The influence of low-frequency variability and long-term trends in North Atlantic sea surface temperature on Irish waters

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Cannaby, H., and Hüsrevoğlu, Y. S. 2009. The influence of low-frequency variability and long-term trends in North Atlantic sea surface temperature on Irish waters. – ICES Journal of Marine Science, 66: 1480–1489.

Sea surface temperature (SST) time-series collected in Irish waters between 1850 and 2007 exhibit a warming trend averaging 0.3°C. The strongest warming has occurred since 1994, with the warmest years in the record being 2005, 2006, and 2007. The warming trend is superimposed on significant interannual to multidecadal-scale variability, linked to basin-scale oscillations of the ocean–atmosphere system. The dominant modes of low-frequency variability in North Atlantic SST records, investigated using an empirical orthogonal function (EOF) analysis, correspond to the Atlantic Multidecadal Oscillation (AMO), the East Atlantic Pattern (EAP), and the North Atlantic Oscillation (NAO) index, respectively, accounting for 23, 16, and 9% of the total variance in the dataset. Interannual variability in Irish SST records is dominated by the AMO, which, currently in its warm phase, explains approximately half of the current warm anomaly in the record. The EAP and the NAO influence variability in Irish SST time-series on a smaller scale, with the EAP also contributing to the current warm anomaly. After resolving the prevalent oscillatory modes of variability in the SST record, the underlying warming trend compares well with the global greenhouse effect warming trend. The anthropogenic contribution to the current warm anomaly in Irish SSTs was estimated at 0.41°C for 2006, and this is predicted to increase annually.

Keywords: Atlantic Multidecadal Oscillation, East Atlantic Pattern, global warming, Ireland, North Atlantic Oscillation, sea surface temperature.

Received 15 August 2008; accepted 14 February 2009; advance access publication 8 April 2009.

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Introduction

The heat content of the world's oceans is estimated to have increased by 14.2×10^{22} J between 1961 and 2003, representing ~90% of the estimated increase in the heat content of the entire Earth system over this period (Bindoff *et al.*, 2007). Understanding variability in ocean heat content is thus vital to resolve the Earth's energy balance and to detect and monitor the effects of climate change. Since the beginning of the observational record during the mid-1800s, each of the ocean basins has exhibited a warming trend in sea surface temperatures (SSTs), superimposed on significant interannual to multidecadal scales of variability. Significant differences in such low-frequency variability exist between the ocean basins (Trenberth *et al.*, 2007), and an understanding of these differences is still developing. In this paper, we focus on the North Atlantic Ocean, which has exhibited a linear warming trend in average SSTs of 0.49°C over the period 1850–2007. Trends in depth-integrated Atlantic heat content between 1955 and 2003 reveal a warming of the Subtropical Gyre and a concurrent cooling of the Subpolar Gyre over this period (Levitus *et al.*, 2005; Lozier *et al.*, 2008). Subtropical Gyre warming extended to deeper than 1000 m (deeper than anywhere else in the world's oceans) and was particularly pronounced under the Gulf Stream and the North Atlantic Current (Levitus *et al.*, 2005).

Anomalously warm SSTs were observed in the North Atlantic between 1930 and 1960, and from 1990 to present (2008), with intermittent cool periods (Kerr, 2000). This is consistent with a 50–88-year oscillation in North Atlantic SSTs, typically referred to in the literature as the Atlantic Multidecadal Oscillation (AMO; Schlesinger and Ramankutty, 1994; Delworth and Mann, 2000; Kerr, 2000). Because the instrumental record only spans two full cycles of the AMO, the robustness of this periodicity has been addressed using proxies, such as marine sediment cores and tree rings (Grey *et al.*, 2004), and model studies (Delworth and Mann, 2000). Paleoclimate reconstructions spanning four centuries have revealed a 60–110-year period of intermittent warm and cool North Atlantic SSTs. Coupled ocean–atmosphere model studies spanning 600 years have revealed an irregular oscillation in both SSTs and the thermohaline circulation (THC), with a time-scale of 40–60 years (Delworth and Mann, 2000). The AMO is thought to arise from predictable internal oscillation of the ocean–atmosphere system, although the mechanisms forcing this oscillation are not yet fully understood. Both observations and model studies have been used to relate the AMO to changes in the strength of the THC, and it has been suggested that the AMO may modulate the *El Niño*-Southern Oscillation (ENSO) teleconnection pattern (McCabe *et al.*, 2004). Evidence has also been presented that the AMO modulates the North Atlantic Oscillation (NAO) index, forming one of three prevalent modes of variance in the NAO index (Higuchi *et al.*, 1999). The AMO has been linked to interannual variability in weather patterns on both sides of the Atlantic, including sea level pressure (SLP) over the southern United States, the North Atlantic, and southern Europe, Atlantic hurricane formation (Goldenberg *et al*., 2001), precipitation anomalies over North America and the Caribbean (Enfield *et al*., 2001), and sea ice cover in the Greenland Sea (Venegas and Mysak, 2000).

The global atmospheric circulation has a number of preferred states of variability, which are expressed in the surface climate. Much of the natural variability in upper-ocean dynamics and water-mass characteristics is linked to such atmospheric teleconnection patterns. The principal modes of atmospheric variability in the North Atlantic are the NAO and the East Atlantic Pattern (EAP). The NAO describes a north–south oscillation of atmospheric mass between the Arctic and the subtropical Atlantic, with implications for climate variability over the mid- and high latitudes of the northern hemisphere (Hurrell, 1995; Hurrell *et al*., 2003). The NAO index records the pressure difference between the Azores high and the Icelandic low pressure systems, with a positive index indicating a stronger pressure gradient. The NAO signal is particularly prevalent during winter, when the mean atmospheric circulation is strongest. Interannual to decadal shifts from positive to negative phases of the NAO are associated with large changes in windspeed and direction over the Atlantic and, therefore, with changes in heat and moisture transports, and in the wind- and buoyancy-driven ocean circulation (Hurrell *et al*., 2003; Hurrell and Dickson, 2004). When the NAO index shifts from low to high values, windspeeds over the North Atlantic increase by up to 4 m s^{-1}, and the latent and sensible heat fluxes from the ocean to the atmosphere increase by 150 W m^{-2} over the Subpolar Gyre in winter. The trend towards more positive phase NAO conditions over recent decades, associated with a more direct storm track across the Atlantic, has been linked to an increased intensity of winter storms and shifts in hydrographic properties throughout the North Atlantic Ocean.

