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 region.
- 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 region.
- Marine heatwaves are increasing in frequency around the UK, particularly in northern regions, significantly altering ocean conditions, with growing ecological impacts and clear spatial variability across the North Sea and English Channel.

What could happen in the future?

- Model simulations indicate a continuing warming trend around the UK, with average annual mean SST values predicted to be up to 3.11°C (±0.98°C) greater at the end of the century (2079–2098) compared to current conditions (2000–2019) under the RCP8.5 scenario.
- Temperatures are also projected to increase on the seafloor, with increases up to 2.49 (±0.94°C) expected by the end of the century.

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- 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.
- Weaker warming is expected in subpolar North Atlantic surface temperature.
- Future warming is expected to increase the frequency of marine heatwaves, with the entire UK coastal region projected to be in marine heatwave conditions for more than half of the year by the end of the century under RCP 8.5.

SUPPORTING EVIDENCE

What is already happening?

Trends in Sea Surface Temperature

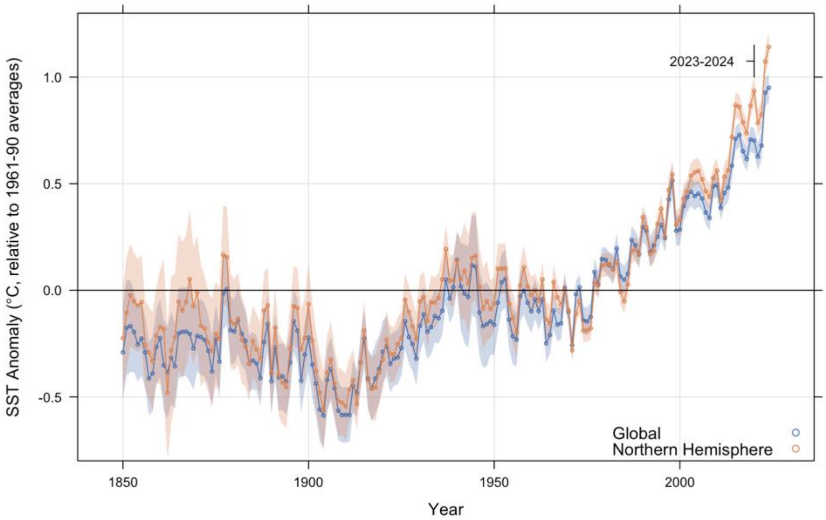


Figure 1*: Average SST anomalies from 1850 to 2024 for the Northern Hemisphere and global oceans. The shaded areas indicate the +/- 2σ uncertainty range. Data were obtained from the HadSST4.2.0.0 dataset (Kennedy et al., 2019) and are expressed as anomalies from the 1961-1990 average.*

On a global mean basis, the eleven years from 2014 to 2024 have been the warmest in the sea-surface temperature (SST) record that extends back to 1850 (Figure 1). During the years 2023 and 2024 an exceptional increase in temperatures was experienced. Average SST anomalies across the Northern Hemisphere were similarly high, with 2024 being the warmest year in the record with a value of 0.62°C (±0.06°C) above the 1991-2020 average. Across the North Atlantic, the annual average SST in 2023 reached 20°C for the first time, which corresponds to an anomaly value of 0.71°C relative to 1991-2020 climatological averages (Guinaldo *et al.,* 2025). The average UK SST across the Northwest Shelf region (NWS) for the decade 2014–2023 was 0.3°C warmer than the 1991–2020 average. Six years in that decade were in the top ten warmest years in the series back to 1870 and all of those top ten years have occurred since 2000 (Kendon *et al*., 2024).

In comparison to other global ocean basins, the Atlantic Ocean has experienced one of the largest increases in temperature since the 1950s

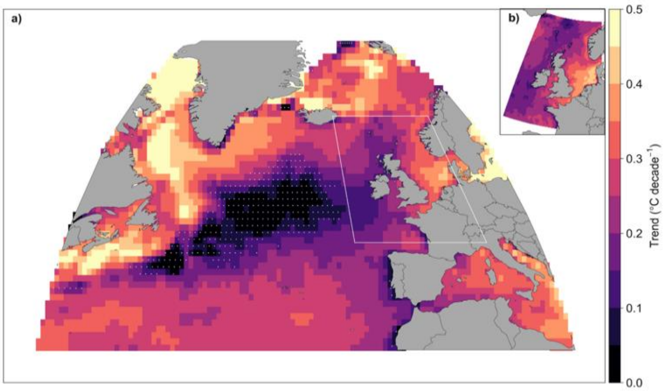


***Figure 2**: Linear trends in annual average SST (˚C per decade) over the period 1982–2024. The white dots indicate grid-cells where the trends are not significant at the 95% confidence level. The data were obtained from the CCI SST dataset (Embury* et al.*, 2024), and a) uses 1° resolution data whereas b) uses 0.1° data.*

(Cheng *et al.*, 2022). However, marked local and regional variations are embedded in the average warming trend. The trend in SST across the North Atlantic region, and around the UK coasts, over the last 43 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, decreasing further towards the central subpolar North Atlantic where the trend is not statistically significant.

The lack of a positive SST trend—or the presence of a negative trend—in the North Atlantic is often referred to as the "cold blob," "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 vary on decadal (Årthun *et al*., 2021) and interannual timescales, with some recent years experiencing particularly intense cold anomalies (Josey *et al*., 2018; Maroon *et al*., 2021).

Observations show that past cold anomalies were linked to freshwater anomalies (Oltmanns *et al*., 2020; 2024), 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 winter 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 shown 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 at lags of up to two years (Figure 3; Chevuturi *et al.,* 2025, Duchez *et al*., 2016; Mecking *et al*., 2019; Oltmanns *et al*., 2024).

