MARINE CLIMATE CHANGE IMPACTS PARTNERSHIP: SCIENCE REVIEW

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Impacts of climate change on temperature (air and sea)

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EXECUTIVE SUMMARY

Relative to the underlying warming trend during the 20th century the surface waters averaged over the north Atlantic were cool in the period between 1900 and 1930, warm from 1930 to 1960, cool between the late 1960s and 1990 and then warm to present. The warming observed in the last three decades has been particularly strong in parts of the north-east Atlantic, the sea surface around the UK and Ireland warming at rates up to six times greater than the global average. It remains difficult to fully distinguish the natural variations in temperature from those due to anthropogenic influence (including emissions of carbon dioxide (CO_2).

Marine Air Temperatures over the North-east Atlantic and southern North Sea have warmed rapidly over the last 30 years. The observed warming is greatest over seas south of Iceland at faster than 0.6 °C decade^{-1}. Locally the most rapid rises have been observed in the Southern North Sea (Charting Progress Region 2) and off the western coast of Scotland (Region 6 and the southern part of Region 7) at a rate between 0.2 and 0.4˚C decade^{-1}. Recent cold years have meant that linear trends in Marine Air Temperature in other regions (Regions 1, 3 and much of Regions 4 and 5) are not statistically significant. Similarly, sea-surface temperatures (SST) in UK coastal waters and in the North-east Atlantic have risen by between 0.1 and 0.5˚C decade^{-1} since the 1980s, and fastest locally in Region 2.

The temperature of the upper ocean (0-800 m) to the west and north of the UK has been generally rising since the 1970s (Region 8) and 1980s (Region 7). Superimposed on the underlying upward trend are decadal variations with relative maxima around 1960 and in the 2000s and relative minima in the 1980s and 1990s.

Despite the long-term warming trends, whether over the century or last 30 years, in evidence in most regions, temperature evolution at a location has not been linear or smooth with some short periods of rapid change over a few years and others of little change. Since 2008 the SSTs observed in most areas have not risen or have been slightly lower than observed in 2003-2007. The observed temperature changes have been due to a combination of global climate change and natural variability, attributed to 'internal' variability in the ocean atmosphere system, the Atlantic Multidecadal Oscillation is thought to be a representative pattern of this internal variability, the decadal scale patterns observed in UK waters are similar to that of the AMO. As a result of both of these 'drivers', a significant period of rapid warming occurred from 1985 to 2003.

West of the UK the water of the deep ocean (>1000m) comes from the Labrador Sea and has generally cooled since 1975. North of the UK, the deep water (800 m) flows from the Nordic Seas and shows no long-term trend since 1950.

Over the 21st century warming in the shelf seas around the UK and Ireland and the upper layers of the North Atlantic is predicted to continue, although perhaps at a lesser average rate to that observed in the last 30 years. Natural variability, driven by atmospheric and oceanic processes introduces a level of uncertainty that makes it difficult to predict the direction of temperature change over the next decade. However, initial experimental forecasts of ocean temperatures are beginning to be published.

1. WHAT IS ALREADY HAPPENING?

a. Marine Air Temperature

Marine surface air temperature is measured from ships, buoys and fixed marine platforms. Near-surface air temperature is not accurately retrievable from satellites. Hence we use marine air temperature estimates from the NOC Flux Dataset v2.0 (NOCv2.0, Berry and Kent, 2009). NOCv2.0 is a gridded and interpolated dataset constructed using Voluntary Observing Ship (VOS) observations, adjusted for known biases (Berry *et al.*, 2004) and changes in the air temperature observing height (Kent *et al.*, 2007).

Figure 1 shows the 30 year trend (1983 – 2012) in marine air temperature (°C decade^{-1}) estimated from NOCv2.0 for the North-east Atlantic and UK waters. Over this period, the warming is greatest in the Atlantic North-west Approaches (Charting Progress Region 8) with warming rates of over 0.6 °C decade^{-1}. Lower, but still significant rates of warming are found over the Southern North Sea (Region 2), and in parts of the South-west Approaches (Region 4) and to the north-west of Scotland (Regions 6 and 7) with warming rates between 0.2 – 0.4 °C decade^{-1}. The recent cold years of 2010 and 2012 mean that trend estimates are lower than in previous assessments and are not significant in the Northern North Sea (Region 1), the Eastern Channel (Region 3) and much of the Celtic and Irish Seas (Regions 4 and 5). In most regions these warming rates are similar to the rises seen in sea-surface temperature (SST) giving confidence in the estimates. Air temperature, however, shows a region of stronger rise than SST to the south and south-west of Iceland (Region 8). Although this is a region with poor sampling and hence higher uncertainty; the trend estimate is significant in this region.

Figure 2 compares the time series of annual mean air temperature estimates for the UK coastal waters to the Central England Temperature (CET, red; Parker *et al.*, 1992; Parker and Horton, 2005). The agreement between the two time series gives confidence in both datasets. The air temperatures measured around UK coastal waters were the lowest for a decade in 2010, CET showed the lowest temperature in 20 years in 2010. 2011 was high relative to the mean over the 1970-2012 period and 2012 slightly lower both for coastal temperatures and CET.

Figure 3a compares the annual cycle of the monthly mean air temperature estimates for UK waters from NOCv2.0 for the past 10 years (2003 – 2012) with estimates for the first 10 years of the dataset (1970 – 1979). For the months March-September average temperatures have been higher in the last decade than in the 1970s, however, November, December and January show little average change. Also shown are the monthly mean air temperatures for 2012. Unusually high air temperatures were observed during March 2012 but the remainder of the year was cold (more similar to the period 1970 - 1979 than the most recent decade). Similar results are also seen for the CET (Figure 3b). As expected, when comparing marine based temperature compared to those inland, the average seasonal cycle of air temperature above coastal waters lags CET, has a smaller amplitude and exhibits smaller interannual variability.

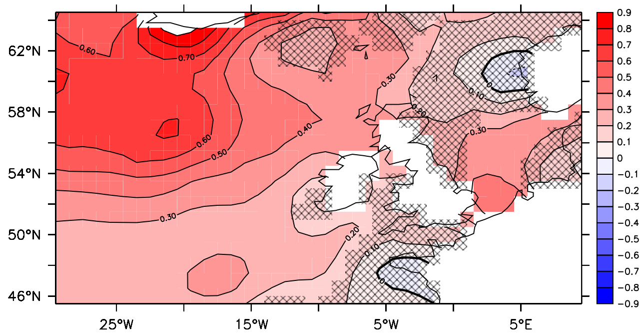


Figure 1: 30 year linear trend for marine air temperature estimates from NOCv2.0 for the period 1983 – 2012 (°C decade^{-1}). The hatched region shows where the regression is not significant at the 95% level using the Cochrane – Orcutt method to account for autoregression within the time series.

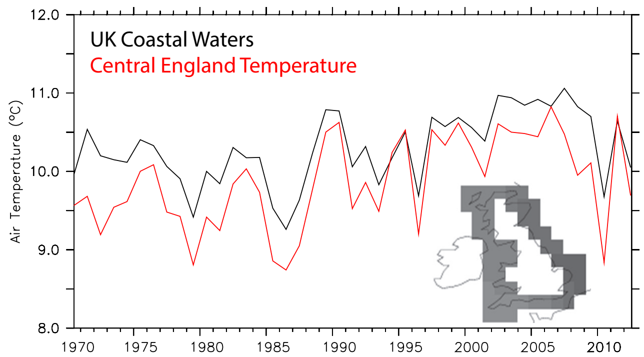


Figure 2: Annual mean air temperature estimates from NOCv2.0 above UK Coastal waters (black) and the Central England Temperature (red). Inset map show the grid locations used define UK Coastal waters.

