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Temperature (Air and Sea)

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EXECUTIVE SUMMARY

Marine Air Temperatures in the Northeast Atlantic and UK waters have warmed rapidly over the last 25 years. The observed warming is greatest in the Southern North Sea with warming rates of over 0.6 °C decade-1. Similarly, sea-surface temperatures (SST) in UK coastal waters and in the north east Atlantic have risen by between 0.2 and 0.8˚C/decade since the 1980s.

The most rapid increases have been observed in the Eastern English Channel (Region 3) and Southern North Sea (Region 2) at a rate between 0.6 and 0.8˚C/decade

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

The observed temperature variability has been attributed to a combination of anthropogenic global climate change and natural variability (i.e. 'internal' variability in the ocean atmosphere system). The Atlantic Multidecadal Oscillation (AMO) is a pattern of variability in North Atlantic SST that is thought to be representative of the internal variability, the decadal scale variations of temperature observed in UK waters are similar to those of the AMO. As a result of both of these 'drivers' (climate change and internal variability) a significant period of rapid warming occurred from 1995 to 2003.

West of the UK the water of the deep ocean (>1000 m) comes from the Labrador Sea and has 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. The deep bottom waters of the Nordic Seas are known to be warming.

Despite the long term warming trend, in 2008 the temperatures observed in most areas were slightly lower than observed in 2003-2007. This is a reflection of the high inter-annual variability, particularly in coastal waters and is not indicative of a decreasing trend.

By the 2080s warming in the shelf seas around UK and the upper layers of the North Atlantic is predicted to continue, although perhaps at a lesser rate to that observed in the last 25 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.

Off the shelf in deeper waters, nearbed temperatures are influenced by deep ocean circulation and little or no warming is projected to occur by 2080. In the shorter term an observed warming trend in the Labrador Sea is likely to cause an increase in temperature in deep waters west of the UK.

FULL REVIEW

1. What is already happening?

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 NOCS Flux Dataset v2.0 (Berry and Kent, 2009). NOCS2.0 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 25 year trend (1984 – 2008) in marine air temperature (°C/decade) estimated from NOCS2.0 for the Northeast Atlantic and UK waters. As previously reported, the warming is greatest in the Southern North Sea (Charting Progress Region 2) with warming rates of over 0.6 °C/decade. Lower rates of warming are found in the Southwest Approaches (Region 4) and to the north east of Scotland (Regions 6 and 7) with warming rates between 0.2 – 0.4 °C/decade. In the remaining regions the warming rate varies between 0.4 – 0.6 °C/decade. In most regions these warming rates are similar to those seen in sea surface temperature (SST) giving confidence in the estimates. Air temperature however shows a region of stronger warming than SST to the south and southwest of Iceland (Region 8). This is a region with poor sampling hence higher uncertainty; confidence in the trend estimates for this region is therefore low.

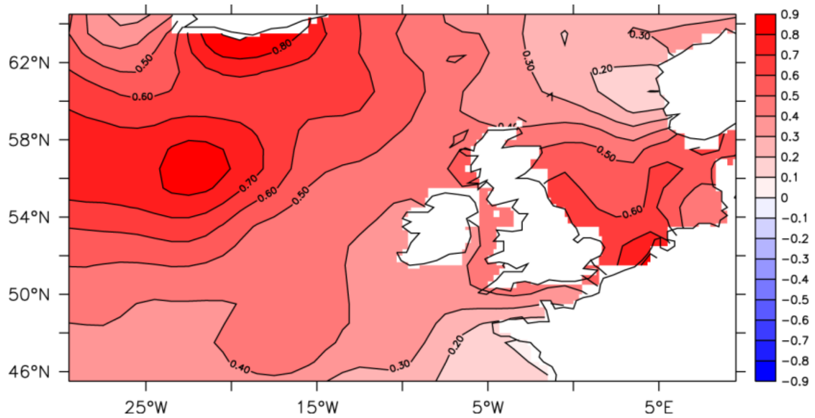


Figure 1*: 25 year linear trend for marine air temperature estimates from NOCS2.0 for the period 1984 – 2008 (°C/decade).*

Figure 2a compares the time series of annual mean air temperature estimates for the UK coastal waters (Figure 2b) 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 higher than average in 2008, and they have remained at this relative high level since 2002. The CET temperature record however indicates that

2008 was one of the coolest in the last decade, (although still warm relative to the 1970-2008 period).

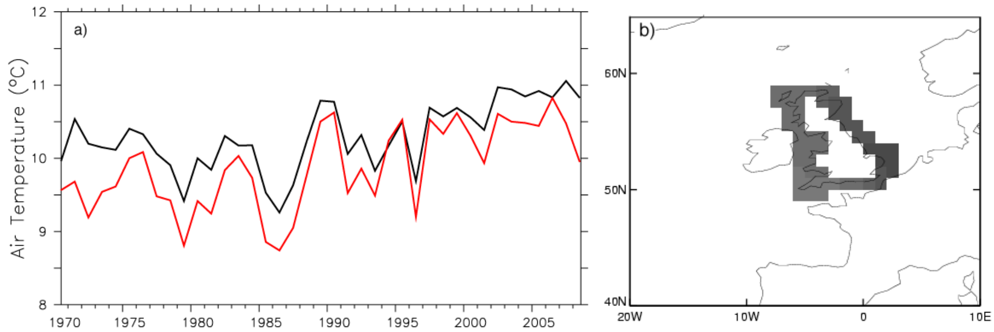


Figure 2: *a) Annual mean air temperature estimates from NOCS2.0 for UK Coastal waters (black) and the Central England Temperature (red). b) Definition of UK Coastal waters as used in (a).*

Figure 3a compares the annual cycle of the monthly mean air temperature estimates for UK waters from NOCS2.0 for the past 10 years (1999 – 2008) (green) with estimates for the first 10 years of the dataset (1970 – 1979) (red). Also shown are the monthly mean air temperatures for 2008. Unusually warm air temperatures were observed during May 2008 followed by an average summer (relative to 1999 – 2008). Air temperatures in the latter half of 2008 (Sep-Dec) were relatively cool compared to the last decade. Similar results are also seen for the CET (Figure 3b).

