Climatology of Surface and Near-bed Temperature and Salinity on the North-West European Continental Shelf for 1971–2000

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Abstract

A 30-year (1971-2000) temperature and salinity climatology is presented for surface and near-bed regions of the NW European shelf seas, with a resolution of 1/6° longitude by 1/10° latitude. The data have been extracted from the International Council for the Exploration of the Sea (ICES) data centre and supplemented by additional records from the World Ocean Data Centre (WODC). From the original data, which are irregularly distributed in space and time, the mean monthly temperature and salinity are calculated, as well as the climatic mean annual cycle. The climatology presented here is an improvement upon all existing climatologies presented in the literature for the NW European shelf; covering a wider area on a finer scale and including the surface and near-bed distribution of both temperature and salinity. Comparison of our data with existing climatologies shows good agreement, with differences occurring where our climatology is an improvement. This climatology, which will prove to be valuable to many users in the marine community will be regularly updated and made available to all users via the ICES data centre.

Key words: Temperature, Salinity, North-West European Continental Shelf, Climatology, Reference conditions 92.05.Df, 92.05.Fg, 92.05.Hj, 93.30.Ge

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1 Introduction

This paper provides a 30-year (1971-2000) estimate of mean conditions and the annual cycle (climatology) for near-surface and near-bed temperature and salinity on the NW European continental shelf, bound to the north and east by the 500 m bathymetry contour with a resolution of approximately 10 km. The climatology presented here covers a wider area on a finer scale than previously presented in the literature.

This work is an extension of an analysis undertaken for the ICES Regional Ecosystem Study Group for the North Sea (REGNS) (ICES, 2005). There is a growing need for good basic descriptions of the status of the marine ecosystem, to underpin scientific research and inform policymakers, for example in fulfilment of the requirements of the European Union Water Framework Directive (Borja, 2005) and Marine Strategy Directive [2]. When trying to understand changes in the marine environment, particularly those caused by global climate change, it is essential to have a standard reference dataset to which to compare changes. For these reasons, we believe that this climatology will be useful to several user groups within the marine sciences community: from biologists or fisheries scientists wishing to investigate the effects of physical conditions

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[2] Protection and Conservation of the Marine Environment: Marine Strategy Directive (COD/2005/0211) `http://ec.europa.eu/environment/water/marine/index_en.htm`

on the marine ecosystem to numerical modellers needing initial conditions for their simulations.

This new climatology offers advantages over existing climatologies for this area. Firstly, there are global scale climatologies (Levitus et al., 1998) and, more recently, the WOCE Hydrographic Climatology (Gouretski and Koltermann, 2004). However, with a spatial resolution of typically 0.5°, they do not provide information at an adequate resolution to resolve the oceanographic features of the NW European shelf region. At a more appropriate regional scale, Janssen et al. (1999) created a 1900-1996 climatology of temperature and salinity at a range of different depth levels for the Baltic and North Sea with a final grid resolution of approximately 10 km and which treats the two regional seas as a single one. The climatology presented here, whilst not covering the Baltic, extends the domain covered by Janssen et al. (1999) westward to include the NW European continental shelf. As an improvement to the Janssen et al. (1999) climatology, it is a referenced to a standard climatological time period (1971-2000), and the climatology is available for electronic download from the ICES data centre. Elliott et al. (1991) presented results of surface and bottom temperature on the NW European shelf from historical expendible bathythermograph (XBT) data with a resolution of 20 nautical miles. A number of comprehensive climatologies of only sea surface temperature have also been prepared, often derived from satellite data in combination with in-situ measurements. Globally complete, interpolated datasets such as HADISST (Rayner et al., 2003) are useful, but with a resolution of 1.0°, are too coarse to fully resolve the features of the NW European Shelf. For the North Sea and Baltic regions, the Bundesamt für Seeschiffahrt und Hydrographie (BSH; Federal Maritime and Hydrographic Agency) in Germany has compiled and published a climatology for the North Sea based on both in-situ measurements and satellite observations (Loewe, 1996; Loewe et al., 2003). Whilst these may offer accurate climatologies for sea surface temperature, it is impossible to obtain the salinity and near-bed temperature conditions on the shelf from these data. A comparison with some of these existing climatologies will be presented in Section 3.3.

