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Temperature

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KEY HEADLINES

- The first MCCIP ARC in 2006 reported following what was then the warmest year globally in 2005 (0.26°C higher than the 1981-2010 average).
- Since 2005, new global record temperatures have been set in 2010 and then in each successive year 2014, 2015 and 2016. In these last three record years the global average temperature anomaly was 0.31, 0.44, 0.56°C higher than the 1981-2010 average.
- 2014 was a record warm year for coastal air and sea temperatures around the UK. Between 1984 and 2014 coastal water temperatures rose around the UK at an average rate of 0.28 °C/decade. The rate varies between regions, the slowest warming was in the Celtic Sea at 0.17 °C/decade and the maximum rate was in the Southern North Sea at 0.45 °C/decade.
- There is also variability over shorter time periods. In all regions of UK seas there was a negative trend in the 10-year period between 2003 and 2013. This is due to variability within the ocean /atmosphere system which is natural.
- There is a trend towards fewer *in-situ* observations, and this will ultimately influence the confidence in future assessments.
- Some gridded datasets can offer alternatives to single point observations, but to understand the patterns of ocean variability, the quality information from ocean time-series cannot yet be replaced by surface observations or autonomous data collection.
- The first MCCIP report card in 2006 used the UKCIP projections from 2002 which had a very limited representation of the SST.
- The latest updates to the UK Climate Projections shelf seas models were published in 2016 and projected increases in sea surface temperature for 2069-89 relative to 1960-89 of over 3 °C for most of the North Sea, English Channel, Irish and Celtic Seas. For the deeper areas to the north and west of Scotland out towards Rockall and in the Faroe Shetland Channel the increase in temperature is projected to be closer to 2 °C.
- Over the last 10 years there has been a steady improvement in the scientific basis underlying centennial sea temperature projections for the seas around the UK, and significant progress in the field of seasonal and decadal projections.

KEY HEADLINES continued

- The scientific basis to such projections and predictions will continue to improve over the next 10 years, with increasing resolution, treatment of climate uncertainties, and methodology. Over the centennial scale the difference between emissions scenarios are still the source of the largest uncertainties.
- Development of North West European Shelf (NWS) modelling systems driven by seasonal forecasting systems may allow NWS temperature prediction over the monthly to decadal period.

1. INTRODUCTION

In 2013-14 the Intergovernmental Panel on Climate Change (IPCC, 2013; 2014a; b; c) published its 5th Assessment set of reports, synthesizing the current state of understanding on climate change, its impacts and adaptation. The IPCC found that it is likely that the 30-year period between 1983-2012 in the Northern Hemisphere was the warmest in the last 1400 years. They conclude that "*the science now shows with 95 percent certainty that human activity is the dominant cause of observed warming since the mid-20th century*", and that "*warming in the climate system is unequivocal, with many of the observed changes unprecedented over decades to millennia, including warming of the atmosphere and the ocean*".

Just as the air temperature of the UK or Europe or the Northern Hemisphere might be thought of as the first order descriptor of the climate of that region so the sea temperature is the first parameter of the marine climate. It is a major driver of marine ecosystems and one of the key factors affecting the physiology and ecology of marine fish and shellfish (Pörtner and Farrell, 2008; Pörtner and Peck, 2010; Frost *et al.*, 2012). Through its control of the density of the ocean, temperature variations drive currents on scales of a few kilometres to an ocean-basin. Temperature affects the way that gases and chemicals behave and are taken up by the sea, and the stores of heat in the sea feed back into the atmosphere affecting the climate of maritime areas. Ocean temperature also affects stratification with impacts on mixing and nutrient supply.

Trends in sea and air temperature around the UK have been well described in each of the MCCIP reviews and the basic story of temperature in a changing marine climate has not changed. There are datasets and a long history of research into the surface temperature of the sea which means that we can make good assessments of the state of this part of the marine environment. Sub-surface temperature is less well monitored and, particularly in the deep ocean of the North Atlantic, fewer measurements are available, but in general there is still high confidence in our understanding of the way that the temperature of the oceans around the UK and in the Northern North Atlantic have varied over the last 50 years.

That there is a general warming trend associated with global warming is not in question but MCCIP has improved its reporting of the variability in temperature over years to decades that show up as periods of cooling or warming reducing or increasing the trend. The first report card in 2006 came towards the end of a decade of strong warming in UK seas that did not continue into the years preceding the last MCCIP report in 2013. The difference between the long-term warming trend versus decadal variability can be demonstrated in the example of the Irish Sea where the warming trend in sea surface temperature reported in MCCIP 2013 for the previous century (1904-2012) was 0.08°C decade-1 but if calculated over 20-year periods it warmed at a maximum rate of 0.7°C/decade (1985-2004) and cooled at a maximum rate of -0.3°C/decade (1968-1987) (Holt *et al.*, 2012).

Unlike the story for temperature observations, the development of information available to make temperature projections over the last 10 years has been dramatic. In the first report card, UKCIP02 (UK Climate Impacts Programme; UKCIP02) projections of SST were reported that were coarse in resolution, heavily interpolated and based on an atmospheric climate model. Projections available in 2016 are fine enough to resolve many of the processes in the UK shelf seas and use multiple runs of the shelf sea models driven by regional climate models so that we can understand variability or uncertainty in the models as temporal variability capturing the same type of variations seen in observations over the last 150 years. Additionally, there have been important developments in the capability to understand the predictability of climatic variations over periods of seasons to decades which drive change in marine climate conditions over these shorter timescales and interact with the long term trends to give the conditions that our seas experience.

As with previous MCCIP reports on temperature we focus on changes in the surface air and sea temperature as the best sampled and most used parameter of the marine climate. Changes to the subsurface temperature are also important as regions of the shelf seas stratify in the summer and the deep areas of UK waters are permanently stratified. While data are more limited we recommend that future MCCIP reports include sections on near bottom temperature but this is beyond the scope of the exercise in this 10-year review.

2. TOPIC UPDATE

Making an assessment of this type requires that we access a wide range of information and data sources. Much of this information remains the same between subsequent reports but some changes have taken place in the last 3 years which are reported on in detail below but are summarised here.

The trends in sea and air temperature around the UK have been well described in each of the MCCIP reviews. Since the last review (MCCIP, 2013) a series of cold winters have resulted in much variability in both sea and air temperature. The trend in global temperatures has not changed, however, and data from HADISST v1 (Rayner *et al.*, 2003) show that both 2014 and 2015 were particularly warm years.

Since the last review, a new gridded product (Adjusted Hydrography Optimal Interpolation - AHOI), has been developed for the North Sea region. AHOI offers an interpolated dataset of sea temperature and salinity from surface to seabed. New developments like these are very welcome and, offer opportunities for analysis that are difficult when using sparse, irregularly spaced observations.

The confidence that can be placed in the different sources of air and sea temperatures were described in (MCCIP, 2013) and these remain valid. However, all gridded products are reliant to some extent on good quality observational data. There is a trend towards fewer *in-situ* observations, and this will ultimately influence the confidence in future assessments.

For assessing future sea temperatures there have been a number of climate projections for the North Sea and wider North West European Shelf (NWS), that have been released since MCCIP ARC 2013 (e.g. Mathis and Pohlmann, 2014; Gröger *et al.*, 2015; Tinker *et al.*, 2016). The UKCP09 shelf seas climate projections have been updated as part of the Defra funded Minerva project (ME5213; Tinker *et al.*, 2015; 2016), with an improved methodology and an estimate of climate uncertainty associated with uncertain atmospheric parameters.

3. HOW HAS OUR UNDERSTANDING DEVELOPED OVER THE PAST DECADE?

This report focuses first on developments in the available datasets that are fundamental to making assessments of a changing climate in UK seas. The second section considers how developments in models have helped develop understanding what could happen in the future. Finally, as a key pillar in support of other topics considering the impacts of temperature changes we include the latest findings from the observational data sources in the report as a "What is happening?" section.

3.1 Developing understanding of "what has happened"

Observational coverage has not changed a great deal over this decade but there have been some losses of individual stations. Availability of data varies, but generally data are available with a year delay, although sometimes more recent data can be found. This has not changed to any large degree over the last 10 years.

Data sources that are most valuable are those that are routinely and reliably updated in a consistent format. Submissions for the first MCCIP Report card identified reduction in observations as a potential issue (Kent *et al.*, 2006). "*…we note that the number of observations collected, in UK waters and globally, has declined in recent years. Uncertainty in marine air temperature fields near the UK has increased by approximately 50% since the mid-1990s.*" In the following decade, a number of sites ceased as long-term continuous time-series (e.g. Port Erin, Millport Marine Biological Station, Tiree Passage Mooring).

3.2 State of the Art: Observational Datasets

Ongoing assessment of temperature for UK seas is reliant on good quality datasets for temperature but also for associated parameters and processes that are thought to affect its year-to-year variations.

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, 2016; 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). The dataset starts in 1974 and the latest update available is for 2014.

B. Sea Surface 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). This dataset starts in 1870 and as the product is updated regularly, at the time of writing data were available up to the end of 2015.

Sea surface temperatures are also available from the NOC Flux Dataset v2.0, and although the data are of a more limited time-period than gridded datasets such as HADISST1.1, the combination of both sea surface and air temperature makes this a useful dataset.

These gridded products collate, quality control and integrate sea-surface temperature from a wide range of sources including research vessels, satellites, ships of opportunity, moored platforms and drifting instruments. The resultant products allow us to use a homogeneous, spatially regular global dataset of SST over a long-term period where observation technology and coverage continually develop and change.

C. In-Situ Temperature Data

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. 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 IROC (Larsen *et al.* (eds.), 2016) was published in September 2016 covering the period up to the end of 2015 and is here after referred to as IROC2015.

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. However, ARGO floats are not designed for shallower regions and the ARGO datasets are known to be unreliable in shelf sea areas. Shelf seas do tend to have relatively good coverage due to the network of fishery and environmental surveys being undertaken, the data from which are collected in national data centres and shared with international databases such as that held at the ICES Data Centre.

A new gridded product, known as the Adjusted Hydrography Optimal Interpolation (AHOI) Dataset created from Optimal Interpolation of collected *in-situ* data in the North Sea (Núñez-Riboni and Akimova, 2015) has recently been made available (https://www.thuenen.de/en/sf/projects/ahoi-a-physical-statistical-model-of-hydrography-for-fishery-and-ecology-studies/). This data product has the advantage of covering all water column layers and includes both temperature and salinity. Whilst temperature is a key climate indicator, examining its variability in combination with changes in salinity can be useful for understanding oceanic circulation changes.

Data from new and emerging technologies such as autonomous underwater vehicles /gliders may offer reliable alternatives to vessel based observation in future; however, there are no time-series available solely from glider data as yet.

D. Climate Indices

To put the trends and observations made in the UK into context with global and regional patterns, we use several climate indices. In Table 1 we give a brief description of each index along with the source data, and where possible briefly describe how the index has varied. Figure 1 shows the evolution of these selected indices over time and was first shown in the MCCIP Report Card Reviews in 2010-11 (Hughes *et al.*, 2010) and has been updated here to include data up to 2015.

