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Long-term sea surface temperature baselines—time series, spatial covariation and implications for biological processes

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Abstract

Coastal areas such as estuaries, bays and fjords usually have hydrographic characteristics (e.g., temperature, salinity) which differ from those at larger spatial scales and in offshore areas. The differences can arise if the areas are subject to different climatic forcing or if they are relatively isolated from each other due to topographic and ocean circulation features which inhibit advective inputs of water mass properties. Local differences in hydrographic conditions can therefore potentially limit the applicability of existing long time series of coastally monitored temperatures for addressing questions at large spatial scales, such as the response of species distributions and phenologies to climate change. In this study we investigate the spatial synchrony of long-term sea surface temperatures in the North Sea–Baltic Sea region as measured daily at four coastal sites (Marsdiep, Netherlands; Torungen, Norway; Skagens Reef, Denmark; and Christiansø, Denmark) and in several large offshore areas. All time series, including two series reconstructed and intercalibrated for this study (Skagens Reef and Christiansø, Denmark), began during 1861–1880 and continue until at least 2001. Temperatures at coastal sites co-varied strongly with each other and with opportunistically measured offshore temperatures despite separation distances between measuring locations of 20–1200 km. This covariance is probably due to the influence of large-scale atmospheric processes on regional temperatures and is consistent with the known correlation radius of atmospheric fluctuations (ca. 1000 km). Differences (e. g, long-term trends, amplitude of seasonal variations) between coastal temperatures and those measured in adjacent offshore areas varied nonrandomly over time and were often significantly autocorrelated up to 2 years. These differences suggest that spatial variations in physical oceanographic phenomena and sampling heterogeneities associated with opportunistic sampling could affect perceptions of biological responses to temperature fluctuations. The documentation that the coastally measured temperatures co-vary with those measured opportunistically in offshore areas suggests that the coastal data, which have been measured daily using standardized methods and instruments, contain much of the variability seen at larger spatial scales. We conclude that both types of time series can facilitate assessments of how species and ecosystems have responded to past temperature changes and how they may react to future temperature changes.

Keywords: Sea surface temperature; North Sea; Baltic Sea; Coastal; Synchrony; Multi-decadal

1. Introduction

Baseline information for environmental conditions is essential for detecting long-term changes in ecosystem structure and function, and for making decisions about

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how ecosystems should be managed sustainably. In this context, time series of sea temperature can be valuable for assessing the level of historical temperature variability (e.g., absolute ranges of temperature, rates of change over time, frequency of extreme cold or warm years) and for comparing recent variations with those observed in the past and those expected in the future due to global warming (IPCC, 2001; Sheppard, 2004; Döscher and Meier, 2004). This understanding of historical variability will be valuable for interpreting how populations, species and entire ecosystems might react to future increases in temperature (Stenseth et al., 2004; ICES, 2005; Drinkwater, 2006).

Biological responses to temperature variations can be direct (e.g., physiological effects of changes in temperature on growth or survival rates) or indirect (e.g., via food web interactions related to the production of food or predators). Time series of both temperature and biota should therefore be sufficiently long so that a wide range of temperature and biotic interactions (e.g., predation, starvation, competition for space) that might affect a species of interest are represented.

Potentially useful datasets for these purposes are temperatures measured daily in coastal and nearshore areas as part of long-term oceanographic and meteorological monitoring programmes. These programmes typically are (were) operated by governments or universities and were originally established to provide information that could assist the shipping and fishing industries (Mills, 1989; Fonselius, 2002).

However if coastal monitoring data are to be applied for interpreting species-level and life history responses to temperature fluctuations, one must first establish whether and to what extent these data co-vary with

Table 1
Summary of sea surface temperature, climatic and hydrographic datasets used in this study

Location	Latitude	Longitude	Source	Data type	Period of Measurements	Number of years in original series
Marsdiep, NL	52.983°N	4.75°E	van Aken (2003)	Daily monitoring	1861–2003	143
Torungen, N	58.333°N	8.883°E	Ottersen et al. (2003)	Daily monitoring	1867–2003	132
Skagens Reef, DK	57.775°N	10.725°E	Sparre (1984)	Daily monitoring	1880–1979	81
Christiansø, DK	55.317°N	15.20°E	Sparre (1984)	Daily monitoring	1880–1998	114
North Sea (HADISST1)	51°N–58°N (54.5°N)	2°W–9°E (3.5°E)	Rayner et al. (2003)	Opportunistic sampling	1870–2003	134
Baltic Sea (HADISST1)	54.0°N–60.5°N (56.75°N)	14.5°E–23.5°E (19.0°E)	Rayner et al. (2003)	Opportunistic sampling	1870–2003	134
Northeast North Sea–Skagerrak	55°N–60°N (57.5°N)	5°E–10°E (7.5°E)	ICES www.ices.dk	Opportunistic sampling	1914–2001	70
Central North Sea	55°N–60°N (57.5°N)	0°–5°E (2.5°E)	ICES	Opportunistic sampling	1905–2001	60
Northwest North Sea	55°N–60°N (58°N)	5°W–0° (1°W)	ICES	Opportunistic sampling	1904–2001	50
Bornholm Basin	55.916°N–54.75°N (55.333°N)	16.333°E–14.8°E° (15.565°E)	ICES	Opportunistic sampling	1923–2003	38
Kattegat–Øresund–Great Belt	55°N–60°N (56.25°N)	10°E–15°E (11.5°E)	ICES	Opportunistic sampling	1911–2002	59
Baltic Sea ice coverage			Seinä and Palosuo (1996)	Annual monitoring	1720–2003	284
North Atlantic Oscillation			Jones et al. (1997)	Monthly monitoring	1824–2003	180
Volume transport across northern North Sea	59.283°N		Reid et al. (2003)	Monthly monitoring	1955–2003	49

See Fig. 1 for geographic locations; the latitude and longitude coordinates in parentheses for offshore areas were used to define central locations for estimating separation distances with other measuring sites. The Skagens Reef and Christiansø data series were extended to 2001 and 2003 respectively in this study. All seasonal and mean annual time series are available as electronic appendices. Note that the column headed "number of years in original series" is intended to be indicative and refers to first quarter data for the temperature data and annual data for other variables; some quarterly or annual time series used in our analyses have fewer years than the number of years indicated here because of missing data (e.g., annual means require measurements in all 12 months, for details see Section 2.1). Websites containing updated data are listed with references in the bibliography.

temperatures at larger spatial scales. Many individuals of an entire population (e.g., larvae of a fish or benthic species, which could eventually settle in a coastal zone) can be located far from the site where the coastal temperatures have been measured. The applicability of the coastal monitoring temperatures for understanding biological processes will be higher if the coastal temperatures co-vary significantly over long periods of time with those at larger spatial scales (e.g., 10s–1000s of km^2). Similarly, if temperatures compiled from opportunistic measuring platforms (e. g. research or commercial vessels) over large areas are to be used for understanding local biological responses to temperature fluctuations, then a time series derived from spatially averaged measurements should reflect not only the trends in coastal data, but also other statistical characteristics (e.g., seasonal amplitude of temperature) of the local time series. These characteristics influence biological processes, such as the link between trophic levels (Edwards and Richardson, 2004; Beaugrand et al., 2004) and the timing (Wiltshire and Manly, 2004) and reproduction success (Philippart et al., 2003; MacKenzie and Köster, 2004) of a wide range of species.

In this investigation, we first establish two new long time series of sea surface temperature (SST) from a coastal temperature monitoring programme. The two series are compiled from archived noncomputerized daily data starting in 1880 and continuing until 1979 and 1998; we calibrate and extend the series until the early 2000s. Neither the sampling methodology nor the data series themselves have been described in widely accessible literature (e.g., peer-reviewed international scientific journals) so we provide a full description of these new data series. We then evaluate and compare the spatial representativeness of the series, and in particular the extent to which the coastal and open sea measurements yield a consistent perception of trends and seasonal variations in local temperature.

2. Methods

2.1. Datasets

Our analyses use two categories of temperature data, which we refer to as coastally monitored and opportunistically measured data. The monitoring data have been collected as part of daily long-term monitoring programmes. In this study, four time series from daily monitoring programmes were used. A short description of these series is given below, and further details of locations, sampling periods and sampling methodologies are given in Table 1 and Appendix A.

The two new monitoring time series which will be presented below have been measured by the Danish Meteorological Institute (Thomsen, 1961; DMI, 1972; Sparre, 1984). These data were measured daily at Skagens Reef (juncture of Skagerrak and Kattegat; Fig. 1) and Christiansø (southern Baltic Sea) starting in 1880. Hydrographic conditions at Skagens Reef are influenced by inflows of North Sea water, outflow from

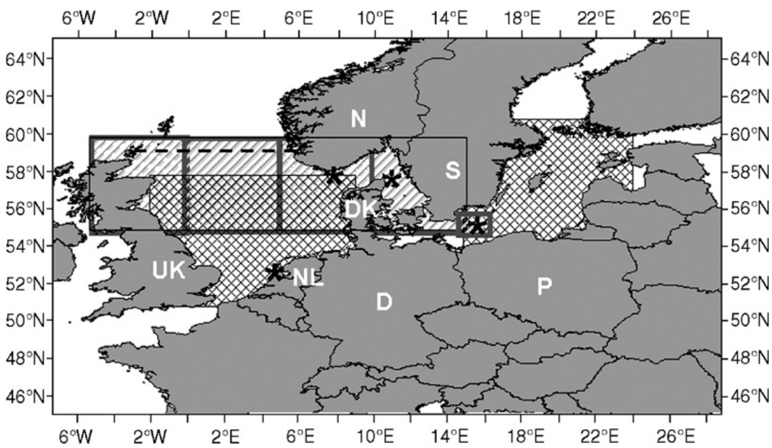

Fig. 1. Map of North Sea, Baltic Sea and transition waters (Skagerrak, Kattegat, Øresund, and Belt Sea). The sites where sea surface temperature was recorded daily are marked with stars. These locations were at Marsdiep (Netherlands), Torungen (southern Norway), Skagens Rev (northern Denmark) and Christiansø (Denmark; southern Baltic Sea). The rectangular boxes on the map are areas where ICES (diagonal line fill) and Hadley Centre HADISST1 (cross-hatched fill) data (Rayner et al., 2003) have been used as sources of sea surface temperature data. Temperatures from the small boxed area located between Sweden and Poland were also obtained from ICES. The horizontal dashed line (59.283°N) in the northern North Sea between the Orkney Islands and Utsira, Norway represents the section through which water volume transports have been estimated (Reid et al., 2003) and used in cross-correlation analyses. See Table 1 for latitude and longitude coordinates for all sampling positions.

the Baltic and to some extent by intrusions of warm Atlantic water into and across the North Sea (Danielssen et al., 1996; Gustafsson and Stigebrandt, 1996). The Christiansø site is heavily influenced by runoff of cold, relatively freshwater from the northern Baltic (Helcom, 2002) and winter ice conditions. The area has no tides and is only weakly and infrequently influenced by inflows of warm Atlantic water (Helcom, 2002). The location where measurements were taken at Christiansø was inside a protected harbour on the island.

The third monitoring time series included was recorded at Marsdiep, Netherlands (van Aken, 2003). This site is located at the entrance of a tidal inlet in the southern North Sea. Monthly averages for the entire data series are available on the Internet (http://www.nioz.nl/nioz_nl/ccba2464ba7985d1eb1906b951b1c7f6.php) and were used in this study. The fourth daily monitoring time series has been recorded at Torungen, southern Norway (Ottersen et al., 2003). This site is located at an exposed location on the western part of the Skagerrak near where it joins the North Sea (Fig. 1). Temperatures here are influenced by several processes, including inflow of Atlantic water across the northern North Sea and outflow of fresh Baltic water along the Swedish and Norwegian coasts.