The increasing possibilities offered by numerical modelling can also be used to generate climatologies: for example, Lynch et al. (2004) used model simulations to create a climatology of water circulation on the continental shelf around Ireland; and climatologies created by the POLCOMS model have been applied in an environmental management context by the Joint Nature Conservation Council (JNCC) in the UKSeaMap Project (Connor et al., 2006). However, small-scale mixing processes are often not directly modelled in shelf sea circulation models as this is computationally intensive, and the choice of mixing parametrisation may have significant effects on the simulated fields (Burchard et al., 2008; Holt and Umlauf, 2008), and thus the reliability of the climatology.

In summary, the climatology presented in this paper offers a dataset with a more comprehensive spatial coverage on the NW European shelf than that of Janssen et al. (1999), a higher resolution grid than that of Elliott et al. (1991), while developing and building on the methodology described by these authors. The new climatology covers both surface and near-bed levels and provides coincident information on both temperature and salinity. The climatology is referenced to the 30-year period (1971-2000) used for many other climatological datasets. In addition, this climatology will be freely available online to all researchers via the Fisheries Research Services webpage (http://www.frsscotland.gov.uk/) and the ICES datacentre (http://www.ices.dk/ocean/), and to update it regularly as new data becomes available or as new methods develop.

2 Methodology

Temperature and salinity data collected between January 1^{st} 1971 and December 31^{st} 2000 in the area of 47° N to 64° N and 15° W to 10° E were extracted from the ICES datacentre and the WODC 2005 dataset (Boyer et al., 2006). From their header information, records were identified and where duplicate records were found, the original record from the ICES datacentre was retained. Quality flags provided with the WODC dataset were used to exclude suspect data points.

Bathymetry data from the ETOPO-1 dataset (Amante and Eakins, 2008) was interpolated to calculate the water depth at each measurement point. A comparison of this bathymetry data with the observation data (either sounding or lowest measurement depth) helped to identify gross errors in the dataset, likely caused by incorrect latitude and longitude co-ordinates. Profiles where the lowest measurement was more than 25 metres below the depth calculated from ETOPO-1 were rejected completely. This method assumes that profiles within the acceptable range were either correct or had small latitude and longitude errors (likely caused by rounding of co-ordinates) or the difference in sounding was due to errors in the bathymetry dataset.

At the initial processing stage, the records were interpolated onto standard depth levels at 10 m intervals using linear interpolation between the upper and lower observation. If missing from the interpolated dataset, values at 0 and 10 metres were calculated, applying a nearest neighbour interpolation from the upper measurement toward the surface. Measurements at 0 and 10 metre depth were then averaged to get a surface measurement. Data from the lowest depth level above the seabed were classed as near-bed observations as long as this value was within 15 metres of the water depth, interpolated from the ETOPO-1 bathymetry (Amante and Eakins, 2008). A total of approximately 230,000 surface records and 131,000 near-bed records were included in the final dataset. Of these measurements, ~70 % originated from the ICES datacentre, and approximately 30 % were unique to the WODC data centre.

The surface and near-bed records were subsequently used to create a climatology on a grid with an approximate resolution of 1/6° longitude by 1/10° latitude (∼ 10 km). The resulting four variables (surface temperature, near-bed temperature, surface salinity and near-bed salinity) were grouped by month for further analysis.

As can be seen from Figure 1, the observations are skewed in time and space. The inclusion of data from the ICES Quarter 1 and Quarter 4 groundfish surveys is the most likely explanation for the secondary peaks seen during February and November. These valuable datasets help to balance the distribution of observations throughout the year and ensure adequate data to resolve the seasonal cycle. There are clearly a higher number of the measurements included in the database from the late eighties to early nineties. The gridding method used, as described in detail by Janssen et al. (1999), has the advantage of robustly dealing with an uneven distribution of measurements in time and space. The method used is described in outline below and differed slightly from that of Janssen et al. (1999), but only in the method of smoothing and filling gaps. Janssen et al. (1999) used a semivariogram to objectively determine the radius to smooth over whereas we chose a fixed radius of 85km. Janssen et al. (1999) used values from above to fill gaps, we didn't find a need for gap filling.

The gridding process involved the detection of outliers in the data to ensure the resultant climatology was not skewed by these values. Within each grid square (1/6° Longitude by 1/10° Latitude), for each month, the median value was calculated for each variable; additionally, in the neighbourhood covering 7 x 7 grid cells (Janssen et al., 1999), the arithmetic mean and standard deviation of the measurements were also calculated for each variable. If the median differed by a certain error value ($\epsilon = 2$ for salinity and $\epsilon = 1^\circ$ C for temperature) from the mean, and if the median was more than 4 standard deviations removed from the mean it was considered an outlier and the observation was discarded.

