Progress in Oceanography 231 (2025) 103404

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Baseline matters: Challenges and implications of different marine heatwave baselines

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ARTICLE INFO

Keywords:
Marine heatwave
Baselines
Adaptation
Climate impact
Climate change
Extremes

ABSTRACT

Marine heatwaves (MHWs), prolonged periods of unusually high ocean temperatures, significantly impact global ecosystems. However, there is ongoing debate regarding the definition of these extreme events, which is crucial for effective research and communication among marine scientists, decision-makers, and the broader public. Fundamental to all MHW analyses is a clearly defined background oceanic climate – i.e., a temperature 'baseline' against which the MHW is defined. While a single approach to implementing a baseline may not be suitable for all MHW research applications, the choice of a baseline for analysing MHWs must be intentional as it affects research outcomes.

This perspective examines baseline choices and discusses their implications for marine organism and ecosystem risks, and their relevance in communicating MHW characteristics and metrics to stakeholders, policymakers, and the public. In particular we analyse five different baseline approaches for computing MHW statistics, assess their technical differences, and discuss their ecological implications. Different baselines suggest widely different trends in MHW characteristics in a warming world. This would, for example, imply differences in future risk, reflective of marine organisms with different adaptive potential, thereby affecting recommendations for management strategies. We also examine the consequences of different baseline choices on ease of implementation and communication with wider audiences. Our analyses highlight the need to clearly specify a chosen baseline in MHW studies, and to be mindful of its implications for MHW statistics, practical considerations, and interpretations concerning the adaptive capacities of marine organisms, ecosystems and human systems. The

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https://doi.org/10.1016/j.pocean.2024.103404
Received 15 July 2024; Received in revised form 19 November 2024; Accepted 4 December 2024
Available online 6 December 2024

challenges and implications of different MHW baselines highlighted here have similar relevance in research and communication for other branches of climate extremes.

1. Introduction

Marine species have adapted to their environments over millennia, with each population having specific environmental ranges in which they can survive (Pinsky et al., 2020). However, prolonged periods of unusually warm ocean temperatures, known as marine heatwaves (MHWs; Pearce et al., 2011; Hobday et al., 2016), can cause temperatures to exceed a marine organism's limit, contributing to the overall risk to marine species (e.g. Cavole et al. 2016; Frölicher and Laufkötter 2018; Kendrick et al. 2019; Cheung and Frölicher 2020; Smith et al. 2023), ecosystems (Wernberg et al., 2024), and ecosystem services (e.g. Smith et al. 2021; Smale et al. 2019). The importance of these extreme events highlights the need for a robust framework to accurately identify and analyse MHWs.

To this end, a common definition of MHWs is desirable for consistency in identifying events and to better compare and communicate their causes, characteristics, trends, and impacts. For example, a MHW framework, proposed by Hobday et al. (2016) and extended to identify increasingly severe MHW categories (Hobday et al., 2018) has been adopted in over 800 studies (Witman et al., 2023). This consistency has allowed many comparative studies, facilitating their interpretation, and increasing communication and community awareness of MHWs. Nevertheless, a single MHW definition is not necessarily the best choice for all applications and alternatives may be better suited to address different questions (Burger et al., 2022; Frölicher et al., 2018; Jacox et al., 2020).

There are several choices to make when defining a marine heatwave (Fig. 1) (Holbrook et al., 2020; Oliver et al., 2021). An initial critical decision is what baseline approach to adopt. Baseline approaches may use a climatological *reference period* (see Table 1) that remains fixed, that continuously shifts or that periodically updates over time. A reference period may reflect preindustrial conditions e.g. 1850–1900 (IPCC, 2023), or for pragmatic reasons coincide with the earliest period of available data (e.g. 1982–2011; the first full 30 years of the satellite record; Hobday et al., 2016, 2018). A minimum reference period duration is often considered to be 30 years (WMO, 2017), however practical consideration might not allow this length (e.g. when using profiling float data from the Argo program that commenced in 1999; Johnson et al., 2022). The choice of baseline strongly affects the *MHW threshold* (i.e., the temperature above which a MHW is defined, Table 1). This threshold has taken various forms including a fixed temperature (e.g. Huang et al., 2021) like the climatologically hottest day of the year (Cael et al., 2024), a seasonally varying temperature (e.g. Hobday et al., 2016), or more complex metrics like cumulative temperature anomalies. The latter is widely used in coral bleaching risk assessments in the form of the degree heating weeks metric, which accumulates temperature anomalies over preceding months that exceed some seasonal maximum temperature (Liu et al., 2003). A MHW threshold can also reflect an organism's upper thermal limit (e.g. Huang et al., 2021) or be determined by local temperature norms (e.g., 90th or 99th percentile of temperature variations). Temporal criteria may also apply, with thresholds being exceeded for a period such as five days (Hobday et al. (2016) or a month (Jacox et al., 2020).

Recent discussions in the literature (Amaya et al., 2023; Giménez et al., 2024; Jacox, 2019; Li et al., 2023; Sen Gupta et al., 2023), have highlighted a range of perspectives regarding the choice of baseline. An overwhelming proportion of studies have historically employed the Hobday et al. (2018, 2016) framework, using a fixed MHW threshold. However, concerns have been raised that defining 'anomalously warm water events' in a warming ocean using a fixed baseline would confound short-term transient warming events with long-term change, possibly leading to incorrect conclusions about changes in MHW-related impacts. Amaya et al. (2023) recently suggested nomenclature to unambiguously indicate whether a fixed or shifting baseline is being used in MHW studies. Specifically, they suggested that the term 'marine heatwave' should be reserved for events calculated from a shifting baseline, where the long-term temperature change is removed. They also proposed warm water events relative to fixed baselines be identified with a separate term such as 'total heat exposure'. In contrast, Sen Gupta et al. (2023) argued that given the existing widespread use of a fixed baseline in investigations into MHWs (see section 4), such a nomenclature change could lead to confusion in the communication around MHWs and would obscure the link between impacts on marine life and the occurrence of stronger, longer and more frequent periods of temperatures exceeding historical thresholds (Smale et al., 2019). Given ongoing disagreement regarding MHW baseline terminology, in this manuscript we have adopted an inclusive approach and used the term MHW irrespective of the baseline used.

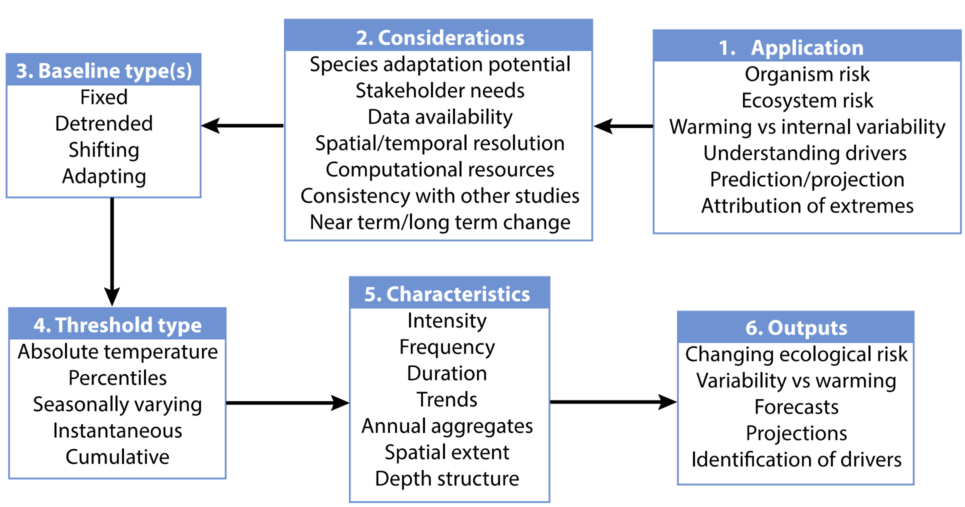

Fig. 1. Process for selecting a threshold: this involves deciding on an application, assessing technical and stakeholder considerations, choosing a baseline type and reference period, deciding on the type of threshold and on the metrics needed to provide the necessary outputs.

Table 1
Glossary of terms related to marine heatwave baselines.

