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40 priority questions to advance understanding of the risks and opportunities of UK marine heatwaves

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Marine heatwaves (MHWs) are periods of anomalously warm sea temperatures that are becoming increasingly recognised as ocean stressors. Globally, MHWs have impacted marine ecosystems, with significant socioeconomic implications for coastal communities and industries. The unprecedented MHW that occurred in the waters surrounding the UK and Ireland in summer 2023 highlighted a crucial gap in our understanding of the region-specific characteristics of MHWs and their impacts on marine ecosystems, the services they underpin, the blue economy and society. Using diverse expert opinion, we propose 40 priority questions for interdisciplinary research in the UK that must urgently be addressed to prepare for future risks and potential opportunities associated with MHWs. The targeted questions are listed under a broad range of themes. Recommendations to policy makers and those influencing the strategic direction and allocation of funding and resources are also suggested to assist decision-makers towards evidence-based action and guide funding streams.

Marine heatwaves (MHWs) are a globally recognised phenomenon that are becoming increasingly prevalent as ocean stressors. These events, which are characterised by prolonged periods of anomalously warm sea temperatures, are currently increasing in intensity, duration and frequency in most regions[1,2]. Globally, MHWs have caused widely documented impacts to marine ecosystems and the services they underpin[3–7], amplifying existing stress induced by gradual ocean warming and other pressures[8], with significant socioeconomic consequences[9].

MHWs are commonly defined as periods of five or more days where sea temperatures exceed the 90th percentile derived from long-term climatology (ref. 10; Fig. 1). They can last for days to years and can occur across various spatial scales, from localised hotspots to large oceanic regions[10,11], although their characteristics vary depending on the baseline by which these events are defined[12]. MHWs can result from a combination of factors, including atmospheric conditions such as high-pressure systems that bring extended periods of sunshine and weak winds, and oceanic processes, particularly increased advection of heat from currents and eddies[13–15]. While warming may be most pronounced in shallow surface waters, many MHWs extend into deeper waters[16], with potentially wide-ranging impacts on biogeochemical processes, marine ecosystems and foodwebs.

To date, global research efforts have primarily focussed on tropical and warm temperate regions where reported impacts are mostly negative, such as widespread loss of habitats and mass mortalities of foundation organisms or socioeconomically important species[4–6]. The Northeast Atlantic and, in particular, the coastal waters around the UK, remain comparatively understudied with regard to the region-specific physical characteristics and drivers of MHWs, along with their impacts on ecosystem services, human health and the blue economy. Potential opportunities associated with MHWs in this region, i.e. where shifts in species distributions result in new or increased economic opportunities, are also poorly understood. For example, given the high connectivity[17] and seasonality[18] of these waters, there is potential for MHWs to result in opportunistic fisheries appearing as species distributions shift and tourism benefits through increased observations of 'traditionally' warmer water megafauna[6]. Similarly, we currently

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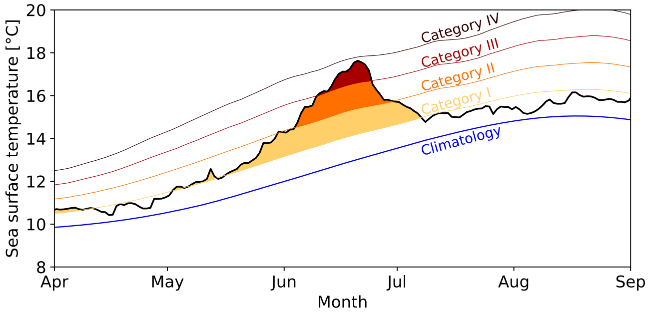

Fig. 1 | Daily sea surface temperature (SST) at 54.1°N, 10.9°W during the MHW in June 2023, selected to illustrate the MHW definition by Hobday et al.[10], i.e., when SST > 90th percentile for at least 5 consecutive days, as well as the MHW category definition by Hobday et al.[11] The 30-year climatology and 90th percentile are calculated over the period 1983–2012. Daily SST data is from the NOAA OI SST V2.1 High Resolution Dataset provided by NOAA PSL (https://psl.noaa.gov).

have a weak understanding of species which are not impacted by MHWs (see ref. 19).

Globally, MHWs have intensified over recent decades, exhibiting a > 50% increase in annual MHW days, as a direct consequence of anthropogenic climate change[1]. Moreover, projections of MHWs under multiple climate change scenarios suggest continued intensification in the coming decades[20,21]. The UK is no exception, with an unprecedented MHW occurring in early summer 2023 hitting the headlines of various media outlets (e.g., refs. 22–24). Although this intense but short-lived event raised awareness of MHWs in UK waters, it also highlighted the crucial gaps in our understanding of these phenomena[25].

Our lack of understanding of MHWs in the UK context makes it challenging to enhance preparedness, be it responding to forecasting in the short term or implementing effective adaptation options in the long term. There are currently no policy or management plans that address the risks specifically associated with MHWs and, unlike atmospheric heatwaves, they are currently not on the national risk register[26]. Given the recent MHW in 2023 and projections of continued MHW intensification, there is a pressing need to identify current knowledge gaps along with opportunities for collaboration to improve identification, monitoring and projections of MHWs, as well as their potential impacts, to inform policymakers and stakeholders. Similar efforts have been made in other locations (e.g. New Zealand) where MHWs are becoming increasingly prominent and impactful[27].

Using diverse expert opinion, we propose 40 priority questions for interdisciplinary MHW research in the UK, aimed at addressing critical knowledge gaps pertaining to their associated risks and opportunities to enhance societal preparedness to these events. Such targeted evidence gathering is needed to boost resilience to future MHWs occurring in UK waters and is the first step towards developing a strategy at the national scale.

Results

A set of 40 questions related to the key research challenges that must be urgently addressed to prepare for increasing impacts of MHWs in the UK is listed below. This is followed by recommendations to policy makers and those influencing (directly and indirectly) the strategic direction and allocation of funding and resources.

