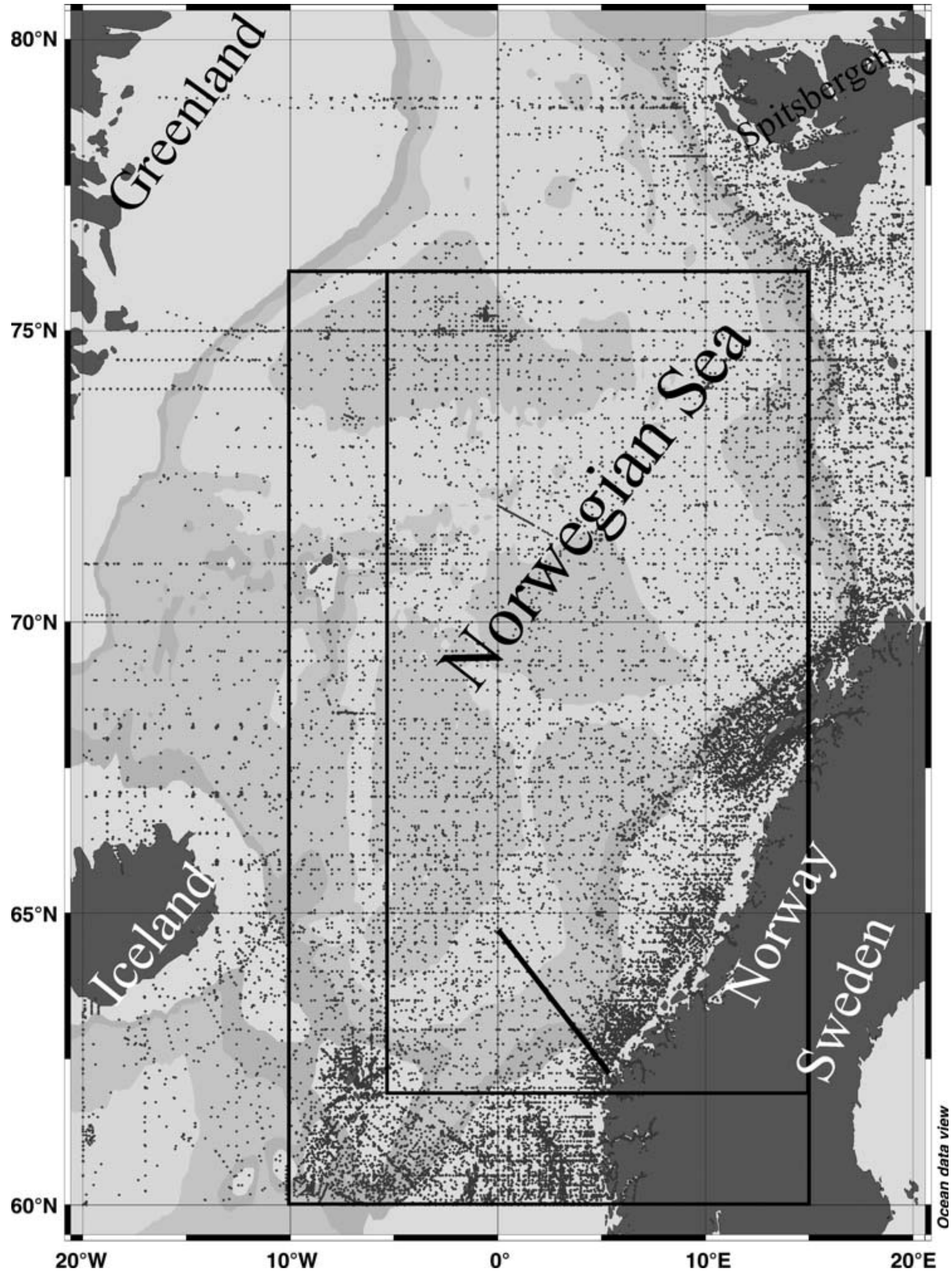

Figure 1. The Norwegian Sea, showing the location of the 59 496 hydrographic stations from 1990 to 2007 that form the basis of the temperature atlas. The Svinøy section from 62°22′N 05°12′E to 64°40′N 0°E is indicated by the thick black line. Data within the boxed areas (62–76°N 5°W–15°E and 60–76°N 10°W–15°E) are used in calculating the average temperatures presented in Figure 9, as well as in calculating the percentage distribution within temperature intervals presented in Figure 10.

The general algorithm for producing the archive

Data from the various databases were imported into ODV source by source and compiled into a single ODV data collection. The data from NISE (Nilsen *et al*., 2006) were available as an ODV collection, and WOD05 data were imported directly. Other datasets were first transformed to a suitable column-based ASCII format by self-developed Fortran programs before being imported. Data were extracted from ODV by year and season in the ODV spreadsheet format. They were then transformed to polar-stereographic grid coordinates, followed by vertical, then horizontal, interpolation. Finally, the fields were converted to a latitude/longitude grid and combined to single files in, respectively, text, SAS, and ODV formats.

The interpolation scheme

An important part of the archive production is how the information in spatially scattered stations is transformed to systematic grids with a single value per grid cell. MODgrid, Model Oriented Data gridder, software developed by Ottersen (1991) and updated in connection with this work, was used.

The first step was a simple linear vertical interpolation performed separately for each station, resulting in values at selected