Climatology	The typical temperature conditions (including long-term seasonal mean and variance) for a given location. These conditions are normally representative of a period of at least 30 years and sometimes referred to as the "baseline" climate.
MHW threshold	The temperature that must be exceeded for an event to be considered a MHW. This threshold may change with background warming (e.g. when using *detrended* or *shifting baselines*) or remain static (e.g. an organism's experimentally determined thermal limit). It may also vary seasonally (e.g. the 90th percentile of the climatology for a given time of year).
Reference period	The period used to establish the *climatology* and *MHW threshold*. This period may be fixed (e.g. 1982–2011), continually updated (e.g. preceding 30 years), periodically updated (e.g. each decade) or could encompass the entire data record.
Analysis period	The period over which MHW characteristics are calculated.
Detrending	In the context of this manuscript, *detrending* refers to the removal of the long-term temperature change. This step includes removal of linear or higher order fits to the temperature data or removal of estimated anthropogenic warming (e.g. via averaging multiple ensemble members of a climate model).
Baseline	While *reference period* and *baseline period* are often used synonymously, we use baseline here to refer to the approach used for defining the reference period.
Fixed baseline	An approach based on an unchanging *reference period* (e.g. 1982–2011 or 1851–1900) whereby the climatology and *threshold* remain fixed over time (apart from possible seasonal variations, e.g. Hobday et al., 2016).
Detrended baseline	An approach in which temperature data are detrended prior to applying a *fixed baseline*. This is equivalent to a *MHW threshold* that changes over time to remove the influence of slow changes in the climatological mean temperature (but not the variability). Note that this method has also been referred to as a *shifting baseline*, but here we make the distinction between the two cases.
Shifting baseline	An approach based on a frequently updated *reference period* prior to (or sometimes centred on) the *analysis period* (e.g. the climatology and *threshold* for a given year is based on the preceding 30-year *reference period*). Under a *shifting baseline*, the *MHW threshold* changes over time, removing the influence of slow changes in climatological conditions (mean and variability). Detrending may also precede the use of a *shifting baseline* (discussed below).
Adaptation-adjusted baseline	An approach in which the *MHW threshold* changes over time in a prescribed manner, to account for the assumed adaptation rate of marine organisms (e.g. threshold increases linearly at 0.01 °C/decade). *Threshold* evolution would typically be species specific (potentially informed by manipulative experiments).
Periodically updated (reference period) baseline	An approach that employs a recently updated *reference period* that reflects the new normal climatology but subsequently applies a *threshold* that remains fixed over time based on the updated *reference period*. WMO (2017) recommends updating the *reference period* at the start of each decade (e.g. the current reference period is 1991–2020). This approach combines the recent reference period of a shifting baseline with the impact of ongoing warming on MHW characteristics of a fixed baseline.
Saturation	A permanent or near permanent MHW state (e.g. when using a fixed baseline approach) when the long-term background warming causes temperatures to frequently exceed historic *MHW thresholds*.

Different baselines and thresholds for analysing temperature extremes each present their own set of advantages and drawbacks, while also posing distinct technical challenges in their implementation. These methods are motivated by varied underlying assumptions, especially when applied to the study of marine organisms. In this synthesis, we focus specifically on baseline choices and discuss their implications for depicting MHW changes over time, attributing marine organism and ecosystem risks, and their relevance in communicating MHW characteristics and metrics to stakeholders, policymakers, and the public. In Section 2, we discuss the different baselines that can be used and identify challenges with each type in Section 3. Section 4 explores the use of baselines in the published literature before examining the impacts of baseline type on marine ecosystems (Section 5) and how adaptation timescales might change these impacts (Section 6). Section 7 reviews baseline approaches within other disciplines, and Section 8 discusses how baseline choice can impact messages communicated with broader audiences. Finally, in Section 9 we provide recommendations for the selection and use of baselines moving forward.

2. Baselines

Several baseline approaches have been employed to calculate the threshold for defining MHWs in research and reporting. To aid clarity in this study, we adopt a naming convention for these approaches (Table 1; acknowledging that alternative terminologies exist in other studies and that Amaya et al. (2023) has argued that only temperature extremes defined with the effect of the long-term warming removed should be referred to as MHWs). Common approaches include a **fixed baseline** (Fig. 2a) where the reference period remains static for all time throughout the *analysis period* (Frölicher et al., 2018; Hobday et al., 2018, 2016), a **shifting baseline** (Fig. 2b) where the *reference period* updates over time, keeping pace with the current *analysis period* (Cheung et al., 2021; Burger et al., 2022; Amaya et al., 2023), a **detrended baseline** (Fig. 2c) where long-term trends are removed from temperature data prior to calculating *thresholds* (Amaya et al., 2023; e.g. Jacox et al., 2020; Xu et al., 2022) and an **adaptation-adjusted baseline** (Fig. 2d) where the *threshold* is updated over time to reflect species adaptation potential (Logan et al., 2014; Li et al., 2023). Since the latter baseline approach would be tailored to understanding consequences of MHWs on a specific species or population, the details of the approach would be distinct in each case. As such, we focus on the other, more well-defined approaches.

Addressing climate extremes more generally, the World Meteorological Organization (WMO) has recommended a **periodically updated baseline** which includes elements of both shifting and fixed baselines. They recommend updating the reference period every 10 years to account for recent climatological conditions. However, this reference period is subsequently held fixed over the analysis period (Table 1). A further recommendation is to also present fixed baseline information based on a default 1961–1990 reference period for the consistent intercomparison of long-term changes over time across studies.

A fundamental distinction exists between using a fixed versus a detrended or shifting method to calculate MHW metrics. The former baselines use an unchanging (or at most seasonally repeating) threshold across the time series, whereas the latter approaches adjust the threshold over the span of the time series to account for long-term ocean warming.

3. Saturation and other challenges

A key trait of the fixed baseline definition is the increasing saturation of MHWs as ocean temperatures rise, a phenomenon also observed in other extremes like ocean acidity and terrestrial heatwaves (IPCC, 2021). As background ocean temperatures increase, conditions that exceed fixed thresholds become more frequent and last longer, even in the absence of increased temperature variability (Hobday et al., 2018; Xu et al., 2022). Eventually, with sufficient warming, the frequency of

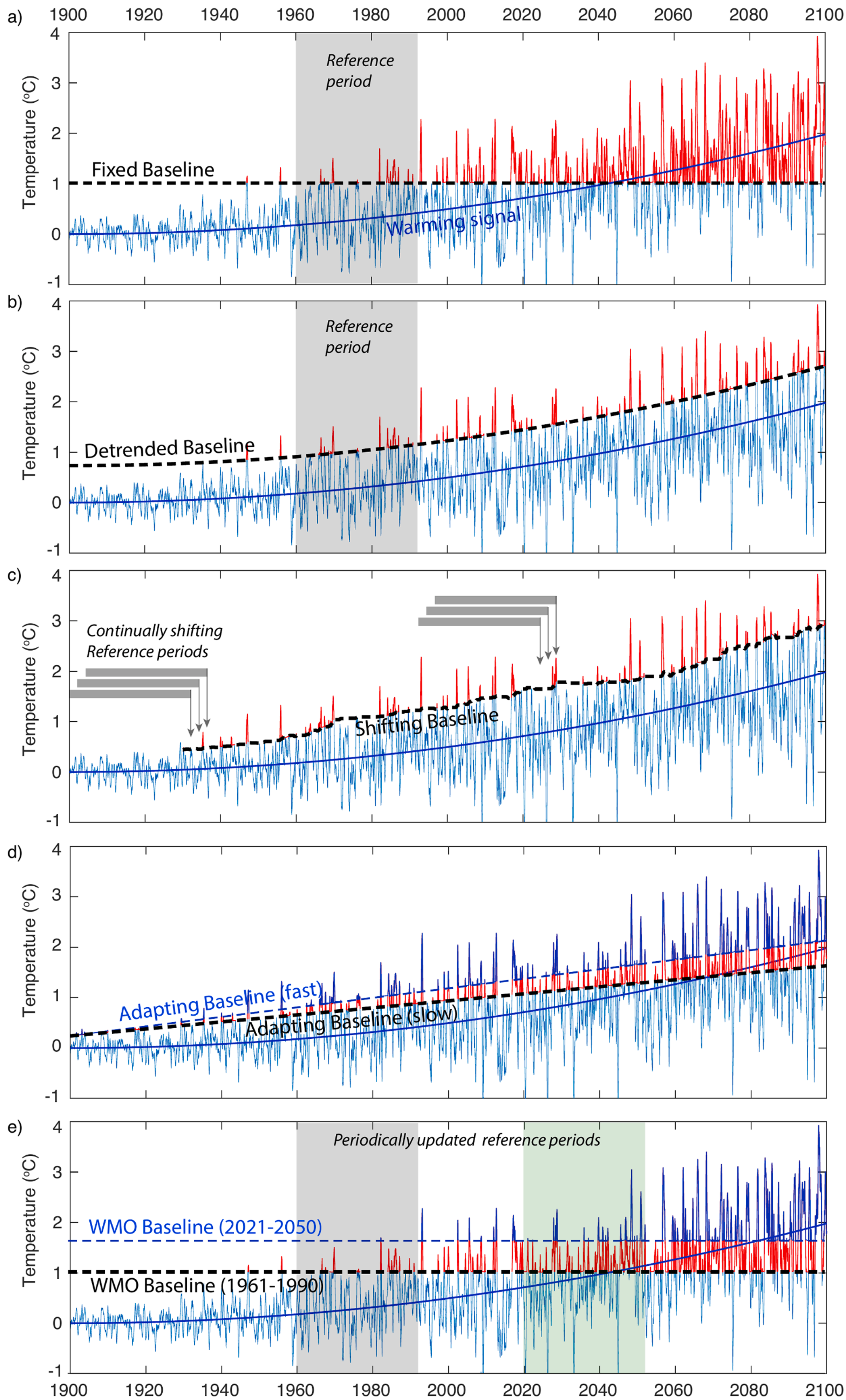

Fig. 2. Illustration of a) fixed, b) detrended, c) shifting, d) adapting and e) periodically updated baseline periods. Thin light blue line depicts a schematic temperature time series with a nonlinear warming trend (thick blue line) and increasing variability. Red (dark blue) lines indicate periods where the thresholds (dashed lines) are exceeded. Grey (green) shaded areas indicate the associated reference periods; d) shows thresholds based on a slow and a fast linear adaptation to warming; e) shows thresholds associated with two sample reference periods.