The EAP (Wallace and Gutzler, 1981; Barnston and Livezey, 1987) describes the second principal component of variability in mean SLP (MSLP) over the North Atlantic and appears as a leading mode in all months, except from May to August. The EAP is structurally similar to the NAO, consisting of a pressure centre in the Northeast Atlantic near 55°N 20–35°W and a strong northwest–southeast pressure gradient over Western Europe, with an oppositely signed centre over North Africa or the Mediterranean Sea. The EAP exhibits strong multidecadal variability and has displayed a tendency towards more positive values since 1970, with particularly strong and persistent positive values in the 1997–2007 period.

Natural variability in SST records over interannual to multidecadal time-scales is of similar magnitude to recent trends associated with global warming. It is therefore difficult to isolate the global warming signal from variability associated with internal oscillations of the climate system. This paper describes the dominant modes of low-frequency variability in North Atlantic SST records using an EOF analysis. The results of this analysis are then applied to the interpretation of variability in SST time-series collected in waters local to Ireland. Because the resolved modes of natural variability cannot alone explain recent intense warming in Irish waters, we extract the underlying warming trend and compare this with the global warming trend attributed to increased atmospheric greenhouse gas concentrations.

Data and methods

Description of SST time-series

HadSST2 is a data product developed by the UK Meteorological Office, comprising a global gridded time-series of monthly mean bulk-SST anomalies on a 5° × 5° grid (Rayner *et al*., 2006). The dataset extends from 1850 to the present and is developed from historical ship and buoy measurements, which for the period 1850–1997 are taken from the International Comprehensive Ocean–Atmosphere Dataset (ICOADS) and for the period 1998 to the present from the National Centers for Environmental Prediction–Global Telecommunications System (NCEP–GTS) dataset. Although bulk-SST measurements from ships and buoys have time-varying biases, studies suggest that these are not large enough to prejudice conclusions about recent warming (Trenberth *et al*., 2007). The HadSST2 data product has been corrected for the widespread use of uninsulated buckets in the 19th and early 20th century and for the switch from uninsulated buckets to engine room intakes by US merchant ships between 1939 and 1941 (Rayner *et al*., 2006). Further corrections to data collected between 1945 and the mid-1960s are, however, considered necessary (Thompson *et al*., 2008) to correct for a sharp discontinuity in global SST records, evidenced as a ~0.3°C temperature drop during the 6 months following August 1945. This discontinuity, attributed to changes in measurement practices, is believed to have caused a sudden switch from a warm bias to a cool bias in the global SST record. Thompson *et al*. (2008) suggest that adjustments to the HadSST2 dataset of the order of 0.3°C may be necessary for the years immediately following 1945, with smaller adjustments necessary through to the mid-1960s. Pre-1940 and post-1960s data are not expected to require further correction, meaning long-term global trends are unlikely to be affected by this measurement bias. The HadSST2 data product is provided as monthly mean SST anomalies, calculated relative to the 1961–1990 monthly climatology. Because this study is concerned only with variability at interannual and longer time-scales, annual mean SST anomalies, calculated from the monthly data, were used in the analysis.

Advanced Very High Resolution Radar (AVHRR) Pathfinder version 5 SST data were obtained from the NASA Physical Oceanography Distributed Active Archive Centre (PO.DAAC) website (http://podaac.jpl.nasa.gov). This study utilizes the level3 processed data products, obtained as annual composites on a 4-km resolution global grid, covering the period 1985–2006. Polar-orbiting infrared satellites provide improved resolution and data coverage over gridded observational products, such as HadSST2. The satellite ocean skin temperature must, however, be adjusted to estimate bulk-SST values through a calibration procedure (Reynolds *et al*., 2002; Rayner *et al*., 2003, 2006). SST anomalies were calculated from the processed data product by subtraction of the annual time-series climatology.

Coastal sea temperature has been recorded at least twice daily at the Met Éireann synoptic weather station located at Malin Head on the north coast of Ireland (Figure 1) since 1958. This dataset forms the longest continuous time-series of SST in Irish waters, providing a valuable resource to climate scientists. Because measurement techniques have not been consistent over the years, however, careful examination of the data is required (Dunne *et al*., 2008). Until 1991, measurements were recorded 2 m below the surface in a well, located in the pier at Malin Head and connected by a pipe to open water 30 m offshore. Since 1991, measurements have been made either by measuring

