Final Draft
of the original manuscript:

Meyer, E.M.I.; Pohlmann, T.; Weisse, R.:
Thermodynamic variability and change in the North Sea (1948–2007) derived from a multidecadal hindcast
In: Journal of Marine Systems (2011), Elsevier

DOI: 10.1016/j.jmarsys.2011.02.001

Thermodynamic variability and change in the North Sea (1948-2007) derived from a multidecadal hindcast

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DOI information: 10.1016/j.jmarsys.2011.02.001

Abstract

Using a 3D baroclinic shelf sea model for the North Sea a multidecadal (1948-2007) hindcast with a resolution of 20 km x 20 km is performed and analysed providing a description of long-term thermodynamic variability and change in the North Sea region. The simulation is validated with short-term, long-term and cross-section temperature measurements. For diurnal sea surface temperature (SST) a correlation between 0.79 and 0.89 was obtained. Comparisons with observed sea surface temperatures from Helgoland Roads (1873-2007) in the German Bight indicate a moderate warm bias in the order of 0.5 °C; but relatively high correlation of 0.89 suggests that long-term variability and change are simulated reasonably. Biases at other stations appear to be negligible. Analysis of hindcast temperatures reveals that SSTs in the German Bight remained relatively constant until the mid 1980s with some inter-annual variability superimposed. Later a strong increase in SST was found reaching values of up to 0.05 °C $year^{-1}$ between 1988 and 2007. A similar behaviour was identified in observations from Helgoland, the only station for which a long temperature record was available. The heat content for the entire North Sea region showed a comparable development, indicating that the surface warming observed over the last decades extends over a larger depth range. The variability of stratification is mainly dominated by year-to-year variability. A number of sensitivity experiments are performed, confirming existing hypotheses, that the local air-sea interactions are the main drivers behind the observed changes in North Sea heat content and SST and in particular for the strong warming emerging in the mid 1980s in the North Sea.

Key words: North Sea, multidecadal hindcast, climate, temperature, heat content, mesoscale modelling

1. Introduction

Long-term changes in water temperature may have profound influences on marine and coastal ecosystems. For the North Sea and the German Bight such changes together with considerable inter-annual and decadal variability have been described for example by Becker et al. (1997), Wiltshire and Manly (2004), or Janssen (2002). Usually measurements from which such changes may be analysed are rare for various reasons. Monitoring programmes providing long (e.g. Wiltshire and Manly, 2004) and mostly homogeneous time series exist at few places only. Moreover, monitoring is often confined to a limited set of variables such as temperature, salinity, or some ecosystem parameters (waterbase.nl and bsh.de). Information about their spatial-temporal variation or other parameters such as the depth of the thermocline is often unavailable. Sometimes data with a high spatial and/or temporal resolution are available, but are normally obtained from time limited measurement campaigns (for example ship based measurements along transects) or are available only for more recent and relatively short periods (such as satellite data).

For the North Sea and other continental shelf seas, hindcasts with numerical shelf sea models have become a frequently used tool to complement the limited observational data.
Early attempts aiming at reconstructing observed hydrodynamical conditions in the North Sea were provided for example by Backhaus and Hainbucher (1987), Kauker (1999) or Schrum et al. (2003). More recent approaches are described in Skogen and Moll (2005), Holt et al. (2005), or Pohlmann (2006). Nowadays more complex mesoscale ocean models are in use (e.g. Holt and James 2001; Holt et al. 2005; Siddorn et al. 2007; Winther and Evensen 2006; Burchard and Bolding 2001; Umlauf and Burchard 2005; Luyten et al. 2003; Skogen and Søiland 1998; de Kok et al. 2001; Pohlmann, 2006; Hjøllo et al., 2009) but hindcast periods are still somewhat limited when compared to those obtained from larger scale models. For example, the simulation for the North Sea and Baltic Sea provided by Schrum et al. (2003) comprises the period 1958 - 1997. A simulation for the North Sea described in Hjøllo et al. (2009) covers the period 1985 - 2007.
A model inter-comparison study [NOMADS2 (NOrth sea Model ADvection Study 2)] for regional ocean models implemented for the North Sea illustrates that the approach has matured significantly in the recent past and that the quality of the models has converged considerably within the last few years (Delhez et al. 2004). Hindcasts with numerical models thus provide an important tool that may complement the observational evidence. They can be used to estimate quantities that are either not observed directly with required accuracy, such as thermocline depth, or provide estimates for variables at places where no measurements have been taken (IOC 2003). Moreover, when observed changes are

reasonably reproduced at the few available measurement sites, models may be used to test hypotheses about potential causes of the observed changes as they provide the opportunity to conduct controlled sensitivity experiments.

When long-term changes and variability over decades of years are of interest, the homogeneity and consistency of the analysed record become important prerequisites (e.g. Karl et al., 1993; von Storch and Weisse 2008). In particular, changes in the density of the observational network, measurement procedures, or analysis techniques over time may introduce spurious signals in the data that do not reflect changes in the variable considered but merely reflect changes in the way the measurements have been taken (e.g. Bengtsson et al. 2004). In atmospheric research, global (e.g. Kalnay et al. 1996; Uppala et al. 2005) or regional reanalyses (e.g. Feser et al., 2001; Sotillo et al., 2005, Kanamitsu and Kanamaru 2007) have become a common way to reduce such inhomogeneities and to provide a dynamically consistent picture in space and time. Later, such atmospheric reanalyses are often used to force and obtain hindcasts from wind-wave models (e.g. Weisse and Günther 2007), tide-surge models (e.g. Langenberg et al. 1999; Weisse and Pluess 2006; Ratsimandresy et al., 2008; Sebastião et al. 2008; Jędrasik et al. 2008; Pilar et al. 2008) or regional ocean models (e.g. Omstedt and Hansson, 2006; Demirov and Pinardi, 2002; Tonani et al., 2008; Gordon and McClean, 1999; O'Driscoll and Kamenkovich, 2009).

In this study we use a three-dimensional baroclinic shelf sea model for the North Sea driven by atmospheric data from the NCEP/NCAR global reanalysis (Kalnay et al. 1996; Kistler et al. 2001) to hindcast the three-dimensional state of the North Sea system over the past 60 years (1948-2007). To our knowledge, this simulation presently represents the longest hindcast of hydrodynamic conditions in the North Sea. The latter enables us to (i) assess the extent to which the model reproduces observed long-term changes, (ii) to provide a description of long-term changes in relevant key parameters such as thermocline depth or heat content for which no long-term measurements exist, and (iii) to test and elaborate on plausible hypotheses about the potential causes of the simulated long-term changes by performing controlled sensitivity studies. So far, such a comprehensive approach has not been tested and provided yet.

The structure of the manuscript is as follows: In section 2 we briefly describe the model and the model set-up. In section 3.1 results from the hindcast are compared with the limited observational evidence and the extent to which the hindcast is able to reproduce observed changes and variability is assessed. Section 3.2 and 3.3 provide a comprehensive description of the hindcast changes. Emphasis is put on derived quantities such as thermocline depth and structure or North Sea heat content for which no direct and/or long-term measurements are available. Eventually existing hypotheses to explain the observed long-term changes are systematically tested in section 4. The manuscript closed with a summary in section 5.