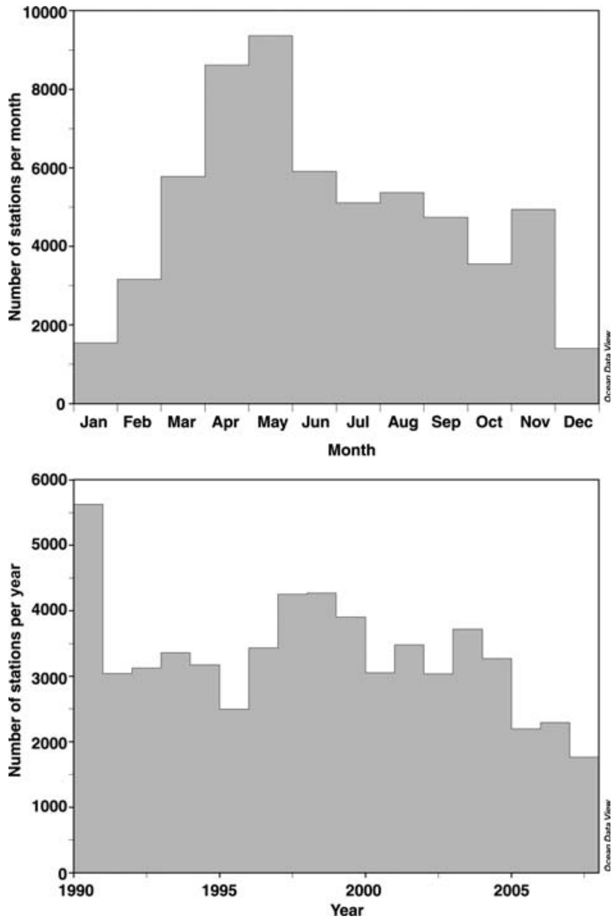

Figure 2. Temporal distribution of stations between months (upper panel) and years (lower panel). Note that whereas in the upper panel the abbreviation for the month along the *x*-axis is centred below the corresponding bar, in the lower panel the value for year is positioned to the left of the corresponding bar.

depth levels down to the deepest measurement, or 500 m. The chosen depth levels were 0, 5, 10, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 125, 150, 200, 250, 300, 400, and 500 m. For each level, a two-dimensional algorithm (Taylor, 1976), combining the Laplace and cubic spline interpolation, was applied horizontally. Although the Laplace interpolation is a two-dimensional analogy to linear interpolation, cubic spline interpolation involves the fitting of polynomials, of at most three degrees, between datapoints. Using the method of successive overrelaxation (SOR), the Laplace-spline equation, $\partial^2/\partial x^2(z) + \partial^2/\partial y^2(z) - K(\partial^4/\partial x^4(z) + \partial^4/\partial y^4(z)) = 0$, was solved over the entire gridnet iteratively, improving the solution for non-data gridpoints. The constant K determined the weight of the spline part of the equation and had a range from 0 (pure Laplacian) to infinity (pure spline). $K = 5$ was used here.

The aim of the interpolation was to construct fields with as correct values as possible in the parts of the sea where there were stations. In other areas, the grid was set to "undefined", not filled with extrapolated values. The inference radius, maximum number of grid cells a gridpoint may be from a datapoint without being set to undefined, was restricted to 15. This value was used homogenously and isotropically throughout the grid, despite non-uniform data coverage. Further, the same value was applied for all years, seasons, and depths, independent of the number of stations. The interpolation scheme was purely two-dimensional. The values in the original datapoints could be adjusted through the interpolation procedure. No smoothing was performed at this stage except for the implicit effect of the interpolation. Points on land (or on "land" at the depth level applied) and "missing" datapoints were explicitly set to specific and different values.

Incorporating "fill-in" climatological values

A balance was found between a high inference radius, which fills in a larger number of grid cells but may extrapolate to unreasonable values, and a lower inference radius, which may leave many grid cells without a real-data value ("missing" values) because their distance to the nearest datapoint was larger than the inference radius. Here, an inference radius of 15 was chosen, a value that is relatively low given the sparseness of data for some seasons and areas, so leaving a number of grid cells with "missing" values.

For some potential uses of the atlas, fields without any "missing" values are needed or at least highly preferable, e.g. for initiation of hydrodynamic models. Therefore, a second version of the temperature atlas was made in which "missing" values were replaced with climatological values. For that version of the temperature atlas, climatological seasonal values for the grid area were first extracted from the larger and coarser WOA archive and stored in separate ODV collections. Values were then exported from ODV, edited and interpolated vertically to the same depth levels as the actual data, still in the coarser resolution of the WOA datasets. Further (by a FORTRAN program), successive iterations were made through the fields gridded from actual data, and "missing" values were replaced with the climatological value from the corresponding location and depth.

To avoid unrealistically large gradients in the fields, attributable to inconsistencies between actual and climatological values, Laplacian smoothing was used. Generally, applying a Laplacian smoother to a gridpoint Z_g, implies that $Z_g = Z_g + 0.25$ [Average(Z_N, Z_S, Z_E, Z_W) $-$ Z_g], where Z_N, Z_S, Z_E, and Z_W are the values of the surrounding cells. Here, the smoother was applied five times. A more elaborate technical description of the atlas is given in Ottersen (2009).

Results

Summary description of the temperature archive

Gridded temperature fields for the Norwegian Sea for the quarters January–March, April–June, July–September, and October–December were prepared for each of the years 1990–2007. The archive spans the area 20°W–20°E 60–80°N with a spatial resolution of 1/2° longitude by 1/3° latitude, and there are 28 depth levels from 0 to 500 m. Two versions of the archive were produced, the first based solely on actual data and including ocean grid cells with "missing" values in addition to real-temperature values and cells on land or shallower than the depth level in question, and the second filling in all "missing" cells with climatological values.

The temperature archive is freely available for scientific non-commercial purposes, although citation to this paper is requested. Both versions can be downloaded from the Institute of Marine Research's web pages in three formats: ASCII/text (1 file 280 Mb), SAS (1 file 400 Mb or four files, one for each season), and ODV (several files, totalling 107 Mb). Each dataline consists of a temperature value for a given year and season, and grid cell

