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Heat content in the Norwegian Sea, 1995–2010

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Spatio-temporal hydrographic data from the Nordic Seas during spring over the period 1995–2010 were investigated in terms of the relative heat content (RHC) above the density surface $\sigma_t = 27.9$, chosen to capture the changes in Atlantic water (AW). Focusing on the Atlantic (eastern) domain of the Nordic Seas, negative anomalies dominated the early part of the series. There was then a gradual transition towards an absolute maximum in 2003/2004, followed by a small reduction with positive values for the period ending in 2010. The maps clearly reveal the events of propagating signals. The variability is regionally comparable, but the persistence on a year-to-year basis is higher in the Lofoten Basin than in the Norwegian Basin. Compared with other studies, in this study, the estimated trend in the RHC of the Nordic Seas was larger than for the global mean and the North Atlantic. The warming of the Nordic Seas derives mainly from the advection of warmer inflowing AW and less from changes in local air–sea heat fluxes. The importance of advection suggests that the variability of the Norwegian Sea's ocean climate can, to a large extent, be predicted based on the observed hydrographic conditions.

Keywords: advection, climate, ecosystem, heat flux, Nordic Seas, predictability.

Introduction

Oceanic heat content is a key parameter in climate change studies (Levitus *et al.*, 2009). Global estimates show a trend corresponding to an oceanic heat input of 0.21 W m^{-2} over the period 1961–2003 (Intergovernmental Panel on Climate Change, IPCC), with approximately two-thirds of the change in the upper 700 m (Bindoff *et al.*, 2007). The main purpose of this study was to investigate the spatio-temporal evolution of the relative heat content (RHC) of the Nordic Seas (Figure 1) during the period 1995–2010. The study focused on the changes of the Atlantic domain, of which the spatial extent has a large impact on the habitat of biological organisms in the Norwegian Sea (Skjoldal, 2004).

Oceanic heat content has traditionally been estimated by calculating the mean temperature above some fixed depth. However, Palmer *et al.* (2007) showed that this method is sensitive to windstress-forced upwelling/downwelling and eddies, and they found a more spatially uniform pattern of ocean warming when using a fixed isotherm instead of a fixed depth as the lower boundary. The method of Palmer and Haines (2009) was followed, but mean temperature was calculated above a fixed density surface (isopycnal) rather than their approach of using a surface of constant temperature. A general advantage of using an isopycnal (or isotherm) is that the respective contributions to changes in the heat content from oceanic advection (changes in the depth of the isopycnal) and changes in the air–sea heat fluxes (warming/cooling above the isopycnal) can be quantified (Moisan and Niiler, 1998; Palmer and Haines, 2009). Most recently, of relevance to this study, the climatology of the Nordic Seas in terms of density (specific anomaly) surfaces was, for the first time, analysed in detailed by Rossby *et al.* (2009) using hydrographic observations from the period 1951–2000.

Because hydrographic data tend to be widely spaced, most studies of the Nordic Seas have been limited to the comparison of data from sections. Based on this approach, the temperature of the inflowing Atlantic water (AW) has increased by ~0.5–1.0°C since the 1970s (Figure 2). However, this change only describes the evolution in some defined core of the AW, whereas other parameters, such as the water mass extent and heat content, are not well represented.

In this study, we took advantage of the survey data during the period 1995–2010 from the annual spring cruises that cover the Nordic Seas. Specifically, the changes in the RHC above the density surface $\sigma_t = 27.9$ are described in detail. These changes were further investigated in terms of trends and regional differences and were compared with the contributions from the atmospheric heat flux.

Data and methods

The hydrographic data used in this study were acquired from the combined datasets from the International Council for the Exploration of the Sea (ICES) and the Argo Global Data Assembly Centre (Coriolis Data Centre, France). The periods of

