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Ocean extremes as a stress test for marine ecosystems and society

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In 2023–2024, widespread marine heatwaves associated with record ocean temperatures impacted ocean processes, marine species, ecosystems and coastal communities, with economic consequences. Despite warnings, interventions were limited. Proactive strategies are needed for inevitable future events.

The global oceans are warming at an unprecedented rate, and temperatures in 2023 and 2024 were exceptionally warm[1]. By March 2023, globally averaged sea surface temperatures (SSTs) had reached record highs and temperature extremes were recorded repeatedly over the following year[1]. This rapid warming, fuelled by human-induced climate change[2], but amplified by El Niño conditions and record low global cloud cover, resulted in an unprecedented number of extreme marine heatwaves (MHWs), with global average MHW days in the summers of 2023–2024 being 240% higher than in any other year in the instrumental record (Fig. 1). These events spanned the globe, with 8.8% of the ocean experiencing the highest SSTs ever recorded, almost four times more than the historical annual average.

Record-breaking events were particularly evident in the North Atlantic, southwest Pacific, eastern Pacific and western Indian Oceans, and affected physical ocean and atmospheric processes, marine species and ecosystems, and socioeconomic systems (Fig. 2). Leading up to these MHWs, warnings were issued, offering society time to prepare. In some regions, these warnings were heeded and led to national efforts by marine managers and stakeholders[3,4], but in most locations little proactive management activity was seen, possibly indicating barriers to action, which resulted in impacts that may have been avoidable.

MHW impacts

Extreme SSTs recorded during multiple MHWs influenced weather patterns, 'supercharging' the heat and moisture exchanges between sea and air (Fig. 2, physical impacts). A near-record number of named storms occurred through the 2023 Atlantic hurricane season[5] and several tropical storms made landfall along Pacific and Indian Ocean coastlines[1]. For example, in July 2023 Typhoon Doksuri impacted China, Taiwan, the Philippines and Vietnam, affecting more than 2 million people and causing around 200 deaths[5]. Similarly, Cyclone Gabrielle was fuelled by MHWs, killing 11 people in New Zealand and with an estimated cost of more than NZ$14 billion[5]. In 2024, Hurricane Beryl (also amplified by MHWs) became the earliest category 5 hurricane on record by time of year and devastated parts of the Caribbean and United States[1]. Prolonged MHWs in 2023 also influenced weather patterns, contributing to extreme air temperatures in the United Kingdom, North America and Japan, and severe flooding in Ecuador, Libya, Japan and Australia[1].

The exceptional MHWs across 2023–2024 were also linked to a multitude of biological impacts (Fig. 2, biological impacts). These included a global coral bleaching event, loss of vital ecosystems off Japan and Peru, and unusual observations of species found outside their typical ranges[5]. Mass mortalities of fish were reported in the Gulf of Thailand and the Gulf of Mexico[5], while diseases impacted fish and threatened extinction of the fan mussel in the Mediterranean Sea[5]. In the North Atlantic, lower phytoplankton productivity affected the wider food web, raising concerns about potential impacts on fish and seabird populations, consistent with observed responses to previous MHWs[5]. Undoubtedly, more impacts of the 2023–2024 MHWs will emerge as more research is published.

Many of the impacts had knock-on effects for ecosystem services, marine industries and wider society (Fig. 2, societal impacts). The global coral bleaching event negatively affected snorkelling and scuba diving tourism with some areas being closed to visitors, whereas off the UK coastline, increases in warm water species resulted in an increase in income for wildlife watching companies[5]. Losses to aquaculture, either as a direct response to increased temperatures or indirectly due to harmful algal blooms, were reported in the Mediterranean Sea and the Gulf of Thailand, while range shifts in Peruvian anchovies led to closure of commercial fisheries with estimated losses of US$1.4 billion, necessitating government payouts for fishers[5]. Off northern Spain, MHWs were linked to reduced growth and reproduction in shellfish, impacting the livelihoods of the women who traditionally harvest this fishery[5]. Small 'wins' for fisheries were also seen, with increased squid landings in Peru and opportunities for new fisheries appearing in the Canary Islands as warmer water species temporarily shifted their ranges[5]. Many of the impacts collated[5] were not yet documented in the primary literature, despite being crucial for understanding and planning for future events. Indeed, the urgency and severity of MHW intensification necessitates more rapid and effective methods to identify and communicate impacts.