Smoothing of the results is necessary to reduce noise caused by the different distribution of data (spatially and temporally) in each gridcell. After removing outliers, the gridded variables were smoothed using a two-dimensional median filter, followed by a two-dimensional Gaussian filter over a neighbourhood of 11 x 11 cells. This translates into smoothing over a radius of approximately 85 kilometres, a distance considered to be adequate to smooth over the data without loosing key features such as fronts (Janssen et al., 1999).

After Elliott et al. (1991), the 95% Confidence Interval (CI) for the calculated climatic averages of each variable can be found from the standard deviation of the observations around the mean. For the temperature distributions, the overall estimated standard deviation was 0.7° C for both near-surface and near-bed observations, whilst that of the salinity distributions was 0.2. The

95% CI around the mean is ± 1.4° C for temperature and ± 0.4 for salinity. It should be noted, however, that this is an overall estimate, and coastal areas with a large fresh water input have a higher variability due to both inter-annual and intra-mensal variability in river discharge.

A Harmonic Analysis Method of Least Squares (HAMELS, see Emery and Thomson (1997), section 5.5), which fitted oscillations with a period of 6 & 12 months, was applied to the monthly-averaged variables of each grid cell. This analysis provides an easy way to visualise the spatial pattern of the seasonal cycle using the annual mean, the range and phase of each variable. We also show how much of the annual variability is explained by this fitted seasonal cycle using the R^2 value from the HAMELS analysis (see Section 3.1 and Figures 2 and 3). The results of the HAMELS analysis in regions of low R^2 and/or with a fitted amplitude smaller than the confidence interval (see above) should be interpreted with care. For example, the month of maximum temperature at the bottom of the Norwegian Trench is found to be January in the HAMELS analysis (Figure 2), but with an R^2 value of approximately 0.75 and a very small amplitude, this is an unreliable result. Similar care should be taken with the interpretation of annual cycles of salinity: in many localities, the amplitude of the fitted salinity cycle and R^2 are low (Figure 3). This is in part because the monthly and interannual variability in salinity are of similar magnitude to the amplitude of the annual cycle (see Section 3.1 and for example, Janssen et al. (1999)).

A consequence of treating the four variables independently is the possibility of artificially creating vertical density instabilities in the resultant climatological dataset. Instabilities occur when more dense water overlies less dense water, and are a physically unrealistic condition which cannot occur in a mean profile.

An unstable condition in the climatology can occur in the analysis due to the different temporal distribution of records for each variable. For example, in a single grid cell, the measurements contributing to the surface value may have come mainly from a survey conducted during a colder year, while those from the bottom may have come from measurements during a warmer year, resulting in the mean near-bed data being slightly warmer than the mean surface data and a resultant unstable vertical profile. Density differences in excess of 0.03 kg m^{-3} were considered too unstable (Janssen et al., 1999). Visual analysis of vertical density difference maps ($\rho_{bottom} - \rho_{surface}$) showed these instabilities were restricted mostly to coastal areas and more specifically, to those with a high freshwater input, such as Liverpool Bay and the Dutch coast. Because these are shallow locations, close to land, with highly variable freshwater input, the salinity distribution at these locations was artificially mixed to be uniform with depth by assigning the average of the surface and near-bed salinity. At the small number of locations where density instability still occurred, the temperature was then replaced by that predicted by the HAMELS fit. This process eliminated all occurrences of density instability.

3 Results and Discussion

The final products of this analysis are monthly mean values for each variable (surface temperature, near-bed temperature, surface salinity and near-bed salinity) at each of the grid points (∼10 km resolution) in the defined region. Figures of these gridded variables may be requested from the authors or be found online at `http://www.ices.dk/ocean/oceanclimate/oceanclimate.asp`.

3.1 Seasonal analysis

Figure 2 shows the annual mean and annual cycle of temperature for the near-surface and near-bed levels. As expected, the distribution of temperature clearly shows an inverse relationship with latitude along with the strong influence of the North Atlantic Ocean, with southern and western regions generally warmer than those further north and within the North Sea. In addition, the strongest signal in amplitude of the annual temperature cycle occurs in the shallower regions of the continental shelf. It can also be seen that in the near-bed layer (Figure 2 d), the areas which are stratified in summer have a much lower amplitude than those which remain mixed throughout the year (eg. northern North Sea compared to southern areas).