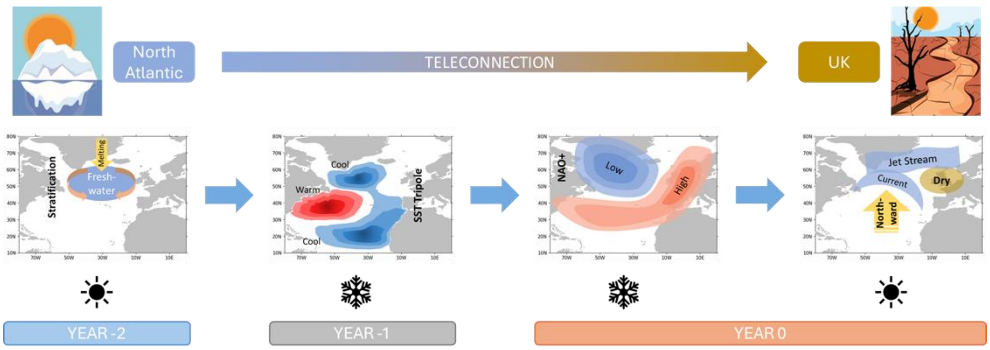


Figure 3: *Summary schematic showing North Atlantic SST teleconnection pathway for UK droughts (i) In the summer two years (YEAR-2) before the droughts melting from the Arctic or sub-Arctic causes freshwater incursion into the subpolar North Atlantic Ocean leading to stratification and enhanced surface cooling in winter; (ii) strong meridional SST gradient forms, leading to atmospheric feedbacks and the formation of a North Atlantic SST tripole pattern in the winter one year (YEAR-1) before the droughts; (iii) positive phase of the NAO circulation pattern is formed with strong westerly winds during the winter (YEAR 0) preceding the droughts; (iv) Northward shift of the North Atlantic Current and Jet Stream leads to UK drought in the summer (YEAR 0) with lower than normal rainfall and streamflow. In the schematic the winter season has been shown with a black snowflake symbol and the summer season with a black sun symbol. From Chevuturi et al. (2025).*

Regional Changes in Sea Temperature

As with earlier reports (Dye *et al*., 2013; Hughes *et al*., 2017; Tinker and Howes, 2020; Cornes *et al.,* 2023) we have examined regional changes in sea temperature (both at the surface and at depth), using the UK Charting Progress Regions (CP2) as the basis for defining regions (Figure 4). In this report we have updated the temperature series through to December 2024 where possible. This has only been possible, however, for five of the sites (A-C and F-H in Figure 4); updates to the other series are not currently available.

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 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’ (Sharples *et al*., 2020). This means that the temperature of the entire shelf area experiences strong seasonal cycles.