The other major data source used in this study is based on opportunistic sampling by scientific research vessels and merchant ships. Two databases of opportunistic data were used. One is maintained by the International Council for the Exploration of the Sea (ICES). These data are collected throughout the entire northeast Atlantic and adjacent seas by research vessels and other sampling platforms, and are subsequently deposited with ICES (http://www.ices.dk). Coverage is greatest after 1950, and for the North Sea–Baltic Sea area.

The second database is the HADISST1 global SST database prepared and maintained by the Hadley Centre of the UK Met Office (Rayner et al., 2003). HADISST1 is itself based on the Comprehensive Ocean Atmosphere Data Set (COADS) database (Woodruff et al., 1987; Woodruff et al., 1998) with updates from various sources including satellite imagery. As is the ICES database, the original COADS data are also based on opportunistic sampling, though by both merchant ships and research vessels. Sampling coverage particularly in the 1800s is limited to commercial sea lanes and is low in the North and Baltic Seas up to the early decades of the 1900s (Woodruff et al., 1987; Kaplan et al., 1998; Diaz et al., 2002; Rayner et al., 2003). Measurements by merchant vessels were made using buckets (insulated and uninsulated) and engine intakes (Parker et al., 1995). However HADISST1 has employed extensive data interpolation and calibration procedures to fill in gaps and correct for different measuring techniques (Parker et al., 1995; Rayner et al., 2003). As a result, a complete (i.e., no gaps) global time series of gridded interpolated SST monthly data is available for $1° \times 1°$ latitude–longitude squares from 1870 to present.

The ICES and Hadley Centre data were used to extend the Skagens Reef and Christiansø time series to the early 2000s, thereby enabling future studies to interpret recent temperature variations in the context of observations since 1880. The ICES and Hadley data were also used to investigate spatial synchrony of temperature variations in coastal and offshore areas of the North–Baltic Sea region.

Temperature data were obtained from ICES and the Hadley Centre for several regions of the North Sea, Baltic Sea and their transitional waters (Fig. 1). Neither the Marsdiep (van Aken, 2003), DMI (Sparre, 1984) nor Torungen (Ottersen et al., 2003) data have been submitted to ICES or the Hadley Centre, so comparisons of these monitoring data with the ICES or HADISST1 datasets involve independent data sources.

Our analyses are conducted with seasonally and annually averaged data. Data were aggregated to seasonal and annual means as described below. In the case of the four monitoring locations and Hadley data, we used existing monthly averages to compute quarterly (winter: January, February, March; spring: April, May, June; summer: July, August, September; fall: October, November, December) and annual (January-December) means.

The seasonal and annual means can be biased relative to true temperatures if sampling intensity or coverage is low in some months. To reduce the possibility that seasonal means were biased because of low or no sampling, the following data inclusion rules were used. For computing seasonal and annual means from daily monitoring data (Marsdiep, Torungen, Skagens Reef, Christiansø), all 3 months within a season, and all 12 months within a calendar year, had to be represented before averaging. Inspection of the DMI yearbooks showed that monthly means typically were based on >25 daily measurements. The Marsdiep and Torungen monthly means are based on a similar number of measurements (van der Hoeven, 1982; van Aken, 2003; Ottersen et al., 2003).

In the case of the ICES data, we first produced monthly averages from available individual SST data and CTD profiles. We then computed seasonal and annual averages from these monthly data. However months having fewer than 15 temperature measurements in each ICES box (Fig. 1) were excluded. In addition, all 3 months within a season having $N > 15$ (i. e. minimum

N per season = 45), and all 12 months within a calendar year having $N > 15$ (i.e., minimum N per year = 180), had to be represented in order to compute seasonal and annual averages.

Variations in regional circulation could influence temperatures at coastal monitoring sites. We used estimates of the volume flux into and out of the North Sea to investigate this possibility (see online material Appendix Table 4). Estimates have been derived from the 3D physical oceanographic NORWegian ECOlogical Model (NORWECOM) model of the northeast Atlantic, including the North Sea and boundary areas (Reid et al., 2003). The estimates are available as fluxes in the upper 150 m of the water column in the southward and northward directions along a transect at 59°17′N from Utsira, Norway to the Orkney Islands, Scotland. The time series of monthly transport indices starts in 1955. Updates from Jan., 2002–Dec., 2005 were kindly provided by Dr. Morten Skogen, Institute of Marine Research, Bergen, Norway. The difference between northward (outflow; positive index) and southward (inflow; negative index) flows of surface (0–150 m) water through this transect represents an index of net waterflow to the North Sea (Reid et al., 2003). A principal components analysis showed that the flows shallower and deeper than 150 m were negatively and significantly correlated (Reid et al., 2003), suggesting that an inflow of a surface water mass and its properties (e.g., heat) is partly counterbalanced by an outflow of deeper water, and vice versa. The flux estimates compare favourably with direct measurements and have been used in many ecological and oceanographic applications (Iversen et al., 2002; Reid et al., 2003). Further details of the model and the estimates are presented in this literature.

Earlier studies have shown that winter severity variables such as the North Atlantic Oscillation (Hurrell, 1995) and ice cover of the Baltic Sea (Seinä and Palosuo, 1996) also affect winter and spring temperatures in the Baltic Sea (MacKenzie et al., 1996; Lehmann et al., 2002; MacKenzie and Köster, 2004). These variables were included in analyses conducted to extend winter SST measured at Christiansø and Skagens Reef (see Section 2.2.1).

All quarterly and annual time series used in this study are available in data files from the journal website.

2.2. Data analyses

2.2.1. Intercomparison and updating of Christiansø and Skagens Reef time series

The intercomparison and updating of the DMI series from Christiansø and Skagens Reef was conducted by comparing each monitoring time series of seasonal or annual data with several independent time series. For Christiansø, ICES data from an area in the southern Baltic Sea (Bornholm Basin), and the HADISST1 dataset for the southern-central Baltic Sea were used (Fig. 1). Winter SST at Christiansø was also compared with Baltic ice cover and a winter index of the NAO (Table 1).

All comparisons were conducted by inspecting bivariate scatterplots and quantitatively using linear regression analysis. The data series which is still being continued and whose linear regression analysis had highest correlation and significance was used to extend the Christiansø time series to the end of 2003. Extension was done by using the linear regression model to predict new Christiansø temperatures (i.e., those from end of the original series to end of 2003) based on input data from the series which is still being continued. This procedure accounts for possible offsets between different series.

The Skagens Reef lightvessel time series was updated in a similar fashion. However, because temperatures at Skagens Reef are influenced by hydrographic processes in both the North and Baltic Seas, the comparisons included data series from several North and Baltic Sea sites (Fig. 1), the Hadley Centre HADISST1 data (Rayner et al., 2003) for the North Sea (Fig. 1), the winter NAO index and the Baltic Sea ice coverage area.

2.2.2. Autocorrelation

Analyses were conducted to investigate if temperatures in one time period depended on those at a previous time period (i.e., presence of autocorrelation). This situation could arise if for example a water mass in one time period retains sufficient heat that it influences heat content one time step (i.e., 1 year) later. As a result seasonal temperature in a given year could reflect hydrographic and climate processes which occurred 1 or more years earlier.

The presence of autocorrelation in time series also has consequences for the interpretation of statistical significance levels. When autocorrelation exists, the degrees of freedom, correlation coefficients and significance levels of linear regression models must be adjusted to compensate for the lack of independence of observations (Thompson and Page, 1989; Pyper and Peterman, 1998; Fox et al., 2000). All time series were investigated for autocorrelation for lags up to $N/5$ years, where N is the number of years in the time series. Autocorrelation in each series was compared with the 95% confidence limits (95% CL $\approx 2/N^{0.5}$) of the autocorrelation in a random time series containing the same number of observations as the temperature series (Chatfield, 1989). When calculating significance levels for statistical tests, the number of independent observations was adjusted by calculating the effective number of degrees of freedom (Pyper and Peterman, 1998; Fox et al., 2000):

$$\frac{1}{N^*} = \frac{1}{N} + \frac{2}{N}\sum_{j}^{N/5} r_{xx}(j) r_{yy}(j), \quad (1)$$

where N^* is the number of independent paired observations in the time series x and y, N is the sample size and $r_{xx}(j)$ and $r_{yy}(j)$ are the autocorrelation of x and y at lag j.

2.2.3. Correspondence of temperatures estimated from coastal monitoring and open sea measurements

We compared temperature variations and seasonality in coastal monitoring datasets with those estimated in adjacent sea areas with opportunistically measured data. We hypothesized that both sources of data would show similar seasonal variations and trends over time, and that the differences between the series at a given sampling date would be random and serially independent. Two sets of statistical analyses were conducted to evaluate these hypotheses. First we constructed time series of differences between our three longest coastal monitoring series and adjacent open sea data (i.e., Marsdiep–Hadley North Sea, Torungen–Hadley North Sea, Christiansø–Hadley Baltic Sea). We then inspected the series visually for evidence of multi-annual trends and evaluated the autocorrelation in each of these time series of differences. To check whether similar patterns were evident with ICES data, we compared the Torungen monitoring series with ICES data from the northeast North Sea–Skagerrak region. This region includes the Torungen monitoring site, but not its data.

As a second evaluation of the comparability of the coastal and open sea datasets, we investigated the seasonal amplitude of temperature variations at Christiansø and in the open Baltic Sea (Hadley Baltic Sea dataset), and at Torungen with the ICES data for the northeast North Sea–Skagerrak region. Seasonal amplitude was calculated as the difference between summer (July–Aug.–Sept.) and winter (Jan.–Feb.–Mar.) measurements for each year. We constructed plots of the time series of seasonal amplitudes and the difference in seasonal amplitude between the two series. Linear regression and autocorrelation analyses were used to evaluate whether there were long-term trends or other nonrandom variations in these differences.

2.2.4. Assessment of spatial synchrony of temperature fluctuations

Covariation of temperature fluctuations in all time series was evaluated by calculating the mean correlation between all pairs of time series, and testing for significance (Thompson and Page, 1989; Fox et al., 2000). Significance of correlations was evaluated with a *t*-test based on autocorrelation-adjusted effective numbers of observations. Correlations were calculated on seasonally and annually averaged data.

We also investigated how the correlation between individual pairs of sampling sites depended on distance between those sites. *A priori* we hypothesized that correlations would fall with increasing separation distance because variability in environmental variables typically increases across space (Bell et al., 1993). We evaluated this hypothesis meta-analytically by inspecting the scatterplot of the correlations between temperatures measured at pairs of sites and inter-site separation distance. Distances between temperature measurement sites were estimated using geographical information system software (ESRI, 2000). Regression analysis was used to quantify the shape of the relationship (e.g., linear, curvilinear) between correlation and separation distance, and the amount of variation in inter-site temperature correlations that could be explained by separation distance.