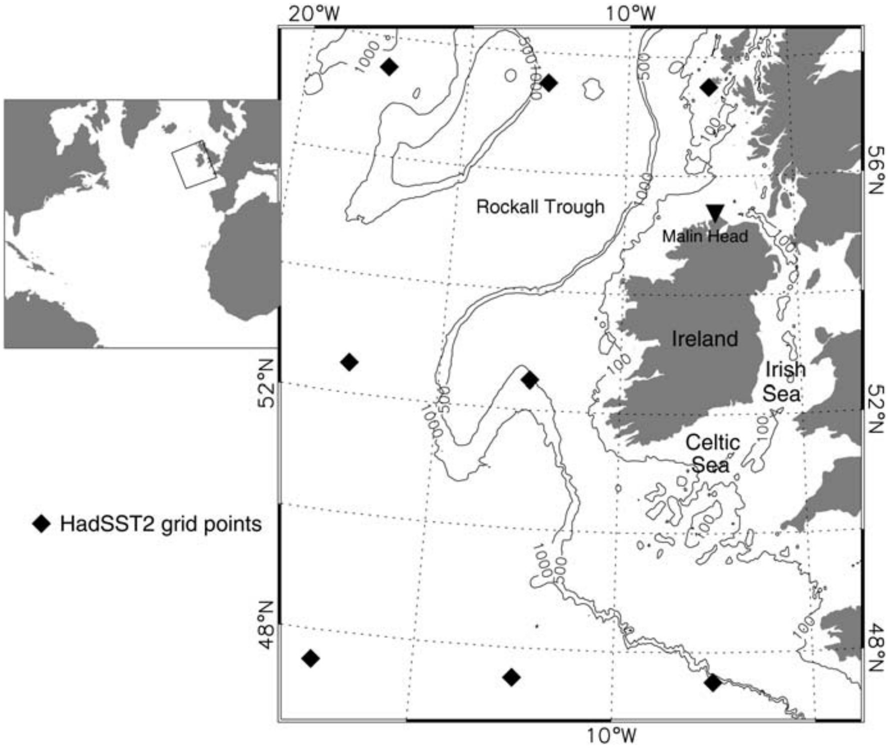

Figure 1. Top left, a map of the North Atlantic with the region illustrated in the main figure (right) indicated, and in the main figure, a bathymetric map of the waters surrounding Ireland, showing the locations of the Malin Head coastal monitoring station, Rockall Trough, Celtic and Irish Seas, and indicating the individual HadSST2 grid point locations. The map area corresponds approximately to that over which HadSST2 and AVHRR data were averaged, as shown in Figure 2.

the temperature of seawater extracted in a bucket or by lowering a temperature sensor into the water beside the pier. Because the location of the measurements has changed from an open-water site on one side of a pier before 1991 to a more sheltered location on the opposite side of the pier thereafter, there is likely to be a bias in the temperature record that has not been possible to remove. The time of day at which measurements were recorded has also changed over the years. To reduce the effects of diurnal heating, only data collected before midday were used for the calculation of annual averages. Where no morning data were available, data collected after midday were used, after normalizing the data using the mean diurnal heating signal per calendar month, calculated over the length of the time-series. Since 2002, the measurement technique has been consistent. Annual mean SST anomalies at Malin Head were calculated relative to the period 1961–1990, allowing direct comparison with the HadSST2 SST anomaly time-series.

Atmospheric teleconnection indices

The Jones NAO index (Jones *et al.*, 1997), a measure of normalized SLP difference between Gibraltar and Reykjavik, was downloaded from the Climate Research Unit, UK website (www.cru.uea.ac.uk/∼timo/projpages/nao_update.htm). The winter (December/January/February mean) NAO index is used throughout this study. The EAP index was obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml), and it is based on the index described by Barnston and Livezey (1987). Derivation of the EAP index requires SLP data in the central North Atlantic. As a result, it has not been possible to extend the EAP index back before 1948, owing to the lack of availability of atmospheric model reanalysis data.

Surface temperature increases related to atmospheric CO_2

After resolving the dominant modes of natural variability from North Atlantic SST records, the underlying warming trend was compared with the global warming trend associated with increased atmospheric concentrations of CO_2. For this purpose, records of atmospheric CO_2 were used to calculate the increased blackbody temperature of the Earth's surface since 1890, thus providing a quantifiable measure of the warming trend attributable to the CO_2-related greenhouse effect. A time-series of atmospheric CO_2 concentration, recorded at the NOAA atmospheric monitoring station at Mauna Loa, Hawaii, was obtained from the station's website (http://www.mlo.noaa.gov/programs/esrl/co2/co2.html). This *in situ* time-series, which extends back to 1949, has been concatenated onto an atmospheric CO_2 dataset derived from three ice cores obtained at Law Dome, East Antarctica, from 1987 to 1993 (Etheridge *et al.*, 1996). The ice core data, which extend back to 1850, were downloaded from http://cdiac.ornl.gov/trends/co2/lawdome.html. The combined time-series of atmospheric CO_2 concentrations was used to derive a first-order estimation of the increased blackbody temperature T_C of the Earth's surface resultant from increased atmospheric CO_2 concentrations since 1850. The empirical methods of Myhre *et al.* (1998), given by

$$\Delta F = 5.35 \log\left(\frac{C}{C_0}\right), \tag{1}$$

and

$$T_C = \sqrt[4]{\frac{F}{\sigma}}, \tag{2}$$

where ΔF is the heat flux, C the atmospheric CO_2 concentration, C_0 a reference level of CO_2 (in this case, the 1850 annual mean), and σ the Stefan–Boltzmann constant (5.6697×10^{-8} W m^{-2} K^{-4}), were followed to calculate T_C.

Statistical analysis

Linear trends in SST records were calculated using a least-squares fitting method, and the significance of the fit was based on calculation of the associated r^2 value. A similar technique was used to establish correlations between independent time-series; in this case, the slope of the line was determined by calculating the geometric mean of the slopes from the regression of Y onto X and X onto Y. Correlation coefficients were calculated between annual mean SST records and the dominant modes of atmospheric variability in the North Atlantic (i.e. the winter mean NAO index and the annual mean EAP). Throughout this paper, correlation coefficients are given at the 95% significance level. For the HadSST2 time-series, correlations were established using data averaged over the region (45–60°N 3–20°W), and on time-series extracted from individual grid points within this region (Figure 1), to demonstrate regional variability in the relationship between atmospheric teleconnections and SST anomalies.

Empirical orthogonal function analysis

Empirical orthogonal function (EOF) analysis is a mathematical technique for the decomposition of time-series of spatial maps, such as satellite data or gridded observations, into a linear combination of orthogonal spatial modes (Wallace and Dickinson, 1972). The spatial maps that result from an EOF analysis, referred to as eigenvector maps, describe the oscillatory patterns associated with each successive mode of variance in the dataset. The sum of the eigenvectors then describes the net response as a function of time of the combined variance in all the spatial modes.

