The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK

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with contributions from

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Citation: Tinker, J.P. and Howes, E.L. (2020) The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK. *MCCIP Science Review 2020*, 1–30.

doi: 10.14465/2020.arc01.tem

Submitted: 11 2019
Published online: 15th January 2020.

EXECUTIVE SUMMARY

- There is high confidence that there is a consistent picture of long-term warming across the UK continental shelf.
- Wider variability at sub-decadal to the decadal scale is important and has an effect on the magnitude and significance of the 30-year trend in Sea-Surface Temperatures (SSTs) across the UK continental shelf.
- Short-term variations are consistent across the UK continental shelf. Time–series stations in different locations consistently showed the 2000–2008 period as relatively warm, followed by five years (2008–2013) of cooler conditions, with warmer conditions again between 2014–2017.
- In addition to warmer average conditions, a seasonal analysis of air temperature over the UK shelf seas shows a greater variability of autumn conditions over the last two decades (1998–2017) than in the previous two decades (1978–1997).
- The subpolar gyre is one of the few regions of the global ocean where SST has been relatively cold over the last 10 years. (The

accompanying MCCIP 2020 paper (McCarthy *et al.*, 2020) on the Atlantic Heat Conveyor summarises hypotheses on the causes.) Atlantic influence appears to have brought cooler conditions (close to the long-term mean) in the North and West since the early 2000s that are probably a reflection of the relatively cooler North-east Atlantic subpolar gyre.

- There are a now a number of North-West European Shelf (NWS) seas climate projections for the end of the 21st century. There is good agreement on the sign of the temperature change on the NWS among the end of century climate projections. However, there is a spread in the magnitude of this warming. Most projections give a warming between 1–4°C.
- Seasonal to decadal predictability: Development of NWS modelling systems driven by seasonal forecasting systems may allow NWS temperature prediction over the seasonal to decadal period.

1. WHAT IS ALREADY HAPPENING?

1.1. Marine air temperature

Marine surface air temperature is measured from ships, buoys and fixed marine platforms. Near-surface air temperature data are not accurately retrievable from satellites. When last reported through MCCIP (Dye *et al.*, 2013) marine air-temperature estimates from the NOC Flux Dataset v2.0 (NOCv2.0, Berry and Kent, 2009) were used. 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), to give an air temperature at a 10-metre reference height. The NOCv2.0 dataset has not been updated since 2014 due to declining observation numbers, so here we also show results from the ERA-Interim re-analysis (Dee *et al.* 2011) air temperature fields at a 2-metre reference height, which are available from 1979 to near present.

Figure 1 shows the 30-year trend (1988–2017) in marine air temperature (°C per decade) estimated from ERA-Interim for the North-East Atlantic and UK waters. Over this period, the trends are not significant over most of the region, with only the area around Iceland and part of the Scottish Continental Shelf (Charting Progress Region 7) showing significant warming. Significant trends range from 0.1–0.5˚C per decade with an average of 0.3˚C per decade. Cooling occurs to the south-west of the UK, but this is not significant. Trends for the most-recent 30-year period for the NOCv2.0 dataset from 1985–2014 are larger than those for ERA-Interim (not shown in Figure 1), and the trend from HadISST1 shows some additional areas in the central and southern

North Sea (Region 2) and the Atlantic North-West Approaches (Region 8) where increasing trends are significant.

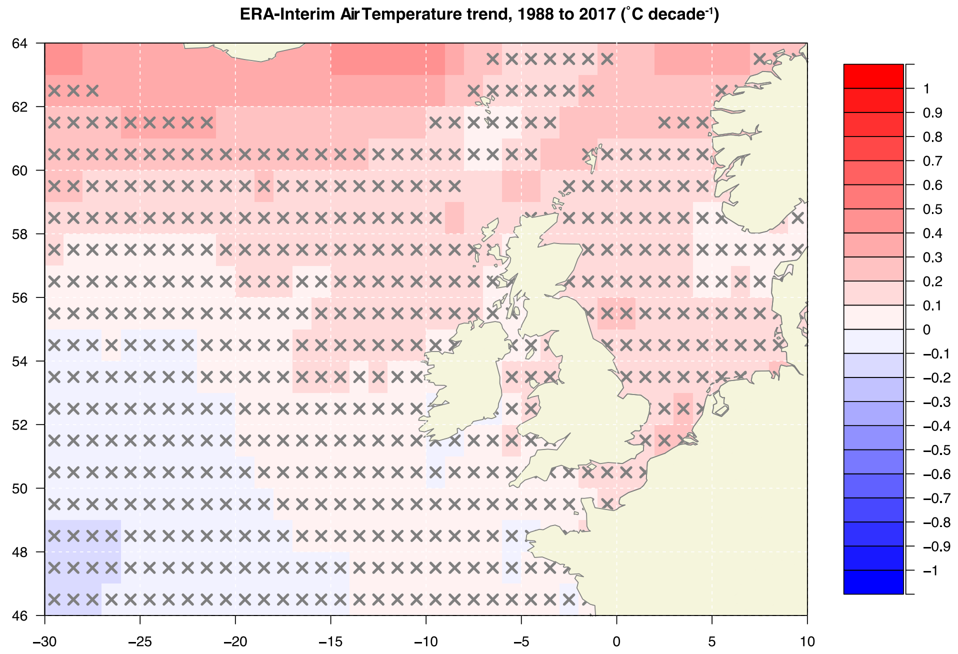


Figure 1: 30-year (1988–2017) trend in annual average ERA-Interim 2-m air temperature (˚C/decade) interpolated to a 1-degree latitude–longitude grid. Crosses indicate where the trends are not significant at the 95% confidence level using the Cochrane-Orcutt method to account for autoregression in the time-series data.

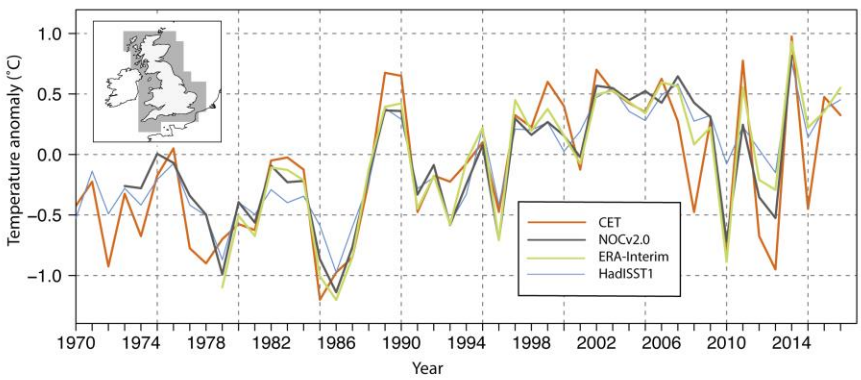


Figure 2: Annual average air temperature and SST anomalies from a 1981–2010 climatological reference period for UK coastal waters (area indicated in the shaded area of the inset map). Central England Temperature (CET, brown); NOC v2.0 (grey); ERA-Interim (green); HadISST1 sea surface temperature (blue; Rayner et al., *2003).*

Figure 2 compares the time–series data for annual mean air-temperature anomalies (relative to 1981 to 2010) for the UK coastal waters from NOCv2.0

(grey) and ERA-Interim (green). Sea-surface temperature (SST) anomalies from HadISST1 are shown in blue (Rayner *et al.*, 2003) and the Central England Temperature (CET), in brown (Parker *et al.*, 1992). The agreement between the time–series data provides some confidence in the variability: as expected, CET (air temperature over land) shows the highest interannual variability and the largest annual range (not shown) and HadISST1 the smallest SST. The air temperatures were the highest in the CET record in 2014, with the annual mean air temperature anomaly in all three datasets between +0.8 and 1.0˚C. December 2015 was the warmest in the CET record, although 2015 overall was not exceptionally warm. Annual mean temperature anomalies during 2016 and 2017 were warmer than average by around 0.5˚C in all three datasets compared here.

Figure 3 compares the annual cycles of the monthly mean air-temperature estimates for UK coastal waters from CET, ERA-Interim and NOCv2.0. The boxplots show the variation of air temperature over the two decades 1978–1997 (wide light grey boxes), for the most recent two decades 1998–2017 (narrow blue boxes) and also individual monthly means for 2014 (yellow circles) and 2017 (red circles). The graphs using NOCv2.0 are plotted using data up to 2014, so do not cover the full period, but are included for additional information. Monthly means were higher than typical for all months in 2014 annual mean (yellow dots), except for August, in all three datasets, leading to the peak temperature in that year. 2017 was also warmer than average, but individual months showed more variability (red dots). The range of monthly values has increased between the earlier period (1978–1997) and the later period (1998–2017). All of the estimates show a consistent picture of increased variability in the monthly means for autumn (September through November). Variability is also larger in the latter 20 years in April and June and noticeably smaller in February, March and August, but no other consistent seasonal patterns are evident.