Cross-correlation analyses were used to estimate the importance of synchronous large-scale climatic forcing on local temperatures relative to advective processes. Cross-correlations should be high at lag 0 and fall rapidly to insignificant levels if temperatures among areas are mainly influenced by common meteorological forcing. In contrast, if advective processes dominate local temperature variability, we hypothesize that cross-correlations will be high for several lags between sites. We used cross-correlation analyses to investigate possible lagged temperature responses among three widely separated coastal monitoring sites (Marsdiep, Torungen and Christiansø). Cross-correlation analyses were conducted by first constructing a single chronologically ordered time series containing all four seasons of data for each of the three sites. Each of these time series therefore contained a strong seasonal variation. This seasonal variability was removed by subtracting the site-specific seasonal mean from each time series (Chatfield, 1989). We then checked using linear regression analysis whether there were long-term trends in the deseasonalized time series. Since trends were present in each of the three time series ($P<0.05$), we used the residuals (also known as “anomalies”) in computations of cross-correlations. Significance of the cross-correlations was assessed in a manner similar to that used for assessing significance of autocorrelations

(Chatfield, 1989). Cross-correlations were calculated for ±50 lags, corresponding to ±12.5 years of seasonal (quarterly) data.

We used the modelled transport indices in cross-correlation analyses to investigate the role of advection on local temperatures. The monthly transport indices values were summed across months to generate four seasonal time series to match the scaling of the temperature data. Preliminary analysis and previous studies (Reid et al., 2003) showed that the transport data also have a significant seasonal component because surface fluxes tend to be largest in winter, partly in response to forcing by the North Atlantic Oscillation. As a result we removed seasonal variation from the transport data in the manner described above (Chatfield, 1989) prior to cross-correlation analyses. There was no linear long-term trend in the deseasonalized data (linear regression: $P>0.05$), so we used the deseasonalized data (instead of linear regression residuals) in cross-correlation analyses. Cross-correlations were calculated for 40 lags (10 years) of data.

2.3. Temporal variability

Temporal variations at multiple scales (e.g., interannual, multi-annual) are evident in the various temperature time series used in this study. These variations are described elsewhere (MacKenzie and Schiedek, in press).

3. Results

Visual inspection of the two newly constructed time series (Skagens Reef and Christiansø; Fig. 2) shows variations at both interannual and multi-decadal scales, and that these series partly co-varied with temperatures measured at other locations in the region. This covariation was used to extend the Skagens Reef and Christiansø time series and is described below.

3.1. Autocorrelation and intercomparison analyses

SST in all seasons and for annual data showed little autocorrelation for the monitoring data (Supplementary Figs. 1 and 2). In general autocorrelation was low (r usually <0.15) and insignificant at all lags considered with a few exceptions. In these cases, autocorrelation was usually only marginally significant (P ca. 0.05). The low autocorrelation reflects the high year-to-year variability in the data series. In contrast autocorrelation was higher in the HADISST1 time series for both the North and Baltic Seas (Supplementary Fig. 2). Autocorrelation was usually significant and positive ($r=0.25$–0.45) for the first two lags in these time series. This pattern may partly be a consequence of the interpolation and gridding procedures used to produce this dataset (Rayner et al., 2003).

The ICES-based time series had many years when data were missing (Fig. 2). As a result it was not possible

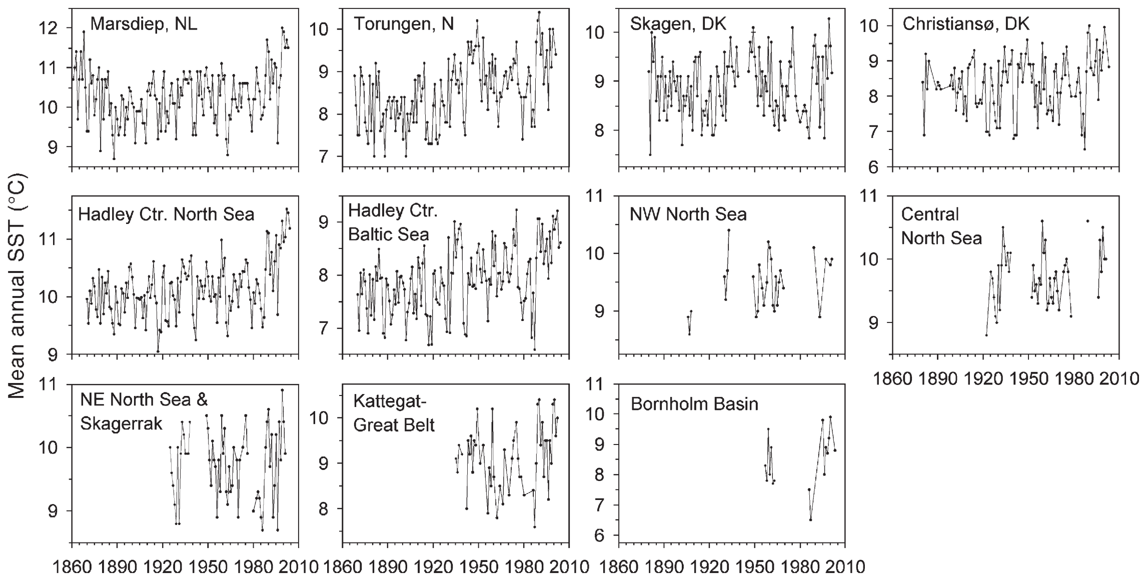

Fig. 2. Time series of mean annual SST measured at different sites in the North Sea and Baltic Sea. Monitoring and Hadley Centre opportunistic data were used to construct the series from Marsdiep, Torungen, Skagens Reef, Christiansø, North Sea and Baltic Sea. ICES data were used to construct the series for the northwest, central and northeast North Sea–Skagerrak, Kattegat–Øresund–Great Belt and Bornholm Basin. Note that scaling on the y-axis differs among panels.

Table 2

Pearson correlation coefficients (*r*), sample size (*N*) and sample size adjusted for autocorrelation (*N**) between fall (October–November–December; above diagonal) and mean annual (below diagonal) SST measured at different sites and with different data sources in the North and Baltic Sea

	Monitoring and Hadley Centre data						ICES data				
Fall→ Annual↓	Skagens Reef	Torungen	Marsdiep	Christiansø	Hadley North Sea	Hadley Baltic Sea	Northwest North Sea	Central North Sea	Northeast North Sea	Kattegat–Belts–Øresund	Bornholm Basin
Skagens Reef	–	0.84 114; 66	0.76 115; 82	0.69 109; 93	0.69 115; 81	0.75 115; 78	0.55 53	0.68 58	0.88 69	0.74 55	0.61 32
Torungen	0.78 109; 83	–	0.74 136; 92	0.59 116; 116	0.62 133; 89	0.64 133; 87	0.65 52	0.64 58	0.72 69	0.63 60	0.59 32
Marsdiep	0.67 112; 90	0.73 130; 77	–	0.49 117; 112	0.63 134; 93	0.58 134; 95	0.54 53	0.54 59	0.60 70	0.57 61	0.40* 33
Christiansø	0.84 98; 73	0.82 102; 75	0.77 107; 76	–	0.66 117; 108	0.70 117; 102	0.30* 53	0.59 59	0.72 70	0.62 60	0.91 33
Hadley North Sea	0.73 112; 89	0.80 128; 63	0.87 134; 74	0.80 107; 75	–	0.75 135; 83	0.66 53	0.74 59	0.73 70	0.56 61	0.65 33
Hadley Baltic Sea	0.70 112; 88	0.81 128; 57	0.75 134; 74	0.83 107; 71	0.84 135; 61	–	0.41** 53	0.58 59	0.76 70	0.73 61	0.67 33
Northwest North Sea	0.62 29	0.66 27	0.66 29	0.55** 28	0.81 29	0.64 29	–	0.77 42	0.62 45	0.61 34	0.53* 21
Central North Sea	0.85 45	0.84 43	0.78 46	0.86 44	0.88 46	0.79 46	0.93 23	–	0.84 55	0.63 40	0.42* 26
Northeast North Sea	0.93 58	0.83 56	0.71 59	0.83 55	0.84 59	0.80 59	0.80 26	0.90 42	–	0.76 51	0.58 32
Kattegat–Belts–Øresund	0.87 41	0.88 43	0.83 48	0.94 42	0.85 48	0.83 48	0.63** 16	0.83 25	0.86 35	–	0.72 29
Bornholm Basin	0.84 14	0.86 14	0.72** 16	0.99 16	0.84 16	0.93 16	0.64^{ns} 8	0.77** 12	0.83 14	0.92 13	–

Tables containing results for winter, spring and summer are available in Supplementary Tables 1 and 2. All correlations are significant at $P<0.001$, except those marked with ** ($P<0.01$), * ($P<0.05$) or ns ($P>0.05$). Analyses using monitoring (Skagens Reef, Torungen, Marsdiep, Christiansø and the NAO index) and Hadley Centre data have used autocorrelation-adjusted degrees of freedom when estimating significance levels (Pyper and Peterman, 1998; Fox et al., 2000). Analyses including ICES data (Northwest North Sea, Central North Sea, Northeast North Sea–Skagerrak, Kattegat–Belt Sea–Øresund, Bornholm Basin) do not show adjusted sample sizes because large gaps in these time series prevented reliable estimation of autocorrelation; statistical significance in these cases is based on the raw number of paired observations in the time series.

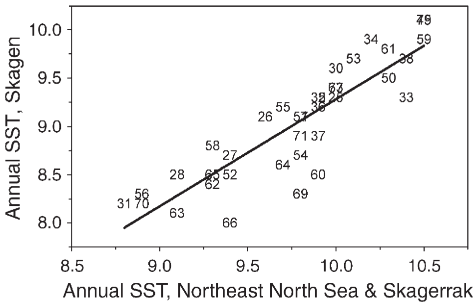

Fig. 3. Example of the calibration regression relationship used to update the Skagens Reef time series for annual mean SST using ICES data from the northeast North Sea–Skagerrak. The regression is significant ($P<0.001$; residual mean square error = 0.29; $y=1.11x-1.80$; $N=37$). See also Table 2 for correlations involving other seasons. Symbols represent years during the 20th century.

to assess the level of autocorrelation in these series nor to adjust significance levels in tests using these series. However given the high statistical significance of nearly all comparisons among series and the relatively low autocorrelation in the Hadley and monitoring series, it is unlikely that levels of autocorrelation in the ICES data affect our conclusions and interpretations. In comparison, there were no or only very short gaps in the monitoring or Hadley time series (Fig. 2).

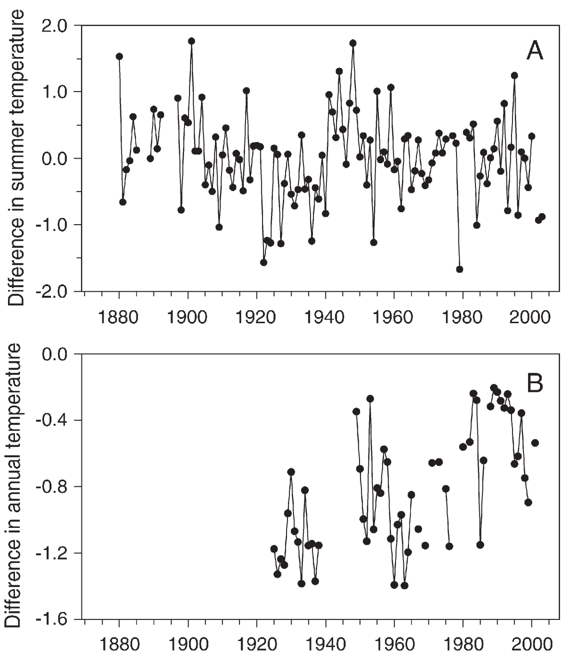

Fig. 4. Interannual variability in the differences between sea surface temperature measured at coastal sites and in adjacent large open sea areas (see Fig. 1 for locations). A: Christiansø (southern Baltic Sea) and Baltic Sea (Hadley Centre data); B: Torungen and the northeast North Sea–Skagerrak (ICES data). See Supplementary Fig. 3 for plots for all four quarters and for annual data for other coastal–open sea comparisons.