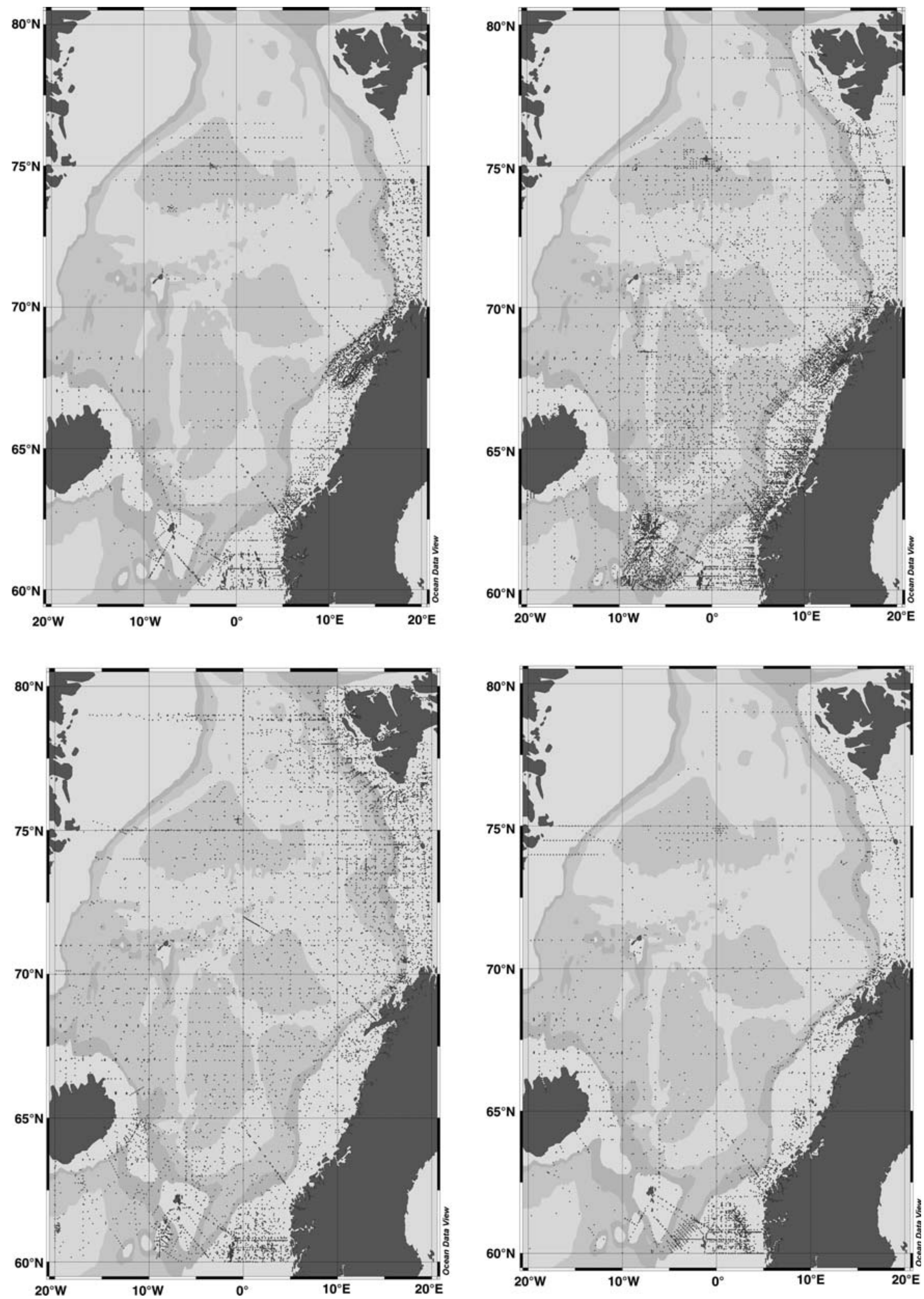

Figure 3. Spatial data coverage per season, all years 1990–2007 for January–March (upper left panel), April–June (upper right), July–September (lower left), and October–December (lower right).

given as latitude, longitude, and depth. In the ASCII and SAS files, each dataline is given in the format date, depth, latitude, longitude, and temperature.

Horizontal temperature fields

Examples of horizontal fields from the temperature atlas based only on actual data are shown in Figure 5. Unsmoothed values

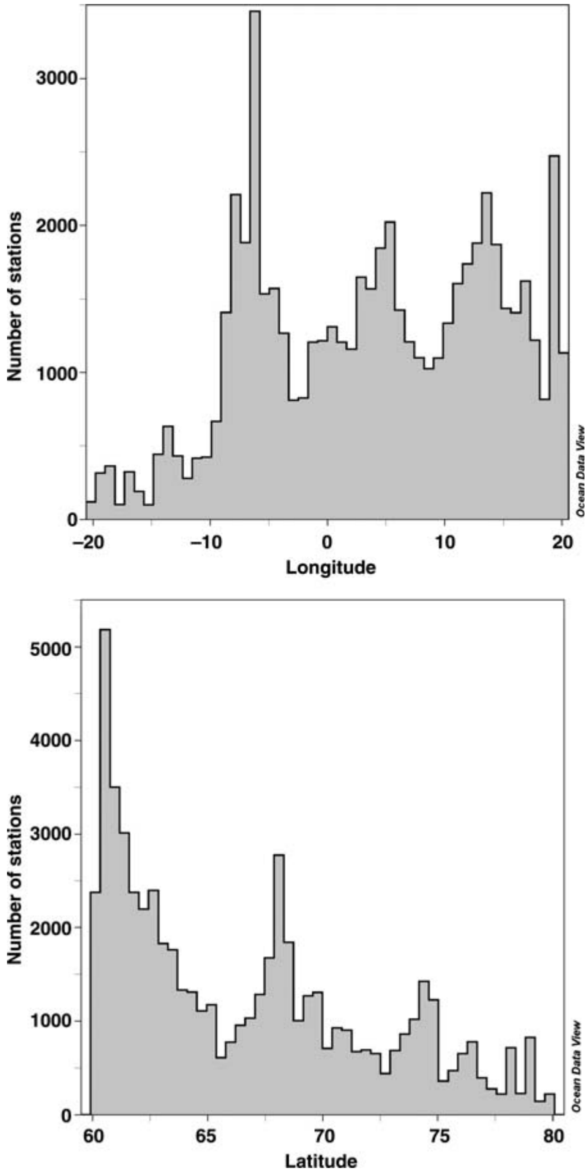

Figure 4. Spatial distribution of data coverage, 1990–2007, by longitude (top panel) and latitude (bottom panel).

for each non-missing grid cell are displayed. The underlying data subsets for a given year, season, or subarea can be extracted from the archive by software such as SAS or ODV. The latter has here been used here for visualization. Similarly, the examples of horizontal fields from the temperature atlas based on actual data and "filled-in" climatological values are shown for the same years and depths as above in Figures 6 and 7. Although Figures 6 and 7 are based on identical data, Figure 6 shows non-smoothed values for each (non-missing) grid cell and Figure 7 shows fields smoothed for visualization by the DIVA interpolation plug-in of ODV (see the "Discussion" for a brief description of DIVA and a link to the DIVA web pages). Again, the underlying data subsets, for any given year, season, or subarea can be extracted from the archive by suitable software (e.g. SAS or ODV).

