REVIEW SUMMARY

CLIMATE CHANGE

# Socioeconomic impacts of marine heatwaves: Global issues and opportunities

Kathryn E. Smith, Michael T. Burrows, Alistair J. Hobday, Alex Sen Gupta, Pippa J. Moore, Mads Thomsen, Thomas Wernberg, Dan A. Smale*

**BACKGROUND:** Anthropogenic climate change is altering the structure and functioning of ecosystems globally. The upper layers of the oceans have absorbed >90% of the excess heat arising from human activities and, as a result, surface waters have warmed at an average rate of 0.15°C per decade over the past 40 years, with global ocean heat content currently at a record high. Many marine species have shifted their distributions in response to this ubiquitous warming, causing community reconfigurations and changes to entire ecosystems. In addition to gradual warming, the frequency and severity of short-term oceanic warming events, marine heatwaves (MHWs), has increased substantially, largely as a consequence of rising anthropogenic carbon emissions and ocean warming. The global annual number of MHW days has risen by 54% over the past century, with eight of the 10 most extreme MHWs ever recorded occurring after 2010. MHWs are forceful agents of disturbance with wide-ranging impacts on marine ecosystems, including driving species range shifts and mass mortalities and altering foodwebs and species interactions. Regional case studies have shown that ecological responses to MHWs can have socioeconomic implications such as loss of fisheries income, erosion of essential ecosystem services, mass mortalities of iconic species, and conflict. Although our understanding of the physical drivers and biological impacts from MHWs are becoming increasingly robust and predictive, only a few studies have examined their consequences for human-ocean interactions, a crucial step in understanding the associated costs and risks and in developing potential adaptation and mitigation measures.

**ADVANCES:** Using a large number of case studies, we provide a global perspective on the impacts of MHWs on the provision of ecosystem services and examine the socioeconomic implications. We show that these discrete warming events are altering ecosystem functioning with present-day ramifications for human-ocean interactions. Ecological impacts commonly include harmful algal blooms, species range shifts, mass mortality events, and ecosystem reconfiguration lasting from weeks to years or longer. Such ecological impacts affect humans by changing provisioning, habitat, regulating, and cultural ecosystem services. Clear socioeconomic consequences have been linked to at least 34 MHWs occurring across a wide range of ecosystems in all major ocean basins globally. Impacts on provisioning services relating to fisheries and habitat services relating to loss of foundation species (e.g., corals, kelps, and seagrasses) have been particularly prevalent. Impacts on cultural services relating to mass mortality of charismatic (e.g., sea lions, sea birds, and corals) and spiritual (e.g., certain kelp) species, and on regulating services relating to carbon sequestration and altered nutrient cycling were also common. Biological responses to extreme warming events can, however, also increase human-ocean interactions and offer short-term socioeconomic opportunities through, for example, increased tourism or fisheries prospects. Economic losses of single MHW events to date exceed US$800 million in direct losses and in excess of US$3.1 billion per annum in indirect losses for multiple consecutive years. The true costs are, however, likely to be much greater because many socioeconomic effects likely remain unknown and underreported, particularly in lower-income countries.

**OUTLOOK:** The likelihood and intensity of MHWs have increased substantially in recent decades, largely due to broad-scale warming attributed to anthropogenic climate change, and are projected to intensify in coming decades. Concurrently, reported ecological impacts, changes in ecosystem services, and economic losses have also increased markedly. We discuss potential adaptation and mitigation measures to reduce risks and consequences for human-ocean interactions and examine knowledge gaps in our current understanding of MHW impacts, for example, in relation to the likely exacerbating effects of other anthropogenic stressors. Globally, marine ecosystems are threatened by a diverse range of anthropogenic stressors, and policy, management, and conservation measures must prioritize approaches to alleviating them to ensure continued provision of ecosystem services. We demonstrate the far-reaching impacts of MHWs on present-day human-ocean interactions and highlight the urgent need to develop a coherent understanding of the linked social-ecological impacts of MHWs and robust approaches to mitigation and adaptation. ■

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**MHWs have caused widespread loss of habitat-forming species, such as reef-building corals, severely compromising ecosystem service provision.**

