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Marine heatwaves are in the eye of the beholder

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Critical methodological choices in marine heatwave detection can yield dramatically different results. We call for context-specific methods that account for regional variability to advance marine heatwave research and socio-ecological outcomes.

Marine heatwaves (MHWs) have become a central focus of ocean and climate science due to their far-reaching socio-ecological impacts[1]. Defined as episodic extreme ocean warming events, MHWs can disrupt ocean ecosystems, fisheries and coastal economies. The term 'marine heatwave' was first introduced by Pearce et al.[2] and formalized by Hobday et al.[3] and refers to temperatures above a climatological seasonal threshold for five or more consecutive days regardless of underlying cause. This definition may obscure important differences in ocean warming events by overlooking region-specific dynamics and incorrectly labelling distinct ocean processes that drive temperature anomalies, leading to misinterpretations of heatwaves and their impacts among researchers and stakeholders.

The current, standardized definition of MHWs is agnostic to both cause and impact, ignoring important methodological pathways that could facilitate important research advances. The interdisciplinary nature of MHW research necessitates more targeted definitions that embrace MHWs diversity to better understand their drivers and consequences. For example, ecologists focus on the biological consequences of MHWs, such as how prolonged warm temperatures affect species' thermal tolerance, fitness or migration patterns[4]. Conversely, physical oceanographers examine the drivers of these events, as the underlying mechanism is essential for deciphering oceanic heat distribution – whether from warm eddies, variability in ocean currents or other physical processes across various timescales. Synergizing across disciplines to promote, rather than impede, understanding of MHW drivers and impacts also requires informed methodological choices, such as selecting appropriate data products, defining relevant baseline climatologies and accounting for regional differences in ocean dynamics. Here, we highlight how dramatically these methodological choices influence the detection and characterization of MHWs and emphasize the importance of tailoring MHW identification methods to regional conditions and specific research questions. We conclude with recommendations for ensuring methodological choices adequately account for regional variability and are clearly communicated.

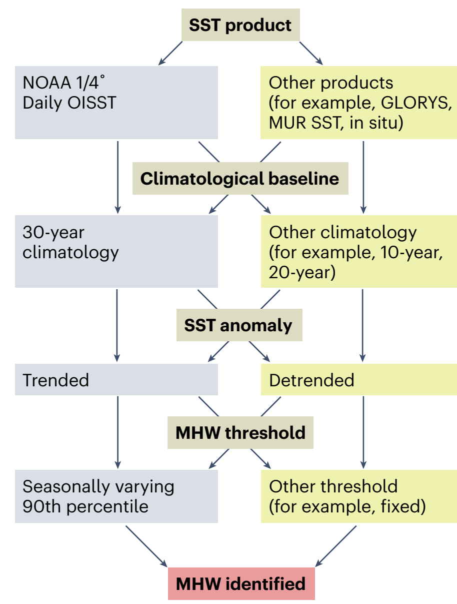


Fig. 1 | A conceptual framework highlighting some decision points and pathways in MHW detection. Decision points (brown boxes) for methodological pathways, with those that are most commonly used listed on the left (grey boxes), while example alternatives are on the right (yellow boxes). Other SST products include high-resolution, data-assimilating ocean models (that is, GLORYS) or direct measurements of ocean temperature (in situ).

Methodological pathways in MHW detection

To capture the complexity of methodological decisions in MHW research, it is essential to consider how these choices shape detection and interpretation of MHWs and how their impact is quantified (Fig. 1). Researchers face numerous methodological decision points, such as choice of data products, baseline climatologies and trend removal (Fig. 1), all of which can profoundly influence the accuracy and interpretability of results. Among these decisions, the choice of the sea surface temperature (SST) product is foundational, determining the spatial resolution and temporal coverage of the analysis. The National Oceanic and Atmospheric Administration (NOAA) 1/4° Daily Optimum Interpolation Sea Surface Temperature (OISST) product is widely used in MHW research due to its long temporal span (1981–present), forming the standard 30-year climatological baseline. However, in dynamic regions with strong spatial gradients, a higher-resolution product such as the NASA Jet Propulsion Laboratory's Multiscale Ultrahigh Resolution (MUR) L4 analysis, given sufficient validation, could provide better insights at more appropriate spatial scales despite its shorter temporal range (2002–present). For ecological studies, higher-resolution products and shorter climatologies could be particularly relevant for short-lived species that occupy smaller habitats; these species could be more affected by recent thermal extremes than long-term warming trends.