Vertical sections

Vertical sections can also readily be extracted from the temperature atlas and displayed using ODV. Examples from the archive based on actual data and climatology are shown from IMR's Svinøy transect (Figure 8).

Three-dimensional box averaging

Mean temperature values were calculated within given latitude–longitude–depth boxes based on the fields combined from data and climatological values. Two examples are chosen representing the water masses theoretically occupied by the full extent of the NSS herring summer distribution in, respectively, April–June and July–September, and similarly for blue whiting habitat during April–June. The selected box for herring was 62–76°N 5°W–15°E, 0–100-m depth, and for blue whiting 60–76°N 10°W–15°E, 200–500-m depth. This was done for each of the years 1990–2007, giving time-series of 18 years duration (Figure 9).

Percentage by area distribution of thermal ranges

The percentage area of any defined region within a selected set of temperature intervals may be estimated for any year, season, and depth level or depth interval by simply counting the number of grid cells. This may be done for the full region covered by the atlas, or in principle for any selected subarea(s). However, if the number of grid cells included is low, the results are less meaningful. Here, an example of the percentage by area distribution of thermal range in the region 60–76°N 10°W–15°E within 2° temperature intervals, for April–June at 200-m depth for four selected years, is shown in Figure 10. The area selected is representative of the full extent of the feeding distribution of the northern component of the blue whiting stock, and 200 m is towards the upper limit of the depth interval normally inhabited by that fish stock. As above, the fields using combined *in situ* data and climatological values were used.

Discussion

Few long-term observations of ocean temperature are available, and this typically causes difficulties for analysing the effects of climate variability and climate change on the marine ecosystem (Hughes *et al.*, 2009). Those authors provide evidence suggesting that gridded sea surface temperatures based on a combination of satellite and *in situ* observations can be used, but with care, to examine variability and long-term trends, because they provide better spatial coverage. The same arguments can be used in favour of the temperature atlas presented here. The atlas is principally intended to provide temperature values in a systematic, uniform, easily accessible manner to fisheries ecologists, oceanographers, and other researchers.

Spatio-temporal data coverage

The general pattern of there being more stations towards the east and south of the gridded area simply reflects the fact that the southeastern part of the Norwegian Sea is close to more populated parts of Norway, whereas most of the sea is distant from any coast (Figures 1 and 3). The peaks in a longitudinal direction in Figure 4 at around 7°W reflect intense sampling around and south of the Faroe Islands, and the peaks at 5 and 15°E are mainly the outcome of pronounced effort along the coast of, respectively, western Norway and the important cod and herring spawning area of Lofoten/Vesterålen in northern Norway. Most stations are sampled during spring (Figures 2 and 3), when IMR's main Norwegian Sea research cruises take place, targeting mainly herring and, in recent years, the whole ecosystem, between April and June.