Preparation, response plans and mitigation

During 2023–2024, MHW forecasts were generated, allowing for effective preparation[4]. However, the detail of the forecasts varied considerably by region. For example, in Australia, specific national briefings and regional response plans were developed to prepare decision-makers, while in the United States, the National Oceanographic and Atmospheric Administration (NOAA) produced monthly reports providing MHW forecasts at a global scale (https://psl.noaa.gov/marine-heatwaves/). In the vast majority of impacted regions,

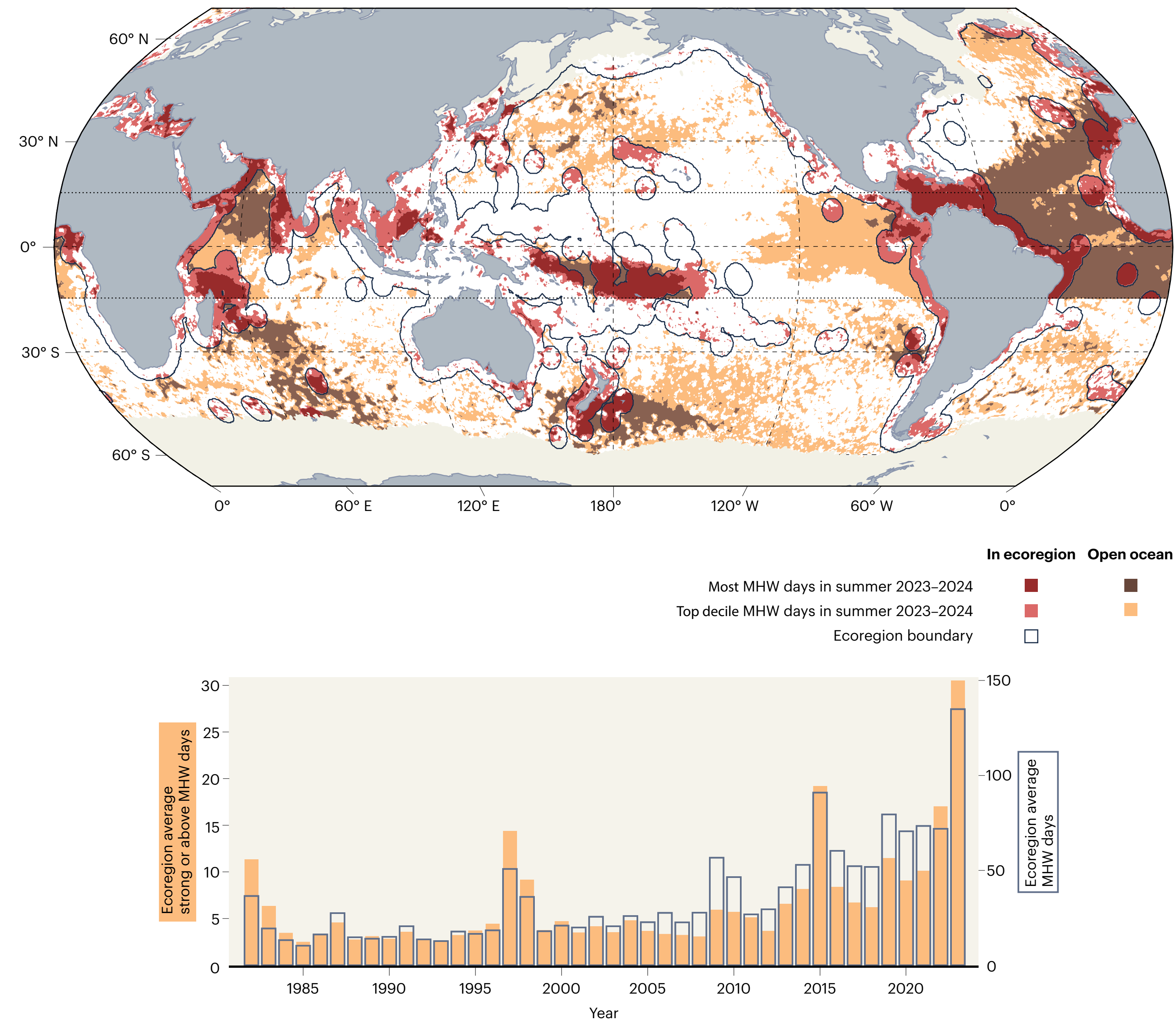
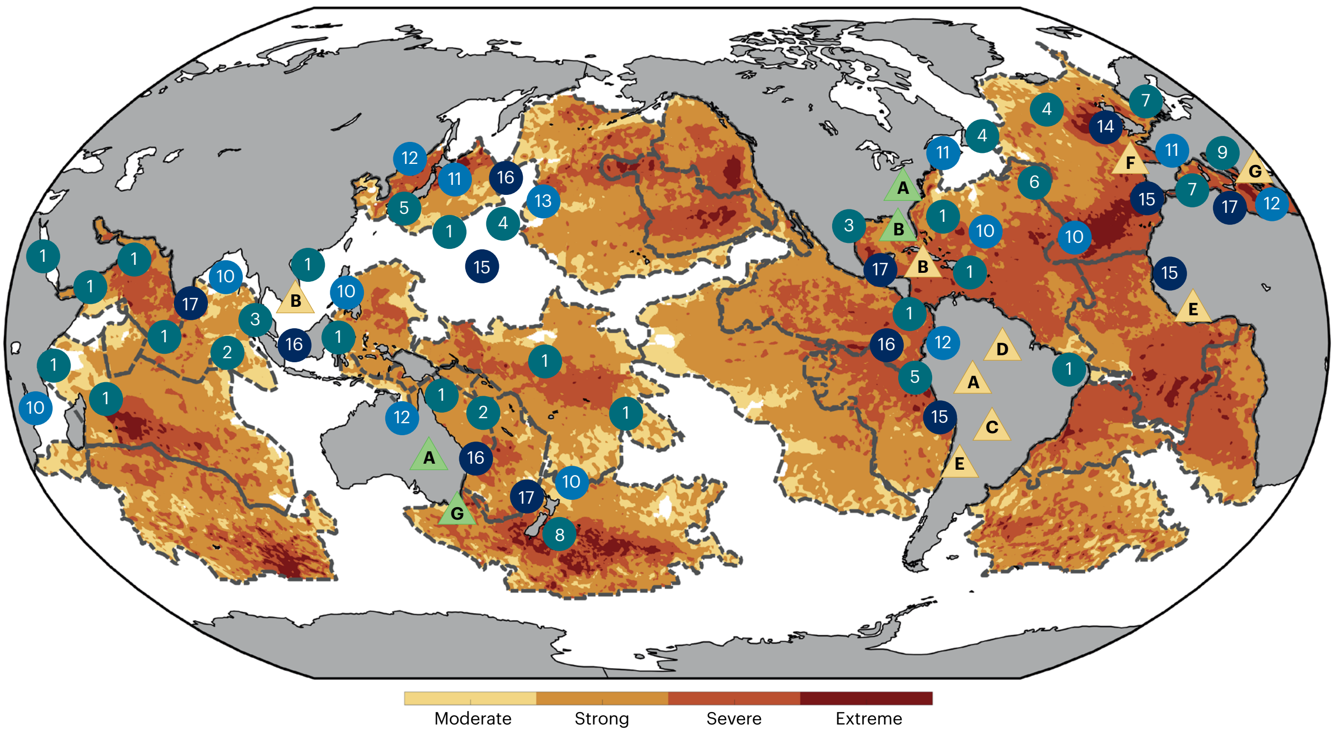