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# Socioeconomic impacts of marine heatwaves: Global issues and opportunities

**Kathryn E. Smith[1], Michael T. Burrows[2], Alistair J. Hobday[3], Alex Sen Gupta[4], Pippa J. Moore[5], Mads Thomsen[6,7], Thomas Wernberg[8,9], Dan A. Smale[1]***

**Extreme climatic events, including marine heatwaves (MHWs), are altering ecosystems globally, often with profound socioeconomic impacts. We examine how MHWs have affected the provision of ecosystem services and evaluate the socioeconomic consequences for human society. Ecological impacts range from harmful algal blooms and mass mortality events to reconfigurations of entire ecosystems, affecting provisioning, habitat, regulating, and cultural ecosystem services globally. Reported economic costs of individual MHW events exceed US$800 million in direct losses or >US$3.1 billion in indirect losses of ecosystem services for multiple years. However, biological responses to MHWs can also increase human-ocean interactions, providing opportunities for coastal societies. Our study provides a global perspective on the far-reaching impacts of MHWs on human societies and highlights the urgent need to develop robust approaches to mitigation and adaptation.**

Anthropogenic climate change is altering the structure and functioning of ecosystems globally (*1*, *2*). The upper layers of the oceans have absorbed >90% of the excess heat arising from human activities and, as a result, surface waters have warmed at an average rate of 0.15°C per decade over the past 40 years (*3*), with rates two to three times higher in some regions (*4*). Marine species have shifted their distributions in response to gradual warming trends, causing community reconfiguration and changes to entire ecosystems (*5*, *6*). In addition to gradual long-term ocean warming, the frequency and severity of discrete warming events, marine heatwaves (MHWs), have increased substantially, with a rise in global annual MHW days of 54% over the past century (*7*). Of the 10 most severe MHWs ever recorded, eight occurred in the most recent decade (*8*). Although MHWs are driven by a range of complex oceanographic and atmospheric processes (*9*), their increasing severity over time can largely be explained by long-term increases in mean ocean temperature caused by anthropogenic greenhouse gas emissions, and they are therefore unequivocally projected to intensify in coming decades (*7*, *10*, *11*).

High temperatures associated with MHWs have been shown to induce physiological stress as thermal thresholds are increasingly exceeded, leading to reduced viability or increased mortality, changes in population structure and species' distributions, and altered ecosystem structure and functioning (*11*). Indeed, ecosystem-wide impacts of MHWs have been reported from a number of regions where foundation species that support a wide range of associated biodiversity have been affected, including loss of kelp forests in the northeast and southwest Pacific and southeast Indian Oceans (*12*–*15*), coral bleaching in the Indo-Pacific and southwest Indian Ocean (*16*–*18*), widespread mortality of habitat-forming invertebrates in the Mediterranean Sea (*19*), and depleted extent and resilience of seagrass meadows in the southeast Indian Ocean (*20*, *21*). MHWs have also been linked to mass dies-offs of invertebrates, fish, seabirds, and marine mammals (*22*–*26*); redistributions of commercially important fisheries species (*27*, *28*); and disrupted food webs and carbon and nitrogen cycles (*21*, *29*). An analysis of eight high-profile MHWs showed that all had negative impacts across a range of taxa and ecological functions (*30*). Responses to extreme climatic events are highly variable, however, with some species or populations showing little response and others even responding positively by extending their ranges (*28*, *31*) or proliferating as a result of increasingly favorable conditions or competitive release (*13*, *28*, *32*, *33*). Broadly, populations found toward their species' poleward range edge are more likely to respond positively to MHW events (*30*), and species exhibiting certain life history traits (e.g., high mobility, generalist feeding, or wide distribution) may proliferate more rapidly with warming (*34*). Crucially, regional species losses or gains may be either temporary or persistent, depending on a variety of factors such as the characteristics of the MHW, the wider environmental and climatological context, and ecological interactions (*11*). Although our understanding of the physical drivers and biological impacts of MHWs is becoming increasingly robust and predictive, only a few scattered regional studies have examined their consequences on linked human-ocean interactions [e.g., (*35*–*37*)], and those that have typically reported regional losses in excess of hundreds of millions USD from individual MHW events, often with acute societal responses (*28*, *38*, *39*). Conversely, MHWs have also resulted in economic gains, for example, through increased fisheries or tourism opportunities (*28*, *31*, *32*, *37*).