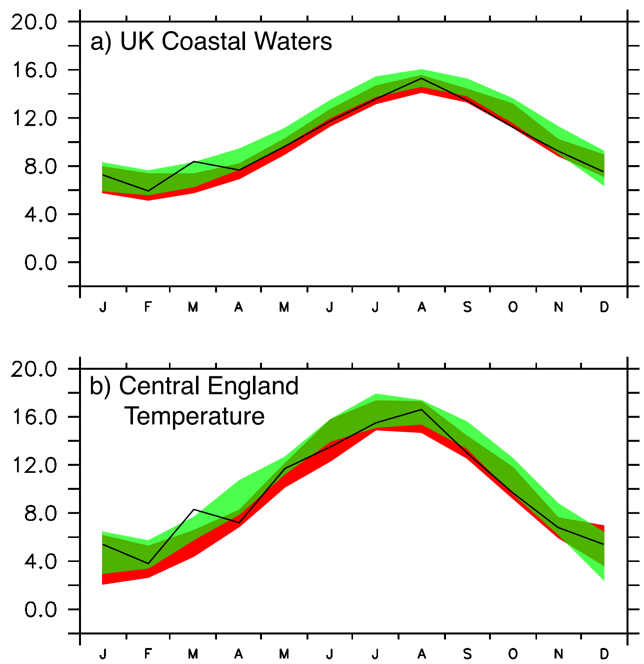


Figure 3: a) Monthly mean air temperatures for UK coastal waters (°C) for 2012 (black line), 2003 – 2012 ± 1 standard deviation (green) and 1970 – 1979 ± 1 standard deviation (red) from the NOCv2.0 dataset and b) from the Central England Temperature time series.

b. Sea Temperature

Sea-surface temperatures can be measured both by *in-situ* observations and satellite. Satellite SSTs require adjustment for biases due to changing atmospheric composition (e.g. changes in aerosol loading) adjustments are made using the *in-situ* network. SST observations are sufficient to allow the preparation of interpolated and gridded datasets such as HadISST1.1 (Rayner *et al.*, 2003).

In contrast to SST, observational evidence for changes in deep ocean temperature is relatively sparse. There are few long-term measurements of shelf or deep waters in the North Atlantic, though two of the longest (Faroe - Shetland Channel since 1900, and Rockall Trough since 1948) are maintained by UK agencies. These together with other long term observations of temperature in the North Atlantic and Nordic Seas and for some NW European shelf sites are summarised annually in the International Council for the Exploration of the Seas (ICES) Report on Ocean Climate (IROC) by the ICES Working Group on Oceanic Hydrography (www.ices.dk/community/groups/Pages/WGOH.aspx). The most recent (Beszczynska-Möller and Dye, 2013) was published in December 2013 covering the period up to the end of 2012 and is here after referred to as IROC2012. Since the late 1990s data from autonomous profiling 'Argo' floats (see http://www.argo.ucsd.edu/) have improved estimates of temperature and salinity variability in the deep ocean.

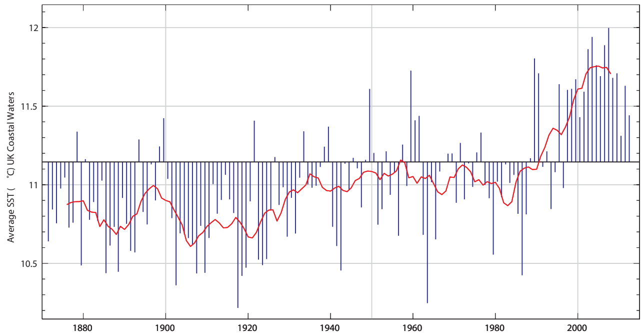


Figure 4: Time series of average SST in UK coastal waters (the area defined in Figure 2). The blue bars show the annual values relative to the 1971-2000 average and the smoothed red line shows the 10-year running mean. Data are from the HadISST1.1 data set (Rayner et al.*, 2003).*

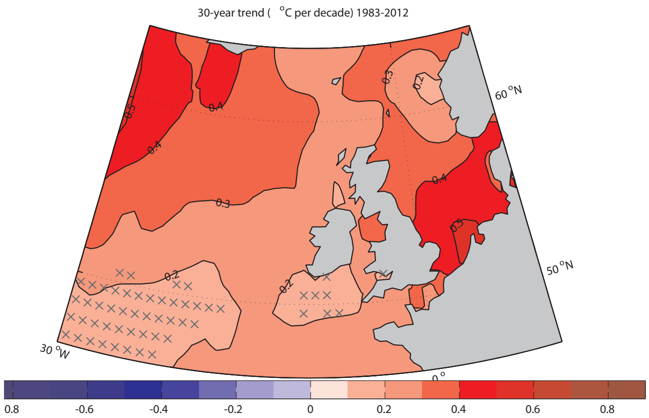


Figure 5: Trend in annual average sea-surface temperature (°C/decade) from 1983 to 2012. Data are from the HadISST1.1 data set (Rayner et al.*, 2003). Hatched areas have a slope which is not significant at the 95% confidence level (alpha=0.05) using Mann-Kendall non-parametric test for a trend.*

Overview

The average surface temperature of the North Atlantic has risen over the last 30 years, with the decade of the 2000 - 2009 being the warmest on instrumental record (IPCC, 2007). There is some regional variability, and not all areas of the Northeast Atlantic show the same long-term trends, but the long-term pattern of warming in the surface waters around the coast of the UK (Figure 4) are similar to the North Atlantic average temperature trend. Relative to the underlying warming trend during the 20th century the surface waters averaged over the north Atlantic were cool in the period between 1900 and 1930, warm from 1930 to 1960, cool between the late 1960s and 1990 and then warm from 1990 to present. Warming due to anthropogenic effects is superimposed onto this pattern of multi-decadal variability, which is thought to be a natural pattern variation and has been described as the Atlantic Multi-decadal Oscillation (AMO) (Knight *et al.*, 2005). Whilst it is clear that there is a significant multidecadal pattern to sea-surface temperatures, there is still much uncertainty about how to determine the relative contribution of these two factors to the recent observed warming (Knight *et al.*, 2005; Cannaby and Hüsrevoğlu, 2009; Swanson *et al.*, 2009; Ting *et al.*, 2009).

Surface waters in the North-east Atlantic and around Ireland and the UK have warmed rapidly over the last 30 years (1983 - 2012; Figure 5), by between 0.1 and 0.5°C decade^{-1}. Analysis of the at least 80-year long time-series of temperature available in the North Sea indicates that the rate of warming for the period 1985 - 2005 was higher than at any period on the observational record (Mackenzie and Schiedek, 2007). The most rapid rises have been observed in the Eastern English Channel (Region 3) and Southern North Sea (Region 2). In coastal waters (area defined in Figure 2) the trend is between 0.2 and 0.5°C decade^{-1}, with an average trend of 0.3°C decade^{-1}.