these events decreases as individual events lengthen. Where warming relative to the reference period exceeds a few degrees Celsius a 'permanent MHW' state may ensue (Fig. 2e, Fig. 3) (Amaya et al., 2023; Oliver et al., 2019). Under these circumstances, MHWs no longer remain rare events. However, while there is tendency towards saturation using a fixed baseline approach, this characteristic may still correctly reflect the escalating real-world impacts of ocean warming in a changing climate.

The effect of background warming under a fixed baseline approach also raises questions about obscuring the relationship between MHWs and their drivers (Amaya et al., 2023; Jacox, 2019). Many previous studies have linked the build-up and decay of MHWs to proximate oceanic or atmospheric heat fluxes, potentially modulated by large scale climate modes like the El Niño – Southern Oscillation (ENSO) (e.g. Holbrook et al., 2019). Attribution studies have examined how anthropogenic warming has increased the likelihood of individual MHW events defined using a fixed baseline (Oliver et al., 2019; Perkins-Kirkpatrick et al., 2019; Laufkötter et al., 2020). However, with increasing warming, fixed baseline MHWs would increasingly be attributed to anthropogenic climate change, dominating over other drivers. To discern more clearly the local drivers of rapid temperature increases and decreases, researchers could adopt higher thresholds within the fixed baseline approach or switch to detrended, shifting or periodically updated baselines. Such strategies would enable the differentiation between the immediate causes of short-term temperature increases and the broader impacts of long-term climate change.

Saturation becomes less of an issue when considering more extreme MHW thresholds. For example, Hobday et al. (2018) proposed a series of higher threshold categories based on multiples of the difference between the climatological mean and the 90th percentile temperatures from a fixed reference period. While lower categories might saturate with sufficient warming, higher category MHWs would remain infrequent events (See Box 1). An important motivation of this approach is to reflect the future hazard posed by MHWs to species with higher levels of thermal tolerance. Similarly, NOAA Coral Reef Watch issues different alert levels for coral bleaching based on increasing bleaching risk categories. Again, different coral types might be able to cope with higher categories of thermal stress. Recently, three additional categories were added to reflect unprecedented heat stress levels (NOAA Coral Reef Watch, 2024). Other methodologies, such as employing the 95th or 99th percentile thresholds for more extreme MHWs, have also been adopted (Frölicher et al., 2018; Gruber et al., 2021). However, accurately estimating increasingly extreme percentile thresholds becomes challenging with short data records or when requiring high temporal resolution (e.g. daily) percentiles.

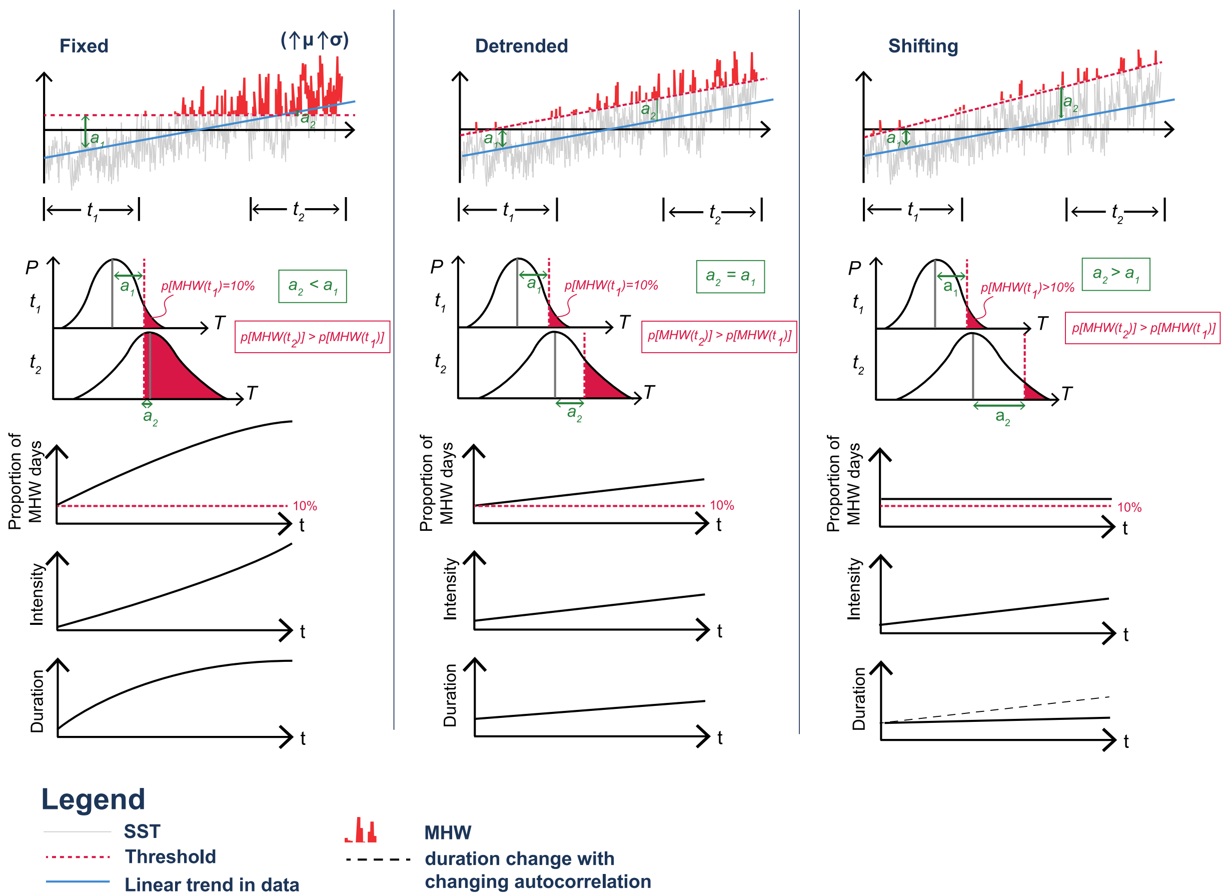

Fig. 3. Characteristics of the fixed (left), detrended (centre) and shifting baseline (right) approaches. The primary distinction between different baselines is whether we maintain the same baseline throughout (fixed), whether we account for mean changes (detrended), or whether we account for mean and variance changes (shifting). Top row: Grey lines show a temperature time series with increasing annual mean temperature (μ) and temperature variance (σ). Blue line shows the linear trend in the mean. Red dashed line indicates the associated threshold and solid red line indicates MHW conditions. Second row: Associated temperature probability distributions for time periods t_1 and t_2 showing the increase in distribution mean and variance; Grey line indicates the mean, red dashed line indicates the threshold and red shading shows the proportion of the probability (p) density function associated with MHW conditions. Bottom three rows: proportion of MHW days per annum, mean intensity and mean duration as a function of time. Fixed baseline: the proportion of MHW days increases over time while the distance between the temperature trend and the threshold reduces over time (cf. a_1 and a_2). Detrended baseline: The distance between the temperature trend and the threshold remains fixed. Despite this there is a small increase in the proportion of MHW days, intensity and duration due to increases in temperature variance. Shifting baseline: The distance between the temperature trend and the threshold increases with time to maintain a constant proportion of MHW days and duration as the temperature variance increases.