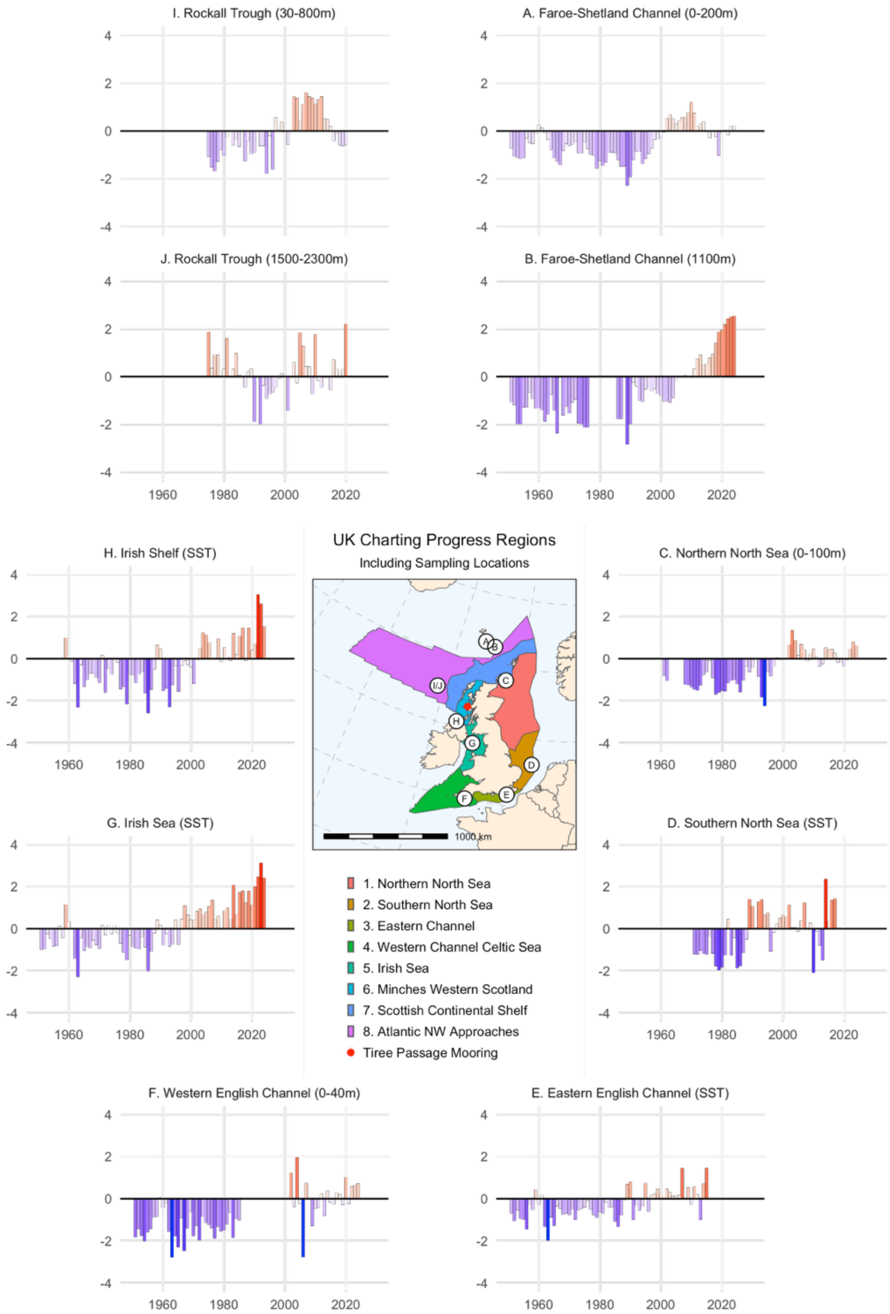


Figure 4*: Normalized annual mean sea temperature anomalies at a selection of stations (labelled A-J) distributed across the UK Charting Progress (CP2) Regions (shown in central map). A: Faroe-Shetland Channel (Modified North Atlantic Water). B: Overflow water in Faroe-Shetland Channel. C: Northern North Sea surface (Fair Isle Current Water). 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, the Western Irish Sea Data Buoy series (53.78°N; 5.63°W) Jan 2012- Oct 2023 and modelled values 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. Details regarding measurement depth are provided in each subplot. The data have been normalised by subtracting the reference period mean* and *normalising by the standard deviation. As a result, the scale represents temperature standard deviations from the reference period mean and are in the units of degrees Celsius. 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. See the Appendix for full details about the providers of these data.*

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 late-1990s, with generally sustained warm SST anomalies since then. In the time series of sea temperature from the Northern North Sea at 0-100m depth (Fig. 4C) most years since 2000 have been around or above the 1991-2020 average, with peaks in 2003 and higher than average values since 2022 after four years of just below average conditions, while years pre-2000 were below the average.

In the Southern North Sea, atmospheric forcing has a dominant influence on temperatures. Since the mid-1980s, SSTs have generally been higher than the 1991-2020 average, although values during 2010-13 were below the average (Figure 4D; note the different reference periods in this and Figure 4C). 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 4D due to a lack of data after 2017.

Evidence from ocean reanalysis data indicates a significant increase (95% confidence level) in sea bottom temperatures in autumn (the warmest season) across the southern North Sea and the English Channel over the period 1993-2024 (Figure 5, bottom row). 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. This suggests that the warming here is driven primarily by summer surface heat flux, from a warming atmosphere. A similar pattern is seen in the top-level values from that reanalysis, which are taken to represent SST values (Figure 5, top row).

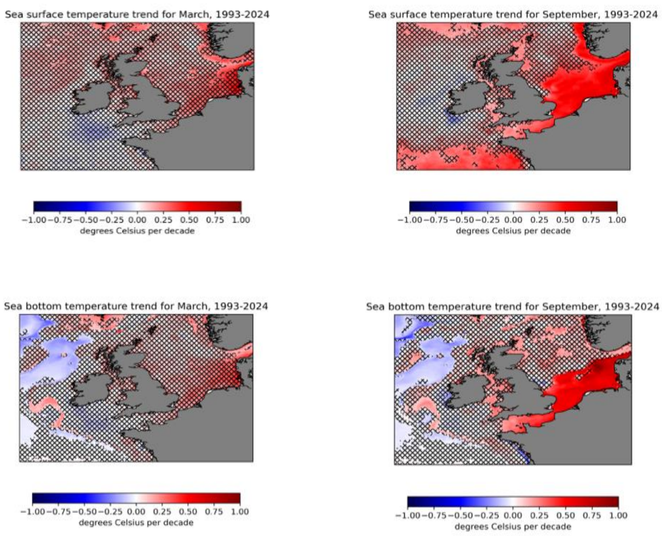


Figure 5: *Linear trend (°C/decade) in surface (top row) and bottom temperatures (bottom row) calculated from the north-west European Shelf re-analysis data for the months March and September over the period 1993-2024. Values calculated from linear fit to data in each grid-cell. Hatched areas have a 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 4E). Since then, 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 4E 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 4). Over that time the ten warmest years were all recorded after 1989, with the highest being 2015 when a SST of 1.9°C above the 1991 to 2015 average was recorded. A similarly high annual mean SST 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. Only data since 1950 are presented here (Figure 4F), and these values represent the upper ocean temperature (0-40m). Distinct interannual to decadal scale variability is evident in these 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); temperature values in more recent years have been slightly higher than average.

Irish Sea (Charting Progress Region 5)

The SST series recorded at the Malin Head Coastal Station, Ireland (55.39°N; 7.38°W) shows a strong warming trend since the 1990s and values since 2000 have been consistently above the 1991–2020 average (Figure 4H). Notably high SSTs were recorded in 2022 and 2023. A data series representative of region 5 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° N; 5.63° W) from 2012-2023 and appending modelled values since 2nd October 2023 (Figure 4G). The data from both sites (Figures 4G and 4H) show a strong increasing trend over the period 1985-2024 (0.8°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 (location marked by the red dot in Figure 4) 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. Unfortunately, the

Tiree Passage Mooring time series is not continued and other time series in this region (i.e. Scottish Coastal Observatory in Loch Ewe) are still too short. However, SST data from the Malin Head station (Figure 4H) are also indicative of this region and show a continued warming trend into the early 2020s.