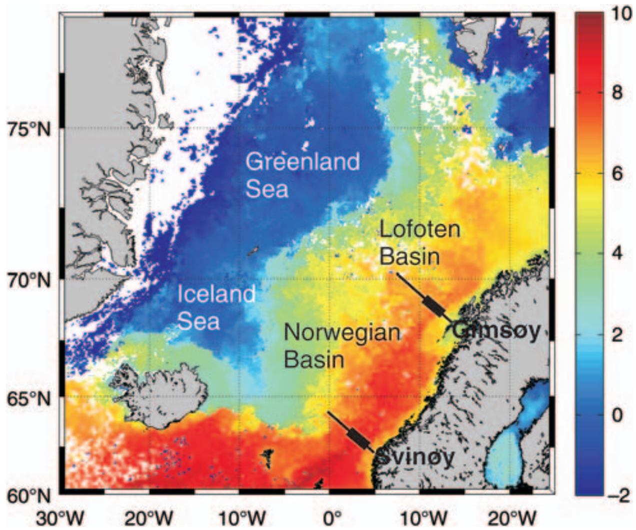

Figure 1. Daily 4-km resolution, sea surface temperature (°C) averaged over February 2008 for the Nordic Seas: Greenland, Iceland, and the Norwegian Sea, divided into the Norwegian and Lofoten Basins. Data are from the National Oceanographic Data Center (NODC), USA (Kilpatrick *et al.*, 2001). The Svinøy-NW and Gimsøy-NW sections are indicated. The small, thick lines within the sections show the locations of the time-series in Figure 2.

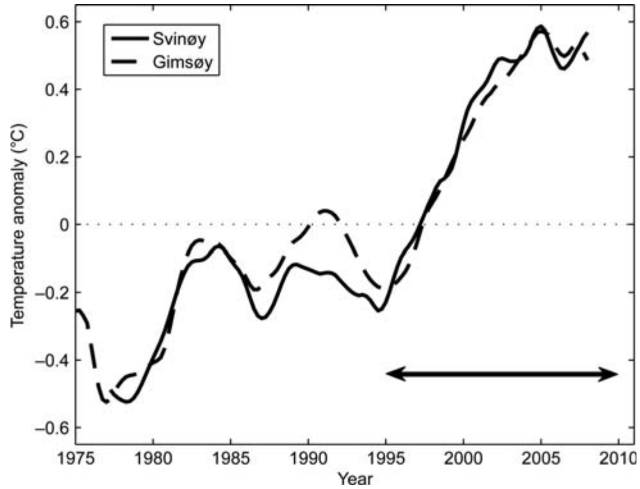

Figure 2. Time-series of temperature, averaged over the depths 50–200 m, in the core of the AW at the Svinøy-NW and Gimsøy-NW sections. See Figure 1 for the locations. The arrow shows the period of the focus in this study. A 5-year moving average filter was applied to the data.

interest were 15 April–15 June of each year from 1995 to 2010. This period was chosen because it coincided with internationally coordinated cruises that occupied the Norwegian Sea. An international effort that is part of an ICES initiative (Working Group on Northeast Atlantic Pelagic Ecosystem Surveys, WGNAPES) aims to measure the pelagic fish stocks in the Norwegian Sea. During these surveys, CTD stations are taken regularly, typically every 60 nautical miles, and the maximum depths of the CTD stations are generally 1000 m or deeper. The number of profiles varies depending on the year and location with regard to the two basins in the Norwegian Sea. Figure 3 depicts an overview of the data coverage.

Most of the hydrographic data have already been checked at the different national data centres and at the international ICES and Argo data centres, yet some additional data handling was performed. First, the temperature and the salinity at each depth were verified to be within the likely ranges in the Nordic Seas, [−1.9, 20°C] and [20, 35.8], respectively. When the data were outside the usual ranges, the temperature/salinity at the given depth was flagged as suspicious and was not used. Second, the CTD profiles were checked for density inversion; when a profile had a density inversion >0.05 kg m^{-3}, the profile was rejected, similar to the methods of Roemmich and Gilson (2009) and Rossby *et al.* (2009). Third, after all the CTD profiles were vertically interpolated at 5-m intervals from 5 to 1000 m, profiles in 4 × 2° spatial grid boxes were compared with the mean and s.d. within the associated grid boxes. When the temperature (or salinity) within a box at a given depth differed by more than 6 s.d. of the mean, the temperature (or salinity) from the profile at that depth was flagged as suspicious and was not used. Profiles with more than two flags were discarded.

As the period of interest had a 2-month range within the year, the temperature may be biased, particularly in the upper layer, because of seasonal warming. The temperature was, therefore, corrected using the monthly trend in the World Ocean Atlas 2009 (WOA09; Antonov *et al.*, 2010; Locarnini *et al.*, 2010) to be centred on 15 May.