Time-series associated with each eigenvector, referred to here as principal component time-series (PC-TS), illustrate temporal variability in the sign and relative amplitude of each eigenvector map. It should be noted that, because the relative significance of each independent mode of variability is spatially dependent, the results of an EOF analysis depend on the spatial area of the data grid on which the analysis is performed. In addition, where distinct modes of variability are not completely independent and a non-stationary relationship exists between individually resolved modes of variability (a possibility that cannot be ruled out when dealing with climate data), the length of the dataset used in the analysis could influence the order of significance of principal components.

An EOF analysis was performed on gridded annual mean North Atlantic SST anomalies for 1890–2007, extracted from the HadSST2 data product. The data were first detrended by subtraction of the mean North Atlantic temporal trend. The EOF analysis was then performed, using a singular-value decomposition method. Normalization of the gridded data is often done before performing an EOF analysis to prevent data from any particular grid point from dominating the analysis. This is achieved by dividing the individual time-series at each grid point by the standard deviation. However, normalization did not modify the results of the analysis presented here significantly. A stronger correlation was obtained between PC-TS and recognized physical modes of variability using non-normalized data, and for this reason, we present these results in the paper. Interpretation of EOFs is difficult, because there is not necessarily a statistical link between resolved EOFs and any independent dynamical modes in the physical environment. To investigate potential physical mechanisms relating to each of the dominant EOFs of North Atlantic SST, correlation coefficients were calculated between the PC-TS and known modes of prevalent climate variability in the North Atlantic, the AMO, the NAO, and the EAP.

Results

Trends and variability in Irish SST records

A comparison of the Malin Head coastal SST time-series and the HadSST2 and AVHRR time-series averaged over the region (45–60°N 3–20°W) is presented in Figure 2. The regional HadSST2 dataset exhibits a linear warming trend of 0.38°C over the 1900–2007 period and unprecedented warming since the early 1990s, with the warmest years in the record being 2007, 2006, and 2005. The Malin Head time-series exhibits a linear warming

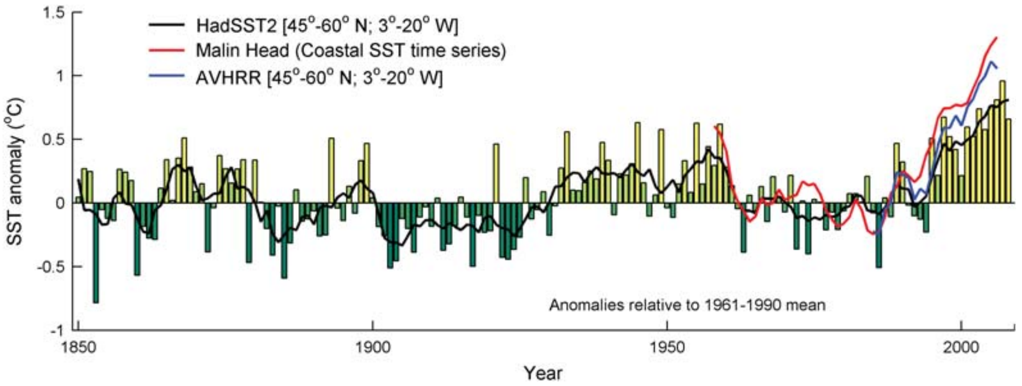

Figure 2. Annual mean SST anomalies (green bars) extracted from the HadSST2 dataset (Rayner *et al.*, 2006), overlain by a 5-year running mean (black) for the period 1850–2006, AVHRR satellite derived SST anomalies for the period 1986–2006 (blue), and the Malin Head coastal SST time-series from 1958 to 2006 (red). Anomalies are calculated relative to the 1961–1990 mean for the case of HadSST2 and Malin Head datasets and relative to the time-series climatology for the case of the AVHRR dataset. HadSST2 and AVHRR data were averaged over the region (45–60°N 3–20°W).

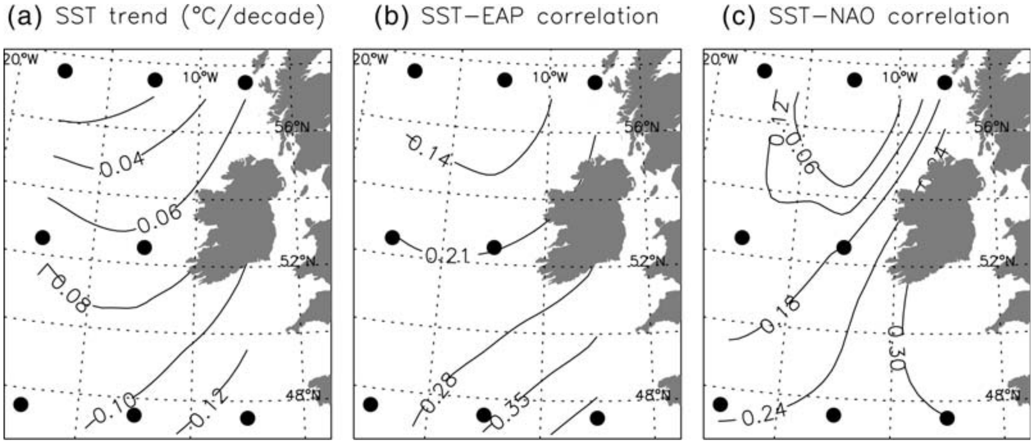

Figure 3. Contour maps illustrating spatial variability in (a) SST trends and correlation coefficients between SST time-series and the (b) EAP and (c) NAO indices. Mapped statistics were calculated at the regional HadSST2 grid points (filled circle) over the period 1950–2007.

trend of 0.85°C in 1958–2006, with the warmest years in the record occurring after 1995. Observed warming trends in each of the datasets are superimposed on significant interannual and multidecadal variability. A strong correlation ($r^2 = 0.85$) was evident between the coastal Malin Head SST time-series and the North Atlantic mean SST time-series calculated from the HadSST2 dataset, suggesting that much of the observed low-frequency variability in the regional time-series is linked to basin-scale processes. The observed warming trend was not uniform throughout Irish waters (Figure 3a), with the strongest warming since 1950 having occurred to the southeast of Ireland. Correlations between SST time-series and the EAP and NAO indices also exhibit significant spatial variability (Figure 3b and c), with the strongest correlation between SST anomalies and the EAP found to the southeast of Ireland, and a weakening of this relationship towards the northwest of the region. NAO index-related variability is most evident in SST records to the southeast of Ireland and in the Irish Sea. Correlations between yearly mean SST data from Malin Head and the EAP and NAO indices were weak, 0.32 and 0.28, respectively, with the EAP explaining a greater percentage of variance in the data.