Open Ocean around the UK (incl. Charting Progress Regions 7 & 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 4A). For the deeper water of the channel, at 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 steady positive temperature anomalies recorded over the past 5-10 years (Figure 4B). 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 4I). Deeper waters have displayed no long-term trend over the last 40 years (Figure 5J).

Inter-regional comparison
SST trends across all CP2 regions show a generally coherent pattern (Figure 6). 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 4) this increase is subdued across the north-west regions. The increases in SST during 2022 and 2023 are clearly seen in Figure 6, with particularly large anomalies experienced across southern regions, notably across the English Channel and Celtic Sea.

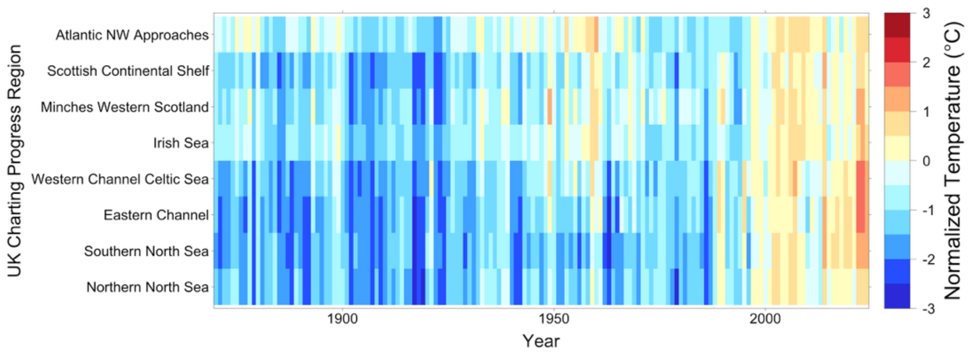


Figure 6*: Anomaly plots of annual average sea surface temperature calculated from HADISST for the period 1870–2024. Anomalies are calculated relative to the period 1991–2020 and are normalised as in Figure 5.*

Marine Heat Waves and Cold Spells

Marine Heat Waves (MHWs) are periods of localised anomalously warm sea temperature (Oliver *et al.*, 2021). These events can last for several days or weeks, and potentially for several months, and can have profound effects on marine ecosystems (Collins *et al.*, 2019; Smale *et al.*, 2019; Smith *et al.*, 2023). Marine heatwaves can occur at any time of year and are commonly defined relative to historical extreme temperatures on each day of the year. Marine cold spells represent the other extreme of temperature conditions, where anomalously cold sea temperatures are experienced for a period (Schlegel *et al.*, 2021).

Several different metrics exist for the quantification of MHWs (Smith *et al.* 2024) and in this report evidence is presented from indices calculated using 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), surface 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 7). 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). The increase in MHW activity in this region agrees with other recent studies (Mohamed *et al.*, 2023; Simon *et al.*, 2023).

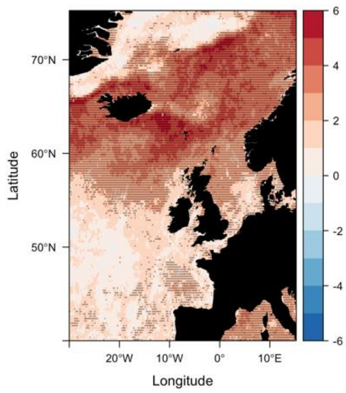


Figure 7: *The difference in the average number of MHW events over the period 2000-2016 compared to 1982-1998. This figure is re-plotted after fig. 1b in Oliver* et al. *(2018)* and *restricted to the North-east Atlantic region. Stippling in indicates significant differences at the 95% level.*

Across the more southerly parts of the study area, Figure 7 shows that increases in marine heatwave (MHW) frequency have generally been lower than in the northerly regions of the NWS. While some southern areas in Figure 7 do exhibit statistically significant increases, more recent analyses—incorporating data up to 2023/24—suggest that significant increases in MHW frequency are now also emerging in seas to the south of the UK. Data from the Western Channel Observatory (WCO), located off the south coast of

Devon, highlight a clear rise in MHW frequency over the past two decades (Berthou et al., 2024). Figure 8 illustrates SSTs at a depth of 2 m from stations E1 and L4, both part of the WCO (note that these data are not included in Figure 7). At station E1 (located 30 km offshore), over 50% of all recorded MHWs since 1903 occurred between 2005 and 2024. At station L4 (7 km offshore), more than 75% of all MHWs since the start of the temperature record in 1988 occurred during the same period. Comparing the two stations during their overlapping monitoring period, L4 recorded 50% more MHWs than E1 (123 vs. 81), and exhibited significantly higher interannual variability. The number of cold spells has also decreased markedly over the past decade. This suggests that these coastal areas are responding more strongly to MHW events than more offshore locations.

Highlighting the spatial heterogeneity of MHW events around the UK, Jacobs *et al.* (2024) analysed satellite data from 1982-2023 and found that, on average, more intense but short-lived events occur in the eastern North Sea, while more moderately intense but longer lasting events occur in the southern North Sea and English Channel. This is also reflected in the reduced increase in MHW frequency shown in Figure 7 for the southern North Sea.

A particularly intense MHW was recorded around the UK in June 2023, which was initiated by strong atmospheric forcing, and was compounded by high levels of sunshine and weak winds (Berthou *et al.*, 2024). While short-lived (16 days), this exceptionally intense event reinforced the land heatwave simultaneously occurring in the UK (Berthou *et al.*, 2024). Throughout that month SSTs across the NWS were 2.9ºC above the 1982-2012 averages, which represent twice the 90th percentile of temperature and were therefore classed as a category II heatwave. SSTs rose locally to +5ºC relative to 1982-2012 averages, which represent category IV values.