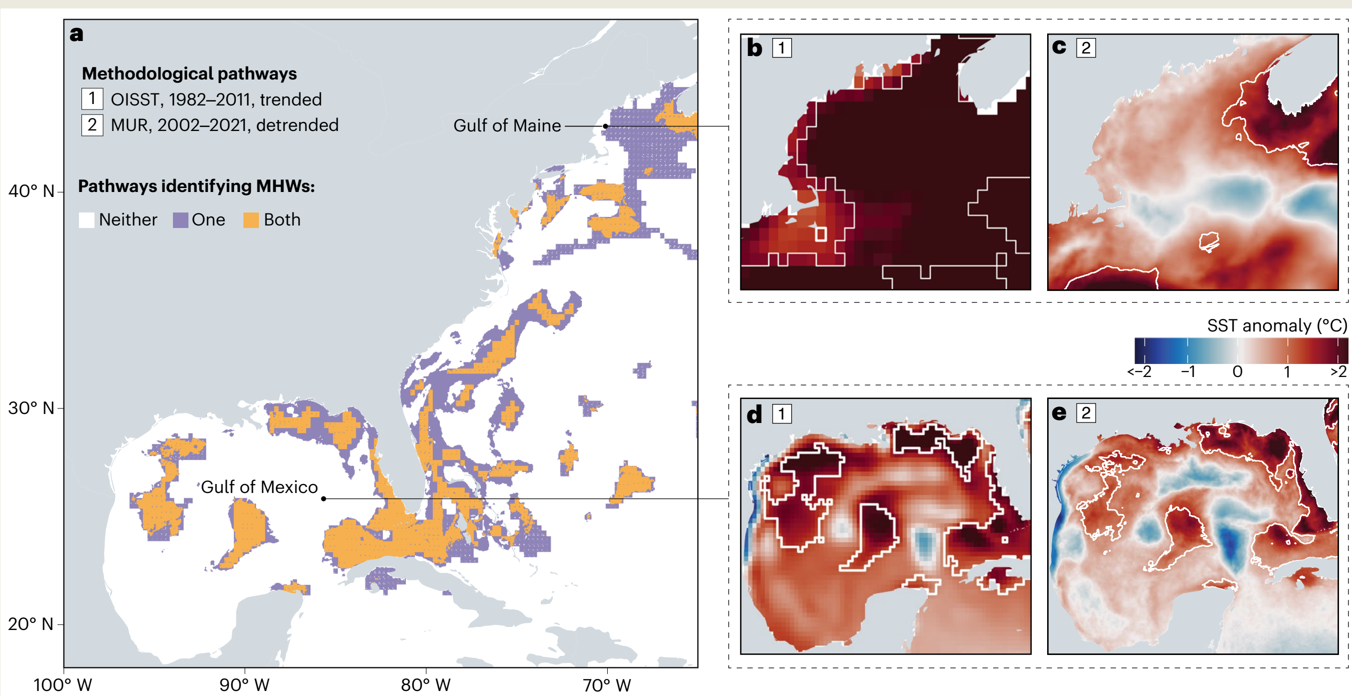
BOX 1

A case study in the western North Atlantic Ocean

Complex oceanographic processes and distinct seasonal patterns characterize the western North Atlantic Ocean. It experiences seasonal temperature fluctuations due to atmospheric conditions, ocean currents and mixing processes and is also subject to decadal ocean regime shifts, which can affect long-term trends in SST and stratification[12]. These temporal trends occur on top of considerable spatial variability, where each region can be uniquely affected by large-scale warming events, adding to the complexity of MHW identification and understanding of ecosystem responses. For example, climatologies for the Gulf of Maine reveal notable warming trends, especially in recent decades. Thus, shorter climatological baselines are important for capturing contemporary environmental conditions, while longer baselines may be important for investigating ecosystem responses to regime shifts. Adequately quantifying the impact of MHWs, including careful and precise identification, is critical in these biologically diverse and commercially important regions that support key fisheries such as Atlantic cod, lobster and scallops[12] and attract many marine predators.

