The Impacts of Climate Change on Sea Temperature around the UK and Ireland

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KEY FACTS

What is already happening?

- Sea surface temperature (SST) around the UK generally shows a significant warming trend of around 0.3°C per decade over the last 40 years.
- Regional variations exist in this trend with surface warming being greatest across the southern North Sea and least across the north-west of the domain.
- Warm-season (Autumn) near-bottom temperatures have increased significantly across the southern North Sea over the last 30 years, but not across other regions of the domain.
- Compared to 1982–1998, the annual number of marine heatwaves increased around the British Isles by an average of four events per year in the period 2000–2016. Larger increases of up to six additional events per year occurred to the north of the British Isles. Smaller changes occurred to the south of the region.

What could happen in the future?

- Model simulations indicate a continuing warming trend around the UK, with average annual mean SST values of 3.11°C (±0.98°C) predicted for the end of the century (2079–2098) greater than current conditions (2000–2019) under the business-as-usual RCP8.5 scenario.
- The warming is expected to be greatest across the North Sea in both SST and bottom temperatures, which is a continuation of the spatial pattern of trend observed in recent decades. The warming is expected to be weaker at the surface in the subpolar North Atlantic.

SUPPORTING EVIDENCE

What is already happening?

Trends in Sea Surface Temperature

This report is an update to the previous MCCIP report (Tinker and Howes, 2020) on temperature change in the seas around the UK. On a global mean basis, the last eight years (2014–2021) have been the warmest in the sea-surface temperature (SST) record that extends back to 1850 (Figure 1). Average SST anomalies across the Northern Hemisphere were similarly warm, with 2020 being the warmest year in the record with a value of 0.93°C (±0.06°C) above the 1961–1990 average.

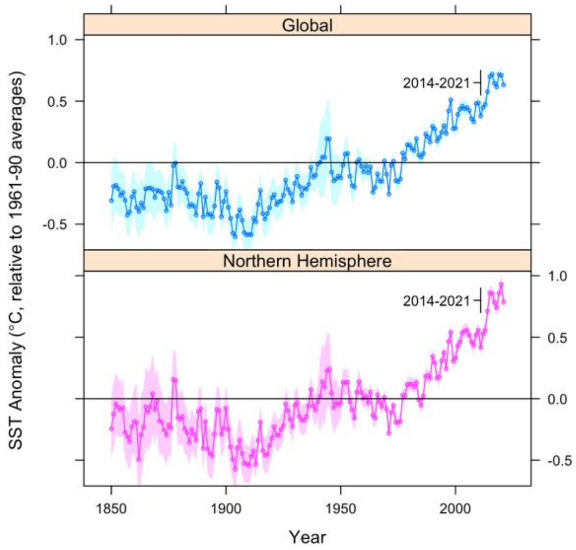


Figure 1*: Average SST anomalies from 1850 to 2021 for the Northern Hemisphere* and *global oceans. The shading areas indicate the ±2σ uncertainty range. Data were obtained from the HadSST4.0.1.0 dataset (Kennedy* et al.*, 2019)* and *are expressed as anomalies from the 1961-1990 average.*

Marked local and regional variations are embedded in the global average trend. The average UK near-coastal SST for the last decade (2012–2021) was 0.7°C warmer than the 1961–1990 average and 0.1°C warmer than the 1991–2020 average. The top ten warmest years in the series back to 1870 all occurred after 1989, and 9 out of 10 of those occurred after 2002 (Kendon *et al*., 2022).

The trend in SST across the North-east Atlantic, including the UK coasts, over the last 40 years is shown in Figure 2. The strongest warming trend across this domain occurred in the southern North Sea where values of greater than 0.4°C per decade were experienced. Trends were lower to the west of the UK with values of 0.1–0.2°C per decade observed across that region. The trends continue to decrease towards the central subpolar North Atlantic, where the warming trend (1982–2021) is not significant at the 95% significance level.

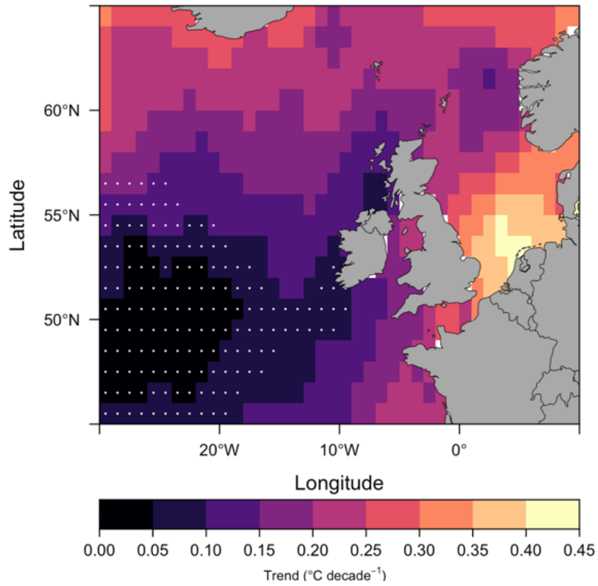


Figure 2*: Linear trends in annual average SST (˚C per decade) over the period 1982–2021. The white dots indicate grid-cells where the trends are not significant at the 95% confidence level. The data were obtained from the HadISST dataset (Rayner* et al.*, 2003).*

The absence of the positive SST trend, or even a negative SST trend, is sometimes referred to as the North Atlantic 'cold blob', North Atlantic 'cold anomaly' or 'warming hole'. It is a persistent feature in historical SST observations and future projections. Superimposed on the trend, the extent, amplitude, and exact distribution of the cold anomaly varies on decadal (Årthun *et al*., 2021) and interannual timescales, with some recent years experiencing particularly intense cold anomalies (Figure 3, Josey *et al*., 2018; Maroon *et al*., 2021).