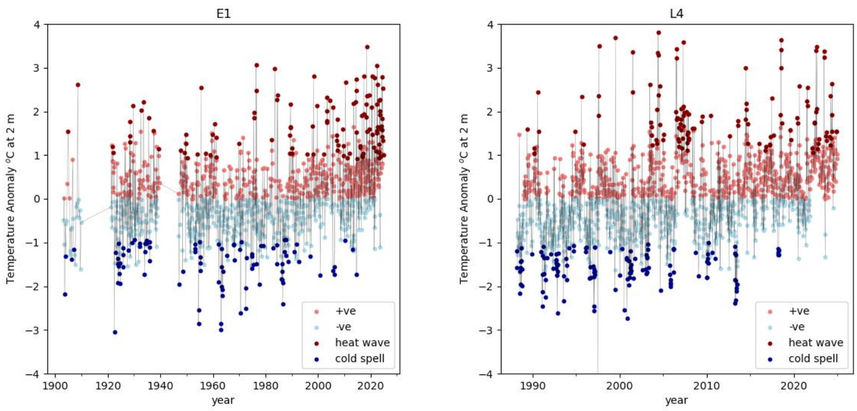


Figure 8*: SST anomalies measured at the two stations of the Western Channel Observatory (E1 left, L4 right) compared to the long-term mean. Heat waves and cold spells are highlighted by darker colours (updated from Berthou et al., 2024)*.

Marine heatwaves have been shown to significantly impact ocean conditions in the North Sea, particularly by influencing thermal stratification. While the Northern North Sea experiences seasonal stratification each year during the warm season, the Southern North Sea typically does not—except during years when marine heatwaves occur (Chen *et al.*, 2022).

Marine heatwaves and cold spells may drive shifts in marine hydrodynamics, with the potential to alter ecosystem structure and function. However, whilst studies have begun to identify spatial patterns, drivers and atmospheric impacts of MHWs around the UK, relatively few studies have examined their influence on marine ecosystems. Jacobs *et al.* (2024) found that some regions around the UK may experience low near-bottom oxygen compound events, which will likely amplify the stress on organisms. Additionally, in the North Sea, population collapses of copepods, the dominant zooplankton species in the region, were found to coincide with MHWs (Semmouri *et al.*, 2023). In terms of fisheries, Wakelin *et al*. (2021) analysed the occurrence of MHWs and of marine cold spells across the North Sea using near-bottom temperature data from the north-west European Shelf re-analysis dataset. 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, although no long-term trend was observed in these extreme events over that time. That study showed that catches of sole and sea bass increased in years with marine cold spells, although catches of red mullet and edible crabs decreased. A lagged relationship was observed between MHWs and 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.

WHAT COULD HAPPEN IN THE FUTURE?

End-of-Century Climate Projections

Evidence for end of the century changes in sea temperature around the UK's coasts comes from the projections generated for the forthcoming 4th UK Climate Change Risk Assessment (CCRA4). This is based on the 12-member HadGEM3 Perturbed Physics Ensemble (PPE), run under RCP8.5 (Tinker et al. 2024). The PPE has been downscaled with NEMO (version 4.04) run on the 7 km AMM7 domain, as transient simulations (1980–2099). The methodology and evaluation are similar to that of Tinker *et al*. (2015).

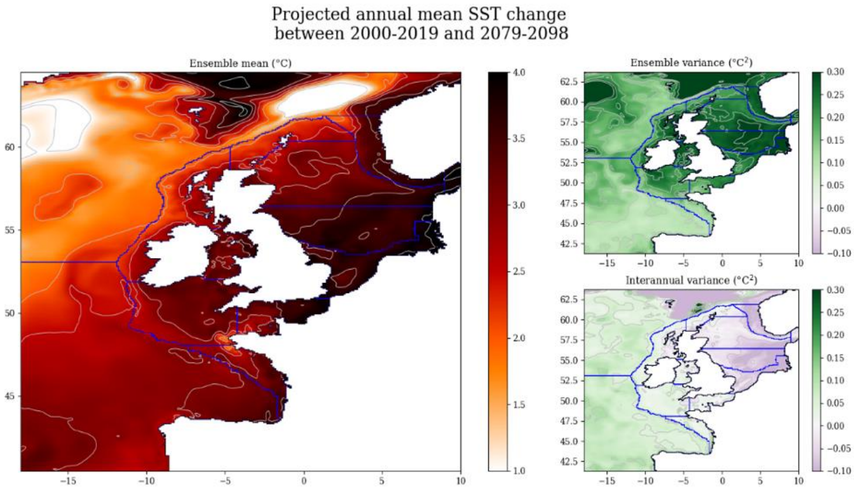


Figure 9: *Projected annual mean SST change between 2000–2019* and *2079–98 from the HadGEM3/AMM7 model. Left: the ensemble mean temperature change; upper right: the change in ensemble variance (the ensemble standard deviation squared); lower right, change in interannual variability. The regions used in the regional mean statistics in Table 1 are given in blue.*

Comparing annual averages in SST over the 2079–2098 period relative to a baseline period of 2000-2019, SST across the NWS is projected to increase by 3.11°C (±0.98°C) by the end of the century (Table 1) and this increase is expected to be greater during the summer and autumn compared to the winter and spring (c.f. 3.73 °C ± 1.07 °C in autumn and 2.43 °C ± 1.01 °C in spring; Tinker et al., 2024). Warming is projected to be higher across the North Sea and lower to the west of the region, and especially across the far northwest (Figure 9 and Table 1). This is a continuation of the pattern seen in recent decades (c.f. Figure 2).