The Christiansø time series was highly correlated with Bornholm Basin (ICES) and Baltic Sea (HADISST1) temperatures for all seasons and with ice coverage in the winter (Table 2). The Bornholm Basin series was chosen to extend the Christiansø time series because it explained more variation than other series, and had less autocorrelation than the HADISST1 series.

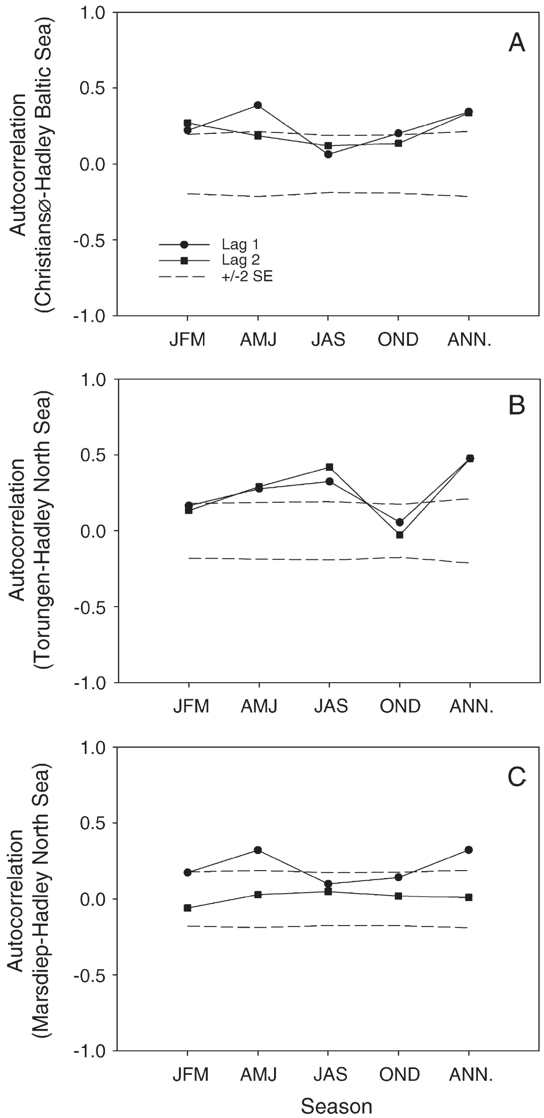

Fig. 5. Autocorrelation of the differences between sea surface temperature measured at a coastal location and in offshore areas (see Fig. 1 for locations). Circles and squares represent autocorrelation at lag 1 and 2 years respectively. The dashed lines represent the range outside which autocorrelation is statistically significant ($P<0.05$; ±2 standard errors).

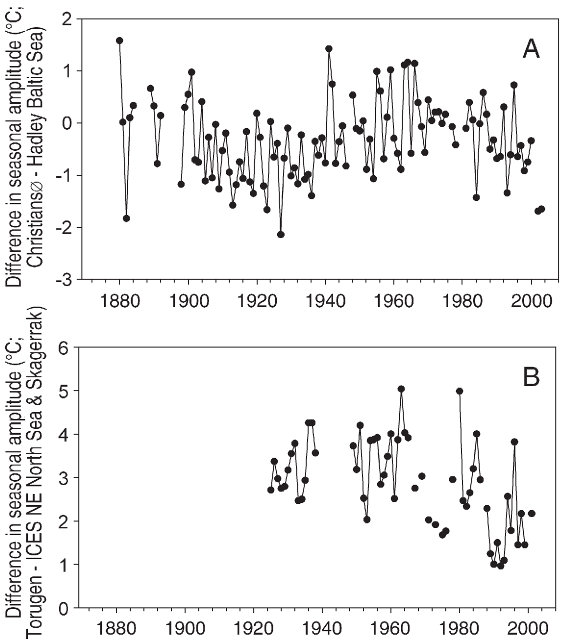

Fig. 6. Interannual variability in the difference of seasonal amplitude of surface temperatures measured in the Baltic Sea–North Sea region. A: difference between seasonal amplitudes measured at Christiansø and with Hadley Baltic Sea data; B: difference between seasonal amplitudes measured at Torungen and with the ICES northeast North Sea–Skagerrak data. Seasonal amplitude is estimated as the difference between summer (July–August–September) and winter (January–February–March) temperatures.

Skagens Reef SST was highly correlated with SST measured at all other sites presented in this study; Baltic ice cover also was correlated with Skagens Reef SST in winter (Table 2; Supplementary Table 1). Among those time series which continue to be maintained or which can be constructed from opportunistic data, the northeast North Sea–Skagerrak had highest correlations in two seasons and with annual data (Fig. 3). Although other sites had high correlations in some seasons (e.g., Christiansø, Kattegat–Øresund–Great Belt, Marsdiep), the northeast North Sea–Skagerrak series was chosen and used for extending the Skagens Reef time series forward.

Inspection of the seasonal Skagens Reef series showed that gaps in single years were more common in the winter than in other seasons. The main reason for the absence of measurements in some years in the winter is due to recall of the lightship to port in severe winters (e.g., those having excess ice; DMI, 1972; Sparre, 1984; Fonselius, 2002). As a result, cold temperature years are under-represented in the winter time series for Skagens Reef. We used the high correlation of the linear regression between Skagens Reef and Torungen winter series to fill in the missing Skagens Reef data. We filled in missing years in the Skagens Reef data using regression-model estimates derived using Torungen data as input. The number of years recovered by this procedure was 15. Most (13) of these years contained temperature measurements in the three other seasons, thereby enabling calculation of annual averages for 13 additional years. We did not use the Torungen data to extend the Skagens Reef series forward because SST is no longer measured at Torungen (K. Iden, Norwegian Meteorological Institute, Oslo, Norway, pers. comm.).

3.2. Correspondence between coastal and open sea temperatures

Differences between coastal and open sea temperatures varied nonrandomly over time: there were many periods when the differences were smaller than during other periods and when differences showed multi-annual trends. For example, the difference between Christiansø and Hadley Baltic Sea temperatures during summer increased during the period 1922–1944 (Fig. 4A; $R^2=0.34$; $P=0.002$). The difference in annual temperature at Torungen and for the northeast North Sea–Skagerrak increased significantly over time (1925–2001) (Fig. 4B; $R^2=0.39$; $P<0.0001$); this pattern was also evident for the difference between Torungen data and Hadley Centre data for the entire North Sea (Supplementary Fig. 3). Autocorrelation of the differences for many of

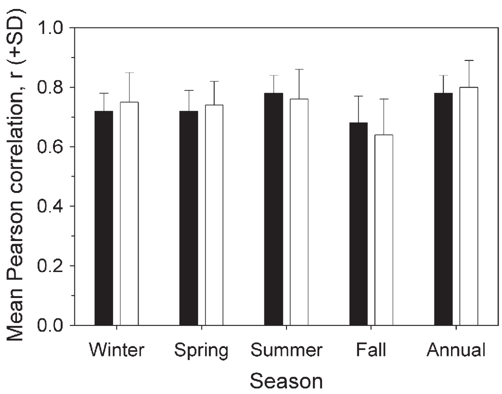

Fig. 7. Spatial synchrony in SST in the North Sea and Baltic Sea region, as expressed by the mean (+SD) correlation coefficient (Thompson and Page, 1989) between SST measured at all pairs of measuring sites for each season and for annually averaged data. Black bars: data series (Marsdiep, Torungen, Skagens Reef, Christiansø and Hadley Centre data for North Sea and Baltic Sea) for which autocorrelation could be estimated and significance levels adjusted (Thompson and Page, 1989; Fox et al., 2000); white bars: all data series (i.e., monitoring, Hadley Centre and ICES data). $N=15$ and 55 for respectively the black and white bars. See text for details.

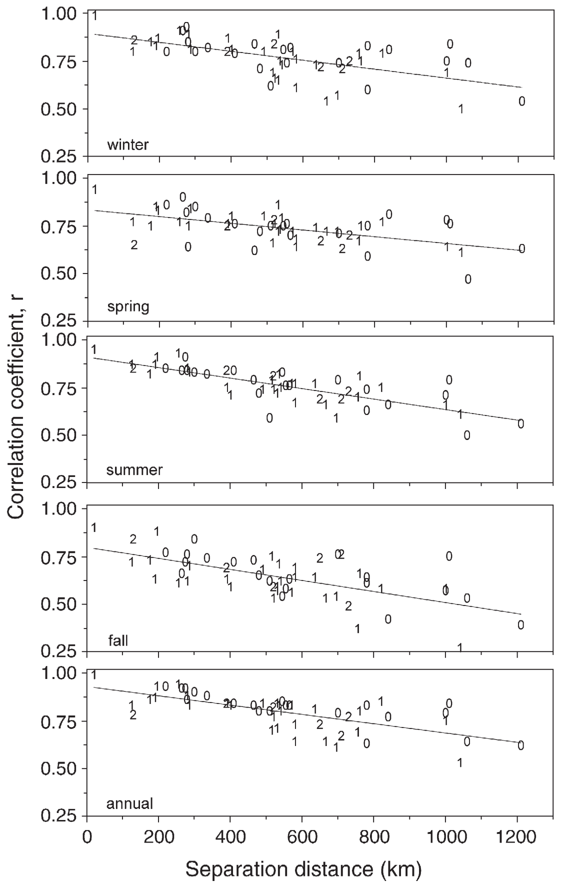

Fig. 8. The dependence of correlation in SST measured at various locations in the North and Baltic Seas on inter-site separation distance for each season of the year and for annually averaged data. Symbols indicate whether the correlation was based on pairs of time series involving no, 1 or 2 daily coastal monitoring series. All regression lines are statistically significant ($P<0.0001$; $N=55$). Distances between all pairs of measuring sites are given in Supplementary Table 3.

the series was significant and positive at 1–2 year lags (Fig. 5).

The amplitude of seasonal variation also differs significantly between coastal and open sea datasets (Fig. 6 and Supplementary Fig. 4). The Hadley Baltic Sea data had a larger seasonal variation than the Christiansø data (t-test: $P=0.0064$; Supplementary Fig. 4A). Although there is no evidence of a long-term trend in the difference of seasonal amplitudes, there were significant multi-annual variations throughout the time series. Differences increased during 1930–1970 (Fig. 6A: $R^2=0.17$; $P=0.0044$), and then decreased during 1971–2003 (Fig. 6A: $R^2=0.28$; $P=0.0019$). The seasonal amplitude at Torungen differed also from open sea measurements in a nearby open sea area (northeast North Sea–Skagerrak; t-test: $P<0.0001$; Supplementary Fig. 4B), and there was a significant long-term decreasing trend in the magnitude of these differences (Fig. 6B: 1925–2001; $R^2=0.19$; $P=0.0003$).