2. Model, Hindcast and Validation

2.1. *Model description*

The HAMburg Shelf Ocean Model (HAMSOM) represents a quasi-realistic, primitive equation, three-dimensional baroclinic shelf sea model with a free surface. Nowadays there are more than 25 years experience in using HAMSOM for modelling physical processes and variability in the North Sea region (e.g., Backhaus and Hainbucher, 1987; Pohlmann, 1996a,b, 2006; Schrum and Backhaus, 1999).

For this study, HAMSOM has been set up using a horizontal grid size of approximately 20km x 20km at 19 vertical levels. Layer thicknesses vary between 5 m in the upper 50 m and 400 m near the bottom at the North Atlantic boundary. The model domain covers the greater North Sea region (Fig. 1).

>>> Fig. 1 <<<

At the open boundaries (English Channel and northwest North Sea), lateral boundary conditions are obtained from a coarse grid large-scale Northwest-European Shelf Sea model (Backhaus and Hainbucher, 1987) driven by long-term monthly mean temperatures and salinities obtained from Levitus (1982). Weather effects in the Northwest-European Shelf Sea model are accounted for by using wind and pressure fields from the NCEP/NCAR reanalysis 1 (Kalnay et al., 1996). At the open boundaries the eight most significant tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, Q_1, and P_1) are further employed as boundary condition for water levels, to make sure, that a realistic amount of vertical mixing is introduced in our simulation.

Under inflow conditions temperature and salinity at the lateral boundaries are obtained from the Northwest European Shelf Sea model, while the Sommerfeld radiation condition is applied for outflow conditions (Orlanski, 1976). Long-term monthly mean river run-off data from the most important sources are included (Damm, 1997). At the bottom a quadratic stress law is applied. At the sea surface fluxes of momentum, heat and fresh water are obtained from meteorological parameters (near-surface marine wind speed and direction, sea surface pressure, air temperature at 2 m height, sea surface temperature, relative humidity, total cloud cover and total precipitation) using bulk formulas described in Pohlmann (2006). The parameterisation of incoming solar radiation is adopted from the COHERENS model (Luyten et al., 1999), while the outgoing long-wave radiation is calculated according to Fung et al. (1984). For sensible and latent heat flux the parameterisations from Kondo (1975) are used.

2.2 *The model hindcast 1948-2007*

A multidecadal hindcast covering the period 1948-2007 has been carried out. The model was driven by 6-hourly air temperature, humidity, cloud cover, precipitation, sea level pressure and near-surface wind speed and direction from the NCEP/NCAR global atmospheric reanalysis (Kalnay et al. 1996; Kistler et al. 2001). Siegismund and Schrum (2001) showed that the main features of the large-scale atmospheric circulation over the North Sea are reasonably represented by the NCEP/NCAR reanalysis.

While NCEP/NCAR atmospheric data are available on a T62 grid (approximately 210 x 210 km^2) only, bi-linear interpolation to the HAMSOM grid was performed. Full model output has been stored every hour, comprising two-dimensional water levels and three-dimensional fields of temperature, salinity, and horizontal velocity components.

2.3. *Validation of the 1948-2007 hindcast results*

A comprehensive validation of the HAMSOM model in the present set-up is provided in Pohlmann (1996a,b; 2006) who compared the model with data from the FLEX'76 experiment (Soetje and Huber, 1980) and with measurements collected at the German Oceanographic Data Centre (bsh.de). Here some additional validations are performed by comparing the simulation results with short-term measurements from three stations (waterbase.nl), which are located between England and the Netherlands (Euro platform and K13) and between Scotland and Denmark (Aukfield) (Fig. 2). It can be inferred that the long-term average annual cycle is reasonably simulated. Maximal monthly deviation ranges from 0.41 °C at Euro to about 1.47 °C at Aukfield (Fig. 2). Correlations between observations and hindcast SST range from 0.79 to 0.89 and biases are generally smaller than -0.04 °C. This is comparable to the results reported in Hjøllo et al. (2009) for monthly mean SST, indicating that SST anomalies on daily and longer timescales are reasonably simulated in our hindcast.

>>> Fig. (2) <<<

The only long-term time-series of SST measurements covering more than 13 decades is available for Helgoland Roads (Wiltshire and Manly, 2004). In the German Bight, three time series (~1950 – ~1988) from light vessels are available. For these stations some additional comparisons are done to access the degree of accuracy to which our hindcast simulations are able to reproduce the observed long-term variability (Table 1).

	Time	**Latitude**	**Longitude**	**Number of data**	**Corre-lation**	**Bias [°C]**	**RMSE [°C]**
Helgoland	2.1.1962-28.12.2007	54.18°N	7.9°E	11,464	0.89	0.60	1.12
Elbe I	1.1.1950-22.4.1988	54.00°N	8.18°E/ 8.12°E	13,852	0.83	0.66	1.20
P11/P8	1.1.1950-11.3.1978	54.27°N	7.20°E	10,143	0.84	0.31	0.82
P15/12	1.1.1950-21.5.1986	54.00°N/ 54.18°N	7.85°E/ 7.45°E	8166	0.83	0.37	0.95

Table 1: Validation statistics for SST at Helogland Roads and three light vessels (Elbe I, P11/P8 and P15/P12) in the German Bight. Periods for which the comparisons have been made are indicated in column time. Statistics (correlation, bias, and root-mean-square error [RMSE]) were obtained from daily data. For the computation of the correlation the annual cycle was removed.

In general, correlations are relatively high varying between 0.83 and 0.89. Bias and root-mean-square-error vary between 0.31 °C and 0.66 °C and between 0.82 °C and 1.20 °C respectively. These statistical errors appear somewhat larger than for the Aukfield, Euro and K13 stations. We assume that this may partly be an effect of specific conditions of the island, which cannot be resolved with a resolution of 20 km x 20 km. Despite the warm bias found for Helgoland roads and for the three light vessels inter-annual and longer term fluctuations appear to be reasonably reproduced. The latter is elaborated on in more detail in the following section.

Apart from sea surface temperature, we also compared our model results with vertical temperature profiles along a cross-section between Aberdeen (Scotland) and Hanstholmen (Denmark) from Kangas et al. (2006). Our model results are shown in Fig. (3). Objective comparisons with the results produced by Kangas et al. (2006; section 4.1) indicate that the large-scale structure of the temperature pattern is reasonably simulated, while smaller-scale details are missing which probably can be attributed to the limited horizontal and vertical resolution of our model hindcast.

>>> Fig. 3 <<<

3. Simulated long-term variability of temperature, thermocline structure and heat content

3.1. Temperature

As we are primarily interested in reproducing observed long-term variability and changes, in the following a more detailed discussion and comparison for Helgoland Roads is provided. For this station a very long observational record exists from 1873 to date including some longer gaps (Wiltshire and Manly 2004; Franke et al. 2004). Moreover, Helgoland (located approximately 60 km offshore) represents the central island in the German Bight and is considered to be representative for the south eastern part of the model domain.
To concentrate on longer time scales, five year running means of observed and hindcast SST at Helgoland Roads were computed (Fig. 4). Again, the aforementioned warm bias in the model simulation is clearly visible. However, good agreement for variations on inter-annual and longer time scales can be inferred also.