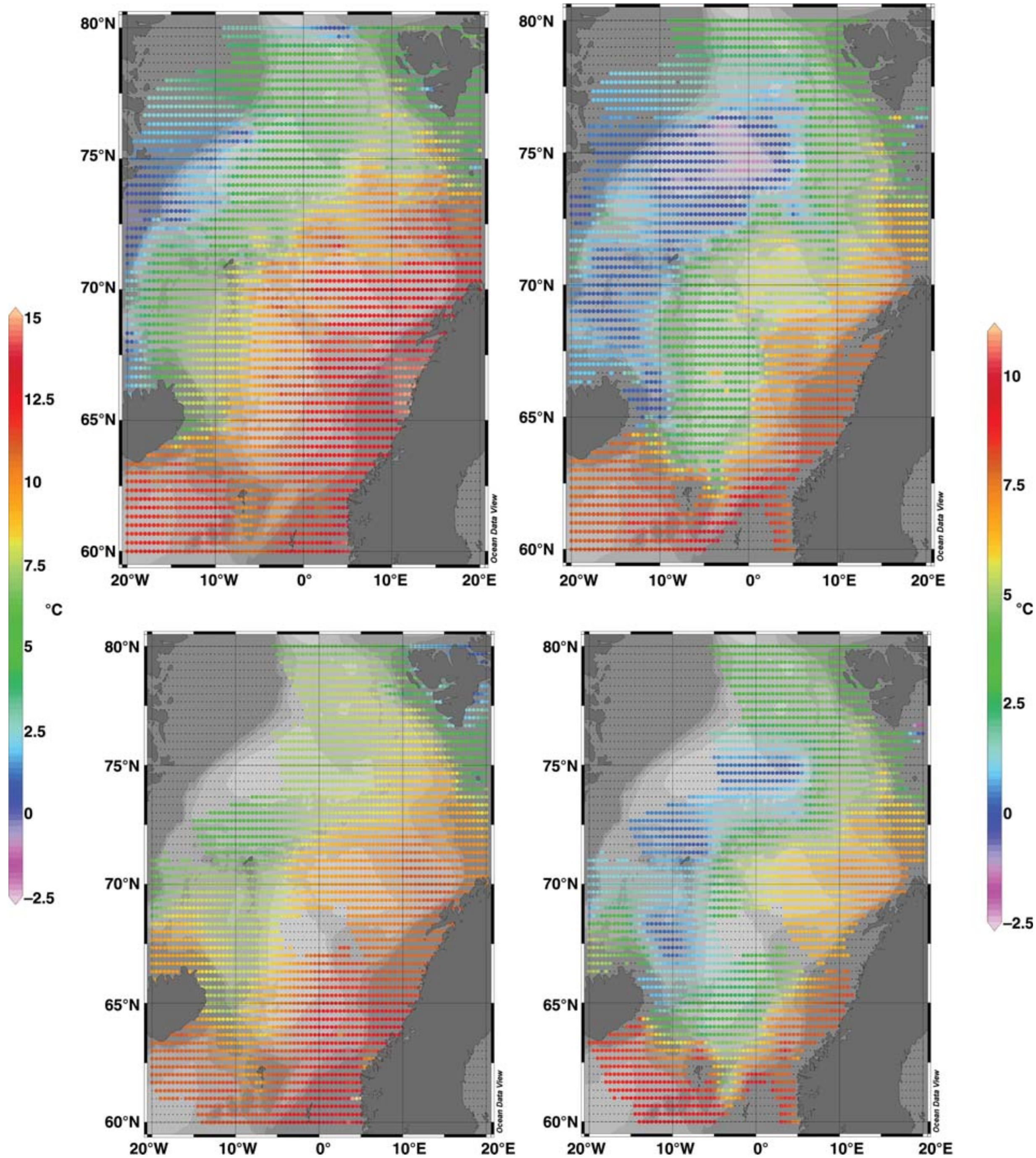

Figure 5. Two-dimensional horizontal temperature fields for the months July–September from the temperature atlas based on actual data for 1990 at 0 m (upper left panel, left colour scale), 1990 at 200 m (upper right, right colour scale), 2005 at 0 m (lower left, left colour scale), and 2005 at 200 m (lower right, right colour scale). Non-smoothed values for each (non-missing) grid cell are shown.

Monthly fields, as opposed to the chosen quarterly fields, would be advantageous for some purposes. However, the statistics (Figures 2 and 4) show that data coverage for some months and areas is far too poor to allow for production of monthly fields of a reasonable quality. On the other hand, spatial resolution is quite high. Technically an even higher resolution could be used, but this would only seemingly give a better archive, because the underlying resolution is determined by the spacing of the stations. Fish distributional data are often characterized by a coarser resolution than that of the atlas, e.g. acoustic densities are typically available at a spatial resolution of 30′ latitude by 1° longitude (Ottersen *et al.*, 1998). Hence, for some of the main uses of the atlas, the current spatial resolution will be sufficient.

Interpolation method

The interpolation techniques employed to produce the atlas have proven well suited for interpolating hydrographic data for a variety of purposes (Martinsen *et al.*, 1992; Ottersen and Ådlandsvik,

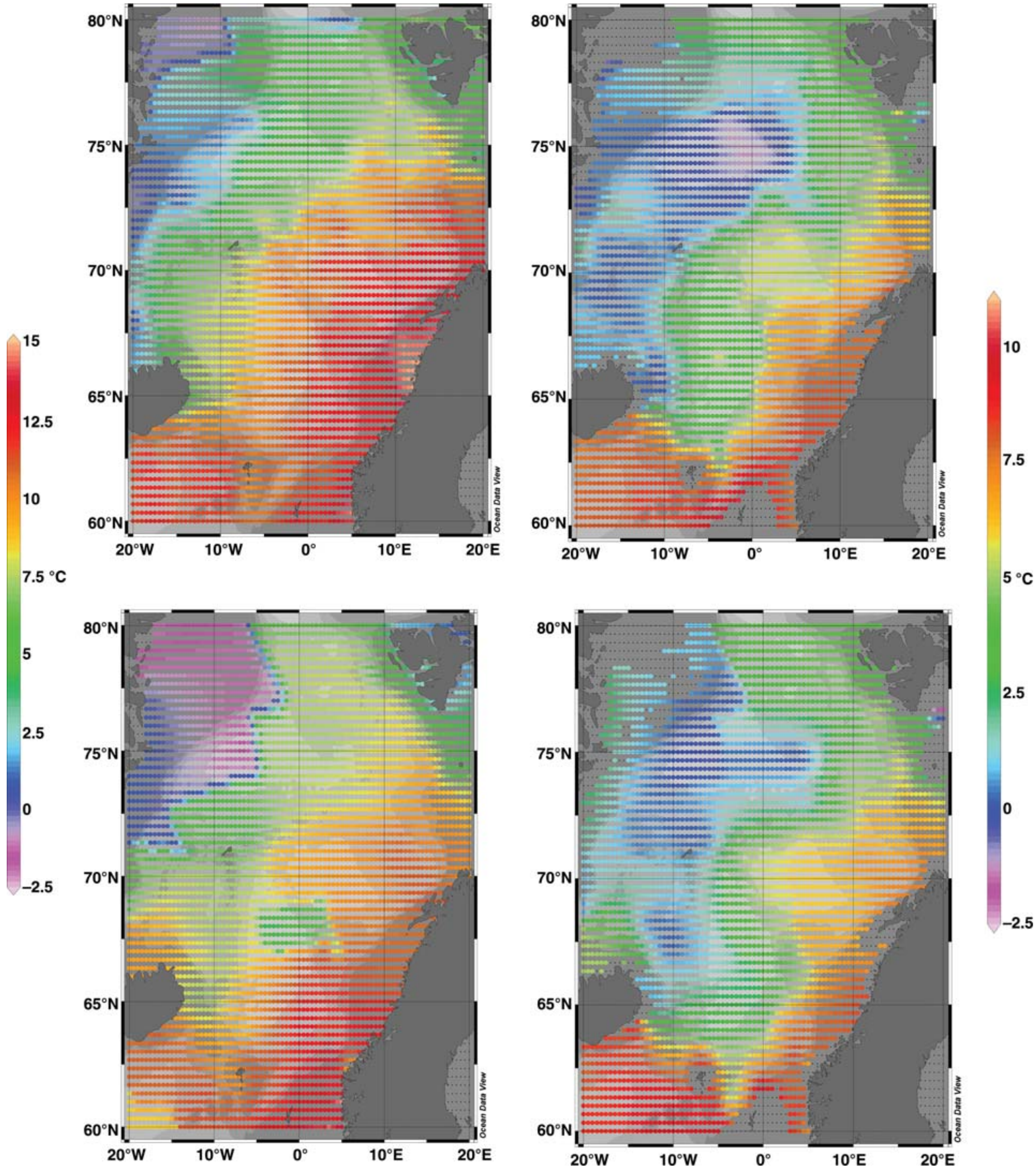

Figure 6. Two-dimensional horizontal temperature fields for the months July–September from the temperature atlas based on actual data and climatology for 1990 at 0 m (upper left panel, left colour scale), 1990 at 200 m (upper right, right colour scale), 2005 at 0 m (lower left, left colour scale), and 2005 at 200 m (lower right, right colour scale). Non-smoothed values for each (non-missing) grid cell shown.