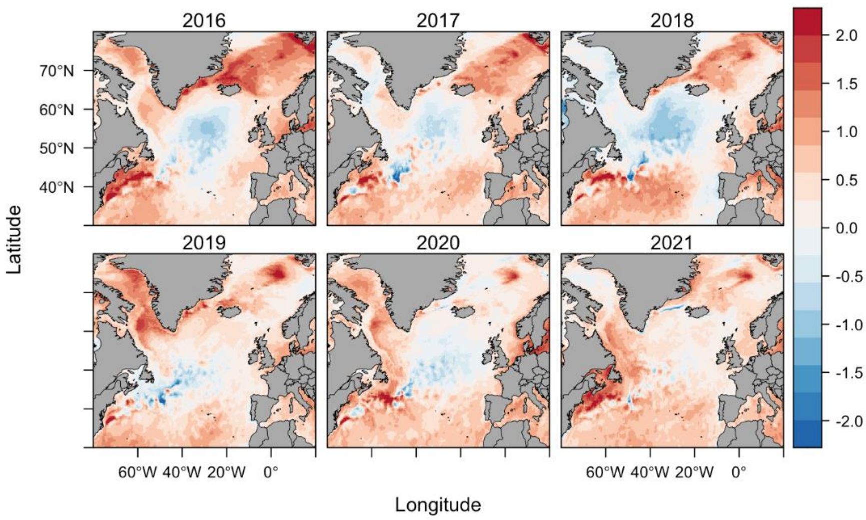


Figure 3: *Maps of annual average SST anomalies across the North Atlantic for the years 2016 to 2021. These values were calculated from the ESA SST CCI OSTIA L4 data product (Good* et al*. 2019). Anomalies are in the unit of degrees Celsius and are relative to 1982–2010 averages.*

Observations show that past cold anomalies were linked to freshwater anomalies (Oltmanns *et al*., 2020), and that different ocean and atmospheric feedback processes subsequently reinforced the cold anomaly (Josey *et al*., 2018; Duchez *et al*., 2016; Oltmanns *et al*., 2020; Fox *et al*., 2022). In addition, the North Atlantic cold anomaly in the subpolar region has been suggested to indicate a slowdown of the Atlantic Meridional Overturning Circulation (Caesar *et al*., 2018).

While there is still a large uncertainty around the influences of the subpolar cold anomaly, initial evidence suggests that it has substantial effects on the large-scale atmospheric circulation. Specifically, it is thought that the associated increased south–north SST gradient over the North Atlantic promotes the development of storms (Oltmanns *et al*., 2020). Thus, consistent with the extreme cold anomalies, the winters in 2014/15 and 2015/16 were characterised by intense winter storms causing flooding over the UK (Barker *et al*., 2016). It has further been suggested that the cold anomalies can modulate the course of the summer jet stream over the North Atlantic and thus influence European summer heat waves and droughts (Duchez *et al*., 2016; Mecking *et al*., 2019; Oltmanns *et al*., 2021).

The region of cool anomalies in the central-north Atlantic was noted in the previous MCCIP temperature report (Tinker and Howes, 2020). Evidence was presented in that report that the cool anomalies developed during the winter 2013/2014. The updated evidence presented here indicates a weakening in the cool SST anomalies in recent years, with annual mean values during 2021 being close to the 1982–2010 average (Figure 3). However, the interannual/decadal variability in SST is relatively strong in this region and as such this sample of six years cannot be taken as representative of the longer-term trend.

Marine Heat Waves and Cold Waves

Since the publication of the previous MCCIP report on marine temperature (Tinker and Howes, 2020), considerable research has been conducted on marine heat waves globally. Marine Heat Waves (MHWs) are periods of localised anomalously warm sea temperature that are superimposed on the long-term warming of the upper ocean (Oliver *et al*., 2021). MHWs last for several days or weeks, and potentially for several months, and can have profound effects on global marine ecosystems (Collins *et al*., 2019). Marine cold waves represent the other extreme of temperature conditions, where anomalously cold sea temperatures are experienced for a period.

Although some of the most extreme MHWs have occurred in the seas around Australia, they have been detected in most ocean basins in recent decades (Oliver *et al*., 2021). Importantly, the spatial pattern of these trends does not simply mirror the trends in monthly or annual SST averages. As such, tailored indices using high-temporal resolution SST datasets are required for monitoring changes in these events. In this report the results from MHW indices are presented from the widely applied threshold exceedance statistics (see Appendix). Comparing the two 17-year periods 1982 to 1998 and 2000 to 2016 (after Oliver *et al*., 2018), MHWs increased in frequency by an average of 3.8 events per year around the British Isles (12°W-5°E; 49-60°N) in the latter period, with a range of 0 to 4.5 events depending on location (Figure 4). Larger increases occurred to the north of the British Isles, where an increase of up to six additional events were experienced on average in the 2000 to 2016 period compared to 1982 to 1998. The increases in the higher latitudes of the North-east Atlantic (north of 50° N) were the highest globally over that timeframe (Oliver *et al*., 2018). Evidence is also presented using the data recorded at the Western Irish Sea (WIS, 53.78° N; 5.63° W) oceanographic mooring station. This is the only instrumented oceanographic mooring station that currently provides the required 25 years of continuous monitoring to adequately identify MHWs against the background climatology (Hobday *et al*., 2016a). These data indicate that 45 MHW events where recorded between 1997 and 2022 (Figure 4b). The series highlights the high degree of interannual variability in MHWs in the seas around the UK although there is no evidence of a change in the duration of MHWs over that period at that location.