>>> Fig. 4 <<<

For example, the relatively low temperatures at the end of 1960s and 1970s can be inferred from both, the hindcast and the observations. Further, a pronounced increase in SST over the last few decades can be inferred from both, the measurements and the hindcast data. We supposed that the bias between modelled and observed SST is not changing in the course of time as year-to-year and longer variations are captured reasonably well by the model simulation. Therefore we assume that the multidecadal hindcast represents an adequate tool to assess long-term changes and variability of SSTs in the German Bight. This view is further supported by a comparison of 20-year moving trends showing the same developing of hindcast and observations (Fig. 5). Estimates of SST trends obtained from 20-year periods, with the start point of each period incremented by one year, indicate significant variability in the magnitude of the trends. These trends show pronounced long-term variability ranging from negative values of about -0.05 °C year^{-1} in the 1930s to rather high values of up to 0.08 °C year^{-1} in the early 1980s. When the entire period is considered, the trend emerging in the early 1980s is found to be the highest on record, although the latest values are somewhat smaller again. On average the 20-year trend of SST at Helgoland Roads over the period 1879-2007 was about 0.006 °C $year^{-1}$ with a standard deviation of about 0.032 °C $year^{-1}$. The latter indicates that the trends emerging in the 1980s deviate from the long-term average by more than two times the standard deviation, emphasising the unusual character of this period.

>>>Fig. 5 <<<

To investigate whether the changes described basically reflect a surface phenomenon limited to German Bight or whether they are representative for a larger area and also at depth, model domain averaged SST and volume averaged annual temperature have been computed and compared to SST at Helgoland Roads (Fig. 6).
Both annual mean SST and volume averaged temperature exhibit pronounced inter-annual and longer variations. The annual mean SST varies between approximately 9.4 °C in 1979 and 11.1 °C in 2007, while the volume averaged temperature average ranges from 8.1 °C in 1979 to 9.0 °C in 2007. Both time series show similar time behaviour when compared to the SSTs at Helgoland Roads. Moreover, while all three time series appear to be quasi-stationary until the early 1980s, while a marked increase appears afterwards.

>>> Fig. 6 <<<

To illustrate the spatial variations and the differences between the periods before and after 1987, linear trends for SST were computed at every model grid points for the two periods (Fig. 7). Note that 1987 was chose as a separation point between both periods to be consistent with other authors, who reported a regime shift (e.g. Beaugrand et al., 2004).
For the first period trends were mostly small (up to about 0.1 °C/decade) and negative while for the second period a strong increase in the sea surface temperatures of up to 0.5 °C/decade occurred over the entire North Sea. The strongest warming is found in the German Bight where the trend after 1987 corresponds to an increase in sea surface temperatures of about 1.0 °C over the last 20 years. For the central North Sea somewhat smaller values in the order of about 0.3-0.4 °C/decade are found, while trends are considerably smaller (about 0.1-0.3 °C/decade) in the northern part of the model domain.

>>> Fig. 7 <<<

3.2. Thermocline structure

For many biological and ecosystem studies any long-term changes in thermocline depth and/or intensity are of central importance. The thermocline separates mixed surface waters from the water masses below the thermocline. Changes in the structure of the thermocline may have implications for ecology, in particular for the phytoplankton production. Note that we refer to thermocline structure for any of its properties such as depth and intensity. For a more detailed definition see below.

While in the winter season the North Sea is generally well mixed, in spring a thermocline develops over much of the North Sea area as the water column gains increasing stability due to stronger solar heating at the sea surface and less turbulent mixing through the wind. However, the permanent turbulence input causes a downward mixing of warm water, and hence, increases the thermocline depth over the summer period.

Intensive ship campaigns are necessary to investigate the structure and development of the thermocline. However, normally such observations only provide information for narrow transects and for limited time periods. Hindcasts performed with high resolution 3-d ocean models may complement such campaigns by providing a better insight into the space-time structure and long-term variability of the thermocline. In the following we use the hindcast to describe the long-term variability of the thermocline structure in the North Sea where the latter is referring to changes in thermocline depth, intensity, extension and the first day in each year at which a noticeable thermocline is observed. Here thermocline depth is defined when the vertical temperature gradient exceeds a threshold value of 0.1 °C m^{-1}. Thermocline intensity is defined as the maximum of the vertical temperature gradient provided it exceeds a threshold of 0.1 °C m^{-1} (Pohlmann, 1996b; 2006) and thermocline extension refers to the mean area of the grid cells, where the threshold value is exceeded.

>>> Fig. 8 <<<

Fig. (8) shows the long-term changes and variability of the thermocline structure as obtained from the multidecadal hindcast when spatially integrated over the entire North Sea and when the spatial extension is greater than 10000km². Generally the thermocline develops around day 100 of each year. For the mean thermocline depth a considerable seasonal and interannual variability was found ranging from about 7.5 m up to more than 40 m but no long-term trend can be inferred. Moreover, there is also no indication of stronger trends after about 1987. Similarly, the mean thermocline intensity appears to be rather stationary over the years with values ranging between 0.1 and 0.4 °C m^{-1}. This indicates that the warming observed since the early 1980s appears to be a phenomenon affecting the entire water column without major changes in thermocline structure. We could not identify a long-term trend in the onset and development of the thermocline, so the warming has a minor influence on them. Schrum et al., 2003 mentioned that the stratification shows a strong inter-annual but also decadal variability. However, in agreement with our findings no clear trend can be deduced from their results.

3.3. North Sea heat content

In order to analyse the role of the North Sea in the climate system its heat content is an important parameter since it integrates the effect of all involved heat flux components. In the North Sea the heat content is mainly governed by solar and long-wave radiation as well as latent and sensible heat fluxes. However, under certain conditions, the advective and diffusive heat fluxes may also be relevant. The solar radiation depends on the declination of the sun and the cloud cover, whereas the long-wave radiation depends on the difference between air and sea temperature and cloud cover. Sensible and latent heat fluxes are controlled by the difference of air and sea temperature, wind speed and water vapour pressure. The sum of all four fluxes yields the total heat flux into the ocean (Pohlmann, 2006). In summer heat fluxes are generally directed into the North Sea (positive heat fluxes) while in winter negative heat fluxes over the North Sea prevail. The depth averaged heat content *H* of the North Sea is calculated by:

$$H = \frac{1}{D}\sum_{i=1}^{N} c_p \cdot \rho \cdot h_i \cdot (T_i - 273.15K) \qquad (1)$$

where D is the total water depth of all grid cells; c_p = 3980 J kg^{-1} K^{-1} is the specific heat capacity for sea water (Feistel, 1993); ρ is the density of sea water; h_i is the thickness and T_i is the potential temperature at the wet grid cell *i*.

The annual and the seasonal mean heat content of the North Sea are shown in Fig. (9). For the annual mean, values vary between about 330 × 10^5 J m^{-3} and 366 × 10^5 J m^{-3}. Seasonally, heat content is largest in the summer months and smallest in winter while inter-annual variability is largest in winter (46.6 × 10^5 J m^{-3}) and spring seasons (47.5 × 10^5 J m^{-3}). For summer and autumn, inter-annual variability is somewhat smaller (31.6 × 10^5 J m^{-3} and 37.5 × 10^5 J m^{-3}, respectively), which corresponds to the findings reported in Hjøllo et al., (2009). As for sea surface temperatures, there is no noticeable trend until the early 1980s, afterwards a stronger positive trend can be inferred (Table 2), which is most pronounced in autumn.

>>> Fig. 9 <<<

	1951 - 1987	1988 - 2007	1951 – 2007
January – March	-0.21 x 10^5	0.58 x 10^5	0.23 x 10^5
April – June	-0.19 x 10^5	0.62 x 10^5	0.24 x 10^5
July – September	-0.03 x 10^5	0.53 x 10^5	0.27 x 10^5
October-December	-0.07 x 10^5	0.83 x 10^5	0.23 x 10^5
January - December	-0.12 x 10^5	0.64 x 10^5	0.24 x 10^5

Table 2: Linear trends of North Sea heat content [J m^{-3} $year^{-1}$] from 1951 - 1987; 1988 - 2007 and 1951 - 2007.