Table 1 *Sources and description of selected climate indicator timeseries for the North Atlantic as used in Figure 1.*

GISS Surface Temperature Analysis (GISTEMP) Hansen *et al.* (2010), GISTEMP Team (2017) http://data.giss.nasa.gov/gistemp/	
This Annual Mean Global Land and Ocean Temperature is used to put local and regional change in the context of global temperature. It combines surface air temperature over land with SST for the ocean.	2016, 2015, 2014 are the 3 warmest years in this global record that dates back to 1880.
Atlantic Multidecadal Oscillation (AMO) AMO v1: Enfield *et al.* (2001) www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data AMO v2: Trenberth and Shea(2006) www.cgd.ucar.edu/cas/catalog/climind/AMO.html	
This is an index of the variability in sea surface temperature in the North Atlantic. Because of the strong links in the ocean-atmosphere system, the variability of this region has been shown to be strongly linked to decadal climate fluctuations across the Northern Hemisphere (McCarthy *et. al.*, 2015) driving variability in the UK and European climate. Different versions of the AMO can be derived in different ways which attempts to remove the component of change that is due to global warming. AMO v1, Annual Mean: Uses the method proposed by Enfield *et al.* (2001), using the Kaplan SST dataset and removing the global climate signal as a linear trend. AMO v2, Annual Mean: Uses the method proposed by Trenberth and Shea (2006), using the HADISST dataset and removing the global climate signal as the mean global SST.	AMO has remained in the positive phase since the mid-1990s adding to the warming associated with long term global change.
The North Atlantic Oscillation (NAO) Hurrell (1996) https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based	
The North Atlantic Oscillation (NAO) is one of the dominant patterns of atmospheric pressure variability and has a significant impact on oceanic conditions (Visbeck, *et al.*, 2001). It affects windspeed, precipitation, evaporation, and the exchange of heat between ocean and atmosphere, and its effects are most strongly felt in winter. During winters with a strong NAO Index the ocean responds quickly and the effects can continue throughout the following year. The Hurrell winter (December-March) NAO index is used to describe the state of the NAO. For the UK seas NAO negative winters tend to be colder than average, with easterly winds bringing particularly cold conditions over the North Sea. NAO positive winters are generally warmer for the UK but also 'windier' and 'wetter' through its relationship to the storm track. Waters to the north and west tend to mix to greater depth during NAO positive winters, mediating the effect of a warmer airflow on the SST.	All but one of the last five winters 2012-2016 have had a positive NAO index. 3 of these winters had strong positive index values above 3 (measured in standard deviations) while the winter of 2013 experienced a strong NAO negative winter (-1.97). This contrasts with the 5 years leading up to the first MCCIP ARC in 2006 which had experienced weak NAO index winters.
The Sub-Polar Gyre index (SPGI)- Berx & Payne (2017) http://data.marine.gov.scot/dataset/sub-polar-gyre-index	
The sub-polar Gyre is a key circulation feature in the North Atlantic and its expansion and contraction are linked to warming and cooling phases as well as changes in the strength of important currents in the North Atlantic system (Hátún *et al.*, 2005). When the SPGI is negative, oceanic water to the west of the UK tends to be warmer and saltier as subtropical water is more influential.	The SPGI peaked at the start of the 1990s and has reduced considerably since then. The index has been negative for the last 10 years. The new Berx and Payne (2017) SPGI suggests the index has reduced further in the last 5 years.

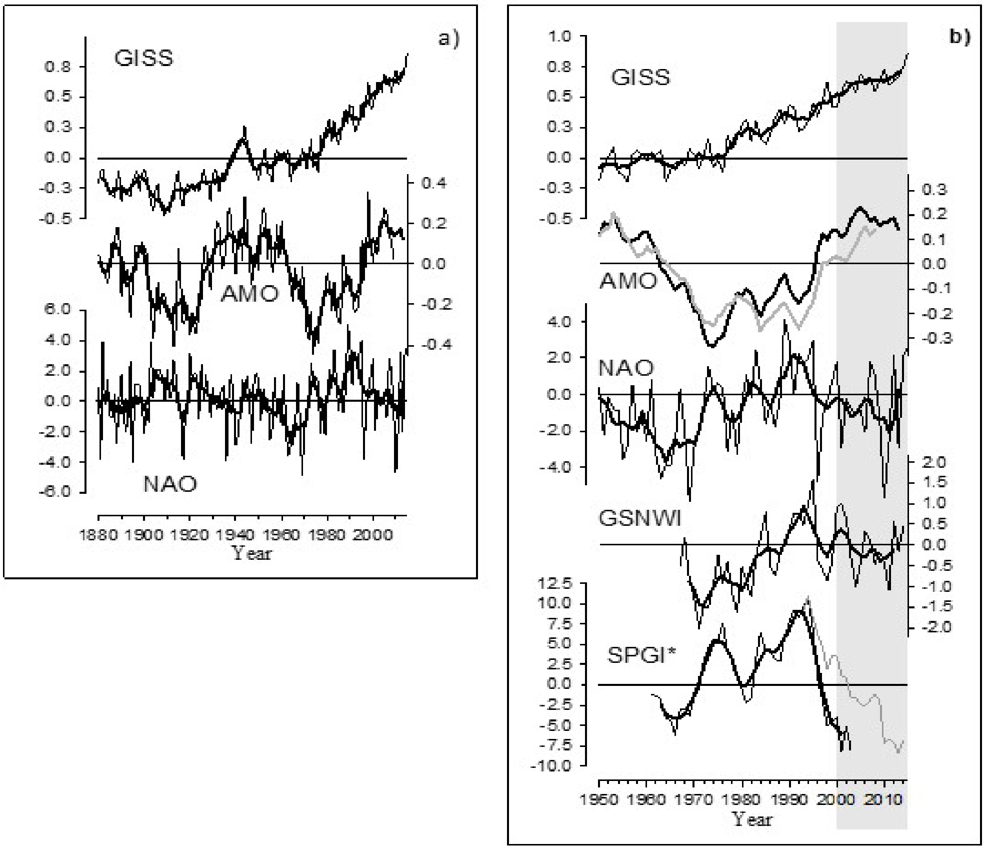

Figure 1*: Selected indicator timeseries for the North Atlantic. This figure was first published in Hughes et al. (2010) and has been updated here to include data up to 2015.*

Panel a) Data period 1880-2015, anomalies referenced to the long term mean. Global Land and Ocean Temperature (GISS), The Atlantic Multidecadal Oscillation (AMO v1 in black) and the North Atlantic Oscillation (NAO). Thin black lines show annual values, thick lines are 5-year running mean values.

Panel b) Shorter Timeseries over period 1950-2015, anomalies referenced to the 1981-2010 mean. Global Land and Sea Temperature (GISS), The Atlantic Multidecadal Oscillation (AMO v1 in black and v2 in grey) and the North Atlantic Oscillation (NAO), The Gulf Stream North Wall Index (GSNWI) and the Sub-polar Gyre Index (SPGI). Thin lines show annual values, thick lines are 5-year running mean values. The grey line shows a preliminary gyre index as obtained from altimetry observations (1992-2014, Berx and Payne, 2017), this is shown only for comparison of trends; the absolute values of the two indices cannot be directly related.

3.3 Developing understanding of "what could happen"

MCCIP and UK Climate Projections

The UK government has funded a series of national climate projections over the years, which have incrementally improved the treatment of the marine environment, and their handling of uncertainty. Over the past 10 years, since the launch of MCCIP, there have been two sets of these national climate projections in use, UK Climate Impact Projections 2002 (UKCIP02, 2002) and UK Climate Projections 2009 (UKCP09, 2009). In this period, there have been four MCCIP report cards dealing with temperature. The first two MCCIP report cards (2006, 2007/8) were based on UKCIP02. The next report card, 2010/2011 was based on the next UK Climate projections UKCP09, while the latest MCCIP report card (MCCIP, 2013) added discussion of a number of other climate projections from the literature.

UKCIP02 ran a global climate simulation with European regional atmospheric downscaling for four emissions scenarios. These were used directly to project North West European Shelf seas (NWS) SST change for three periods, relative to the baseline. SST change was effectively prescribed by the HadCM3 ocean, and so was at a very coarse resolution, and took no account of tides, which are an important shelf seas process.

For UKCP09, the underlying climate modelling procedure was greatly improved (relative to UKCIP02), in terms of model resolution and treatment of uncertainty. A Perturbed Physics Ensemble (PPE) was run to capture the effect of uncertain parameters within the GCM. This, together with the Multi-Model Ensemble (MME) from the CMIP3 models, allowed a quantification of most of the dominant sources of uncertainty for many terrestrial parameters. UKCP09 had a dedicated marine component, which included temperature projection for the NWS within a section on changes to the shelf seas hydrography and circulation (Lowe *et al.*, 2009). This analysis was made by downscaling two time-periods from a single ensemble member from the UKCP09 PPE with a shelf seas model (POLCOMS). In addition to the higher spatial resolution, this shelf seas projection included important shelf seas processes (tides) neglected in the global simulations. This allowed realistic climate projection for the NW European shelf seas to be made. However, only one ensemble member of the PPE was downscaled, and only as a single pair of time slices (1960-1989 and 2070-2099) for a single emission scenario: while the methodology was significantlyimproved, there was no treatment of uncertainty..

The UKCP09 shelf seas projections have been significantly updated, with an improved methodology, transient experiments, and a quantification of an important aspect of uncertainty (Tinker *et al.* ,2015). Tinker *et al.* (2015) used the same shelf seas model (POLCOMS) to downscale all 11 members for the PPE, as transient simulations (running from 1952-2098). The ensemble spread allows estimates to be made of the uncertainty associated with uncertain parameters within the GCM atmosphere, while the transient experiments (rather than time slice approach of UKCP09) allow an assessment of how robust the projected changes are, given the presence of low-frequency climate variability. These data have been released as part of the Defra funded MINERVA project and are reported by Tinker *et al.* (2016; see Figure 2). In these model runs the ensemble mean projected rise in temperature for 2069-89 relative to 1960-89 is over 3 °C for most of the North Sea, English Channel, Irish and Celtic Seas. For the areas to the north and west of Scotland out towards Rockall and in the Faroe Shetland Channel the rise in temperature is projected to be closer to 2 °C.

3.4 Other NWS sea water temperature projections of the last 10 years.

There have been a number of studies presenting climate projections for the NWS over the last 10 years, and here we briefly describe them. With Figure 3 we illustrate the comparison between their resolutions and domain size, alongside total number of years simulated.

Meier (2006) undertook one of the first regional seas climate projections for the Baltic Sea. They downscaled two GCMs (HadCM3 and ECHAM4) under two emission scenarios (SRES A2 and B2) for the Baltic Sea; however, their model domain did not extend into the wider NWS. The first climate projections for the North Sea (part of the NWS) was undertaken by Ådlandsvik (2008) who provided a single realisation of the future climate (2072-2097) in the North Sea, under the SRES A1B scenario. Ådlandsvik (2008) downscaled the AR4 model BCM and compared it to a previous consistent study downscaling the same climate model forced with observed forcings (Ådlandsvik and Bentsen, 2007).

More recently, Olbert *et al.* (2012) have produced projections specifically for the Irish Sea, focusing on changes in temperature, structure, circulation and sea level (not salinity). They downscaled a transient model run (1980-2100) of the global ocean model MPI-OM, forced by (rather than coupled to) the global atmosphere model ECHAM5 run under the SRES A1B scenario. MPI-OM was run with an enhanced resolution over Europe, with a horizontal resolution of 15km over the Irish Sea, allowing the shelf seas model ECOMSED to be run at a high resolution (1.5 x 2 km

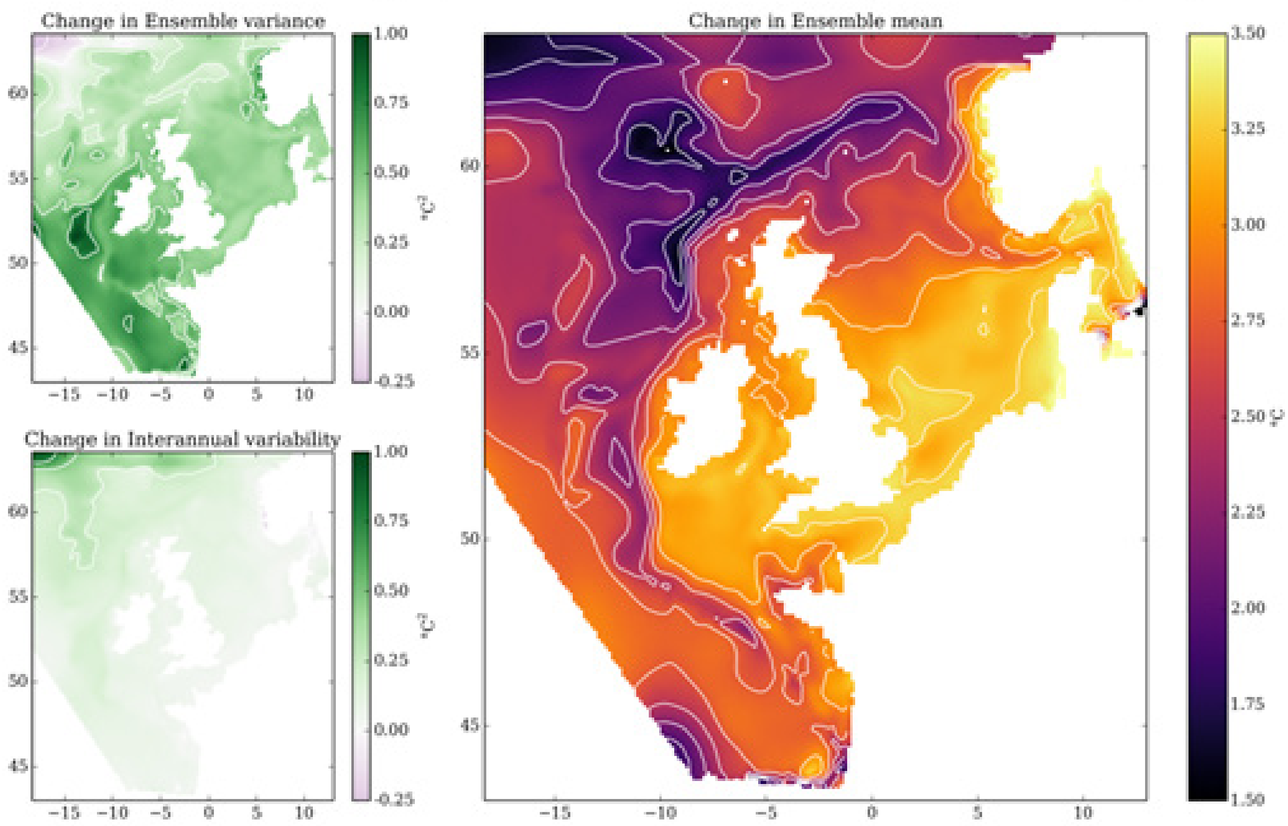

Figure 2: *Projected SST change (right): the annual mean change in SST is calculated between two 30-year mean periods representing the near present day (1960-1989) and the end-of-century (2069-2089). The increase in ensemble variance (upper left) over the same period shows how the spread associated with model parameter uncertainty increases – this is greater than the change in inter-annual variability over the same period (lower left), which is fairly constant. Adapted from Tinker et al. (2016).*

model ECOMSED to be run at a high resolution (1.5 x 2 km horizontal resolution with 21 s-levels). The high resolution, with the use of transient model runs, was an improvement on previous studies, in that it provided timeseries of impact of climate change, and so allowed the change signal to be isolated from inter-annual (and longer) variability. No account of emissions uncertainty, model resolution, model selection or other aspects of uncertainty was taken.