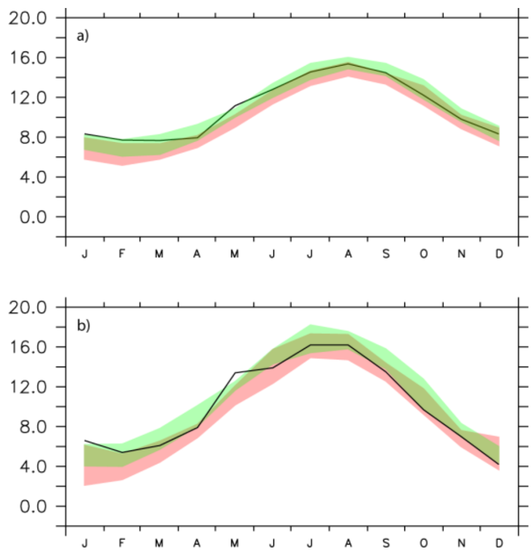


Figure 3*: a) Monthly mean air temperatures for UK coastal waters (°C) for2008 (black line), 1999 – 2008 ± 1 standard deviation (green) and 1970 – 1979 ± 1 standard deviation (red) from the NOCS2.0 dataset and b) from the Central England Temperature time series.*

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 (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 to Shetland since 1900, and Rockall Trough since 1948) are maintained by UK agencies. Offshore observations in the North Atlantic and Nordic Seas are summarised annually in the International Council for the Exploration of the Seas (ICES) Report on Ocean Climate (IROC)

(Holliday *et al.*, 2009). 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.

Coastal and shelf sea monitoring stations are maintained around Scotland by the Fisheries Research Services, Marine Laboratory Aberdeen (FRS, 2007), and the Scottish Association for Marine Science, Oban. ICES co-ordinate an annual winter survey (IBTS – International Bottom Trawl Survey) which provides an annual snapshot of winter bottom temperatures over the whole of the North Sea.

Overview

The average surface temperature of the North Atlantic has increased over the last 25 years, with the decade of the 2000s 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 are similar to the North Atlantic average temperature trend (Figure 4).

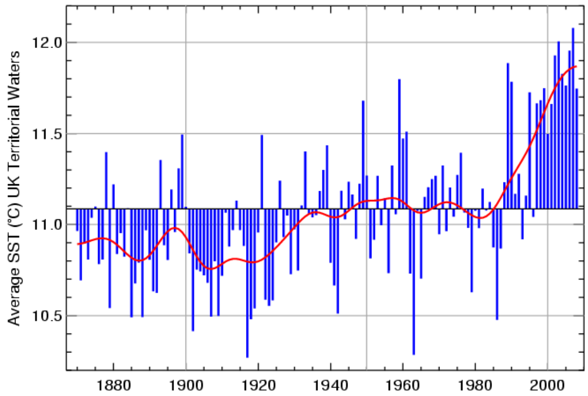


Figure 4 *Time series of average temperatures in UK coastal waters (Figure 2b). The blue bars show the annual values relative to the 1961-1990 average and the smoothed red line shows the decadal variations. Data are from the HadISST1.1 data set (Rayner et al., 2003).*

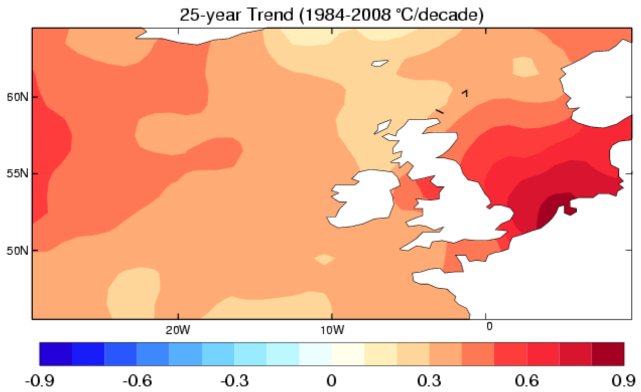


Figure 5 *Trend in annual average sea-surface temperature (°C/decade) from 1984-2008. Data are from the HadISST1.1 data set (Rayner et al., 2003).*

SSTs in the Northeast Atlantic and UK waters have warmed rapidly over the last 25 years (Figure 5), by between 0.2 and 0.8˚C decade-1 since the 1980's. The most rapid increases have been observed in the Eastern English Channel (Region 3) and Southern North Sea (Region 2).

Sea-surface temperatures in the North Atlantic as a whole have also risen faster than the global-average over the past 25 years. Analysis of long time-series of temperature in the North Sea indicates that the recent rate of warming is higher than at any period on the observational record (Mackenzie and Schiedek, 2007).

Warming due to anthropogenic effects is superimposed onto a pattern of multi-decadal variability, which is thought to be a natural oscillation 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; Ting *et al.*, 2009; Swanson *et al.*, 2009).

Since the end of the 1990s, the annual UK coastal-average SST has been higher than the 1961-1990 average. Although there is clearly a long term trend, there is a large amount of year-to year variability and the coastal-average SST in 2008 was the coolest since 2002 (Figure 4). Figure 6 shows how the temperatures in 2008 varied throughout the year. Air temperatures in the UK and northwest Europe were unusually warm in May and this was reflected by high SSTs and air temperatures in UK coastal waters. Between June and August SSTs fell relative to the average for the recent run of warm years and from August to December UK coastal SSTs were among the coolest in the past 10 years.