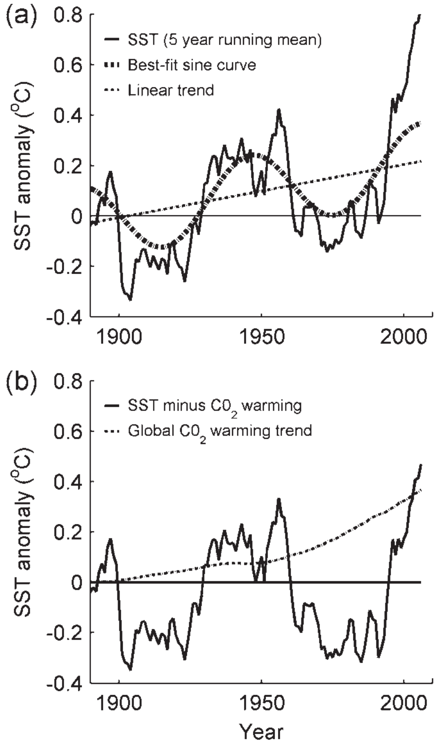

Figure 4. (a) Five-year running mean SST anomaly time-series extracted from the HadSST2 dataset (Rayner *et al.*, 2006) averaged over the region (45–60°N 3–20°W), overlain by a linear trend and the sum of the linear trend and a best-fit sine curve. (b) Global mean surface temperature rise attributed to increased atmospheric CO_2 concentrations since 1890, and the same subtracted from the regional SST anomaly time-series displayed in (a).

A notable feature of the time-series displayed in Figure 2 is a ~60-year cycle of warming and cooling in the HadSST2 SST anomaly record. Prolonged periods of anomalously warm SSTs were observed in 1864–1880, 1893–1890, 1930–1960, and 1990–2007, with cool periods in 1881–1892, 1900–1930, and 1960–1990. This oscillation between warm and cool SST anomalies is consistent with the basin-scale AMO. Strong correlations between the HadSST2 dataset and the shorter Malin Head time-series suggest that the recent warming evident in the Malin Head time-series is related to the current warm phase of the AMO. Because the observational record is short relative to the period of the AMO, little is known about the temporal variability in this signal in Irish waters. The mean phase and amplitude of the AMO over the past 120 years were determined by fitting a sine curve to the regional HadSST2 time-series, using an iterative method to achieve a best fit to the data (Figure 4a). A best fit was achieved with a phase of 60 years and an amplitude of 0.18°C. To improve the fit of the curve to the data further, a linear trend of 0.23°C was added, representative of a global warming signal. The sum of the best-fit sine curve and the linear trend correlates with the local HadSST2 SST anomaly time-series with a strong fit ($r^2 = 0.76$; Figure 4a). Because greenhouse gas concentrations have not risen linearly, the associated global warming signal is also unlikely to exhibit a linear trend, with an increase in the rate of warming occurring in recent years. Recent intense warming evident in regional SST records is larger than that associated with AMO-scale fluctuations (Figure 4a). To gain some insight into whether the combined effects of the AMO and global warming could explain the current extreme warm SST anomalies in Irish waters, the increase in global surface temperature (T_C) associated with increased atmospheric CO_2 levels since 1850 was subtracted from the local SST time-series (Figure 4b). This process reduced the residual warming trend in the regional SST time-series from +0.41 to +0.04°C. Comparing Figure 4a and b, the current warm SST anomalies can be explained by the sum of natural variability (dominated by the AMO) and global warming in close to equal measure. If the trends and periodicity in long-term SST anomalies observed over the past 120 years continue into the coming decades, the current warm period of the AMO could be expected to extend until ~2020, when another cool period should begin. If current SST warming trends continue, as may be expected based on future CO_2 emission scenarios, future cool cycles of the AMO are likely to be evident as warm anomalies relative to the 1961–1990 mean.

Basin-scale modes of variability in North Atlantic SSTs

The first three eigenvector maps of long-term SST change in the North Atlantic Ocean are presented in Figure 5a–c. Also included is the corresponding eigenvalue spectrum (Figure 5d), illustrating the percentage variance explained by each successive mode. Associated PC-TS are included in Figure 6. The first PC-TS (Figure 6a), representing 23% of the total variance in the dataset, is significantly inversely correlated with North Atlantic mean SST anomalies ($r^2 = 0.34$), and therefore, the first PC-TS exhibits a similar 60-year periodicity to the AMO. The corresponding first eigenvector map (Figure 5a) describes a single-phase oscillation of North Atlantic SST anomalies. The amplitude of this oscillation is largest in the region of the Subpolar Gyre (centred at 48°N 40°W), and it approaches zero towards the peripheral regions of the North Atlantic basin. In some coastal regions, however, specifically around Ireland, east Newfoundland, the west coast of the UK, and the south coast of Iceland, the amplitude of this signal is significant, close to a quarter of the maximum amplitude in the central Subpolar Gyre. Coastal SST records collected in these regions can therefore be expected to exhibit multidecadal variability consistent with the AMO, as has already been demonstrated for the Malin Head dataset (Figure 2).