Region-specific UK exposure

Compared with other regions, there have been relatively few studies investigating MHWs in UK waters. A recent study found that, from a basin-wide perspective, the UK is not an area where intense MHWs are commonly observed but some regional variability is apparent[28]. Over the period 1982-2023, on average, they found that the southern North Sea and English Channel tended to experience longer but relatively weaker MHWs, while the eastern North Sea experienced shorter but more intense MHWs[28]. However, the location, strength, duration and seasonality of MHWs around the UK varied considerably. Furthermore, it is apparent that MHW activity in this region is on the rise, with studies finding increased MHW frequency in the North Sea[29] and increased MHW activity in the English Channel compared with regions further south off the west coast of France[30].

Over the past 40 years, mean sea surface temperatures (SSTs) in the UK region have risen by approximately 0.3 °C per decade, but with significant spatial variation[31]. While rising SSTs due to anthropogenic climate change are making MHWs more likely[1], the trends are not uniform in either mean warming or MHW metrics. For instance, the southern North Sea has experienced the strongest warming, while the greatest increase in MHW frequency has occurred to the north of the UK, highlighting the complex regional disparities[32].

The MHW that occurred around the UK and wider Northeast Atlantic region during the summer of 2023, unprecedented in intensity[28], generated substantial scientific and public interest, as SST anomalies exceeded 4 °C in some areas[33]. This event was primarily driven by weak winds and elevated solar radiation[25], and these unusually stable atmospheric conditions reduced oceanic mixing, which contributed to its persistence in the upper 25 m of the water column[33]. Model projections indicate that the extreme conditions experienced during the summer of 2023 could align with the 2050 s mean state[25,32]. However, trends in MHW metrics may differ by season, with summer SSTs projected to increase more than those in winter[25].

Aside from those examining the 2023 event, very few studies have documented the physical characteristics of MHWs around the UK, such as depth structure, spatial extent, and seasonality. It is also important to understand the potential for biogeochemical extreme compound events, whereby a second stressor (e.g., ocean acidification or hypoxia extreme) occurs simultaneously with anomalously high temperatures. For example, Jacobs et al.[28] found that MHWs are associated with significantly reduced near-bottom oxygen concentrations in the English Channel, southern North Sea, and around Orkney and the Shetland Islands. Furthermore, the unique bathymetry, extensive and varied coastline, atmospheric and oceanic circulation of the region and how these factors affect MHW characteristics remain poorly resolved.

1. What are the historical characteristics (e.g., frequency, duration, intensity, seasonality) and trends of MHWs observed around the UK?
2. What are the primary drivers of MHWs across different spatio-temporal scales?
3. What are the future projections for MHW activity and are they distinct from the projected global average?
4. What insights can analogues from other temperate oceanic regions offer regarding MHW properties, trends and drivers?
5. How do observed MHWs in UK waters co-vary with other environmental variables (e.g. nutrients, salinity, oxygen) to form compound extreme events?

Marine ecosystem impacts

Responses of marine organisms to extreme temperatures experienced during MHWs are complex, being influenced by a range of factors including life history traits and stage, behavioural shifts, thermal tolerance, biogeographical context and ecological interactions[5]. Our understanding of this in UK waters is poor due to a lack of routine long-term community-level monitoring for most locations and ecosystem types. MHWs of any significance are a relatively new phenomenon for UK waters, with the 2023 event being the first that was highly publicised. As such, our knowledge of ecological responses (either positive, neutral or negative) stems predominantly from anecdotal evidence, either because research was not carried out or results have not yet been published. The anecdotal evidence available suggests the 2023 MHW resulted in fish migrations that impacted breeding and survival in seabirds, shifts in plankton communities, and an increase in charismatic megafauna in some locations (https://www.thetimes.com/uk/scotland/article/how-marine-heatwaves-have-left-species-in-hot-water-0632h9g9q). A study looking at the impacts of MHWs and cold spells (i.e. discrete periods of anomalously cold water[34]) on a range of fish and shellfish catches between 1993 and 2019 in the North Sea, found both negative and positive impacts from cold spells and MHWs in the same year but also a few years after the events, indicating that they also affect recruitment[35].

While we lack understanding of ecological impacts in a UK context, we can gain an understanding of potential impacts from other ecosystems. For example, in other temperate or warm-temperate regions, reported MHW impacts include shifts in primary production (e.g., refs. 36,37), harmful algal blooms (e.g., refs. 38,39), mass mortality events (e.g., refs. 31,40), increases in non-native species (e.g. ref. 41), and loss of foundation species (e.g., refs. 5,7,42). Some groups of marine organisms, like sea birds, sessile invertebrates, and seagrasses, may be particularly susceptible to MHWs, while other groups, like fishes and mobile invertebrates, that are more able to temporarily relocate in response to elevated temperatures, may be more resilient[3]. More generally, populations of a given species persisting towards their warm (equatorward) range edge are more vulnerable to MHWs as temperatures are more likely to become stressful and exceed physiological thresholds[3,4]. In contrast, populations persisting towards their cool (poleward) range edge have, in some cases, been shown to prosper during MHWs as temperatures become optimal[5,31]. Within the context of UK marine ecosystems, it may be possible to make predictions drawn from longer-term responses to gradual warming. The UK and Ireland represent a biogeographic transition zone between Boreal and Lusitanian provinces in the Northeast Atlantic, with many warm-adapted species persisting towards their poleward range edges and, conversely, many cool-adapted species found towards their equatorward range edges[43]. As such, gradual increases in sea temperature have been linked with range shifts and changes in population structure as conditions become more or less favourable for any given species[44,45]. Species and communities that have exhibited sensitivity to long-term warming may be the most vulnerable to MHW intensification, although responses to short-term extreme temperatures are complex and mechanisms underpinning ecological resistance are poorly resolved.

There is some evidence to suggest that marine protected areas may facilitate community-level resilience, although results are inconsistent[4,46–48]. Finally, biogeochemical compound events are becoming increasingly common globally[49–51] and have the potential to exacerbate or suppress the ecosystem impacts of a MHW.