For each year and at every depth, the observations were interpolated using objective analysis utilizing a Gaussian correlation function (Gandin, 1963; Bretherton *et al.*, 1976). The influence radius was chosen to be 140 km. Following earlier studies (e.g. Lavender *et al.*, 2005; Roemmich and Gilson, 2009; Voet *et al.*, 2010), the effective distance r between the analysis (grid) and the observation points was modified based on the difference in bottom depths, as follows:

$$r^2 = r_x^2 + r_y^2 + \left(\lambda \frac{H_a - H_o}{H_a + H_o}\right)^2, \qquad (1)$$

where r_x (r_y) is the geographic distance between the observation and analysis points in the zonal (meridional) direction, and H is the bottom depth at the analysis (subscript a) and observation (subscript o) points. The topography parameter λ was set to 300 km, as in Lavender *et al.* (2005) and Voet *et al.* (2010). A background field for the temperature and salinity at every depth was made by interpolating all the observations using the WOA09 data as the background field. The calculated background fields were used in the interpolation of the data for individual years. The interpolation was performed on a grid with intervals of 0.25 and 0.5° in the zonal and meridional directions, respectively.

The heat content was calculated above the $\sigma_t = 27.9$ surface using the time-averaged temperature (i.e. 1995–2010) at this surface as the reference temperature. This surface is close to the lower depth of the Atlantic layer in the Norwegian Sea (Mork and Blindheim, 2000). Because heat content is calculated relative to a reference temperature, the RHC term proposed by Palmer and Haines (2009) was used. The RHC is defined as follows:

$$H = c_p \rho_0 \int_{-h}^{0} (T - T_{\mathrm{ref}}) \mathrm{d}z, \qquad (2)$$

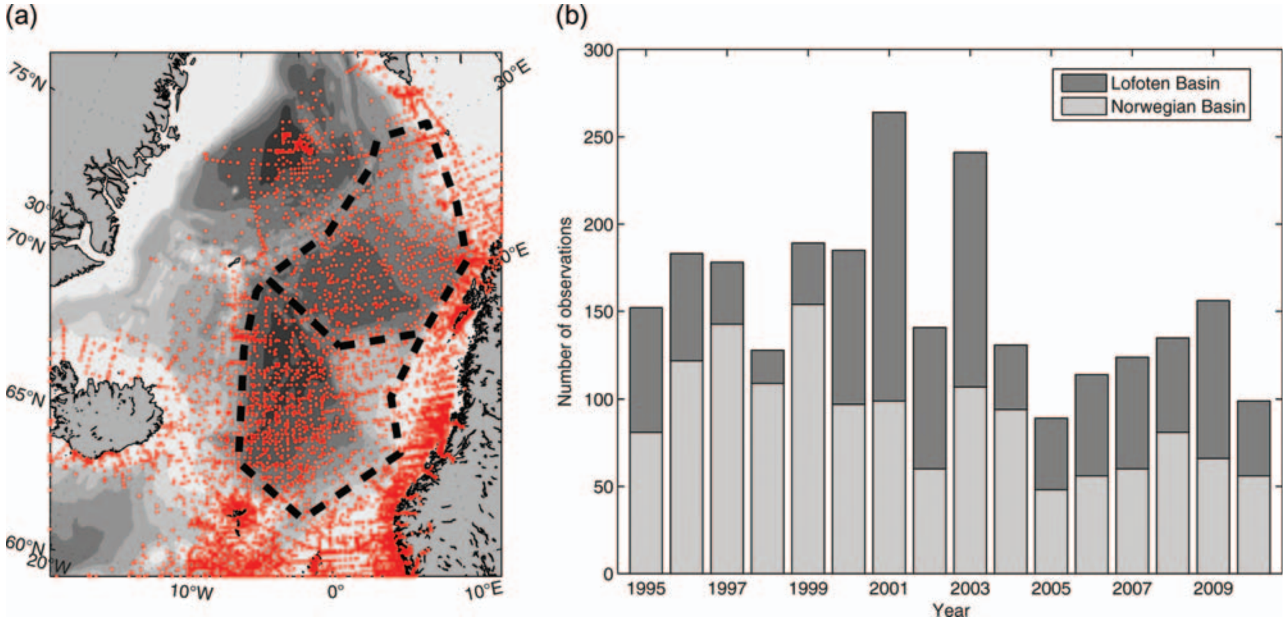

Figure 3. (a) Distribution of all hydrographic stations during the period 15 April – 15 June, 1995 – 2010, and (b) the number of stations each year within the Norwegian Sea divided into the Norwegian and Lofoten Basins. The dashed lines in (a) indicate the northern (Lofoten Basin) and southern (Norwegian Basin) areas used for the spatial averages.