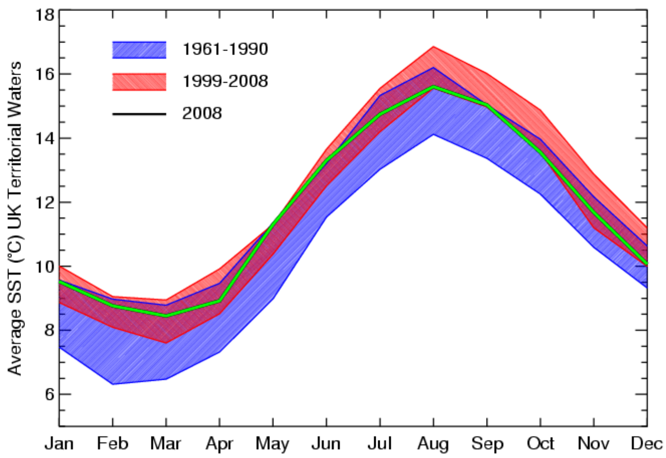


Figure 6*: Annual cycle of sea-surface temperature in UK coastal waters (for definition see Figure 2b) from the HadISST1.1 data set (Rayner et al., 2003). The range of temperatures from the period 1961-1990 is shown in blue, the range of temperature from the past 10 years is shown in red and the data for 2008 are shown in green.*

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

In-situ observations show that the upper layer of the deep ocean (0-600m) has warmed since the mid-1970s including around the UK (Figures 7b, Holliday *et al.*, 2009). There was a brief maximum in the early 1980s, but in 2006 temperatures reached the highest levels recorded since 1900, although temperatures have decreased slightly since then. 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).

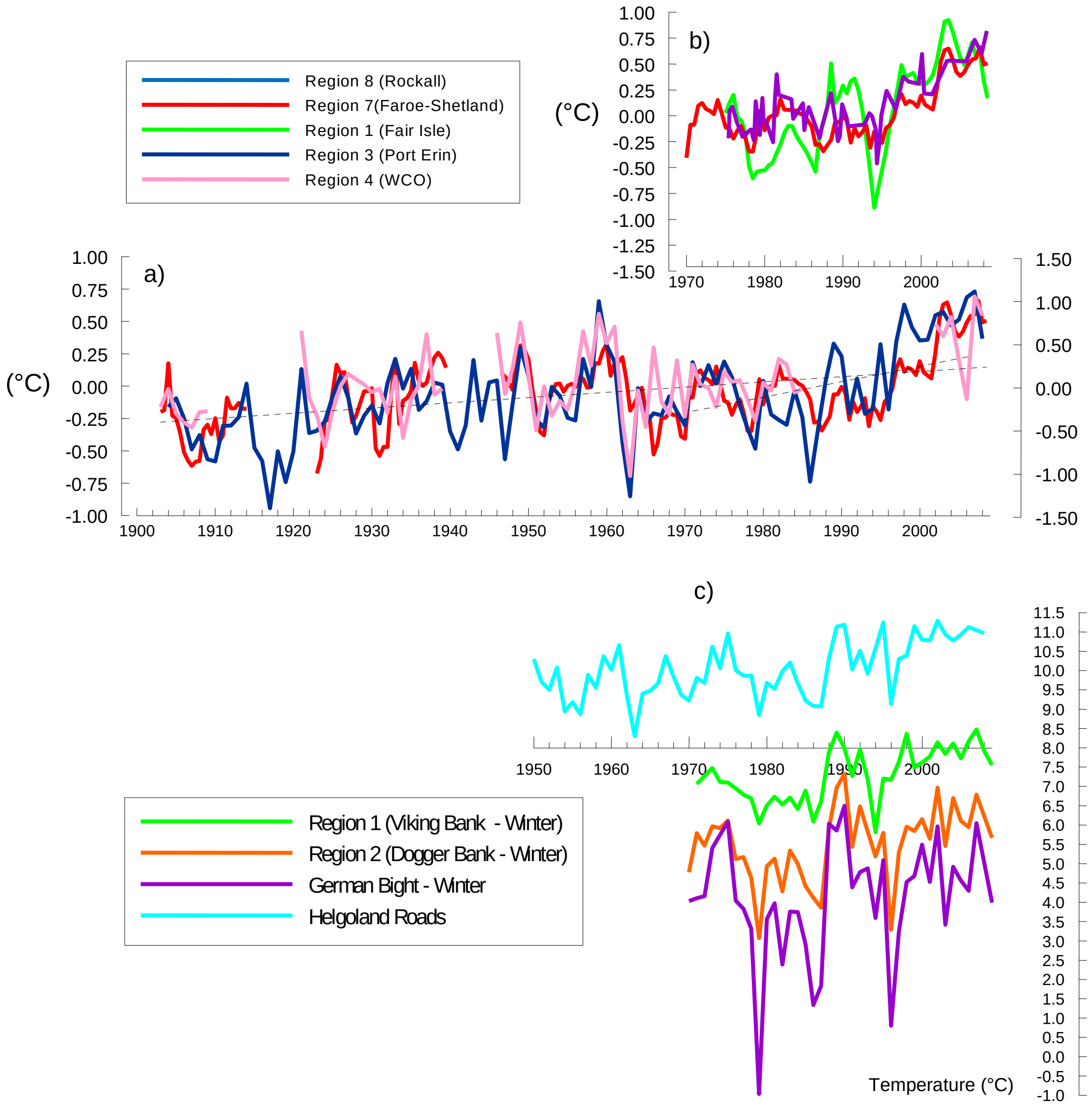


***Figure 7**: Comparison of temperature trends across regions .*

***a)** Long temperature timeseries: left axis, temperature anomaly of the Atlantic Water in the slope current (Region 7, North Atlantic Water in the Faroe Shetland Channel). Long term trends and trend since 1970 are indicated with dashed line (simple linear fit). Right axis, temperature anomaly in the Irish Sea (Region 3, Port Erin) and Western English Channel (Region 4, Western Channel Observatory Station E1 in the English Channel (50.03°N 4.37°W))*