1993; Engedahl *et al*., 1998; Ottersen *et al*., 1998; Ingvaldsen *et al*., 2003). An interpolation procedure with a homogenous inference radius was applied throughout the whole area even where data coverage was better than at other locations, and despite the assumption of isotropy generally not holding for ocean properties (Lemos and Sanso, 2009). Although one locally might be able to obtain values that are more representative by dynamically adjusting the inference radius, this would complicate the overall picture and possibly introduce additional artificial features. A better improvement might be an interpolation procedure that is homogenous throughout the grid region, but non-isotropic. The same inference ellipsis would then be used over the whole region, but directionally differentiated according to, for example, the direction of the principal local residual currents. Several varieties of an approach where globally anisotropic processes are built from convolutions of locally isotropic ones have been

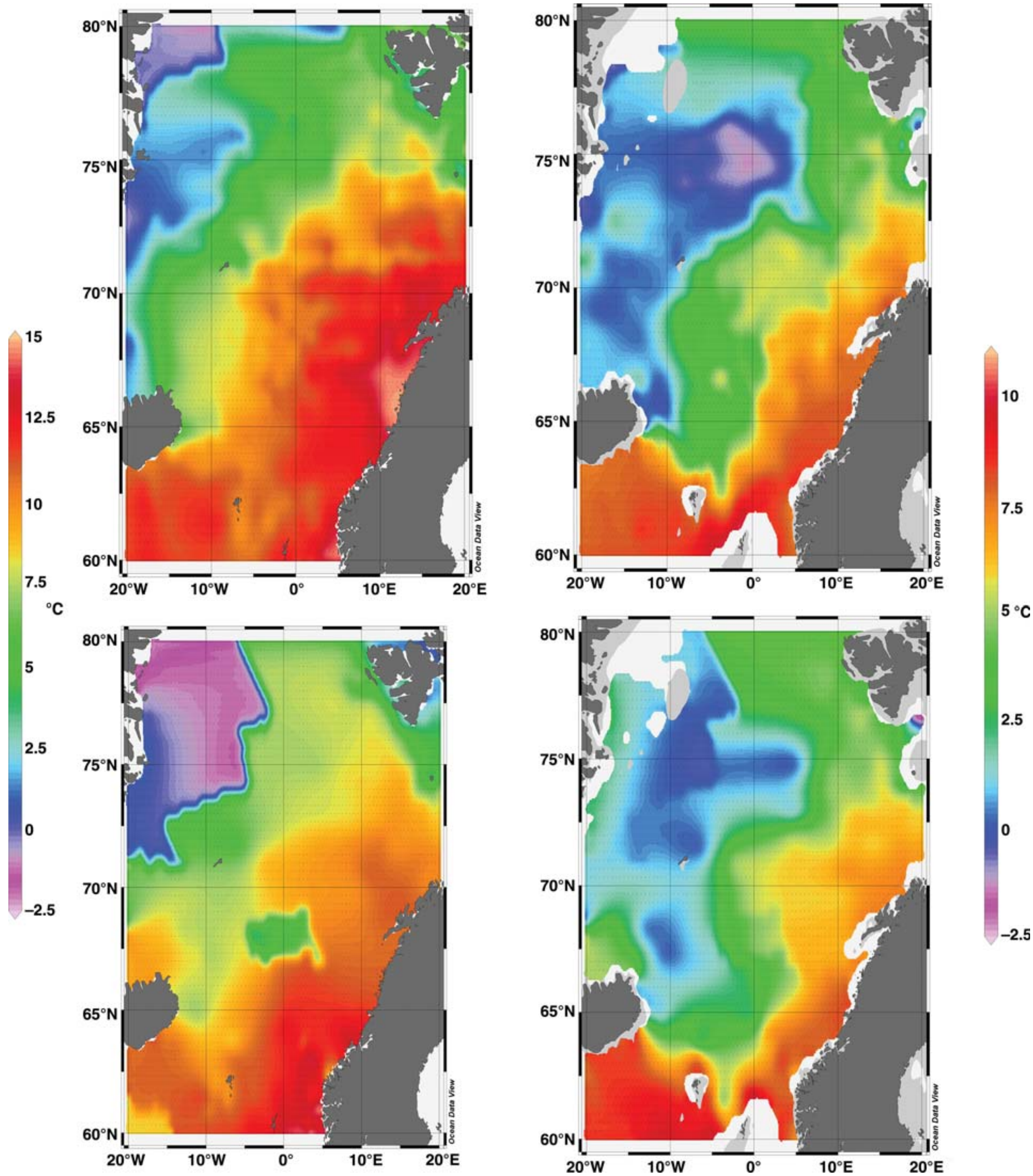

Figure 7. Two-dimensional horizontal temperature fields for the months July–September from the temperature atlas based on actual data and climatology for 1990 at 0 m (upper left panel, left colour scale), 1990 at 200 m (upper right, right colour scale), 2005 at 0 m (lower left, left colour scale), and 2005 at 200 m (lower right, right colour scale). Temperature fields are smoothed for visualization by the DIVA interpolation plug-in of ODV.

described (Higdon *et al.*, 1999; Fuentes, 2002). Such procedures are, however, complex, especially if the seasonal variations in the current pattern are to be taken into consideration. A promising approach is that of the DIVA (data-interpolating variational analysis) interpolation tool. The methodology is comparable with optimal interpolation, but takes into account coastlines, sub-basins, and advection, and allows for non-uniform correlation length (see http://modb.oce.ulg.ac.be/projects/1/diva for information on DIVA).