A study by Friocourt *et al.* (2012) focused on ecosystem changes in the North Sea by the 2040s. They dynamically downscaled ECHAM5 under the SRES A1B scenario with two region ocean models (Delft3D and NORWECOM) for the North Sea. There were several complications with domain size (with the northern boundary within the North Sea) and the validity of the GCM modelled ocean forcings on the shelf, so present day ocean forcings were used for the future period for one of the models. However, despite the methodological challenges, this study did attempt to quantify additional aspects of uncertainty.

Gröger *et al.* (2012) took a different approach to providing climate projections for the North West European shelf. Rather than nesting a shelf seas model within a global ocean, they used a global ocean model with stretched grid to give increased resolution over Europe (~10km in the German Bight). Their global ocean model was modified to include tides, and so was pertinent to the simulation of shelf seas. They drove this ocean model by atmospheric forcings from a consistent but separate GCM rather than as a coupled ocean-atmosphere model. They ran transient simulations, from pre-industrial period to the end of the 21st century (1860 – 2100, under the SRES A1B emissions scenario) and a climate control simulation with repeating 1860 radiative forcings (although this is not a free running pre-industrial control run with unforced climate variability). They made no attempt to assess uncertainty in their projections – indeed with their complex ocean model set up, they identify the difficulties in forcing their model with different atmospheric models forcings. Their approach of enhanced resolution compared to nesting models was designed to remove the uncertainty associated with model edge effects, and they included an interactive Baltic Sea.

A recent study by Mathis and Pohlmann (2014) ran a single transient climate simulation for the North Sea, running from 1951-2099. They downscaled the global climate model ECHAM5/MPIOM with the shelf seas model HAMSOM at a 3km resolution. They bias-corrected the forcings, and used their resulting 150-year time-series to estimate the robustness of their results, using a median regression analysis. They compared their results with those of Ådlandsvik (2008) and Holt *et al.* (2010) thus adding to the literature based ensemble of opportunity.

Few of these climate projections cover the full NWS, most focus on specific areas, with many concentrating on the North Sea. Here we briefly show how North Sea annual mean SST projections, from the literature, have evolved over the last 10 years. There are a number of complications with this as each study defines the North Sea differently and some do not even give a clear value. Furthermore, if warming is not linear, the period spanned by the projection is important, and this varies from study to study.

This multi-model ensemble of opportunity should not be treated like the CMIP MME as there is no underlying experimental design. It is difficult to use it to draw conclusions about the most likely rate of warming for a number of reasons: there are varying levels of independence between the different simulations due to the use of common GCM forcing, or down-scaling models; there are different time periods involved (likely to be have an influence if the rate of warming is not constant), there is a range of complexity in model set up, and no attempt has been made to assess comparative model skill. It is also difficult to use the multi model ensemble to assess the range of uncertainty, as it includes a number

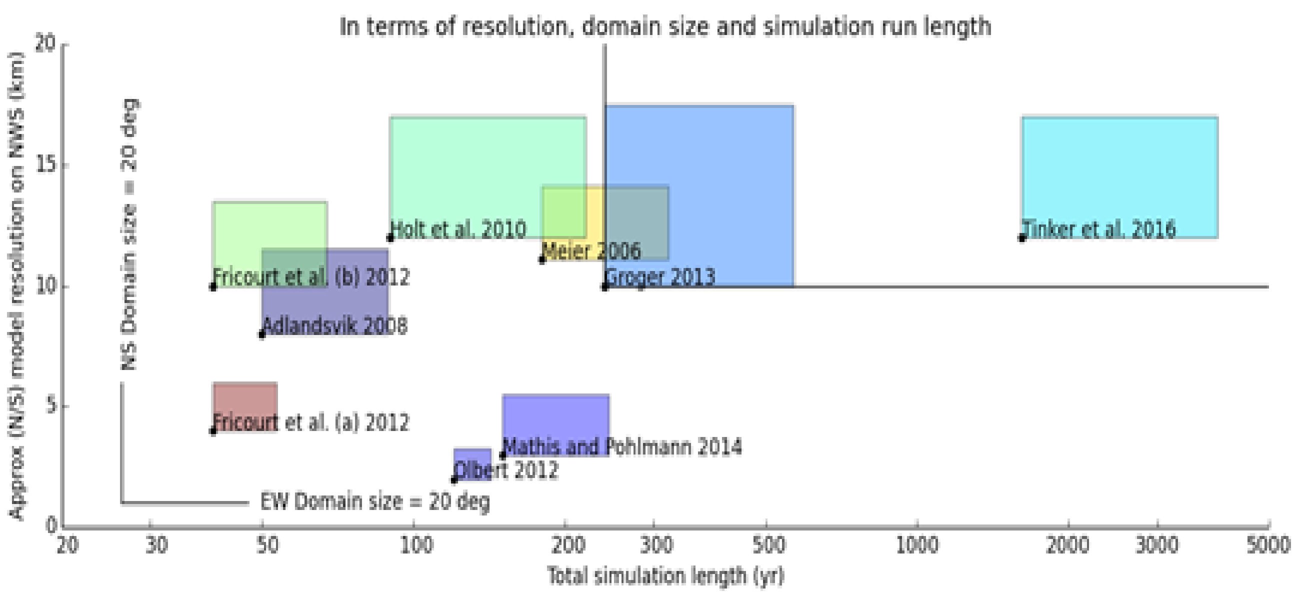

***Figure 3**: Comparison of modelling systems used to make climate projections for the NWS (in terms of model resolution and domain size) and total number of years simulated. For each modelling system, the black dot in the lower left hand corner shows the model resolution (km) and the total number of years simulated (i.e. the sum of the two time slices, number of years in the transient simulation, total years across the ensemble). The coloured box associated with each modelling system denotes the domain size compared to the scale bars (in the lower left hand side of the plot) denote 20° latitudinal (longitudinal) extent in for the vertical (horizontal) bar. The black lines extending up and right of Gröger et al. (2013) illustrate the model is global. Friocourt et al. (a) (2012) represents the Delft3d model (with spatially-varying resolution 2-20km) and Friocourt et al. (b) (2012) represents the NORWECON model. (Numbers taken from Meier 2006; Ådlandsvik 2008; Holt et al. 2010; Friocourt et al. 2012; Olbert et al. 2012; Gröger et al. 2013; Mathis and Pohlmann 2014; Tinker et al. 2016).*

of sources that are treated to varying degrees. However, given these caveats, the ensemble of opportunity suggests a range of North Sea SST warming of ~0.09-0.32°C/decade, and if we only consider simulations of ~100 years (excluding the shorter simulation of Friocourt *et al*. (2012)) we reduce this range to ~0.17 to 0.325°C/decade.

3.5 Seasonal to Decadal Prediction

The evolution of temperature within the UK seas is not smooth and through the last 10 years MCCIP has reported on the influence of variability in the marine climate over years to decades on top of the global warming trend. Looking forward over these shorter sub-centennial timescales becomes an issue of prediction rather than projection as the uncertainty associated with greenhouse emission is not so important and the prediction period is relatively close to the known starting conditions. Over the past 10 years there have been significant improvements in the field of seasonal and decadal forecasting. Ten years ago there was very little skill in forecasting at these longer time periods outside the tropical regions. We now have statistically significant skill in seasonal predictions of the European winter through predictability of the winter North Atlantic Oscillation (NAO) (Scaife *et al.*, 2014; see Figure 5), Arctic Oscillation (AO), and Sudden Stratospheric Warming (SSW) events (Scaife *et al.*, 2016). Recent results published by the Met Office suggest that there is even significant skill in predicting the winter NAO index one year ahead (Dunstone *et al.* 2016) with a correlation coefficient (r) between observed NAO and predicted of about 0.4 for the second winter comparing well with that of about 0.6 for the first winter as described in Scaife *et al.* (2014).

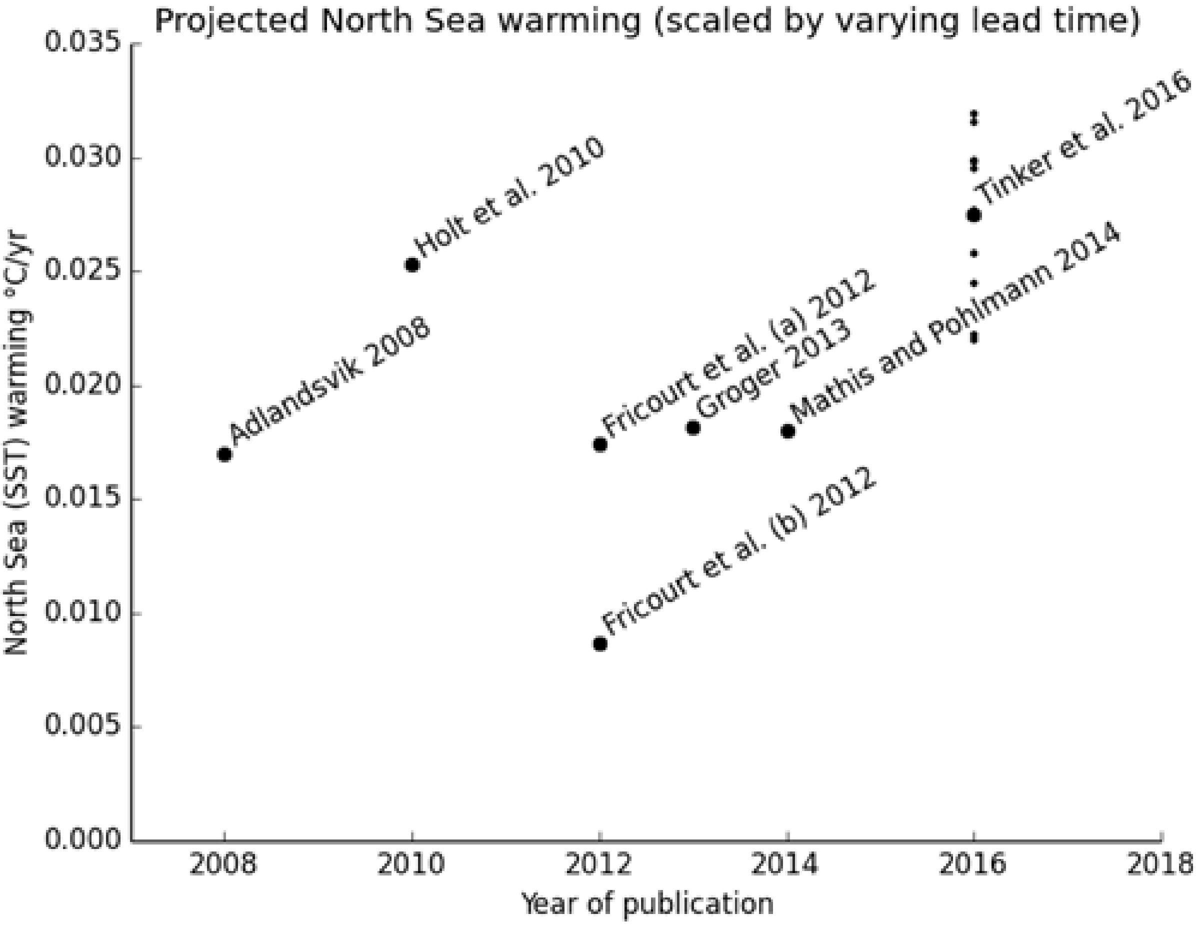

Figure 4: *Comparison of SST projections for the North Sea in terms of a warming rate plotted against the publication date. Most studies used give a North Sea temperature projection for a given period. The North Sea region was extracted from the wider NWS domain for Holt et al. (2010) and Tinker et al. (2016). Friocourt et al. (2012) say there models project between 0.4°C and 0.8°C from the southern North Sea – these values have been used. Gröger et al. (2013) find about 2K warming over the 21st century - we have used the 1960-1990 and 2070-2100. Mathis and Pohlmann (2014) report increase in SST as a rate (°C/100 yrs). The ensemble mean from Tinker et al. (2016) is given, with the 11 individual ensemble members given in small dots. Note that the rate of warming may not be linear – if the rate of warming is accelerating, the rate of warming between the present day and mid century (i.e. Friocourt et al. (2012)) would be less than that between the present day and the end of century.*