***b)** Comparison of temperature anomalies in Regions 1, 7 and 8. Region 1: Northern North Sea. Temperature anomaly in the Fair Isle current entering the North Sea from the North Atlantic, Region 7: North Atlantic Water in the Faroe Shetland Channel, Region 8: Rockall Trough. Temperature of the upper ocean (0-800 m).*

***c)** Comparison of winter bottom temperature from ICES IBTS dataset at Viking Bank, Dogger Bank and German Bight. Annual mean temperature data from Helgoland Roads also included for comparison.*

***Note:** In panels **a** and **b**, anomalies are calculated relative to the long-term mean (all data available in the period 1971-2000)*

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 a higher values in the early 1960s to a lower values in the 1980s and 1990s (Holliday *et al.*, 2009) and has been high again in the last decade . The mean salinity shows a similar pattern (Holliday *et al.*, 2009 and *MCCIP ARC Science Review 2010-11 Salinity* - Holliday *et al*., 2010).

This basin-wide, decadal-scale variability is overlain by shorter time-scale changes and regional patterns. Interannual variability can be high 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 surface layer of the ocean (the top 100m) is most heavily influenced by the atmosphere and is more variable than deep temperature. 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). Surface conditions in a few key locations remote to the UK, where surface water sinks into the deep ocean, also affect the temperature of UK deep waters (Dickson et al., 2002).

Below 1000m 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 8). The Labrador Sea has become warmer again since the late 1990s, and we expect the deep water west of the UK will also increase in temperature over the next few years, as indicated by the temperatures in 2007 and 2008. North of the UK, the deep water (800m) flows from the Nordic Seas and shows no long-term trend since 1950s (Figure 9).

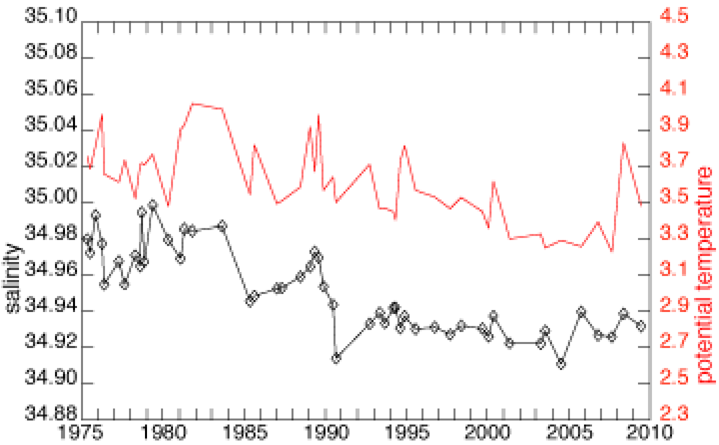


Figure 8. *Region 8, Rockall Trough. Temperature (in red) and salinity of the deep ocean (Labrador Sea Water, 1800 - 2000 m)*

Analysis of data from profiling Argo floats has shown that the upper 1500m 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 1000m and in the zone 50-70°N but there is a complex variation in changes in heat content both with latitude and with depth.

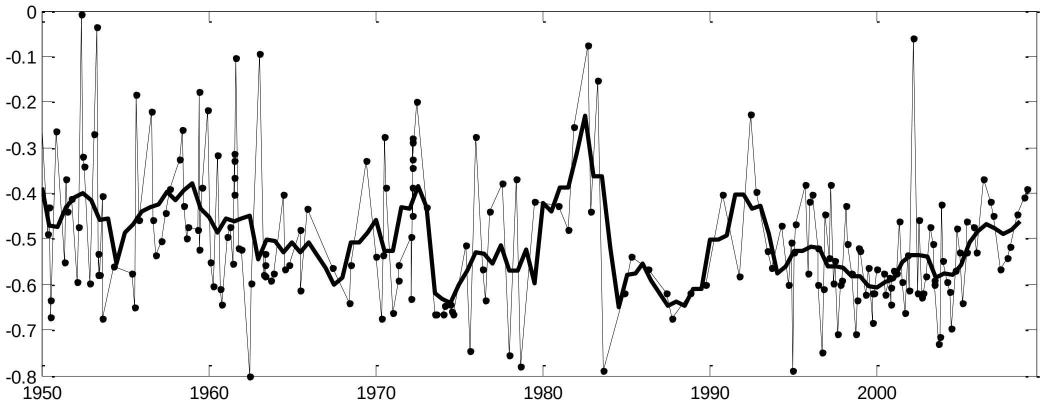


Figure 9*. Region 7, Faroe Shetland Channel. Temperature (°C) of overflow water at 800 m.*

North Sea (Charting Progress Regions 1 and 2)

In the northern North Sea the temperature is strongly influenced by inflowing North Atlantic water, showing similar decadal variations and a general warming since the mid 1980s (Figure 7b). Temperatures in 2008 were higher than the long-term average, but have decreased from the highest values observed in 2003.

In the southern North Sea, atmospheric forcing is the dominant influence and inter-annual variability can be high. Overall temperatures were cooler from 1970 to 1987 when a "switch" to warmer conditions occurred (Figure 7b, Figure 10). Temperatures reflect this state and remain higher than the long term mean (1971-2000).