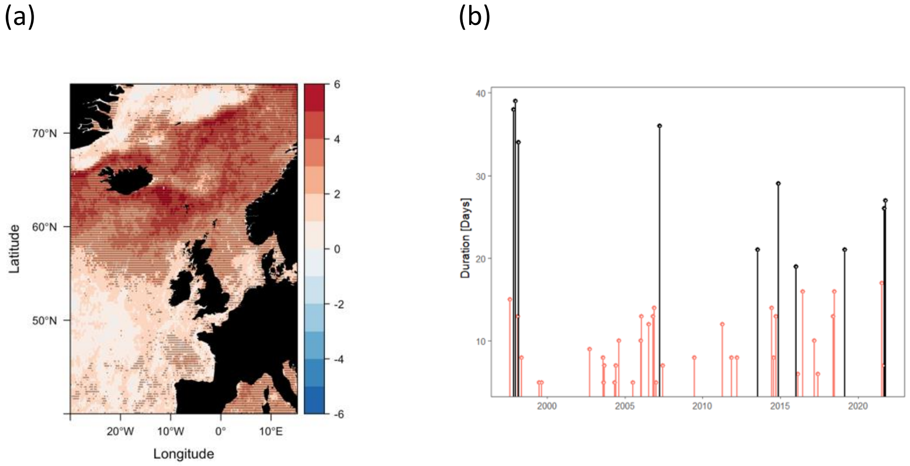


Figure 4: *(a) The difference in the average number of MHW events over the period 2000-2016 compared to 1982-1998; (b) the duration of marine heatwave events recorded in the western Irish Sea between 1997* and *2022, with values above 20 days highlighted in black. (a) Is re-plotted after fig. 1b in Oliver* et al. *(2018)* and *restricted to the North-east Atlantic region. Stippling in (a) indicates significant differences in the means of the two periods at the 95% level.*

Relatively few studies have examined the influence of MHWs on marine ecosystems around the UK. An exception is the analysis by Wakelin *et al*. (2021) who analysed the occurrence of MHWs and of cold waves across the North Sea using near-bottom temperature data from the north-west European Shelf re-analysis dataset, and the effect of these events on fisheries in the region. Over the period 1993-2019 MHWs occurred in every year apart from 1996 and 2013, and cold waves occurred in all years except for 2016. No long-term trend was observed in these extreme events over that time. The authors identified that catches of sole and sea bass increased in years with *Cold* Waves, although catches of red mullet and edible crabs decreased. A lagged relationship was observed between MHWs and catches: catches of sole, European lobster and sea bass increased five years following a heatwave, whereas catches of red mullet decreased after these events at that lagged interval.

Regional Changes in Sea Temperature

As with earlier reports (Dye *et al*., 2013; Hughes *et al*., 2017; Tinker and Howes, 2020) we have examined regional changes in sea temperature (both at the surface and at depth), using the UK Charting Progress Regions as the basis for defining regions (Figure 5). In this report we have updated the temperature series through to December 2021 where possible. We examine annual mean temperature values in this section to highlight the long-term changes in sea temperature across the region. However, it should be noted that this masks seasonal variations that may be present in the data. These seasonal variations 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' (see Sharples *et al*., 2020). This means that the temperature of the entire shelf area experiences strong seasonal cycles. Furthermore, recent research across the North Sea has indicated that while thermal stratification occurs in the Northern North Sea during the warm season each year, it only occurs in the Southern North Sea during years that experience a marine heatwave (Chen *et al*., 2022). This suggests that these extreme events may lead to changes in marine hydrodynamics that could lead to certain ecosystem changes.

North Sea (Charting Progress Regions 1 and 2)

In the most northern part of the North Sea, the temperature is influenced by inflowing water from the North Atlantic, showing similar decadal variations to the water in regions 7 and 8 and a strong increase in temperature since the mid-1980s. In the time series of SST from the Northern North Sea at 0-100m depth (Fig. 5c) most years since 2000 have been above the 1991-2020 average, while all years before that time were below the average.

In the Southern North Sea, atmospheric forcing has a dominant influence on temperatures. Since the mid-1980s, temperatures have generally been higher than the long-term average, although values during 2010-13 were below the average (Figure 5D; note the different reference periods in this and Figure 5C). This region has experienced the strongest positive trend across all regions in the last 40 years (up to 0.5°C per decade; Figure 2); this is not readily apparent in Figure 5D due to a lack of data after 2017.

A significant increase (95% confidence level) in autumn bottom-temperatures (the warmest season) is seen across the southern North Sea and the English Channel over the period 1993-2021 (Figure 6). While this analysis is limited by the relatively short duration, an important difference is apparent during the spring season (the coolest season), where there is no significant temperature trend over that period.