6. How will different species respond to MHWs in UK waters and across the wider Northeast Atlantic at different timescales?
7. What do we know about community and ecosystem-level (including ecological interactions and processes) impacts?
8. How will MHWs affect microbes, pathogens, parasites and harmful algal blooms, and the consequent spread of marine disease?
9. Do biogeochemical compound events exacerbate or suppress ecosystem impacts and how do these interactions vary across spatiotemporal scales?
10. What drives resilience of different species, communities and ecosystems to MHWs and is it enhanced by spatial management or genetic adaptation?

Impacts on marine natural capital, ecosystem services and the blue economy

Studies from around the world have shown that MHWs have wide-ranging impacts on marine ecosystem services, with important socioeconomic implications for coastal communities. Reported impacts include losses to the diving tourism industry[52], commercial fisheries closures and associated economic losses[9,12], but gains for whale watching industries, recreational sports fishing and opportunistic commercial fisheries[31,53]. Given the relatively limited occurrence of very intense MHWs in UK waters to date, little research has focussed on the impacts to UK ecosystem services, marine natural capital and sectors of the blue economy. Specifically, a lack of baseline data and spatially explicit information on ecosystem services means that impacts of MHWs are difficult to quantify (e.g., ref. 54).

In recent years, however, there has been greater attention given to the actual and anticipated impacts of MHWs on commercial fisheries, in recognition of the sensitivities of particular commercially valuable stocks, including oysters[55], whelk[56] and pollock[57]. Whilst multiple factors can lead to a fisheries crash, the intensity of MHWs on heat-sensitive commercial species suggests that the growing frequency of collapsed fisheries attributable to MHWs is likely[58]. Certainly, a mass mortality of whelk, reported in the Thames Estuary in August 2022, coincided with an MHW that was smaller than the 2023 event, but during which temperatures exceeded those of 2023. In addition to potential impacts on the blue economy, fishing livelihoods and the strong cultural and heritage values of fisheries serve as an important conduit for transferring marine ecosystem services into multiple wellbeing outcomes[59].

The concept of ecosystem services was defined and categorised as "the benefits that people derive from ecosystems" by the Millennium Ecosystem Assessment[60]. These benefits encompass provisioning services like food and water; regulating services such as flood and disease control; cultural services, including spiritual, recreational, and cultural benefits; and supporting (or habitat) services like nutrient cycling, which sustain necessary environmental conditions. Ecosystem services classifications (e.g., ref. 61) have been developed specifically for the marine environment[62], including for the UK[63]. Since 2011, an approach has been developed in the UK to incorporate the role of the ecological system in supporting the delivery of ecosystem services and human well-being into decision making[64]. This has included the development of the Natural Capital Approach as a framework of the United Kingdom's 25 Year Plan to Improve the Environment[65]. Operationalising the Natural Capital Approach centres on four definitions[66]:

- Natural capital: The elements of nature that directly or indirectly produce value to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions.
- Assets: A distinctive component of natural capital as determined by the functions it performs, for example, soils, freshwater and species.
- Ecosystem services: Functions and products from nature that can be turned into benefits with varying degrees of human input.
- Benefits: Changes in human welfare (or well-being) that result from the use or consumption of goods, or from the knowledge that something exists.

Similar to those found in other temperate environments worldwide, in the UK, natural capital assets provide numerous crucial marine ecosystem services (habitats and species). These include natural flood and coastal defences from vegetated habitats that protect coastlines from erosion and storm surges[67] as well as blue carbon habitats (e.g., saltmarsh, seagrass meadows and shelf sea sediments) that capture and store carbon dioxide from the atmosphere[68,69]. Other critical ecosystem services include the removal of excess nutrients (e.g., nitrogen and phosphorus) from runoff and wastewater by plants (e.g., macroalgae) and animals (e.g., mussel beds) to improve water quality[70] and the provisioning of favourable habitat (e.g., biogenic reefs, kelp forests) as essential nursery and feeding grounds for juvenile fish and other organisms[71,72].

Any changes to the environmental status of natural capital assets (habitats and species) as a result of an MHW can directly change the flow or availability of ecosystem services. This can pose risks to any beneficiaries that may have an economic, social or cultural reliance on the marine environment[73]. This includes those economic sectors of the 'blue economy' such as fisheries, (some forms of) aquaculture, and tourism that directly depend on the health of marine ecosystems and may be adversely affected by MHWs.

11. Which UK natural capital assets are most at risk from MHWs?
12. What are the potential risks and opportunities that MHWs may bring to the UK's ecosystem services and blue economy?
13. How will commercial fisheries be impacted by MHWs?
14. How and where will MHWs affect the lives and livelihoods of coastal communities?
15. How can the effects of MHWs be managed to alleviate the impacts on the UK's coastal communities and sectors of the blue economy that are dependent on ecosystem health?

Impacts on physical and mental human health

MHWs are likely to provide favourable environmental conditions for certain pathogens that thrive in warmer marine and estuarine waters. Most human pathogenic diseases have been exacerbated by climate change[74] such that various bacterial pathogens, for example *Vibrio*, have been deemed a key "barometer" of warming and climate-associated impacts[75]. *Vibrio* are bacteria that are natural constituents of estuarine and marine environments, that tend to grow in warm (>15 °C) waters. Around a dozen *Vibrio* species can cause infections in humans[76]. There have been increases in infections (including seafood-associated outbreaks) reported globally, e.g., notable outbreaks in colder/temperate regions such as Alaska[77], Canada[78], the East coast of the USA[79], along with an increase in wound infections reported in Northern Europe[80,81]. It is also unknown if MHWs will exacerbate the health impacts of sewage outflows into the sea, which still occur frequently in coastal areas[82], e.g., through nutrients entering coastal waters undergoing significant warming.

Alongside V*ibrio*, there is growing interest in the role of MHWs in modulating risks associated with harmful algal biotoxin species, with instances reported in other temperate regions like the Pacific[31] and Australia[83]. Within the UK, the presence of the harmful toxin tetrodotoxin in shellfish from southern England and Scotland has been reported, with the highest concentrations when water temperatures exceeded 15 °C[82], indicating the potential for MHWs to increase the occurrence and distribution of such toxins in UK waters.