The NW European continental shelf is strongly influenced by density gradients due to both temperature and salinity. In summer months, regions where tidal mixing is relatively weak become stratified due to the large buoyancy input from solar heating being insufficiently mixed down (Bowers and Simpson, 1987). Where there is a transition from stratified to fully-mixed waters, tidal mixing fronts occur. The location of these seasonally occurring tidal mixing fronts, such as the Celtic Sea front and North Sea front, can be seen in Figure 2 (c). Comparison of these results with published work on the location of tidal mixing fronts (Elliott et al., 1991; Holt and Umlauf, 2008) shows a good agreement.

The seasonal stratification on the NW European shelf has a strong influence on the phase of the near-bed temperature cycle (Figure 2 f). In the surface layer (Figure 2 e), the month of maximum temperature is quite uniform and tends to occur in late August/early September. In well mixed areas (Figure 2 f), the month of maximum near-bed temperature also occurs around August/September. In areas of seasonal stratification, the maximum near-bed temperature occurs during October, once the thermocline breaks down, and the warm surface layer is mixed downwards.

From the annual mean salinity (Figure 3, a and b), it can be seen that waters close to the North Atlantic Ocean are more saline. Furthermore, throughout the year, density stratification due to large fresh water inputs occurs in some regions of the NW European continental shelf. These regions of freshwater influence (ROFIs) are the Baltic outflow region, the Dutch coastal region, the Clyde Sea and the Liverpool Bay area (Simpson and Rippeth, 1993; Simpson, 1997; Fisher et al., 2002). The seasonal cycle in salinity (Figure 3) at a point is caused by the changing balance of evaporation (fresh water loss) with precipitation and land and river runoff (freshwater gains) throughout the year, combined with the effects of advection of water masses. The variability in salinity within each month, as well as between seasons and between years, are all of similar magnitude (for example, Janssen et al. (1999)) which makes it difficult to determine the seasonal cycle with any confidence (see regions of low R^2 in Figure 3, g and h). For all near-bed locations and most surface regions of the NW European continental shelf, the amplitude of the seasonal salinity cycle lies below the 95% confidence bounds; therefore it is not possible to make any firm conclusions about the seasonal signal in these areas (Figure 3, c and d). There is, however, a clear seasonal signal in salinity within the Baltic surface outflow (Figure 3, c). The salinity in this region of the NW European continental shelf reaches a maximum in winter time (January-March) when the presence of ice in the Baltic Sea locks up freshwater, increasing the salinity of the outflow.

3.2 Reliability of climatology

For most research purposes, it is desirable to have a single index which represents the reliability of the data. The two indices presented show the distribution of observations throughout the (climatic) year and in space, and the distribution in time of the observations (both throughout the year and within the 30-year period).

The first index was calculated for each grid cell as a percentage of months of the year where there were observations, or as a percentage of years in the 30-year period with measurements. Areas with observations in one month of the year are those where the index is equal to 8% in Figure 4 (a and b). It is clear from this analysis that the sparseness of available data in the south-west of the region significantly reduces the confidence that can be placed on the results in this area, and this is clearly an area in which more observational effort is required. Figure 4 (c and d) also demonstrate the value of the repeat hydrographic sections which are included in the ICES database. Most locations are visited less than 10 years out of the 30 included in the period, but the standard lines used for long-term monitoring purposes are visited more regularly; some like the Ellet line (Scottish West coast; Holliday et al., 2000 & Hughes and Holliday, 2007), JONSIS-Utsire line (Orkney-Stavanger; Turrell et al., 1996 & Sjøtun, 2004 & Hughes and Holliday, 2007) and Feie-Shetland line (Shetland-Bergen; Sjøtun, 2004) are occupied yearly or several times per year (not shown). In the absence of repeat hydrographic data, observations from regular repeated surveys also provide valuable additional data, for example the

BSH North Sea survey and the quarterly ICES International Bottom Trawl Survey.

As well as the distribution of data in time, the skewness of the underlying observations, throughout a year or throughout the measurement period (1971-2000) was assessed. In general, no particular region was strongly biased by skewness. Results in the German Bight indicated some measurement bias toward the earlier years and toward measurement made later in the year. Figure 1 shows an overall bias in the number of measurements to the 1990's, but this was not reflected in the spatial distribution of skewness indicating that the increased number of measurements during the 1990's was distributed over a fairly wide area. The majority of these data are likely to be those collected during the North Sea project (Charnock, 1994), with a range of stations distributed across the southern North Sea, south of 56° N, between August 1988 and October 1990. Despite the significance of this project to the number of observations collected, the assessment of skewness showed no particular bias of the southern North Sea compared to other areas.