3.3. Spatial synchrony

The intercomparison tests to develop the new Skagens Reef and Christiansø time series showed that temperatures at these sites were correlated with those at several other sites in the North–Baltic Sea region. When all pairs of time series were compared with each other, nearly all correlations were highly significant ($P<0.001$) and all correlations were positive (Table 2 and Supplementary Tables 1 and 2). This result applied for all

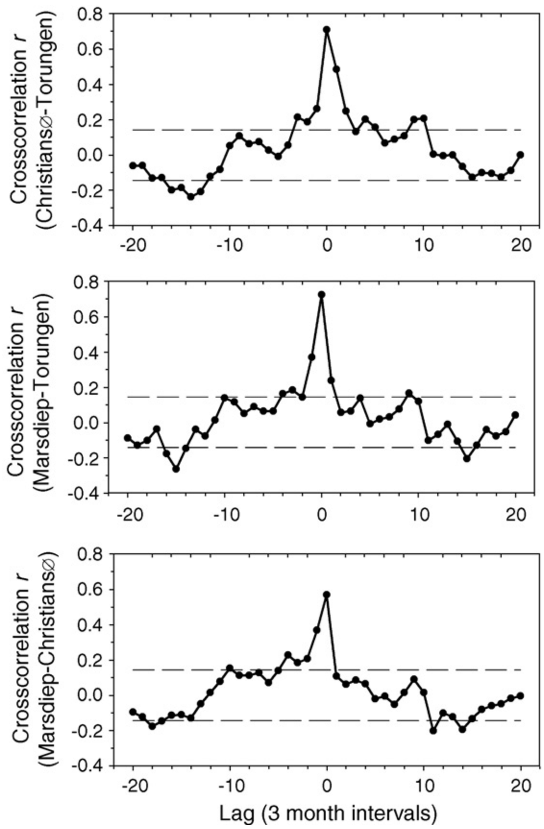

Fig. 9. Cross-correlations of SST measured at three widely separated coastal sites in the North Sea–Baltic Sea region. Seasonal variations and long-term tends have been removed from the series before cross-correlations were computed (Chatfield, 1989). In the top two panels, positive lags mean that temperature variations at Christiansø and Marsdiep follow variations in temperature at Torungen; in the bottom panel, positive lags mean that temperature variations at Marsdiep follow temperature variations at Christiansø. Solid line with circles: cross-correlation; dashed lines: ±2 standard errors for cross-correlation between two random time series. Cross-correlations at lags 21 to 40 and −21 to −40 were generally low and insignificant (results available from corresponding author).

seasons and for annually averaged data. The average correlation among sites, which is a measure of spatial synchrony (Thompson and Page, 1989), was highly significant (also after adjusting for autocorrelation-related loss of degrees of freedom) for all seasons (Fig. 7). This result was obtained for tests using monitoring and Hadley Centre data, and for tests using monitoring, Hadley Centre and ICES data.

The strength of the correlations between pairs of sites depended significantly ($P<0.0001$) on inter-site separation distance for all seasons and for annually averaged data (Fig. 8). Separation distance explained most variation in inter-site correlations during the summer and least variation during the spring. The amount of decay in spatial synchrony of temperature correlation with separation distance is estimated by the slope of the season-specific regressions. These slopes were typically 0.02 correlation units per 100 km (Fig. 8).

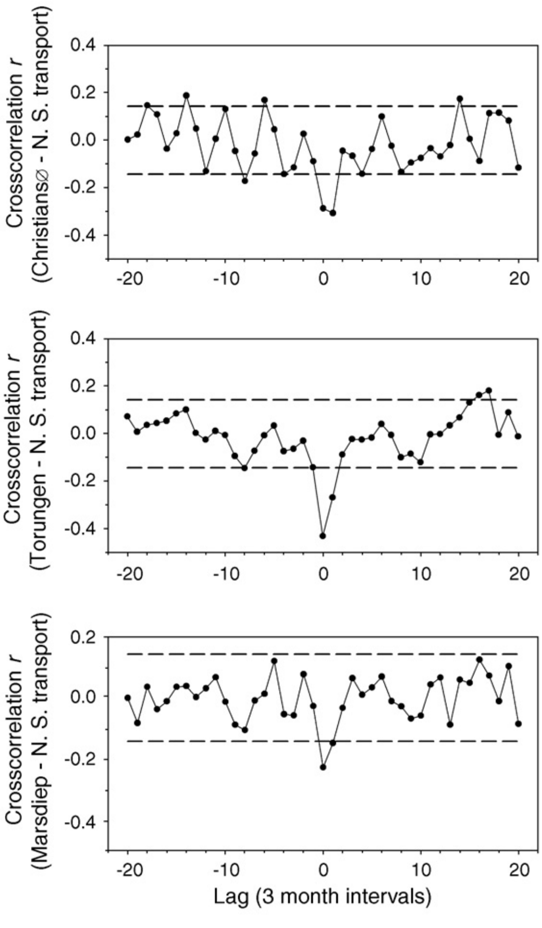

Fig. 10. Cross-correlations of SST measured at three widely separated coastal sites in the North Sea–Baltic Sea region with the net transport of water across the Utsira–Orkney transect (59°17′N) in the upper 150 m of the water column. Seasonal variations and long-term tends have been removed from the series before cross-correlations were computed (Chatfield, 1989). In this representation, positive lags mean that temperature variations follow variations in flow. Note that the scaling of the transport indices means that export from the North Sea (northward flow) is associated with positive transports. Solid line with circles: cross-correlation; dashed lines: ±2 standard errors for cross-correlation between two random time series. Cross-correlations at lags 21 to 40 and −21 to −40 were generally low and insignificant (results available from corresponding author).

The cross-correlation analysis of deseasonalized and detrended temperatures at three widely separated coastal monitoring sites (Marsdiep, Torungen, Christiansø) showed that correlation was highest at lag 0 and usually declined to insignificant levels within 1–1.5 year (i.e., 4–5 lags of 1 season per lag; Fig. 9). All significant correlations up to 1.5 years of lag were positive, and the cross-correlation function for all three pairs of sites was generally symmetric about lag 0 (i.e., correlations were positive and of similar magnitude for both positive and negative lags). Cross-correlations at lags >±20 were generally low and insignificant (results available from authors).

Deseasonalized and detrended temperatures at all three monitoring sites were significantly correlated with the deseasonalized and detrended net flow of water from the North Sea, as expressed by the transport indices (Fig. 10). Cross-correlations between temperature and flow were significant and negative at lags 0 and +1 (i.e., temperature variations lagged behind flow variations by one time step, corresponding to 3 months). Cross-correlations were higher at Christiansø and Torungen than at Marsdiep, and were nearly always insignificant at other lags (Fig. 10; lags between 20 and 40 available from authors).

4. Discussion

We have reconstructed and extended two long-term temperature time series from existing daily monitoring data. Moreover when these series were compared with two other coastal monitoring series and several offshore temperature series, we documented the spatial synchrony of the various datasets up to scales of 1200 km.

We note that two (Marsdiep and Torungen) of the SST monitoring programmes are, to our knowledge, the longest daily recorded, calibrated sea temperature series in the world. In comparison the longest record of coastal water temperature in North America was 117 years long in 2004 (Nixon et al., 2004). Another long time series exists for the North Sea (Helgoland Roads from 1873 to present though with gaps between 1894–1906 and 1944–1962; Wiltshire and Manly, 2004). The Helgoland Roads and Marsdiep series are still being maintained (van Aken, 2003; Wiltshire and Manly, 2004) but daily monitoring at Torungen, Skagens Reef and Christiansø has been discontinued.

4.1. Homogeneity of time series

When investigating long-term trends and variability in environmental data, care must be taken to ensure that the measurement techniques have not changed by amounts sufficient to produce spurious trends and variations. This situation could arise if for example thermometers in early decades are biased relative to newer thermometers. In addition to changes in thermometer technology, measuring practices can also influence temperature recordings. For example many older SST measured on merchant ships were estimated using buckets of seawater placed on shipdecks (Parker et al., 1995). In comparison, present merchant ship sampling methods employ temperature sensors located in ship seawater intakes. These intakes are located several meters below the sea surface where temperatures can be much colder than true surface temperatures. Moreover differences in bucket insulation and exposure to wind on the shipdeck can influence temperature measurements (Parker et al., 1995; Parker et al., 1995; Rayner et al., 2003). Both the change in sampling methodology (buckets vs. intakes) and the change in depth associated with the sampling (upper 1 m vs. several meters below the surface) can potentially contribute to variations in temperatures when data from different sources are compiled into common datasets. Measuring practices can therefore potentially contribute to trends and variations observed in such datasets. Extensive efforts have been made on a post hoc basis to minimize the role that these sampling heterogeneities over time played in the Hadley time series (Rayner et al., 2003).

In the case of the monitoring data, several factors minimize the likelihood that these potential sources of bias contaminate data series. First, the sampling is conducted in the same depth, location and time during the monitoring period. Second, the instruments used are identical over long periods of time. Third, the instruments undergo frequent calibration and corrections are applied where necessary (Thomsen, 1961; van der Hoeven, 1982; K. Iden, pers. comm.). Fourth, the measurements are made by professionally trained personnel employed by meteorological, hydrographical or fisheries/zoological institutes (Thomsen, 1961; van der Hoeven, 1982; Fonselius, 2002; K. Iden, pers. comm.). All of these factors contribute to ensuring high quality and consistency of measurements. It is unlikely that the major variations and trends in monitoring data are due to sampling heterogeneities.

4.2. Spatial synchrony

Our analyses quantify the degree of spatial synchrony in SST measured at several different sites in the North Sea–Baltic Sea region over multi-decadal temporal scales (up to 100–120 years). Temperatures at all of our sites strongly co-vary and typically have high correlation (mean $r=0.74$; standard error $=0.01$), regardless of site pairings and time of year. The robustness of this result demonstrates that temperatures at coastally monitored sites reflect much (average ca. 50%) of the variability in temperatures at many other locations and at larger spatial scales. In particular, the high correlations among sites, and with the HADISST1 dataset indicate that the single-site temperature measurements associated with long-term monitoring data are representative of major temperature fluctuations over much larger spatial scales than those in the immediate vicinity of where temperatures were measured.

We also quantified the magnitude of spatial decorrelation in SST variability in the North Sea–Baltic Sea region at scales of 100s of km. Correlations in SST between sites decrease with increasing separation distance in a simple monotonic fashion. The decline with distance is not surprising (Thompson and Page, 1989; Bell et al., 1993), but appears relatively weak: temperatures at sites separated by nearly 1200 km were still highly and significantly correlated (mean r at 1200 km for the four seasons and annual data is 0.6 based on the patterns in Fig. 5).

The significant correlations at spatial scales up to 1200 km are consistent with the known correlation radius of atmospheric fluctuations (ca. 1000 km; (Frankignoul and Hasselmann, 1977)). Many large-scale climatic and hydrographic processes (e.g., transport of air masses, heat fluxes across the air–sea interface associated with regional cooling/warming, inflows of Atlantic water, the North Atlantic Oscillation) have been documented to affect thermal conditions over large areas of northern Europe (Otto et al., 1990; Dippner, 1997; Omstedt et al., 2004; Stenseth et al., 2004; Omstedt and Hansson, 2006). Our results with century-long sea temperature series also show relatively high spatial synchrony within these spatial scales.

While the dominant mechanism responsible for spatial synchrony of temperatures in our study is large-scale climatic processes, there were also significant differences in temperature variability between coastal sites and adjacent sea areas. Although it is not surprising that a coastal series might be warmer or colder than an open sea time series from a nearby area, the differences between series and seasonal amplitudes varied non-randomly and differed significantly over time. The nonrandom pattern of variation was unexpected; we believe that the long time period of regular sampling covered by our datasets (up to 120 years) allowed us to identify levels of autocorrelation and periods when differences were consistently above or below average.