The Gulf of Mexico offers a contrasting regional comparison, exhibiting less seasonal and decadal variability than the Gulf of Maine due to its subtropical climate and less variable oceanographic conditions. However, even in this more stable subregion, careful method selection remains important to ensure an accurate assessment of MHWs and their impacts: when they do occur here, MHWs can have dire ecological consequences for the diverse marine life[13], including critical habitats such as coral reefs and economically important fisheries (for example, shrimp and red snapper), where some may be affected by absolute threshold (for example, corals) while others, such as highly mobile species, are likely to respond to relative change thresholds.

Assessing MHWs in regions throughout the western North Atlantic Ocean demands careful consideration of methodological choices,



Box Fig. 1 | SST anomalies and MHWs in the western North Atlantic. **a**–**e**, MHW in the Gulf of Maine (**b**,**c**) and the Gulf of Mexico (**d**,**e**) in February 2023 as measured by two contrasting methodological pathways (**a**) (pathway 1: OISST, 1982–2011 climatology, trended SST anomalies (**b**,**d**) versus pathway 2: MUR SST, 2002–2021 climatology, detrended SST anomalies (**c**,**e**)); see also Fig. 1. Both pathways use a 3-month rolling window to identify seasonal anomalies and a 90th percentile threshold for MHW identification. The map in **a** shows the overlap in MHW detection of these two methods across the US East Coast and the Gulf of Mexico eastern seaboard, with purple representing areas where only one of the pathways identified MHWs and orange representing areas where both pathways identified them. In **b**–**e**, areas identified as MHWs are outlined in white, while the colour gradient indicates the SST anomaly (red, warm; blue, cool). Box Fig. 1 was made with Natural Earth free vector data (naturalearthdata.com) and temperature data from the OISST product[14] and the MEaSUREs Multi-scale Ultra-high Resolution (MUR) Sea Surface Temperature Data[15]. Publ. note: Springer Nature is neutral about jurisdictional claims in maps.

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as different approaches can yield pronounced variations in MHW identification and characterization (Box Fig. 1a). In the Gulf of Maine, contrasting methodological pathways reveal starkly contrasting identification and interpretations of MHW conditions and their extent and intensities. Using the classic methodological pathway (OISST, 30 year, trended data; Box Fig. 1b), 81.3% of the region is identified as experiencing MHWs in February 2023, with an average intensity of 2.25 °C and a peak of 2.94 °C. By contrast, the second methodological pathway (MUR, 20 year, detrended data; Box Fig. 1c) classifies only 1.71% of the Gulf of Maine as being in an MHW state at this time, with substantially lower average and maximum intensities of 1.16 °C and 1.37 °C, respectively. These pronounced differences underscore the critical need for deliberate and consistent methodological choices when evaluating MHWs in this and other dynamic, high-variability regions. Attempts to synthesize results from existing studies that employ different methods in this region may be problematic, potentially leading to inconsistent or misleading conclusions about the occurrence and representation of MHWs and their impacts.

By contrast, in the Gulf of Mexico, these same methodological choices yield much subtler, though still important, discrepancies. The classic pathway identifies 24.7% of the area as experiencing a MHW (Box Fig. 1d), with a mean intensity of 1.62 °C and a maximum of 2.70 °C, whereas the second pathway (Box Fig. 1e) identifies 21.0% area with a slightly lower mean intensity of 1.25 °C and a higher similar maximum of 2.95 °C. The relatively small differences in MHW identification and characterization between these pathways may be due to the region's more stable baseline conditions, where less variability in temperature leads to more consistent MHW metrics across methods.