3.3 Comparison to existing climatologies

Comparisons with existing climatologies have also been carried out. The climatology presented by Janssen et al. (1999) for the North and Baltic Seas is the most directly comparable data set, although it extends over a longer period (1900-1996). In the absence of public availability, visual comparison of the monthly-averaged surface and near-bed temperature and salinity distribution from our climatology with that of Janssen et al. (1999) shows a reasonable agreement in the spatial pattern, and the main difference between the two datasets appears to be an overall minor increase in the average values. This is not against expectation as the period 1997-2000 was much warmer than average. Also, the temperature distributions are visually well correlated with those published by Elliott et al. (1991).

Figures 5 and 6 show a direct comparison of our sea surface temperature climatology with those of BSH[3] and ICOADS[4], respectively. As can be seen from Figure 5, comparison with BSH in the North Sea for the same period (Loewe, 1996; Loewe et al., 2003) shows good agreement. Furthermore, comparison with the ICOADS 1° climatology (interpolated onto a 1/6° longitude by 1/10° latitude grid) shows the annual mean sea surface temperature not to differ by more than 1° C. In Figure 6, it can also be seen that regions with the largest discrepancies are either regions where our climatology is known to be less reliable (SW continental slope), or areas where global scale climatologies lack the resolution to resolve hydrographic features important to the region such as the Baltic outflow, Atlantic inflows and shallow areas of freshwater influence.

4 Conclusions

We have presented a climatology of temperature and salinity at the surface and near the seabed for the period 1971-2000, on a more refined spatial scale ($\sim$ 10 km), and covering a larger area (NW European continental shelf) than

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[3] `http://www.bsh.de/en/Marine_data/Observations/Sea_surface_temperatures/index.jsp`

[4] Data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA; `http://www.cdc.noaa.gov/`

those previously published in the literature. Furthermore, this climatology will be freely available from Fisheries Research Services and the ICES data centre.

The climatology shows the expected distributions of temperature and salinity throughout the year and across the region. The locations of tidal mixing fronts and ROFIs agree well with those presented by other researchers (Simpson and Rippeth, 1993; Simpson, 1997; Fisher et al., 2002; Holt and Umlauf, 2008). Moreover, comparison with other climatologies, such as those by Janssen et al. (1999), Elliott et al. (1991), BSH (Loewe, 1996; Loewe et al., 2003) and ICOADS show good agreement of the annual cycles and monthly averages.

The process of generating this climatology has highlighted the sparsity of available observations in the more remote areas of the continental shelf. Although a high density of observations occurs within the North Sea region, the available measurements are more scant in the Western regions of the domain. It is possible that measurements in these regions exist but are not collated within the databases we used (ICES and WODC). If not, more observations in these data sparse areas are essential if we are to be able to accurately describe the hydrography of the region.

As with all data products, there will be scope to enhance this climatology in future with additional data or advanced data analysis techniques. Future areas of work are currently being explored, which include the development of anomaly maps of seasonal surface and near-bed temperature in each year, products which we feel are in demand to the scientific community but are not currently available.

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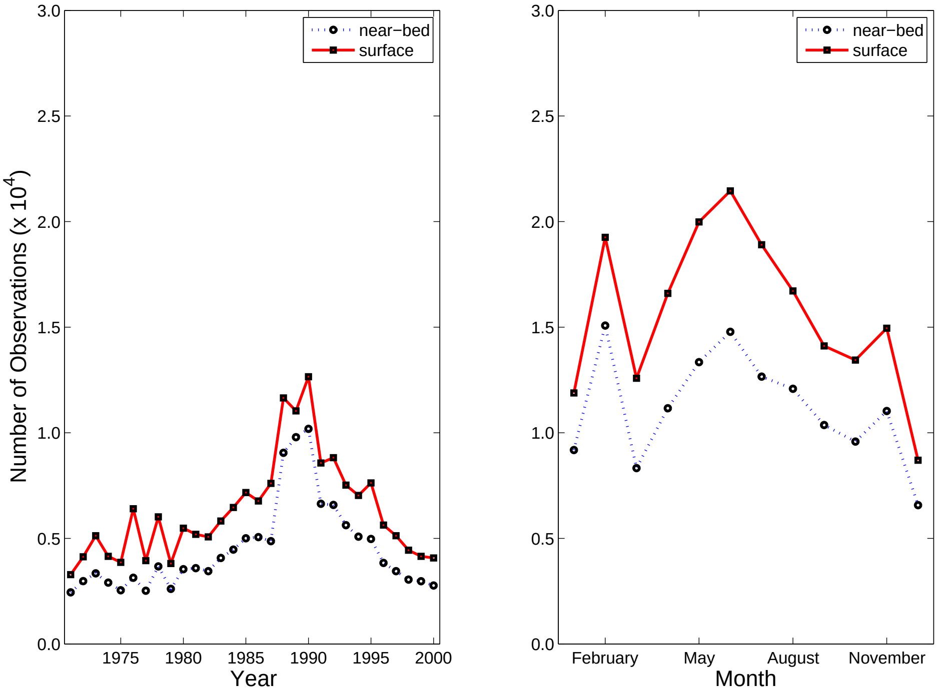