Similar to the analysis for SSTs, linear trends for heat content over the two periods 1951-1987 and 1988-2007 are computed at every model grid point (Fig. 10). As for SSTs, trends are small and mostly negative during the first period but stronger and mostly positive during the second. Again largest values are obtained for the German Bight (up to 2.0 × 10^5 J m^{-3} $year^{-1}$).

>>> Fig. 10 <<<

This warming in the second period may have significant impact and partly be responsible for observed changing in many biological and ecosystem processes including the linkages between different components of the ecosystem, such as phytoplankton, zooplankton, benthos, fish and seabirds (Alheit et al., 2010; Beaugrand et al. 2002; Beaugrand 2004). They mentioned also that the North Sea plankton communities directly respond to the environmental changes and a large number of studies have reported a regime shift in the late 1980s. As a result of warming the zooplankton community shifted from a typical cold-boreal community to a warm-temperate community (Beaugrand et al., 2002; Beaugrand 2004). For example anchovies and sardines expanded their area of distribution into the entire North Sea and established spawning populations and their entire life cycle in this region (Alheit et al., 2010). We suggest that our hindcast data may provide a tool to elaborate on the causes of such changes in more detail. The latter is however, beyond the scope of the present study.

4. Sensitivity experiments

A remarkable feature is the strong warming beginning in the 1980s. This feature is presented in both, the observations and the multidecadal hindcast. We infer from the hindcast that this warming is not limited only to the sea surface and the German Bight, but also extends over much of the North Sea and is visible in the total North Sea heat content. This feature is remarkably well resolved in the hindcast, so it offers the opportunity to elaborate on possible reasons and test hypotheses put forward by various authors (Becker et al. 1997; Kauker 1999; Janssen 2002). The strategy is based on following assumption: In the long-term hindcast, the strong warming in the 1980s must result from corresponding changes in one or any combination of the driving variables. In particular these are air temperature, cloud cover, near surface marine wind, sea level pressure and humidity. Thus we performed a number of sensitivity experiments in which each of the driving variable a_{ikt} was reset to an annual climatological average $\bar{a}_{it} = \frac{1}{N}\sum_{k=1}^{N} a_{ikt}$ (2).

Here *i* denotes the model grid points and the indices *k* and *t* both represent time with *k* referring to the *k=1…N* for the years 1948 to 2007 and *t=1…4x365* counting the four times daily frequency at which the forcing was available times the 365 days in a year. In each experiment, only one forcing variable was reset to climatological $\bar{a}_{it}$ while for all other variables the same time dependent forcing as in the multidecadal hindcast was applied (Table 3). By this proceeding it is possible to deduce which of the forcing parameter most decisively determines the observed hydro-thermodynamic variability. For leap years the climatological forcing for February, 29th is derived from interpolating corresponding values of February, 28th and March, 1st, because NCEP/NCAR reanalysis data considers leap year. Note that for wind a somewhat different strategy was applied. Here, data of wind and sea level pressure were chosen, but from two different years representing on average either relatively strong or weak wind conditions over the entire North Sea domain (Table 3). Subsequently, for each experiment, time series of total North Sea heat content were derived (Fig. 11). Provided that the variable reset to climatology represents a major driver of the strong warming emerging in the 1980s we thus expect the trend in North Sea heat content to disappear or to weaken considerably, while it should be almost unaffected when the reset forcing variable is unimportant.

Fig. (11) shows that all experiments except one share relatively strong similarities and variability retaining the strong trend emerging in the 1980s. The only exception is the experiment in which air temperature was reset to climatology. In this experiment the strong warming after about 1980 almost disappeared indicating that the information removed by averaging air temperatures was essential in producing the strong warming trend after 1980 in our multidecadal hindcast. In our experiments, air temperature thus represents the main driver beyond the strong warming trend emerging in the early 1980s accounting for about 75% of the observed (hindcast) changes.

Forcing

Name	Air temperature	Cloud	Wind	Sea level pressure	Humidity
Reference	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR
Air temperature	Climate mean	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR
Cloud cover	NCEP/NCAR	Climate mean	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR
Wind weak	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR 1957	NCEP/NCAR 1957	NCEP/NCAR
Wind strong	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR 1990	NCEP/NCAR 1990	NCEP/NCAR
Humidity	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR	NCEP/NCAR	Climate mean

Table 3: List of sensitivity experiments**.**

>>> Fig. 11 <<<

This result confirms the hypothesis put forward by e.g. Becker and Pauly (1996) who concluded that observed SST variability in the German Bight is primarily a result of local atmosphere-ocean heat exchange, which in turn depends on the state of the large scale atmospheric circulation, while oceanic advection plays a role only at the northern and southern boundaries. With two more years of data and a slightly different methodology Dippner (1997) reached similar conclusions. A similar explanation was later put forward also by Sharples et al. (2006) and by Hjøllo et al. (2009). Kauker (1999) studied the relation between North Sea inflow and North Sea SST anomalies based on a model reconstruction 1979-1993. He also concluded that the observed SST anomalies are to a larger extent a result from local atmosphere ocean interaction than from oceanic advection. Similarly, by varying lateral boundary conditions in an ocean model experiment Pohlmann (2003) showed that changing lateral temperature conditions have only a limited influence on the temperature in the southern North Sea and German Bight. Janssen (2002) performed a canonical correlation analysis between large scale sea level pressure and North Sea SST anomalies. He found that NAO like sea level pressure (SLP) anomalies are positively correlated with warm North Sea SST anomalies and concluded that changes in the atmospheric large scale circulation modify air temperatures above the North Sea and, as a result, local sensible and latent heat fluxes.

5. Summary

The hydrodynamical conditions in the North Sea were reconstructed at high temporal detail using the three dimensional baroclinic shelf sea model HAMSOM with a resolution of 20 km x 20 km and atmospheric reanalysis data from NCEP/NCAR for the period 1948-2007. Comparison of the multidecadal model results with short-term and long-term observations indicated a high correlation between simulation and observations (0.79-0.89; Fig. 2). Furthermore the bias is small for the short-term observations. Comparison of the long-term observations indicated that the model exhibits a moderate warm bias in the order of about 0.5 °C while changes and variability on annual and longer time scales appear to be reproduced reasonably (Figs. 4-6). The bias can be explained by the specific conditions of the observation station, which cannot be resolve from the model, because of the resolution. An objective comparison with cross-section results from Aberdeen (Scotland) to Hanstholmen (Denmark) produced by Kangas et al. (2006, section 4.1) indicate that the large scale structure of the temperature pattern is reasonably simulated (Fig. 3). These model results encourage further investigations of the variability and change in thermocline structure and heat content, two parameters for which only limited observations are available.

In the present study, we have shown that North Sea temperature and heat content have changed considerably during the last few decades. In particular, strong increases are obtained after the 1980s that are consistent with the available observational record, which have been highest on record (Fig. 4). Calculations of the running 20-year trend of Helgoland Roads observations show alternating periods of negative and positive trends until the beginning of the 1980s. Since then 20-year trends have been constantly positive and largest on record (0.08 °C $year^{-1}$; Fig. 5). Strong positive trends of up to 0.5 °C/decade for SST (Fig. 7) and up to 2.0×10^5 J m^{-3} $year^{-1}$ for heat content (Fig. 10) are appearing since 1987. Sea surface temperatures and heat content show no noticeable trend until the early 1980s, afterwards a stronger positive trend can be inferred (Table 2), which is most pronounced in autumn.