The end-of-century increases in Near Bottom Temperature (NBT) are also greater to the east of the UK but the region of highest increase is restricted to the southern North Sea and across the English Channel (Figure 10; 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. These regions relate to the blue regions shown in Figs. 9 and 10.*

	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)

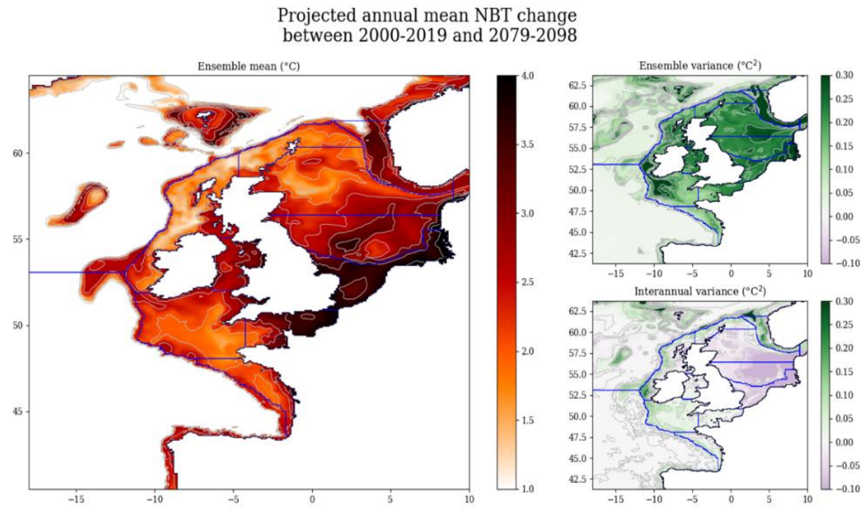


Figure 10: *As Figure 9 but for Near Bottom Temperature.*

Figures 9 and 10 present two measures of uncertainty: one associated with model parameterization choices (ensemble variance), and the other with projected interannual temperature variability (see Figure 4 in Tinker *et al.*, 2016, for details on these calculations). The ensemble variance increases across the entire NWS with particularly large increases projected for the North Sea and in the seas to the south of Ireland. In contrast, projected interannual temperature variability is lower than the 2000–2019 baseline across the eastern part of the region, while in the western part of the NWS region it remains comparable to or slightly above baseline levels. The fact that ensemble variance consistently exceeds interannual variance across the NMS suggests that model parameterisation is the dominant source of uncertainty in these projections.

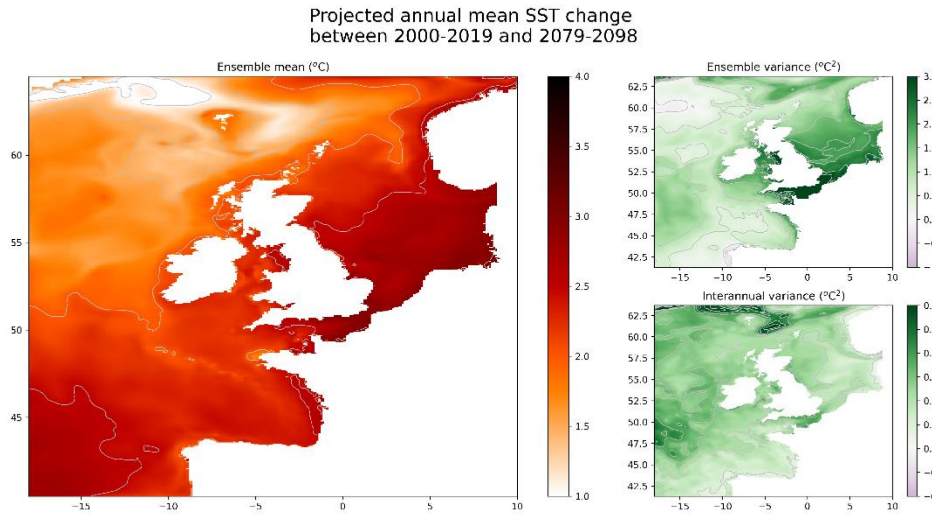


Figure 11: *Projected annual mean SST in 2079-2098 compared to 2000-2019 from the average of eight CMIP5 models downscaled using the NEMO model on the AMM7 domain. Future variance changes are shown in a similar manner to Figure 9. Please note that the colour scale for the ensemble variance has different range compared to figure 9..*