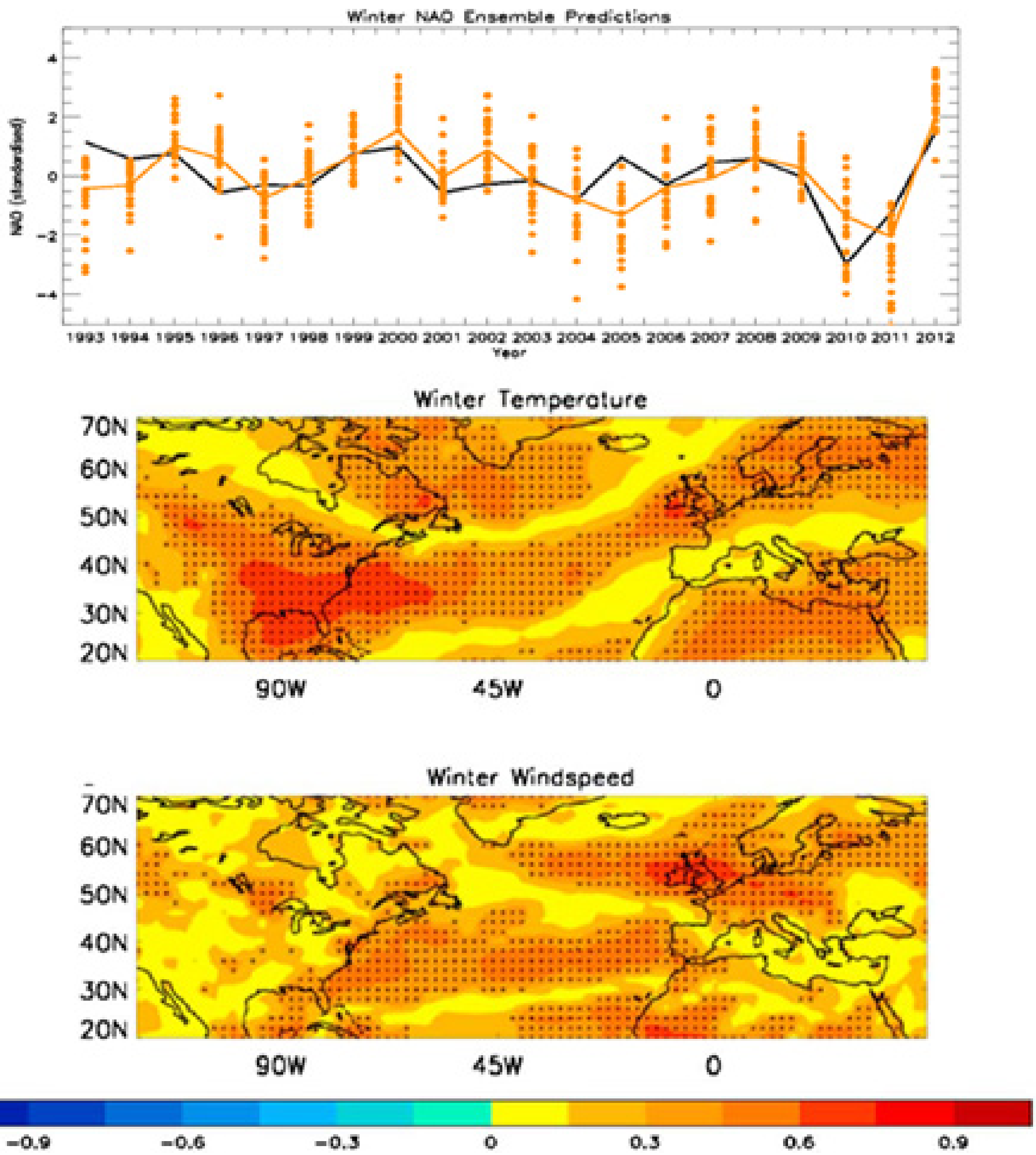

Figure 5*: Ensemble prediction of the NAO index (top panel) and correlation between predicted NAO index and winter conditions in the North Atlantic (middle & lower panel). Ensemble prediction of the winter NAO (top panel) from the preceding November (orange line ensemble mean of orange dots) versus the observed winter NAO index (black line). Temperature (middle panel) and Wind speed (lower panel) – stippling indicates areas where the correlation has statistical significance (above 90%).*

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http://onlinelibrary.wiley.com/doi/10.1002/2014GL059637/full#grl51580-fig-0001

http://onlinelibrary.wiley.com/doi/10.1002/2014GL059637/full#grl51580-fig-0004

On multi-annual time-scales, predictability of the state of the sub-polar gyre has been demonstrated in, for example, Hermanson *et al.* (2014). Their analysis found that initialisation (in simple terms beginning the model with observed conditions) improved the correlation between hindcasts and observations on a 5-year average basis (Figure 6), allowing them to make a prototype 5-year forecast of the North Atlantic temperature. This level of skill lending predictability to aspects of the European climate that are correlated to upper ocean temperature.

Model initialisation is essential for seasonal and decadal forecasts, for example, the presence or absence of a heat reservoir in the upper ocean can affect the phase of the variability over the following months to years. On short time scales, the atmosphere drives the ocean, but on these longer timescales, the ocean drives the atmosphere, and so the ocean provides memory to the system, and so predictability.

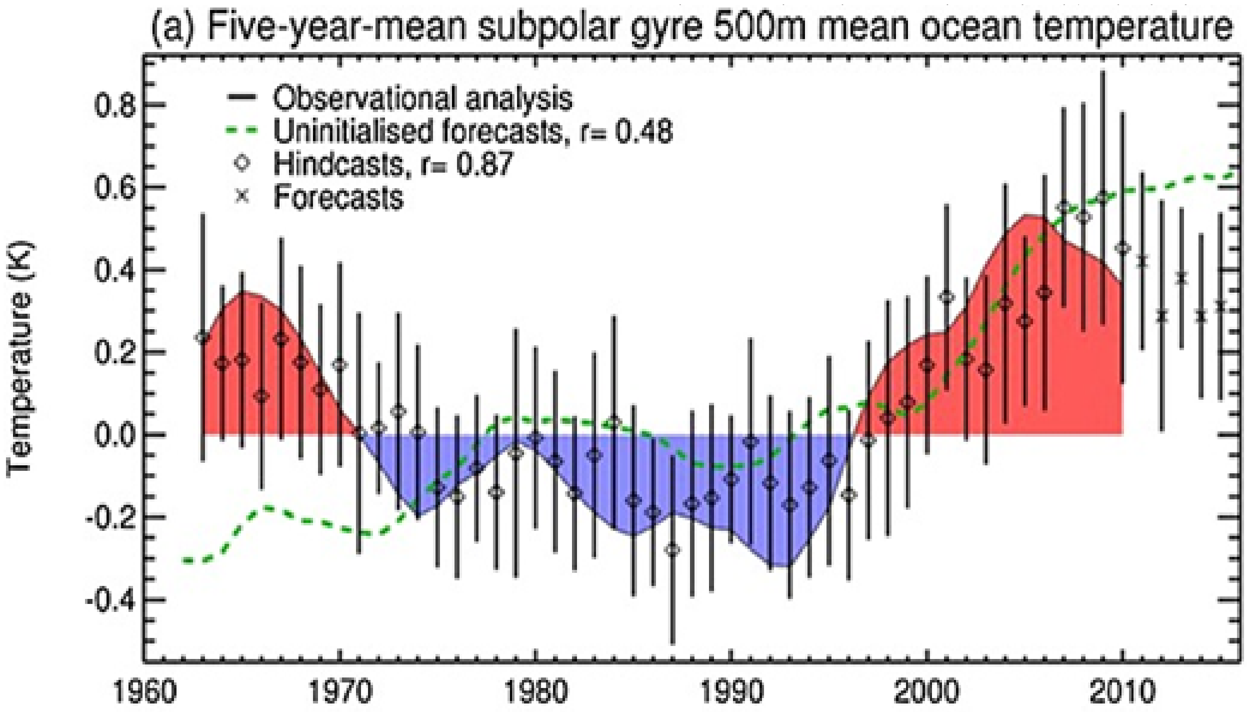

***Figure 6**: The 5 year (centred) mean temperature anomaly of the sub polar gyre (upper 500m). Comparing the hindcasts, uninitialized "forecasts", forecasts and observational analyses. Error bars give the 90% probability spread of the hindcasts/forecasts. Reproduced from Hermanson et al., (2014) Crown Copyright – Reproduced under CCBY Open Access.*

Early work on decadal prediction focused on understanding how and where model initialisation was important. The Atlantic Meridional Overturning Circulation (AMOC) is a key process for the predictability in the European region, with research over the last 10 years focusing on understanding the underlying processes, and improving our ability to predict it. The RAPID array was deployed in 2004, to measure the AMOC at 26.5°N. This array has now provided 10 years of data, allowing AMOC predictions to be validated and improved over several years (see the accompanying MCCIP report on AMOC; McCarthy *et al.,* 2017).

4. WHAT IS HAPPENING

A. Marine Air Temperature

Figure 7 shows the 30-year trend (1986 – 2015) in marine air temperature (°C/decade) estimated from NOCv2.0 for the Northeast Atlantic and UK waters. The average warming rate over UK coastal waters for this period was 0.26 °C/decade. The warming is greatest in the Atlantic Northwest Approaches (outermost area of Charting Progress Region 8) with warming rates of 0.3-0.4 °C/decade. Similar rates of warming are found over the Southern North Sea (Region 2) and to the north-west of Scotland (Regions 6 and 7) with warming rates between 0.2 – 0.4 °C/decade. The cold years of 2010 and 2013 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). The lowest significant trend is in the Celtic Sea at 0.09 °C/decade. Over the last decade there has been little significant trend. 2014 was a very warm year (Figure 8), with higher than normal temperatures observed in all months except July.

B. Sea Temperature

Global average surface temperatures continue to rise, and prior to 2016, 2015 was the warmest year on record (GISTEMPteam, 2017). The surface temperatures of the North Atlantic have a similar temperature trend, although variability in this region of the ocean has previously been noted as higher than in the global temperature trend (Hansen *et al.*, 2010). The evidence we use to report on variability of the sea temperature across the North Atlantic region is available in gridded datasets such as HadISST but also in the station based time-series that are assembled together with an assessment of upper ocean climate across the Atlantic every year in the ICES report on Ocean Climate (IROC2015).

Any warming in the Atlantic due to anthropogenic effects is superimposed onto a 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; Ting *et al.*, 2009; Swanson *et al.*, 2009; Cannaby and Hüsrevoğlu, 2009). Despite the uncertainty in calculating the AMO versus a long-term trend, its variability reveals that relative to the underlying global average 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. The AMO has been in a warm phase from 1990 to present (AMO, Figure 1), however, there is evidence that large regions of the central North Atlantic have been cooler in 2014 and 2015 (IROC2015).

In UK Coastal Waters the sea temperature is on average 0.85°C higher than the air temperature above it (calculated form NOCSFlux2.0 for the period 1981-2010) but the general trend and variation in temperature in the atmosphere and sea are broadly similar (Figure 8, 9).