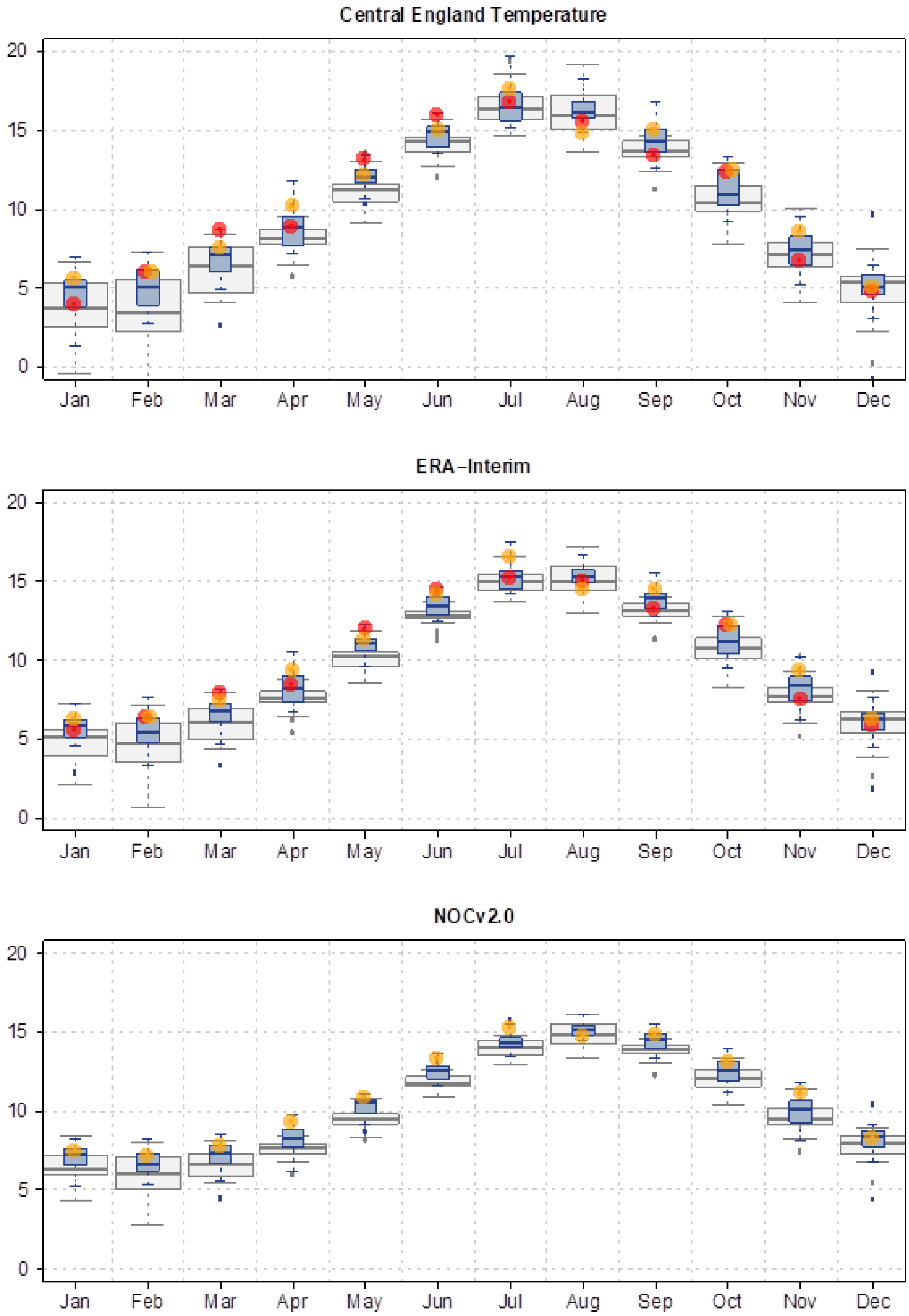


*Figure 3: Boxplots of variations of monthly mean temperature showing median; first and third quartile (Inter-Quartile Range, IQR, shown as a 'box'); range excluding outliers ('whiskers'), and outliers more than 1.5*IQR beyond box as a circle). Wider light-shaded boxes show distributions from 1978–1997 and darker narrower boxes from 1998–2017 (NOCv2.0 plotted using data up to 2014). Yellow circles show values for 2014 for reference as the warmest year in the last two decades, red circles show the values for 2017.*

1.2 Sea temperature

Overview

On a global scale, the five years since the last MCCIP full report card was published in 2013 have been the five warmest since records began (Figure 4), with 2017 being recorded as the warmest year on record for the global ocean (Cheng and Zhu, 2018).

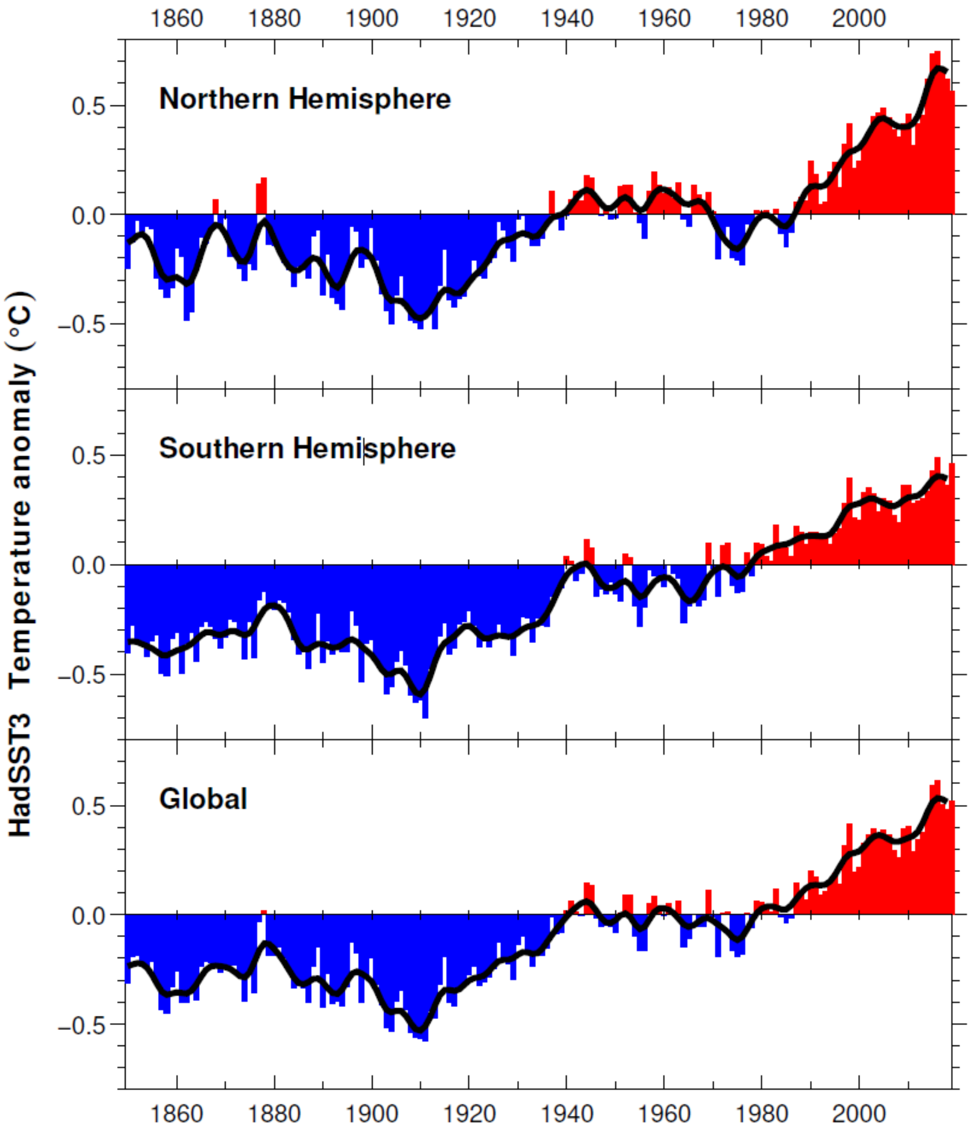


Figure 4: Average Sea-Surface Temperature (SST) anomalies in °C from 1850 to 2019 for the Northern Hemisphere, Southern Hemisphere and Global oceans (base period 1961–1990) . Data from the Hadley Centre SST data set, (Kennedy et al.*, 2011a; Kennedy* et al.*, 2011b). Figure reproduced from Climatic Research Unit, University of East Anglia www.crudata.uea.ac.uk/cru/data/temperature/*

Embedded in the global average trend are local and regional variations; cold-ocean temperature anomalies have been observed in the mid- to high-latitude North Atlantic, starting in the winter 2013/2014, with temperatures at their lowest in 2015 (Figure 5). The cause is thought to be extreme ocean-surface heat loss as a result of atmospheric forcing (Josey *et al.*, 2018). This expression of regional scale climate variability in a warming world has been coined the North Atlantic 'Big Blue Blob'. After 2015, it weakened but persisted through 2017; early indications suggest that it was re-inforced in 2018.

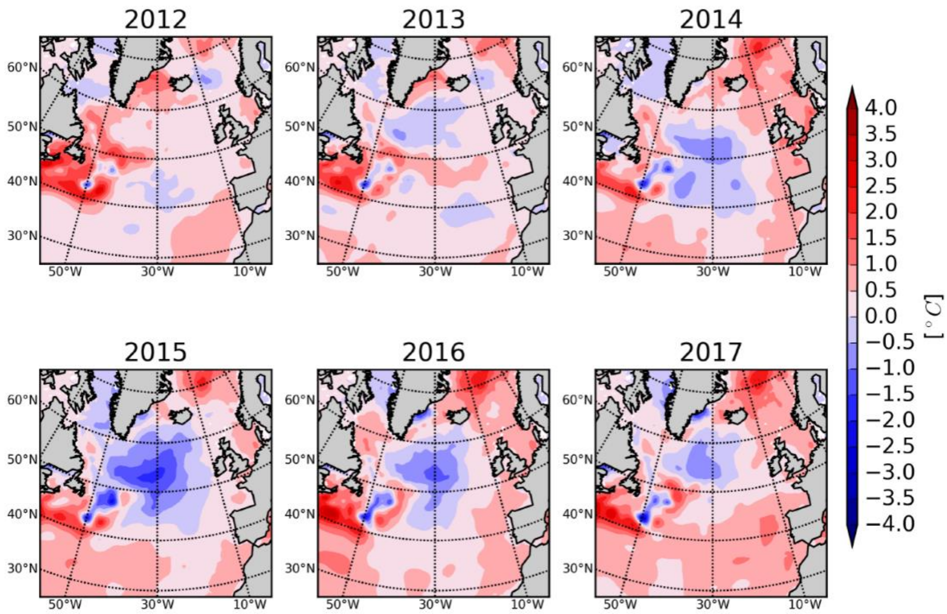


Figure 5: Maps of annual temperature (upper) anomalies at 10 m in the North Atlantic for the period 2012–2017. Anomalies are the differences between the In Situ Analysis System (ISAS) monthly mean values and the reference climatology, World Ocean Atlas 5 (WOA5). The colour-coded scale is the same in all panels. Data from Coriolis, ISAS monthly analysis of Argo data. Reproduced from the ICES Report on Ocean Climate (IROC2017).