Since the end of the 1990s, the annual UK coastal-average SST has been higher than the 1971-2000 average. Although there is clearly a long term trend, there is a large amount of year-to-year variability. The coastal-average SST in 2010 was the coolest year in the period 2000-2012 Compared to the previous decade, 2012 was also a relatively cool year, but the average of 11.4°C was slightly higher than recorded in 2000 (11.2°C) (Figure 4).

Figure 6 shows how the temperatures in 2012 varied throughout the year, compared to previous years. The annual mean values for the last three years (2010, 2011 and 2012) are lower than observed in the earlier part of the decade partly as a result of cold winter temperatures but also with peak summer temperatures low compared to 2000-2009.

In 2010, February and March were the coldest of the decade, but the summer months (June and July) were close to

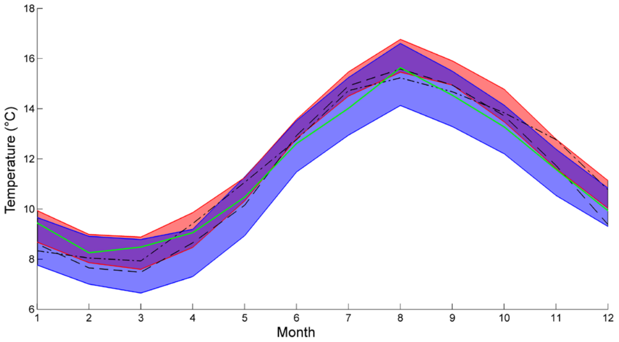


Figure 6 Annual cycle of sea-surface temperature in UK coastal waters (for definition see Figure 2) from the HadISST1.1 data set (Rayner et al.*, 2003). The range of temperatures from the period 1971-2000 is shown in blue, the range of temperature for the decade (2000-2009) is shown in red. Data for 2010 is plotted as a dashed line, 2011 as a dash-dot line. The data for 2012 are shown in green.*

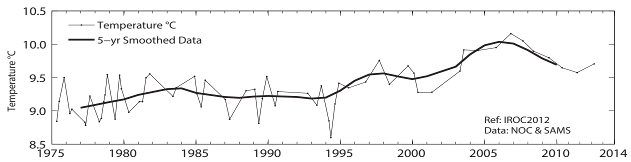


Figure 7: Charting Progress Region 8 - Rockall Trough. Temperature of the upper ocean (0-800 m) for the period 1975 to 2011. [Image modified from IROC2012 Figure 45]

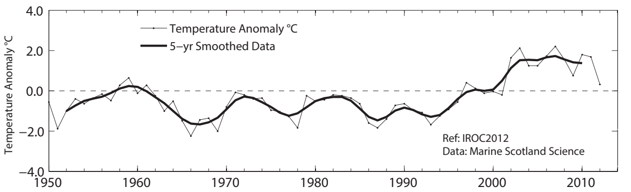


Figure 8: Charting Progress Region 7 – Faroe Shetland Channel - Temperature anomaly (base period 1981-2010) of the Atlantic Water in the slope current in the Faroe Shetland Channel for the period 1950 to 2012. [Image modified from IROC2012 Figure 52.]

average for the decade and well above the long-term mean. Temperatures fell again later in the year, with December 2010 being particularly cold (9.38˚C), below the long-term mean (9.97˚C), although still above the coldest December on record (8.77˚C in 1917).

After a cold start in 2011, spring (April and May) temperatures were higher than average for the previous decade. November 2011 was particularly warm (12.76˚C), very close to the record high value (12.78˚C in 2006). The early months of 2012 retained the warmth seen in autumn 2011, cooled quickly between January and February but began to warm early with relatively warm early spring temperatures. From May onwards the year was cool compared to the previous decade and June -July, and September-November were colder than any of the years since 2000.

1.1 Deep Ocean around the UK (including Charting Progress Region 8)

In-situ observations show that the upper layer of the deep ocean has warmed since the mid-1970s (IROC2012) and this is evident north-west of the UK in Rockall Trough (Region 8; Figure 7). There was a weak maximum in the early 1980s, but in 2006 temperatures reached the highest levels recorded since 1900, although temperatures have fallen slightly since then. North of Scotland (Region 7; Figure 8) the progression of change is slightly different with warming most evident after the mid 1980s. The pattern reflects the changing balance of the inflow of subtropical (warm and salty) versus subpolar (cool and fresh) water into the area (Holliday, 2003).

Examining the long-term variability, it can be seen that over the last 50-60 years the large-scale mean temperature of the northern North Atlantic and Nordic Seas has evolved from higher values in the early 1960s to a lower values in the 1980s and 1990s and has been high again in the last decade. The mean salinity shows a similar pattern (IROC2012; Dye *et al.*, 2013). This basin-wide, decadal-scale variability is overlain by shorter time-scale changes and regional patterns. Interannual variability can be large compared to multi-decadal trends and is related to locally important processes such as changing positions of fronts, passing of eddies, river run-off, the changing inflow of different water masses, and the exchange of heat with the atmosphere.

The subsurface deep ocean temperature is less variable and more lightly and indirectly influenced by the atmosphere and the seasonal cycle than the surface layer of the ocean. Below the surface, the deep ocean around the UK is strongly influenced by changes in ocean circulation, which in turn is affected by large-scale atmospheric conditions (Holliday, 2003; Hátún *et al.*, 2005).

Analysis of data from profiling Argo floats has shown that the upper 1500 m of the North Atlantic has, on the whole, warmed throughout the period 1999 to 2008 (Ivchenko *et al.*, 2009). Warming was strongest in the upper 1000 m and in the zone 50-70°N but there is a complex variation in changes in heat content both with latitude and with depth.

Below 1000 m the deep ocean west of the UK has become cooler since 1975, reflecting a period of cooling in the Labrador Sea where the deep water originates (Figure 9a). The Labrador Sea has become warmer again since the late 1990s (IROC2012), our expectation is that the deep water west of the UK will also warm in response as it appeared to have done in the 4 years prior to 2012; but the temperature fell in 2012 and was similar to that between 2000 and 2007. North of the UK, the deep water (>800 m) flows from the Nordic Seas and shows no long-term trend since 1950s (Figure 9b).

1.2 North Sea (Charting Progress Regions 1 and 2)

In the most northern part of the North Sea the temperature is influenced by inflowing North Atlantic water, showing similar decadal variations to the water in CP Regions 8 and 7 (Figure 7 & 8) and a general warming since the mid 1980s (Figure 10). The advective influence on temperature

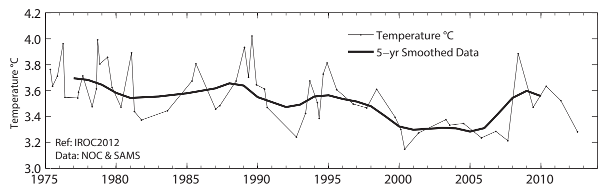


Figure 9a: Charting Progress Region 8 – Rockall Trough, temperature in the Labrador Sea Water layer (1800 - 2000 m) for the period 1975 to 2012. [Image modified from IROC2012 Figure 83]