Globally, coastal populations appear to be growing faster than those inland[84], with the time people spend at the coast being positively correlated with air temperatures. A surge in recreational use of the ocean during MHWs could also increase the risk of environmental injuries such as jellyfish stings, an increased risk of water sport injuries, and a potential rise in skin cancers due to increased UV exposure[85–87].

As well as physical injuries and illness, MHWs can also affect mental well-being. Recreational use of coastal areas, for example, through wild swimming or recreational fishing activities can have positive mental and physical health benefits[88–90]. Given that MHWs (positively and negatively) impact industries such as aquaculture, fisheries and tourism[3,9,91], there are also likely to be knock-on effects for those dependent on the industries[92]. For example, the negative mental health impacts of a crash in fish stocks on commercial fishers and their families, along with the wider coastal communities in which they are embedded, are well documented[93,94]. Despite raising awareness, the increased reporting of MHWs (e.g.,[24,95]) could also be increasing environmental anxiety, further impacting mental health[96,97].

16. Will MHWs lead to changes in pathogens and biotoxins, including the emergence of novel pathogenic organisms, and what health risks do they pose to the general public?
17. What are the immediate and long-term impacts of human health in response to changes in pathogens from UK MHWs?
18. Given that MHWs often compound with atmospheric heatwaves, will a potential increase in recreational use of the ocean during an MHW lead to greater health risks e.g,. skin cancers, jellyfish stings?
19. How will MHWs impact the mental health of coastal communities that are dependent on marine resources?
20. What positive wellbeing impacts could UK MHWs have on the general public, for example, increased wild swimming opportunities?

Forecasting, and strategy-implementation to enhance preparedness

Measurements of SST have been available globally since the advent of the satellite era (now in its fifth decade), enabling global services such as the "Marine Heatwave Tracker" (https://www.marineheatwaves.org/) for surface MHWs. Whilst long-term in situ monitoring data is also available for some sites around the UK (e.g. the Western Channel Observatory L4 buoy, 105)[98], subsurface information is limited spatially. Reanalyses provide a more complete, if less certain, three-dimensional record, with one study utilising such data to assess seabed MHWs in the North Sea[35]. Climatologies from observations or reanalyses are essential in providing a baseline for comparison, central to the definition of MHWs. Hobday et al.[99] recommend increased monitoring of all aspects of ocean health (physical, chemical, and biological) to improve our understanding of MHW impacts.

MHWs are often driven by the weather, with most MHWs forming under anticyclonic conditions[14]. This enables forecasting over various timescales, with varying degrees of reliability[100]. Mercator Ocean International provides forecasts globally up to 7 days ahead using observations assimilated into models[101]. NOAA's MHW tracker (https://psl.noaa.gov/marine-heatwaves/) uses a multi-model ensemble of global forecasts to offer predictions up to a year ahead[102]. However, predictability varies by region and time of year, with regions affected by large-scale climate oscillations like the El Niño Southern Oscillation (ENSO), a common driver of MHWs, allowing for longer lead times[99]. For example, compared with the tropical east Pacific, where predictability is around 1 year in advance due to the influence of ENSO, the UK is one of the least skilful regions for MHW prediction with lead times of just 2 months'[103].

However, global models have a limited ability to resolve some features important for MHWs, such as vertical stratification and tides[25,104]. In contrast, regional systems such as the MHW portal provided by SOCIB for the Mediterranean[105] and "Moana" for the seas around New Zealand[106] monitor and forecast MHWs at higher spatial resolution up to 10 days ahead. The UK also has a regional marine forecast system, producing daily forecasts of SST up to 6 days ahead[107]. Seasonal SST predictability has also been examined around the UK, with the most skill found in winter when persistence in the atmospheric circulation is higher compared with in summer, when there is low persistence[104,108,109]. It would also be useful to distinguish between short-lived, intense surface MHWs in stratified regions and longer but less intense MHWs that occur throughout the water column in non-stratified regions. These deeper column MHWs are likely to reflect longer timescale anomalies in atmospheric forcing, potentially making them more predictable. The use of Artificial Intelligence and Machine Learning techniques has also been shown to improve SST forecasts and could be novel tools to improve MHW prediction on weekly to monthly timescales (e.g.[110–112]).

While there is potential to forecast MHWs on seasonal timescales around the UK, no such regional MHW-specific prediction system exists for the Northeast Atlantic.

21. What monitoring systems, tools and datasets are currently in place to track MHWs and their impacts around the UK?
22. How can the UK enable optimal monitoring to ensure the appropriate variables, locations, spatial and temporal scales are captured, and existing infrastructure and technologies are utilised?
23. What can the UK learn from other MHW monitoring systems globally in terms of novel approaches, technologies and collaborations between different sectors?
24. What are the knowledge gaps associated with MHW forecasting around the UK and what needs to be improved to overcome them?
25. Which stakeholders require forecasting of MHWs and what information do they need to facilitate informed decision-making and develop early warning systems?

Effective adaptation and management options to mitigate future impacts

Immediate management responses have the potential to limit the impact of an upcoming, recent or ongoing MHW, while long-term, adaptive management responses can be applied to reduce the impact of future MHWs. The management responses/mitigation measures needed to protect UK waters are currently unknown, but we can be informed by approaches taken overseas. Nature-based solutions[113,114] such as restoring mangrove forests[115,116] encouraging heat-resistant coral reefs[117,118], changing the timing and intensity of harvesting adults in fisheries and aquaculture[119], and encompassing at-risk regions into Marine Protected Areas[120] have been suggested to reduce the impact of MHWs by increasing the marine ecosystem's resilience to climate extremes in some regions.