We draw on a large number of case studies to provide a global perspective on MHW-associated risks, costs, and opportunities, and use it to guide priorities and management decisions that counter or take advantage of more frequent and severe MHWs in the future. We review the linked impacts of MHWs globally to quantitatively examine associated changes in ecosystem service provision and evaluate socioeconomic consequences. Through analyses of global datasets, we identify a broad range of biological response variables related to ecosystem services and investigate variability across 10-year periods spanning prominent MHWs. We classify responses by associated ecosystem services using The Economics of Ecosystems and Biodiversity framework [TEEB; (*40*)] alongside a coherent framework to identify and describe MHWs (*41*, *42*), allowing for direct comparisons of events, regions, and type of impacts. Specifically, an event is considered a MHW if it lasts for 5 or more days, with temperatures warmer than the 90th percentile based on a 30-year historical climatology (*41*). We then examine the impacts of MHWs in the context of United Nations Sustainable Development Goals (SDGs), because these extreme events will affect the achievement of several of these goals that seek improved socioeconomic outcomes for the planet. Finally, we explore possible adaptation measures and highlight future directions for research.

## Impacts of MHWs on ecosystem services

We found compelling evidence for MHW impacts globally, on all major types of ecosystem services, with extensive socioeconomic consequences (Tables 1 and 2 and Fig. 1). Over the past 25 years, at least 34 MHW events have affected provisioning, regulating, habitat, and cultural ecosystem services (Fig. 1). For example, MHWs spanning the Indo Pacific associated with the extreme 1997/1998 El Niño caused

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**Table 1. Examples of direct economic outcomes of MHWs.**

| Location | Year(s) | Socioeconomic impact | Location of impact | Value/loss/gain | Primary industry affected | Affected TEEB ecosystem service | Reference(s) |
|---|---|---|---|---|---|---|---|
| Gulf of Alaska | 2014–2019 | Population decline and low recruitment affects Gulf of Alaska commercial Pacific cod fishery catch limits | Alaska, USA | Fishery valued at US$103 million per annum; loss unknown; funding relief: In 2018, Congress appropriated US$24.4 million in federal disaster relief funding.* | Commercial fisheries | Provisioning and habitat services | (29) |
| | 2020 | Population decline and low recruitment closes Gulf of Alaska commercial Pacific cod fishery for the season | Alaska, USA | Fishery valued at US$103 million per annum; comparative loss likely; federal disaster relief funding requested (pending as of 5 May 2021)* | Commercial fisheries | Provisioning and habitat services | (29, 48) |
| Northeast Pacific Ocean | 2015 | Harmful algal blooms cause closure of recreational razor clamming | Washington, USA | US$40 million loss in tourist spending | Tourism and recreational fisheries | Regulating and cultural | (49, 66) |
| | 2015–2016 | Harmful algal blooms cause closure of commercial Dungeness crab fisheries | West coast, USA | US$97.5 million loss; funding relief: Congress to appropriate US$27.3 million in federal disaster relief funding including US$1.5 million to the native American Quileute Tribe* | Commercial fisheries | Provisioning and regulating | (67, 103) |
| | 2015–present | Population decline of red sea urchin due to kelp loss causes closure of commercial fishery | California, USA | Fishery valued at US$3 million per annum; funding relief: Congress appropriated US$3.3 million in federal disaster relief funding for 2016 and 2017* | Commercial fisheries | Provisioning, regulating, habitat, and cultural | (14) |
| | 2018–present | Population decline of abalone due to kelp loss causes closure of recreational fishery | California, USA | US$44 million loss per annum | Tourism and recreational fishing | Provisioning, regulating, habitat, and cultural | (14) |
| Southeast Pacific Ocean | 2016–2017 | Mass mortality of farmed salmon due to harmful algal blooms | Southern Chile | Export loss of US$800 million | Aquaculture | Provisioning and regulating | (38) |
| Coral Sea | 2016,,–2018 | Bleaching and mass mortalities of corals | Great Barrier Reef, Australia | The Great Barrier Reef is valued at US$4.2 billion annually, with a total value estimated at US$41 billion; loss related to bleaching unknown; gains related to "last chance tourism" also unknown | Tourism | Habitat and cultural | (69) |