The warming trend in surface waters around the UK over the last 30 years is shown in Figure 6. Warming has been strongest in the North Atlantic north of 60°N, with the fastest rate of warming reaching 0.4°C per decade, just off the east coast of Iceland. Significant increases in SSTs have also been recorded to the North of Scotland and in the majority of the North Sea, up to 0.24°C per decade. The warming of the North Atlantic is consistent with the trends in marine air temperature, with only the area around Iceland and part of the Scottish Continental Shelf (Charting Progress Region 7) showing significant warming trends in air temperature (Figure 1). Evidence of the larger scale patterns of SST in the North Atlantic are evident on the UK continental shelf. The influence of the 'Big Blue Blob', has weakened the warming along the UK's south-west coast and resulted in an increase of areas where warming trends are not statistically significant, compared to the analysis in MCCIP's 2013 and 2017 temperature papers (Dye *et al*., 2013; Hughes *et al*., 2017).

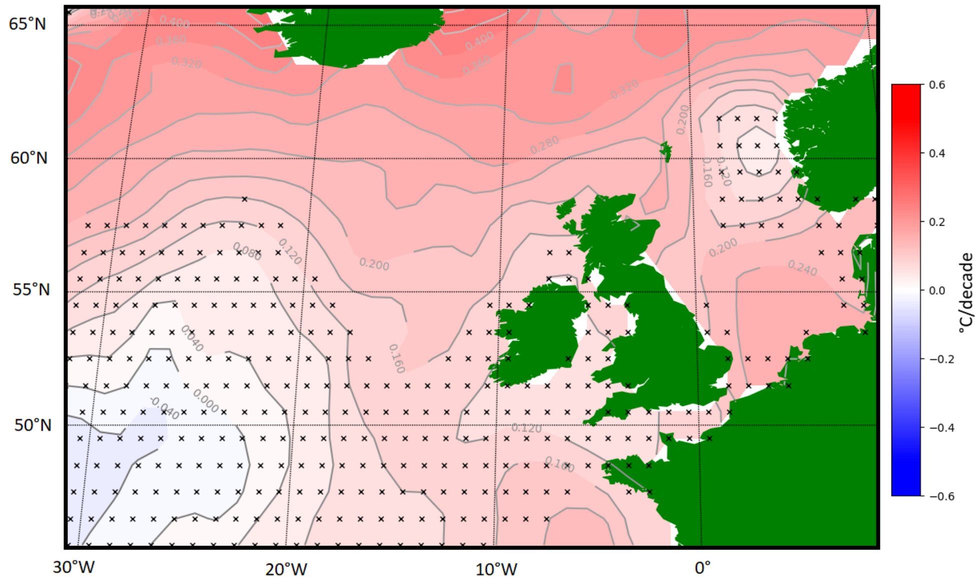


Figure 6: Trend in annual average sea-surface temperature (°C/decade) from 1988 to 2017. Data are from the HadISST1.1 data set (Rayner et al.*, 2003). Crosses indicate where the trends are not significant at the 95% confidence level (alpha=0.05) using Mann-Kendall non-parametric test for a trend (Mann, 1945; Kendall, 1975; Gilbert, 1987).*

Next we update the long-term time–series observations used in earlier MCCIP reports (Dye *et al*., 2013; Hughes *et al*., 2017) to summarise changes in the regions around the UK. These are predominantly found on the continental shelf (> 200 m water depth) that surrounds the UK. On the shelf, the full whole water column becomes fully mixed during the winter months through cooling and wind mixing. In the spring–summer, some areas of the shelf remain fully mixed while others form a warm surface and cool bottom layer system known as 'seasonal stratification' (described in the accompanying MCCIP 2020 report on stratification, Sharples *et al*., 2020). This means that the temperature of the entire shelf area experiences strong seasonal cycles.

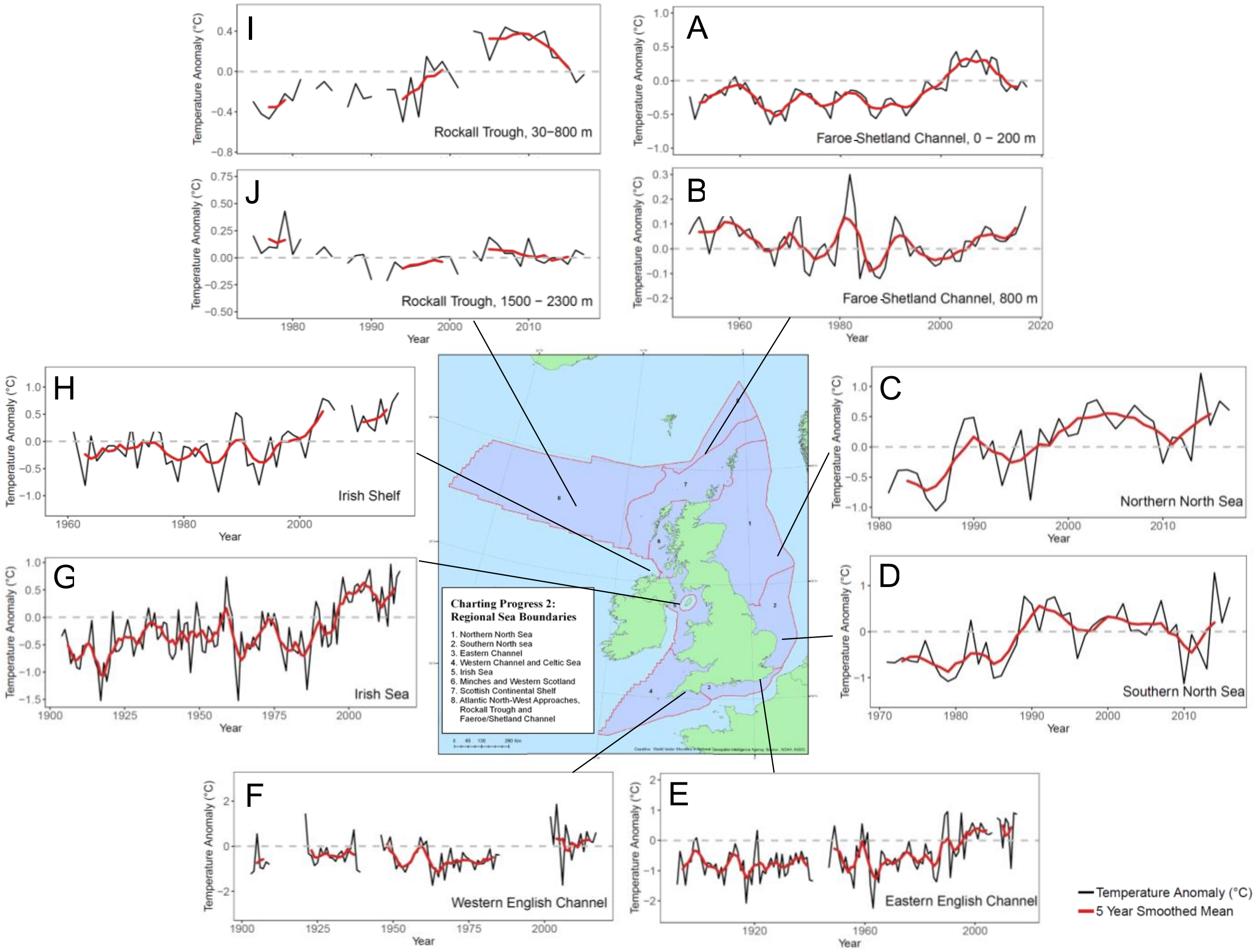


Figure 7: Temperature anomalies (black line) and five year running mean (red line) for the UK Charting Progress regions, data sourced from IROC2017 time-series data (González-Pola et al., *2018a ; note different x-axes are specified in the caption [See data acknowledgement for full details]). A: Faroe-Shetland Channel for the period 1950 to 2012, 0–200 m (base period 1981–2010). B: Temperature of overflow water in Faroe-Shetland Channel at 800 m for the period 1950 to 2012 (base period 1981–2010). C: Northern North Sea surface temperature anomalies for the period 1981 to 2017 (base period 1981–2010). D: Southern North Sea temperature anomalies for the period 1981 to 2017 (base period 1981–2010). E: Temperature anomalies (base period 1981–2010) for Eastern English Channel from 1892–2017. F: Temperature anomalies (base period 1981–2010) Western Channel Observatory Station E1. G: Port Erin temperature anomalies (base period 1981–2010). H: Malin Head coastal station sea surface temperature anomlies (55.39°N 7.38°W) for the period 1959 to2017 (base period 1981–2012). I: Rockall Trough 30-800 m for the period 1975 to 2017 (base period 1981–2010). J: Rockall Trough, temperature in the Labrador Sea Water layer (1500–2300 m) for the period 1975 to 2017 (base period 1981–2010).*

North Sea (Charting Progress Regions 1 and 2)

In the most northern part of the North Sea, the temperature is influenced by inflowing North Atlantic water, showing similar decadal variations to the water in Regions 8 and 7 (Figure 7C) and a general warming since the mid-1980s. Temperatures in the Northern North Sea had been declining from a peak in 2003, but in the last few years have increased again with 2014 and 2016 the warmest and third warmest years since 1981, respectively. 2015 was markedly cooler than the preceding and following years, although still above the average temperature for the time–series data.