For operational applications, the WMO suggests periodically updating the default reference period by 10 years at the start of each decade, such that future extremes are defined relative to a recent climatological period (WMO, 2017). This method effectively employs progressively higher temperature thresholds for defining extremes, such that in the near term they are still affected by warming but do not saturate (Fig. 2e, See Box 1). For example, a multi-year MHW forecast initialised today would use a threshold calculated over the 1991–2020 reference period, but the forecast would include the effect of subsequent anthropogenic warming. To maintain consistency with previous studies that examine multi-decadal historical or future changes in extreme characteristics, the WMO additionally recommends reporting results based on a fixed baseline with a 1961–1990 reference period. We note that for MHWs analysed with satellite data, which only became available in the early 1980s, many studies have opted for the 1982–2011 period as a practical alternative for intercomparison. Due to long-term warming, this later period would produce different results in MHW characteristics relative to a 1961–1990 reference. We also note that there can be large discrepancies between temperature products during the 1980s, suggesting that a more recent default climatological period may be a more robust choice (Yang et al., 2021).

The detrended baseline approach does not suffer from saturation as the threshold increases with time. However, this approach requires the additional step of removing the low-frequency warming signal. Often the goal is to remove the anthropogenic signal. Identifying this is challenging, particularly when using shorter or discontinuous observational records. In a climate modelling framework, it is possible to average over large numbers of single-model ensemble simulations, which possess distinct internal variability, to accurately determine the anthropogenic warming contribution (Burger et al., 2022, 2020; Deser et al., 2024). While such an approach cannot be applied to real-world data, improved estimates of the anthropogenic warming signal may be obtained through various statistical or dynamical approaches (Wills et al., 2020; Xu et al., 2022). For example, Xu et al., (2022) presented an innovative approach based on an empirical Linear Inverse Model (LIM), where the anthropogenic signal emerges as one of the eigenmodes of the LIM dynamical operator. Often, assumptions about the nature of warming (e.g., linear, or higher-order trends) are made, with the risk that higher-order trends may inadvertently remove important low-frequency natural variability along with the anthropogenic warming signal. Differences in the assumed anthropogenic warming can lead to notable differences in perceived changes in MHW characteristics over time (see Box 1). Moreover, distinct seasonal trends, like accelerated warming in summer, or shifts in seasonal timing, can falsely suggest an increase in variability if they are not adequately factored in (Wang et al., 2022b).

Like the detrending method, the shifting baseline approach eliminates the warming signal by updating the threshold based on characteristics (e.g. 90th percentile) of preceding (or flanking) multi-decadal periods (Fig. 2). However, in this case, slow changes in both the climatological mean and variability alter the MHW threshold. If variance is stationary, then MHW characteristics would exhibit little change over time, despite background warming. If variance were to change over time, related changes in MHW intensity would be expected, but the amount of time spent above the threshold as well as MHW frequency and duration would remain unchanged (Fig. 3, see Box 1), although changes in other temporal characteristics (e.g. autocorrelation) could change frequency and duration (Shi et al., 2022). Where the goal is to remove the anthropogenic warming, the use of a running reference period may also suppress the low-frequency modulation of MHW characteristics associated with natural multi-decadal variability. A notable limitation of the shifting baseline is that MHW analysis may commence only after the initial baseline period has elapsed, unless some approximate method is employed for earlier data. For instance, with satellite data available from 1982 to present, MHWs can be calculated only post-2011 when using a lagged 30-year shifting baseline (Fig. 4a). This approach becomes particularly problematic with fragmented data (Fig. 4f). Wang et al. (2022a) also showed that, in the case of accelerating warming, various MHW metrics show a spurious negative trend under a shifting baseline. Additionally, when implementing a shifting baseline based on a lagged reference period in a warming scenario, caution is needed in interpreting MHW characteristics. For example, a simple 90th percentile threshold would result in a MHW occurrence probability exceeding 10 % (Fig. 3, see Box 1). These issues can be addressed by detrending the temperature data prior to applying the shifting baseline.

Based on a systematic analysis of the shifting baseline approach, Wang et al. (2022a) proposed an alternative ‘partial’ shifting baseline approach. This approach removes many of the statistical artifacts discussed above, but also retains MHW changes associated with changes in temperature variability.

4. Use of baselines in published literature

The fixed baseline arguably provides the simplest approach both conceptually and computationally. The motivation for this approach is intimately tied to an assumption that ecological risk is, to first order, related to fixed thermal limits (see below), and as such it is widely employed in ecological studies. To provide a rough indication of baseline usage, a survey of the first 100 ‘most relevant’ results in a Google Scholar search on “marine heatwaves” shows 96 of the 100 studies exclusively employing this approach for assessing MHW presence. Two studies compared fixed and detrended baselines, and another two exclusively used a detrended baseline.

While most studies exploring changes in MHW characteristics over time have used a fixed baseline (Frölicher et al., 2018; IPCC, 2023; Oliver et al., 2018), including studies examining event attribution (Barkhordarian et al., 2024; Laufkötter et al., 2020; Oliver et al., 2017), there are exceptions. Notably these include studies that contrast detrended with fixed baselines attempting to separate the contribution of long-term warming, typically related to anthropogenic warming, from changes in higher-frequency variability. For instance, a variety of studies have demonstrated that the long-term mean change dominates MHW characteristics compared to variability changes in most regions (Alexander et al., 2018; Frölicher et al., 2018; Oliver, 2019). Xu et al. (2022) revealed that nonlinear background warming can suggest an apparent increase in temperature variability and MHW frequency, underscoring the importance of using an accurate detrending approach. Deser et al. (2024) used a large ensemble to remove a robust estimate of anthropogenic SST changes, to identify the drivers of the internally driven component of MHWs and cold spells. In ecological studies, Cheung et al. (2021) and Cheung and Frölicher (2020) also detrended the temperature based on a model ensemble average to discern the distinct impacts of background warming and temperature extremes on marine biodiversity, fisheries, and economics, discovering significant losses from both factors. Jacox et al. (2020) used a detrended SST baseline to investigate thermal displacement during MHWs, finding that over the satellite era, their results remained qualitatively similar to a fixed baseline approach.

Separating long-term background warming from residual variability is also important for understanding predictability and for the accurate assessment of prediction skill. The long-term trend and the various components of shorter-term variability are driven by different processes and, therefore, have different predictability timescales. In the presence of long-term trends, forecasts at seasonal and longer lead times can exhibit inflated skill levels (Wulff et al., 2022), including when forecasting extremes, and hence may not accurately reflect the model’s true capability in simulating the processes driving shorter-term variability. For instance, elevated skill can simply result from the higher frequency of MHWs, defined using a fixed threshold, in a warmer world (Jacox et al., 2022; Wulff et al., 2022). As such, skill metrics must be interpreted with care, when predictions are made in the context of a fixed baseline.

Examples of shifting baselines in the literature are comparatively scarce. Oliver et al. (2021) investigated the implications of future MHWs