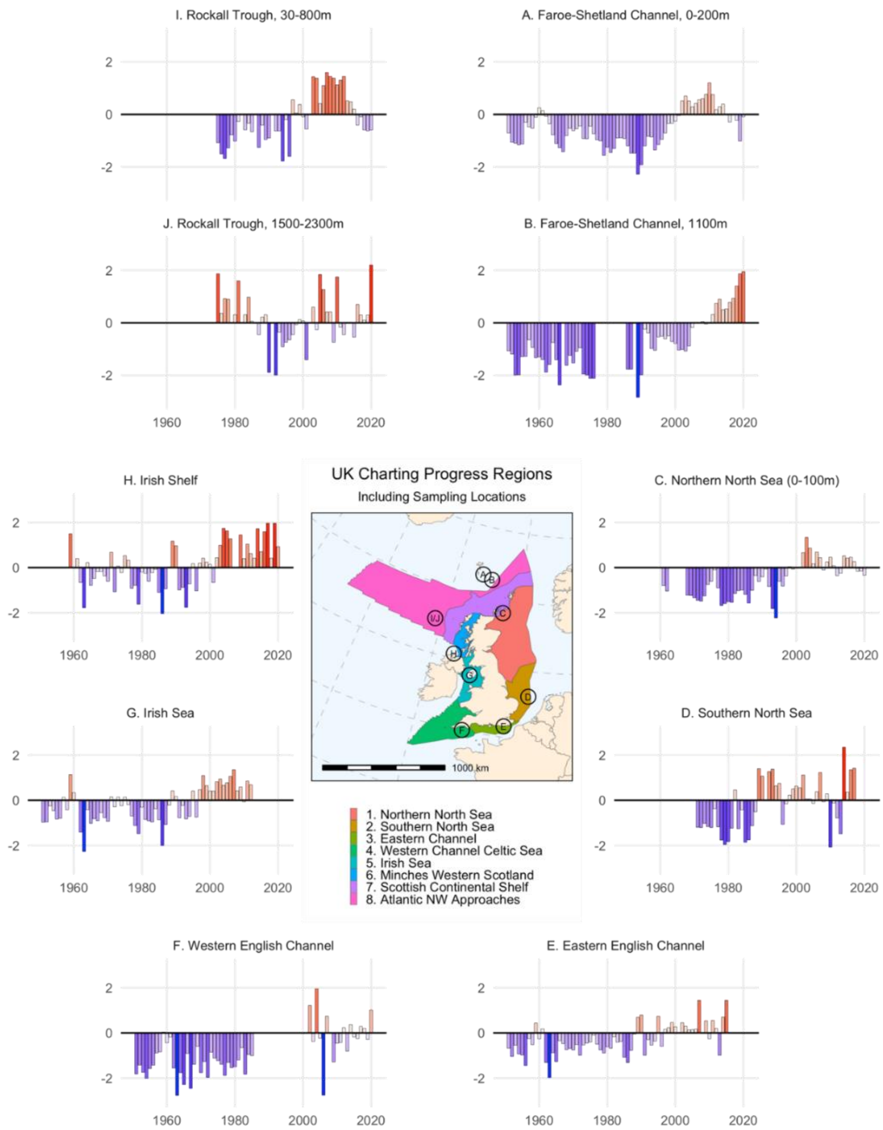


Figure 5*: Normalized sea temperature anomalies at a selection of stations distributed across the UK Charting Progress (CP2) regions. A: Faroe-Shetland Channel, 0-200 m. B: Temperature of overflow water in Faroe-Shetland Channel at 1100 m. C: Northern North Sea surface (0-100 m). D: Felixstowe-Gabard Ferry submerged smart buoy. E: Eastbourne coastal monitoring site. F: Western Channel Observatory Station E1. G: Irish Sea series, combining the Port Erin, Isle of Man series until 2011* and *the Western Irish Sea Data Buoy series (53.78º N; 5.63º W) thereafter. H: Malin Head coastal station (55.37°N 7.34°W). I: Rockall Trough 30-800 m. J: Rockall Trough, temperature in the Labrador Sea Water layer (1500-2300 m). See the Appendix for full details about the providers of the data.The data have been normalised by subtracting the base period mean* and *normalising by the standard deviation. As a result the scale represents temperature standard deviations from the reference period mean. A reference period of 1991-2020 is used in these calculations, except for D and E where 1981-2010* and *1991-2015 is used respectively due to the data not being available for more recent years. In F, the reference period is 2002-2020 due to missing data over the period 1986-2001. Certain time series extend back to the nineteenth century, however only data for the period after 1950 are plotted here.*

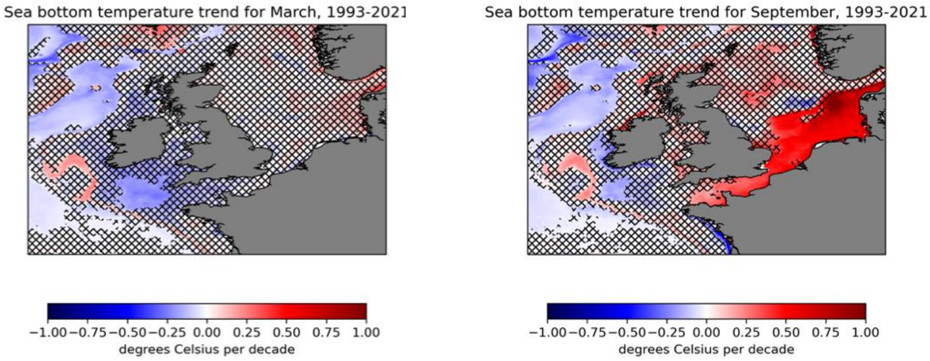


Figure 6: Linear trend (°C/decade) in Bottom temperature calculated from the north-west European Shelf re-analysis data for the period 1993-2021. Values calculated from linear fit to data in each grid-cell. Hatched areas have a trend which is not significant at the 95% confidence level (alpha=0.05) using the Mann-Kendall non-parametric test for a trend.

Eastern English Channel (Charting Progress Region 3)

SSTs in the Eastern English Channel displayed no significant trend until the mid-1990s; after that time temperatures began to increase (Figure 5E). SST has continued to rise and all annual mean values, apart from during 2010 and 2013, were above the base period average. The series used in Figure 5E was recorded at Eastbourne (50.8N; 0.3E) and provides a continuous series of data from 1892 to 2015 (although only data after 1950 are plotted in Figure 5). Over that time the ten warmest years were all recorded after 1989, with the highest being 2015 when a temperature of 1.9°C above the 1991 to 2015 average was recorded. A similarly high annual mean temperature anomaly of 1.8°C was recorded in 2007.

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. The strength of tidal currents and influence of local weather conditions govern 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 records at a depth of 75 m. Strong interannual to decadal scale variability is evident in this time-series data, but an extended data-gap that coincides with the period of strong warming apparent in most of the other datasets at the end of the 1980s makes it difficult to identify trends. Average or below average temperatures in the early 1980s were replaced by warmer than average waters on resumption of sampling, although notably the year 2006 experienced the coldest anomaly of the series (-2.09°C relative to the 1991 to 2020 average); SST values in more recent years have been slightly higher than average (Figure 5F).