Investigations of the thermocline structure show no major changes due to the warming (Fig. 8). The onset of the thermocline is around day 100 of each year. The thermocline depth varies between 7.5 m and more than 40 m in autumn. The thermocline intensity and extension show neither a positive nor a negative trend. So the warming has a minor influence on the thermocline structure and the year-to-year variability dominates.

A number of sensitivity experiments were performed to elaborate on the potential drivers of the observed changes (Fig. 11). The results from these experiments indicate that local air-sea interactions are primarily responsible for the observed long-term changes and broadly confirming existing hypotheses.

We conclude that our simulation provides a reasonable tool to advance the study of long-term changes in North Sea thermodynamics and that it may be of use and relevance for follow-up studies, in particular, in the field of marine biology or ecology e.g. Alheit et al., (2010).

Acknowledgements

The authors thank the DOD (German Oceanographic Data Centre; bsh.de) for providing Helgoland Roads data and for providing data from light vessels in the German Bight. The Helgoland Roads Data are also provided by Biologische Anstalt Helgoland/Alfred-Wegener-Institut für Polar- und Meeresforschung. The data from the platforms Aukfield, Euro and K13 are provided from the Netherlands Waterbase datasets (www.waterbase.nl). NCEP/NCAR reanalysis data are provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/. Thanks to Peter Damm for preparing NCEP/NCAR data and Mrs. Beate Gardeike for preparing some of the figures.

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Figure 01

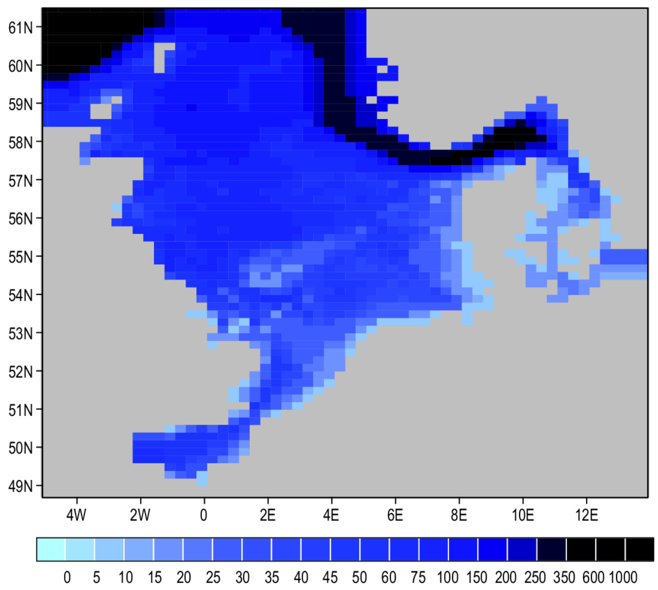

Figure 1: Model domain and bathymetry of HAMSOM [m].

Figure 02

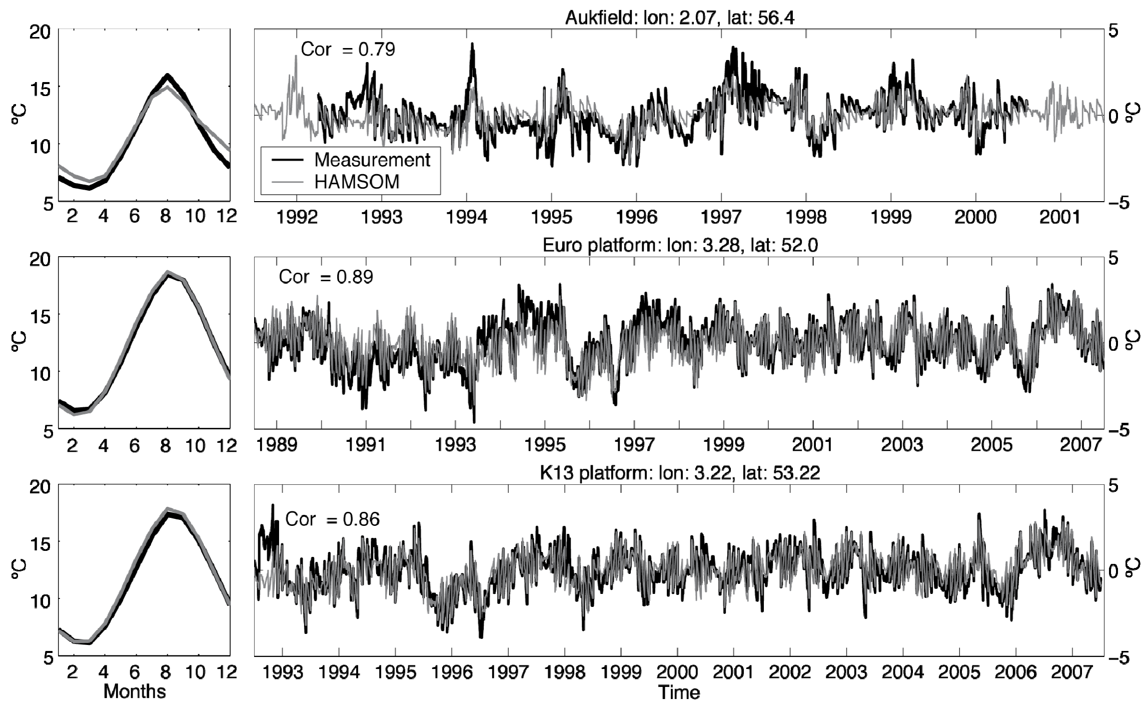

Figure 2: In the left column the seasonal cycles of temperature are calculated for observed (black) and simulated (grey) data for the stations Aukfield, Euro and K13 during the observed period (waterbase.nl). The right column shows the diurnal anomaly (diurnal data(station) – seasonal cycle(station)) of observed (black) and simulated (grey) data from these stations.