More targeted responses of fisheries management to reduce MHW impacts have also been successfully demonstrated. An MHW off Western

Australia in 2011 led to the collapse of several fisheries, including the blue swimmer crab fishery in Shark Bay[121]. The closure and a subsequent change in the management of the quota system allowed the fishery to fully recover by 2018[119]. Following this, the power of effective management has since been recognised within the MHW Response Plan by the New South Wales government[122,123]. In the United States, previous experience combined with long-term management actions prevented a crash of the Maine lobster fisheries. Following an MHW in 2012 in the Northwest Atlantic Ocean, which led to high spring landings and a US$38 million loss to the lobster industry[124], early management intervention during a second event in 2016 proved beneficial. Measures such as increasing processing and storage capacity and linking dealers to buyers directly resulted in an industry gain of US$108 million[125].

In the Mediterranean, to mitigate the effects of MHWs, coastal aquaculture adaptation recommendations include the use of submergible cages to deeper water to avoid surface-intensified MHWs based on fish welfare thermal thresholds[126]. The benefits offered by this type of technology include avoiding extreme temperatures, reduced oxygen and harmful algal blooms[127] and could be considered by the UK aquaculture industry.

26. What adaptation options are available and what opportunities are there to strengthen resilience to minimise the impacts of MHWs on the UK's ecosystems and communities?
27. How can nature-based solutions be employed as adaptation options in response to MHWs, for example, by using more resilient species for habitat restoration, commercial fishing and aquaculture?
28. What novel technologies or adaptation options from around the world can be employed to mitigate the impacts of MHWs on key industries?
29. What is the range of flexible management options for MHWs across temporal (short- and long-term) and management scales (e.g., local council, regional, national)?
30. What role can socio-economic innovations, such as insurance mechanisms and community-based initiatives, play in enhancing the resilience and adaptive capacity of coastal communities and marine ecosystems during MHWs?

Public attitudes and engagement via effective communication

The unprecedented in magnitude, but short-lived MHW that occurred in UK waters during the summer of 2023 garnered much media attention from British news sources such as the BBC[22], The Guardian[24], and itvNEWS[23]. When it comes to public opinion, we have evidence about public perceptions of terrestrial heatwaves in the UK[128] and extensive datasets concerning public attitudes to the environment and climate change more broadly[129]. Nothing like this exists, however, for UK MHWs. It is likely that the general public were mostly unaware of the term "marine heatwave" until the 2023 media coverage due to it being a relatively new area of focussed study even for scientists and especially in the UK.

Understanding public attitudes to MHWs and their consequences to different communities and stakeholders in the UK would be useful data for considering effective engagement with those impacted by their occurrence. The act of conducting and – perhaps more importantly – communicating the results of a survey on UK MHWs with different UK audiences could also contribute to ocean literacy efforts, considered by McKinley et al.[130] as "the development of effective tools and approaches to transform ocean knowledge into meaningful behaviour change and action for ocean sustainability." This may be particularly important given that pessimistic perceptions of the UK marine environment have been found to be a barrier to engagement[131]. However, there has been a positive shift in UK public attitudes towards greater concern and increased willingness to support adaptation to climate change[132], making effective communication from scientists and government essential.

The Marine Climate Change Impacts Partnership (MCCIP) is the primary independent source of marine and coastal climate change evidence and advice in the UK and alongside government agencies (e.g., the UK Met Office, Cefas, Environment Agency etc.), could provide opportunities for dissemination of MHW-related information to relevant stakeholders.

31. What are the prevailing public attitudes and behaviours regarding MHWs in the UK?
32. How does the media portrayal of MHWs affect public perception?
33. To increase ocean literacy and MHW knowledge, what are the most effective communication and outreach strategies to target different audiences, communities and demographics?
34. How do we facilitate community and public participation in the UK's MHW management decisions as part of an inclusive approach?
35. How can we develop clear and understandable early warning and response procedures for the public during dangerous events associated with MHWs e.g. beach closures due to harmful algal blooms?

Harnessing the power of social media to gather data and communicate science

The increasing use of social media offers a large dataset for scientists to study public attitudes and perceptions and to validate their hypotheses in various areas of research[133–138]. This use of non-expert data is gaining traction in certain areas of environmental sciences where data collection at a similar scale has a greater demand on resources[139]. The idea of utilising social media data in the context of MHWs could be further explored as a tracking measure on environmental changes (e.g., mass mortality events observed along the coast), and for analysing public sentiment trends (e.g.,[140,141]) during and after MHWs. For example, Teh et al.[142] employed social media analysis to understand public opinions about plastic pollution.

Citizen science is also another promising way to crowdsource data, particularly when the researchers inform participants on best practices for data collection[143–145]. However, challenges associated with uncertainty and reliability of such data must be taken into consideration (e.g.,[144,146]). The development of citizen science programmes could have social benefits, such as people feeling closer to nature and general community development[147–149]. These programmes could be encouraged via social media to promote and increase the accessibility for the public to participate in MHW data collection for research.

A pertinent example of a citizen science project directly relevant to MHWs is the Australian Redmap (Range Extension Database & Mapping project, https://www.redmap.org.au/[150]). This web-based initiative encourages a diverse range of coastal and marine users to submit photographs documenting encounters with 'out-of-range' species. Launched in 2009, the program has facilitated numerous ecological studies on range expansions, including research on the ecological impacts of MHWs (e.g.,[151,152]). This kind of initiative could be applied to UK waters. For example, there is a growing literature that evidences the value of connecting scientists with fishers, often via social media, to monitor change[153–155]. Communications with commercial and recreational fishers, who are frequently at sea, carefully monitoring variation in what they catch, could be utilised as early warning systems to detect MHWs.

Social media can also be a powerful tool in its ability to close the gap between distant communities and the ocean, as well as between key stakeholders (e.g., fishers and scientists). With effective utilisation, social media could expose these communities to the ocean virtually and grow a deeper connection to it, as well as raise awareness of the impacts of MHWs[156].

36. How can social media platforms and other digital sources be used to collect real-time observational data on the UK's MHW impacts in the marine environment and blue economy?
37. Is there a citizen science programme that could be developed, or adapted from elsewhere (e.g., Redmap in Australia) to track the socio-ecological impacts of UK MHWs and can this be encouraged via social media?
38. How can social media be used to conduct public sentiment analysis to contribute to an understanding of the social impacts of MHWs?
39. How can social media be utilised effectively to enhance public engagement and to close the gap between different groups to spread awareness and understanding of MHWs e.g., coastal and inland communities, and scientists and key stakeholders?