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| Location | Year(s) | Socioeconomic impact | Location of impact | Value/loss/gain | Primary industry affected | Affected TEEB ecosystem service | Reference(s) |
|---|---|---|---|---|---|---|---|
| Tasman Sea | 2016 | Pacific oyster mortality syndrome closed hatcheries and decimated juvenile stocks | East coast of Tasmania, Australia | Aquaculture valued at US$19 million; loss unknown | Aquaculture | Provisioning and habitat | (*104*) |
| | 2016 | Poor performance of salmon limited production | East coast of Tasmania, Australia | Aquaculture valued at US$545 million; loss unknown | Aquaculture | Provisioning and habitat | (*104*) |
| | 2016 | Mortality of wild caught abalone led to smaller catch and reduced quotas | South/southeast coast of Tasmania, Australia | Wild-caught fishery valued at US$62 million; loss unknown | Fisheries | Provisioning and habitat | (*104*) |
| Southeast Asia seas | 2010 | Bleaching and mass mortalities of corals | Indonesia, Malaysia, Thailand | US$49 to 74 million loss | Tourism | Habitat and cultural | (*73*) |
| Southeast Indian Ocean | 2011–present | Closure of abalone fishery due to mass mortality event | West Coast, Australia | Estimated loss per annum ~US$0.16 million | Commercial and recreational fisheries | Provisioning, habitat, and cultural | (*51*) |
| | 2011–2013 | Closure of commercial swimmer crab fishery for 18 months to protect breeding stock after low catch rates | Shark Bay, Australia | US$3.1 million loss | Commercial fisheries | Provisioning and habitat | (*105*) |
| | 2011–2016 | Closure of commercial scallop fishery for 3 years (Shark Bay) or 5 years (Abrolhos Islands and Midwest) due to low recruitment | West Coast, Australia | Estimated losses per annum: Shark Bay ~US$8.2 million†; Abrolhos Islands and Midwest ~US$3 million† | Commercial fisheries | Provisioning and habitat | (*51*) |
| | 2011 | Loss of carbon storage and other ecosystem services provided by seagrass | Shark Bay, Western Australia, Australia | US$3.1 billion loss per annum for multiple consecutive years | Multiple ecosystem services | Provisioning, regulating, habitat, and cultural | (*21*) |
| Gulf of Maine | 2012 | Early lobster migration led to record landings and drop in lobster value | Gulf of Maine, USA | US$38 million loss | Commercial fisheries | Provisioning and habitat | (*77*) |
| | 2016 | Proactive management of lobster fishery after 2012 MHW led to economic gains | Gulf of Maine, USA | US$108 million gain | Commercial fisheries | Provisioning and habitat | (*77*) |

*Funding relief values in the United States are from the National Oceanic and Atmospheric Administration (NOAA; https://www.fisheries.noaa.gov/national/funding-and-financial-services/fishery-disaster-determinations). †Values estimated from the Government of Western Australia State of the fisheries annual reports (https://www.fish.wa.gov.au/About-Us/Publications/Pages/State-of-the-Fisheries-report.aspx).

extensive coral bleaching and depleted zooplankton abundance, leading to mass mortalities of a range of marine mammals and seabirds. Ultimately, the disruption of ecosystem functioning had major ramifications for tourism and fishing across the Pacific (*43*). Similarly, the Mediterranean Sea has been repeatedly affected by strong MHWs, causing mass mortality of seagrass, corals, invertebrates, and fish and population explosions of invasive species and pathogens (*19*, *24*, *44*, *45*). These responses have markedly reduced provisioning (e.g., fisheries), cultural (e.g., mass mortalities of iconic species), regulating (e.g., carbon capture, water quality), and habitat (or supporting, e.g., restructuring, disease) ecosystem services (*19*, *24*, *43*–*45*) (Fig. 1), which, collectively, are of global socioeconomic importance.