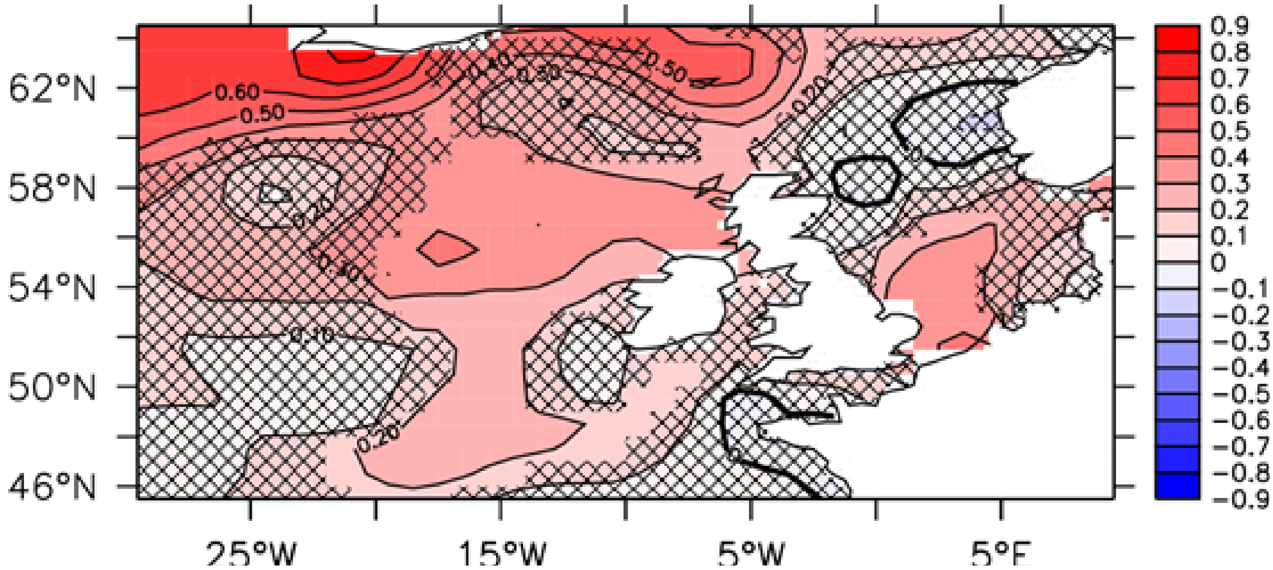

Figure 7: *30-year linear trend for marine air temperature estimates from NOCv2.0 for the period 1986 – 2015 (°C/decade). Hatched areas have a slope which is not significant at the 95% confidence level (alpha=0.05) using Mann-Kendall non-parametric test for a trend.*

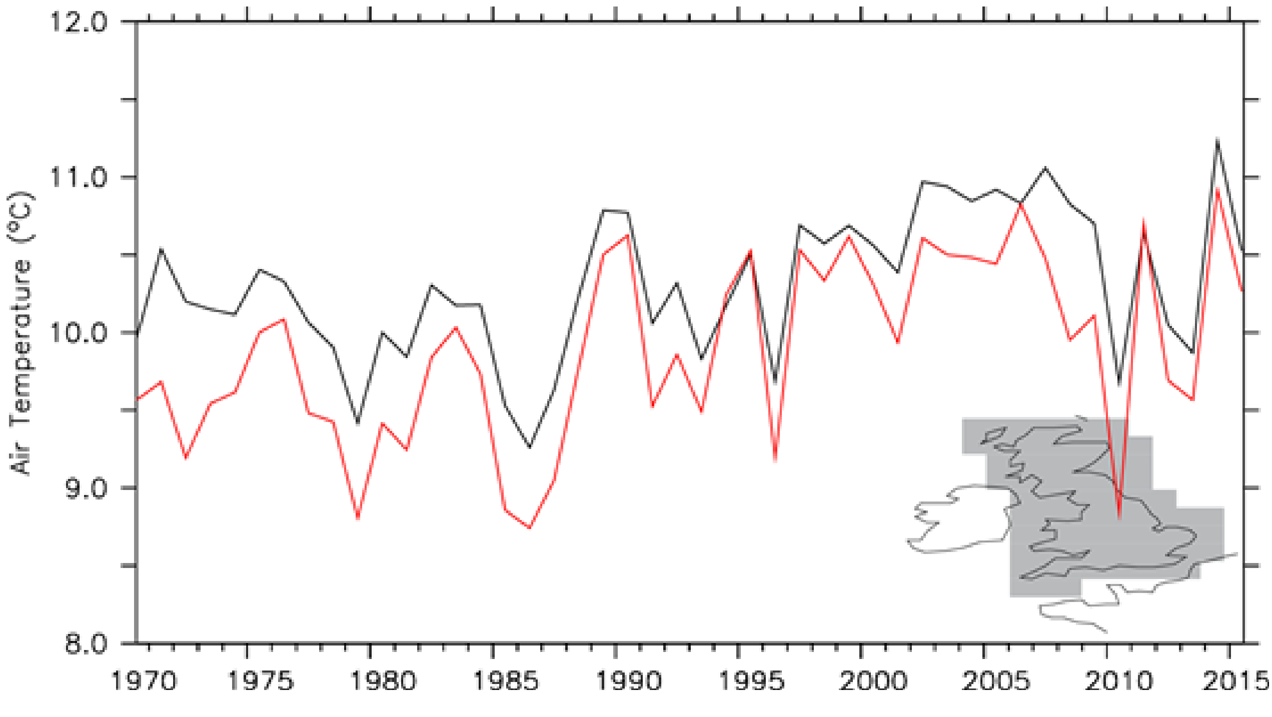

Figure 8: *a) Annual mean air temperature estimates from NOCv2.0 above UK Coastal waters (black) and the Central England Temperature (red). b) Inset map shows the grid locations used define UK Coastal waters.*

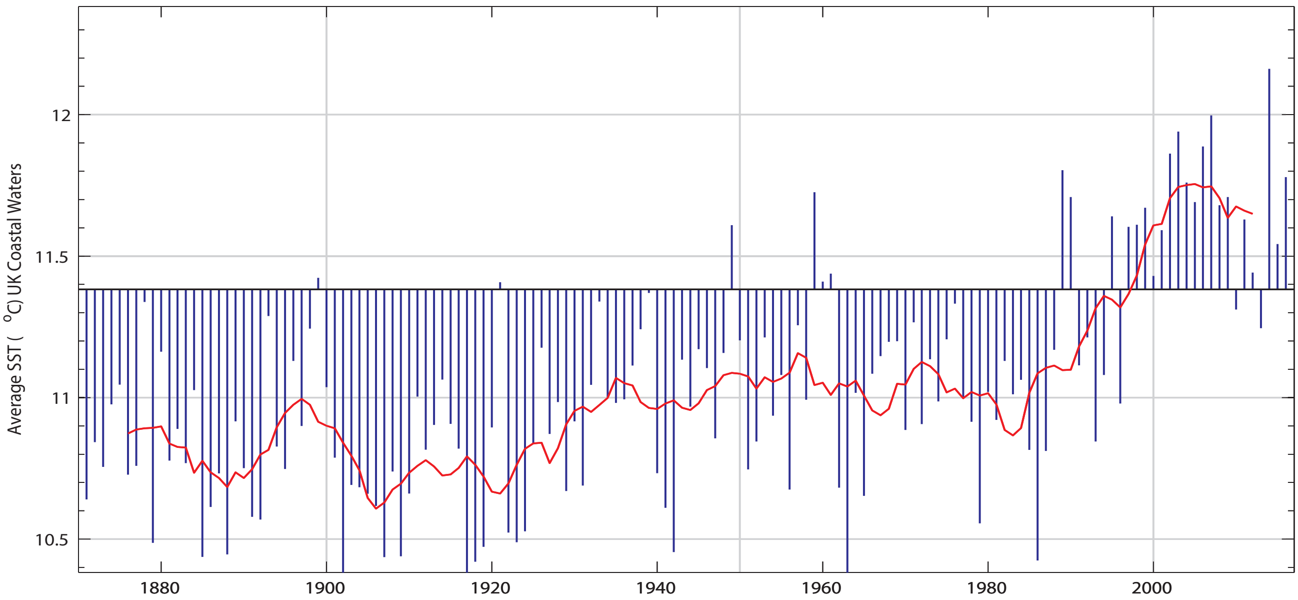

***Figure 9**: Time series of average SST in UK coastal waters (the area defined in Figure 8b) for period 1870 to 2016. The blue bars show the annual values relative to the 1981-2010 average and the smoothed red line shows the 10-year running mean. Data are from the HadISST1.1 data set (Rayner et al., 2003).*

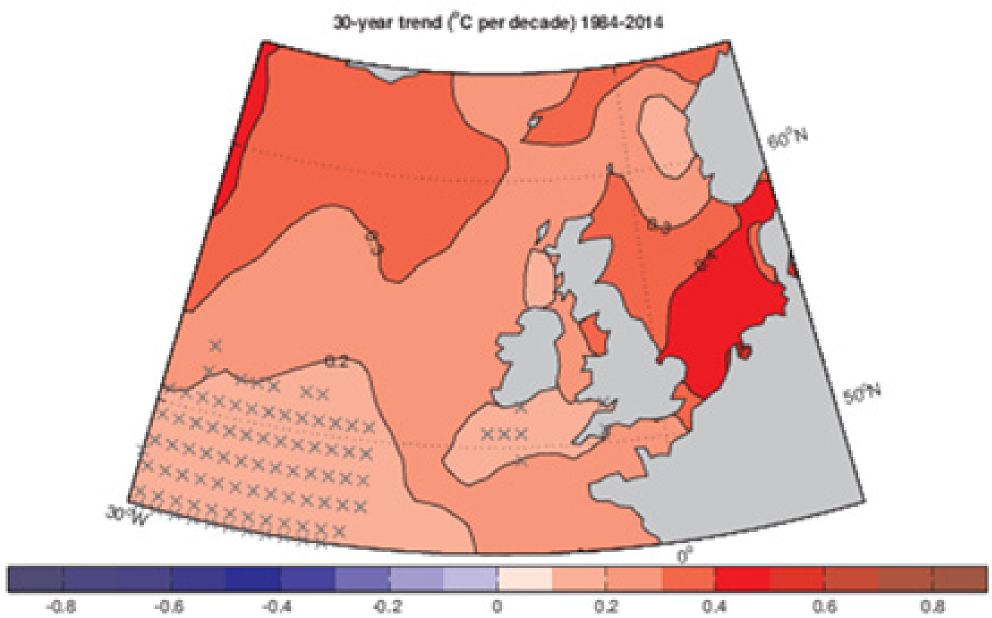

***Figure 10**: Trend in annual average sea-surface temperature (°C/decade) from 1984 to 2014. Data are from the HadISST1.1 data set (Rayner et al., 2003). Hatched areas have a slope which is not significant at the 95% confidence level (alpha=0.05) using Mann-Kendall non-parametric test for a trend.*

Using the Hadley Gridded Sea Surface Temperature dataset (HADISST1.1) the regional trends in sea surface temperature have been examined. The warming trends for this period are slightly reduced compared to those presented in previous assessments (MCCIP, 2013) and this is the result of several cooler years. Since the end of the 1990s, the annual UK coastal-average SST has been higher than the 1981-2010 average in all years except for 2010 and 2013 (Figure 9). Over the last 30 years (1985-2014, Figure 10), on average coastal sea surface temperatures have been warming at a similar rate (0.28 °C/decade) to the air temperatures (0.26 °C/decade). The strongest trend in sea surface temperatures has been in the southern North Sea (Region 2) with warming rates of 0.45 °C/decade. In the northern North Sea (Region 1) and Atlantic Northwest Approaches (outermost area of Region 8), sea surface temperatures have been warming at a rate of between 0.3 and 0.4 °C/ decade. The slowest warming of 0.17 °C/decade was in the Celtic Sea.

Following the same pattern as the coastal average air temperatures (Figure 8), in UK Coastal waters, 2014 was an extremely warm year (Figure 11), with temperatures in all months above the long term mean (1981-2010). The spring/early summer period was particularly warm and June and July, as well as November temperatures were the highest on record (since 1870).

In order to examine variability between various UK regions, average values have been calculated for each of the 8 UKMMAS Charting Progress (CP2; UKMMAS 2010; see www.mccip.org.uk/annual-report-card/2013/regional-snapshots) reporting regions. Variability differs between regions and this can make direct comparison of temperature change difficult. To assess annual variations in each region, normalised anomalies have been prepared. This methodology offers a description of the temperature change relative to the variability, so, for example, a year can be characterised by the number of standard deviations higher/lower than normal for that region, rather than quoting absolute values for temperature change. Regional anomalies from HADISST1.1 are presented in Figure 12, and from the *in-situ* timeseries in Figure 13.