40. Can Artificial Intelligence be used to distill published media and big data into useful products for tracking the impacts of and public response to MHWs?

Recommendations to the government for effective policy

The Climate Change Act 2008 sets out a framework for the UK to meet its climate obligations in reaching Net Zero and adapting to climate change. This requires assessment of both risks and opportunities in the context of climate change adaptation through publication of a 5-yearly Climate Change Risk Assessment (CCRA), which is delivered by the Climate Change Committee, the statutory body established under the Act. CCRAs are followed by a National Adaptation Programme (NAP), within which CCRA risks and opportunities are addressed with planned actions, published by the UK Government. Devolved Administrations produce their own NAPs, maintaining their own accountability against legal obligations on climate change risks and opportunities, with the CCRA3 and England's NAP3 released in 2022 and 2023, respectively. Whilst there is some marine information throughout the assessment, as it stands, there is no marine-specific chapter in CCRA4, to be published in 2026, but MHWs are just one example of why marine risks should be included.

MHWs are not currently addressed explicitly within existing climate change actions in the NAP3, instead being contained within broader actions, risks, and opportunities. They are also not currently included on the National Risk Register, which sets out the most serious risks facing the UK and is published by the Cabinet Office. It is therefore possible that potentially serious future risks may not be accounted for or prioritised, such as the health hazards discussed in Section 2.4.

There is a range of policies currently in development by the UK Government that are underpinned by legislation or commitments that require consideration of climate change. From fisheries policies (e.g., Fisheries Management Plans) under the Fisheries Act (2020) and Joint Fisheries Statement, to environmental policies aiming to address objectives under the UK Marine Strategy and Environmental Improvement Plan (2023); one challenge in these areas is that their climate change considerations can be difficult to measure.

It is useful to consider if existing policy frameworks are effective in facilitating the development of relevant evidence to improve our understanding of UK MHWs, given that they are not addressed directly in legislation. These should enable scientific advice that makes clear recommendations on how MHWs should be considered in existing and future policies, whilst assessing how existing frameworks could be used to draw attention to research needs. This is especially important given that MHWs are often contained within wider climate change ambitions, which may result in marginalisation of specific issues.

Implementation of specific policies will require increased evidence of MHW impacts across varying spatiotemporal scales. This evidence will need to be effectively communicated to the appropriate government bodies and other relevant stakeholders through suitable channels. There is a pressing need to identify areas that are susceptible to, or protected from, MHWs to enable appropriate management, and to identify the key public sector bodies or industries that may be impacted. In the short-term, it is widely thought that a coordinated response to MHWs is important to coordinate data and information, public communication and enable an effective response. However, understanding adaptation measures that could be implemented is key to any response to enable quick action to protect vulnerable areas. It is proposed that coordination of an emergency response in relation to the UK's devolved governance system and across shared international borders for small water bodies e.g., the North Sea, the Irish Sea and the English Channel, is needed. In the longer term, coordinated information may involve the strategic implementation of marine protected areas (MPAs), the development of innovative technologies to enable effective adaptation methods and the diversification of the UK's blue economy portfolio to increase resilience.

To coordinate emergency responses, long-term strategic management and more effectively utilise funding streams, a dedicated network of researchers, stakeholders and practitioners should be considered. The Marine Climate Change Impacts Partnership (MCCIP) may be a suitable forum for such a network, as it is the leading provider of climate change impacts evidence and adaptation advice in the UK.

To address the growing challenges posed by UK MHWs and ensure effective climate adaptation, the following key recommendations are proposed for policymakers, emphasising the importance of cross-border coordination and long-term strategic planning:

1. **Include marine heatwaves in national climate assessments**
   Include MHW risks in the next Climate Change Risk Assessment (CCRA) to address their growing impact on ecosystems and coastal communities.
2. **Incorporate marine heatwaves in relevant policies and management strategies**
   Develop frameworks to incorporate MHWs in a broad range of policies, capturing their potential impacts across scales from domestic to international and across sectors such as fishing, aquaculture and conservation.
3. **Implement marine heatwave risk evidence collection**
   Create a coordinated response to collect evidence of MHW impacts across sectors by a broad range of stakeholders and government bodies.
4. **Focus on vulnerable areas and blue economy resilience**
   Identify regions, economic sectors and conservation developments that are vulnerable to MHWs and ensure climate impact assessments include risks and adaptation to MHWs.
5. **Establish a collaborative network for research and preparedness to MHWs**
   Utilise the Marine Climate Change Impacts Partnership (MCCIP) to create a dedicated network for integrating marine research, strategic management, and emergency response to risks from MHWs.

Recommendations to research funding bodies and beyond

MHW research spans various disciplines and interdisciplinary approaches, from single-discipline studies on, e.g. ocean-atmosphere interactions (e.g., ref. 25) or biological responses (e.g., refs. 4,31) to complex transdisciplinary collaborations focusing on societal preparedness (e.g., ref. 99). While funding for single-discipline research is accessible through entities like UK Research and Innovation (UKRI) or Horizon Europe, the primary challenge lies in financing multidisciplinary and transdisciplinary projects involving academic and non-academic stakeholders. These partnerships are crucial for developing societal preparedness, yet they are inherently expensive and difficult to fund and establish effectively.

In the UK, despite a growing recognition of the significance of such collaborations (exemplified, for instance, by the UKRI programs such as the Sustainable Management of UK Marine Resources, SMMR, www.smmr.org.uk), the urgency and gravity of MHWs have not fully resonated with industry, policymaking, and funding bodies, given the UK mainland's perceived distance from hotspots of MHWs. Examining funding approaches in countries like Australia, which has confronted significant MHW events (e.g.,[42,157]), and the US West Coast, which has grappled with MHWs like "The Blob"[158], is critical for the UK research community. The imminent challenge lies in responding to major MHWs in the UK swiftly and comprehensively. Even the UKRI urgency funding scheme (www.ukri.org/opportunity/nerc-urgency-funding), though crucial, is unlikely to suffice for an efficient and timely multidisciplinary research response.