The most pervasive socioeconomic impacts of MHWs reported to date relate to provisioning services, particularly fisheries, which directly influence markets, employment, food availability, and wider ecosystem services (Figs. 1 and 2). Impacts on provisioning services often closely align with cultural services by affecting tourism and recreational fisheries. In the northeast Pacific, "the blob" was associated with multiple regional MHWs between 2014 and 2016 that affected ecosystem services (*46*). In the Gulf of Alaska, the zooplankton community shifted

**Table 2. Reported impacts of MHW events.** Responses in **bold** indicate positive socioeconomic consequences, those in *italics* are negative consequences, and those in roman are both negative and positive.

| Location | Year(s) | Recorded response variable | Reference(s) |
|---|---|---|---|
| Southeast Atlantic (Benguela Niño) | 1995 | *Mass mortalities of fish*, southward displacement of fish species | (22) |
| South Indian Ocean | 1997 | *Mortality and reproductive failure in king penguins, range shift in prey species* | (106, 107) |
| East Pacific El Niño | 1997–1998 | Shift in fisheries species, *mass mortalities and reproductive failure of Galapagos sea lions, decline in kelp forests, low zooplankton abundance, coral bleaching, ecosystem disruption* | (26, 27, 43, 108, 109) |
| West Indian Ocean | 1998 | *Coral bleaching, restructuring of ecosystems* | (61, 110) |
| Red Sea | 1998, 2007, 2010, 2012, 2015, | *Coral bleaching* | (111) |
|  | 2017 | *Mass mortalities of coral reef fish, fish disease* | (112) |
| Mediterranean Sea | 1999 | *Mass mortalities of benthic organisms, habitat loss, reduced growth and reproduction, coral bleaching* | (19, 24, 113, 114) |
| Mediterranean Sea | 2003 | *Mortalities in mollusk fisheries (multiple life stages), mass mortalities of benthic organisms, coral bleaching, seagrass flowering and shoot mortality, reduced growth and reproduction, disease* | (24, 44, 45, 114–116) |
| Caribbean Sea | 2005 | *Coral bleaching, loss of fisheries* | (16, 117, 118) |
| Mediterranean Sea | 2006 | *Mortalities in mollusk fisheries (multiple life stages), mass mortalities of benthic organisms, shoot mortality in seagrass* | (24, 44, 45) |
| Canadian Arctic | 2009 | Earlier sea ice breakup, decreased sea ice, **increased productivity**, **increased cod reproduction** | (32, 33) |
| Bay of Bengal | 2010 | *Coral bleaching* | (16, 17) |
| Southeast Indian Ocean (Ningaloo Niño) | 2011 | *Loss of seagrass and kelp, coral bleaching, fisheries closures, reduced fisheries quotas*, shifts in recruitment, **range expansion of tropical fish** | (15, 31, 36, 50, 51, 119–121) |
| Northwest Atlantic | 2012 | Spring boom in lobster landings, range shift of a range of commercially valuable fisheries species (e.g., squid, cod, flounder, hake) | (35, 39, 77, 84) |
| Great Australian Bight | 2013 | *Mass mortalities of fish and abalone, harmful algal blooms, disease* | (122) |
| Northeast Pacific (The Blob) | 2014–2016 | *Mass mortalities of California sea lions, seals, seabirds, and marine invertebrates*; *sea star wasting disease*; range shifts in a variety of species; *harmful algal blooms*; *fisheries disruptions and closures*; *shifts in kelp forest ecosystems*; **increase in orca births**; *coral bleaching*; **increased abundance of tuna**; **unusual sightings of warm water species**; increases and decreases in fisheries recruitment; **increased observations of whales**; *increased whale entanglement* | (25, 28, 38, 123–125) |
| Northwest Atlantic | 2015–2016 | *Loss of seagrass*, **early migration of lobsters** | (58, 77) |
| Southwest Atlantic | 2015 | *Harmful algal blooms, mass fish mortalities, closure of fisheries, flags flown on beaches to indicate potential health risks* | (126) |
| Central Pacific | 2015–2016 | *Mass coral bleaching and mortality, shift from coral to encrusting macroalgae and crustose coralline algae, decreased fish biomass, reduction in seabirds and seabird breeding* | (61, 127, 128) |