The second PC-TS of long-term temperature change in the North Atlantic Ocean, representing 16% of the total variance in the dataset, is significantly inversely correlated with the Barnston

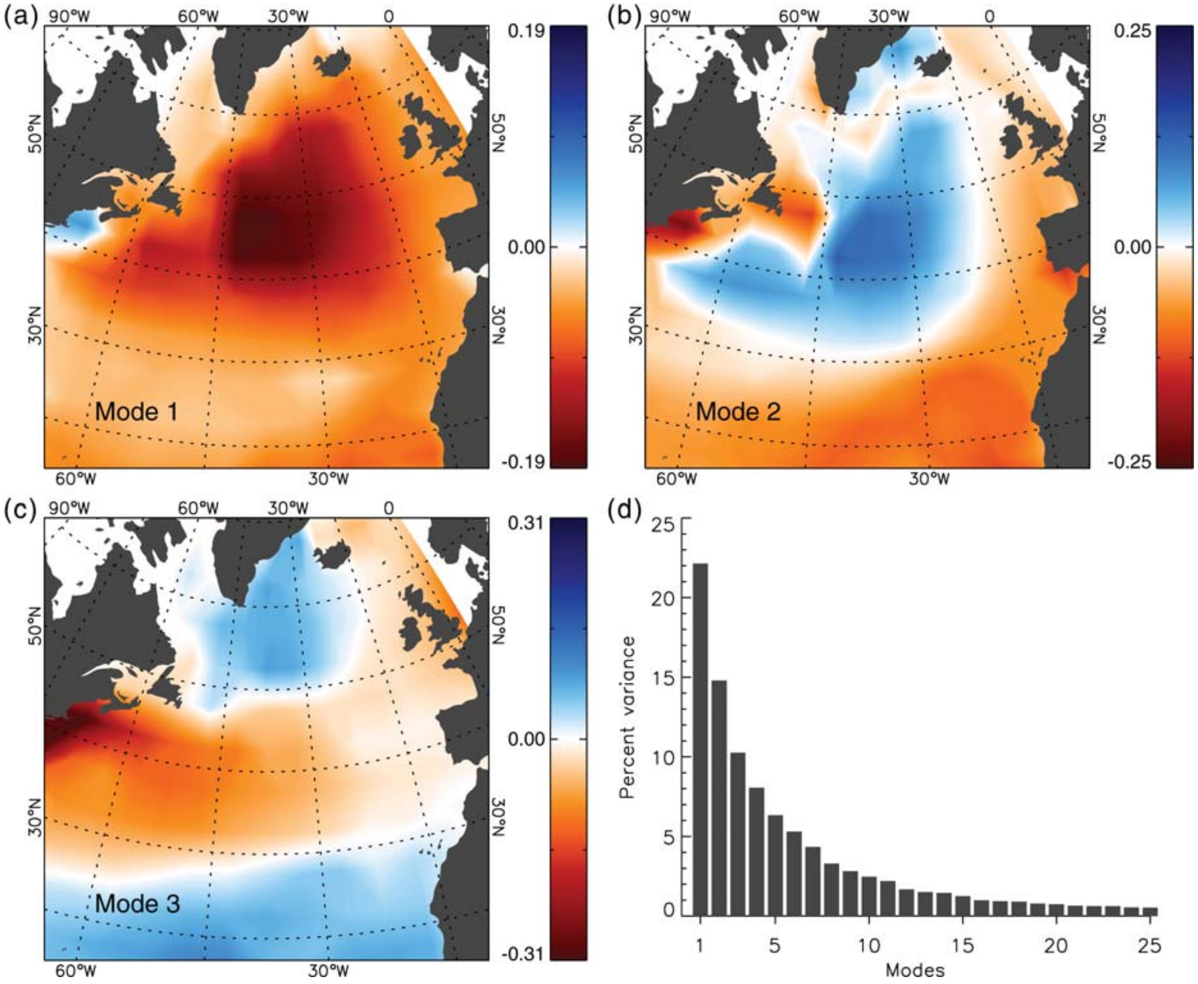

Figure 5. Eigenvector maps illustrating the (a) first, (b) second, and (c) third modes of variability in annual mean North Atlantic SST anomalies with (d) the corresponding eigenvalue spectrum. The analysis was performed over the period 1890–2006 using the HadSST2 data product (Rayner *et al.*, 2006).

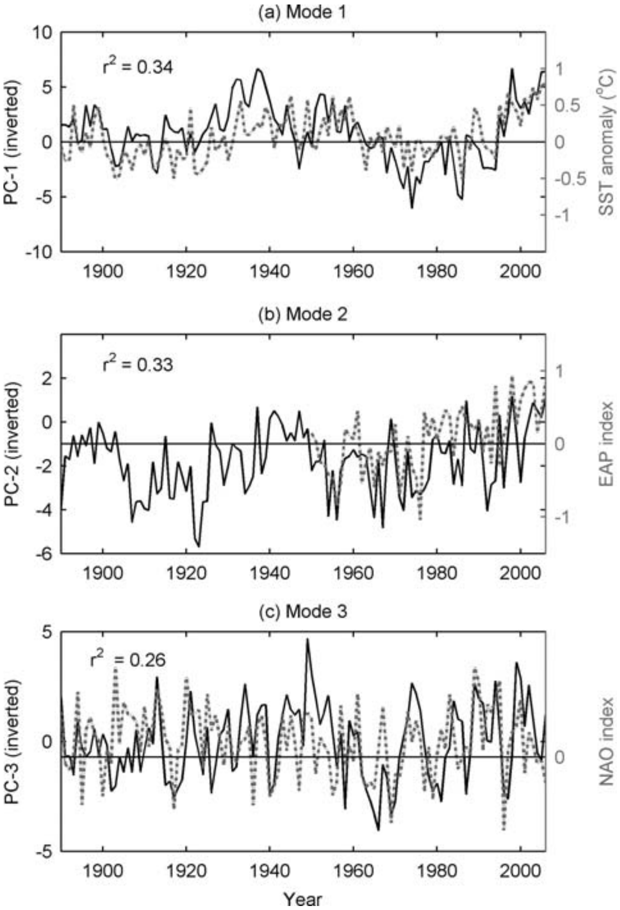

Figure 6. PC-TS of long-term changes in North Atlantic SST (a) first PC-TS series (solid line) overlain by North Atlantic temperature anomalies (dotted line); (b) second PC-TS (solid line) overlain by the Barnston and Livezey (1987) EAP index (dotted line); and (c) third PC-TS (solid line) overlain by the Jones winter NAO index (dotted line; Jones *et al.*, 1997). Correlation coefficients between PC-TS and physical modes of variability are included in the inset of each plot.