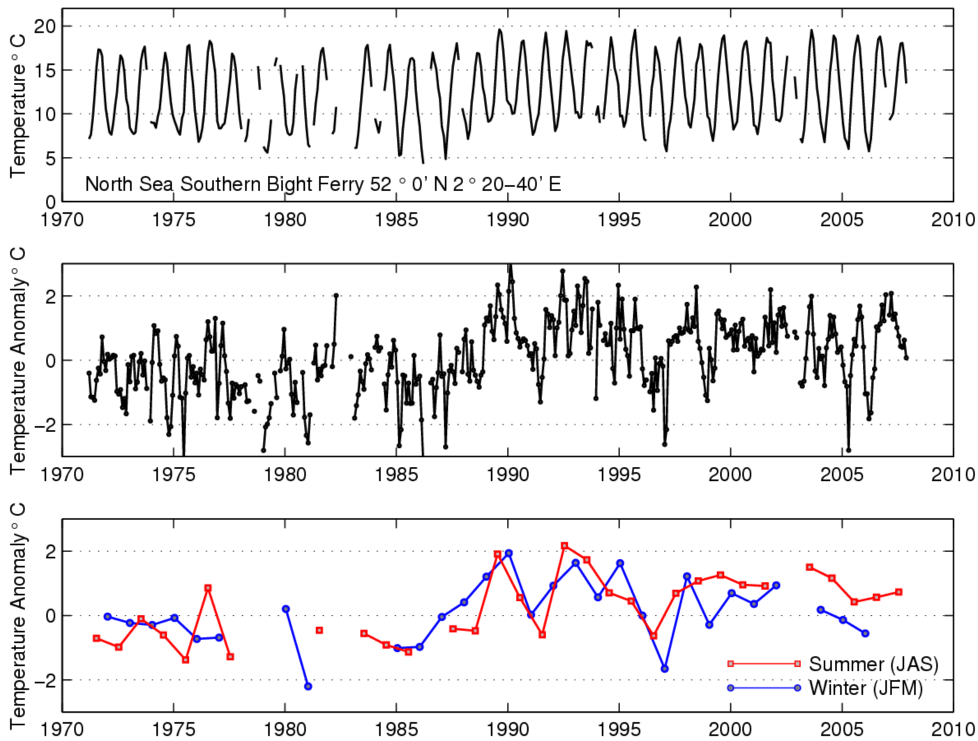


Figure 10 *Region2: SST offshore time-series 1970-2007 from Harwich-Rotterdam ferry. Respective panels show monthly mean, monthly anomaly relative to 1971-2000 average, winter and summer anomaly.*

Winter bottom temperatures have also shown an overall warming since the 1980s (Figure 11) but values in 2008/2009 decreased somewhat from the higher values observed in 2007 (Figure 7c).