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| Location | Year(s) | Recorded response variable | Reference(s) |
|---|---|---|---|
| Southeast Indian Ocean | 2015–2016 | *Coral bleaching* | (121, 129) |
| Tasman Sea | 2015–2016 | *Loss of fisheries, loss of kelp, POMS, mortality of abalone*, fish species noted outside of their range | (74, 130) |
| Bering Sea | 2016 | *Range expansion of bowhead whales, mass mortality of puffins, low sea ice, reduced ice-based fishing, low snow and unsafe river ice making winter transportation difficult, topicalization of copepods* | (131) |
| Southern Ocean | 2016 | *Decreased sea ice* | (132) |
| Southeast Pacific | 2016–2017 | *Mass mortalities of farmed salmon, harmful algal blooms* | (38, 65) |
| Southeast Asia seas | 2016–2017 | *Mass coral bleaching, reefs closed to tourism* | (132) |
| Coral Sea | 2016–2018 | *Mass coral bleaching, mass coral mortalities, failed coral recruitment, species range shifts, loss of seagrass, poor reproductive effort in seagrass,* increased abundance and biomass of coral trout | (37, 53, 121, 133–138) |
| Tasman Sea | 2017 | *Loss of kelp*, range shift of fish and jellyfish, early spawning in snapper, *salmon mortalities in fish farms* | (13, 139) |
| East China Sea | 2017 | *Harmful algal blooms, coral bleaching, mass mortalities of farmed fish* | (140–142) |
| Southwest Atlantic | 2017 | *Harmful algal blooms, mass mortalities of fish, closure of recreational beaches* | (143, 144) |
| West Pacific | 2017 | *Mass mortality of coral after successive bleaching events in 2013, 2014, 2016, and 2017* | (61, 145) |
| Persian Gulf | 2017 | *Mass coral bleaching, coral mortality, increase in turf algae* | (146) |
| Northeast Pacific | 2018 | *Loss of kelp* | (12) |
| Northwest Atlantic | 2018 | *Loss of kelp forest* | (55) |
| North and Baltic Seas | 2018 | *Loss of kelp forest* | (55) |
| Northeast Pacific | 2019–2021 | *Harmful algal blooms, Dungeness crab fisheries closures, recreational razor clam fisheries closures, fish mortalities at fish farms*, olive Ridley sea turtles observed off British Colombia, *coral bleaching* | (38, 147–150) |

from cold-water, lipid-rich copepods to less nutritious warm-water species, reducing food availability and thus the abundances of groundfish, including Pacific cod (*Gadus macrocephalus*) (29) and Alaskan pollock (*Gadus chalcogrammus*) (47), and resulting in a massive die-off of fish-eating seabirds, including common murres (*Uria aalge*) (25) (Fig. 2A). The effect of the MHW on the life cycle of cod persisted for >5 years, as recruitment rates and spawning biomass remained well below pre-MHW levels (29, 48). This had major implications for the regional fishery and ecosystem services worth US$103 million per year, with reduced quotas for several years and closure of the federal fishery in 2020 (49). Impacts of the blob were widespread: Throughout the West Coast, mass die-offs of finfish, shellfish, seabirds, sea lions, and seals were reported (25, 28); harmful algal blooms were extensive; and commercial and recreational fisheries were closed (14, 49). Moreover, off the coast of California, a poleward range shift of market squid [*Doryteuthis (Loligo) opalescens*] resulted in higher and lower landings in northern and southern Californian counties, respectively, thereby altering supply chains and market values.