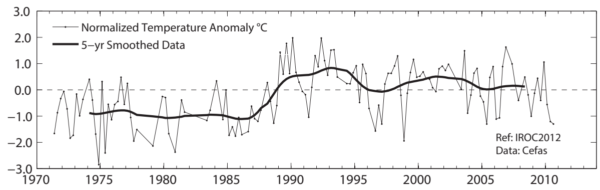


Figure 11: Charting Progress Region 2 Southern North Sea. Normalised SST anomaly (base period 1981-2010) measured along 52°N, a regular ferry at six standard stations. The time series show the seasonal section average (DJF, MAM, JJA, SON) of the normalised variable (normalised relative to monthly std. deviations) for the period 1971-2011 (no data 2012). [Image modified from IROC2012 Figure 57]

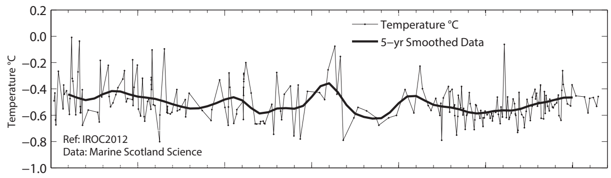


Figure 9b: Charting Progress Region 7 - Faroe Shetland Channel. Temperature of overflow water at 800 m for the period 1950 to 2012. [Image modified from IROC2012 Figure 78]

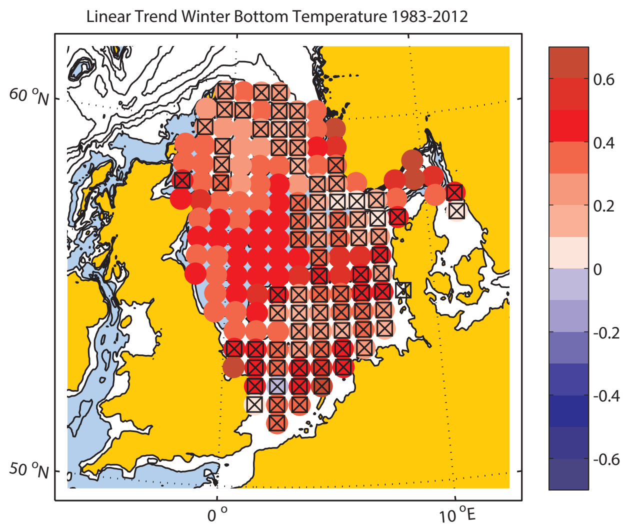


Figure 12: Linear trend (°C /decade) in Winter Bottom temperature calculated from the ICES International Bottom Trawl Survey Quarter 1 data for the period 1983-2012. Values calculated from linear fit to data in ICES rectangles. Hatched areas have a trend which is not significant at the 95% confidence level (alpha=0.05) using Mann-Kendall non-parametric test for a trend.

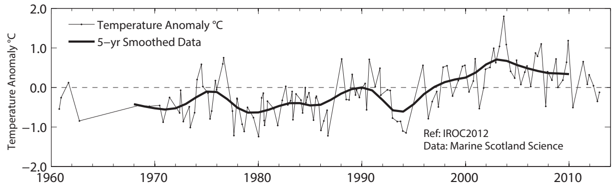


Figure 10: Charting Progress Region 1 -Northern North Sea. Temperature anomaly (base period 1981-2010) in the Fair-Isle Current for the period 1960 to 2012. [Image modified from IROC2012 Figure 52]

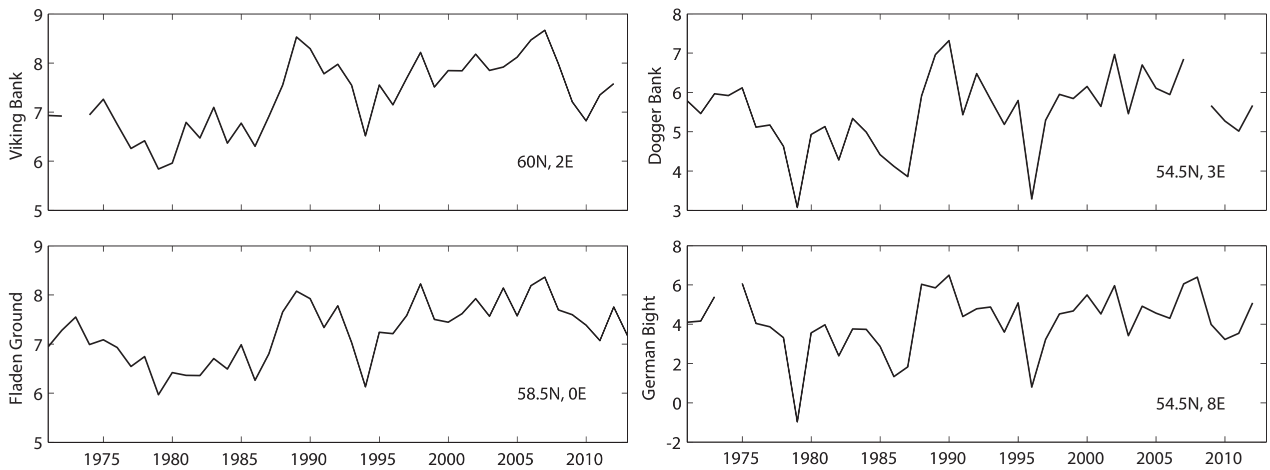


Figure 13: Winter bottom temperatures (°C) at four fishing grounds within the North Sea. Data from the ICES International Bottom Trawl Survey Quarter 1 data for the period 1971- 2012. Note that the temperature scale varies between figures.

is decreasingly evident in the shallower areas of in Region 1 (Holt *et al*., 2010) where most of the interannual variability in winter temperature can be explained by interaction between and with the local atmospheric conditions (Sharples *et al*., 2006). Colder conditions in the last few years have brought lower SSTs than at their peak in around 2003 but remain above the long-term average.

In the southern North Sea, atmospheric forcing is the dominant influence and inter-annual variability can be large relative to multi-decadal trends. Overall temperatures were lower from 1970 to 1987 followed by a "switch" to warmer conditions (Figure 11). Temperatures reflect this state and have remained generally higher than the 1981-2010 average, cooler conditions nearer to the long term mean are evident here since 2009.

In the North Sea winter bottom temperatures have also shown an overall rise since the 1971 (Figure 12) although temperatures in 2009, 2010 and 2011 were low compared to recent years as a result of the very cold conditions that occurred during these winters. Winter temperatures rose again 2012 (Figure 13).

Eastern English Channel (Charting Progress Region 3)

Annual mean surface temperature measurements at Eastbourne (Figure 14) show an overall rise since the early 1980s. The linear trend over the last 3 decade accounts about 30% of the variance during this period and there is considerable inter-annual variability. The years 2008-09 and 2011-12 are amongst the warmest in the record while cooler conditions in 2010 made this year close to the 1971-2000 average temperature.