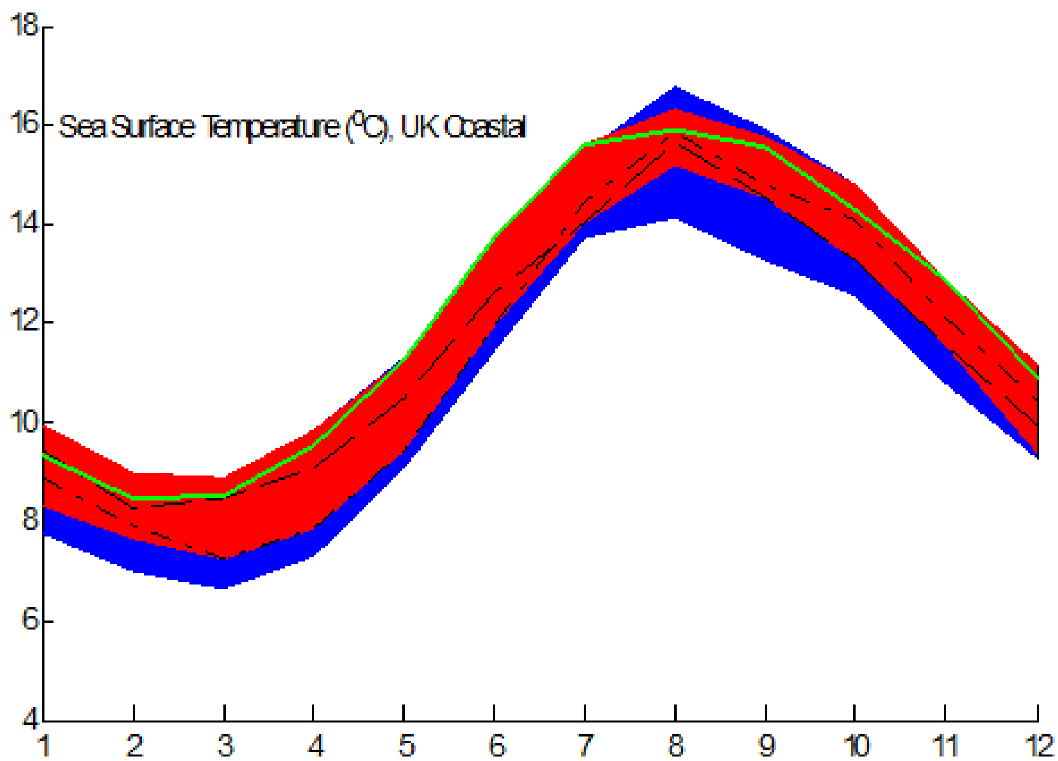

Figure 11: *Monthly mean sea surface temperatures for UK coastal waters (°C) (for definition see Figure 8b) from the HadISST1.1 dataset. The range of temperatures from the period 1981-2010 is shown in blue; the range of temperature for the decade (2005-2014) is shown in red. Data for 2012 is plotted as a dashed line, 2013 as a dash-dot line. The data for 2014 are shown in green.*

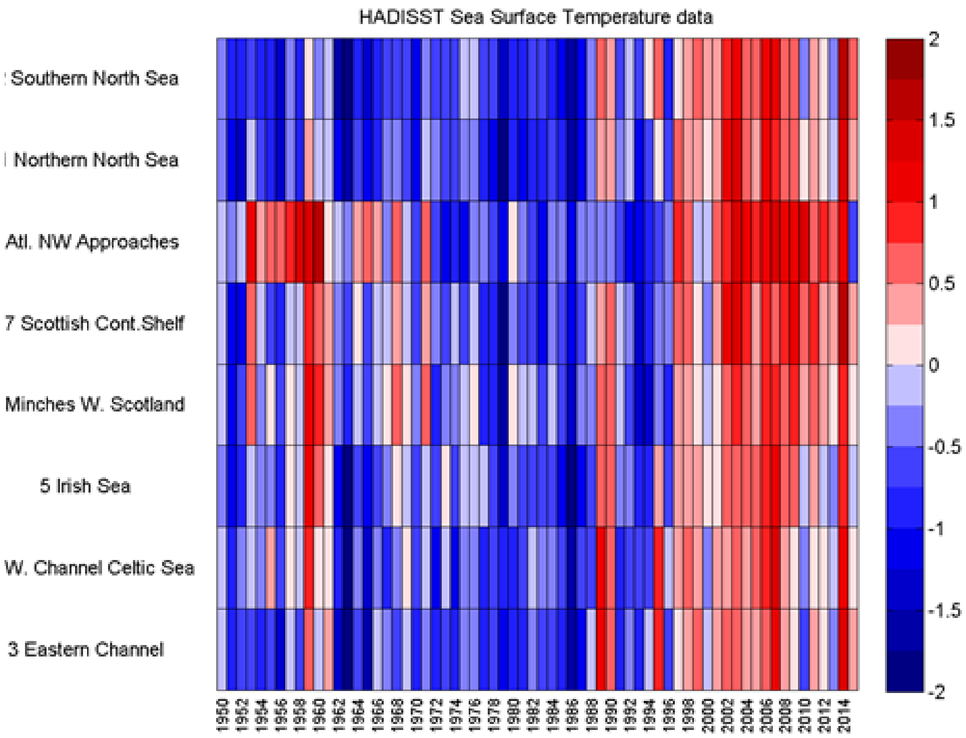

Figure 12: *Anomaly plots for sea surface temperature anomaly (°C) calculated from HADISST v1 for the period 1950-2015. Anomalies are calculated relative to the period 1981-2010 and are normalized with respect to the standard deviation (e.g. a value of +2 indicates 2 standard deviations above normal). Colour intervals 0.5; reds = positive/warm; blues = negative/cool.*

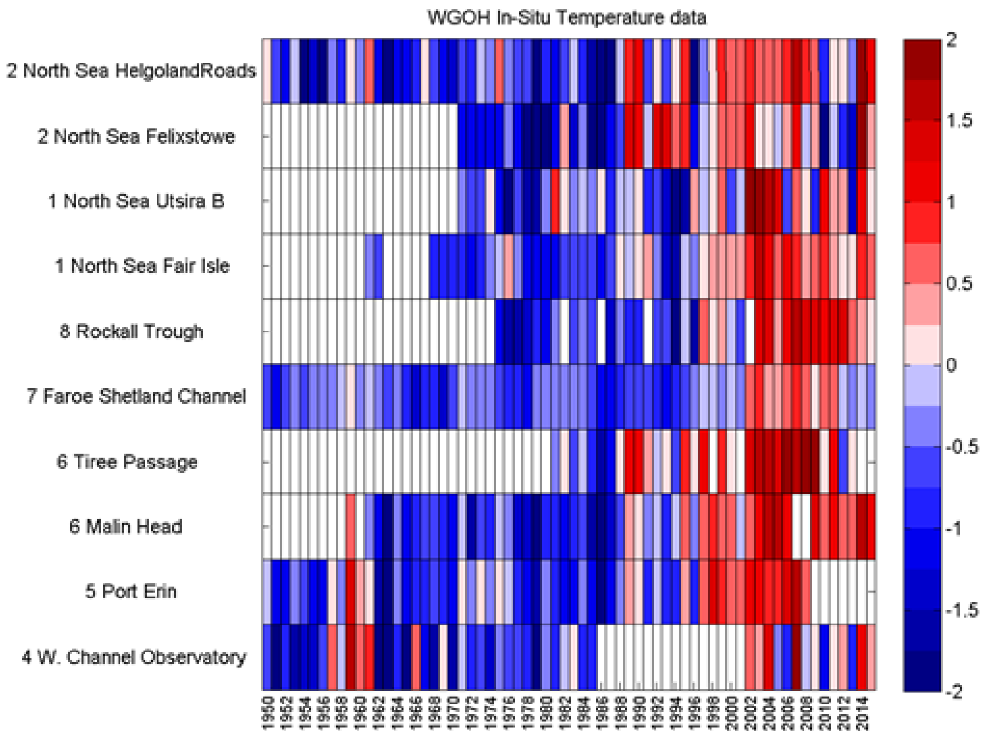

Figure 13: *Anomaly plots for sea surface temperature anomaly (°C) calculated from selected in-situ timeseries, as published in the IROC2015. Region 4 – Western Channel Observatory, Region 5, Port Erin (discontinued). Region 6 - Malin Head and Tiree Passage (discontinued), Region 7 – Faroe Shetland Channel, Region 8 – Rockall Trough. Region 1 – Fair Isle Channel and Utsire B. Region 2 – Helgoland Roads and Felixstowe. Anomalies are calculated relative to the period 1981-2010 and are normalized with respect to the standard deviation (e.g. a value of +2 indicates 2 standard deviations above normal). Colour intervals 0.5; reds = positive/warm; blues = negative/cool*

The long-term variability calculated from the HADISST1.1 dataset has been compared with other temperature datasets in Figure 14. There is a very good agreement between the various products which gives more confidence to the results as each product has its own errors and uncertainties. The very warm period of sea surface temperatures seen in the HADISST dataset in Region 8 between 1955 and 1960 has been detected in the *in-situ* data from the North Atlantic, but these datasets suggest that although warm, it was not warmer than the most recent period. The feature does appear in other datasets such as the AHOI data in the northern and southern North Sea.

The regional variability in sea surface temperature over the last decade can be seen clearly in Figure 14. In all regions, the recent period has been exceptionally warm and the average sea surface temperatures in the decade 2005-2014 rank as the warmest decade in the observational record (1870). Within this period 2010 and 2013 were relatively cool years, particularly in the shallower and easternmost regions, away from the main influence of the North Atlantic. 2014 was the warmest year on record in the Eastern Channel (Region 3), on the Scottish Continental Shelf (Region 7) and in the North Sea (Regions 1 and 2). Note that for this dataset, the warmest year in Region 6 occurred in 1949, and in Region 8 it was 1960. Prior to 2014, the warmest year was 2007 in Regions 3, 4 and 5. However 2002 and 2003 was also a warm, particularly in the regions to the north and west of the UK. The influence of this warm period also extended into the North Sea, which experienced warm years in both 2003 and 2007 (Regions 1 and 2).

Early work on decadal prediction focused on understanding how and where model initialisation was important. The North Atlantic region was found to be predictable several years ahead and forecast initialization is important to achieve this. The Atlantic Meridional Overturning Circulation (AMOC) is a key process for the predictability in the European region, with research over the last 10 years focusing on understanding the underlying processes, and improving our ability to predict it. The RAPID array was deployed in 2004, to measure the AMOC at 26.5°N. This array has now provided 10 years of data, allowing AMOC predictions to be validated and improved over several years (see the accompanying MCCIP report on AMOC McCarthy *et al.,* 2017, Figure 4). Comparison of SST projections for the North Sea plotted against the publication date. Most studies used give a North Sea temperature projection for a given period. These were calculated from the data for Holt *et al.* (2010) and Tinker *et al.* 2016). Friocourt *et al.* (2012) say there models project between 0.4°C and 0.8°C from the southern North Sea – these values have been used. Gröger *et al.* (2013) says there has been about 2K warming over the 21st century - we have used the 1960-1990 and 2070-2100. Mathis and Pohlmann (2014) report increase in SST as a rate (°C/100 yrs). The ensemble mean from Tinker *et al.* (2016) is given, with the 11 individual ensemble member given in small dots.

5. KNOWLEDGE GAPS / KEY CHALLENGES / EMERGING ISSUES

Many knowledge gaps for future projections of marine climate have been overcome during the life of MCCIP (the last 10 years), however important knowledge gaps remain.

Shelf seas specific climate projections, necessary for sea temperature projections for the NWS, were unavailable 10 years ago - now there are many published studies. Estimates of the uncertainty in shelf sea water temperature are starting to be addressed, but are still generally *ad hoc*, with the systematic approach of Tinker *et al. (*2016) being the exception rather than the norm. This is an on-going knowledge gap. There has significant progress within the seasonal and decadal forecasts of global to regional climate parameters, however, this has not yet translated into forecasts of NWS sea temperature, as the extent to which a decade ahead might be inherently unpredictable is itself an important research question.

The gaps for observations have not changed as much as those for projections and remain broadly like those reported in previous MCCIP reports. 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. This might be seen as an opportunity as much as a gap as increased understanding here will improve forecasts and model reanalysis.

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.

The deep ocean (below ca. 2 km depth) is poorly sampled. The Argo programme has, to some extent, addressed the lack of sampling for the upper 2km of the open 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 mean that the homogeneity of the current observing system, and its consistency with earlier observations, needs urgent assessment.

There are several areas where it is likely that there will be improvements for NWS sea water temperature predictions and climate projections. There will be an inevitable increase in resolution and process representation, and improved treatment of uncertainty. In addition to traditional uninitialised centennial climate projections, work will continue in the field of monthly to decadal shelf seas forecasts.

6. IMPROVED METHODOLOGY

Most temperature projections for the NWS employ nesting a regional ocean model with one-way coupling, to a global climate model (e.g. Ådlandsvik, 2008; Holt *et al.*, 2012), so that the regional climate model is forced by conditions in the global climate model, but cannot feed back into it. Others have used a single global ocean model, with enhanced resolution over the NWS (Gröger *et al.*, 2013), but without two-way coupling with the atmosphere. This approach does not impose boundaries at the edge of a predefined domain - these often lead to complications and errors in the vicinities of the boundaries. On shorter time scales the coupled regional atmosphere-ocean coupled models have been used (e.g. Schrum *et al.*, 2003), allowing atmosphere and ocean to interact within areas of interest, however, the shelf seas model still cannot feed back into the adjacent oceans or atmosphere.