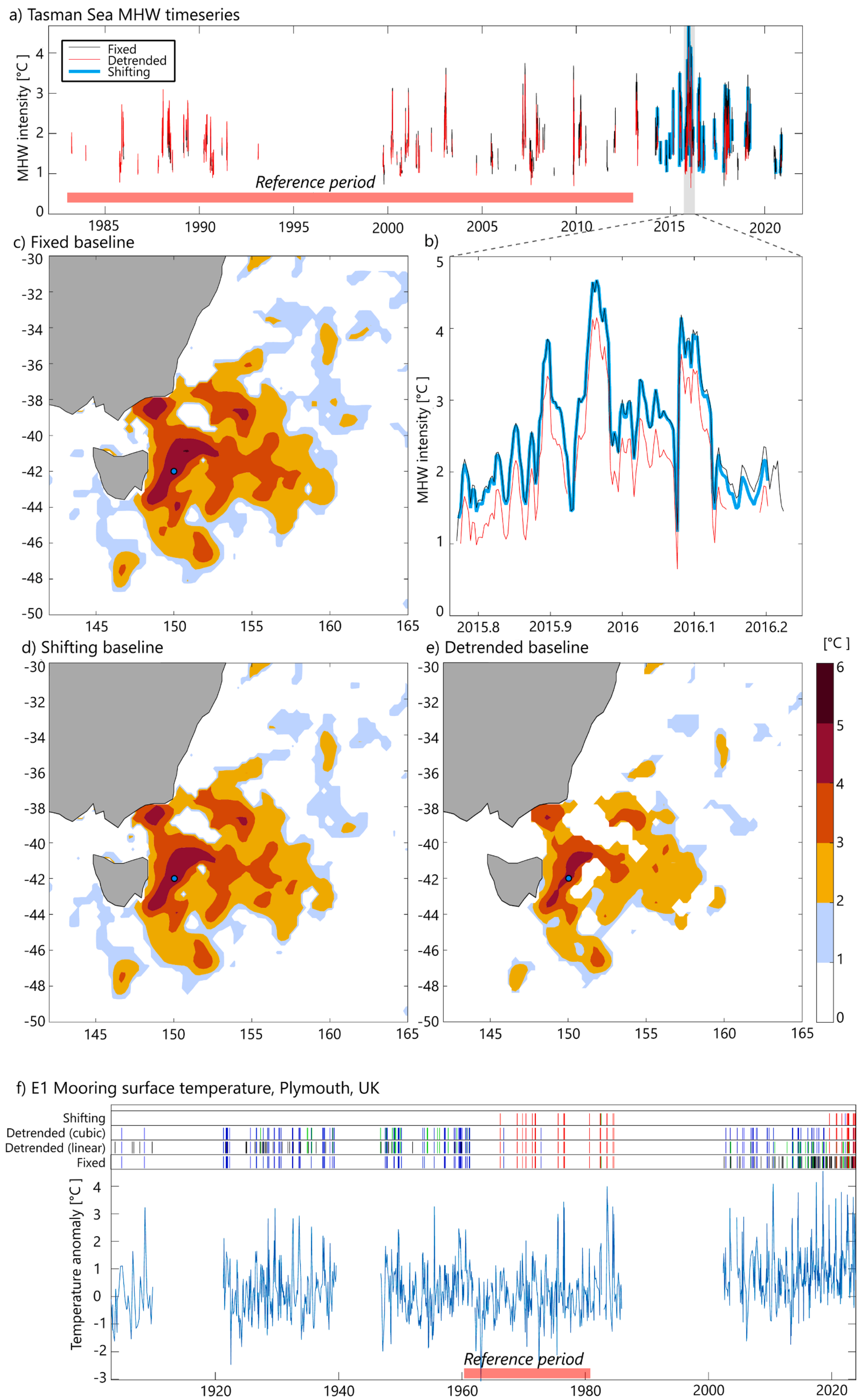

Fig. 4. Baseline comparison example for the a-e) Tasman Sea showing fixed baseline (1982–2011), detrended baseline (where a linear trend is removed over the entire time period, 1982 to 2022, and added to mean conditions for the 1982–2011 period), and shifting baseline (where the reference period is updated annually). a) time series of MHW intensity at 150°E, −42°N; b) as in a) for the period of the 2015/16 Tasman Sea heatwave; c-e) snapshot of the MHW intensity on 19/12/2015, using three baseline definitions; f) Example baseline comparison for long station-based mooring (E1; data from the Western Channel Observatory) off Plymouth UK showing temperature anomalies (bottom) and MHWs identified using fixed, linear detrended, cubic detrended and shifting baselines (vertical lines). Line colours indicate where one (black), two (green), three (blue), and four (red) baseline methods agree on the timing of MHW events.

using both fixed and shifting (termed 'moving') baselines to represent the extremes of species adaptability with no adaptation versus rapid adaptation. Similarly, Giménez et al. (2024) compared a fixed versus shifting baseline on the occurrence of MHWs in the North Sea to understand how slowly and rapidly adapting systems might experience future events. They identified that a fixed baseline increased the frequency of MHWs compared with a shifting baseline but did not change the duration of events. Burger et al. (2022) compared fixed, detrended and shifting baselines to examine future changes in compound MHW and ocean acidity extremes. They found a large increase in compound events primarily driven by long-term mean changes in temperature and acidity. However, examination based on a detrended baseline indicated some change related to variance changes in acidity, while examination of the shifting baseline results revealed subtle additional changes related to the strength of the mechanistic link between temperature and acidity.

5. Baselines and risks to marine organisms and ecosystems

The primary reason that MHWs and other extremes gain so much public and scientific attention is the ecosystem impacts they cause, along with their associated impacts to human systems. As a result, it is important to ensure that the way a MHW is defined reflects observed impacts and expected future risk, which in turn relate to the temperature limits a particular species or ecosystem can tolerate and how these might change. Outside of these limits, performance is reduced and if an individual is unable to adapt or relocate, eventually death may occur. The perceived risk of MHWs and other climatic extremes will vary with baseline choice. For example, for contemporary, slowly adapting organisms MHWs identified using a fixed baseline might most accurately reflect the changes experienced. Conversely, for a rapidly evolving organism, a fixed baseline approach would overestimate risk and a baseline that accounts for slow background warming may be more appropriate.

Of particular relevance to the baseline question is how ecological impacts are evolving in a warming world. There have been many reports indicating that observed ecological impacts associated with MHWs have become increasingly severe and frequent over time (Fig. 5). Mass mortality events in invertebrates, fish, birds and marine mammals (Garrabou et al., 2022; Gómez-Gras et al., 2021; Jones et al., 2018; Smith et al., 2023, 2021), declines in foundation species (Smith et al., 2024) and increases in coral bleaching (Cooley et al., 2022; Hughes et al., 2021) have been observed with ever shorter recovery periods (Cooley et al., 2022). More specifically, a recent study demonstrated that the number of global locations each year where foundation species are negatively impacted by MHWs are increasing over time (Smith et al., 2024).

Similarly, fisheries closures linked to warm water anomalies, are becoming increasingly common worldwide (Barbeaux et al., 2020;

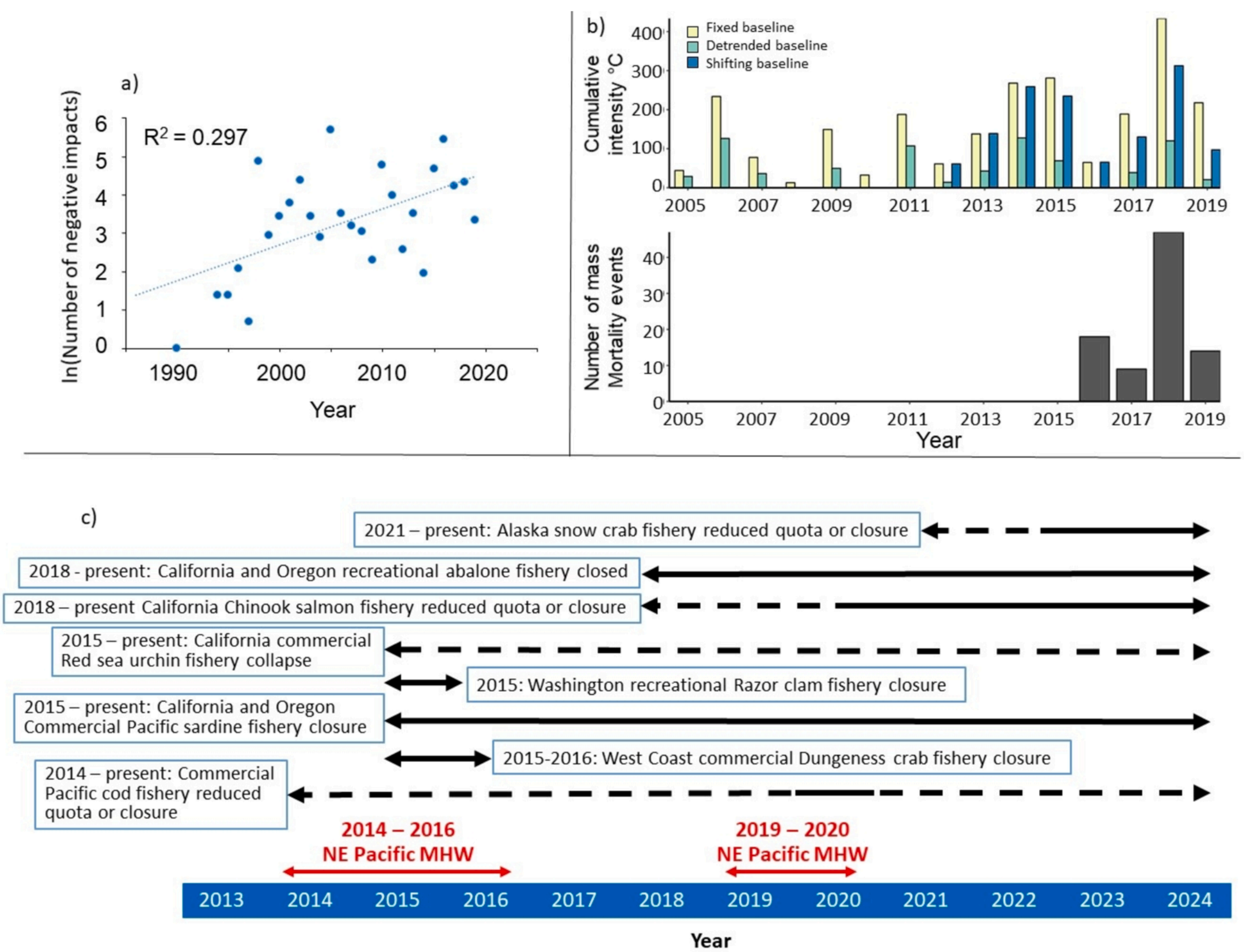

Fig. 5. A) observations of loss of foundation species caused by MHWs by year. Data includes re-analyses of global historical long time series datasets. b) Mass mortality events near Medes Islands, Western Mediterranean Sea (bottom) and cumulative intensity of MHWs for this location showing the three main baseline choices (top). Note: the shifting baseline does not begin until 2012 as thresholds require 30 years of prior data. The fixed and detrended baselines are based on data from 1982 to 2011. c) US fisheries impacted by MHWs. Solid line indicates fisheries closure. Dashed line indicates reduced fisheries quotas. Data from Free et al. 2023, and
adapted from Smith et al., 2024, Smith et al., 2021 https://t-mednet.org/, Szuwalski et al., 2023 and www.fisheries.NOAA.gov.