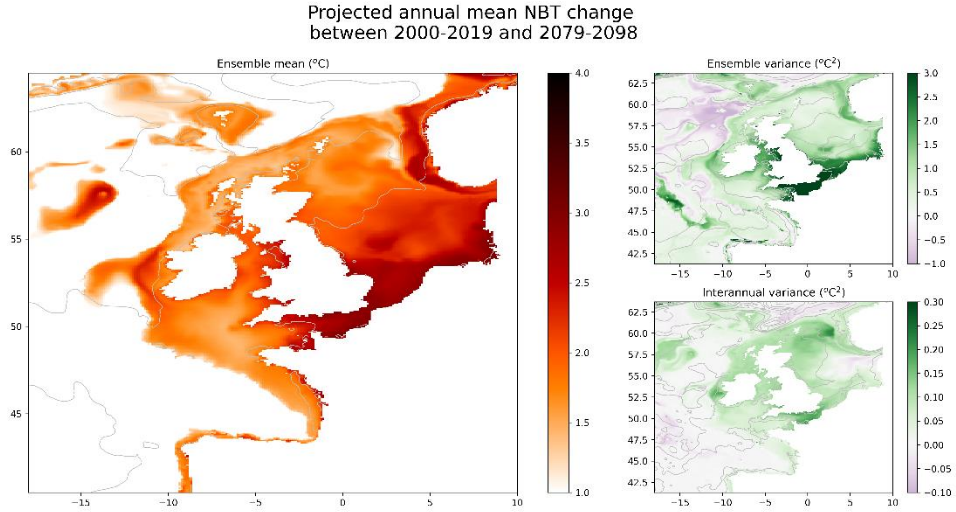


Figure 12: *As Figure 11 but for Near Bottom Temperature.*

In addition to the uncertainty associated with model parameters, another important source of uncertainty in climate projections is associated with the diversity of climate and earth system models and their representations of climate processes and feedback. Some climate models are more sensitive to the increase in greenhouse gas emissions and project a stronger warming for the same emission scenario. To assess this uncertainty, figures 11 and 12 show the outputs of an ensemble simulation of downscaled projections using the NEMO model on the AMM7 domain using atmospheric forcing from a collection of eight different CMIP5 for the high emissions scenario RCP8.5 (Holt *et al.*, 2022). Compared to the HADGEM3/AMM7 simulation (Figures 9 & 10), the mean of the warming is lower, which is in line with HadGEM3 having the highest climate sensitivity. However, the spatial distribution is similar, with stronger warming on the shelf and in the southern part of the off-shelf area. For SST (Figure 11), the ensemble projects an increase in the variance of the multi-model means in most of the domain, with the highest increase in the English Channel and the coastal areas of England and Wales, and a much smaller increase in interannual variability elsewhere on the shelf. Patterns for bottom water warming (Figure 12) are similar on the shelf (but with a smaller increase) and are below one degree in the deep ocean.

The increase in ensemble variance in the multi-model means (Figures 11 and 12) is much larger than in the perturbed parameter ensemble (Figures 9 and 10). Note that due to these four figures showing ensemble variance, the spread is not as great as it may appear. This is likely due to the larger spread in climate sensitivities and model structural differences within the parent CMIP5 models compared to the NWSPPE, whose spread results from parameter uncertainty within the same model, HadGEM3.

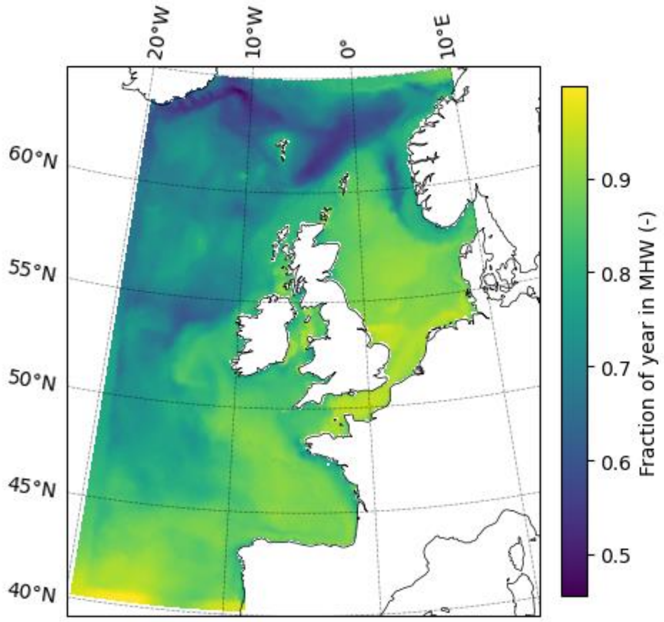


Figure 13*: Projected fraction of the year the sea surface is in a marine heatwave by the end-of-the-century under RCP 8.5. The projections used an ensemble of five downscaled global climate models.*

The increase in SST due to climate change is projected to cause a large increase in the rate of MHWs (Figure 13). Under RCP 8.5, UK and Irish waters are projected to be in MHW conditions for most of the year by the end-of-the-century (Wilson et al. 2025), and on average the UK's Exclusive Economic Zone (EEZ) and Ireland's EEZ surface waters are projected to be in MHW conditions for 81% and 78% of the year in 2080-2099 respectively. In addition, the increases in MHW occurrence are expected to be larger at the seafloor because of the lower inter-annual variability in Near Bottom Sea Temperatures. Note, however, that these projections define MHW relative to present-day conditions. A key area of ongoing debate in the scientific literature concerns whether MHWs should instead be defined using a fixed historical baseline or a moving (temporally varying) baseline that reflects temperature extremes relative to contemporary climate conditions (Smith et al., 2025).

Other time horizons

The UK Met Office 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 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/).

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).

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 and global decadal 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 between, 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).

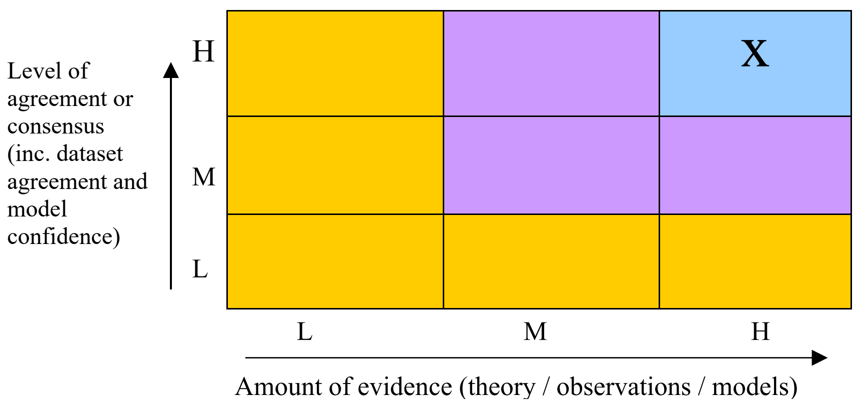
Tinker and Hermanson (2021) also investigated the impact of downscaling a case study of two winters with opposing conditions. They were able to show that downscaling improves the NWS residual circulation, and so the physical consistency of the SST field with the observations. With only two years, they could not 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), which are both important in the North Atlantic (Dong *et al.*, 2025). 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).