Overall, this contrast between the Gulf of Maine and the Gulf of Mexico demonstrates how methodological choices interact with regional oceanographic characteristics — such as dynamism, short- and long-term variability, and SST trends — to profoundly shape the sensitivity, detection and characterization of MHWs and suggest very different interpretations of their impacts on socio-ecological systems.

Similarly, the choice of climatological baselines — 30, 20 or 10 years — can substantially affect MHW detection, with shorter and more contemporary baselines better capturing and controlling for the most recent oceanic changes[3]. In regions such as the Northwest Atlantic and Northeast Pacific, where decadal shifts in ocean regimes are well documented, a 30-year climatology beginning in the 1980s may not adequately account for recent regime shifts or directional warming. Thus, using this 'standard' climatology would suggest more anomalous heatwave conditions relative to a shorter climatology that better captures more recent changes. Using long historical baselines could also be less biologically relevant as it can obscure the detection of MHWs that are more relevant to the conditions an ecosystem is experiencing right now regardless of the historical regime.

Beyond selection of data products and baseline periods, researchers must also navigate a suite of other critical decisions. For example, a seasonally varying threshold at a certain percentile has traditionally been used to identify temperature anomalies; however, for certain research questions, for example, impacts on a particular species, it might be more suitable to define a fixed threshold[4]. Another crucial decision is how to incorporate temporal trends. Retaining the temperature trend highlights anomalies relative to long-term climate change, such as intensifying MHWs under mean warming, while removing the trend better isolates anomalies relative to contemporary conditions, focusing on short-term variability[4]. Explicitly and intentionally accounting for these decisions ensures clarity and consistency across studies, strengthening the quality and utility of MHW science.

Regional dependence of methodology

Over the past decade, considerable effort has been devoted to understanding and detecting MHWs globally. However, many of these efforts have employed methodologies that remain agnostic to the region-specific oceanographic and atmospheric processes (for example, Hobday et al.[3]). Regional ocean circulation patterns introduce complex spatial variability in temperature anomalies, leading to variations in MHW drivers and characteristics — such as intensity, size, duration and depth structure — even across geographically proximate areas[5–7]. For example, the spatial heterogeneity and distinct seasonal patterns in the Northwest Atlantic Ocean give rise to regionally specific types of MHW[6,7]. In this region, air–sea heat fluxes and the interaction of warm eddies from the Gulf Stream with the continental shelf are key drivers, leading to more intense thermal anomalies at both the surface and at depth[5]. Conversely, in other regions of the western North Atlantic, such as the Gulf of Mexico, MHWs are more frequent and cover a larger area, particularly at depth, due to the combination of surface air–sea heat fluxes and the relatively shallow water depth that together allow mixing of anomalous temperatures across the whole water column, from surface to seafloor[6]. These distinct regional drivers can lead to markedly different outcomes when identifying and interpreting the impacts of MHWs that critically depend on the methodological approaches used to detect them (Box 1).

While standardized methods offer consistency and comparability, the complexity and region-specific nature of MHWs suggest that a more flexible approach that explicitly accounts for regional dynamics is necessary for many research questions. To achieve this, researchers need to identify region-specific drivers of heatwave formation and persistence and adapt methods to accurately detect and characterize MHWs at the appropriate scale. In some cases, this may involve analysing extreme values for multiple variables (for example, temperature and salinity), which can provide deeper insights into the drivers, variability and impact of MHWs. For instance, in the Northwest Atlantic, a MHW that is both warm and highly saline may be attributed to the influence of Gulf Stream waters, whereas a warm MHW with low salinity indicates shelf waters being heated through air–sea interactions[5]. These distinct drivers of MHWs in the same location are likely to lead to divergent ecosystem impacts due to the involvement of different source water masses and/or physical processes. Given the complexity of MHWs, tailoring methodological approaches to regional atmosphere and ocean dynamics can enhance the detection and interpretation of these events, which might otherwise be undermined by a 'one-size-fits-all' approach.