Caputi et al., 2019; Cavole et al., 2016; Fisher et al., 2021; McCabe et al., 2016; Oliver et al., 2017). Over the past decade, MHWs have led to the closure of multiple commercial and recreational fisheries across the USA (Fig. 5) resulting in losses of hundreds of millions of US dollars (Smith et al., 2021). In the Barents Sea, for example, the $150 million snow crab fishery was closed for the first time in 2022 as a consequence of MHWs (Szuwalski et al., 2023).

Species migration and ecosystem change have also been linked to the compound effect of anthropogenic warming and short-term ocean temperature variability. Instead of a slow monotonic poleward shift of organisms that an examination of the long-term trend by itself would suggest, rapid episodic shifts have been observed for many individuals, populations and communities concurrent with temperature extremes that persist even after the events have abated (Ishida et al., 2023; Thomsen et al., 2021, 2019; Wernberg et al., 2016, 2013). In general, while mobile species like fish and squid may rapidly track temperature shifts, temporarily extending their ranges (Cavole et al., 2016), communities made up predominantly of benthic invertebrates and macrophytes, which are less able to relocate, may be permanently altered after temperature extremes (Wernberg et al., 2016, 2013).

A fixed baseline approach used for contemporary analyses identifies an increasing occurrence of MHWs that is reflective, at least qualitatively, of the rise in number of observed impacts discussed above. By contrast, MHWs defined with the long-term warming removed will fail to reproduce this general trend. Conversely, exclusive use of a fixed baseline MHW does not reveal that a large proportion of the change in MHW characteristics over time originate from increased long-term warming.

The disparity between different baseline approaches will increase with further ocean warming (Supplementary Fig. 1). Indeed, in some ocean areas, e.g. warming hotspots, notable differences between MHWs identified using different baselines are already apparent (Fig. 4). With long-term warming, a fixed baseline will typically suggest considerable increases in risk over time, with longer lasting and more intense events. Baselines that account for warming will suggest more subtle changes in risk. Detrended baseline MHWs will only reflect changes in risk associated with altered frequency and intensity of events caused by long-term shifts in temperature variability. The situation is more complex for a shifting baseline as increases in variability result in more intense MHWs but not more frequent MHWs (Fig. 3, see Box 1).

To apply the most appropriate baseline, we need to understand which system we are assessing the risk for. A fixed baseline reflects the risk to a specific cohort of organisms that are adapted to the conditions under the associated reference period. However, without adaptation, this cohort will change over time as mobile species shift their ranges or low-tolerance species die out. Human systems will also change, such as fisheries targeting new species that are more thermally tolerant or have shifted to new areas. To understand the risk to a modified cohort or a new fishery, considering a recent climatological period, i.e. employing an updated or shifting baseline, would be most relevant.

Ultimately, the real extent of risk will hinge on the marine species, population or human system we are considering in addition to the adaptive capacity of both marine organisms and the human systems dependent on them. Given this uncertainty, a pragmatic approach for decision-makers might involve providing MHW information derived from multiple baseline methods. This strategy would enable them to plan based on both best- and worst-case scenarios, thus facilitating more informed decision-making (e.g. forecasts provided by the National Oceanographic and Atmospheric Administration Physical Sciences Laboratory *psl.noaa.gov/marine-heatwaves/*).

6. Adaptation timescales

Ecological studies commonly seek to determine the impact of these MHWs on historical, current, or future populations. In such cases, a goal is often to estimate the level of biological impact resulting from the stress of single or repeated events (Witman et al., 2023). The choice of a baseline in these studies requires significant biological assumptions, especially in future studies, where some level of species adaptation may be expected to have occurred. Biological adaptation rates are influenced by various elements, including demographic factors (e.g. population size and connectivity), genetic elements (e.g. allele diversity and frequency), life history traits (e.g. generation time), and environmental stress (e.g. thermal history and exposure to previous extreme events) (Bernhardt and Leslie, 2013; Miller et al., 2018). Epigenetic mechanisms also play a pivotal role in the short term, enabling species to modify gene expression on intragenerational timescales without altering their DNA, thereby providing increased resilience to future events. Research indicates that species can adapt to extreme conditions over a few to hundreds of generations (Dam et al., 2021; Geerts et al., 2015; Listmann et al., 2016; Schaum et al., 2022). With marine species experiencing generation times ranging from hours (e.g. microbes) to decades (e.g. whales), adaptation timescales can vary from weeks to several centuries. Understanding these adaptation timescales is crucial in selecting an appropriate climate baseline for specific studies. Shifting or detrended baselines may suit species with short generation times (e.g. much shorter than the reference period length), while a fixed baseline would better represent species with medium to long generation times and slower adaptation rates. However, predicting adaptation potential in marine species is complex, and our understanding remains limited. Given the evident increase in impacts over time (Garrabou et al., 2022; Gómez-Gras et al., 2021, p. 2; Hughes et al., 2021; e.g. Marbà et al., 2015), a precautionary approach to estimating future population responses to environmental stress would favour a fixed baseline.

Community and ecosystem-level responses to MHWs vary from population level responses. Within a community, warm-affinity species may replace cold-affinity ones (Brown et al., 2024; Burrows et al., 2019; Wernberg et al., 2016) which can in turn lead to considerable change to ecological function (e.g. nutrient cycling, carbon fixation). Similarly, extreme climatic events can result in a reduction in abundance of sensitive species, thereby increasing the overall resilience of the remaining community (Witman et al., 2023). Metrics like the *Community Temperature Index* track the average thermal affinity of a community, identifying changes in community assemblage (Devictor et al., 2008). These metrics suggest that community-level adaptation (i.e. where the type and abundance of species making up the community shift to those better adapted to warmer conditions), particularly as a result of low trophic level changes, can closely track individual events. For studies considering the future community composition, use of a shifting baseline may more effectively identify extreme events impacting current community compositions.

7. Baselines in other disciplines

The consideration of baseline approaches is a necessary step in all fields of extremes' research. Most commonly a fixed baseline approach has been adopted in other fields exploring extreme events (IPCC, 2023), though approaches that shift or detrend the baseline also appear.

Atmospheric heatwaves, which closely parallel marine heatwaves, are typically analysed and reported using a fixed baseline (IPCC, 2023). The saturation issue while present, is less extreme for atmospheric than oceanic events, as the relative scale of temperature variability to long-term warming trends is greater (Frölicher and Laufkötter, 2018). Like Hobday et al., (2018) additional more extreme heatwave categories, indicative of increasing levels of risk, have been added to atmospheric heatwave scales in recent years (Bettio et al., 2019). In sea level studies, a fixed reference period is used to calculate *return periods*, *extreme sea level* and *amplification factors* based on historical data (Rasmussen et al., 2022), essential for assessing risks to infrastructure designed to endure rare events across multi-decadal timescales. However, considerable effort goes into separating anthropogenic versus the multiple natural drivers given differences in their predictability. Similarly, research on droughts, extreme rainfall, flooding, and tropical cyclones typically reports changes relative to a fixed baseline, though the specific reference periods may vary (e.g. IPCC, 2023).

There are important exceptions where a fixed baseline approach is inappropriate, including assessing the impacts of ENSO events. Many investigations into long-term ENSO strength examine a moving multi-decadal standard deviation (e.g. Cai et al., 2014) effectively ignoring shifts in the background mean. Another strategy involves metrics based on temperature differences, such as equatorial versus tropical Pacific SST anomalies (Oldenborgh et al., 2021), which effectively filter out part of the global warming signal. An important motivation here is that ENSO-driven convection, that triggers changes to the atmospheric circulation and remote impacts, depends more on relative temperatures between regions than on absolute temperatures (Izumo et al., 2020).

Like MHWs, different baseline approaches have been applied to a single phenomenon. For example, atmospheric rivers, episodes of extreme integrated water vapor transport, are expected to intensify with global warming due to the higher level of water vapor in the atmosphere. Studies have considered both the total amount of water vapor (Hughes et al., 2022; Zhang et al., 2024) and the detrended signal to isolate dynamic from thermodynamic climate related changes (Shields et al., 2022).