where c_p is the heat capacity, ρ_0 a density reference, h the depth of the $\sigma_t = 27.9$ surface, z the vertical axis with $z = 0$ at the sea surface, and T_{ref} the reference temperature at h. Both T_{ref} and h vary spatially, and h varies additionally with time. Equation (2) can be written as follows:

$$H = c_p \rho_0 h (T_{\mathrm{a}} - T_{\mathrm{ref}}), \tag{3}$$

where

$$T_{\mathrm{a}} = \frac{1}{h} \int_{-h}^{0} T \, \mathrm{d}z. \tag{4}$$

To estimate the different contribution to the changes in the RHC, the variables are decomposed into a time mean and fluctuating parts, as follows:

$$H = \bar{H} + H', \quad h = \bar{h} + h', \quad T_{\mathrm{a}} = \overline{T}_{\mathrm{a}} + T'_{\mathrm{a}}. \tag{5}$$

Because the focus is on the variability, the time-mean terms are removed. When omitting the $h'T'$ term, which is small, the RHC changes give the following:

$$H' \cong c_p \rho_0 h' (\overline{T}_{\mathrm{a}} - T_{\mathrm{ref}}) + c_p \rho_0 \bar{h} \, T'_{\mathrm{a}}. \tag{6}$$

The first term on the right side contributes to the heat content changes attributable to changes in the depth of the density surface, whereas the second term contributes through temperature changes. The former term is sensitive to changes in the ocean circulation, whereas the air–sea heat fluxes influence the latter term (Palmer *et al.*, 2007).

Results

The time-mean depth of the $\sigma_t = 27.9$ surface shows the largest values in the eastern part of the Nordic Seas that shoal to the west, with maximum values of ~800 m in the Lofoten Basin (Figure 4). There is a marked boundary in the central region of the Nordic Seas along the ridge areas, south along the Jan Mayen Ridge and north along the Mohn and Knipovich Ridge, which separates the AW to the east and the Arctic Water to the west. The temperature at the density surface had a relative minimum in the Atlantic domain in the southern part of the Norwegian Sea, and the values increased in the Lofoten Basin and northwards. In the northern Lofoten Basin, the temperature was higher than the lower temperature range of the AW. Therefore, the chosen density surface did not capture the entire AW in this region. This region, however, was not the main focus of this study and had minor influence on the results.

The RHC anomalies show a spatio-temporal variability at many scales (Figure 5). Focusing on the Atlantic domain, negative anomalies dominated in the early part of the series; then a gradual transition towards an absolute maximum in 2003/2004 was followed by a small reduction with positive values. The maps indicate the events of the propagating signals. The clearest events are negative anomalies from 1995 to 1998 and positive anomalies from 2003 to 2006(7) that propagate northwards in the direction of the general circulation. The year-to-year shift of the anomalies from along the continental margin to the interior basin is also notable. Outside the Atlantic domain, the anomalies are considerably weaker. This result can, at least partly, be explained by the shallow depth of the density surface (Figure 4a).

Based on the data from Figure 5, the linear change in the heat content during the years 1995–2010 was calculated (Figure 6a), and the change was positive over the entire Norwegian Sea, except in the south where it was influenced by Arctic Water derived from the East Icelandic Current. The largest values were recorded in the Lofoten Basin, with a maximum change of 8 W m^{-2} in the central part of the basin, and on the eastern side along the pathways of the AW. To resolve the persistence of the RHC, an autocorrelation with a 1-year time-lag was estimated