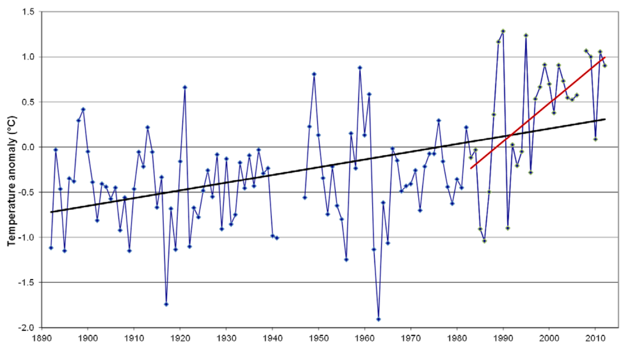


Figure 14: Charting Progress Region 3: Eastbourne Annual Average Sea Temperature Anomaly (base period 1971 – 2000). Trend lines for 1892 to 2012 (black)= 0.1°C decade^{-1} and 1983 to 2012(red) = 0.4°C decade^{-1}. [Data source Eastbourne Borough Council]

Western English Channel (Charting Progress Region 4)

The western English Channel, away from the coast, is mainly influenced by the inflow of North Atlantic Water from the west. Tidal currents and local weather conditions induce stratification in the spring and summer, and deep mixing in the autumn and winter. Station E1 of the Western Channel Observatory has been sampled since 1903 and lies in 75m of water.

Strong interannual to decadal scale variability is evident in this time-series, combined with a period without data this makes it difficult to identify trends, and in particular the data-gap coincides with the period of strong warming apparent in most of the other datasets at the end of the 1980s. Average or below average temperatures in the early 1980s were replaced by warmer than average waters on resumption of sampling, with particularly warm conditions around 2007, more recent years have been close to but slightly higher than average (Figure 15).

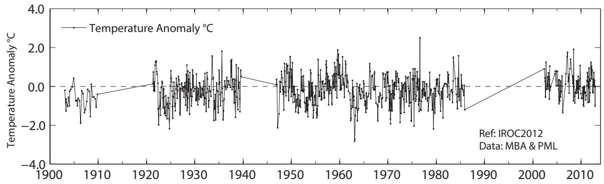


Figure 15: Charting Progress Region 4 Western English Channel – Western Channel Observatory Station E1 (50.03°N 4.37°W). SST anomaly (base period 1981-1985 & 2002-2010, the time when data was collected in the standard IROC2012 base period 1981-2010) for the period 1903-2012. [Image modified from IROC2012 Figure 41]

Irish Sea (including Charting Progress Region 5)

Port Erin Bay, Isle of Man is a central Irish Sea site. Daily SST has been recorded since 1904 and continues (Figure 16).

Conditions in the Irish Sea are to some extent influenced by waters from the North Atlantic, but in this shallow coastal zone atmospheric processes are also important. Data at Port Erin show a rising trend in temperature, with warming at a rate of 0.08°C decade^{-1} over the whole time-series and at a rate of 0.4°C decade^{-1} over the last 3 decades.

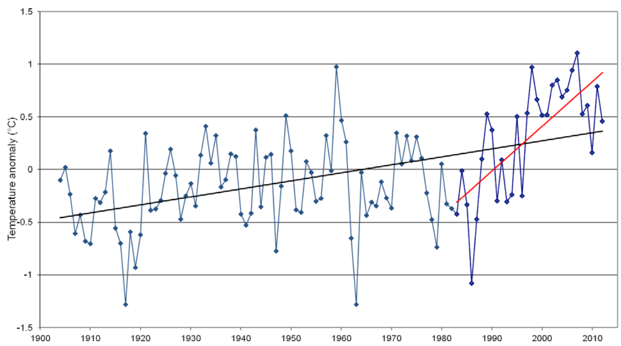


Figure 16: Charting Progress Region 5: Port Erin Isle of Man Annual Average Sea Surface Temperature Anomaly (base period 1971 – 2000). Trend lines for 1904 to 2012 (black) = 0.08°C decade^{-1} and 1983 to 2012 (red) = 0.4°C decade^{-1}. [Data source- Isle of Man Government Laboratory]

West Scotland (Charting Progress Region 6)

The temperature anomaly series (Inall *et al*., 2009) from the Tiree Passage (Figure 17) shows a cooling from 1981 to the mid 1980s, strong warming between 1986 and 1990, a minimum in the early 1990s and then generally warm conditions apparent between 2002 and 2008. The progression of temperature shows some similarities with that shown for the Irish Sea (Region 5 - Figure 16) and at Malin Head (Figure 18).

Ireland

The time-series of surface observations at the Malin Head coastal station (the most northerly point of Ireland) has been maintained since the late 1950s. Cannaby and Hüsrevoğlu (2009) estimated that about half of the warming trend over 1958–2006 at this location was contributed by anthropogenic

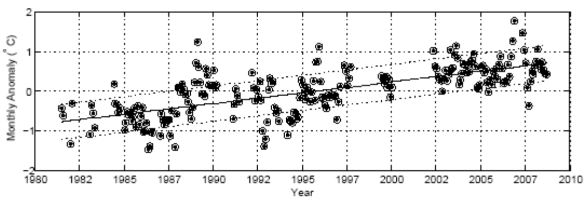


Figure 17: Charting Progress Region 6: Monthly mean temperatures for the Tiree Passage time series (temperature 1981-2008) as an anomaly from the mean temperature for each month of the year. Error estimates of one standard deviation are shown. [Courtesy of M. Inall, SAMS.]

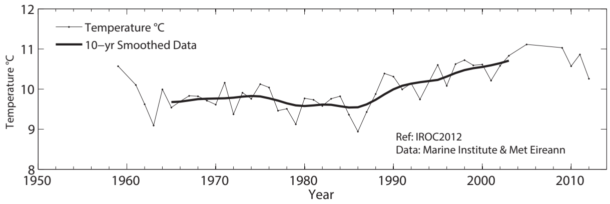


Figure 18: Ireland- Temperature at the Malin Head coastal station (55.39°N 7.38°W) for the period 1959-2011. [Image modified from IROC2012 Figure 43]

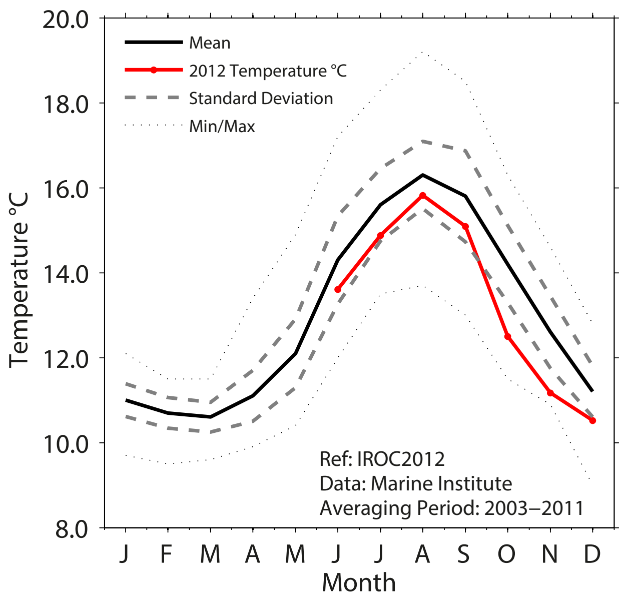


Figure 19: Ireland M3 Weather Buoy southwest of Ireland (51.22°N 10.55°W). The 2012 monthly temperature is compared with the 2003-2011 average monthly seasonal cycle and maximum/minimum observations in the period. [Image modified from IROC2012, Figure 44]

global warming. Here sea surface temperatures have been rising since the late 1980s, and those for the period 2004-2006 were the highest since the record began (Figure 18). Conditions in 2009-2012 were cooler than the peak but remain slightly warmer than the long term average of the time-series.