We suspect that the significant variations in differences between coastal and open sea data are due to real physical oceanographic phenomena and sampling artifacts. The open sea data are compiled over large spatial areas which contain latitudinal gradients in temperature, as well as complex and intermittent hydrographic features (e.g., fronts, spatially varying ocean currents). Moreover the open sea data are collected opportunistically, and data sampling heterogeneities within the area could lead to spurious temperature trends in time series constructed from those datasets. As a result, the perception of temperature variability derived from such a series, relative to temperatures measured at a fixed sampling site, can vary over time. As an example, fall temperatures at Christiansø during 1979–1988 were on average 0.7 °C warmer than those estimated using Hadley Centre data, but this difference was 1.2 °C during 1989–1998 (Supplementary Fig. 3).

The presence of nonrandom and temporally varying differences in temperature as estimated by multiple time series has to be considered when linking temperature fluctuations to some biological responses. When relating a biological time series to, for example, the Torungen or the ICES northeast North Sea–Skagerrak or Hadley North Sea temperature data one could arrive at different conclusions regarding the role of temperature on the measured response: the level of explained variability, statistical significance of the response and the functional dependence on temperature (i.e., slope) would most likely be different. Empirical relationships between temperature and biotic responses will therefore inherently have unexplained variability, depending on how closely the different temperature indices reflect those actually experienced and perceived by the target species of the investigation, or how closely they serve as proxies of key foodweb processes that affect an investigated species.

A secondary mechanism that may have affected spatial patterns in temperature variability is advection of water masses. We found low but significant cross-correlations in sea temperature at lags up to 12–15 months (i.e., corresponding to 4–5 lags of our seasonally scaled data). These lagged cross-correlations among sites suggest that horizontal exchange processes (Otto et al., 1990; Rodhe, 1996; Gustafsson, 1999) may have contributed to some of the variability in local temperatures by transporting water masses and heat among areas. Our cross-correlation analyses involving temperature and transport of water to/from the North Sea (Fig. 10) support these findings because cross-correlations existed but were much lower than the correlations between sites where temperature was measured. For example, outflowing surface Baltic water will affect Christiansø and Torungen temperatures because this current tends to flow along the Swedish and Norwegian coasts (Otto et al., 1990). In our study, temperatures at Torungen and Christiansø were negatively correlated with the (net) flow of water leaving the North Sea: large outflows from the North Sea were associated with colder temperatures at these sites, and conversely large inflows to the North Sea through the Utsira–Orkney section were associated with warmer temperatures at these sites. We believe that our correlations between transport and temperature at these sites are due partly to the outflowing of Baltic water and the advection of warm Atlantic water into the North Sea (Otto et al., 1990; Reid et al., 2003).

We found the weakest cross-correlation between the transport indices and Marsdiep temperatures. This result is likely due to the relative remoteness of this site from the sources of inflowing Atlantic water (northwest North Sea) and outflowing Baltic water (northeastern North Sea), which would allow other processes (e.g., tidal and wind mixing) and phenomena (e. g. bottom topography) to degrade the impacts of these processes on Marsdiep temperatures. We emphasize however that the dominant mechanism affecting the spatial covariation of temperature among sites is the interaction with large-scale atmospheric processes (e.g., transport of air masses of different temperatures across northern Europe, heat fluxes across the air–sea interface; (Omstedt et al., 2004; Omstedt and Hansson, 2006)).

5. Conclusion

We have developed two long time series of SST variability and then used these series, two other coastal monitoring series, and several offshore datasets to assess the spatial synchrony of SST over the last 50–120 years. The newly reconstructed time series and the evidence for spatial synchrony up to scales of 1200 km will be beneficial for assessing how climate change affects local biota (e.g., benthos, fish, plankton), and for interpreting the magnitude and rates of recent climate and hydrographic change in the context of historically measured temperatures. The presence of nonrandom and temporally varying differences in temperature as estimated with the long-term SST series has to be considered when linking temperature fluctuations to some biological responses.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jmarsys.2007.01.003.

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Long-term sea surface temperature baselines – time series, spatial covariation and implications for biological processes **(Web-based information)**

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Web Appendices (abridged descriptions below; full captions in main text file):

1. Web appendix text (sampling methodology)
2. Appendix Figure 1. Autocorrelation of sea surface temperature measured at Marsdiep (Netherlands), Torungen (Norway), and Skagens Rev (Denmark)
3. Appendix Figure 2. Autocorrelation of sea surface temperature measured at Christiansø (Denmark) and large areas of the North Sea and Baltic Sea
4. Appendix Figure 3. Differences in sea surface temperature between coastal monitoring and open sea datasets
5. Appendix Figure 4. Interannual variability in the seasonal amplitude of temperatures measured in the Baltic Sea – North Sea region
6. Correlation matrix for all sites and areas used in study for winter (table; contained in main text file).
7. Correlation matrix for all sites and areas used in study for spring and summer. (table; contained in main text file).

8. Separation distances between all pairs of recording sites (table; contained in main text file).
9. Electronic data files containing all quarterly and annual time series used in this study (to be supplied later).

Appendix:

Datasets containing daily monitored temperature:

This section contains details of the sampling of sea surface temperature at the four sites where tempeature was monitored daily since the mid-late 1800s. In brief, measurements were made daily by professional staff over long periods of time at fixed locations (e. g., harbours, lightships) with calibrated thermometers.

DMI maintained an extensive network of lightvessels and harbour monitoring stations throughout the eastern North Sea, Skagerrak, Kattegat, Belt Sea and southwestern Baltic Sea starting in the late 1880s. These measuring stations were gradually withdrawn from service during the decades following the Second World War (Sparre, 1984) and replaced by a combination of automated measuring devices at fewer locations, satellite imagery, and process-oriented physical oceanographic modelling. This study uses two of the longest available monitoring time series available from DMI.

Temperature measurements during the monitoring programme were made by professional DMI staff using two types of thermometers. During 1880-1938, staff used thermometers with thick rubber insulation which therefore only slowly changed their readings (DMI, 1972; Fonselius, 2002). These instruments were deployed directly in the sea for two hours before being removed from the water for recording of temperatures (DMI, 1972). Starting in January 1939, staff used thermally insulated water samplers designed by Martin Knudsen (Knudsen, 1923; Thomsen, 1961; DMI, 1972). Throughout the period, individual thermometers at measurement sites were calibrated monthly and, when necessary, corrections made to recorded temperatures (Thomsen 1961).

One of the DMI series was measured at the Danish island of Christiansø, near Bornholm in the south-central Baltic Sea (Fig. 1). This series started in 1880 (Sparre 1984) and was maintained until winter 1998 (J. Cappelen, Danish Meteorological Institute, Copenhagen, Denmark, pers. comm.). These data were used to construct a long time series of temperature variations in the Baltic Sea. The site where temperatures were recorded is heavily influenced by runoff of cold, relatively freshwater from the northern Baltic (Helcom, 2002) and winter ice conditions. The area has no tides and is only weakly and infrequently influenced by inflows of warm Atlantic water (Helcom 2002). The location where measurements were taken was in a protected harbour on the island.

The second DMI daily time series used in this study was recorded at Skagens Reef, northern Denmark at the juncture of the Skagerrak and Kattegat (Fig. 1). Measurements started in 1880 and continued until 1979 (Sparre 1984). Hydrographic conditions in the Skagerrak and at Skagens Reef are influenced by inflows of North Sea water, outflow from the Baltic and to some extent by intrusions of warm Atlantic water into and across the North Sea (Danielssen *et al.*, 1996; Gustafsson and Stigebrandt, 1996). The Skagens Reef time series was recorded from a DMI light vessel (Sparre 1984). The Skagens Reef lightship was located in an area where strong currents flowing into and out of the Kattegat collide and create a vigorous mixing zone. The series has interruptions during wars and severe ice winters (Sparre 1984) when the lightvessel was temporarily withdrawn from service.

Monthly averages since 1931 of both series are computerized and were obtained from DMI. Prior to 1931, daily and monthly data are only available in DMI Meteorological Yearbooks. Monthly averages were extracted from these yearbooks and entered into computer files to extend the time series back to the start of measurements (1880). Because the two DMI series were stopped several years ago, they have been prolonged to the early 2000s by intercomparison with other data. The updating has been conducted to facilitate comparisons of historical temperature variations with those which have occurred after the monitoring programme stopped. The intercomparison is described in *2.2.Data analyses*.

The third monitoring time series we used was recorded at Marsdiep, Netherlands (van Aken, 2003). This site is located at the entrance of a tidal inlet in the southern North Sea. Monthly averages for the entire data series are available on the internet (http://www.nioz.nl/nioz_nl/ccba2464ba7985d1eb1906b951b1c7f6.php) and were used in this study. Measurements were (are) made daily by professional staff with calibrated thermometers during the entire time period (van der Hoeven, 1982). Surface water samples from the upper 20-50 cm were collected with a bucket and temperature recorded immediately afterwards with a mercury thermometer (van der Hoeven 1982). Sampling location and techniques changed slightly in the 1940s and these changes have been accommodated by calibration in the data available on the internet (van Aken 2003).

The fourth daily monitoring time series has been recorded at Torungen, southern Norway (Ottersen *et al.*, 2003). This site is located at an exposed location on the western part of the Skagerrak near where it joins the North Sea (Fig. 1). Temperatures here are influenced by several processes, including inflow of Atlantic water across the northern North Sea and outflow of fresh Baltic water along the Swedish and Norwegian coasts. Measurements were made daily at noon UTC with calibrated thermometers by professional staff of the Norwegian Meteorological Institute (K. Iden, Norwegian Meteorological Institute, Oslo, Norway, pers. comm.). A bucket was lowered 25-50 cm below the water surface and allowed to reach the same temperature as the water before being raised. When the bucket was filled and equilibrated, it was removed from the sea and a thermometer was placed in it and rotated for 2 minutes, after which the temperature was recorded. There are no major breaks in the series, but monitoring became irregular after 2000 and was stopped completely at the end of 2003 (K. Iden, Norwegian Meteorological Institute, Oslo, Norway, pers. comm.).