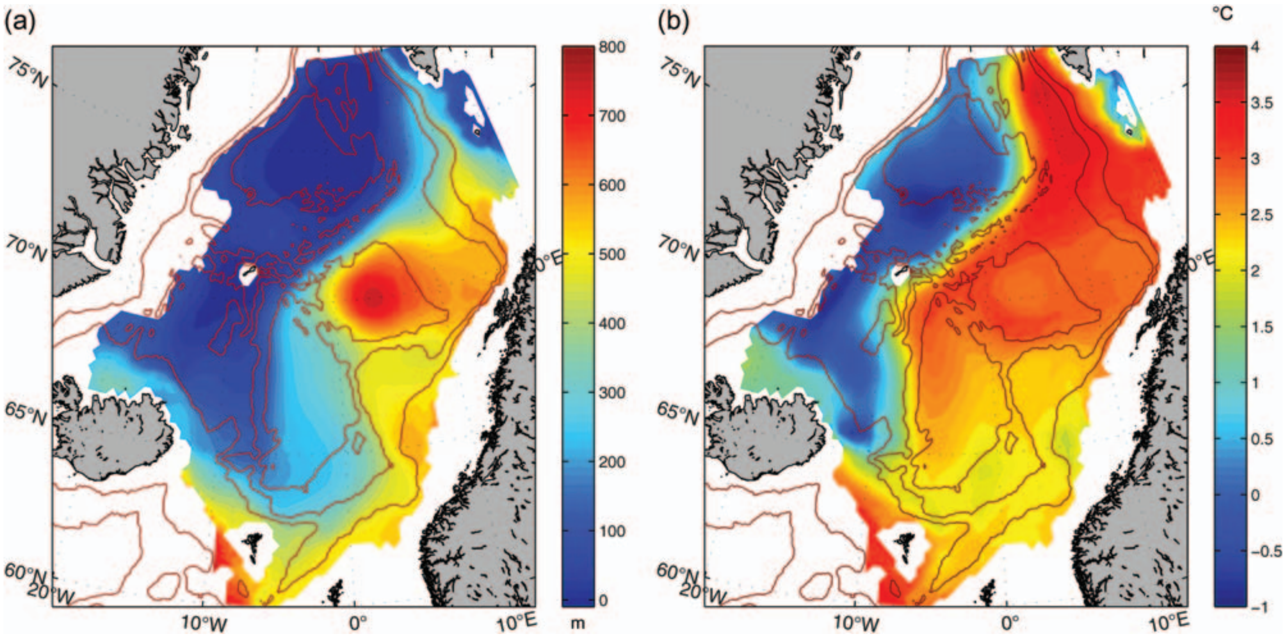

Figure 4. (a) Time-averaged (15 April – 15 June of each year, 1995 – 2010) depth of the $\sigma_t = 27.9$ surface, and (b) temperature at the $\sigma_t = 27.9$ surface.

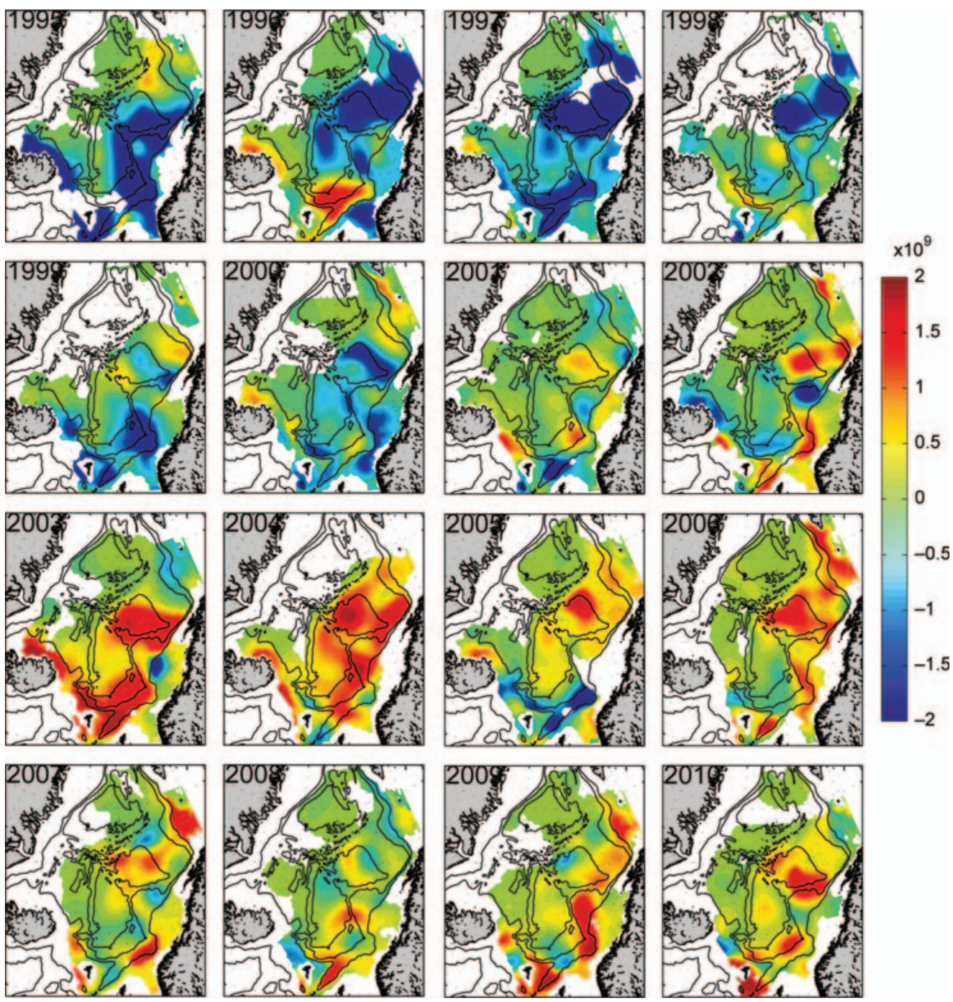

Figure 5. Heat content anomalies for each individual year between 1995 and 2010.