An offshore weather buoy (M3) has been maintained at 51.22°N 10.55°W off the southwest-coast of Ireland since mid-2002 (Figure 19). The data series is too short to consider trends but has shown considerable interannual variability during its first decade of deployment. The highest recorded summer temperatures were in 2003 (August 19.2°C), and the highest winter temperatures in 2007. In 2012, the buoy was out of operation until June. Temperatures were below the time series mean (2003-2011) from June until the end of the year most notably from October onwards.

2. WHAT COULD HAPPEN?

Although there is high confidence in the long term rise in sea temperatures on a global scale (IPCC, 2007), on shorter timescales and at regional spatial scales there is much more uncertainty (Hawkins and Sutton, 2009; Lean and Rind, 2009). Some analyses suggest that natural variability could account for 50% of the recent (1990s-2000s) warming (e.g. Ting *et al*., 2009; Swanson *et al*., 2009) and may explain why the recent (30 year) warming in the region has exceeded the IPCC global trends. The underlying ocean warming trend associated with anthropogenic climate change is superimposed upon natural variability on interannual to multi-decadal timescales and between regions. The result is that, even with a long-term 'anthropogenic' warming trend, in different regions there will be some decades in the future that will show particularly strong warming while others will exhibit little change or even cooling (Hawkins *et al*., 2011).

Answering the question of what could happen in the future has generally been done using climate projections where a climate model run under a particular emissions scenario is used to examine plausible conditions 50 to 100 years in the future (Adlandsvik, 2008; Lowe *et al*., 2009; Holt *et al*., 2010; Friocourt *et al*. 2012; Olbert *et al*. 2012). In recent years studies examining both coupled atmosphere-ocean models and empirical statistical models have begun to demonstrate the potential for skillful climate predictions on decadal time scales particularly in the North Atlantic region and using observations (e.g. Argo floats, CTD surveys, satellite SST) to set initial conditions (Keenlyside *et al*., 2008; Smith *et al*., 2007; Hawkins *et al*., 2011; Ho *et al*., 2013; Zanna, 2012; DelSole *et al*. 2013; Hazeleger *et al*., 2013). In particular the retrospective multiyear forecasts of North Atlantic ocean characteristics by Hazelager *et al*. (2013) can skilfully predict variability associated with the Atlantic Multidecadal Oscillation, (an important contributor to change in the seas around UK and Ireland) 2–9 years ahead. Building on this work there is a move from assessing the potential for decadal scale predictions to making experimental forecasts. For example Smith *et al*. (2013) present the first climate prediction of the coming decade made with multiple models. They report a statistical model forecasting that the AMO will

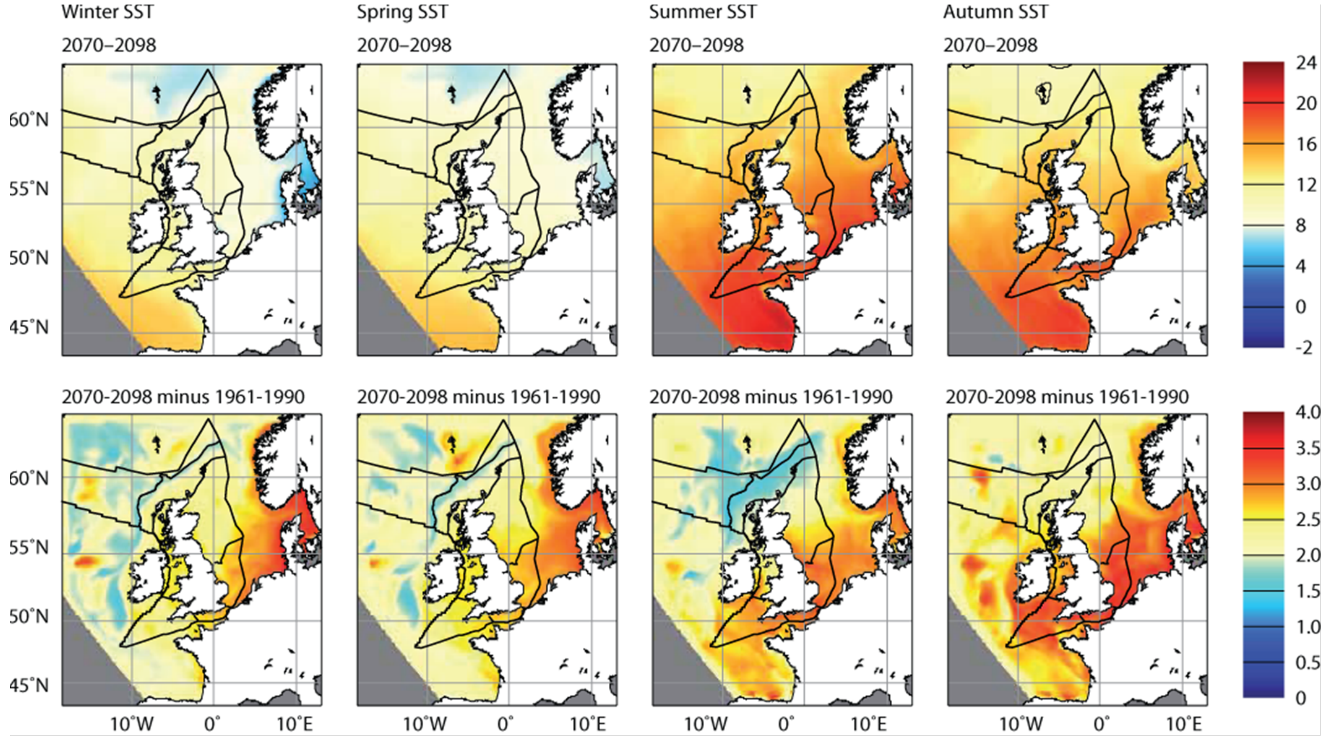


Figure 20: Top row - Seasonal-mean sea surface temperature (SST) for 2070-2098 (°C). Bottom row- Change in seasonal mean SST, relative to modelled 1961-1990 conditions. Black lines depict 'Charting Progress' regional borders. [Adapted from UKCP09, Lowe et al. *(2009)]*