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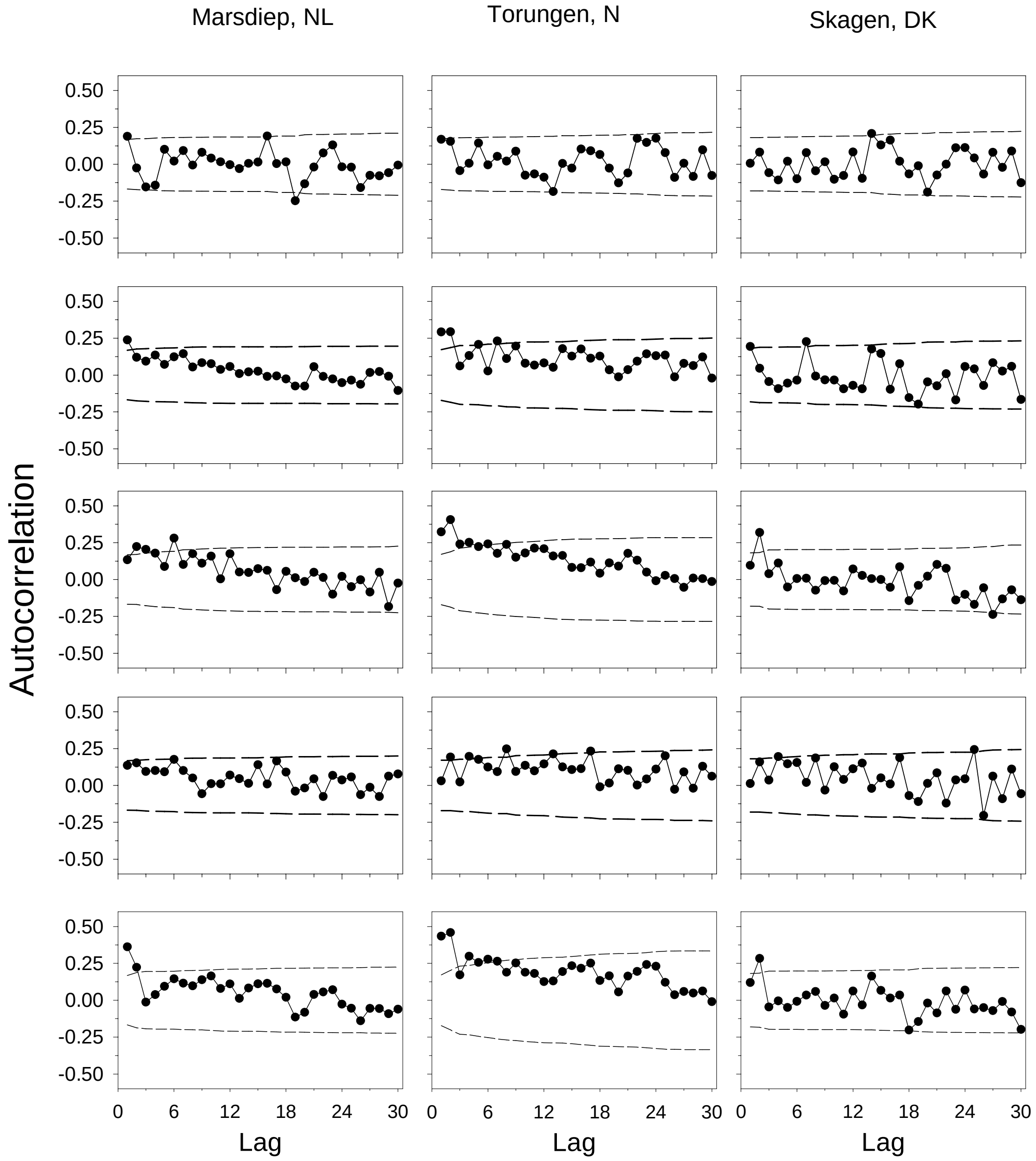
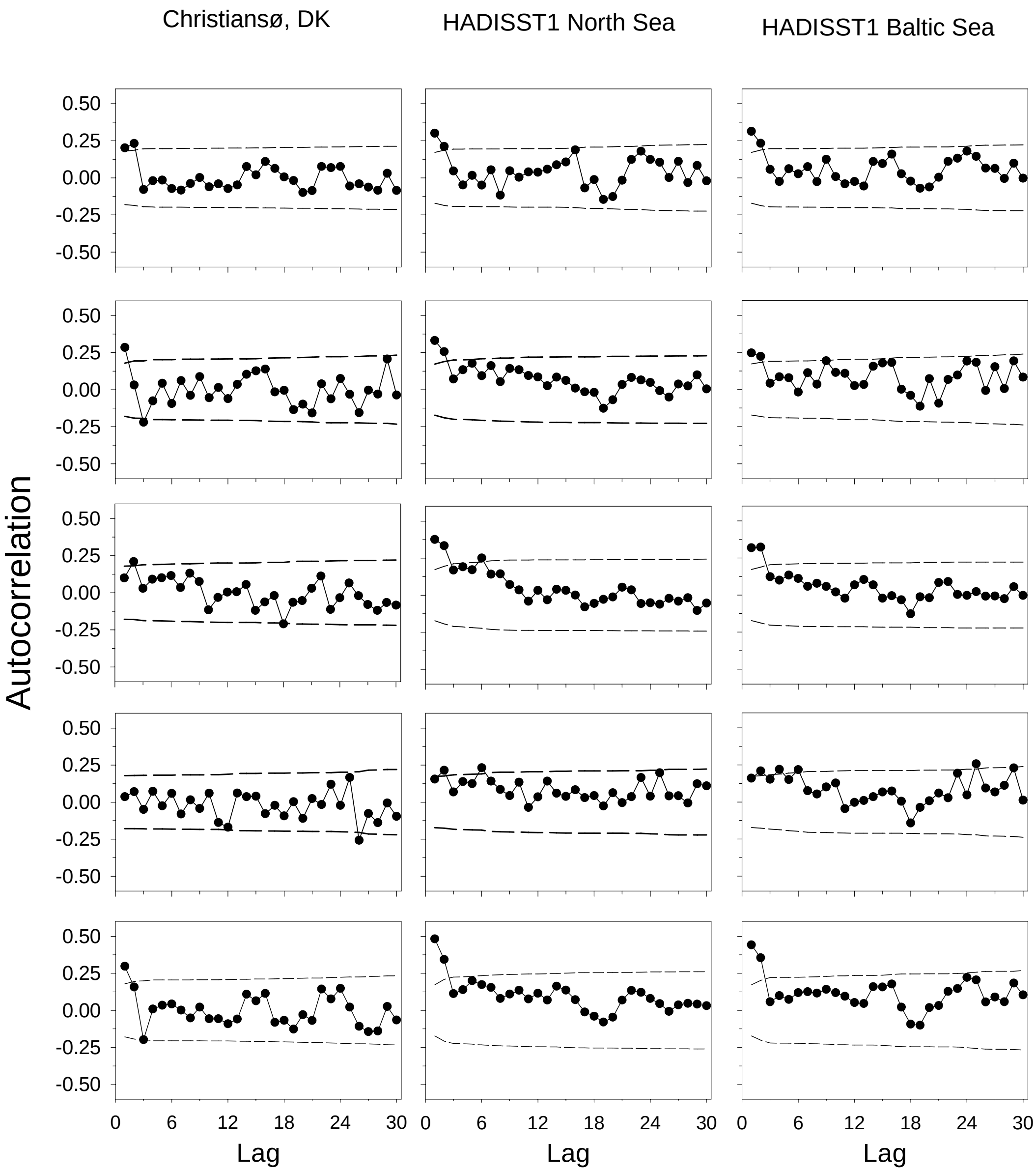
Web Appendix Figure 1. Autocorrelation of sea surface temperature measured at Marsdiep (Netherlands), Torungen (Norway), and Skagens Rev (Denmark). The panels within a column represent autocorrelation at lag j for (from top to bottom) winter, spring, summer, fall and the annually-averaged data. Each lag corresponds to 1 year. Solid lines with dots: autocorrelation; dashed line: 95% confidence limts for autocorrelation for a random time series with the same number of observations as used in the autocorrelation calculations.



Web Appendix Figure 2. Autocorrelation of sea surface temperature measured at Christiansø (Denmark) and large areas of the North Sea and Baltic Sea (see Fig. 1 of manuscript for areas). The panels within a column represent autocorrelation at lag j for (from top to bottom) winter, spring, summer, fall and the annually-averaged data. Each lag corresponds to 1 year. Solid lines with dots: autocorrelation; dashed line: 95% confidence limts for autocorrelation for a random time series with the same number of observations as used in the autocorrelation calculations.



Web Appendix Figure 3. Differences in sea surface temperature between coastal monitoring and open sea datasets. Top row: Christiansø – Hadley Baltic Sea; 2nd row: Torungen – ICES data for northeast North Sea and Skagerrak; 3rd row: Torungen – Hadley North Sea; 4th row: Marsdiep – Hadley North Sea. Columns from left to right show data for Jan.-Feb.-Mar., April-May-June, July-August-September, Oct.-Nov.-Dec., and Jan.-Dec. Note that scaling on the y-axis differs among panels.

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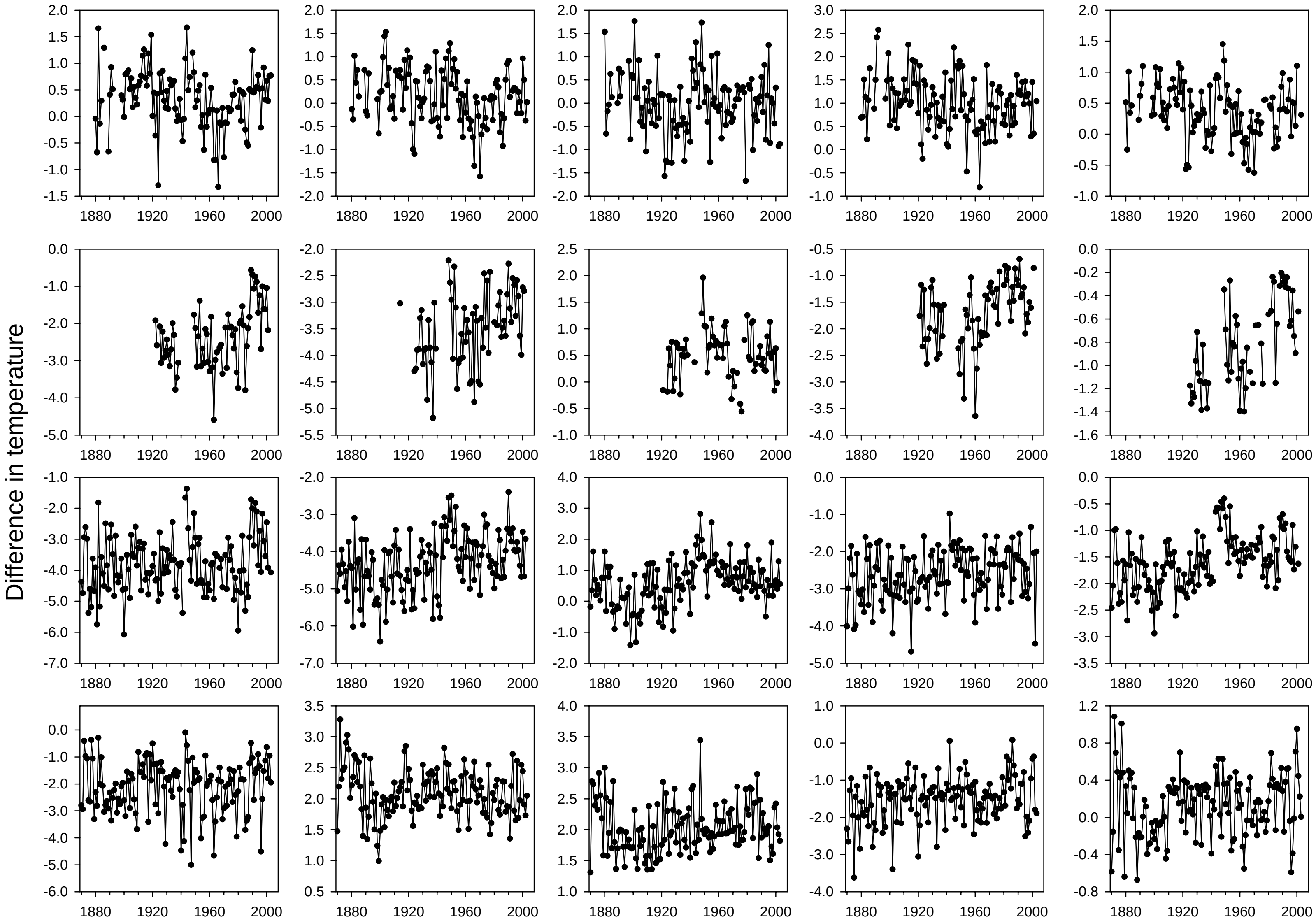
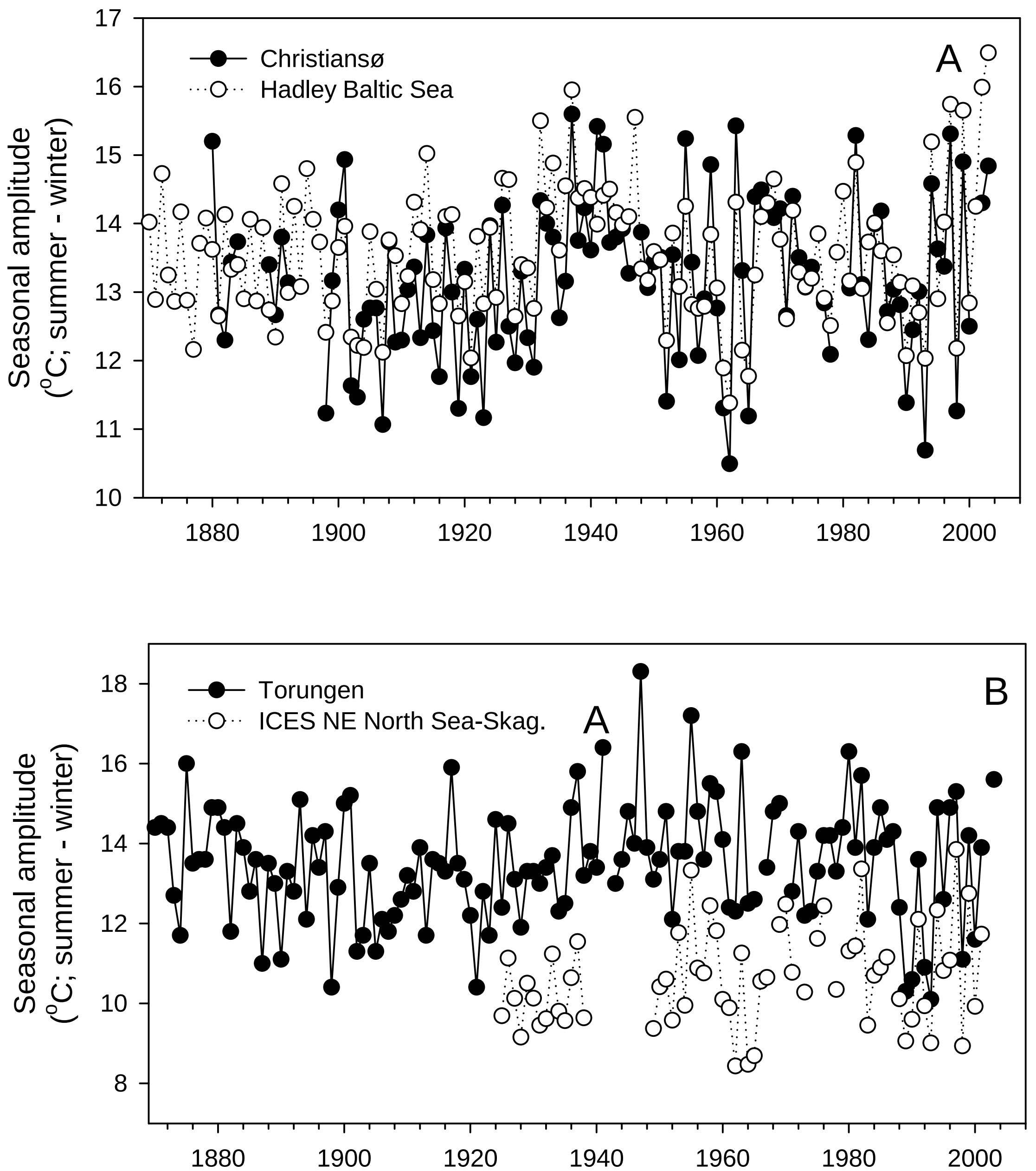