Some of the earliest research on droughts used either a fixed reference or the full period of record (often exceeding 50 years) in an effort to more accurately characterize the tails of the distribution (e.g., Palmer 1986). However, over time, studies began to recognize and acknowledge the sensitivity of widely used drought indices, such as the Palmer Drought Severity Index, to the choice of baseline period (e.g., Karl 1986; Alley 1984). Given the growing appreciation of the non-stationarity in extreme precipitation (Parker et al., 2023) there is now ongoing discussion over the choice of drought reference period. Lisonbee et al., 2024, suggest neglecting climate non-stationarity in defining drought indices could lead to errors in drought assessment. They suggest that the "correct" reference period should be tailored to the purpose of the assessment. For understanding climatological extremes, a full historical and possibly paleo-data record may be appropriate. When assessing impacts on systems like agriculture, the reference period should align with the timeframe for which the system is designed, such as the past few decades of many agricultural applications. For evaluating the risk of extreme events in the context of the current climate, non-stationary metrics should be used to account for shifts in the frequency and severity of these events. Understanding the implications of different baseline approaches is a priority for drought research (Parker et al., 2023), particularly as small changes in the definition of what constitutes a drought could have large financial implications for drought relief.

8. Nomenclature and communication to wider audiences

The presentation of MHWs and how they change over time, subject to different baseline approaches, convey different messages to the wider audience. Approaches that remove the warming signal suggest that systems are keeping pace with 'new normal' conditions, which may indeed be the case, for example through species relocation or shifting fisheries practices, but also because of the loss of existing or arrival of new species. Applying a fixed baseline on the other hand presents a worst-case scenario of the changing risks experienced by systems without the capacity to adapt. The optimistic scenario can lead to 'shifting baseline syndrome' or 'environmental generational amnesia' where people accept the current state of the environment as normal, even if it is undergoing significant detrimental changes (e.g. Soga and Gaston, 2018). Conversely, the pessimistic scenario may lead to climate anxiety, which can in turn prompt either more (Bouman et al., 2020) or

Box 1
Baseline Case Study.

To highlight the implications and challenges of employing different baselines, we analysed a large ensemble of synthetic sea surface temperature (SST) time series (Fig. 6). These series are crafted to mimic observed temperatures at an extratropical location, incorporating an (anthropogenic) nonlinear trend, a seasonal cycle, and multiple realisations of autocorrelated daily variability. Qualitatively, our conclusions are insensitive to the specific choice of temperature characteristics. We examine the impact of different baseline choices on MHW occurrence rate, i.e., the proportion of days per year experiencing MHW conditions, annual average MHW duration, and MHW intensity (SST above the climatological mean). MHWs are identified using a seasonally varying 90th percentile threshold (Hobday et al., 2016); however, to simplify interpretation, we do not impose a minimum MHW duration.

- **Fixed Baseline Approach**: Utilizing a fixed baseline (e.g. 1982–2011 reference period) by construction results in a 10 % occurrence rate, over the reference period (Fig. 6b). In future scenarios with warming, this percentage increases. If the amplitude of variability is stationary over time, this rise is exclusively due to shifts in the background temperature. As what once constituted extreme temperatures becomes cooler than the reference period average, occurrence rate saturation occurs, leading to nearly constant MHW conditions. Avoiding saturation is possible by using a more extreme threshold. For example, Hobday et al. (2018) adopts a higher category threshold based on the same reference period. Alternatively, a more recent reference period can be employed for calculating the threshold for a fixed baseline (Fig. 6b).
- **Detrended Baseline**: With the anthropogenic warming removed, this baseline consistently maintains a 10 % occurrence rate over time, provided variability is stationary (Fig. 6c, e). However, removal of an incorrectly estimated anthropogenic warming signal (such as detrending using a linear instead of the imposed nonlinear signal) results in spurious MHW characteristics (Fig. 6c).
- **Shifting Baseline**: A fully shifting baseline displays a gradual increase in occurrence rate from about 15 % to 20 % between 1931 and 2100 (Fig. 6e). The fact that percentages are greater than 10 % and increase over time arise because (i) warmer temperatures, when compared against a cooler preceding reference period, typically yield occurrence rates above 10 %, and (ii) the nonlinear warming trend intensifies the temperature discrepancy over time, giving a perception of increased variability (as discussed in Xu et al., 2022). This effect can be mitigated by detrending the temperature data prior to applying the shifting baseline. A major limitation of this approach, as depicted in Fig. 6e, is the inability to ascertain MHW characteristics for the first 30 years of the series, significantly impacting shorter datasets like the ∼ 40-year satellite record.
- **Increased SST Anomaly Variability**: Examining the effects of non-stationary increasing SST anomaly variability (Fig. 6d), we find the detrended baseline clearly reflects the impact of variance growth over time, with increases in occurrence rate, duration and intensity (Fig. 6e,f, g). In contrast, a shifting baseline exhibits negligible changes in occurrence rate due to variance alterations (minor changes are linked to the trend-variance ratio) and duration, but does show increases in MHW intensity. The fixed baseline demonstrates complex behaviour: initially, the occurrence rate climbs more rapidly but later slows as saturation nears, with the larger negative anomalies offering more non-MHW periods.