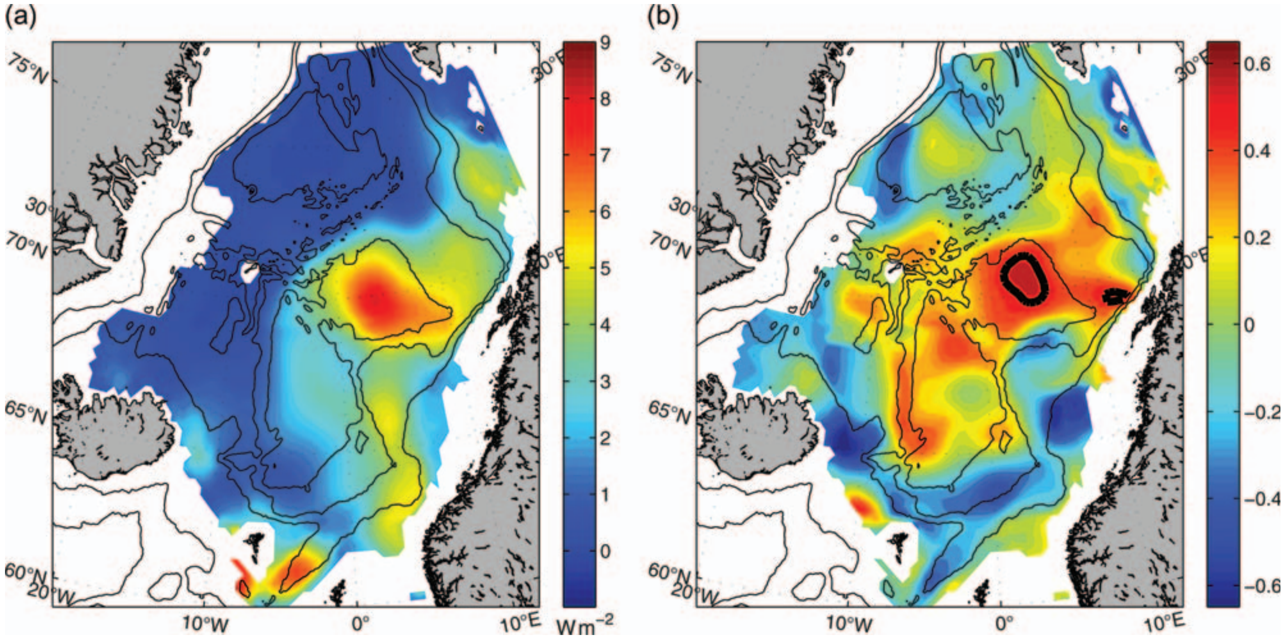

Figure 6. (a) Linear increase in heat content (W m^{-2}) during the period 1995–2010. (b) Autocorrelation with a 1-year time-lag using detrended data. All values in (a) are positive, and the thick lines in (b) indicate the 95% significance level.

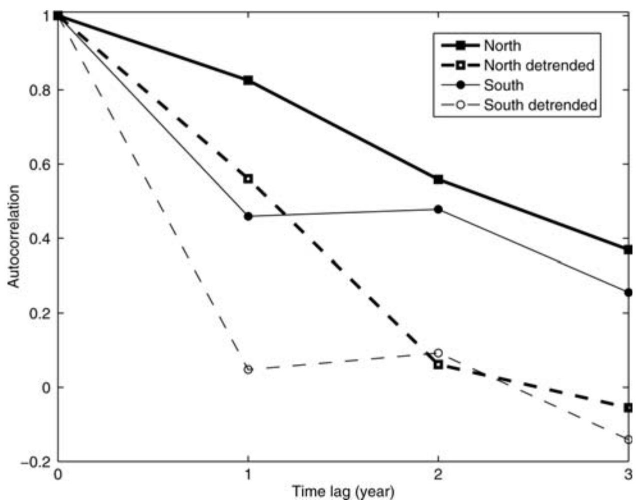

Figure 7. Autocorrelation of the heat content in the Lofoten (north) and Norwegian (south) Basins using both raw and detrended data.