Irish Sea (Charting Progress Region 5)

The temperature series recorded at the Malin Head Coastal Station, Ireland (55.39°N; 7.38°W) shows a strong warming trend over the period 1960 to 2020 of 0.3°C per decade, with values since 2000 being consistently above the 1991–2020 average (Figure 5H). A data series representative of CP5 has been constructed by joining the SST series from Port Erin, Isle of Man with the data buoy series recorded from the Western Irish Sea (53.78^{o} N; 5.63^{o} W)

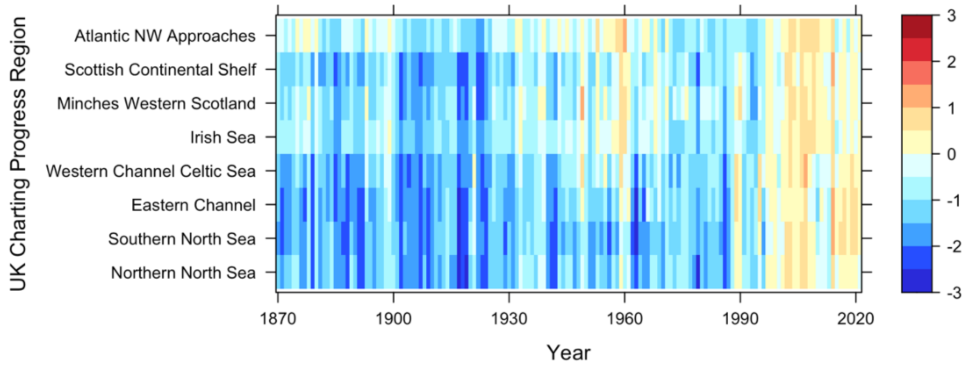


Figure 7*: Anomaly plots for sea surface temperature calculated from HADISST for the period 1870–2021. Anomalies are calculated relative to the period 1991–2020 and are normalised as in Figure 5.*

after 2012 (Figure 5G). That series also shows a strong increasing trend over the last 70 years (0.2°C per decade), with positive values relative to the base period since 2000.

West Scotland (Charting Progress Region 6)

The Tiree Passage Mooring time series from the Inner Hebrides shows a short initial cooling from 1981, strong warming between 1986 and 1990, a minimum in the early 1990s and then generally warm conditions are apparent in the data between 2002 and 2008 (Inall *et al*., 2009). Updated analyses by Jones *et al*. (2018) have indicated that although 20-m depth sea temperature values show a trend of 0.57°C per decade between 1981 and 2006, values decreased towards the end of the 2000s, which is consistent with the input of cooler water that is associated with the increase in the subpolar gyre strength.

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

Measurements taken in the Faroe-Shetland Channel show a warming trend (0.5°C per decade) since the mid-1980s in the upper levels of the open ocean (0–200 m), reaching a peak in 2010 and declining values thereafter (Figure 5A). For the deeper water of the channel (below 1100 m) where the water has no direct contact with the atmosphere, there has been a declining trend in temperatures from the 1950s to the 1990s. Since the 2000s through to the early 2020s an increasing trend is evident in the data, with a sequence of positive temperature anomalies recorded over the past 5-10 years (Figure 5b). Upper ocean waters in the Rockall Trough (30–800 m), display a similar decadal pattern to the Faroe-Shetland Channel (0–200 m) with a period of elevated temperatures during the mid-2000s, declining thereafter (Figure 5I). Deeper waters have displayed no long-term trend over the last 40 years (Figure 5J).

Inter-regional comparison

Sea surface temperature trends across all CP2 regions show a generally coherent pattern (Figure 7). Since the late-nineteenth century and the early twentieth century there is some variability with short, warm periods interspersed throughout what was a predominantly cool phase. These warm years are most prominent across the Atlantic NW Approaches (CP2 region 8) and particularly during the late 1950s; relatively warm anomalies were also experienced across the Scottish Continental Shelf and Western Scotland (CP2 regions 6 and 7) during that period. In the mid-1990s, there was a shift to predominantly warm anomalies across all regions although as seen in the station series (Figure 5) this increase is subdued across the north-west regions.

WHAT COULD HAPPEN IN THE FUTURE?

End-of-Century Climate Projections

The first sea temperature climate projections for the North-West European Shelf Seas (NWS) included in the UK Climate Projection (UKCP) was an exploratory study (Holt *et al*., 2010) in the marine report (Lowe *et al*., 2009). This was extended by the Defra funded Minerva project (Defra project number: ME5213) in 2016 (Tinker *et al*., 2015, 2016; Tinker, 2016). The most recent UK climate projections (UKCP18) marine report (Palmer *et al*., 2018) did not include an update to the Minerva Projections. However, the Met Office Hadley Centre is investigating whether it is possible to release an update in time for use within the 4th UK Climate Change Risk Assessment (CCRA4). This will be based on the 12-member HadGEM3 Perturbed Physics Ensemble (PPE), run under RCP8.5. This PPE has been downscaled with the NEMO (version 4.04) run on the 7 km AMM7 domain, as transient simulations (1980–2099). The methodology and evaluation will be similar to that of Tinker *et al*. (2015). Early results are included here.