Figure 1. Distribution by year (left) and month (right) of near-surface and near-bed observations of temperature and salinity for the period 1971-2000.

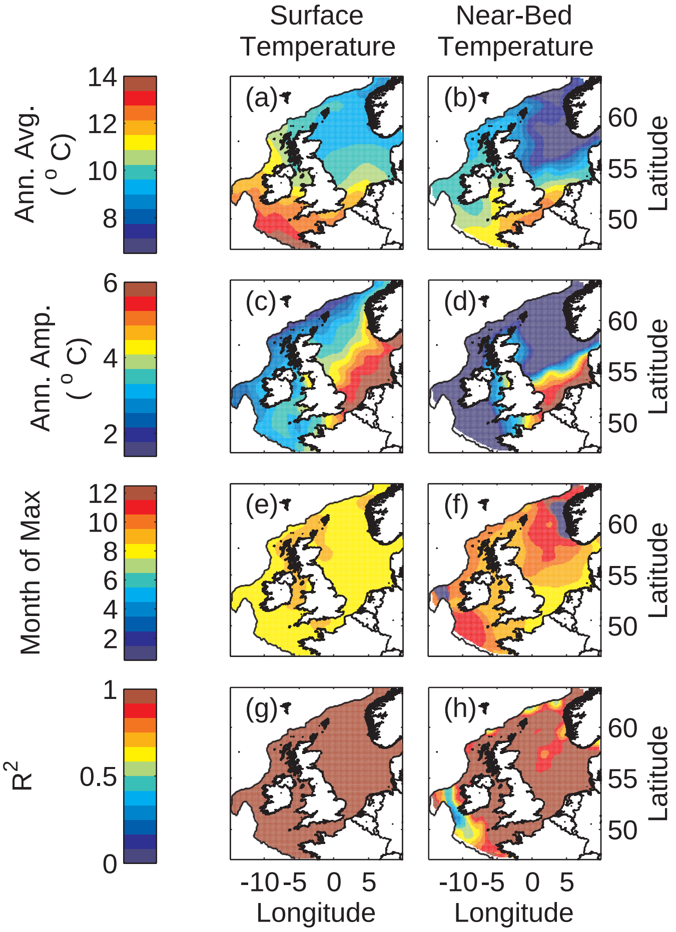

Figure 2. Left - surface layer, right - near-bed layer: (a,b) annual mean temperature (° C), (c,d) annual seasonal cycle amplitude (° C), (e,f) phase (expressed as month of maximum), and (g,h) R^2 of the HAMELS analysis; for the period 1971-2000.