Figure 03

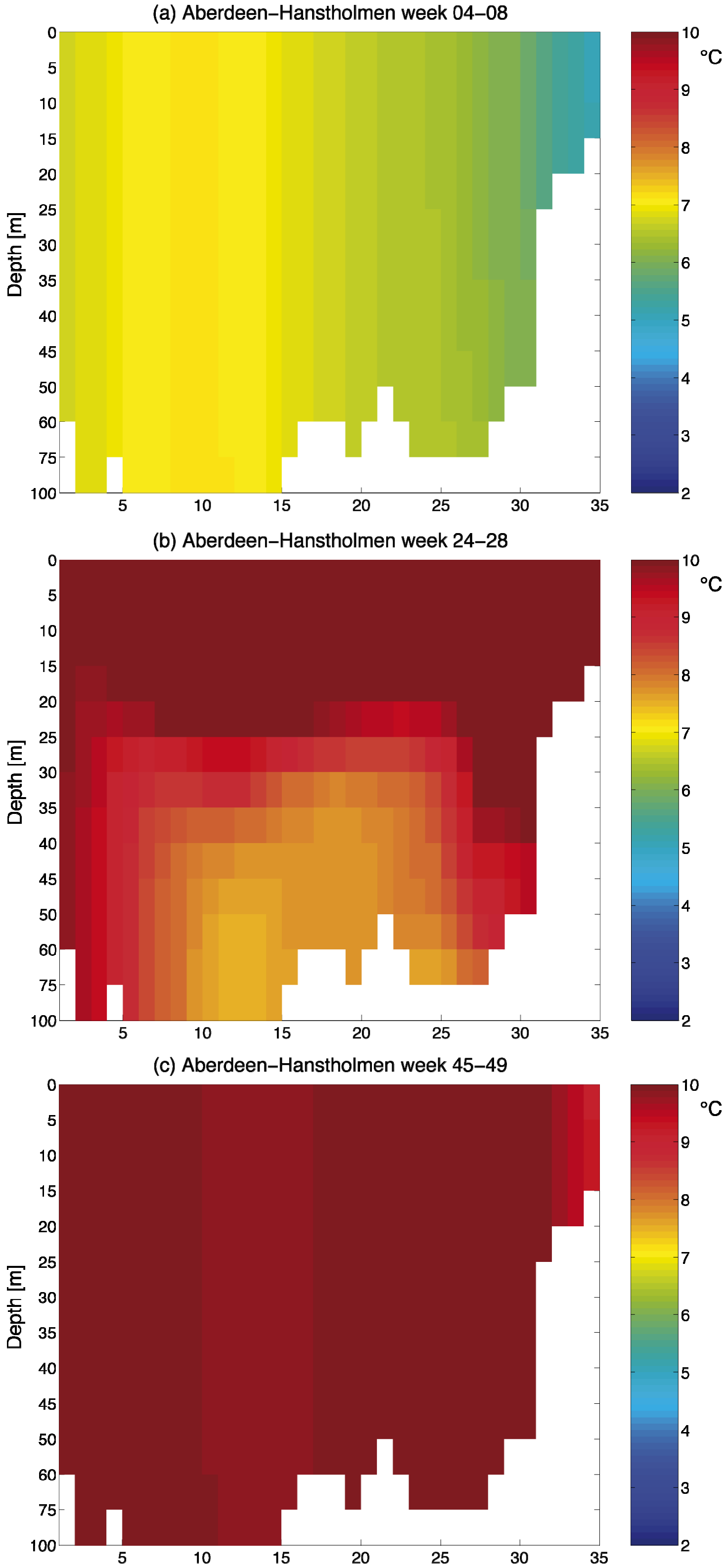

Figure 3: Averaged (1980-1999) temperature along a cross-section between Aberdeen (Scotland) and Hanstholmen (Denmark) for winter (weeks 04-08) [a]; summer (weeks 24-28) [b] and autumn (weeks 45-49) [c].

Figure 04

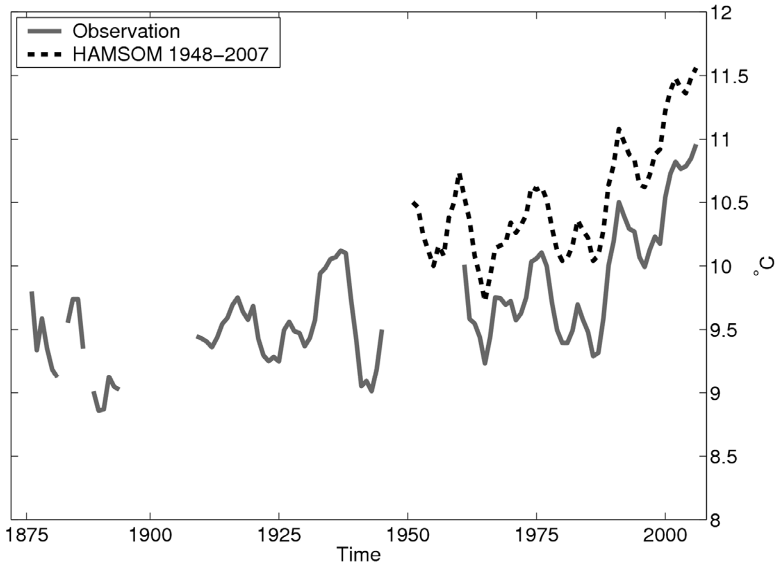

Figure 4: 5-year running means of observed (grey solid line) and simulated (black dashed line) SST [°C] at Helgoland Roads.

Figure 05

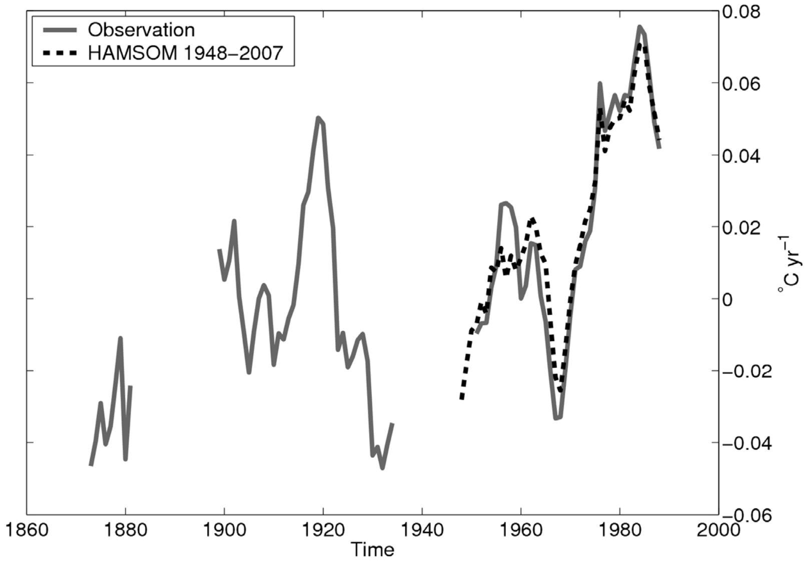

Figure 5: Running 20-year trends [°C year^{-1}] for Helgoland Roads are derived from observations (grey solid line) and HAMSOM results (black dashed line). Trend values are associated with the first year of each 20-year window for which the analysis are performed.

Figure 06

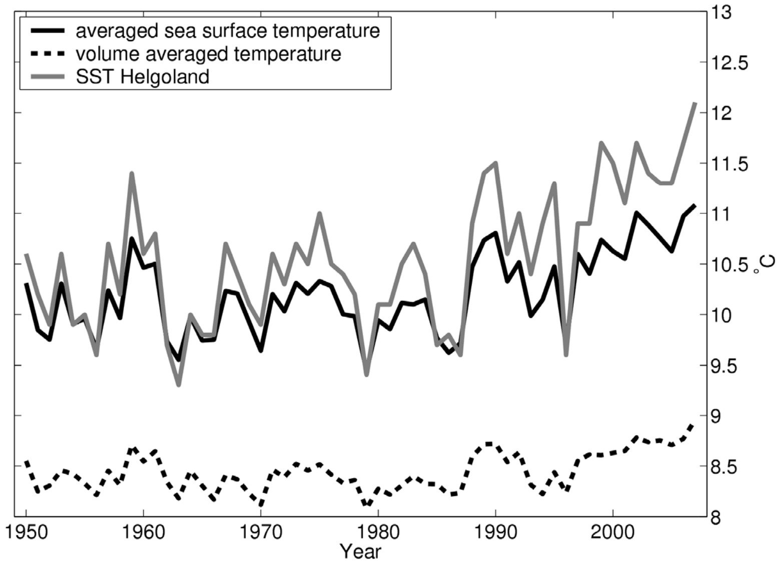

Figure 6: Annual mean SST [°C] from Helgoland Roads (solid grey line); annual mean North Sea SST (solid black line) and annual mean North Sea volume averaged temperature (dashed black line).