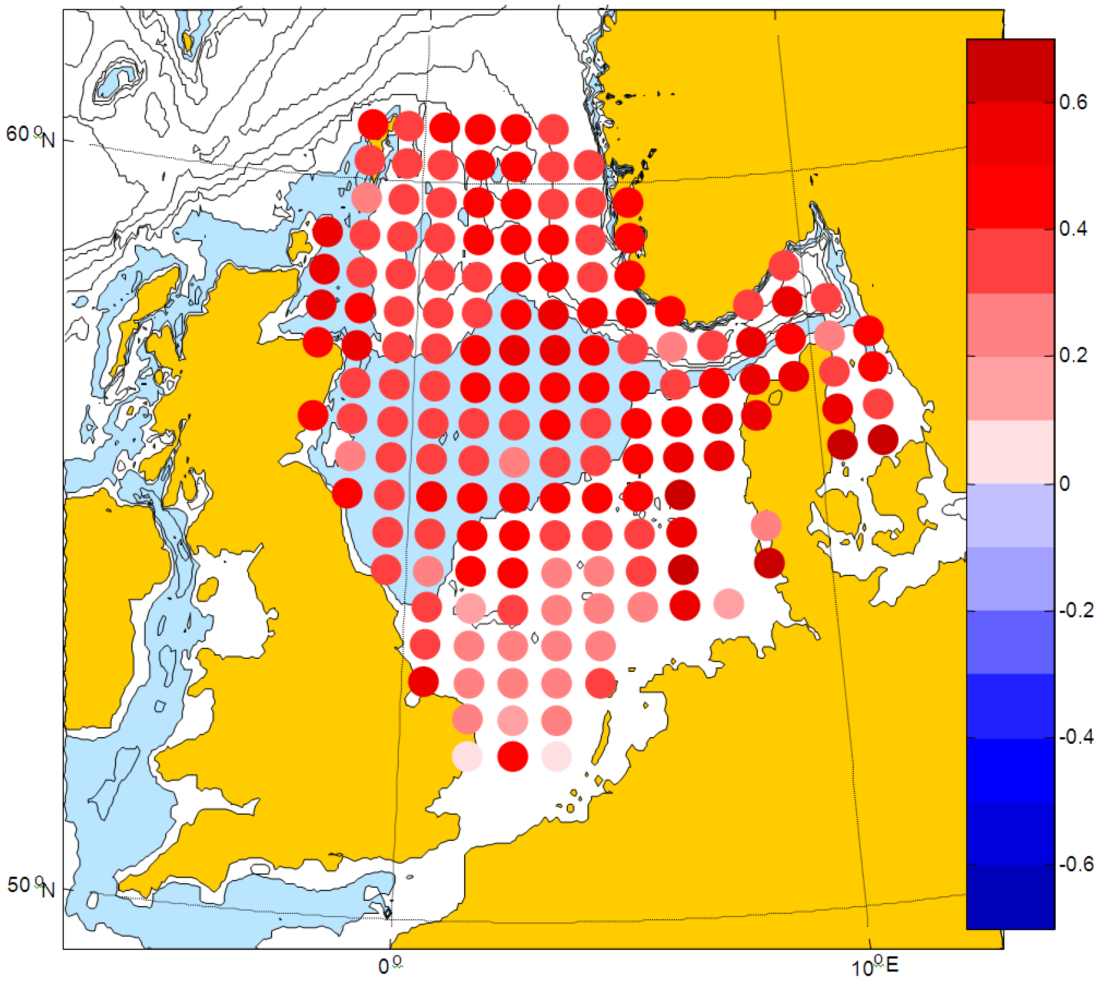


***Figure 11**:. Linear trend (°C /decade) in Winter Bottom temperature calculated from the ICES International Bottom Trawl Survey Quarter 1 data for the period 1971-2009. Values calculated from linear fit to data in ICES rectangles with more than 30 years of data.*

Eastern English Channel (Charting Progress Region 3)

Surface temperature measurements at Eastbourne (Figure 12) show an overall increase in temperature since 1985. There is considerable inter-annual variability and 2007 temperatures were close to normal values (relative to 1971-2000 average).

Western English Channel (Charting Progress Region 4)

The western English Channel, away from the coast, is mainly influenced by North Atlantic Water. It is heavily influenced by tidal currents and local weather conditions which 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.

After decreasing from higher than normal temperatures in the 1960's, temperatures have shown a rapid increase over the last 20 years, and were higher than normal in 2007 with a slight decrease from these values in 2008 (Figure 7a).

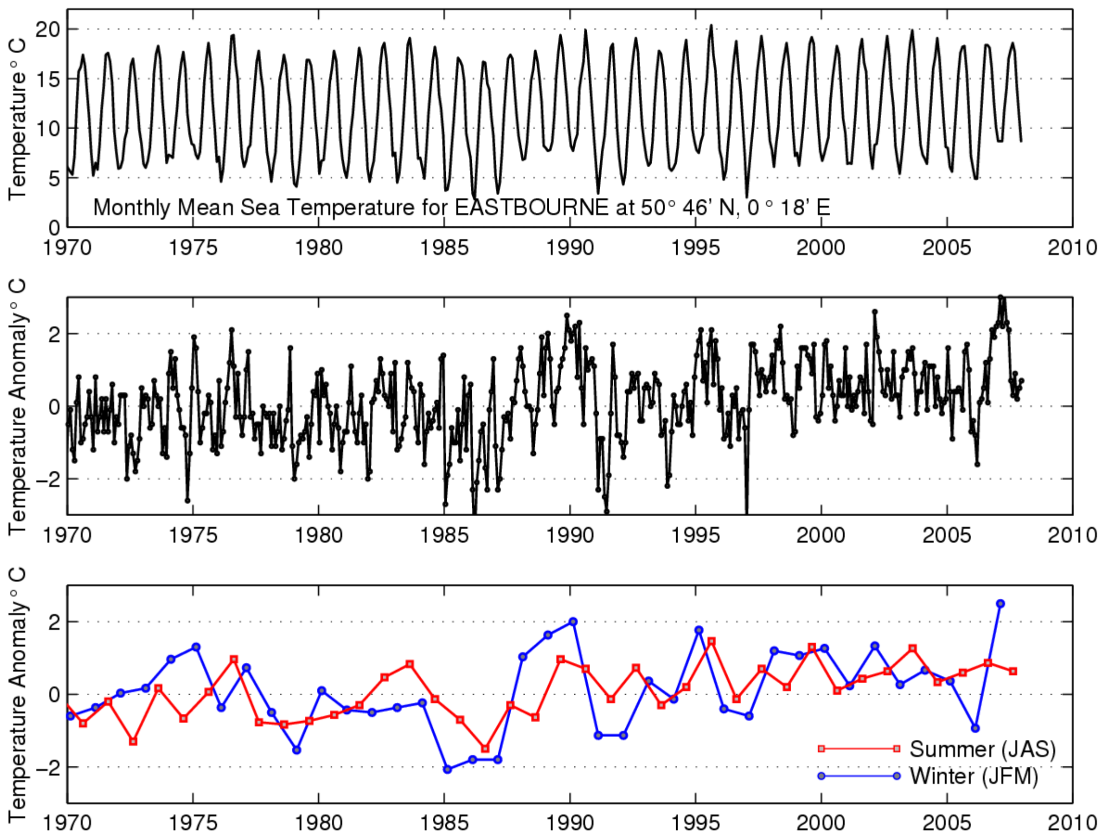


Figure 12: *Region 3: Sea temperature time-series 1970-2007 at Eastbourne. Respective panels show monthly mean, monthly anomaly relative to 1971-2000 average, winter and summer anomaly.*

Irish Sea (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 7a).

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 a warming of about 1°C over the last 50 years and a faster rise in the last 20 years.

West Scotland (Charting Progress Region 6)

The temperature anomaly series (Figure 13) shows a cooling from 1981 to the mid 1980s, maxima in the late 1980s and mid to late 1990s with a minimum in the early 1990s in a pattern similar to that of offshore waters in region 8.