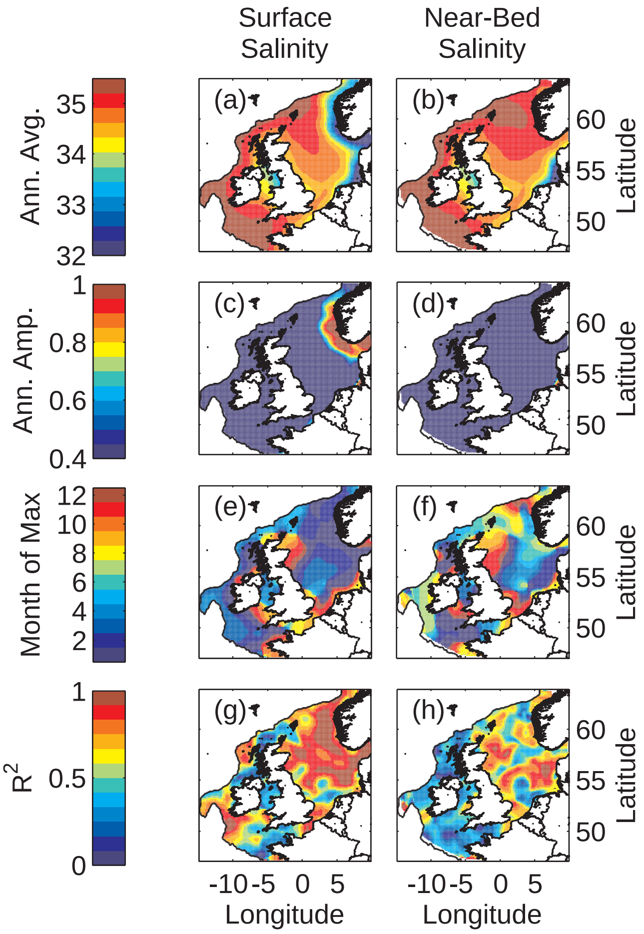

Figure 3. Left - surface layer, right - near-bed layer: (a,b) annual mean salinity, (c,d) annual seasonal cycle amplitude, and (e,f) R^2 of the HAMELS analysis; for the period 1971-2000. Please note that phase of the annual salinity cycle is not shown (see text).

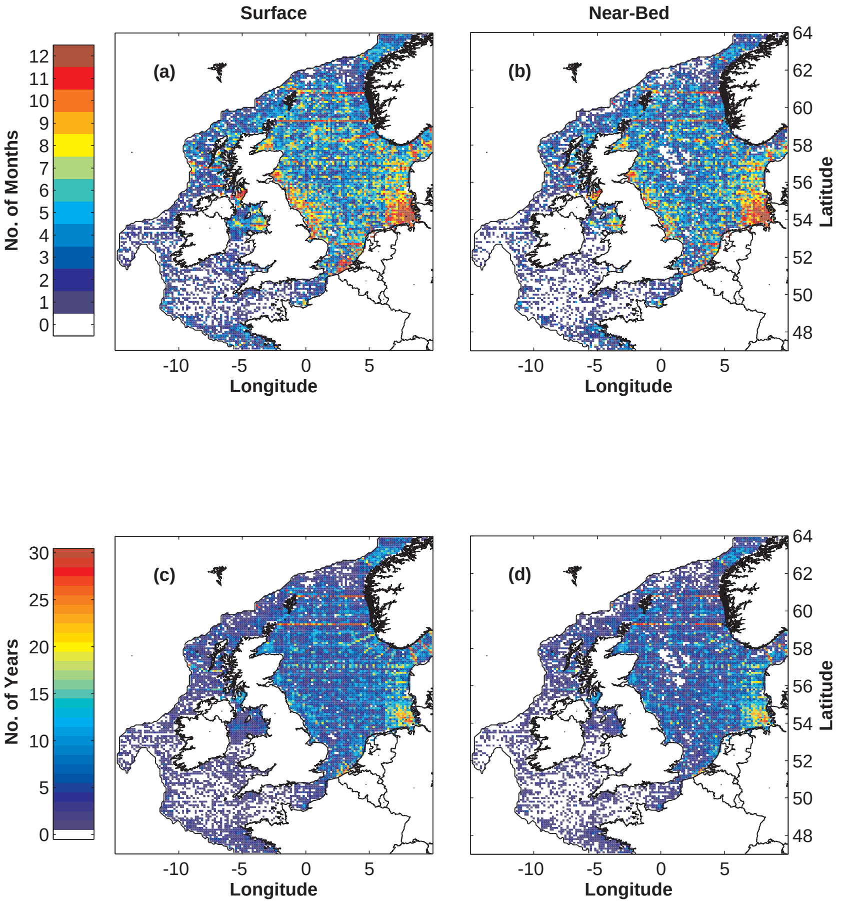

Figure 4. Percentage of months with valid measurements for (a) near-surface and (b) near-bed observations in the period 1971-2000 and percentage of years with valid measurements for (c) near-surface and (d) near-bed observations in the period 1971-2000. White areas are regions outside the domain, or where no valid observations were found. Regions coloured red are locations where the calculated annual cycle is thought to accurately represent the conditions throughout the year/within the 30-year period; blue areas on the other hand carry less confidence.