and Livezey (1987) EAP ($r^2 = 0.33$; Figure 6b). In the northwest subpolar regions, positive values of the EAP are associated with negative SST anomalies. Conversely, in the southeastern North Atlantic, positive values of the EAP are associated with positive SST anomalies. The result is a dipole oscillation in SST anomalies, with centres in the subpolar North Atlantic at 40°W 45°N and to the southeast of the Cape Verde Islands at 17°W 12°N. On consideration of the second eigenvector map (Figure 5b), SST records from Irish waters may be expected to exhibit a weak mode of variance linked to the EAP, with the strongest EAP signal found to the southeast of Ireland. The contour map displayed in Figure 3b, illustrating regional variations in the correlation between SST time-series and the EAP, confirms this result. After subtraction of the larger amplitude AMO signal and linear trend from the SST data (using the sine curve displayed in Figure 4a), regional mean SSTs averaged over the region (45–60°N 3–20°W) significantly correlate with the EAP index ($r^2 = 0.41$).

A significant inverse correlation ($r^2 = 0.26$) was evident between the third PC-TS of North Atlantic SST anomalies (representing 9% of the total variance in the dataset) and the Jones winter NAO index. The third eigenvector map (Figure 5c) represents a zonal oscillation in SST anomalies, with, during its positive phase, warm anomalies in a band extending across the Atlantic, approximately between 30 and 50°N, and negative SST anomalies to the north and south of this region. The amplitude of the third eigenvector is largest along the east coast of America, in the region extending from 35 to 45°N, and decreases eastwards, with a reduction in the zonal temperature gradient east of 30°W. Interpretation of this pattern in relation to the NAO index indicates positive SST anomalies associated with positive NAO values in the mid-latitudes and along the northeast margins of the Atlantic basin, with weaker cool SST anomalies in the subtropics and Irminger Seas, matching the pattern described by Kushnir (1994). The amplitude of the third eigenvector of North Atlantic SST anomalies, with links to the NAO, is close to zero in waters to the north, south, and west of Ireland, explaining the absence of a significant correlation between regional SST records and the NAO index (Figure 6c) in these areas. In the Irish Sea, there is a stronger correlation between SST records and the NAO index. This is attributed to the increased significance of atmospheric forcing, as opposed to oceanic forcing, in determining SSTs in the semi-enclosed Irish Sea.

Discussion

In summary of the above analysis, SSTs in the waters surrounding Ireland have exhibited intense warming since the early 1990s, which is unprecedented in the 150-year observational record. This warming signal can be attributed in approximately equal measure to the combined affects of an anthropogenically induced global warming trend and internal oscillations of the ocean–atmosphere system. Natural variability in SSTs within Irish waters is dominated by the AMO; it is also influenced to a lesser extent by the EAP. Both the AMO and the EAP indices have exhibited a trend towards more positive values since the late 1970s, in both cases associated with a warming of SSTs in Irish waters. The anthropogenic contribution to the warming signal in North Atlantic SST anomalies since 1850 was estimated as ~0.41°C in 2006 and, based on future CO_2 emission scenarios, it is likely to increase over the coming years.

The sharp discontinuity in the global SST record during 1945, as described by Thompson *et al.* (2008), is also evident in the North Atlantic mean SST record. The period of predominantly warm SST anomalies between 1930 and 1960 was interrupted by a number of cool years following 1945. Adjustment of the relatively warm bias pre-1945 and cool bias post-1945 is likely to at least partly remove the 1945 cool anomaly and further emphasize the AMO periodicity in the time-series. Because adjustments to the existing measurement bias in the HadSST2 dataset are unlikely to influence overall trends in the data and are likely to distinguish the AMO variability further, the analysis presented in this paper should not be overtly affected by this issue. Improved error corrections might result in an improved correlation between SST time-series and known modes of climate variability. Specifically, the divergence between the third PC-TS and the NAO index between 1945 and 1955 (Figure 6c) could be a consequence of this discontinuity.

Throughout much of the North Atlantic, interannual variability in SST time-series is dominated by the AMO. There is no leading mode of variability in MSLP exhibiting a similar periodicity to the AMO, suggesting that the AMO is forced by internal shifts in ocean dynamics. Although the mechanisms driving the AMO are not well understood, modelling studies suggest a link to the THC (Delworth and Mann, 2000). The AMO has also been proven to modulate weather patterns, including ENSO (McCabe *et al.*, 2004), and it forms one of three prominent modes of variability in the NAO (Higuchi *et al.*, 1999), with feedbacks for SST. The AMO clearly represents a significant mode of variability in the North Atlantic climate system, with likely feedbacks for the global climate. Understanding of this process is thus basic to understanding climate variability and change. The ability of climate models to reflect past variability and to predict the future course the AMO is thus basic to their ability to predict future changes in the North Atlantic and global climate.