Other recent MHWs that have (positively or negatively) affected provisioning and cultural services include a MHW in the Canadian Arctic in 2009, which led to early sea ice breakup, resulting in increased primary productivity and enhanced polar cod (*Boreogadus saida*) recruitment (32). The Ningaloo Niño MHW in the southeast Indian Ocean during 2010–2011 (15, 50) caused poleward range extensions of tropical fish species, leading to a short-term boom in landings of valuable aquarium species (West Australian butterflyfish; *Chaetodon assarius*) off the coast of Perth, Western Australia (Fig. 2B), and the opening of a new commercial rabbitfish fishery (*Siganus* spp.) in Cockburn Sound, Western Australia (31). At the same time, reduced growth rates of abalone (*Haliotis* spp.) led to a 50% drop in recreational landings near Perth (Fig. 2B), whereas farther north, mortalities and reduced recruitment of Roe's abalone (*Haliotis roei*), scallops (*Amusium balloti*), and blue swimmer crabs (*Portunus armatus*) necessitated closures affecting these fisheries for several years (36, 51). In the Gulf of Maine, a MHW in 2012 resulted in an early lobster (*Homarus americanus)* migration from deep to shallow water and an early molt to legal size (35). This led to high spring landings that were beyond processing capacity, causing a drop in lobster value (35, 39). Civil unrest followed as Canadian protests and blockades attempted to prevent imports of lobster from the United States into Canada for processing, and values