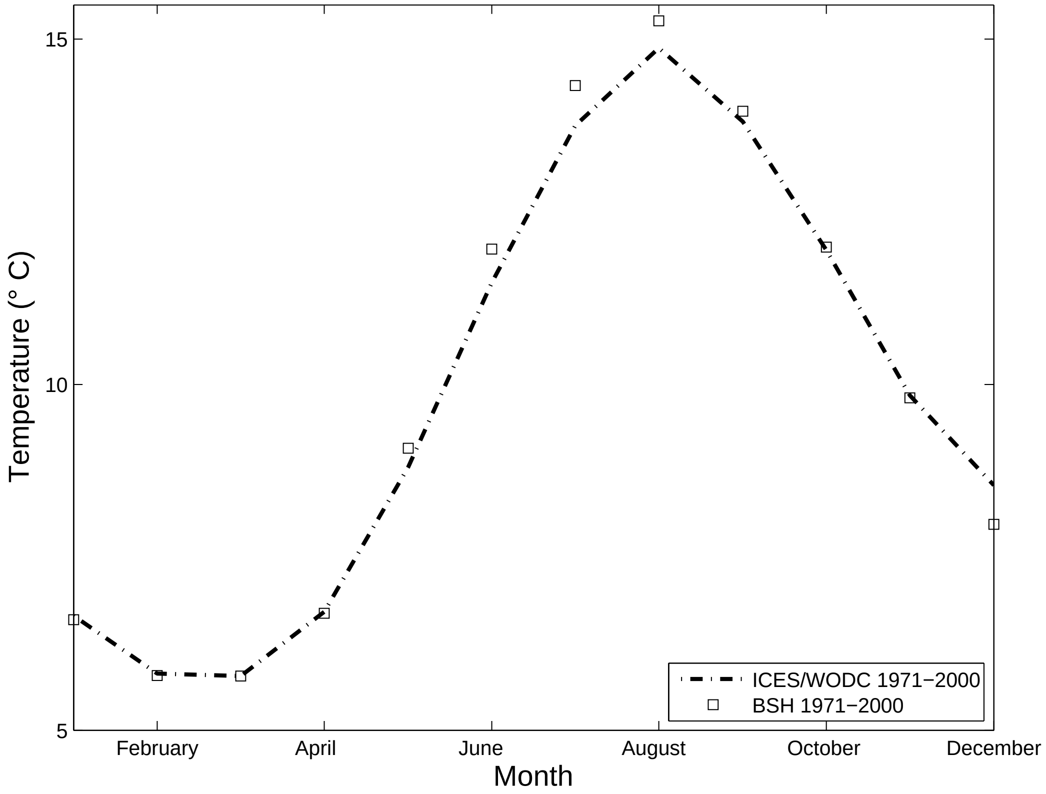

Figure 5. Comparison of temperature (° C) from the ICES/WODC Climatology and BSH Climatology in the North Sea in the period 1971-2000.

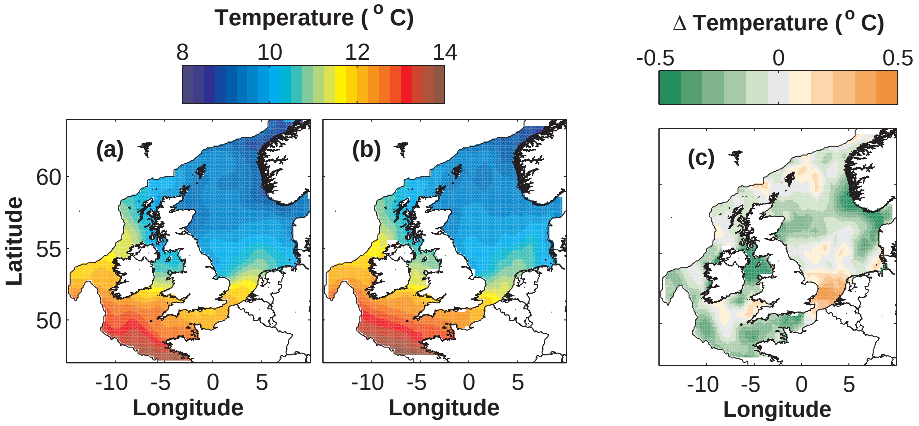

Figure 6. Annual mean sea surface temperature (° C) from (a) the ICES/WODC Climatology and (b) the ICOADS Climatology on the NW European Shelf for the period 1971-2000, and showing (c) the difference of ICES/WODC - ICOADS (° C).