Fig. 1 | MHW activity in 2023–2024. Top: locations where summer MHW days were either the highest or in the top decile during the summer of 2023–2024 (June 2023–September 2023 for the Northern Hemisphere, December 2023–March 2024 for the Southern Hemisphere and June 2023–July 2024 for the tropics). Bottom: average number of MHW days within ecoregions[12] for the summer period in each year, for all MHWs and strong and greater MHW categories based on the satellite record commencing in 1982. MHWs are calculated following ref. 13 using a 1983–2012 fixed baseline[14]. The map is plotted using the MATLAB M_Map toolbox[15]. Ice-covered areas have been excluded. Publ. note: Springer Nature is neutral about jurisdictional claims in maps.

however, forecasts, briefings and response plans were neither issued nor implemented, which may be a result of issues such as limited resources, disconnection between institutions/organizational bodies and lack of communication. Across the globe, with relevant country expertise, ideally national-level briefings and response plans could have been produced and used more extensively, and should be a future priority. Indeed, for most impacted regions, limited or no forecasts were issued.

In some locations, either proactive or reactive interventions were implemented following forecasts or observations (Fig. 2, interventions). While these interventions were progressive and innovative, the majority of known impacts from the 2023–2024 MHWs come from reported observations where no known mitigating action was carried out, suggesting that enhanced preparation for future events is still needed. Lack of mitigating action was probably owing to a combination of lack of information or confidence in MHW forecasts and the possible interventions, inadequate lead time, and resource and logistical limitations for planning and implementing interventions. Regional response plans could assist in overcoming some of these barriers. Interventions that were carried out focused on



MHW category

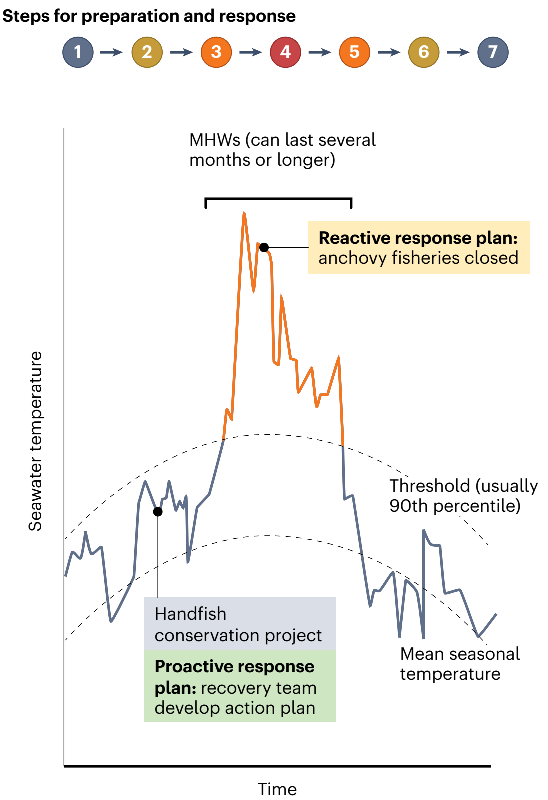
Impacts		Interventions
Biological	**Physical**	Proactive (green triangle) / Reactive (yellow triangle)
1. Coral bleaching 2. Harmful algal bloom 3. Mass mortality event 4. Species range shift 5. Habitat loss 6. Reduced primary productivity 7. Reduced growth and reproduction 8. Increased cetacean stranding 9. Disease	10. Tropical cyclones or storms 11. Atmospheric heatwaves 12. Flooding 13. Oceanic currents **Societal** 14. Tourism 15. Fisheries 16. Aquaculture 17. Infrastructure	A. Warnings issued B. Coral conservation C. Commercial fisheries cancelled/quotas issued D. Government subsidies provided E. New/increased commercial fisheries F. Increased tourism opportunities G. Species collected/monitored for conservation

Fig. 2 | Impacts of MHWs during 2023–2024. Top: global MHW activity in June 2023–September 2023 (Northern Hemisphere), December 2023–March 2024 (Southern Hemisphere) and June 2023–May 2024 (tropics). Bottom: impacts of MHWs and mitigating interventions taken as identified across news platforms, social media and peer-reviewed literature[5]. The map is plotted using the MATLAB M_Map toolbox[15]. Publ. note: Springer Nature is neutral about jurisdictional claims in maps.

biological interventions (typically on sessile or aquaculture species) or changing human behaviour (for example, through conservation or management strategies).

Proactive interventions included moving corals and conches to deeper, cooler water in Florida to prevent bleaching and to assist mating, respectively. In Tasmania, a quarter of the remaining population of the critically endangered red handfish were collected and maintained in aquaria for the duration of MHWs to aid conservation, before being released back into their natural environment when conditions became less stressful[4] (Fig. 3). Ongoing initiatives to propagate corals via assisted sexual reproduction to increase genetic diversity also showed potential, with increased resilience to bleaching being observed in trial populations of reef-building corals across the Caribbean and Mexico[6]. Reactive interventions, carried out in response to already changing conditions, included closures of reefs to scuba divers, fisheries closures and shifting fishing practices to target opportunistic species (Figs. 2 and 3). Intensive monitoring of physical and biological variables was carried out in many locations either proactively or reactively, although results are generally not yet available in the scientific literature or government reports.