In the Southern North Sea, atmospheric forcing has the dominant influence over temperatures. Since the mid-1980s, temperatures increased, peaking in the late 80s to early 90s. Temperatures then declined with a cool period beginning in 2010 where temperature anomalies were below the average for the period 1981–2012 (Figure 7D). In recent years, temperatures have been warmer, displaying a similar trend to the Northern North Sea with 2014 the warmest year since the late 1970s and temperature anomalies remaining above average. As in the Northern North Sea Region, 2015 was a cooler year but was still warmer than average for the period 1981–2012.

Winter bottom-temperatures in the North Sea have been increasing since 1971, but with a cooler period between 2009 and 2011. Since 2012, temperatures have increased; updating the data with recent years produces a more-significant warming trend relative to the same analysis performed for the 2013 MCCIP review (Figure 8).

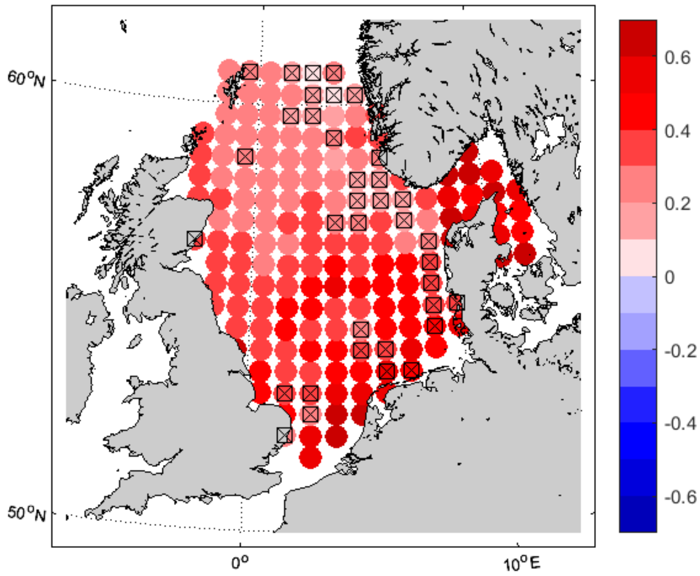


Figure 8: Linear trend (°C/decade) in Winter Bottom temperature calculated from the ICES International Bottom Trawl Survey Quarter 1 data for the period 1981–2018. Values calculated from linear fit to data in ICES rectangles. Hatched areas have a trend which is not significant at the 95% confidence level (alpha=0.05) using Mann-Kendall non-parametric test for a trend.

Eastern English Channel (Charting Progress Region 3)

Sea-surface temperatures in the Eastern English Channel displayed no significant trend until the mid-1990s when temperatures began to increase (Figure 7E). No data were recorded for 2016, but 2017, 2014 and 2015 were the second, fourth and sixth warmest years in the 125-year record.

Western English Channel (Charting Progress Region 4)

The western English Channel, away from the coast, is mainly influenced by the inflow of North Atlantic Water from the west. Tidal currents and local weather conditions induce stratification in the spring and summer, and deep mixing in the autumn and winter. Station E1 of the Western Channel Observatory has been sampled since 1903 and lies in 75 m of water. Strong interannual to decadal scale variability is evident in this time-series data, but with a period without data this makes it difficult to identify trends, and in particular the data-gap coincides with the period of strong warming apparent in most of the other datasets at the end of the 1980s. Average or below average temperatures in the early 1980s were replaced by warmer than average waters on resumption of sampling, with particularly warm conditions around 2007, more recent years have been close to but slightly higher than average (Figure 7F).

West Scotland (Charting Progress Region 6)

The Tiree Passage Mooring time–series from the Inner Hebrides has been maintained since 1981. The mooring collects hourly current and temperature measurements at a depth of ~20m (Jones *et al*., 2018) between Coll and Mull (56.62° N, 6.4° W). The time–series data up to 2014 were recently published (Figure 9; Jones *et al*., 2018) updating work used in previous MCCIP reports (Inall *et al*., 2009; MCCIP, 2013, 2017). The temperature series shows a cooling from 1981 to the mid-1980s, strong warming between 1986 and 1990, a minimum in the early 1990s and then generally warm conditions apparent between 2002 and 2008 (Inall *et al.*, 2009). As at many of the UK shelf temperature time series locations (see Figure 7 panels C, D, H and G) the years between 2008 and 2013 were slightly cooler than 2002–2008 but warm relative to the 1980s. At this location the winter of 2013 appears to have been the coldest since 1994.

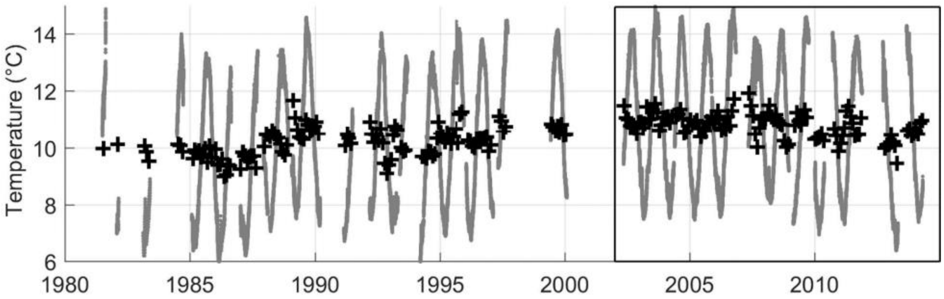


Figure 9: Hourly data from the Tiree Passage Mooring 20-m temperature time–series (grey); black crosses show month mean temperature with seasonal cycle removed. The black box indicates where salinity observations are additionally available and used by Jones et al. *(2018). (Reproduced under CCBY4 license from Jones* et al.*, (2018), doi:10.1016/j.pocean.2018.01.012).*

Open Ocean around the UK (including Charting Progress Regions 7 and 8)

For the open ocean around the UK, the water column temperature can be simply characterised by the comparison between subsurface deep ocean and the upper ocean surface layer. In contrast to the upper ocean, the subsurface deep ocean temperature is generally less variable and only indirectly influenced by the atmosphere and the seasonal cycle. Below the surface, the deep ocean around the UK is strongly influenced by changes in ocean circulation, which in turn is affected by large-scale atmospheric conditions (Holliday, 2003; Hátún *et al*., 2005). Analysis of data from profiling Argo floats has shown that the water column of the North Atlantic shallower than 1500 m has generally warmed throughout the period 1999 to 2008 (Ivchenko *et al*., 2009). Warming was strongest in the upper 1000 m and in the zone 50-70°N but there is a complex variation in changes in heat content both with latitude and with depth.

Measurements taken in the Faroe-Shetland Channel show a warming trend since the mid-1980s in the upper levels of the open ocean (0–200 m), reaching a peak in 2007 (Figure 5A). Since the last full MCCIP report in 2013, temperatures have decreased, however average temperatures for 2014, 2016 and 2017 are within the 20 warmest in the record. Since the early 2000s, the deeper water of the channel, below 800m where the water has no direct contact with the atmosphere, appears to be warming, with 2017 the third warmest year on record (Figure 7B).

Upper ocean waters in the Rockall Trough (30–800 m), display a warming trend since the mid-1990s, peaking in 2007. Since 2007, temperatures have been decreasing and the last 4 years of data appear to be a continuation of this trend (Figure 7I). Deeper waters have displayed little trend over the last 30 years (Figure 7J).

Ireland

The temperature series shown in panel H of Figure 7 is undertaken off Malin Head Coastal Station, Ireland (55.39°N 7.38°W). Sea-surface temperatures have been increasing since the late eighties and most recent four years are some of the warmest in the 58-year record. 2017 was the warmest year on record, with average annual temperatures reaching 11.44°C, 2014 and 2016 were the third and fifth warmest years, respectively. 2015 was significantly cooler, although still well above the average for the time–series data (Figure 7H).

An offshore weather buoy (M3) has been maintained at 51.22°N 10.55°W off the south-west-coast of Ireland since mid-2002 (Figure 10). The data series is too short to consider trends, but has shown considerable interannual variability during its first decade of deployment. The highest recorded summer sea-surface temperatures were in August 2003 (19.2°C), and the highest winter temperatures in 2007. In 2017, the buoy was out of operation during August and September. Temperatures were around average (2003–2010) for the time–series mean during January February March, June and July and above average during April, May, November and December.