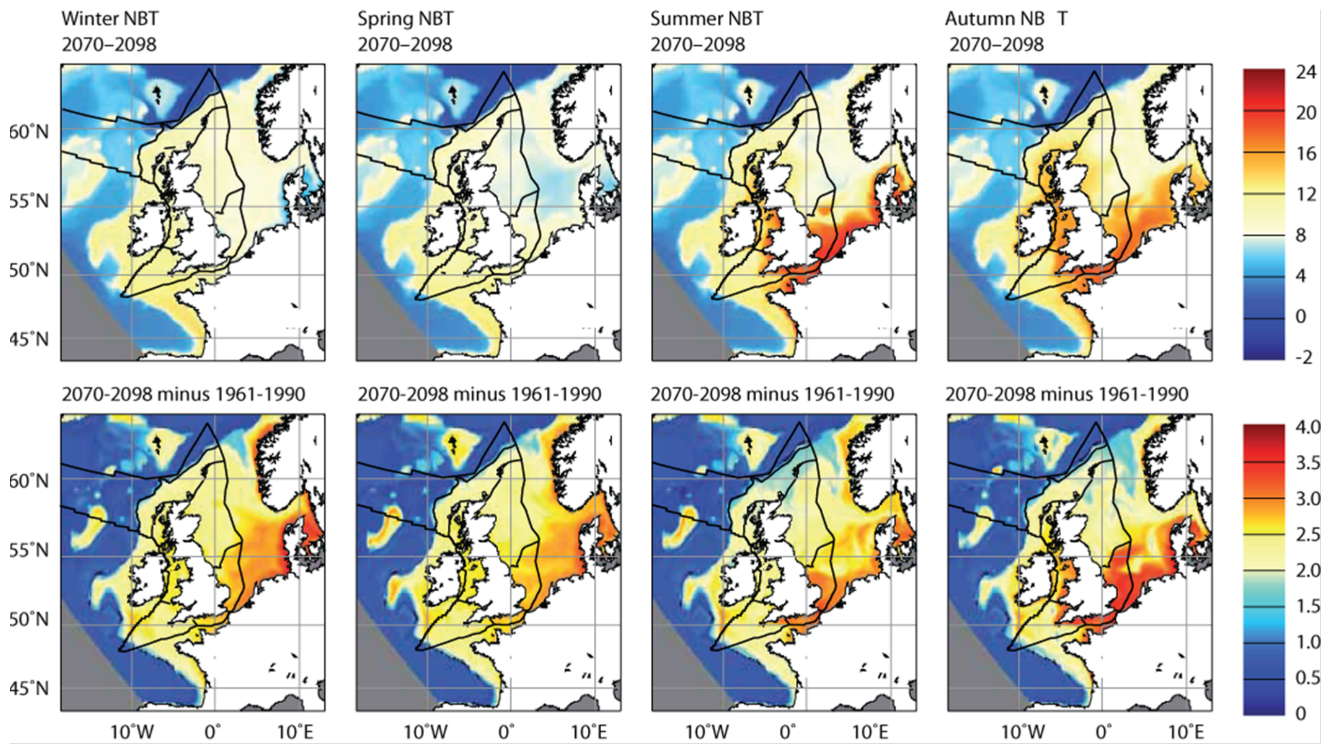


Figure 21. Top row- Seasonal-mean near-bed temperature (NBT) for 2070-2098 (˚C). Bottom row- Change in seasonal mean NBT, relative to modelled 1961-1990 conditions. Black lines depict 'Charting Progress' regional borders. [Adapted from UKCP09, Lowe et al. *(2009).]*

remain positive for the rest of this decade while the AMO forecast by dynamical models cannot be distinguished from climatological values.

UK Climate Projections 2009

The UK Climate Projections 2009 (UKCP09; Lowe *et al.*, 2009) included for the first time a projection of the possible change in the hydrographic conditions of the seas around UK and Ireland and forms a basis for many impacts studies in the UK. This projection indicates that the seas in all of the regions will continue to warm (Figure 20 & 21). Warming is evident in all regions during all seasons and in all areas. In the surface waters, annual temperature rises of ~1.5–2.5°C are projected in open ocean, shelf edge, and the northern North Sea by 2070–2098 (relative to the 1961–1990 average). Larger rises of ~2.5–4°C are projected for the Celtic, Irish and southern North Sea over the same period. Southern regions are projected to warm faster than northern regions and summer and autumn to warm faster than winter and spring in the south of the region. These projections present just one physically plausible future using a medium emissions scenario (SRES A1B, Nakicenovic and Swart, 2000), derived from a single model, and therefore cannot provide a full assessment of uncertainty.

Other climate projections

There are now projections of future temperature in the seas around the UK and Ireland other than those produced under UKCP09. The studies reviewed all use the same medium emissions scenario but cover slightly different time-periods, have different spatial domains, are forced by different atmospheric models or use alternative baseline periods all of which makes close comparison difficult, but they all show the same general warming pattern on the scale of UK and Ireland regional seas.

North Sea (including Charting Progress Regions 1 and 2)

One study ran two models of the North Sea under the same medium emissions scenario as UKCP09 but only to the mid 21st century (Friocourt *et al.* 2012). The models project a general warming of the North Sea in the 2040s by up to 0.8°C relative to the 20 year period 1984–2004 finding that the change is more pronounced in the eastern North Sea.

A Norwegian study (Adlandsvik, 2008) also focused on the North Sea and used the same medium emissions scenario as UKCP09, projecting forward to almost the same period as UKCP09 (2072-2097) but using a later reference period (1972-1997). This study also examined the difference between the projections of sea temperature change using a Global Climate Model with a relatively course spatial grid versus those produced by a downscaled model that might represent the local processes better. They found that the downscaled model showed stronger warming than the GCM. In the downscaled model the North Sea average SST rose by 1.7°C and the month of strongest warming (2.2°C) was June. In the GCM average warming was 1°C and the peak was in May (1.5°C). In Figure 22 (reproducing Figure 2 from Adlandsvik, 2008), they show the change in the seasonal cycle of the monthly average water column temperature of their downscaled model North Sea. May shows the strongest warming here and November the least and the 'future' and 'present' seasonal cycle do not overlap to within 1 standard deviation of each other.

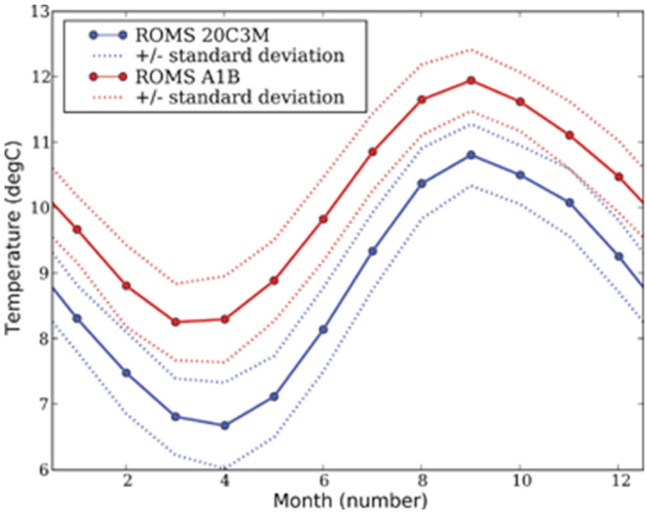


Figure 22. Seasonal cycle of averaged temperature in the North Sea for 1972–1997 (20C3M) and 2072–2997 (A1B). The dotted lines indicate plus/minus one standard deviation as computed from the monthly averages. [Reproduced from Adlandsvik et al. *2008 their Figure 2 License– creativecommons.org/licenses/by-nc/3.0/]*

Irish Sea (including Charting Progress Region 5)

Researchers in Ireland recently published a projection for the Irish Sea (Olbert *et al.* 2012) under the same medium emissions scenario as UKCP09 but run over the full period 1980-2099. They find that the Irish Sea SST rises by around 1.9°C over this period and that the timing of both the maxima and minima in the annual temperature cycle shifts later by about 2 weeks. Warming is strongest in the shallow waters along the coastline and in the eastern Irish Sea and weaker in the deep waters of the western Irish Sea.

3. KNOWLEDGE GAPS

Satellite observations of SST have resulted in good data coverage in the surface waters around the UK, whilst data from below surface is still relatively sparse. Satellite SST also requires continuity of satellite missions and availability of adequate *in-situ* data for validation and bias adjustment. Further research is required to understand the impact of changes to the *in-situ* observing network for SST. The number of air temperature observations in UK coastal waters and globally have declined in recent years increasing the uncertainty of marine air temperature datasets.