No interventions to modify the weather and/or ocean directly to reduce the risk or effect of MHWs were reported. Such interventions remain an area of controversial discussion, as geoengineering governance is not yet agreed, yet a range of smaller-scale ocean interventions such as the oxygenation of Macquarie Harbour, Australia (https://go.nature.com/4jLzHux), and marine cloud brightening in the Great Barrier Reef[7] and North Pacific[8] are being tested and, if successful, could be implemented on larger scales in the future.



Steps for preparation and response	Proactive response plan (Red handfish conservation project, Tasmania)	Reactive response plan (Anchovy fisheries closure, Peru)
1 Establish baseline and deliver forecast	Forecast delivered providing three months warning	No action taken
2 Assess risk and plan responses	Recovery team for critically endangered red handfish develop action plan. Options included removal of individuals from natural habitat, habitat restoration and closures to human activities	No action taken
3 Respond to forecast	Approximately a quarter of remaining population (25 individuals) caught and placed in captivity	No action taken
4 Adjust to cope	Monitoring of in situ temperatures to determine if additional removals are needed	Exploratory fishing at beginning of season shows high number of juveniles. Opening of fishery first delayed and then later cancelled
5 Evaluate impacts	Handfish released back into environment and remaining population assessed	Second season of year closes early before quota is reached. Fisherman receive government payout towards end of MHW event
6 Collect new baseline data	Continued population monitoring	Surveys carried out to inform quota for next season
7 Reset quotas and activities	Assess success of intervention measures and adjust future action plan accordingly	Quotas adjusted based on survey results

Fig. 3 | Appropriate preparation and responses to MHWs result in response plans being formed. Response plans can either be proactive, with interventions being put into place before the MHW begins, or reactive, where response plans begin once changes have been identified. Figure adapted from ref. 11, Springer Nature Limited.

Ways forward

Effective response strategies and interventions for MHWs rely on skilful forecasts at the required lead time and represent the most useful tool for decision-makers. Efforts in forecasting have improved in recent years[4,9], although the skill of different forecasts varies globally. Across the 2023–2024 period, forecasts were generally accurate, although there were areas where MHW activity was over- or underestimated.

Improving forecast accuracy will lead to greater confidence for proactive decision-making, while longer-range forecasts will extend the preparation window[10]. The NOAA has now added three new alert levels to its coral reef watch programme, which acts as a warning system for scientists, conservationists and managers globally (www.coralreefwatch.noaa.gov). These advancements are made possible by the ocean's long-term dynamics, and partially predictable ocean–atmosphere feedback processes, particularly in tropical regions. Understanding how recurrent climate patterns such as the El Niño–Southern Oscillation influence subseasonal to seasonal predictability is crucial for developing MHW forecast models with lead times of weeks to months. Achieving greater forecast skill will depend on improving the initial ocean and atmosphere conditions used in models, requiring enhanced observational networks and real-time reporting of ocean data[9].

While progress is clearly being made towards forecasting and proactively responding to impending MHWs rather than reporting impacts after the event, there is still much room for improvement[11]. Efforts should be enhanced on global and regional levels to build capacity to use and disseminate recently developed forecasting and warning systems. At present, national briefings and proactive planning for MHWs is largely limited to locations where these events have previously had substantial impacts resulting in major socioeconomic losses, and where funding and infrastructure allow for research and interventions to be carried out.

Proactive targeted response plans, such as red handfish conservation efforts (Fig. 3), coral species relocation to cooler water and shifts in fishery activity, could be implemented much more widely. Ecological resilience to MHWs can also be improved by reducing other stressors, creating refugia or adapting conservation activities. Developing new interventions and improving access to both early results and long-term outcomes of intervention trials, such as relocating vulnerable species (Fig. 2), will allow for faster learning, increasing opportunities for successful intervention in the future. Broadly disseminating such information across sectors through stakeholder engagement, industry briefings and public guidance will further build capacity for proactively responding to MHWs in the future[11].

The past two years (2023–2024) have been the warmest on record across both land and ocean, and increases in MHWs due to anthropogenic heating are expected to continue. There are challenging times ahead and there is a pressing societal need to better prepare for unprecedented ocean heat extremes. Response plans are being developed and tested, albeit in very few regions. Where interventions are being trialled, their effectiveness should be rapidly shared to enable use in other locations and to deploy at effective scales. This will require alternative communication to the traditional scientific literature, such as reporting impacts and interventions via MHW websites (for example, https://www.marineheatwaves.org/). Rapidly improving preparedness and proactive response for future events is paramount.

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Competing interests

The authors declare no competing interests.