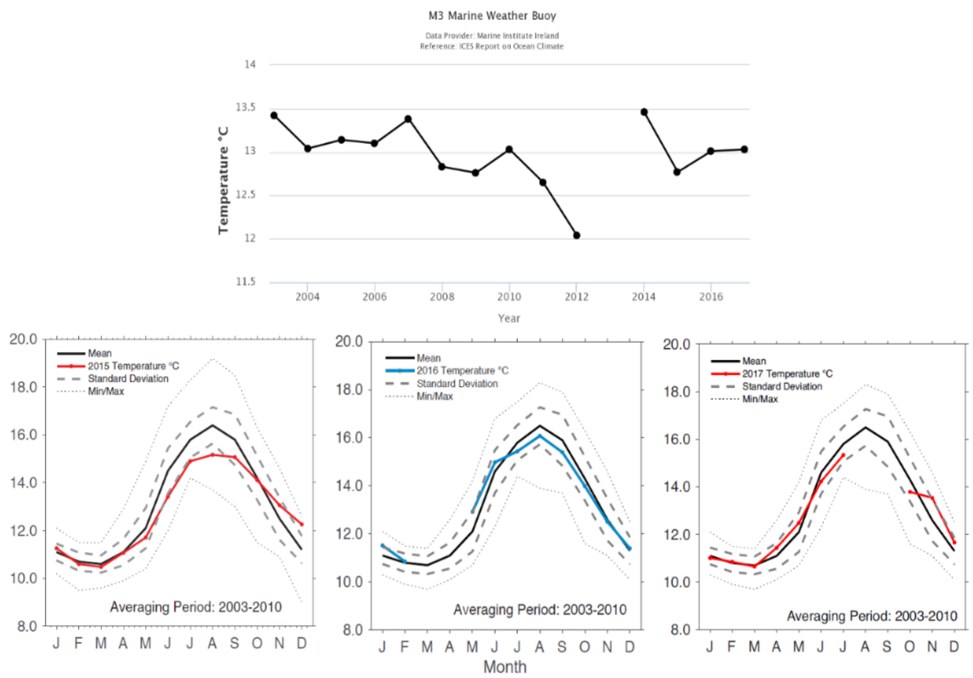


Figure 10: Ireland M3 Weather Buoy south-west of Ireland (51.22°N, 10.55°W). Upper panel show the time–series of annual average sea-surface temperature, the lower panels show the 2015, 2016 and 2017 monthly temperature respectively, compared with the 2003–2010 average monthly seasonal cycle and maximum/minimum observations in the period. (Reproduced from IROC2015- Larsen et al.*, 2016, IROC2016 -González-Pola* et al.*, 2018b, IROC2017-González-Pola* et al.*, 2018a Data Provider Marine Institute Ireland Kieran Lyons (kieran.lyons@marine.ie))*

Inter-regional comparison

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 using the Hadley Gridded Sea Surface Temperature dataset (HADISST1.1). 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 11.

When viewing the data in this format, the similarity in sea surface temperature trends across all CP2 regions is evident. Over the first 45 years of the time-series data, there is some variability with short, warm periods interspersed in a predominantly cool phase. In the mid-1990s, there is a shift to predominantly warm anomalies across all regions with 2007 and 2014 being exceptionally warm years across all regions (Figure 11).

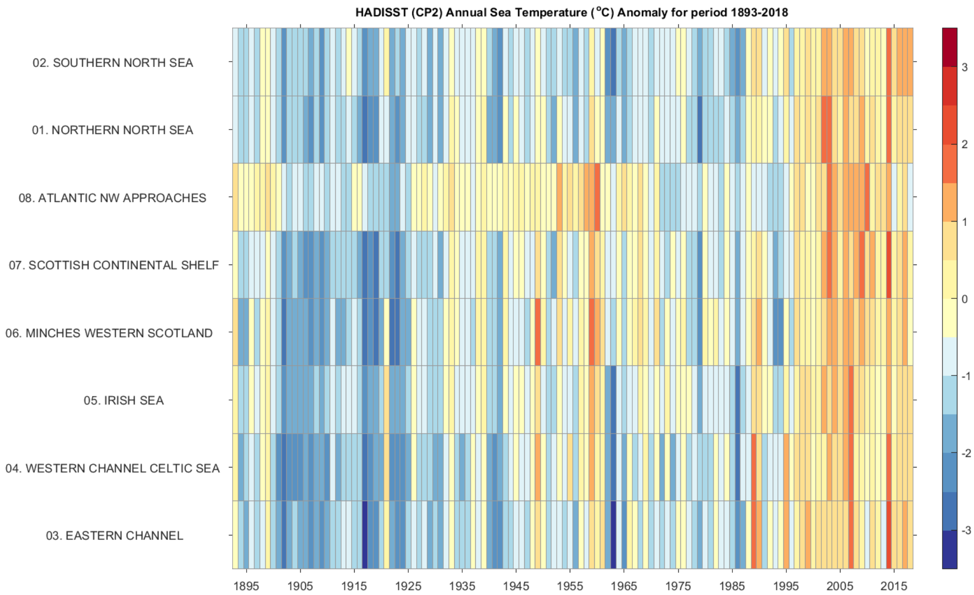


Figure 11: Anomaly plots for sea-surface temperature anomaly (°C) calculated from HADISST v1 for the period 1950–2018. Anomalies are calculated relative to the period 1981–2010 and are normalised with respect to the standard deviation (e.g., a value of +2 indicates 2 standard deviations above normal). Colour intervals 0.5; reds = positive/warm; blues = negative/cool, thicker black lines denote the boundaries of the baseline period.

2. WHAT COULD HAPPEN IN THE FUTURE?

In this section we (1) provide end of century projections for the UK, with an overview of the UKCP temperature projections and specific regional projections (2) discuss sources of uncertainty, (3) the possibility of predictions on monthly-decadal time horizons.

2.1 End of Century Projections

Overview

There exist a number of NW European Shelf Seas (NWS) Climate projections for the end of the century. There is good agreement on the sign of the temperature change on the NWS among the end of century climate projection despite their diversity (e.g. Schrum *et al*., 2016 for the North Sea). However, there is a spread in the magnitude of this warming. Most projections give a warming between 1–4°C.

UK projections: UKCP and Minerva

The UK Climate Projections (UKCP) provides a national set of climate projections for the UK. These have included a marine component, with the UKCP09 having a dedicated marine report (Lowe *et al*., 2009) and a chapter on the circulation and hydrography (including temperature) of the NWS. These NWS projections were published by Holt *et al.* (2010) as a pair of 'time slices' with no explicit estimate of uncertainty.

The UKCP09/Holt *et al.* (2010) projections were extended by Tinker *et al.* (2015, 2016), as part of the Defra funded Minerva project (Defra project number: ME5213). These projections were based on an ensemble of transient projections, designed to capture an important aspect of climate uncertainty (large-scale atmosphere parameter uncertainty). They were run from 1952–2098 with SRES scenario A1B although Tinker *et al.* (2016) focus on the end of century change (Sea-Surface Temperature (SST): Figure 12; Near-Bed Temperature (NBT): Figure 13). They projected a mean shelf SST warming of 2.90°C (with an ensemble spread of $\pm 2\sigma_{ens}$ =0.82°C Table 1).

These climate projections are available for download from the Centre for Environmental Data Analysis:
http://catalogue.ceda.ac.uk/uuid/9eba512621144dbaacda1ddb470f885b
(including the data in Figure 12 and Figure 13). Additional data are available to collaborating scientists.

One of the aims of the Tinker *et al*. (2015, 2016) was to give an estimate of impact of one of the leading sources of climate uncertainty, model parameter uncertainty (see below for more details). Their ensemble was designed to span the range of likely outcomes, given this model parameter uncertainty. They therefore reported the ensemble mean, and the ensemble standard deviation (Table 1)/ensemble variance (Figures 12 and 13) – as the ensemble is normally distributed, these two statistics provides simple way of describing projected distribution. They also compare the ensemble variance to the interannual variance, both of which are given in Figure 12 and 13.

Table 1*: Regional and annual mean SST and NBT projected changed between 1960–1989 and 2069–2098 (with spread of two ensemble standard deviations) from the UKCP09 Minerva updates (Tinker* et al.*, 2016).*

	Shelf	Southern North Sea	Central North Sea	Northern North Sea	English Channel	Irish Sea	Celtic Sea	Outer Shelf Region
dSST	2.90°C (±0.82°C)	3.26°C (±0.72°C)	3.15°C (±0.75°C)	2.75°C (±0.75°C)	3.13°C (±0.82°C)	3.08°C (±0.85°C)	3.01°C (±1.04°C)	2.50°C (±0.78°C)
dNBT	2.71°C (±0.75°C)	3.22°C (±0.71°C)	2.92°C (±0.63°C)	2.53°C (±0.63°C)	3.04°C (±0.79°C)	3.00°C (±0.82°C)	2.54°C (±0.88°C)	2.44°C (±0.80°C)

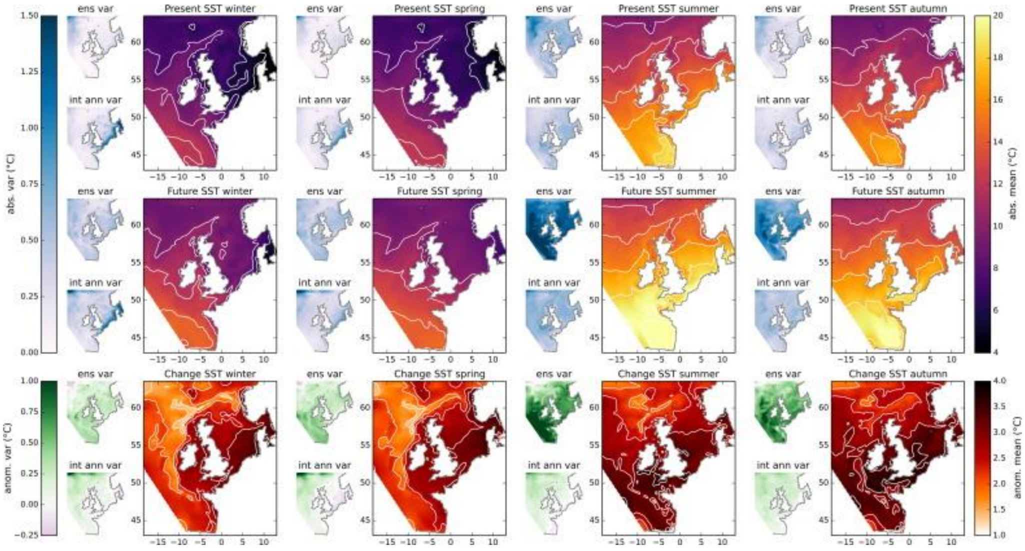


Figure 12: Projected end-of-century SST changes (2069–2098 to 1960–1989) of Tinker et al. *(2016). Each column shows a different season (Winter, DJF; Spring, MAM; Summer, JJA; Autumn, SON). The upper row shows the present day (1960–1989), the middle row show the future period (2069–2098), and the bottom row shows the difference (2069–2098 to 1960–1989). For each row and column, the main panels show the 30-year mean, and the two panels on the left hand shows aspects of the variance (upper is the ensemble variance (ens var), lower is the inter-annual variance (int var)). See Tinker* et al. *(2016) for full details.*