Because of the strong correlation between the NAO index and North Atlantic SST anomalies in recent years, and because the NAO is recognized as the dominant mode of variability in northern hemispheric MSLP, interactions and feedbacks between the NAO and ocean dynamics have been a focus of recent studies. The NAO forms the third principal component of variability in North Atlantic SSTs, and the trend towards more positive phase NAO conditions over recent decades has been linked to shifts in hydrographic properties throughout much of the North Atlantic, including interannual variability in the Subpolar Front and in the strength and shape of the Subpolar Gyre. In 1996, when the NAO shifted from a positive to a negative phase, a deep-reaching warming occurred along nearly the whole World Ocean Circulation Experiment (WOCE) section from Greenland to Ireland, leading to decreased density, despite a partial increase in salinity (Bersch *et al.*, 1999). This trend is to be expected in consideration of the third eigenvector map (Figure 5c), which illustrates that the NAO does not significantly influence SSTs along much of the eastern margin of the North Atlantic. Eden and Willebrand (2001) described the Subpolar Gyre response to the NAO as an almost instantaneous barotropic and a delayed baroclinic response. This modelling study suggests that the immediate effect of a high NAO index in the eastern Subpolar Gyre is a northwestward shift of the Subpolar Front, south of the Rockall Trough. The delayed response, 3–8 years after the increase in surface heat fluxes caused by a high NAO, is a strengthening of the Subpolar Gyre and enhanced meridional overturning circulation. The complexity of interactions between the NAO and ocean dynamics, particularly concerning ocean–atmosphere interactions and feedbacks and interactions between immediate and delayed responses, leave many questions relating to the effect of atmospheric teleconnection patterns on ocean dynamics unanswered.

The effect of the EAP on ocean dynamics in the North Atlantic basin has received less attention than has the NAO. Because the EAP appears in this study as the second principal component in SST anomalies over multidecadal time-scales, the effect of the EAP on North Atlantic ocean–atmosphere heat and freshwater fluxes and current structures requires further investigation. The EAP signal in its positive phase amplifies the positive phase AMO signal in Irish waters and throughout much of the subtropics. Within the central North Atlantic basin, including the Subpolar Gyre and Subpolar Front, the AMO and EAP patterns are out of phase. Hence, the current warming of the Subpolar Gyre associated with the current positive phase AMO is inhibited by the concurrent positive phase EAP.

The results of the EOF analysis on SSTs presented here differ from the results presented in some other publications (e.g. Beaugrand *et al.*, 2002), which relate the NAO to the second or in some cases first PC-TS of North Atlantic SST anomalies. The explanation for these differences is primarily attributed to difference in area over which the analysis was performed and with the length of the time-series used for the EOF analysis. Because the individual modes of variability in SST are not independent, and the relationships between them not stationary over time, the results of the principal component analysis depend on the length of the time-series used for the analysis.

Atmospheric teleconnection patterns modulate the hydrographic properties of the oceans over both global and regional scales, just as oceanic variability is known to modulate atmospheric teleconnections. Although we have aimed to resolve the dominant modes of natural internal climate variability from an underlying anthropogenically induced global warming trend, the prevalent modes of variability discussed in this paper are unlikely to be stationary over time and in themselves might be influenced by anthropogenically induced change. The AMO exhibited a 60-year periodicity post-1890. However, this pattern of variability is less well-defined for the observational record pre-1890. The EAP meanwhile has exhibited a positive linear trend since the beginning of the record in 1948. Climate change may result through a change in the prevalence of one polarity or state of these modes over another or through a change in the nature or number of states. Understanding changes in the ocean–atmosphere interactions, and atmospheric teleconnection patters, is central to understanding the potential effects of future climate change, yet remains one of the greatest challenges facing the climate scientist.

Conclusions

SST time-series from the waters surrounding Ireland exhibit a warming trend averaging 0.38°C over the period 1900–2007. The rate of warming since the late 1990s is unprecedented in the 150-year observational time-series, and 2005–2007 were the warmest years on record. The warming trend is superimposed on significant interannual and multidecadal scales of variability, linked to basin-scale oscillations of the ocean–atmosphere system. The recent intense warming of SSTs in Irish waters since the late 1990s can be attributed in approximately equal measure to the combined effects of an anthropogenically induced warming trend and internal oscillations of the ocean–atmosphere system, in the form of the AMO, and to a lesser extent, the EAP and NAO. The anthropogenic contribution to the warming signal in Irish waters SST anomalies since 1950 was estimated to be 0.41°C in 2006 and is increasing annually.

The first three principal components of interannual variability in North Atlantic SST anomalies are correlated with the AMO, the EAP, and the NAO indices. These individual modes represent in respective order 23, 16, and 9% of the total variance in the dataset over the period 1890–2006, together explaining 48% of the total variance in North Atlantic SST anomalies. The basin-scale modes of variability associated with the AMO, the NAO, and the EAP influence regional SST records very differently. The effect of both the EAP and the NAO on Irish shelf SST records is spatially dependent, with the strongest correlation between SSTs and the EAP found to the southeast of Ireland, and the strongest correlation between SSTs and the NAO index in the Irish Sea. Both the AMO and the EAP indices have exhibited a trend towards positive values since the late 1970s, in both cases associated with a warming of SSTs in Irish waters.

Since 1890, the AMO signal in Irish waters has exhibited a 60-year periodicity, with an amplitude of 0.18°C. If the cyclic nature of the AMO continues into the coming decades, the current warm phase should extend until ∼2020, when another cool period can be expected. The next cool phase of the AMO should appear as a warm anomaly relative to the 1961–1990 mean, because of the underlying global warming trend. The AMO clearly signifies a prevalent mode of variability in the North Atlantic climate system. The ability of climate models to predict the future course of the AMO is therefore basic to their ability to predict decadal to multidecadal-scale changes in North Atlantic and global climate.

Acknowledgements

This project was carried out with the support of the Marine Institute, Galway, Ireland, under the Sea Change Strategy and the Strategy for Science Technology and Innovation (2006–2013), funded under the National Development Plan 2007–2013. The AVHRR Oceans Pathfinder SST data were obtained through the online PO.DAAC Ocean ESIP Tool (POET) at the Physical Oceanography Distributed Active Archive Centre (PO.DAAC), NASA Jet Propulsion Laboratory, Pasadena, CA, USA. Thanks are due to the staff of Met Éireann who collected and supplied the SST time-series from the Malin Head meteorological station.

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doi:10.1093/icesjms/fsp062