Quality control

The methods applied for quality control here were somewhat *ad hoc* and relied on the bulk of the data already having been through rigorous quality-control procedures. Ideally, a fully

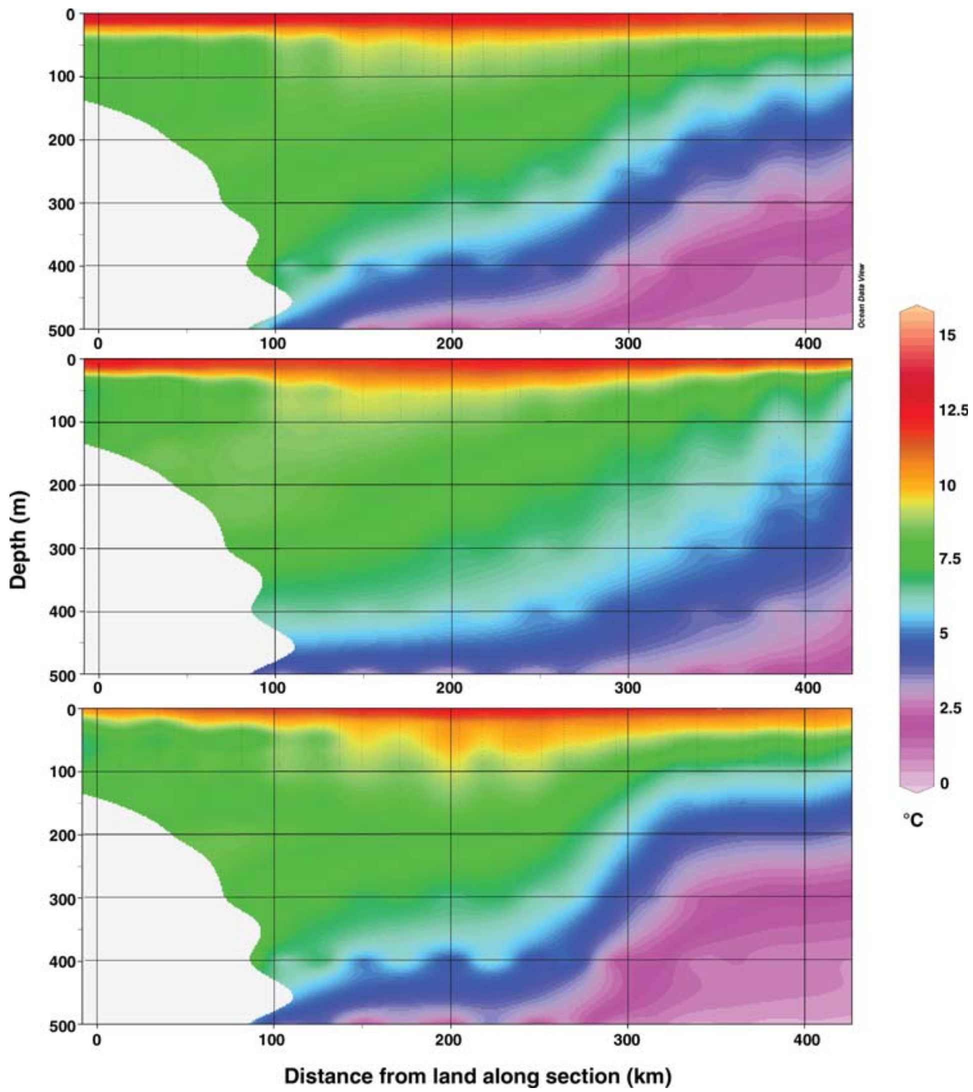

Figure 8. Example of interannual differences along a vertical section, the Svinøy section from 62°22′N 05°12′E to 64°40′N 0°E (see location in Figure 1) at 0–500 m for the months July–September. Climatological values for 1990–2007 (top panel), 1990 (centre panel), and 2000 (bottom panel). The temperature atlas is based on both data and WOA 5 climatology, with the ODV DIVA interpolation plug-in used for visualization. A moderately non-linear colour scale with higher colour resolution towards lower and higher temperature values is applied.

automated process should be implemented, but this would seem to be completely unrealistic if retaining a high percentage of erroneous stations or the removal of many accurate ones is to be avoided. Gronell and Wijffels (2008), for example, describe a method consisting of both automated statistical screening and manual quality control through expert visual inspection, which produces a historical ocean temperature archive of high quality. When applied to an archive of about 121 000 profiles, they found that they had to inspect manually 35% of the profiles to remove 95% of the bad data. The complete process of Gronell and Wijffels (2008) involved comprehensive duplicate elimination, a check for unreasonable gradients, and statistical screening to distil out suspect profiles, which were eliminated (or partially so) then only during an expert manual visual inspection step.

Horizontal temperature fields

The most obvious difference between the examples of fields based only on actual data (Figure 5) and those including climatological values (Figures 6 and 7) is that the latter have fewer missing values in the northwestern corner at both 0- and 200-m depth. This is to be expected as, per definition, the fields including climatological values should have no missing points at sea at all. However, there remain some missing datapoints close to land because of discrepancies between the depth matrix used when gridding actual values and that of the climatology. This is partly due to the coarser resolution of the climatology. In cases when the cell value is "missing" in the fields from actual data and "land" in the climatology, the resulting value is set to "land", because there is no other option. The final fields therefore consist of three types of value; actual temperature values, climatological values, and "land" values.

Laplacian smoothing was applied to flatten the gradients between actual and climatological values. However, it may be argued that this has not been totally successful over the full grid at 0 m (see Figures 6 and 7, towards the upper northwestern corner).

Figure 9. Time-series 1990–2007 of averages of temperatures within three-dimensional boxes extracted from the temperature atlas based on both data and WOA 5 climatology. Upper line, open circles: 62–76°N 5°W–15°E (see location in Figure 1), 0–100-m depth, July–September (representative of the full extent of NSS herring feeding distribution). Centre line, dots: 62–76°N 5°W–15°E, 0–100-m depth (same box as above), April–June. Lower line, open squares: 60–76°N 10°W–15°E (see location in Figure 1), 200–500-m depth, April–June (representative of the full extent of the northern component of blue whiting feeding distribution).

Vertical sections

One of the strengths of the temperature atlas is that sections can be defined from anywhere within the grid area. Moreover, ODV allows one to construct quite complicated sections following, for instance, arbitrary cruise tracks. Figure 8 shows that compared with the climatology based on all the years studied (1990–2007), autumn values for the 2000 show no particular anomalies, whereas in 1990 the water masses 200–400 m deep in the outermost 150 km or so of the transect were cooler than normal.