It is important that the existing *in-situ* time series are maintained. For many time series there is a lack of funding security; most are maintained through a rolling programme of grants for a short number of years. Many time series face periodic funding shortages, some have suffered major gaps as a result, and some have reduced temporal resolution in recent years. At many stations the existing sampling is not sufficient for a full understanding of variability and hence reduces confidence in the representativeness of measurements made.

The addition of more *in-situ* stations and improved sampling of the seasonal cycle is also therefore desirable.

The deep ocean (below ca. 2 km depth) is poorly sampled. The Argo programme has addressed this to some extent for the upper 2 km of the deep ocean, but funding for this programme is also uncertain. For the surface to mid-depth ocean questions of the homogeneity of data from Argo floats and between Argo and other sampling technologies (e.g. XBTs) remain. Recent rapid changes in the *in-situ* observing system means that the homogeneity of the current observing system, and its consistency with earlier observations, needs urgent assessment.

Further research on ocean processes is necessary to help understand the inter-annual to decadal variability observed at regional and ocean scales and investigate the mechanisms that determine hydrographic properties and ocean transports.

4. SOCIO-ECONOMIC IMPACTS

The socio-economic impacts of changing marine temperatures will be through their role as the key underlying driver of climate impacts across all components of the ecosystem. These are considered within specific MCCIP topic reviews.

5. CONFIDENCE ASSESSMENTS

What is already happening?

Air Temperature (*in-situ *observations)

The number of Voluntary Observing Ship(VOS) observations of the marine air temperature has declined in recent years. Additionally, an increasing number of observations are reported with a masked or missing call sign due to ship security and commercial concerns, preventing the association of the observations with the metadata required to height and bias adjust the observations. Both the reduction in number of observations and the loss of the ability to match the observations to metadata act to increase the uncertainty in the air temperature estimates. The highest confidence (lowest uncertainty) in our air temperatures can be found over the North Sea, English Channel and South West Approaches whilst the lowest confidence in the air temperature values can be found to the south and south-west of Iceland (Figure 23a). There has been little change since 1970 in the uncertainty in the air temperature for the regions where we have highest confidence whilst the uncertainty in regions where we have low confidence has increased (Figure 23b).

Sea-Surface Temperature (*in-situ *and satellite observations)

The gridded SST data presented here come from the HadISST1.1 dataset. The dataset uses a combination of *in-situ* and satellite observations, gridded and interpolated to create a complete dataset. Data coverage in the area of interest is generally good and a recent comparison of this dataset with independent *in-situ* data (Hughes *et al.*, 2009) indicated that there was good agreement in the region of interest. Recent research (Reverdin *et al.*, 2010; Kennedy *et al.*, 2012) has shown that changes in the composition of the *in-situ* SST observing system may cause systematic biases in the data.

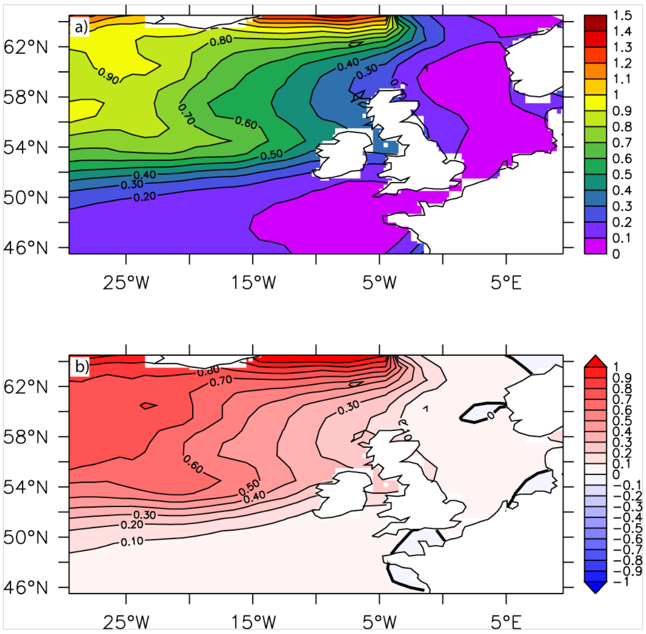


Figure 23: a) Average uncertainty (°C) in the monthly mean air temperature averaged over 2004 – 2008 and b) change in the uncertainty (°C) for the period 2004 – 2008 relative to 1970 – 1974.

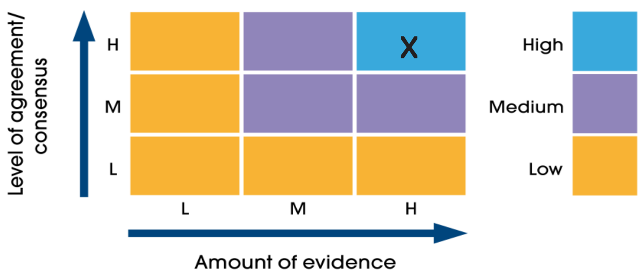
However, the nature of these biases is unlikely to change the picture of rising temperatures and their distribution. This conclusion is reinforced by the agreement of SST changes with those in air temperature which is measured using different methods.

In-situ *sea temperature*

Measurements of temperature profiles at offshore sites are made 1-3 times per year, under-sampling the seasonal cycle which may alias the results. Shelf sea and coastal stations are sampled more frequently (up to daily), so the seasonal cycle is usually better resolved. Calibration is good (although data prior to 1970 are less reliable), so high confidence can be put on *in-situ* measurements.

Temperature profile information in the North Atlantic is now much better sampled than in the past due to the deployment of many Argo profiling floats. However, questions of biases in recent batches of floats (Willis *et al.*, 2007) and in homogeneity between Argo and eXpendable BathyThermographs (XBT's) data (Gouretski and Koltermann, 2007) mean the overall confidence probably remains moderate, pending further research.

Although there are gaps in the observational record of subsurface temperature and some areas are poorly observed,

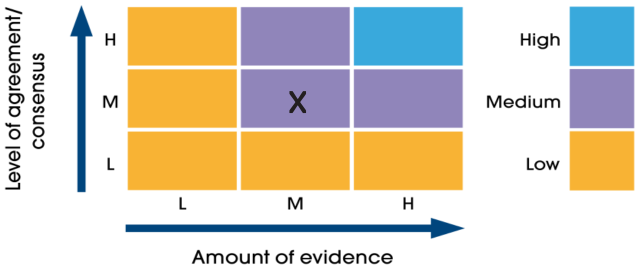


temperature is the most widely measured parameter and there is therefore a large amount of evidence. Although some of the observational records are shorter than others and have difference in sampling, they all offer a coherent picture of long term and shorter variability, giving rise to a higher level of confidence in the results.

What could happen?

For shorter term predictions (i.e. 2 year to decadal scale) whilst experimental forecasts have begun to appear, natural internal variability cannot currently be predicted with any confidence and it is therefore difficult to determine if natural variability will enhance or oppose the long term warming trend over the next decade.

Confidence in the global rise in SST is high (e.g. IPCC, 2007) and there is high confidence in the long-term future



warming trend. However, our confidence in the exact rates of warming at regional scales is lower. With the UKCP09 scenarios, as the ocean model was run only once (medium emission scenario), there are no estimates of upper or lower bounds of change and consequently no confidence intervals. The effect of decadal uncertainties has been addressed by averaging model output over a 30-year period.

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