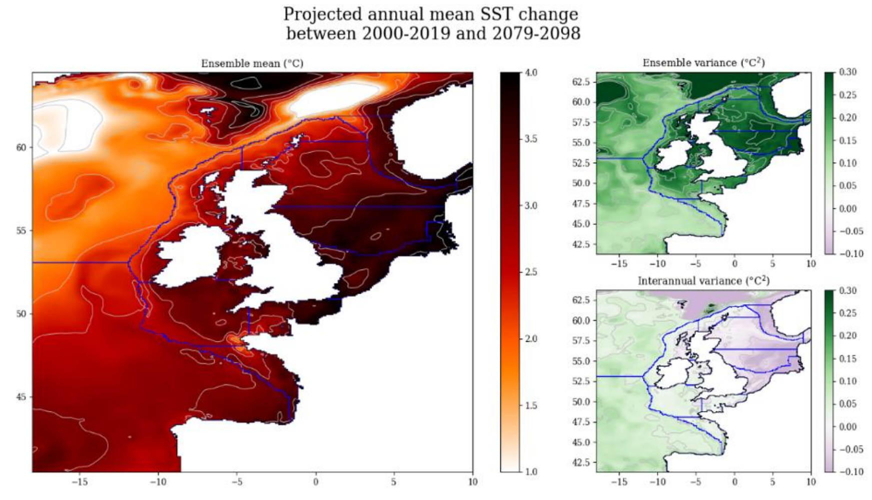


Figure 8: *Projected annual mean Sea Surface Temperature change between 2000–2019* and *2079–98. Left: the ensemble mean temperature change; upper right: the change in ensemble variance (the ensemble standard deviation squared); lower right, change in interannual variability. The regions used in the regional mean statistics in Table 1 are given in blue.*

In Figure 8, the annual mean SST change is presented for 2079–2098, compared to a baseline of 2000 to 2019. Changes in the ensemble variance and interannual variance are also included (see fig. 4 of Tinker *et al*. (2016) for details). This projects greater warming on the NWS than the Minerva does, especially given the later present-day baseline period (cf. 1960–1989 in Tinker *et al*. 2016). There is also reduced warming to the north-west of the domain, compared to the Minerva projections, and to the north of the North

Sea.**Error! Reference source not found.** Figure 9 gives the projected changes in Near Bottom Temperature (NBT). Regional mean values, based on the blue-region masks in Figures Figu and ***Figur***, are given in Table 1.

Table 1: *Regional mean changes for SST* and *NBT, between 2000–2019* and *2079–2098. Regional mean of the ensemble mean is given with the regional mean of 2 times the ensemble standard deviation.*

	Shelf	Southern North Sea	Central North Sea	Northern North Sea	English Channel	Irish Sea	Celtic Sea
dSST	3.11°C (±0.98°C)	3.72°C (±1.03°C)	3.59°C (±1.07 °C)	3.14°C (±1.02°C)	3.34°C (±0.88°C)	3.22°C (±1.03°C)	3.01°C (±0.90°C)
dNBT	2.49°C (±0.94 °C)	3.65°C (±1.01°C)	2.84°C (±0.96°C)	2.28°C (±0.96°C)	3.15°C (±0.85°C)	2.87°C (±0.97°C)	2.19°C (±0.87°C)

Other time horizons

The Met Office in the UK produces operational synoptic forecasts for the NWS, extending out to six days. There are two products with the physical 3d ocean model coupled with: (1) the wave model at a 1.5 km resolution (AMM15); and (2) the biogeochemistry (BGC) model at 7 km resolution (AMM7). They also produce a NWS re-analysis (with BGC) from the 1993 to the present day on the AMM7 grid. Re-analyses combine shelf seas models with data assimilation to give a best estimate of the NWS conditions in the recent past, providing good estimates of prevailing condition and climatology. Both these products are currently released via the Copernicus Marine Service (https://marine.copernicus.eu/).

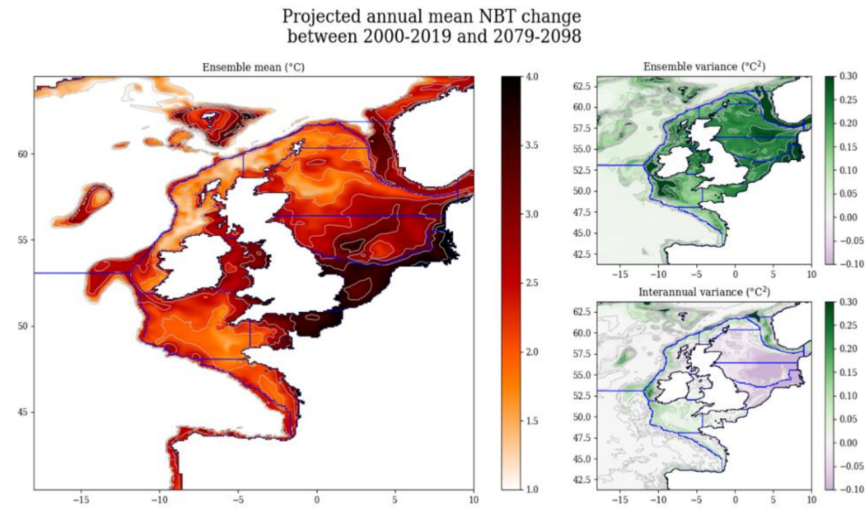


Figure 9: *Projected annual mean Near Bottom Surface Temperature change between 2000–2019 and 2079–2098, see Figure 8 for details.*

A present-day climate control simulation was run for the NWS for the UKCP18 Marine Report. This gave a 200-year simulation with greenhouse gases fixed at the year 2000 level to provide an estimate of unforced year-to-year variability (Tinker *et al*., 2020), which would be released with the additional UKCP18 product described above.

Between the recent past/present-day variability and synoptic forecasts, and the end of century climate projections, there is the seasonal-to-decadal timescale. There has been considerable progress in terrestrial prediction for the UK on these time scales, and in the marine environment in other parts of the world (e.g. Hobday *et al*., 2016b; Brodie *et al*., 2017). However, the nature of the broad NWS makes it difficult to use global seasonal predictions for the seas around the UK. Here, we give an overview of the research on these time scales at the Met Office, with a focus on their relevance to the NWS.