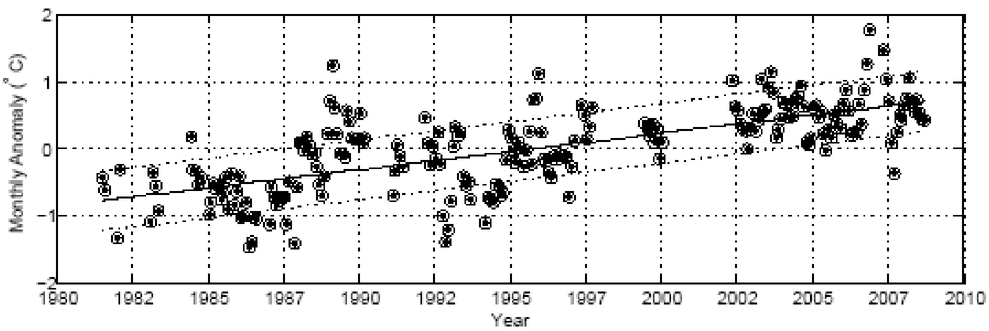


Figure 13*: Region 6: Monthly mean temperatures for the Tiree Passage time series (temperature 1981-2008) as an anomaly from the mean temperature for each month of the year. Error estimates of one standard deviation are shown. Courtesy of M. Inall, SAMS*

2. What could happen in the future?

The UK Climate Predictions 2009 (Lowe *et al.,* 2009) indicate that the seas in all of the regions will continue to increase in temperature. Warming is indicated in all regions during all seasons and in all areas. In the surface waters, the temperature is predicted to increase by between 1.5-3.5 degrees (relative to the 1961-90) by the 2080s. Southern regions are predicted to warm faster than northern regions and summer and autumn are predicted to warm faster than winter and spring in the south of the region.

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 (last decade) warming (e.g. Ting *et al.,* 2009; Swanson *et al.,* 2009) explaining why recent warming has exceeded the IPCC predictions. This also suggests that in the short term, if natural variability leads to a reduction in temperature, it could temporarily mask the long term warming trend. However there is still much uncertainty and it is also possible that natural variability could lead to further enhancement of the long term warming trend.

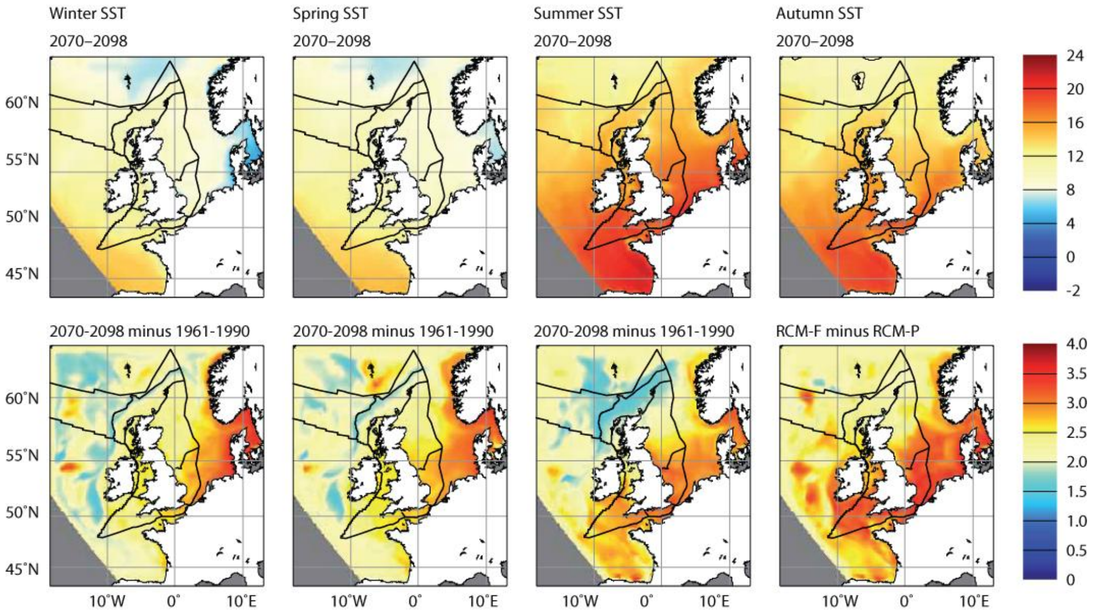


Figure 14. *(top row) Seasonal-mean sea surface temperature (SST) for 2070-2098 (deg. C) . (bottom row) Change in seasonal mean SST, relative to modelled 1961-1990 conditions. Black lines depict 'Charting Progress' regional borders. From UKCP09, Lowe et al., 2009.*