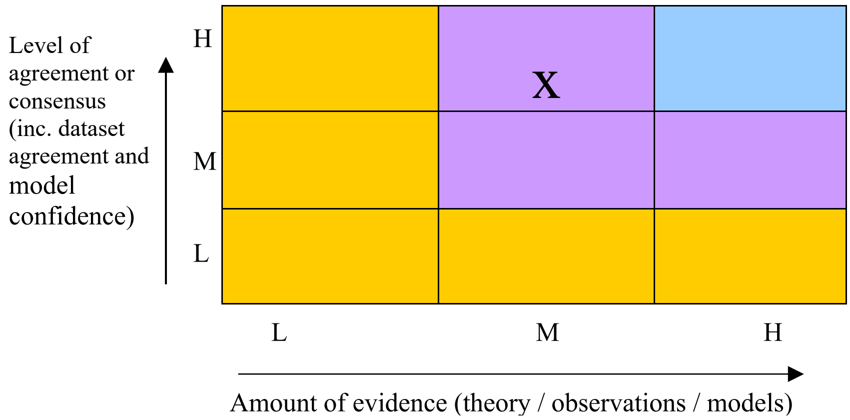
The World Meteorological Organisation (WMO) Lead Centre for Annual to Decadal Climate Predictions (www.wmolc-adcp.org) produces a consensus forecast once a year using forecasts contributed from centres worldwide (Hermanson *et al.*, 2022). These coarse-resolution climate models are unable to adequately capture small-scale shelf sea processes and, notably, do not currently simulate tides — a key driver of seasonal stratification on the NWS. However, they are still valuable for representing the large-scale ocean state (e.g., regional average sea surface temperature) and for assessing the broader influence of the ocean on shelf seas. The latest predictions for 2024–2029 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, and there is high confidence in the global rise in SST (e.g. Gulev *et al.*, 2021). 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 long-term future warming trend. However, our confidence in the exact rates of warming at regional scales is lower. Regional projections under the high emission scenario projects an average surface warming of +2.34 °C ± 0.84 °C.

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. Although an increasing number of studies are being conducted on future changes in Marine Heatwaves, the local-scale uncertainty related to future mean conditions also applies to these events-based metrics. In addition, questions remain about the most appropriate heatwave index to use for examining future changes in heatwaves. Nonetheless, using the commonly used definition, UK and Irish waters are projected to be in MHW conditions for most of the year by the end-of-the-century under the RCP 8.5 scenario (Wilson et al. 2025).

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 their impacts on industry, society and ecosystems. The near shore environment plays a critical role in providing marine ecosystem services and is affected by local processes (e.g. river plumes, coastal currents) that are usually not well captured by synoptic products, especially the future projections. Moreover, increasing temperatures will be felt more strongly in these regions due to the shallower waters, and the impacts of increasing temperature near the shore may be aggravated by compound changes due to other near-shore hazards (e.g. sea level rise and storm surges).

- Improve our understanding on the connections between the open ocean changes and shelf-sea temperatures (including the causes and effects of change in the North Atlantic subpolar gyre).

- 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.

- Facilitate the collection and dissemination of observational data (from moored-buoys and standard sections/stations) around the UK, since only five sites could be updated to 2024 for this report using *in situ* measurements

- Advance climate change modelling by developing a more comprehensive treatment of uncertainty in projections. This includes improving prediction accuracy at monthly to sub-decadal timescales, generating a more diverse ensemble of realisations to better explore sources of uncertainty, producing improved near-future decadal and multi-decadal projections, and downscaling these outputs to relevant regional scales.

- Account for tidal processes in global ocean models, as global ocean models currently do not simulate tides. This omission affects the accuracy of their representation of seasonal stratification, particularly in summer on the Northwest Shelf (NWS).

- Investigate machine learning as an affordable way of downscaling projections.

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). Accounting for autocorrelation in this way gave a more accurate estimate of statistical significance in the trends.

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.4.2.0.0: 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
- Most of the data in Figure 4 were taken from the ICES report on Ocean Climate (IROC) station series: https://ocean.ices.dk/core/iroc (González-Pola *et al*., 2023) (data in Fig 4A (Faroe-Shetland-Channel surface) and 4C (Northern North Sea surface) are uncalibrated for the years 2023-2024 but calibrated data will be available online)
- Faroe-Shetland Channel 1100 m data series (Figure 4B) provided by Marine Directorate, Scottish Government, Aberdeen (Berx *et al*., 2018; Larsen *et al*., 2018, updates available by request) (data are uncalibrated for the years 2023-2024 but calibrated date will be available by request)
- The Port Erin SST data series (Figure 4G) provided by the British Oceanographic Data Centre (BODC): https://www.bodc.ac.uk/resources/inventories/edmed/report/176/
- Eastbourne SST series (Figure 4E) from the Cefas data portal: https://data.cefas.co.uk.
- 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). See Tinker *et al.* (2024) for links to the data.
- NOC NEMO RECICLE model simulations (https://gws-access.jasmin.ac.uk/public/recicle/)

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