Seasonal Predictability

The Met Office in the UK has an established seasonal global forecasting system, GloSea (MacLachlan *et al*., 2014), which has significant skill at predicting winter North Atlantic Oscillation (NAO), the dominant mode of climate variability over Europe (Scaife *et al*., 2014). This has led to several forecast applications, including the likely number of transport disruption (road, rail, and air) impacts (Palin *et al*., 2016) and annual briefings to the energy industry (Clark *et al*., 2017). There has been much less attention given to the seasonal predictability of the NWS. However, work has begun towards making seasonal predictions of the conditions on the NWS. Tinker *et al*. (2018) laid out a 'roadmap' to NWS seasonal predictions, with a series of increasingly complex options:

1. Making predictions directly from Global Seasonal Forecasting systems (such as GloSea);
2. Making parametric forecasts, by finding statistical relationships, for example, the NAO, and a variable of interest (e.g. English Channel winter SST);
3. Dynamically downscaling the Global Seasonal Forecasting systems for the NWS using a regional shelf seas model.

Tinker *et al*. (2018) evaluated the GloSea5 NWS, and assessed the predictability and persistence in the Copernicus Marine Environmental Monitoring Service (CMEMS) reanalysis. They concluded that: (1) the direct use of GloSea data was not appropriate in some places and conditions; (2) parametric forecasts are possible for some parameters and regions, but rely on the existence of underlying robust statistical relationships. They explored the relationship between the NWS and the atmospheric and oceanic conditions, and concluded that dynamic downscaling may be appropriate.

This work was continued by Tinker and Hermanson (2021) who focused on the winter predictability of the NWS. First, they evaluated how well GloSea simulates the mean state of the NWS winter, and its year-to-year variability and predictability. They then assessed the SST and SSS persistence with and without a consideration for the mean flow field (the Lagrangian and Eulerian persistence respectively). Finally, the used a case study to investigate the dynamic downscaling approach.

Tinker and Hermanson (2021) found that GloSea simulates the climatological spatial patterns and winter evolution of NWS SST and SSS reasonably well. However, they found that deficiencies in NWS flows fields in the global ocean component of GloSea (based on the NEMO on the ORCA025 ¼ degree grid) led to increased temperature biases and reduced the predictability in the Irish and Celtic Seas, English Channel and Southern North Sea.

The NWS exhibits relatively high persistence in temperature with November temperatures being highly correlated with the December to February mean (r > 0.6) over most of the NWS, although lower temperature persistence occurs in the southern North Sea. The GloSea SST deterministic skill is slightly higher than persistence over most of the NWS, apart from in the northern North Sea. They concluded that the direct use of GloSea5 output is suitable for NWS winter seasonal prediction in some regions for some variables. For example, GloSea has good SST deterministic skill along the route of the northern North Sea inflow (around western Ireland, Scotland, and into the north-western North Sea. Despite the incorrect circulation affecting the climatological SST in the Celtic Sea, western English Channel and Irish Sea, there is also good deterministic skill in these regions, which may be used with care (Tinker and Hermanson, 2021).

Tinker and Hermanson (2021) also investigated the impact of downscaling a case study of two winters with opposing conditions. They were able to show that downscaling improves the NWS residual circulation, and so the physical consistency of the SST field with the observations. With only two years, they were not able to assess the impact of downscaling on predictability, but the improvements in the circulation provide a mechanism that may allow downscaling to improve the deterministic temperature skill (particularly in the southern North Sea). Tinker and Hermanson (2021) concluded that the improvements to the simulation of the NWS afforded by dynamically downscaling GloSea5 may improve the deterministic skill of NWS winter predictions, including temperature predictability in the Irish Sea, English Channel, and southern North Sea, and perhaps in the northern North Sea. This research is being continued with a Met Office CASE-funded PhD with Exeter University and Cefas.

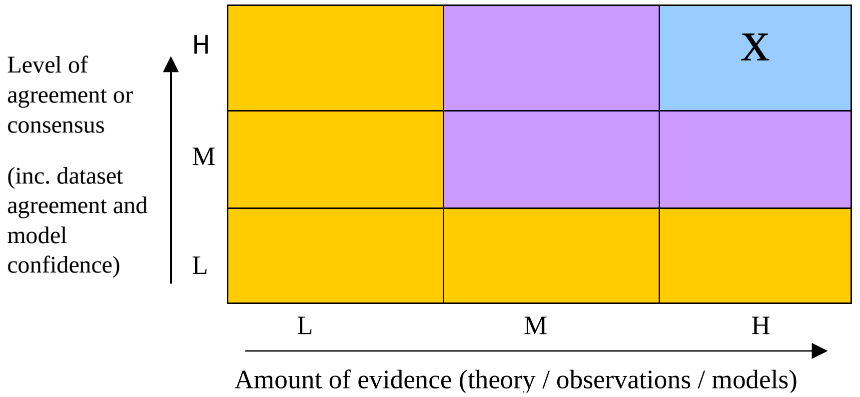
Decadal Predictability

Decadal climate predictions are designed to fill the gap between seasonal forecasts and climate projections, providing climate information to users on timescales of a year to decades (Boer et al., 2016). These predictions use information both from initial conditions (as in seasonal forecasts) and from external climate forcing (as in projections). Decadal climate predictions typically have lead times of up to ten years, but they can be used to constrain climate projections, by removing unlikely members of the climate projection ensemble, to reduce uncertainty in projections decades ahead (Mahmood et al., 2021; Befort et al., 2020).