Examples where urgent funding is required to comprehensively understand the impacts of, and adaptation potential to, MHWs across varying spatiotemporal scales include:

1. **Perform system-level long-term monitoring and data collection**
   Allocate funding for long-term, high-risk site monitoring to capture physical, ecological, and socioeconomic data on MHWs and their impacts across a range of blue economy sectors and conservation projects.

2. **Develop novel monitoring technologies**
   Invest in innovative technologies such as autonomous vehicles to enhance responsive data collection on MHWs and improve response and adaptation strategies through cutting-edge technology.
3. **Enhance forecasting capabilities**
   Develop MHW forecasting systems to better predict and manage future MHW events and identify the necessary information to enable a broad range of emergency response plans.
4. **Improve resilience of existing restoration projects to marine heatwaves**
   Fund research to evaluate whether current climate change resilience efforts, such as habitat restoration projects, are robust enough to withstand and adapt to the impacts of MHWs.
5. **Develop transdisciplinary collaborations and stakeholder engagement**
   Prioritise funding for collaborations involving interdisciplinary academic teams and non-academic stakeholders to address societal preparedness for MHWs and effectively communicate their risks.

The key issue confronting the UK research community is perhaps that of communication, as it remains unclear how researchers can effectively convey the forthcoming impacts of MHWs to engage industry, philanthropy, and traditional research funding streams.

Discussion

Globally, MHWs are projected to continue to intensify, fuelling concerns about their wider ecological and socioeconomic impacts. Unlike many other countries worldwide, to date, the UK has not experienced major MHWs that have caused substantial ecological or societal damage or serious economic losses. It is largely unknown what impacts these extreme events will cause over the coming decades, making it challenging to put appropriate measures in place to protect or take advantage of potential opportunities for UK marine ecosystems, coastal communities and the blue economy.

Here, we proposed 40 key questions based on expert knowledge from an interdisciplinary team, which, if answered, could help to achieve an improved understanding of the risks and opportunities of MHWs around the UK. This targeted list of questions spanning *region-specific UK exposure; marine ecosystem impacts; impacts on marine natural capital, ecosystem services, and the blue economy; impacts on physical and mental human health; forecasting and strategy-implementation to enhance preparedness; effective adaptation and management options to mitigate future impacts; public attitudes and engagement via effective communication* and *harnessing the power of social media to gather data and communicate science*, will guide funding streams and assist decision-makers towards evidence-based action suitable for effective monitoring, communication and policy. Similar themes have been suggested for research into MHWs in other locations globally (e.g., ref. 27). Concurrently, it may be helpful to undertake risk assessments for possible impacts, although many of the questions we propose need to be addressed, at least in part, before any such evaluation is carried out.

A more holistic, interdisciplinary approach is needed to better understand the future occurrence of MHWs and their impacts on marine species, habitats and ecosystems. This is essential for futureproofing the marine environment and continued delivery of ecosystem services to society. Further work is also required to understand the potential impacts on coastal communities in terms of physical and mental human health and socioeconomic changes that may arise due to the increased occurrence of MHWs. However, it is worth stressing that while the majority of documented MHW impacts around the world are negative, there are also some cases where benefits have been reported (e.g., refs. 6,9,35). Given the high seasonality and connectivity of UK waters, opportunities may arise for marine organisms that can adapt and thrive, while the UK economy may experience temporary benefits in the tourism and fishing sectors, for example, due to increased abundances of warm-adapted commercially and/or recreationally important species. Careful exploration of the ecological 'winners and losers' is required to identify both heat-resilient species and those that are unlikely to tolerate MHW intensification, which will inform future adaptation plans.

Questions across the themes all point towards the increasing need for monitoring the marine environment to enable us to understand the range of impacts associated with MHWs. This monitoring is not just limited to MHWs but also the background environment, which requires continuous, longitudinal monitoring to enable a comparison with baseline conditions so that any changes as a result of marine ecosystem stressors can be measured. Given the relatively extensive and complex UK coastline, identifying where and when MHW impacts occur and understanding what will likely be affected (e.g., specific species, industries, or communities), will help develop a UK-wide optimal monitoring system. This could be enhanced by creating citizen science initiatives and bolstered by using social media, which may also improve ocean literacy in the UK.

A UK-wide monitoring strategy would be further optimised with the development of innovative marine technologies. For example, the responsive deployment of mobile sensors in the marine environment during the onset of an MHW to capture real-time data. This, combined with the development of UK MHW forecasting capabilities for an early warning syste,m would enable a rapid response to alleviate potential impacts on marine ecosystems, the economy and society. On longer timescales, using climate projections to inform the planning of mitigation and adaptation measures is important. Utilising this and real-time monitoring data will enable the identification of areas that are most at risk of MHWs or protected from MHWs, which will facilitate policy and inform management approaches for sectors such as aquaculture, fisheries and marine spatial planning. However, it is important to establish a coordinated data sharing mechanism to maximise the value of data from existing and new observational systems, including from citizen science and social media initiatives, that can also ensure high data quality standards are maintained.

Strong governance, policy and management will be required to effectively mitigate and adapt to MHW impacts. It is important to understand which actions may work and in which settings. A key theme that arises from the questions is that the UK is presented with a unique opportunity to incorporate successful management interventions and adaptation practices implemented in other countries into decision-making and learn from those that were unsuccessful. This in turn, will enable research and innovation that produces targeted and realistic interventions across short, medium and long timeframes that support policymakers in identifying opportunities that can minimise risk and mitigate impacts effectively. This will also be achieved by developing plans at both the national and regional scales to account for the highly variable spatial extent and intensity of MHW events and their impacts across UK waters. Using interdisciplinary approaches will support MHW evidence needs across many of the questions highlighted in this paper. In order to achieve this, the formation of a collaborative network of UK researchers, stakeholders and practitioners to utilise funding streams is essential. This will help address complex interacting issues across both society and the environment, alongside overcoming barriers around the current landscape of fragmented marine monitoring that can support MHW research.