Figure 07

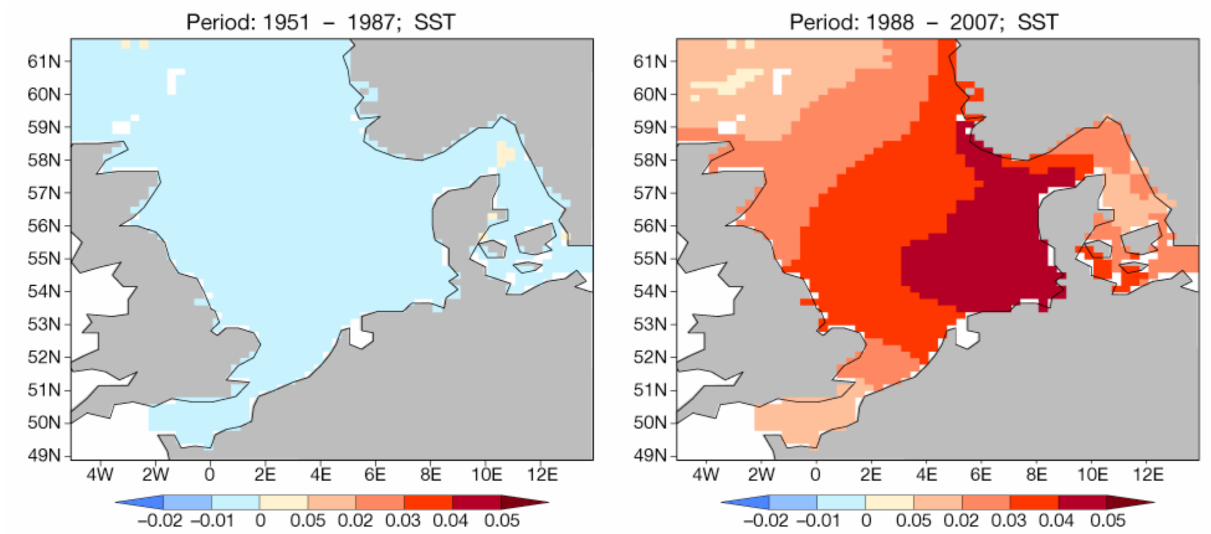

Figure 7: Linear trends 1951-1987 (a) and 1988-2007 (b) of SST [°C year^{-1}].

Figure 08

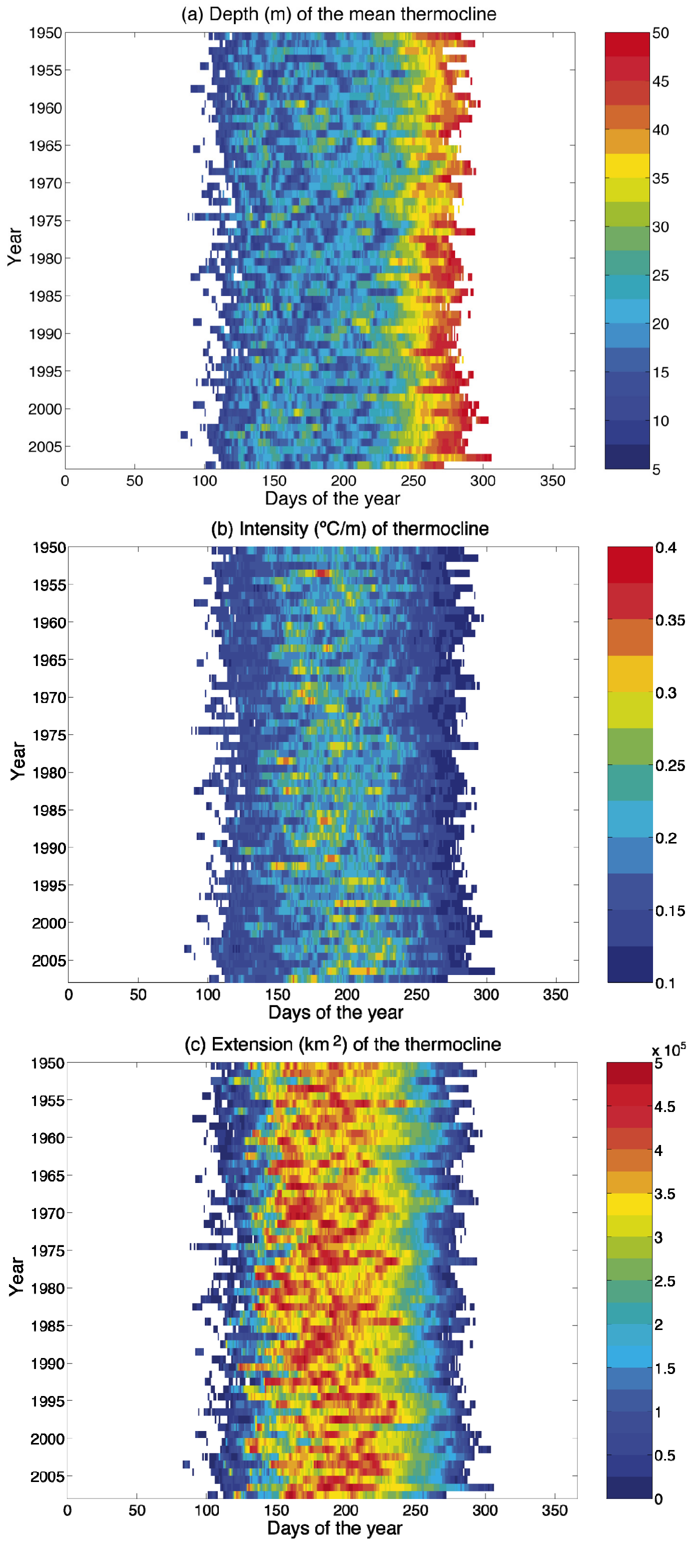

Figure (8): Development of thermocline structure 1950-2007. (a) Depth in m; (b) intensity in °C m^{-1} and (c) extension in km²; on the x-axis the days of the year and on the y-axis the years from 1950 to 2007.