(Figure 6b). The Lofoten Basin had the highest values, with a maximum in the centre of the basin. There was also a positive autocorrelation band in the western part of the Norwegian Basin, indicating persistence in the Jan Mayen Frontal zone. The Norwegian Basin is affected by the different inflows of AW and Arctic Water, leading to a weak autocorrelation. The persistence of the RHC in both the Lofoten Basin and the Norwegian Basin is due to the long-term trend of the RHC. After removing the trend for each site, there was no significant autocorrelation anywhere, except in the Lofoten Basin, which showed some persistence at a 1-year lag (Figure 7).

The average heat content in the Norwegian Sea increased linearly by 3.2 W m^{-2} (Figure 8), with a larger contribution from the Lofoten Basin (3.7 W m^{-2}) than the Norwegian Basin (2.6 W m^{-2}). The variability in the heat content is mainly due to changes in the mean temperature above the density surface, and the heat gain during the period 1995–2010 in both basins was the result of increased temperature. The contribution from depth changes of the density surface was relatively minor, except for 2004, when it contributed more than the temperature changes. The depth anomaly for 2004 showed a deepening of the density surface in the western part of the Norwegian Sea, with the largest deepening anomaly of $>$200 m in the Lofoten Basin (data not shown). The rate of yearly change in the heat content had the highest variability in the Norwegian Basin, when compared with the Lofoten Basin. The air–sea fluxes can only partly explain the variability in the heat content.

Discussion

Estimates of the heat content and its rate of change for the Nordic Seas based on hydrographic observations are presented. These estimates are new in several ways. First, they are based on the spatial coverage of observations that constitute the Nordic Seas at the same time of year, every year, since 1995. Several studies of the variability of the heat content (and other properties) in the Nordic Seas have focused on regularly monitored fixed sections and/or patchy data locations (e.g. from single surveys or Argo floats). Second, the calculation of the heat content is based on the integration from the surface to a density surface instead of the traditional approach using a fixed depth. The local time-averaged temperature at the density surface is also used as the temperature reference, which better reflects the local changes.

The linear change in estimated heat content from 1995 to 2010 is much higher ($\sim$3.2 W m^{-2}) than the global ($\sim$0.2 W m^{-2}) and North Atlantic ($\sim$0.7 W m^{-2}) estimates for the period 1970–2000 (Levitus *et al.*, 2009; Palmer and Haines, 2009). Despite there being some relationship, the change in the heat content for the Nordic Seas could not be explained by the changes in the local air–sea

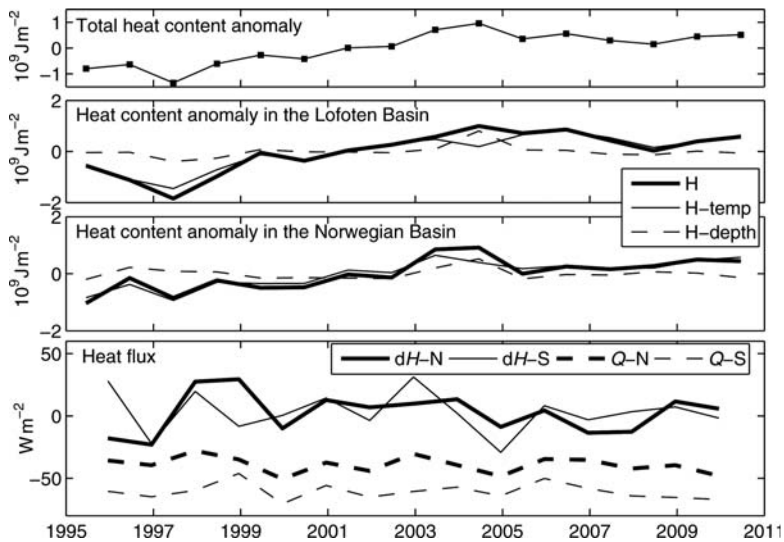

Figure 8. Time-series of the total heat content anomaly in the Norwegian Sea and the heat content anomaly and its temperature and depth contributions for the Lofoten and Norwegian Basins. Lower panel: heat content changes (dH) and yearly averaged net air–sea heat fluxes (Q) for the Lofoten and Norwegian Basins, where N/S in the legend indicates the northern (Lofoten Basin)/southern (Norwegian Basin) area. The heat content time-series is centred on 15 May for each year, and the heat flux values on 15 November for each year.