Ambient temperatures for fish

As the main fish stocks in the Norwegian Sea are pelagic, highly migratory, and inhabit regions of relatively large horizontal temperature gradients, they may experience temperature variations that are quite different from those measured at any geographically fixed station. To obtain a more realistic approximation of the temperatures in which a fish population lives, one could instead estimate the population's ambient temperature either by (i) inference from the thermal histories of fish equipped with data storage tags (DSTs; Neuenfeldt *et al.*, 2007; Hüssy *et al.*, 2009), or (ii) by calculating fish density weighted average temperatures from spatially explicit survey data describing fish distribution and temperature fields. To allow for this latter approach, one needs spatially

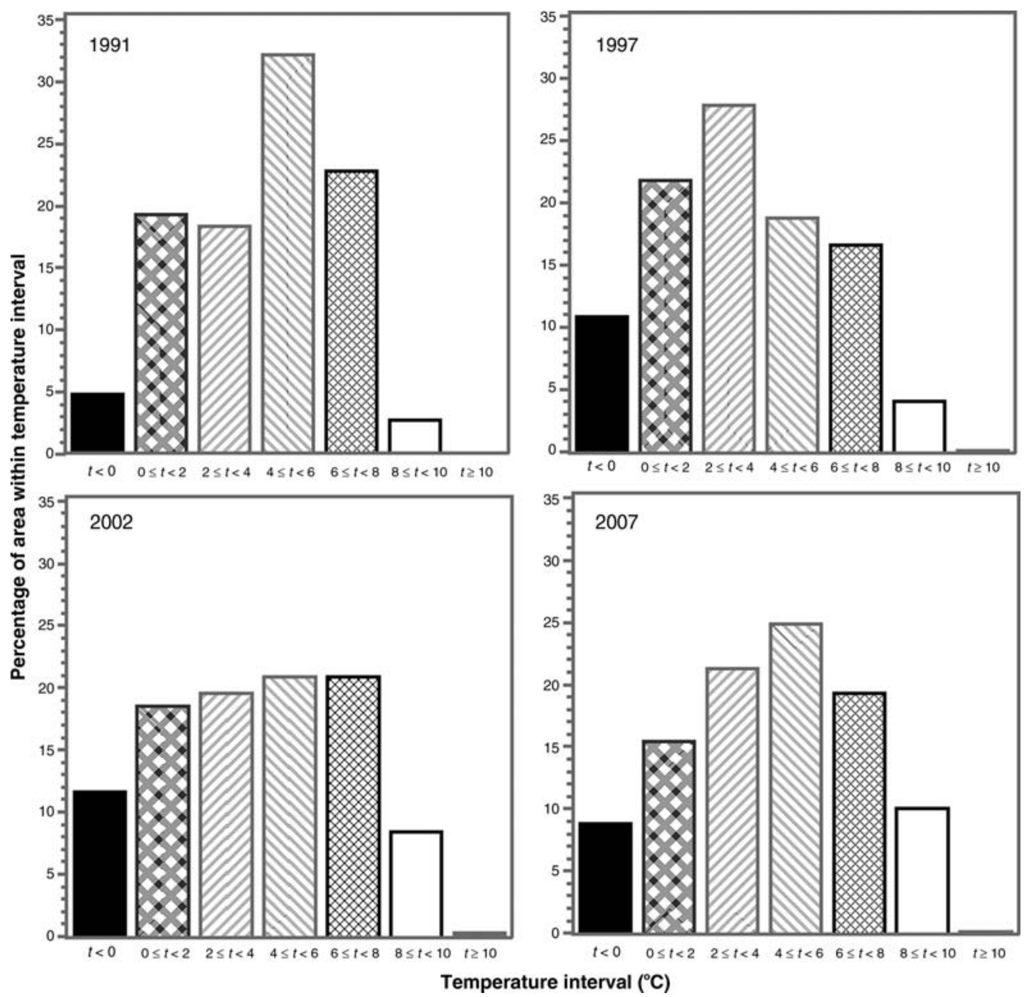

Figure 10. Percentage distribution within temperature intervals of the number of grid cells in the region 60–76°N 10°W–15°E (see location in Figure 1) at 200 m during the months April–June for four selected years, 1991 (upper left), 1997 (upper right), 2002 (lower left), and 2007 (lower right).

resolved and preferably uniformly distributed fish distribution and temperature values. The atlas is well suited for providing such temperature distributions. In practice, the sum of the products of the number of fish $[N(x, y)]$ and temperature $[T(x, y)]$ over the cells in a given grid would be divided by the number of fish in the same cells, i.e. $T_{amb} = \sum(N(x, y) \times \sum T(x, y))/\sum N(x, y)$.

For an estimate of the "temperature history" (T_{amb}) of a fish population, it would then be necessary to integrate (or in practice sum) over time, including as many of the ambient temperature snapshots described above as possible. Using the seasonal temperature archive, it is possible, depending on the availability of fish distribution data, to make four such estimates per year. Ambient fish temperatures calculated in this manner have, for instance, been applied to North Sea cod (Heessen and Daan, 1994) and Barents Sea cod (Ottersen *et al*., 1998).

A main strength of this method compared with a tagged fish approach is that, unless a large number of fish is tagged, ambient temperature estimates from the data integration method are likely to be more representative for the whole population. Moreover, ambient temperatures can be calculated per age or size group of fish. On the other hand, a weakness of the data-based method is that there would likely be only a very few research surveys that spatially covered the target area each year, whereas the DSTs return more or less continuous temperature histories for the tagged fish. Ideally, both methods should be combined.

Year-to-year changes in the temperature of water masses theoretically occupied by the full extent of the distribution of a fish stock (or a specific age or length fraction) may be estimated from the temperature atlas without applying actual data on the distribution of the fish. There is a positive trend in the time-series of this type for herring and blue whiting, but it is weak (Figure 9). However, the interannual variability at 200 m within the overall area possibly occupied by blue whiting is more pronounced (Figure 10), and the difference between years is likely to be underestimated because some grid cells have the same climatological values each year.

Model initiation and verification

The temperature atlas provided here should be well suited for initiation and verification of regional Norwegian Sea models. Indeed, for providing boundary conditions and fields for model verification when studying interannual differences, the atlas should be more appropriate than any climatology.

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