Most of these approaches have drawbacks. Eventually, global climate models may include all the relevant shelf seas processes (namely tides and appropriate vertical coordinates to capture downslope flows) and be run at sufficiently high resolution, or with locally enhanced resolution, as to make downscaling unnecessary. Such an approach may overcome many of these limitations. The Met Office is already investigating the implementation of tides into their 1/12° resolution ocean model for use in ocean forecasting. High resolution

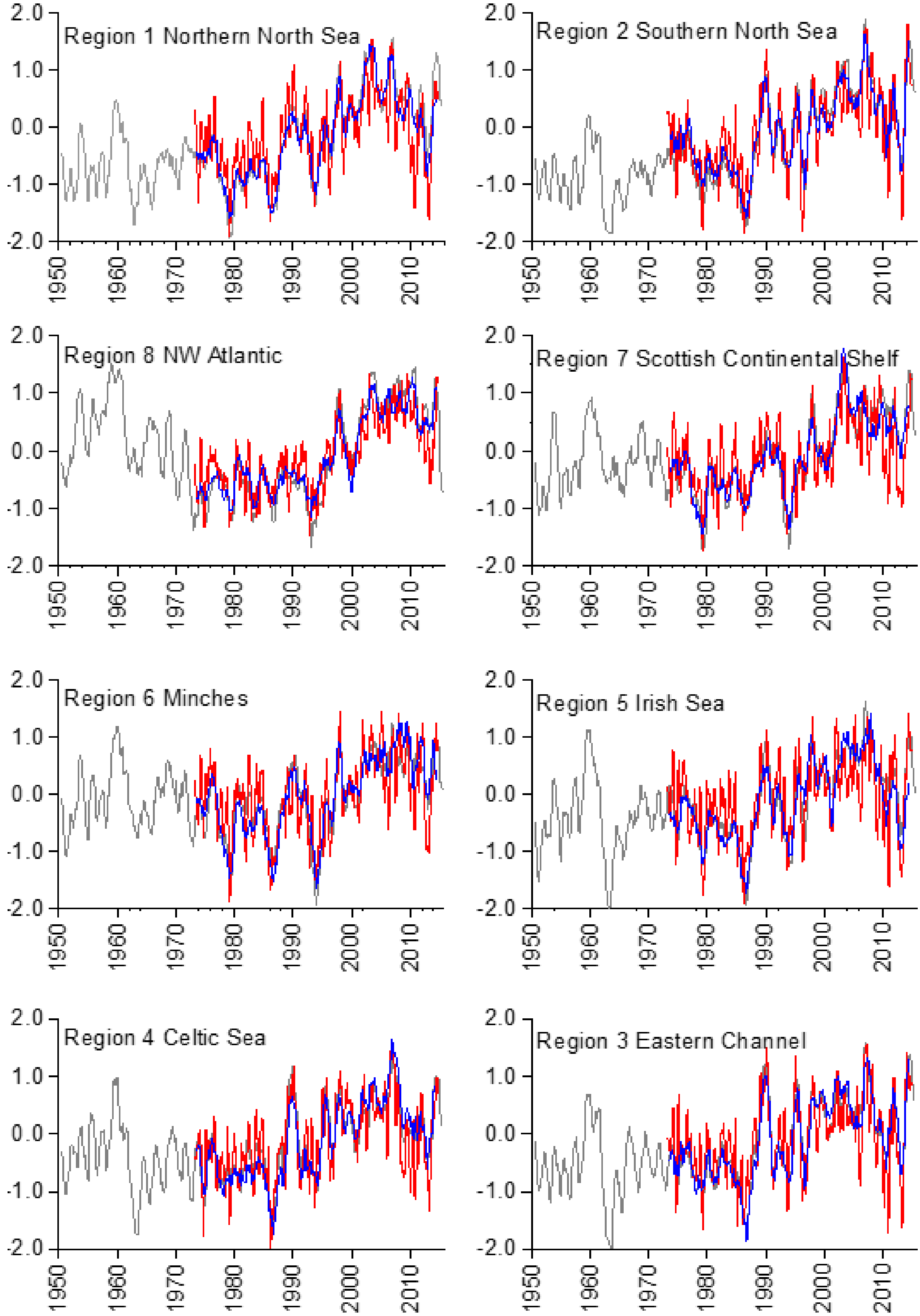

Figure 14: *Timeseries of Air and Sea temperature anomaly (°C) calculated from 3 different datasets. For each timeseries data have been averaged across all valid grid points within each of the 8 CP2 regions. Grey is HADISST v1, blue is sea surface temperature from NOCSFlux v2.0 and red is air temperature from NOCSFlux v2.0.*

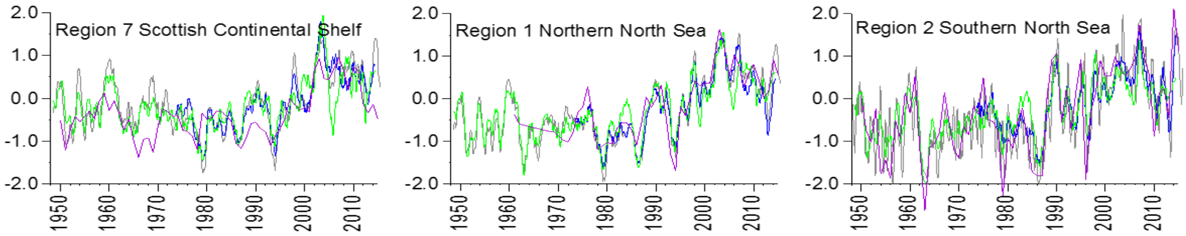

***Figure 15**: Comparisons of sea surface temperature anomaly timeseries calculated from 4 different datasets, averaged across Regions 7, 1 and 2. Grey is HADISSTv1, green is AHOI, blue is NOCSFluxv2.0 and purple shows the nearest in-situ timeseries. In Region 7, this is North Atlantic Water from Faroe-Shetland Channel, Region 1 this is Fair Isle Current, Northern North Sea and Region 2, it is Helgoland Roads.*

(atmosphere only) regional climate simulations have already been run been run at 1.5km (e.g. Kendon *et al.*, 2012) and global coupled climate models have been run with an ocean (and atmosphere) resolution of 9km (and 25km) at the equator (Hewitt *et al.*, 2016). High resolution coupled regional models (with 1.5km atmosphere and ocean) covering the NWS domain are also in development (e.g. Siddorn *et al.* 2016). Ocean models with adaptive grids have also been developed (ICOM) but these are unlikely to be adopted within the next 10 years.

The resolution of the shelf seas model is likely to increase to resolve the Rossby radius. This will allow more processes to be directly represented rather than parameterised, and allow a better representation of mixing, improving water column structure. Few NWS models currently include the Baltic Sea, and so rely on a boundary condition for the Baltic exchange. There is very complex circulation within this region, and the model is very sensitive to the Baltic exchange in this region (Skagerrak) and downstream (Norwegian Coastal Current). The bathymetry between the North Sea and the Baltic is very complex, so additionally, high resolution would be required within this region.

Many early shelf seas climate projection studies have used the time-slice approach (Ådlandsvik, 2008; Holt *et al.*, 2012). Despite the computational savings of such an approach, there are drawbacks. This approach does not account for cumula-tive effects (such as fluxes) that can integrate over the full time-period. It is difficult to assess whether any changes are the result of climate change, or low-frequency variability, as the state evolution between the two periods is not known. More recent studies (e.g. Olbert *et al.*, 2012; Mathis *et al.*, 2013; Tinker *et al.*, 2016) have run transient experiments and have been able to assess the robustness of their results. Future projections are unlikely to rely on the time-slice approach.

6.1 Initialised forecasts rather than projections

Operational forecasts of the state of the NWS, out to 5 days, are made daily and are freely available via the Copernicus Marine Environment Monitoring Services (CMEMS). Like traditional weather forecasts, these rely on a knowledge of the present state of the ocean and atmosphere (from ob-servations) and are possible as it is several days before the uncertainty introduced by the chaotic nature of the ocean and atmosphere dominates. Simply extending such (atmos-phere-only) forecasts further into the future is naïve. Climate projections rely on the strength of the climate change signal dominating the natural climate variability, and so tend to be for further into the future, to ensure the climate change sig-nal is much greater than the climate variability. Most climate projections are not initialised, so the modelled present day does not necessarily match the "weather" of the real-world present day – it is not meaningful to use the first few years of such climate simulation to make predictions.

Monthly to decadal forecast systems, such as the Met Office GLOSEA system (MacLachlan *et al.*, 2014), combine these two approaches. They use a coupled climate model initialised from observations and rely on the slowly-evolving components of the climate system to provide predictability for some parameters. Success in predicting the winter NAO months in advance (Scaife *et al.*, 2014) suggests that this may be possible for the NWS, as the NAO is such an important mode of climate variability for the region. A recent study investigating predictability on the NWS, builds on the Scaife *et al.* (2014) study, and found that lagged relationships between the observed NAO and parameters such as the English Channel SST, are still significant when driven by the fore-cast NAO (Tinker *et al.*, in prep). Decadal forecasts for the European region gain predictability from the sub-polar gyre and AMOC. A new observation array, OSNAP (Overturn-ing in the Sub-polar North Atlantic Program), now measures AMOC at 45-50°N (analogous to the RAPID array) and will lead to new insights into the variability, and underlying pro-cesses at work, which should generate model improvements and improved forecasts. Currently the seasonal and decadal forecasting systems are separate, but these will be combined into one seamless system, which should allow the model-ling system to be tested over a range of timescales, allowing model development to focus on any identified deficiencies.

6.2 More sources of uncertainty explored

The UKCP09 terrestrial climate projections (UKCP09; Tink-er *et al.*, 2016) made a systematic assessment of a wide range of uncertainties in the climate system, and provided a set of probabilistic climate projections. In contrast, most NWS climate projections make no estimate of the associated climate uncertainty, running a single simulation (e.g. Ådlandsvik, 2008; Holt *et al.*, 2010; Olbert *et al.*, 2012; Mathis *et al.*, 2013), although these studies still add to a literature based "ensemble of opportunity". A few studies have run a pair of experiments to provide a minimum estimate of uncertain associated with choice of emission scenario (Meier, 2006), driving global climate model (Meier 2006) or choice of shelf seas model (Friocourt *et al.*, 2012). Tinker *et al.* (2016) has made a comprehensive assessment of uncertainty in parame-ters within the atmospheric component of the driving model that leads to spread in the shelf seas projections. Future shelf seas projection studies are likely to provide a more system-atic assessment of uncertainty.

6.3 Observational system continuity

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 when the ocean monitoring science is less fashionable. 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, hence reducing 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.

Acknowledgements

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REFERENCES

Ådlandsvik, B. (2008) Marine downscaling of a future climate scenario for the North Sea. Tellus A 60: 451-458.

Ådlandsvik, B. and Bentsen, M. (2007) Downscaling a twentieth century global climate simulation to the North Sea. Ocean Dynamics 57: 453–466.

Adjusted Hydrography Optimal Interpolation (AHOI) Dataset: https://www.thuenen.de/en/sf/projects/ahoi-a-physical-statistical-model-of-hydrography-for-fishery-and-ecology-studies/: date of access (01052016).

Berx, B. and Hughes, S.L. (2009) Climatology of Surface and Near-bed Temperature and Salinity on the North-West European Continental Shelf for 1971-2000. Continental Shelf Research, 29, 2286-2292.

Berx, B. and Payne, M.R., (2017) The Sub-Polar Gyre Index–a community data set for application in fisheries and environment research. Earth System Science Data, 9(1), pp.259-266.

Berry, D.I., Kent, E.C. and Taylor, P.K. (2004) An analytical model of heating errors in marine air temperatures from ships. J. Atmos. Oceanic Tech., 21(8), 1198 – 1215, doi:10.1175/1520-0426(2004)021<1198:AAMOHE>2.0.CO;2.

Berry, D.I. and Kent, E.C. (2009) A new air-sea interaction gridded dataset from ICOADS with uncertainty estimates, Bulletin of the American Meteorological Society, 90(5): 645-656. doi:10.1175/2008BAMS2639.1.

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 J. Mar. Sci., 66, 1480–1489.