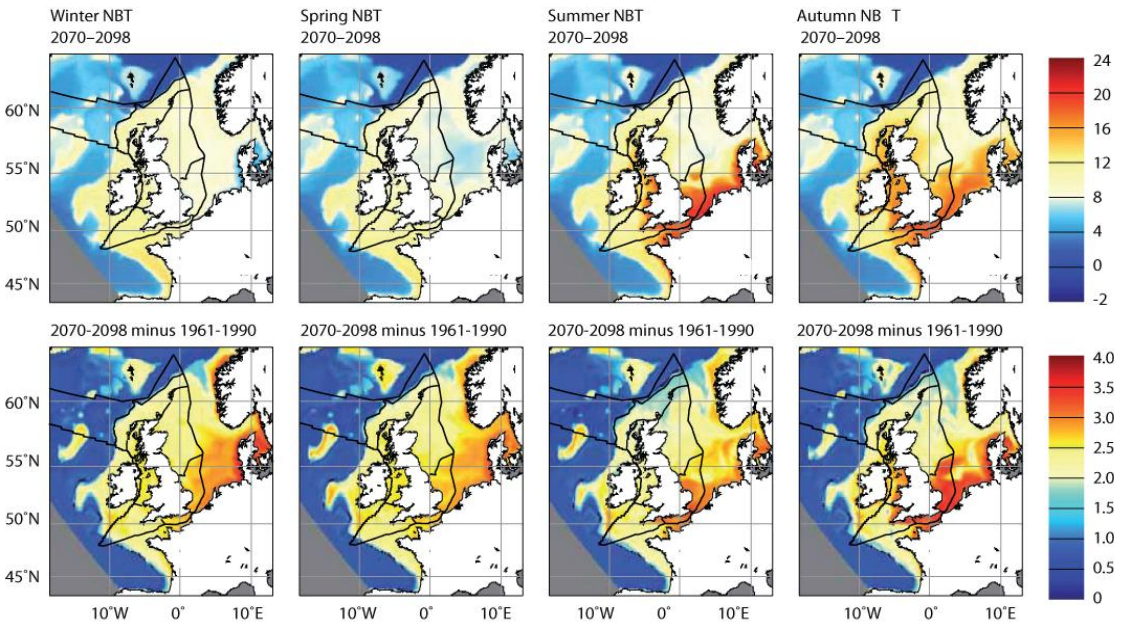
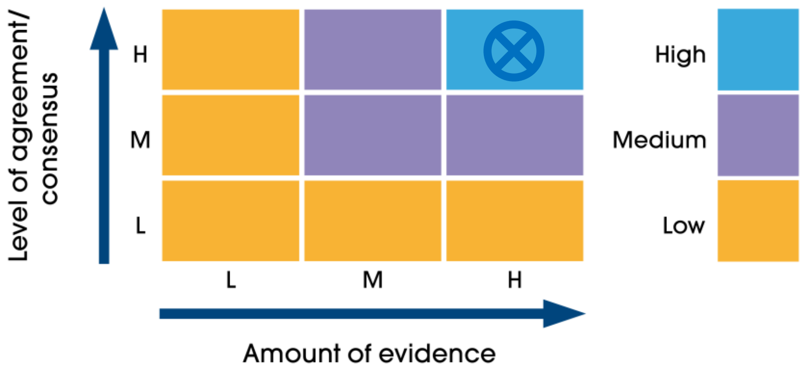


***Figure 15**. (top row) Seasonal-mean near-bed temperature (NBT) for 2070-2098 (deg. C) . (bottom row) Change in seasonal mean NBT, relative to modelled 1961-1990 conditions. Black lines depict 'Charting Progress' regional borders. From UKCP09, Lowe et al., 2009.*

3. Confidence in the science

What is already happening: **High**



Air Temperature (in-situ observations): The number of 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 16a). 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 16b).

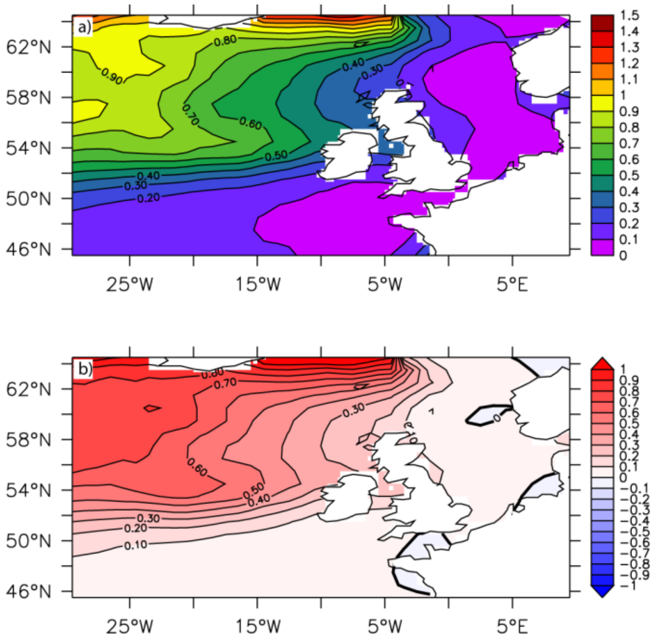


***Figure 16**: a) Average uncertainty (°C) in the monthly mean air temperature averaged over 2004 – 2008 and b) change in the uncertainty (°C) for the period 2004 – 2008 relative to 1970 – 1974.*

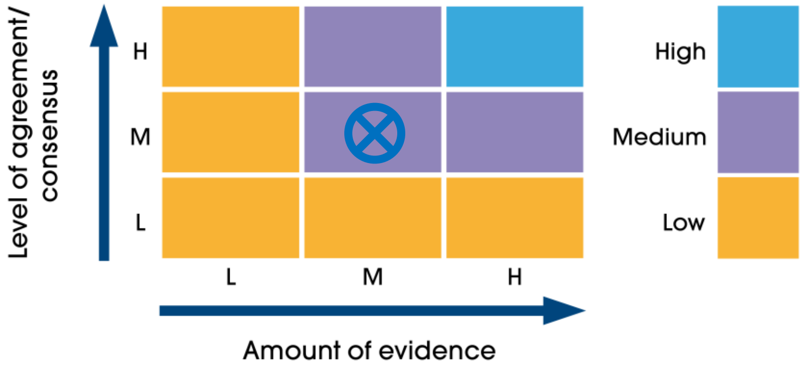
Sea-Surface Temperature (in-situ and satellite observations) The gridded SST data presented here come from the HadISST1.1 dataset. The dataset uses a combination of *in-situ* and satellite observations, gridded and interpolated to create a complete dataset. Data coverage in the area of interest is generally 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 (Kennedy *et al.* 2009; Reverdin *et al.* 2009) has shown that changes in the composition of the in situ SST observing system may cause systematic biases in the data. 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: **Medium**



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

Confidence in the global increase 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 30year period.

4. Knowledge gaps

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to be given to policy makers are:

1. 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.

2. It is of vital importance 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, especially during times when the political climate turns against ocean monitoring. Some series 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.

3. The deep ocean (deeper than about 2 km) 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.

4. 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.

5. 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.

6. References

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