The World Meteorological Organisation (WMO) Lead Centre for Annual to Decadal Climate Predictions (www.wmolc-adcp.org) produces a consensus forecast once a year using forecasts contributed from centres worldwide (Hermanson et al., 2022). These coarse resolution climate models cannot adequately resolve shelf seas, especially when stratification is important, but the models can give a good picture of the large scales and the influence of the ocean on the shelf seas. The latest predictions for 2022–2026 show that surface temperatures in the shelf seas around the UK are likely to warm as expected from climate change. In contrast, the temperature of the North Atlantic subpolar gyre is likely to stay at or below the 1991–2020 average. This absence of warming has been linked to reduced heat transport from the subtropics due to the slowing of the northward branch of the Atlantic Meridional Overturning Circulation with climate change (see, for example, Menary and Wood, 2018).

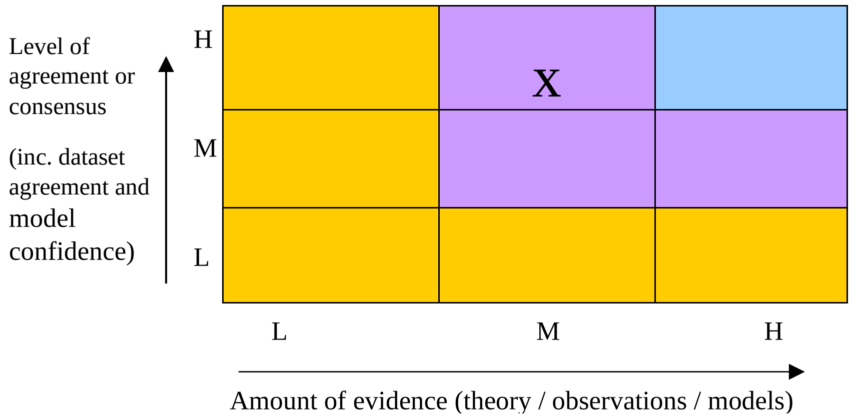
CONFIDENCE ASSESSMENT

What is already happening?



Sea-surface temperatures are one of the most-measured parameters in the ocean and as a result there is an abundance of evidence. Measures of sea temperature at various depths are also well-established, although the data are generally only available for specific sites or sampling regions/lines. Although some of the observational records are shorter than others and have variable spatial sampling (from point observations obtained from moored buoys through to complete global coverage provided by satellite observations), they all offer a coherent picture of both long-term and shorter-term variability, giving rise to a higher level of confidence in the results. Indices relating to changes in marine heatwaves are a relatively new line of evidence, but these are based on well-established datasets of SST.

What could happen in the future?



There is high confidence in the global rise in SST (e.g. Gulev *et al.*, 2021) 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. An update has been made to the end-of-the century projections used in the previous MCCIP report on temperature, and preliminary results are presented here. These simulations provide improvements to the projected temperature change around the UK and to the uncertainty in the predictions. Given the nature of the broad NWS it remains difficult to use global seasonal and decadal predictions for the seas around the UK. Nonetheless, recent research has indicated improved skill in winter predictions for certain regions around the UK using downscaling techniques.

KEY CHALLENGES AND EMERGING ISSUES

There is a need to:

- Improve our understanding of changes in the near-shore environment (both long term trends and short-lived extreme events) and the connections between the open ocean changes and shelf-sea temperatures (including the causes and effects of change in the North Atlantic subpolar gyre); and how these affect industry, society and ecosystems.
- Improve gridded data products of marine air and sea temperatures to be of a higher spatial and temporal resolution and to extend further back in time.
- Advance modelling of climate change by constructing a more thorough treatment of different sources of climate uncertainty in projections, by producing more accurate predictions (monthly-seasonal; sub-decadal) and near future decadal and multi-decadal projections, and by downscaling these to relevant regional scales.

APPENDIX

Trend Calculations

The trends in Figure 2. and as reported throughout the present report were calculated using the Theil-Sen approach, with lag1-autocorrelation taken into account using the Yue and Pilon method (Yue *et al*., 2002).

Marine Heatwave Calculations

Heatwaves are defined after Hobday *et al*. (2016a) as periods of at least five days greater than the 90th percentile of temperature calculated over the climatological period.

Datasets used in this report

- Near-bed temperatures from north-west European Shelf re-analysis and analysis/forecast simulations from the E.U. Copernicus Marine Service (https://marine.copernicus.eu/), https://doi.org/10.48670/moi-00059
- Met Office Hadley Centre's sea surface temperature data set, HadSST.4.0.1.0: https://www.metoffice.gov.uk/hadobs/hadsst4/
- Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST1.1.0.0): https://www.metoffice.gov.uk/hadobs/hadisst/

- North Atlantic Climate System Integrated Study (ACSIS) Atlantic Ocean medium resolution SST dataset: http://dx.doi.org/10.5285/83b0cd7e7cc6495a90b4cb967ead3577
- ESA SST CCI OSTIA L4 product: http://www.esa-sst-cci.org
- ICES report on Ocean Climate (IROC) station series: https://ocean.ices.dk/core/iroc (Gonzalez-Pola *et al*., 2020)
- Faroe-Shetland Channel 1100 m data series (Figure 5B) provided by Marine Scotland Science, Aberdeen (Berx *et al*., 2018; Larsen *et al*., 2018, updates available by request)
- The Port Erin SST data series (Figure 5G) provided by the British Oceanographic Data Centre (BODC): https://www.bodc.ac.uk/resources/inventories/edmed/report/176/
- Eastbourne SST series (Figure 5E) from the Cefas data portal: https://data.cefas.co.uk.
- Pre-release of HadGEM3 Perturbed Physics Ensemble (12-member), run under RCP8.5 and downscaled with the NEMO (version 4.04) run on the 7 km AMM7 domain, as transient simulations (1980-2099).

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