Figure 09

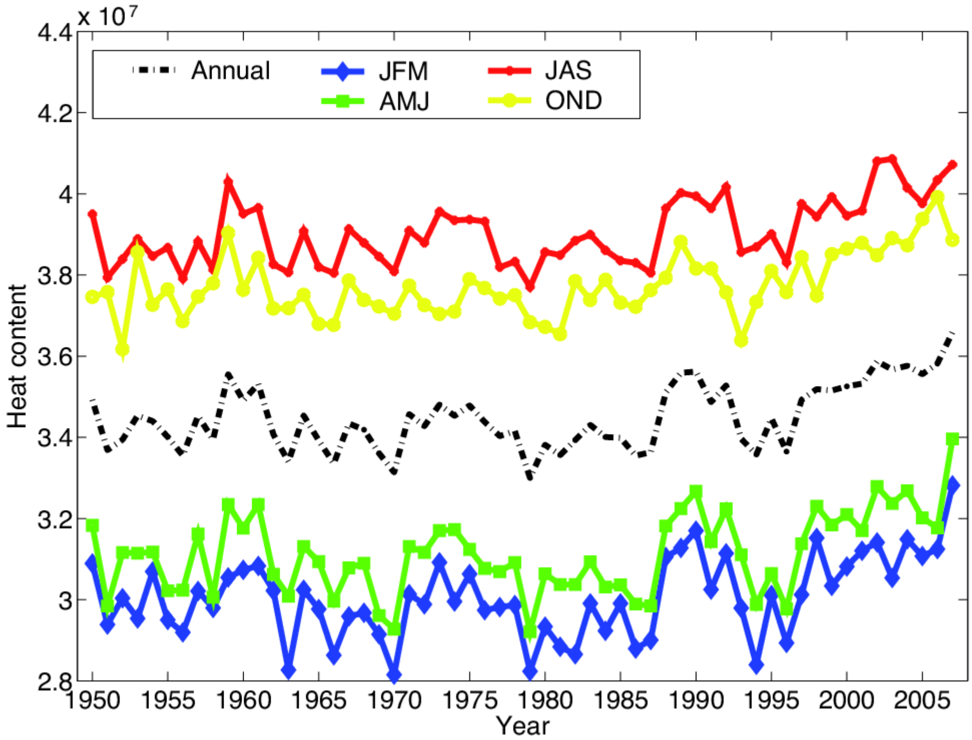

Figure 9: Annual (black) and seasonal (JFM-blue, AMJ-green, JAS-red, OND-yellow) mean North Sea heat content in 10^7 J m^{-3}.

Figure 10

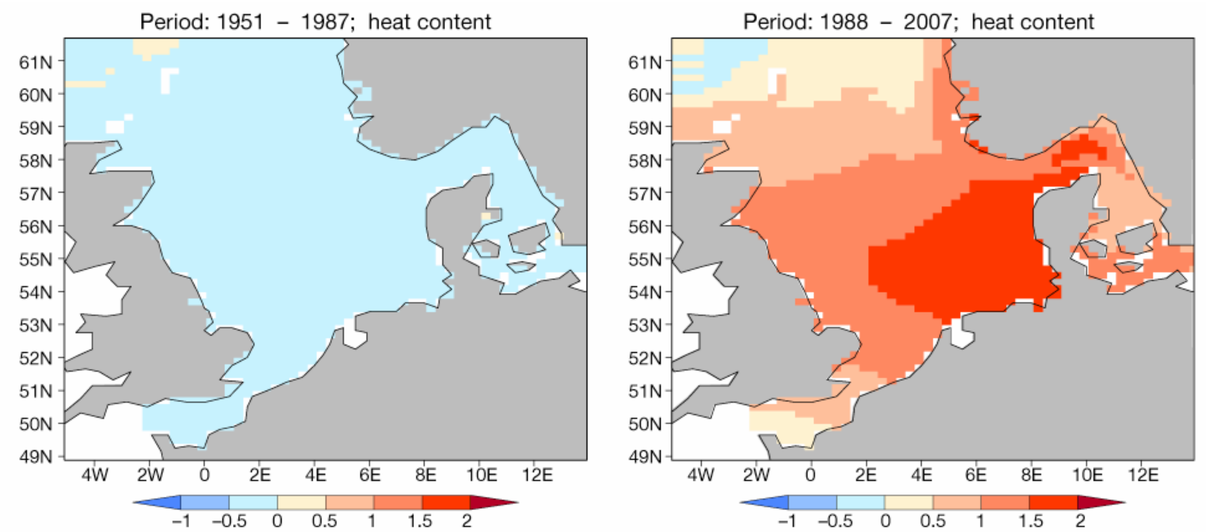

Figure 10: Linear trends 1951-1987 (a) and 1988-2007 (b) of North Sea heat content [10^5 J m^{-3} year^{-1}].

Figure 11

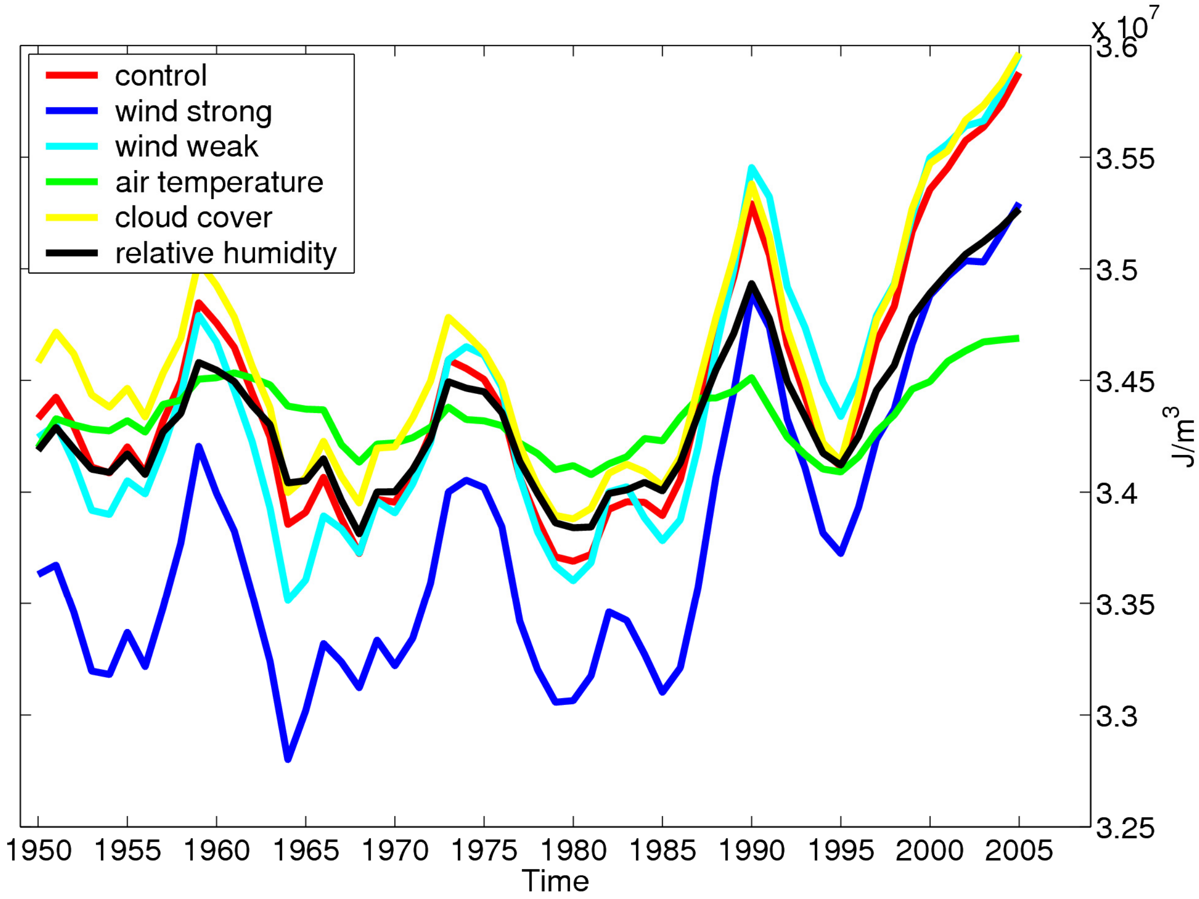

Figure 11: Results from 5-years moving average of heat content from sensitivity experiments; 'control' red; 'wind strong' blue; 'wind weak ' light blue; 'air temperature' green; 'cloud cover' yellow and 'relative humidity' black [10^7 J m^{-3}].