Dunstone, N, D Smith, A Scaife, L Hermanson, R Eade, N Robinson, M Andrews & Jeff Knight (2016) Skilful predictions of the winter North Atlantic Oscillation one year ahead. Nature Geoscience 9, 809–814 (2016) doi:10.1038/ngeo2824

Enfield, D.B., A.M. Mestas-Nunez, and Trimble, P.J. (2001) The Atlantic Multidecadal Oscillation and its relationship to rainfall and river flows in the continental U.S., Geophysical Research Letters, 28: 2077-2080.

Friocourt, Y.F., Skogen, M., Stolte, W., and Albretsen, J. (2012) Marine downscaling of a future climate scenario in the North Sea and possible effects on dinoflagellate harmful algal blooms. Food Additives & Contaminants: Part A, 29(10), 1630-1646.

Frost, M., Baxter, J.M., Buckley, P.J., Cox, M., Dye, S.R. and Withers Harvey, N. (2012) Impacts of climate change on fish, fisheries and aquaculture. Aquatic Conservation: Marine and Freshwater Ecosystems, 22(3), pp.331-336.

GISTEMP Team (2017) GISS Surface Temperature Analysis (GISTEMP). NASA Goddard Institute for Space Studies. Dataset accessed January 2017 https://data.giss.nasa.gov/gistemp/.

Gröger, M., Dieterich, C., Meier, H.E. . and Schimanke, S. (2015) "Thermal air–sea coupling in hindcast simulations for the North Sea and Baltic Sea on the NW European shelf." Tellus A 67: 1 DOI: 10.3402/tellusa.v67.26911.

Gröger, M., Maier-Reimer, E., Mikolajewicz, U., Moll, A. and Sein, D. (2012) NW European shelf under climate warming: implications for open ocean – shelf exchange, primary production, and carbon absorption. Biogeosciences 10: 3767-3792 doi:10.5194/bg-10-3767-2013.

Gröger, M., Maier-Reimer, E., Mikolajewicz, U., Moll, A. and Sein, D. (2013) NW European shelf under climate warming: implications for open ocean – shelf exchange, primary production, and carbon absorption. Biogeosciences 10: 3767-3792 doi:10.5194/bg-10-3767-2013.

Hansen, J., R. Ruedy, M. Sato, and Lo, K. (2010) Global surface temperature change. Reviews in. Geophys., 48, RG4004, doi:10.1029/2010RG000345.

Hátún, H., Sando, A.B., Drange, H., Hansen, B., and Valdimarsson, H. (2005) Influence of the Atlantic subpolar gyre on the thermohaline circulation, Science, 309, 1841-1844.

Hermanson, L., Eade, R., Robinson, N. H., Dunstone, N.J., Andrews, M.B., Knight, J.R., Scaife, A.A. and Smith, D.M. (2014) Forecast cooling of the Atlantic subpolar gyre and associated impacts. Geophysical Research Letters 41(5167-5174) DOI: 10.1002/2014GL060420.

Hewitt, H.T., Roberts, M.J., Hyder, P., Graham, T., Rae, J., Belcher, S.E., Bourdalle-Badie, R., Copsey, D., Coward, A., Guiavarch, C., Harris, C., Hill, R., Hirschi, J.J.-M., Madec, G., Mizielinski, M.S., Neininger, E., New, A.L., Rioual, J.-C., Sinha, B., Storkey, D., Shelly, A., Thorpe, L. and Wood, R. A. (2016) The impact of resolving the Rossby radius at mid-latitudes in the ocean: results from a high-resolution version of the Met Office GC2 coupled model. Geosci. Model Dev., 9, 3655–3670. doi:10.5194/gmd-2016-87.

Holt, J., Butenschön, M., Wakelin, S., Artioli, Y. and Allen, I. (2012) Oceanic controls on the primary production of the northwest European continental shelf: model experiments under recent past conditions and a potential future scenario. Biogeosciences 9: 97–117.

Holt, J., Wakelin, S., Lowe, J.A. and Tinker, J. (2010) The potential impacts of climate change on the hydrography of the northwest European continental shelf. Progress In Oceanography 86(3-4): 361-379 doi:10.1016/j.pocean.2010.05.003.

Hughes S.L., Holliday, N.P. , Kennedy, J., Berry, D.I., Kent, E.C., Sherwin, T., Dye, S., Inall, M., Shammon, T. and Smyth, T. (2010) Temperature (Air and Sea) in MCCIP Annual Report Card 2010-11, MCCIP Science Review, 16pp. www.mccip.org.uk/arc.

Hughes, S.L., Holliday, N.P., Gaillard, F., and The ICES Working Group on Oceanic Hydrography (2012) Variability in the ICES/NAFO region between 1950 and 2009: observations from the ICES Report on Ocean Climate. ICES Journal of Marine Science: Journal du Conseil, 69(5), 706-719. doi:10.1093/icesjms/fss044.

Hurrell, J.W. (1996) Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. Geophysical Research Letters, 23(6), pp.665-668.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., et al (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp

IPCC (2014a) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC (2014b) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

IPCC (2014c) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.

IROC2015: Larsen, K. M. H., Gonzalez-Pola, C., Fratantoni, P., Beszczynska-Möller, A., and Hughes, S. L. (Eds). (2016) IROC2015 ICES Report on Ocean Climate 2015. ICES Cooperative Research Report No. 331. 79 pp.

Janssen, F., Schrum, C., and Backhaus, J. O. (1999) A climatological data set of temperature and salinity for the Baltic Sea and the North Sea. Deutsche Hydrographische Zeitschrift / German Journal of Hydrography, Supplement 9, 1-245.

Kendon, E.J., Roberts, N.M., Senior, C.A. and Roberts, M. J. (2012) Realism of Rainfall in a Very High-Resolution Regional Climate Model. Journal of Climate 25(17) http://dx.doi.org/10.1175/JCLI-D-11-00562.1.

Kent, E., Berry, D. and Hill, J. (2006) Impacts of Climate Change on Marine Air Temperature in Marine Climate Change Impacts Annual Report Card 2006 (Eds. Buckley, P.J, Dye, S.R. and Baxter, J.M), Online Summary Reports, MCCIP, Lowestoft, www.mccip.org.uk.

Kent, E.C., Woodruff, S.D. and Berry, D.I. (2007) WMO Publication No. 47 Metadata and an Assessment of Voluntary Observing Ships Observation Heights in ICOADS. J. Atmos. Oceanic Tech., 24(2), 214–234. doi:10.1175/JTECH1949.1.

Knight, J.R., Allan, R.J., Folland, C.K., Vellinga, M. and Mann, M.E. (2005) A signature of persistent natural thermohaline circulation cycles in observed climate. Geophys. Res. Lett. 32, L20708. doi:10.1029/2005GL024233.

Lowe, J.A., Howard, T.P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. and Bradley, S. (2009) UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK.

MacLachlan, C., Arribas, A., Peterson, K. A., Maidens, A., Fereday, D., Scaife, A. A., Gordon, M., Vellinga, M., Williams, A., Comer, R.E., Camp, J., Xavier, P. and Madec, G. (2014) Global Seasonal forecast system version 5 (GloSea5): a high-resolution seasonal forecast system. Quarterly Journal of the Royal Meteorological Society doi: 10.1002/qj.2396.

Mathis, M., Mayer, B. and Pohlmann, T. (2013) An uncoupled dynamical downscaling for the North Sea: Method and evaluation. Ocean Modelling 72: 153-166.

Mathis, M. and Pohlmann, H. (2014) Projection of physical conditions in the North Sea for the 21st century. Climate Research 61: 1-17 doi:10.3354/cr01232.

McCarthy, G.D., Haigh, I.D., Hirschi, J.J.M., Grist, J.P., and Smeed, D.A. (2015). Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. Nature, 521(7553), 508-510.

McCarthy, G., Smeed, D.A., Cunningham, S., and Roberts, C.D. (2017) Atlantic Meridonal Overturning Circulation. MCCIP Science Review 2017, doi:10.14465/2017.arc10.002-atl

MCCIP (2013) Marine Climate Change Impacts on Report Card 2013. (Eds. Frost M, Baxter JM, Bayliss-Brown GA, Buckley PJ, Cox M and Withers Harvey N) Summary report, MCCIP, Lowestoft, 12pp.

Meier, H.E.M. (2006) Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios. Climate Dynamics 27: 39-68 DOI 10.1007/s00382-006-0124-x.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T.P., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R. and Wood, R. A. (2009) UK Climate Projections Science Report: Climate change projections. Exeter, Met Office Hadley Centre.

NOCv2.0 (2016) The Climate Data Guide: Surface Flux and Meteorological Dataset.National Oceanography Centre (NOC) V2.0. Kent, E & National Center for Atmospheric Research Staff (Eds). https://climatedataguide.ucar.edu/climate-data/surface-flux-and-meteorological-dataset-national-oceanography-centre-noc-v20. Last modified 02 Mar 2016.

Núñez-Riboni, I., and Akimova. A. (2015) Monthly maps of optimally interpolated *in situ* hydrography in the North Sea from 1948 to 2013. Journal of Marine Systems, 151, 15-34.

Olbert, A. I., Dabrowski, T., Nash, S. and Hartnett, M. (2012). “Regional modelling of the 21st century climate changes in the Irish Sea.” Continental Shelf Research 41: 48-60 http://dx.doi.org/10.1016/j.csr.2012.04.003.

Pörtner H.O. and Farrell AP. (2008). Physiology and climate change. Science 322: 690–692.

Pörtner H.O. and Peck M.A. (2010). Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. Journal of Fish Biology 77: 1745–1779.

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C. and Kaplan, A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late Nineteenth Century. J. Geophys. Res., 108(D14), 4407. doi:10.1029/2002JD002670.

Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R. T., Dunstone, N., Eade, R., Fereday, D., Folland, C. K., Gordon, M., Hermanson, L., Knight, J. R., Lea, D. J., MacLachlan, C., Maidens, A., Martin, M., Peterson, A. K., Smith, D., Vellinga, M., Wallace, E., Waters, J. and Williams, A. (2014). "Skillful long-range prediction of European and North American winters." Geophysical Research Letters 41: 2514-2519 DOI: 10.1002/2014GL059637.

Scaife, A. A., Karpechko, A. Y., Baldwin, M. P., Brookshaw, A., Butler, A. H., Eade, R., Gordon, M., MacLachlan, C., Martin, N., Dunstone, N. and Smith, D. (2016). "Seasonal winter forecasts and the stratosphere." Atmospheric Science Letters 17: 51-56 doi: 10.1002/asl.598.

Schrum, C., Hübner, U., Jacob, D. and Podzun, R. (2003)."A coupled atmosphere/ice/ocean model for the North Sea and Baltic Sea." Climate Dynamics 21(2): 131-151.

Siddorn, J. R., Good, S. A., Harris, C. M., Lewis, H. W., Maksymczuk, J., Martin, M. J. and Saulter, A. (2016). "Research priorities in support of ocean monitoring and forecasting at the Met Office." Ocean Science 12: 217-231 doi:10.5194/os-12-217-2016.

Swanson, K., Sugihara, G. and Tsonis, A. (2009) Long-term natural variability and 20th century climate change. Proc. Natl. Acad. Sci., 106(38), 16120

Ting, M., Kushnir, Y., Seager, R. and Li, C.H. (2009) Forced and Internal Twentieth-Century SST Trends in the North Atlantic. J. Clim., 22(6),1469-1481.

Tinker, J., Lowe, J., Holt, J., Pardaens, A. and Barciela, R. (2016) Uncertainty in climate projections for the 21st century northwest European shelf seas. Progress In Oceanography 148, 56-73.

Tinker, J., Lowe, J., Holt, J., Pardaens, A. and Wiltshire, A. (2015). Validation of an ensemble modelling system for climate projections for the northwest European shelf seas. Progress In Oceanography 138(Part A): 211-237 10.1016/j.pocean.2015.07.002.

Tinker et al (in prep) Seasonal Prediction of the Marine Environment of the NW European Shelf.

Trenberth, K.E. and Shea, D.J., (2006). Atlantic hurricanes and natural variability in 2005. Geophysical Research Letters, 33(12).

UKMMAS (2010) Charting Progress 2- Feeder Report: Ocean Processes, Huthnance J (ed.). Published by the Department for Environment Food and Rural Affairs on behalf of UKMMAS.

UKCIP02: Hulme M, Jenkins GJ, Lu X, Turnpenny JR, Mitchell TD, Jones RG, Lowe J, Murphy JM, Hassell D, Boorman P, McDonald R, Hill S. (2002) Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia: Norwich; 120.

UKCP09: Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, .B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J. and Betts,.A., (2009). UK climate projections science report: UKCP09. Met Office Hadley Centre: Exeter, UK.

Visbeck, M.H., Hurrell, J.W., Polvani, L. and Cullen, H.M., (2001). The North Atlantic Oscillation: past, present, and future. Proceedings of the National Academy of Sciences, 98(23), pp.12876-12877.