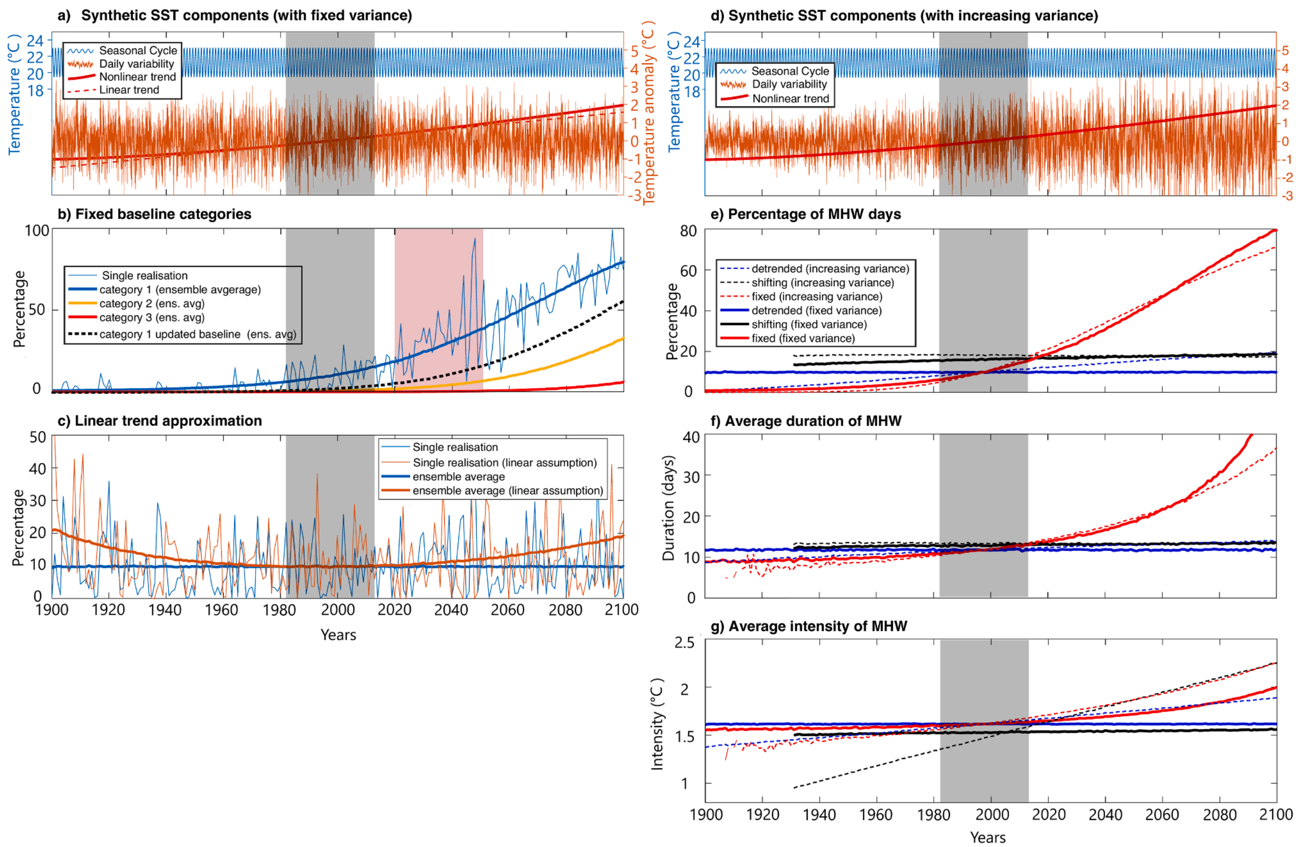

Fig. 6. Properties of different baseline approaches based on synthetic daily SST time series. a) components of a 200-year synthetic time series based on a location in the extratropical ocean: seasonal cycle (blue line), nonlinear warming trend (3 °C over 200 years, thick red line) and internal variability (based on an autoregressive model from 40 years of observed SST at a single location, orange line). Also shown is a linear approximation to the warming trend (red dashed line); b) the percentage of days per annum exceeding a seasonally varying 90th percentile (category 1) threshold (similar to Hobday et al. (2016), but without a 5 day minimum duration, for simplicity; thin blue line). Thick lines are the same using category 1, 2 and 3 thresholds (as per Hobday et al., (2018)), but averaged over 5000 synthetic SST time series with same seasonal cycle and warming, but randomly varying internal variability; dashed line shows category 1 occurrence rate using an updated 2020–2050 reference period; c) the percentage of days per annum exceeding a seasonally varying 90th percentile after removing the warming signal, with the associated average for 1000 synthetic SST time series (thick blue line). Also shown are equivalent results where instead of the warming signal, the best fit linear trend is removed from the SST (orange lines); d) as a) but the amplitude is scaled linearly with time so that the standard deviation at 2100 is double that at 1900; e) percentage of days per annum exceeding a seasonally varying 90th percentile based on fixed (a) and varying (d) variability for the three baseline approaches; (f) as (e) for MHW average duration; (g) as (e) for MHW average intensity. Fixed and detrended approaches use 1982–2011 as the climatological baseline period, so we expect about 10 % of days to exceed the 90th percentile during this period.

less (Heeren et al., 2022) action to mitigate further change.

To date, communication of MHWs and other climate extremes among various groups has largely been shaped by studies and reports using a fixed baseline approach. This includes public engagement materials (Laffoley and Baxter, 2016), briefings for fisheries and aquaculture industries (MSC, 2024), and scientific assessments like the Intergovernmental Panel on Climate Change (IPCC, 2023). Although, some organizations have recently begun to report detrended MHW results relative to a shifting baseline (NOAA Northeast US SOE, 2024). In addition, MHWs garner significant interest in the media, and numerous stories have noted the large rise in MHW numbers and intensity over the historical period that a fixed baseline approach portrays. Altering this established narrative through a change in terminology could result in confusion, particularly in the general public, where future stories would report much reduced or no changes to MHWs over time, without explaining the subtleties of a changing nomenclature. This could lead to the misperception that scientists are uncertain about the ongoing changes. However, precedence, while important, is not a sufficient reason to maintain the status quo. Having an unambiguous terminology, where a MHW and its constituent components are uniquely defined would be desirable (Amaya et al., 2023). However there remains disagreement in the community and between the authors on the nomenclature that would most clearly and effectively describe extreme events.

9. Recommendations and conclusions

Deciding on what baseline to use for defining MHW characteristics is complex, with choices having important implications. We provide the following recommendations for selection and use of baselines:

1. **Consideration of baseline type**: Researchers should consider carefully what baseline type is appropriate for their application, including considerations of the science question at hand as well as how the information will be used. For example, using a:
   a. '*Fixed baseline*' to understand changes in ecological risk under the assumption of limited adaptation or in attribution studies aimed at understanding the increased likelihood of temperature extremes because of human-caused warming;
   b. '*Shifting baseline*' to understand ecological risk in the case of rapidly adapting species, or to investigate local drivers of extremes relative to new normal conditions;

   c. '*Detrended baseline*' to separate the effect of long-term mean anthropogenic warming from variability changes in driving MHWs;
   d. '*Adaptation adjusted baseline*' to account for empirical or assumed adaptation rates of specific organisms, where such information exists;
   e. '*Periodically updated baseline*' for near term and operational assessment following adaptation of systems to contemporary conditions.
2. **Clear description of baselines, their assumptions and implications**: Studies should clearly describe the baseline approach used in computing MHW thresholds (including details of the baseline calculation and reference period). Further, studies should explicitly outline how the choice of baseline affects the interpretation of their results and conclusions (e.g. future MHW changes under a fixed baseline will typically be dominated by changes in the mean rather than variability, or detrended and shifting baselines will reflect risk associated with species and ecosystems that rapidly adapt to changes in background warming).
3. **Practical baseline considerations**: The following issues need to be considered when selecting the appropriate baseline type for a given application, including:
   a. If and how saturation should be addressed, e.g. does saturation realistically reflect the risk to the ecosystem being studied, or is it better represented by more extreme thresholds or non-fixed baseline approaches;
   b. the challenge of identifying local non-linear anthropogenic trends when detrending temperature time series
   c. conflating anthropogenic trends and low frequency variability when using a shifting baseline;
   d. the loss of MHW information over the initial baseline period when implementing shifting baseline as well as difficulties posed by breaks in the temperature record;
   e. detrending temperature data prior to using a shifting baseline to avoid artificially inflating estimates of variability
   f. differences in computational effort needed to calculate different baselines, particularly when dealing with large domain, high resolution datasets.
4. **Common MHW definition for intercomparisons**: Where intercomparisons between past and future studies are made, particularly for the examination of long-term changes, MHWs would ideally be reported against a common threshold. In this case, a fixed baseline may be the most appropriate choice, as recommended by the WMO (WMO, 2017). Where a fixed baseline is used, we would further recommend:
   a. When comparing to past studies, it is desirable to maintain the same reference period if possible. For example, many studies that adopted the Hobday et al. (2016) framework used a 1982–2011 reference period (although there is evidence that a reference period starting from the 1990 s may avoid certain early data issues inherent to satellite datasets);
   b. Use higher MHW categories or thresholds, or update the climatological period for calculating the baseline (as recommended by the WMO), when examining future changes to reflect the increased risk to more temperature tolerant species;
   c. Consider also reporting changes based on detrended or shifting baselines to provide best- and worst-case risk estimates.

While we have focused exclusively on high temperature extremes given their particular importance in a warming climate, our discussion also applies to cold extremes – marine cold spells (MCS; Schlegel et al., 2021). Under a fixed baseline, MCSs will become increasingly rare as oceans warm. However, under shifting or detrended baselines, MCS occurrences will remain more similar over time. Again, this suggests very different risk trajectories with, for example, reduced risk to organisms in the future under a fixed baseline but more limited changes in risk under detrended or shifting baselines.

Clearly, there is no one-size-fits-all baseline; the choice depends on the research questions and characteristics of the biological, physical, or human systems under study. However, it is crucial to explicitly state which baseline is used and how that choice influences the interpretation of results and to be cognisant of how our choice of baseline impacts the messaging of our science to a broader audience.

Funding Sources

ASG was supported by an Australian Research Council Future Fellowship (FT220100475). AC was supported by the NOAA Climate Program office MAPP program and by NASA Physical Oceanography grant #80NSSC21K0556. TLF was supported by TipESM. TipESM is funded by the European Union. NJH acknowledges support from the ARC Centre of Excellence for Climate Extremes (CE170100023) and the National Environmental Science Program Climate Systems Hub. ECJO was supported by a National Sciences and Engineering Research Council of Canada Discovery Grant (RGPIN-2018–05255) on the "Prediction and Predictability of Climate Extremes". DAS was supported by a UK Research and Innovation Future Leaders Fellowship (grant MR/X023214/1). TW was supported by the Australian Research Council (grant DP200100201). MST was supported by a University of Canterbury Seeding Grant and the New Zealand Ministry of Business, Innovation and Employment (Toka ākau toitu Kaitiakitanga – building a sustainable future for coastal reef ecosystems). PJM and MTBwere supported by the Natural Environment Research Council Newton Fund (grant NE/S011692/2).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect those of the European Union, the European Climate, Infrastructure and Environment Executive Agency, the US National Oceanographic and Atmospheric Administration, Office of Oceanic and Atmospheric Research or the US Department of Commerce. Neither the European Union nor the granting authority can be held responsible for them. The Western Channel Observatory is funded by the UK Natural Environment Research Council through its National Capability Long-term Single Centre Science Programme, Climate Linked Atlantic Sector Science, grant number NE/R015953/1. **Data on mass mortality events were extracted fromMME-T-MEDNet database onmassmortality events in the Mediterranean (https://t-mednet.org/MME).**

We thank Dr. Michael Jacox and Dr. Vincent Saba from the National Oceanographic and Atmospheric Administration and Dr Helen Beggs of the Australian Bureau of Meteorology for constructive comments on the manuscript. We would also like to thank the two anonymous reviewers for their constructive comments and recommendations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pocean.2024.103404.

Data availability

Data will be made available on request.

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