Web Appendix Figure 4. Interannual variability in the seasonal amplitude of temperatures measured in the Baltic Sea – North Sea region. A: Christiansø and Hadley Centre data for the Baltic Sea; B: Torungen and the ICES data for the northeast North Sea – Skagerrak. Seasonal amplitude is estimated as the difference between summer (July-August-September) and winter (January-February-March) temperatures.



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Web Appendix Table 1. Pearson correlation coefficients (r), sample size (N) and sample size adjusted for autocorrelation (N*) for winter (January-February-March) SST measured at different sites and with different data sources in the North and Baltic Sea. ***All correlations are significant at P < 0.001, except those marked with ** (P < 0.01) , * (P < 0.05) or ns (P > 0.05).*** Analyses using monitoring (Skagens Reef, Torungen, Marsdiep, Christiansø and the NAO index) and Hadley Centre data have used autocorrelation-adjusted degrees of freedom when estimating significance levels (Pyper and Peterman 1998; Fox et al. 2000). Analyses including ICES data (Northwest North Sea, Central North Sea, Northeast North Sea -Skagerrak, Kattegat-Belt Sea-Øresund, Bornholm Basin) do not show adjusted sample sizes because large gaps in these time series prevented reliable estimation of autocorrelation; statistical significance in these cases is based on the raw number of paired observations in the time series.

	Monitoring and Hadley Centre data						ICES data				
Winter	Torungen	Marsdiep	Chris.ø	Hadley North Sea	Hadley Baltic Sea	NAO-DJFM	Northwest North Sea	Central North Sea	Northeast North Sea	Kattegat-Belts-Øre.	Bornholm Basin
Skagens Reef	0.86 114; 88	0.71 116; 97	0.80 106; 88	0.76 116; 96	0.69 116; 102	0.63 116; 97	0.58 50	0.80 60	0.87 69	0.85 54	0.82 36
Torungen	-----	0.72 132; 107	0.84 110; 89	0.73 130; 103	0.73 130; 94	0.67 132; 110	0.62 48	0.88 58	0.81 67	0.89 55	0.90 36
Marsdiep	-----	-----	0.75 114; 93	0.83 134; 96	0.69 134; 103	0.69 143; 114	0.56 50	0.67 60	0.65 69	0.80 59	0.80 38
Chris.ø	-----	-----	-----	0.75 114; 87	0.81 114; 87	0.57 114; 105	0.52 49	0.79 59	0.76 68	0.91 58	0.99 38
Hadley North Sea	-----	-----	-----	-----	0.84 136; 85	0.57 136; 118	0.72 50	0.82 60	0.80 69	0.82 59	0.83 38
Hadley Baltic Sea	-----	-----	-----	-----	-----	0.48 136; 114	0.56 50	0.76 60	0.74 69	0.84 59	0.91 38
Northwest North Sea	-----	-----	-----	-----	-----	-----	-----	0.80 44	0.62 46	0.60 32	0.74 24
Central North Sea	-----	-----	-----	-----	-----	-----	-----	-----	0.80 59	0.82 39	0.80 30
Northeast North Sea	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.85 49	0.74 36
Kattegat-Belts-Øre.	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.93 33

Web Appendix Table 2. Pearson correlation coefficients (r), sample size (N) and sample size adjusted for autocorrelation (N*) for spring (April-May-June) and summer (July-August-September) SST measured at different sites and with different data sources in the North and Baltic Sea. ***All correlations are significant at P < 0.001, except those marked with ** (P < 0.01) , * (P < 0.05) or ns (P > 0.05).*** Analyses using monitoring (Skagens Reef, Torungen, Marsdiep, Christiansø and the NAO index) and Hadley Centre data have used autocorrelation-adjusted degrees of freedom when estimating significance levels (Pyper and Peterman 1998; Fox et al. 2000). Analyses including ICES data (Northwest North Sea, Central North Sea, Northeast North Sea -Skagerrak, Kattegat-Belt Sea-Øresund, Bornholm Basin) do not show adjusted sample sizes because large gaps in these time series prevented reliable estimation of autocorrelation; statistical significance in these cases is based on the raw number of paired observations in the time series. Spring data are above the main diagonal of the table, and summer data are below the diagonal.

	Monitoring and Hadley Centre data						ICES data				
Spring → Summer ↓	Skagens Reef	Torungen	Marsdiep	Chris.ø	Hadley North Sea	Hadley Baltic Sea	*Northwest North Sea*	*Central North Sea*	*Northeast North Sea*	*Kattegat-Belts-Øre.*	*Bornholm Basin*
Skagens Reef	------	0.65 114; 95	0.63 114; 96	0.75 104; 68	0.64 114; 93	0.66 114;97	0.73 60	.80 68	0.84 67	0.76 57	0.81 43
Torungen	0.85 114; 82	-----	0.67 135; 107	0.78 112; 81	0.79 133; 84	0.74 133; 75	0.69 61	0.76 70	0.77 68	0.75 63	0.86 44
Marsdiep	0.69 114;90	0.69 137; 69	-----	0.70 113; 93	0.85 134; 101	0.64 134; 111	0.72 61	0.77 70	0.72 68	0.72 63	0.68 45
Chris.ø	0.84 105; 81	0.81 114; 80	0.73 114; 86	-----	0.75 113; 90	0.84 113; 82	0.62 59	0.77 68	0.74 66	0.78 61	0.94 45
Hadley North Sea	0.77 114; 82	0.75 134; 69	0.87 134; 78	0.81 114; 81	-----	0.76 135; 84	0.72 61	0.79 70	0.77 68	0.76 63	0.75 45
Hadley Baltic Sea	0.79 114; 83	0.77 134; 73	0.66 134; 88	0.83 114; 83	0.79 135; 79	-----	0.64 61	0.78 70	0.72 68	0.63 63	0.90 45
Northwest North Sea	0.60 64	0.68 66	0.67 66	0.62 64	0.72 66	0.57 66	-----	0.86 53	0.75 51	0.58 44	0.47** 34
Central North Sea	0.75 68	0.76 71	0.75 71	0.75 68	0.83 71	0.72 71	0.85 59	-----	0.85 60	0.70 48	0.81 35
Northeast North Sea	0.91 63	0.88 65	0.73 65	0.82 62	0.85 65	0.79 65	0.59 52	0.83 58	-----	0.64 53	0.76 41
Kattegat-	0.82	0.85	0.78	0.93	0.83	0.79	0.63	0.76	0.84	-----	0.82

Belts-Øre.	*53*	*60*	*60*	*57*	*60*	*60*	*44*	*47*	*49*		*40*
Bornholm Basin	*0.72* *32*	*0.73* *35*	*0.71* *35*	*0.95* *35*	*0.75* *35*	*0.85* *35*	*0.50*** *26*	*0.66* *29*	*0.76* *31*	*0.91* *33*	-----

Web Appendix Table 3. Approximate straight line distances in km between pairs of sampling sites or centres of sampling areas where SST was measured in this study. See Table 1 for latitude and longitude coordinates.

Separation distance (km)	Skagens Reef	Torungen	Marsdiep	Chris.ø	Hadley North Sea	Hadley Baltic Sea	Northwest North Sea	Central North Sea	Northeast North Sea	Kattegat-Belts-Øre.	Bornholm Basin
Skagens Reef	------	130	650	390	580	515	695	490	195	177	400
Torungen		-----	645	520	540	635	580	390	125	280	530
Marsdiep			-----	730	190	1000	665	520	530	570	755
Chris.ø				-----	760	285	1040	820	535	255	20
Hadley North Sea					-----	1010	480	335	410	545	780
Hadley Baltic Sea						-----	1210	1000	700	465	265
Northwest North Sea							-----	215	510	780	1060
Central North Sea								-----	300	565	840
Northeast North Sea									-----	280	555
Kattegat-Belts-Øre.										-----	275
Bornholm Basin											-----