This set of questions serves as a starting point for addressing UK MHW research gaps and should be periodically reviewed as our understanding develops, for example, through assessing the published literature and holding stakeholder engagement workshops every five to ten years. They should be seen as an opportunity for the UK research and policy community to address knowledge gaps, encourage action, maximise preparedness, minimise risks, and capitalise on the potential positive impacts of MHWs.

Methods

This study was guided by similar previous exercises that have identified priority questions needed to address a particular research topic, including seagrass conservation[159], marine and coastal policy[160], sustainable ocean governance[161], conservation of biodiversity[162,163] and microbial ecology[164]. Our policy-salient research questions have been proposed using an

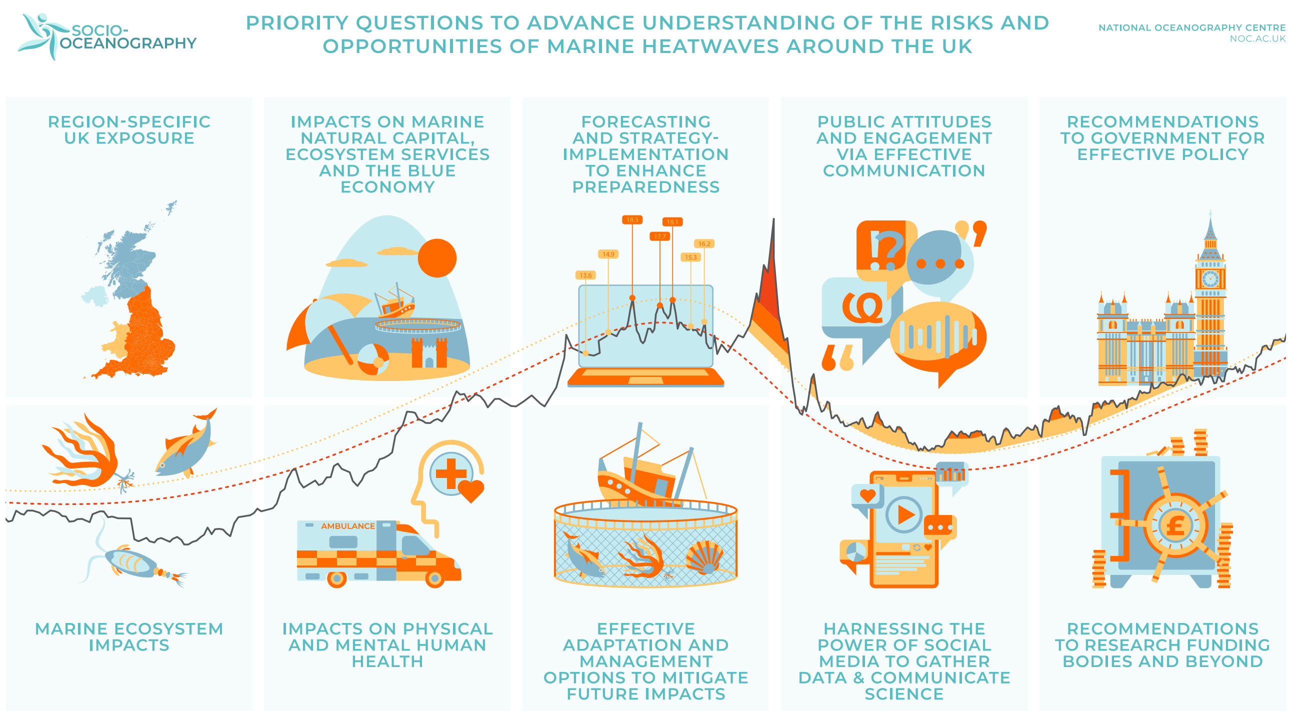

Fig. 2 | Themes for research questions and recommendations. The lines crossing the centre of the figure depict representative examples of UK marine heatwaves (orange/red).

interdisciplinary approach to address the potential risks and opportunities of MHWs around the UK.

The list of questions was generated by an interdisciplinary team of 14 scientists that attended the "Socio-Oceanography"[165] in-person workshop hosted by the National Oceanography Centre, UK in March 2024, of which UK MHWs was one of four themes. Researchers from a range of UK academic institutes, government scientific agencies and governing bodies were invited via email to attend the 3-day workshop. The workshop was also promoted via social media channels (Facebook, LinkedIn, and Twitter) to gauge wider interest and encourage registration.

Ten themes (Fig. 2) were pre-defined by the workshop conveners to address the interdisciplinary nature of potential MHW research around the UK. While some minor amendments were made to research theme titles during the workshop, no major gaps were identified. The workshop was an interactive, collaborative process, with the participants split into breakouts of 2-3 per group to generate questions (themes 1-8) and recommendations (themes 9-10) under each theme. The same amount of time was dedicated to each theme, with breakout group participants rotated frequently to encourage active input from all participants and to ensure varied perspectives were captured. A total of 352 questions were generated, which were reduced to 112 after removing duplicates and merging similar questions.

After the workshop, key expertise gaps were identified by the workshop leads and 3 additional experts were invited to contribute to reviewing the questions and potentially proposing new ones. Through an iterative process involving all participants, the questions were further refined to a set of 40 questions. This refinement also included some editing of the questions for clarity, conciseness and style. We attempted to minimise the effect of individual preference by convening a group that had a balanced representation of expertise, institute and career stage.

Data availability

Temperature data to generate Fig. 1 was downloaded and sourced from [http://marine.copernicus.eu/services-portfolio/access-to-products/] (http:/marine.copernicus.eu/services-portfolio/access-to-products). No new datasets were generated.

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Author contributions

Z.J. wrote the main manuscript and prepared Figs. 1 and 2. Z.J., K.S., J.K., D.S., P.M., F.S., M.B., C.R., R.R., S.O., M.J.P., F.P., A.K., C.B.A., and E.P. attended the workshop that generated the original questions. B.T., S.R. and S.C. contributed to later versions of the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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