heat fluxes. Our next step was to assess whether advection could explain the increase in the heat content. For the volume flux, the observations indicated no significant trend over the past few decades in the North Atlantic Current (Willis, 2010) or in the Norwegian Atlantic Current (Orvik and Skagseth, 2005; Mork and Skagseth, 2010). However, during the same period, the temperature of the inflowing AW increased by ~0.5–1°C (Figure 2), an increase that is associated with circulation changes in the North Atlantic (Häkkinen and Rhines, 2004; Hatún *et al.*, 2005). By assuming that the volume flux was constant (4×10^6 m^3 s^{-1}), the temperature changes in the inflowing and outflowing AW gave an equivalent heat flux of ~2 W m^{-2}, which is approximately two-thirds of the mean linear increase of the heat content (3.2 W m^{-2}). Therefore, advection plays a key role in the heat budget of the Norwegian Sea.

The results show the largest change in the RHC located in the Lofoten Basin, which is consistent with a relatively direct transfer of warmer AW along the Norwegian Atlantic Slope Current before being deposited in the Lofoten Basin. The mechanism for this process appears to be the formation of anticyclonic eddies at the continental margin of the Lofoten Islands that, subsequently, drift west into the centre of the Lofoten Basin (Köhl, 2007), where the change was greatest. This result is further supported by the increased persistence (larger autocorrelation) of an anomalous heat content in the Lofoten Basin, compared with the Norwegian Basin. Another contribution to the trend in the RHC may be attributed to an increase in the North Atlantic Oscillation (NAO) and a corresponding increase in the westerly winds from the 1960s to the mid-1990s. In response to these changes, Blindheim *et al.* (2000) found a freshening and cooling of the upper layer and a reduced extent of AW in the Nordic Seas. It can, therefore, be speculated that the AW extent of the Nordic Seas has again increased in response to the subsequent period studied here (1995–2010) and is characterized by a relatively neutral NAO. Therefore, the circulation changes in both the North Atlantic Ocean and in large-scale atmospheric forcing (NAO) may have contributed to the recent warming trend in the Norwegian Sea.

A main result of this study is that the contribution to the anomalous heat content is mainly due to temperature changes. The depth change contributes most in some of the individual years evaluated, e.g. 2003 and 2004. In contrast, Palmer and Haines (2009) found that, in the North Atlantic, the depth change is a significant contributor to the heat content changes, and they further related this factor to the changes in the ocean circulation and the NAO. However, the depth of their surface was much shallower, ~200 m, compared with the surface depth in the present study. Another point is that Palmer and Haines (2009) investigated the period 1970–2000, a period characterized by sequences of years with strongly positive and negative NAOs. In comparison, the period investigated in this study (1995–2010) is more characterized by relatively small and shifting excursions in the NAO, suggesting that several consecutive years of anomalous NAO forcing are needed to change the depth of a given density surface significantly.

The density surface used in this study was chosen to capture the heat content changes in the AW domain of the Nordic Seas. To test the robustness of our results, a comparison was made with estimates that used the traditional method of a fixed depth, which was set to 500 m to capture the Atlantic layer. The reference temperature was set to zero, but this value is not important when the variability is the focus. Compared with the isopycnal approach, this method resulted in comparable large-scale variability but a less uniform trend.

The spatial extent of warm water has a large impact on the habitat of organisms in the Norwegian Sea and varies with atmospheric conditions such as the NAO (Blindheim *et al.*, 2000; Skjoldal, 2004). There are also links between the sea temperature and herring growth (Holst, 1996). The distribution of water masses also affects primary production: in the AW, the algae bloom is weaker and more prolonged, whereas in Arctic Water, the formation of a low-salinity surface layer induces a relatively early algae bloom (Skjoldal, 2004). Notably, the absolute minimum of the heat content in 1997 coincides with a local minimum in the zooplankton biomass, in both the Atlantic and Arctic Waters, and with a minimum fat content in herring (Holst *et al.*, 2004). The datasets used in the present study, together with the method of averaging properties over a density surface, have clear prospects of being compared with changes in the extent of fish and plankton in the Nordic Seas; this is, however, a task for the future.

Concluding remarks

During the period 1995–2010, there was an increase in the ocean heat content in the Norwegian Sea, corresponding to a heat flux of 3.2 W m^{-2}. These changes were most likely attributable to the advection of the warmer AW. Therefore, hydrographic changes in the Norwegian Sea can be predicted through regular monitoring of the hydrography in the Atlantic region.

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