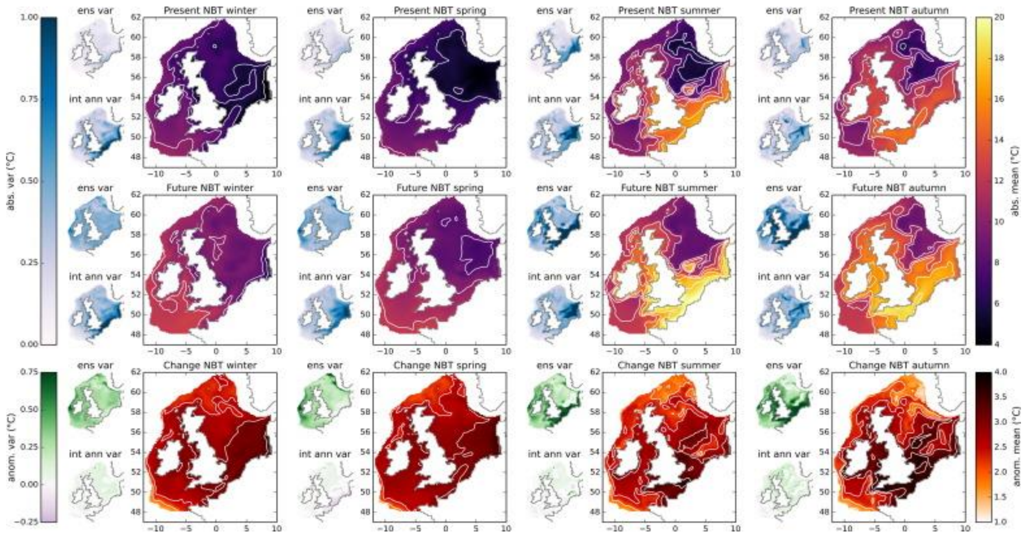


Figure 13: Projected end-of-century Near Bottom Temperature (NBT) changes (2069–2098 to 1960–1989) of Tinker et al. *(2016). Each column shows a different season (Winter, DJF; Spring, MAM; Summer, JJA; Autumn, SON). The upper row shows the present day (1960–1989), the middle row shows the future period (2069–2098), and the bottom row shows the difference (2069–2098 to 1960–1989). For each row and column, the main panels show the 30-year mean, and the two smaller panels on the left show aspects of the variance (upper is the ensemble variance (ens var), lower is the inter-annual variance (int var)). See Tinker* et al. *(2016) for full details.*

The latest UK climate projections were released in winter 2018 (UKCP18), the marine report (Palmer *et al.*, 2018) focuses on sea level (mean, extremes and waves) and does not provide an update to the MINERVA temperature projections. The modelling for the UKCP18 marine report did involve the NWS (for projections and estimates of year-to-year variability), so these may be published and released in future.

Regional Summaries

Here we give an overview of the temperature projections for the different regions.

Table 2: Projected warming (for Sea-Surface Temperature (SST) and Near-Bottom Temperature (NBT)) for the English Channel, Irish Sea, Celtic Sea and Outer Shelf (north and west of Ireland and Scotland – see inset in Figure 4) regions according to the studies of Holt et al. *(2010) and Tinker* et al. *(2016). Note that Holt* et al. *(2010) gives warming between 1960–1989 and 2070–2099, while Tinker* et al. *(2016) gives warming between 1960–1989 and 2069–2098.*

	Holt *et al.* (2010) dSST	Tinker *et al.* (2016) dSST	Holt *et al.* (2010) dNBT	Tinker *et al.* (2016) dNBT
North Sea	2.74°C	3.00°C (±0.72°C)	2.61°C	2.81°C (±0.61°C)
English Channel	2.83°C	3.13°C (±0.82°C)	2.76°C	3.04°C (±0.79°C)
Irish Sea	2.64°C	3.08°C (±0.85°C)	2.58°C	3.00°C (±0.82°C)
Celtic Sea	2.68°C	3.01°C (±1.04°C)	2.42°C	2.54°C (±0.88°C)
Outer Shelf Regions	2.25°C	2.50°C (±0.78°C)	2.25°C	2.44°C (±0.80°C)

North Sea

The North Sea is bounded by a number of European nations and is the most studied region of the NWS (in terms of temperature projections). As well as being part of studies of the wider NWS (e.g., Gröger *et al*., 2013, Holt *et al*., 2010, Tinker *et al*., 2016), there are studies focusing on both the Baltic Sea and North Sea (e.g., Schrum, 2001, Schrum *et al*., 2003a, Pushpadas *et al*., 2015), and of the North Sea alone (e.g., Ådlandsvik, 2008, Friocourt *et al*., 2012, Mathis *et al*., 2018).

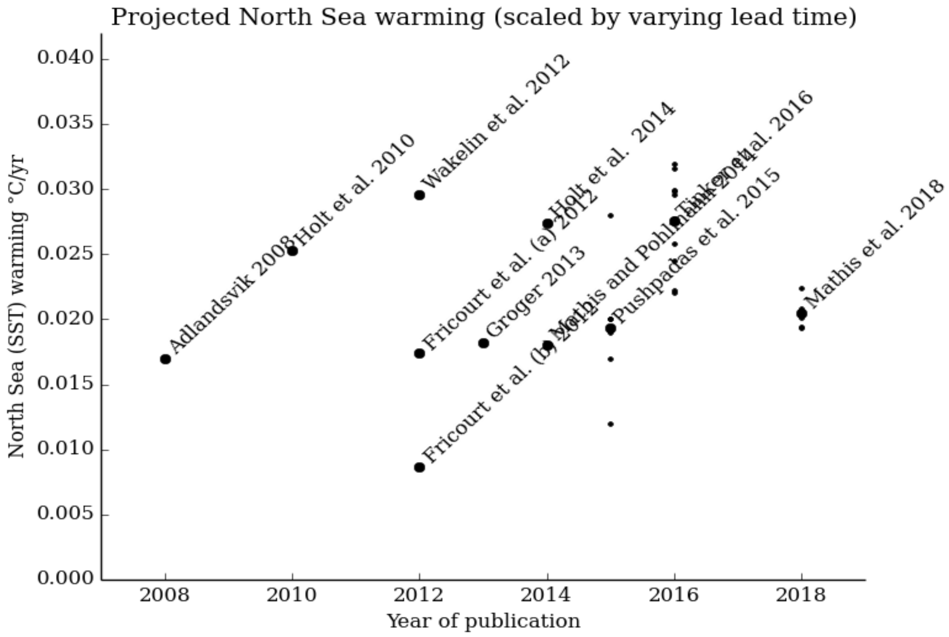


Figure 14: Comparison of SST projections for the North Sea plotted against the publication date. Most studies used give a North Sea temperature projection for a given period. These were calculated from the data for Holt et al. *(2010) and Tinker* et al. *(2016). The Friocourt* et al. *(2012) models project between 0.4°C and 0.8°C increase for the southern North Sea – these values have been used. Gröger* et al. *(2013) has about 2°C of warming over the 21st century – we have used 1960–1990 and 2070–2100 as the timeframe. 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 as small dots). Mathis et al. (2018), Wakelin* et al. *(2012) and Holt* et al. *(2016) values were estimated by digitising the figures from their papers.*

All studies agree that the North Sea is warming on a multi-decadal time-scale, however, there is a range of estimates of the magnitude (Figure 14), which depend on methodology, averaging periods, driving General Circulation Models (GCMs, also known as global climate models) and other uncertainties described in more detail in the ‘Model Comparison’ section, below. In order to illustrate the spread of these magnitudes, we have plotted the effective rate of warming derived from a range of studies in Figure 14, while the values from Holt *et al*. (2010) and Tinker *et al*. (2016) are given in Table 2.

Irish Sea

There has been one climate projections study that has focused on the Irish Sea (Olbert *et al*., 2012), and a number of studies which include the Irish Sea within the wider NWS (e.g., Holt *et al*., 2010, Tinker *et al*., 2016).

Olbert *et al.* (2012) found SST and depth averaged warming of 1.89°C and 1.79°C respectively between the 1980s and the 2090s. Holt *et al.* (2010) found an SST warming of 2.64°C (NBT = 2.58°C) between two time slices (1960-1989 and 2070-2099), while using a related methodology, Tinker *et al.* (2016) found an SST warming of 3.08°C with an ensemble spread of $\pm 2\sigma_{ens}$ = 0.85°C (NBT = 3.00°C $\pm$ $2\sigma_{ens}$ = 0.82°C; with slightly different time slices 1960–1989 and 2069–2098). Irish Sea SST warming estimates are summarised in Figure 15.