Methodology tailored to regional dynamics

The definitional and methodological choices practitioners make can greatly affect how MHWs are identified and characterized. While a single methodological difference may only slightly influence MHW detection (for example, removing or retaining the trend[1]), the cumulative effect of multiple decisions can lead to substantial differences (Box Fig. 1). Therefore, clearly communicating methodological choices is essential to ensure findings are accurately interpreted and studies remain comparable. These differences can be especially pronounced when applied across diverse regions, where unique oceanographic mechanisms and drivers of MHWs can elicit varied biological responses. For instance, during unprecedented MHWs in the Northeast Pacific, highly migratory species exhibited differential responses depending on the underlying oceanographic and climatic drivers[8]. These responses are both event- and species-specific, with ecological impacts ranging from changes in phytoplankton productivity[9] to shifts in the distribution of marine predators[8]. As such, adopting a definition based on the effects on marine ecosystems or at a resolution matching the scale of ecological processes may better align MHW detection methods with the studied systems and species[10]. This underscores the importance of balancing comparable, standardized approaches for MHW definition and detection with the development of methods tailored to region-specific dynamics and drivers of heatwaves and highlights a need for future research.

Ocean ecosystems are experiencing unprecedented long-term changes. Episodic MHW events often exacerbate these changes, further stressing socio-ecological systems by altering oceanographic processes, leading to cascading effects including declines in biodiversity, shifts in species distributions, reduced fisheries yields and increased human–wildlife conflicts[1,11]. As ocean warming continues and intensifies, the compounded impacts on ecological and human systems will pose growing challenges for management and adaptation efforts. Adopting refined methodologies tailored to disciplinary needs is essential for improving research and policy outcomes. As MHWs intensify globally, explicit and intentional approaches that consider regional dynamics at every step of detecting and interpreting MHWs will be critical for protecting marine ecosystems and dependent human livelihoods.

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References

1. Smith, K. E. et al. *Annu. Rev. Mar. Sci.* **15**, 119–145 (2023).
2. Pearce, A. et al. *The "Marine Heat Wave" off Western Australia during the Summer of 2010/11* Fisheries Research Report No. 222 (Department of Fisheries, Western Australia, 2011).
3. Hobday, A. J. et al. *Prog. Oceanogr.* **141**, 227–238 (2016).
4. Smith, K. E. et al. *Prog. Oceanogr.* **231**, 103404 (2025).
5. Großelindemann, H., Ryan, S., Ummenhofer, C. C., Martin, T. & Biastoch, A. *Front. Clim.* **4**, 857937 (2022).
6. Amaya, D. J. et al. *Nat. Commun.* **14**, 1038 (2023).
7. Farchadi, N. et al. *Fish Fish.* **25**, 602–618 (2024).
8. Welch, H. et al. *Nat. Commun.* **14**, 5188 (2023).
9. Shen, X. et al. *Environ. Res. Lett.* **20**, 014042 (2025).
10. Li, T., Tong, S. & Shi, X. *Nature* **618**, 30 (2023).
11. Smith, K. E. et al. *Science* **374**, eabj3593 (2021).
12. Pershing, A. J. et al. *Science* **350**, 809–812 (2015).
13. Feng, Y.-T. et al. *Adv. Clim. Change Res.* **14**, 560–572 (2023).
14. Huang, B. et al. *NOAA 0.25-degree Daily Optimum Interpolation Sea Surface Temperature (OISST)* Version 2.1 (NOAA National Centers for Environmental Information, accessed 15 September 2024); https://doi.org/10.25921/RE9P-PT57
15. *MEaSUREs Multi-scale Ultra-high Resolution (MUR) Sea Surface Temperature Data* Version 4.1 (NASA JPL, Physical Oceanography Distributed Active Archive Center, accessed 15 September 2024); https://podaac.jpl.nasa.gov/MEaSUREs-MUR

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Competing interests

The authors declare no competing interests.