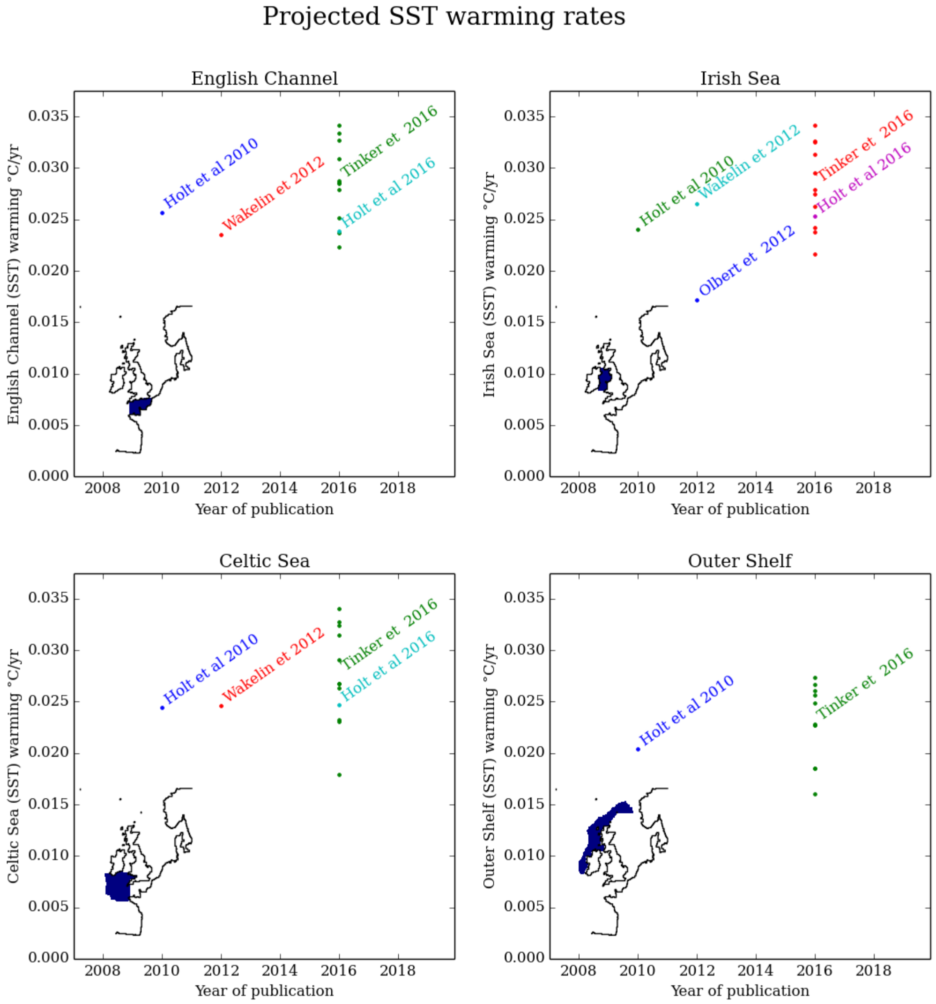


Figure 15: As with Figure 14, but for other regions. Inserts show the geographical extent of the regions.

English Channel, Celtic Sea, and Outer Shelf Region

The other regions around the UK have not had dedicated studies, and so we rely on results from the wider NWS projections. The studies of Holt *et al.* (2010) and Tinker *et al.* (2016) are summarised in Table 2, where Holt *et al.* (2010) gives warming between 1960–1989 and 2070–2099, while Tinker *et al.* (2016) gives warming between 1960–1989 and 2069–2098. SST warming estimates sorted by year of publication are summarised in Figure 4.

2.3 Sources of uncertainty

Model comparison

There is now a considerable body of research providing climate projections of sea temperature for the UK waters and the North West European Shelf seas (NWS). Across all the studies, there is a consistent agreement on the sign of the NWS temperature change. However, due to the variety of experimental designs, model domains, and averaging periods, it is difficult to quantitatively compare the magnitudes of the projected warming. Additionally, there are many studies investigating the NWS ecosystem response to climate change (e.g. Holt *et al*., 2012; Wakelin *et al*., 2012; Holt *et al*., 2016) – which also consider temperature change.

General Circulation Models are the most credible tools to make climate projections (Lowe *et al*., 2009). However, due to model resolution and missing processes (e.g. tides), they are typically poor at representing the NWS. Dynamical downscaling (with a regional shelf-seas model) is a well-established method to improve the representation of the NWS (or other regions) in a GCM. This approach uses the model output from the GCM as model input for the shelf seas models. This can provide a realistic simulation of the NWS under a projected future climate. Most studies considered in this report use a version of this approach (i.e. Holt *et al.* 2010; Wakelin *et al.* 2012; Tinker *et al.* 2016).

There are a number of sources of uncertainty in climate projections (including for NWS sea temperature projections) but there have been few studies (such as Wakelin *et al*., 2012; Pushpadas *et al*., 2015; Tinker *et al*., 2016) that systematically and comprehensively explore these sources. This has been a focus of terrestrial projections for many years, but uncertainty quantification in the NWS temperature projections is still in its infancy.

The North Sea Regional Climate Change Assessment (NOSCCA, 2016) has been published. This is an IPCC-style assessment of the recent and future climate of the North Sea and its surroundings. There have also been a few new studies published but much of the content presented in the 10-year report is still relevant.

Improving methodology

Over the last decade there has been evolution and improvement in the methodology used for climate projections of temperature change on the NWS (and regions within). In general:

- Time slices with delta change (creating future boundary conditions by adding a warming (delta temperature) to the present-day boundary conditions) have been superseded by time slices where both present day and future boundary conditions are from climate models. These have again been superseded by transient simulations. The prior delta change approach allowed the use of biased GCM forcings and thus this tendency towards transient simulations may reflect improvements in the underlying GCMs.
- The resolution has increased (e.g. 12 km in Holt *et al.* (2010) and 3 km in Mathis and Pohlmann (2014))
- There is increased evidence of the importance of using coupled regional models (e.g. Mathis *et al*., 2018)
- There has been increased focus on marine biogeochemistry, with temperature of secondary interest.

Climate projection uncertainty

There are several different types of uncertainty associated with climate projections that will be present in NWS temperature projections: emission scenario uncertainty (how will emissions evolve over time), initial condition uncertainty (how well do we know the conditions at the start of the model period), model structure uncertainty (differences due to modelling frameworks), model parameter uncertainty (how well known are the parameters that are set in the model) and model coupling (how do models link together different systems) approach.

Although there are studies for most of these categories (e.g., Tinker *et al*., 2016; Pushpadas *et al*., 2015), there are few systematic (with an experiment designed to quantify/qualify that aspect of uncertainty) and comprehensive studies that allow each source of uncertainty to be assessed. Of the studies that systematically address climate projection uncertainty, most contrast just two simulations – giving a minimum estimate of uncertainty. Nonetheless, there are now sufficient numbers of studies to build an ensemble of opportunity that allows some (minimum) assessment of these categories of uncertainty by comparing different model studies with similar model set ups (see below). Such ad-hoc comparisons are complicated by differences in time periods, model domains etc. and so often only qualitative assessments can be made.

Emission scenario uncertainty

There has been surprisingly little attention given to emission scenario uncertainty. Almost all CMIP3 based studies have focused on SRES A1B (e.g. Gröger *et al*., 2013; Holt *et al*., 2016; Holt *et al*., 2010; Mathis and Pohlmann, 2014; Tinker *et al*., 2016; Wakelin *et a*., 2012), and recent CMIP5 studies on RCP4.5 (e.g., Wakelin *et al*., 2012; Pushpadas *et al*., 2015). There are currently no studies published that systematically assess emission scenario uncertainty (i.e. the same models and set up, but with different emission scenarios). This is in contrast to terrestrial climate projections where this is often one of the first uncertainty aspects considered (e.g. Murphy *et al*., 2009).

Initial condition uncertainty

Initial condition uncertainty (where the initial state is perturbed) has not been considered in NWS projections but given the boundary constrained nature of the NWS (e.g., Holt *et al*., 2016), this is likely to be negligible for end of the century projections of SST change.

Model structural uncertainty

Due to differences in the choice of numerical schemes and parameterisation of processes (see next section), different GCMs project different magnitudes of warming, even under the same experimental design – hence the CMIP comparisons (Taylor *et al*., 2012). The choice of the GCM boundary conditions has a big impact on NWS climate projections. All modelling centres try to develop the best possible model, particularly when evaluated against observations, so there is a potential that this may act as selection bias and impact on the possible uncertainty captured with an ensemble of opportunity (such as the CMIP). The choice of regional atmosphere model to downscale the European atmosphere, and the shelf seas model used to produce the NWS projections are also sources of uncertainty.

Systematic (e.g. Pushpadas *et al*., 2015; Wakelin *et al*., 2012) and *ad hoc* (e.g. Holt *et al*., 2012, Holt *et al*., 2016, Holt *et al*., 2010) studies of the GCM multi-model uncertainty suggest this is a major source of NWS temperature projection uncertainty and may lead to an uncertainty in SST of 2°C (Schrum *et al*., 2016). Systematic (Bülow *et al*., 2014; Wakelin *et al*., 2012) and *ad hoc* (Gröger et al., 2013; Holt *et al*., 2016; Mathis, 2013), studies of shelf seas model structure uncertainty suggest it is much smaller, of the order of 0.1°C (Schrum *et al*., 2016).

Model parameter uncertainty

In addition to the choice of the driving (and downscaling) model, the choice of parameters within the model physics of these models can be a significant source of uncertainty. This aspect of climate projection uncertainty requires significant model computation and model development to be undertaken by the GCM modelling community, and so there are few such GCM Perturbed Physics Ensembles (PPEs) (e.g. Stainforth *et al*., 2005; Murphy *et al*., 2014; Yokohata *et al*., 2010).

For the NWS, Tinker *et al.* (2016) downscaled 11 transient simulations from such a PPE, to give an estimate of this parameter uncertainty for the NWS. This led to a substantial uncertainty range of $4\sigma_{ens} = 1.6°C$ ($\equiv \pm 2\sigma_{ens}$=0.82°C) for the NWS. There have been no published studies looking at the parameter uncertainty for the regional ocean model. However, given the estimate of the shelf seas model structural uncertainty being of order 0.1°C (Schrum *et al*., 2016), this is likely to be smaller than that of the GCM.

Downscaling and coupling approach

There are various ways in which the global and regional models can be linked together: (1) in terms of the model chain (e.g. GCM driving regional climate model (RCM), and the RCM and GCM driving the regional ocean model (ROM)), (2) the coupling (1-way or 2-way), and (3) experimental design (e.g. time slices, transient runs). Each will have strengths and weaknesses. There are now studies that investigate the impact of experimental design on NWS projections (e.g., Mathis *et al.*, 2018).

Due to the geography and tidal nature of the NWS, making SST projections based directly on the GCMs is problematic, but there were early studies using this approach (e.g. UKCIP02). Early downscaling studies used a GCM to drive the shelf seas model directly (e.g. Ådlandsvik, 2008), but most use atmospheric forcings from an intermediate regional atmosphere-only climate model (e.g. Holt *et al*., 2010; Tinker *et al.*, 2016). Recent studies have also used atmospheric forcings directly from a GCM with higher atmospheric resolution (through a local 'zoom' (e.g. Gröger *et al*., 2013) or through improved model atmospheric resolution).

The use of 'time slices', where two model runs for the present day and future are contrasted (either using GCM forcings or delta-change, where the future forcings are created by adding a 'warming' offset to the present day forcings), are now often being replaced by transient simulations, where the model is run continually from the present day (or pre-industrial times, e.g. Gröger *et al*., 2013) to the future period of interest. This has a number of benefits, including allowing the robustness of the modelled temperature change to be compared to low frequency variability (Tinker *et al*., 2016), and allowing sufficient time for the slowly evolving open ocean (adjacent the NWS) to respond to the surface fluxes.

Most studies use one-way coupling, where the atmosphere affects the ocean, but the ocean cannot feed back into the atmosphere. However, an early study of the North Sea present day, identified the importance of this feedback on the North Sea temperature (Schrum *et al*., 2003b). Bülow *et al.* (2014) presented three coupled regional atmosphere-ocean models for the North Sea, which had analogous uncoupled versions (Mathis *et al*., 2013; Wakelin *et al*., 2012). This showed that the coupling led to a similar projected value, but the uncertainty spread associated with the different regional models was greater compared to uncoupled models (Schrum *et al*., 2016).

A recent study by Mathis *et al.* (2018) systematically explored the impact of different coupling approaches, including that of 1-way and 2-way coupling, and found that this can have a large effect on the projected temperatures (~0.4°C difference between their CF and RF). They found that the un-coupled model simulations were tightly constrained by the global fields, whereas the coupled runs were able to evolve freely.

Probabilistic projections

Terrestrial climate projections are converging on an experimental design for probabilistic climate projections (e.g. Harris *et al*., 2013; Murphy *et al*., 2007; Murphy *et al*., 2014), where probabilities are assigned to the different temperature thresholds for a given location and time. This is a complex undertaking that requires all sources of climate projection uncertainty to be assessed, and very good observation datasets. The state of the art for marine climate projections is a long way behind this and, due to the sparsity of the observational network (relative to its terrestrial equivalent), this may not be possible.

Other time horizons

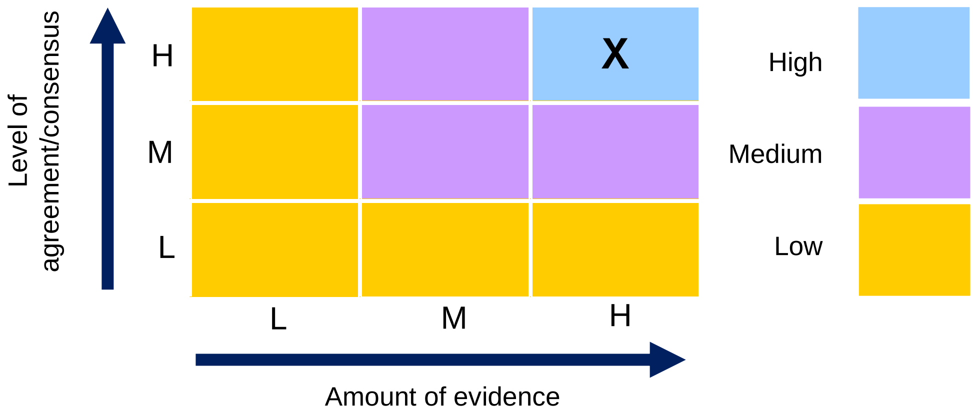
Beyond 5-day operational forecasts, there are far fewer studies for other time horizons: monthly-seasonal; decadal; near future projections or mid-century projections. Making predictions and projections of the future state of the NWS is a balance between two drivers – persistence of initial conditions being overcome by the chaotic nature of the climate system, and the emergence of the forced climate signal from the climate variability (i.e. initialisation versus external forcing). Operational forecasts of the very near future rely on the predictable nature of the weather to provide forecasts before they are overcome by chaos. However, end of century climate projections do not need to consider the present-day state of the variability as the climate signal is so strong, and the system has had so long to evolve that any memory of the present day conditions is overwhelmed. In the time periods between these two extremes, both mechanisms have to be considered, and so monthly forecasts to mid-century projections are far more difficult to make. Consequently, there are no specific NWS projection/predictions published within this period. There are global systems that will include the NWS but are unlikely to treat the NWS realistically (particularly in the summer, when much of the NWS is stratified) and so they must be interpreted with care.

The Met Office Global Seasonal forecasting system GloSea5 (MacLachlan *et al*., 2014) has demonstrated skill at forecasting the winter NAO (North Atlantic Oscillation) months ahead (Scaife *et al*., 2014). The NAO is the dominant mode of climate variability over Europe, so this may provide a basis for seasonal forecasts of the NWS. Tinker *et al.* (2018) have shown that it may not be appropriate to use GloSea5 directly for the NWS. They outline two other approaches: building parametric models based on the NAO (with a demonstration forecast for the southern North Seas); and dynamically downscaling GloSea5 with a shelf seas model. The NWS response is tightly coupled to the boundary conditions, so Tinker *et al.* (2018) consider that this approach may be possible. Additional work is being undertaken at the Met Office to explore this approach.

On multi-annual to decadal timescales, recent work has highlighted that the skill (and thus potentially utility) of predictions of the dynamics of the North Atlantic Ocean (an important driver of the NWS) is very hard to determine based on the past observational record and ocean state estimates (Menary and Hermanson, 2018). Further work to understand the uncertainties in these ocean state estimates, in particular in the amplitude of annual temperature and salinity variability, is required. Finally, we also note that on centennial timescales, the wider North Atlantic (excluding the NWS) is projected to warm far slower than the global mean in all climate models (Menary and Wood, 2018). However, the pattern of this relative cooling varies greatly between models, which implies further uncertainties in the response of the NWS to these somewhat different boundary conditions.

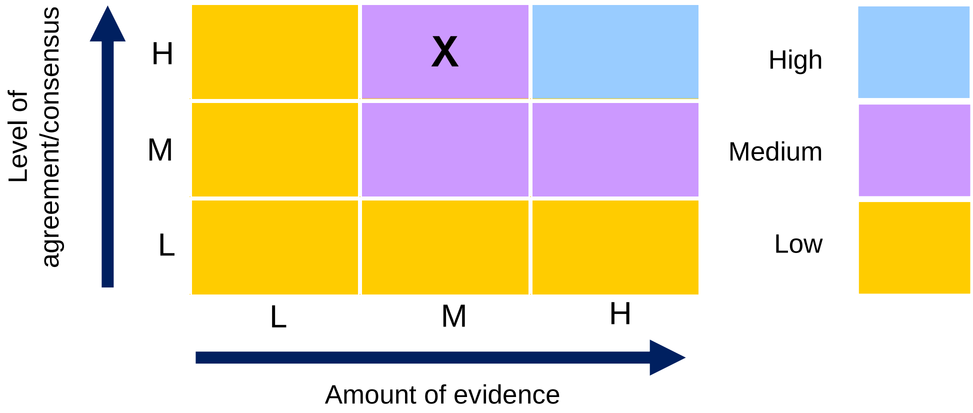
3. CONFIDENCE ASSESSMENT

What is already happening



Sea-surface temperatures are one of the most-measured parameters in the ocean, as a result there are high levels 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-term variability, giving rise to a higher level of confidence in the results. Reductions in marine air temperature measurements are also noted, but here well-established reanalysis (that use observations integrated into models) can be used to maintain confidence.

What could happen in the future?



There is high confidence in the global rise in SST is high (e.g. IPCC, 2007) and there is high confidence in the long-term future warming trend. However, our confidence in the exact rates of warming at regional scales is lower. Since 2013, more evidence has been produced, with multiple studies of each of the regions around the UK and development of multi-run ensembles that have enabled us to understand model uncertainty versus climate variability in the projections. Although the number of studies have increased, and there are a good range of studies in the North Sea other regions around the UK have not had dedicated studies, and so we rely on results from the wider NWS projections.

4. KEY CHALLENGES AND EMERGING ISSUES

1. Projections tend to focus on the end of the century; however, there is a requirement for greater accuracy in predictions of SSTs over shorter (monthly-seasonal; decadal; near future projections or mid-century) timescales. Shorter projections would better align with management and policy decision timescales and provide a solid basis for more adaptive management measures.
2. Ocean scale influence on shelf-sea temperatures, the causes and effects of change in the North Atlantic subpolar gyre and the extent that we understand how this will change into the future. Holt and co-authors (2018) recently published the first paper direct oceanic link between climate-driven change in the North Atlantic and Arctic Oceans with an end of century scenario that had a dramatically reduced inflow of Atlantic water into the North Sea.

3. The long-term warming trend has also increased the frequency of discrete periods of regional extreme temperatures (marine heatwaves). Smale *et al.* (2019) identify the North Sea as a region where there are a high proportion of species are at the edge of their range of thermal tolerance and high levels of non-climatic human stressors and marine heatwave intensification has concurrently affected the ecosystem. More research is required on the near-shore experience of heat wave conditions and the extent to which these affect industry, society and ecosystems.

Acknowledgement: *Jonathan Tinker was supported by the Met Office Hadley Centre Climate Programme, funded by BEIS and Defra.*

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Data sources in Figure 7: using IROC2017 time–series data (González-Pola *et al*., 2018a).