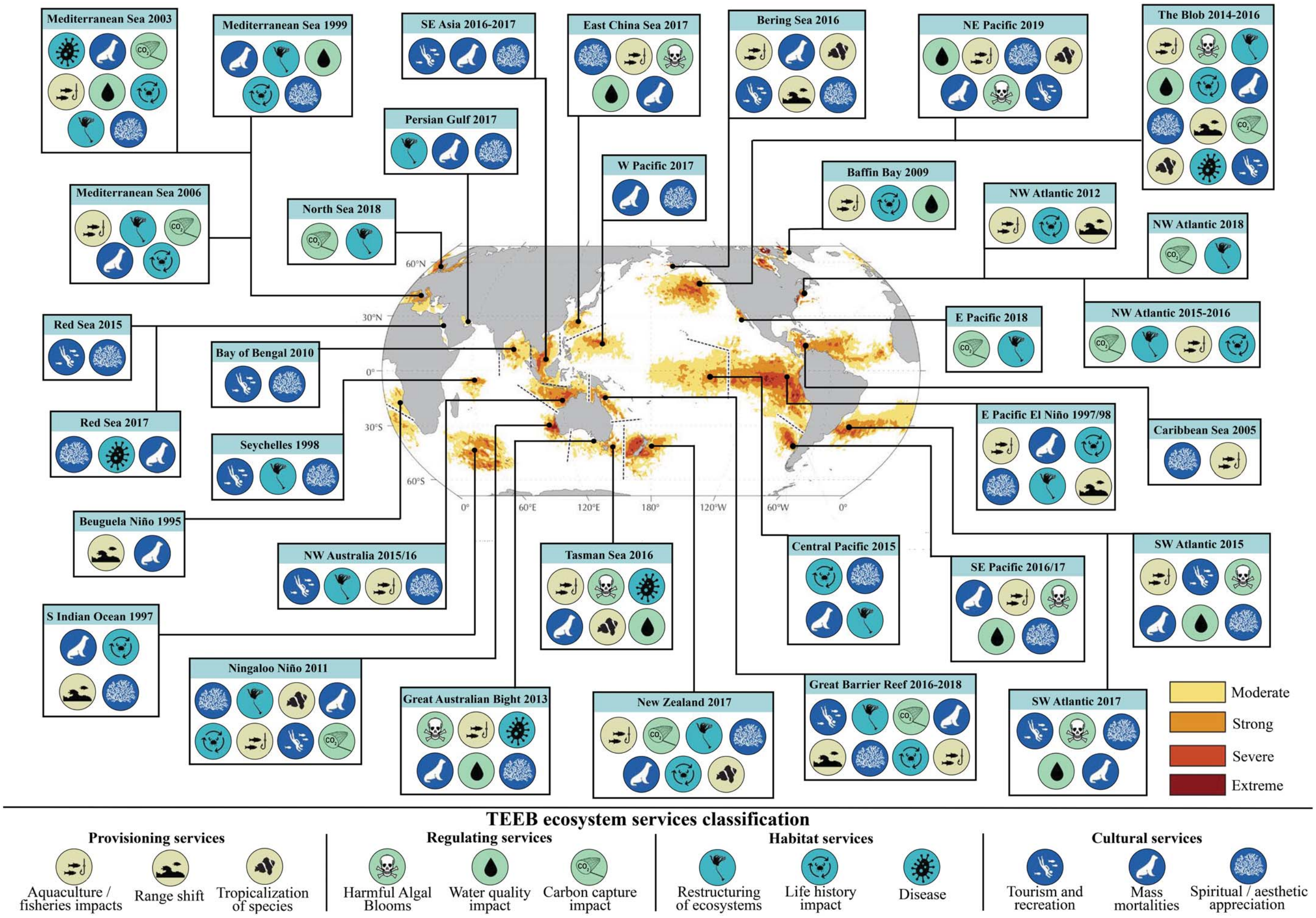

**Fig. 1. Socioeconomic impacts of major MHW events since 1995.** An event was considered a MHW if sea surface temperatures (SSTs) exceeded the 90th percentile for ≥5 days. The intensity scale of each event (moderate to extreme) represents conditions corresponding to the peak date of the event as defined by (*41*). Intensity categories are identified as sequential multiples of the difference between the 90th percentile and the mean climatology as defined by (*42*). For each event, biological responses have been linked to ecosystem services based on TEEB ecosystem services classifications [provisioning services, cultural services, regulating services, and habitat services; (*40*)], which recognize the economic value of nature. For further details on positive and negative biological responses and a full reference list, see Table 2.

fell on either side of the border (*52*). By contrast, the same MHW shifted longfin squid [*Doryteuthis (Amerigo) pealelli*] distribution poleward, enabling the Maine fishing fleet to develop a profitable new market within the season (*35*). Recent MHWs during 2016–2017 along the Great Barrier Reef have resulted in bleaching, and ultimately mortality, of coral (*53*), with the unexpected side effect of an increase in the presence of coral trout (*Plectropomus* and *Variola* spp.) near reefs, resulting in higher catch-per-unit effort by the commercial fishery (*37*).

Kelp forests, seagrass meadows, and coral reefs are globally distributed coastal marine habitats that deliver regulating services via nutrient cycling and carbon storage (blue carbon) and habitat services by offering biogenic structure for socioeconomically important species and by maintaining high levels of biodiversity (*54*). However, species that underpin these habitats are susceptible to MHWs (*30*), particularly where populations are situated toward upper thermal limits (i.e., equatorward range edges). Off the coast of Baja California, Mexico, giant kelp (*Macrocystis pyrifera*) populations were negatively affected by multiple MHWs between 2014 and 2018, although the magnitude of responses varied between locations within the species range (*12*) (Fig. 2C). The loss of giant kelp populations at the equatorward range edges after the MHWs affected several regulating (i.e., carbon capture and transfer, nutrient cycling, and storm protection) and habitat (i.e., ecosystem restructuring and habitat for associated species) services. Similarly, kelp populations on either side of the North Atlantic (the eastern United States and southern Norway) suffered mortalities during MHWs in 2018 (*55*), with similar implications for ecosystem service provision. Loss of southern bull kelp in New Zealand after the 2017–2018 Tasman Sea MHW (*13*) have, in addition to the loss of the aforementioned kelp-forest services, also affected traditional knowledge and spirituality because indigenous tribes on the South Island rely on abundant bull kelp to make "poha" bags for food storage. Indeed, ancient stories repeated across generations detail "sacred poha kelp bags" that symbolize the regions wealth, "mana," and authority over food supplies. MHW-associated loss of bull kelp can thereby reduce tribal spiritual power and their long-term connection with the land and sea (*56*). Widespread loss of seagrass meadows as a result of MHWs have been reported off eastern and western Australia (*21*, *57*), off the east coast of the United States (*58*), and in the Mediterranean Sea (*44*), reducing habitat for economically and culturally important associated species and compromising long-term carbon stocks (*59*). Reef-building corals are particularly sensitive to extreme heat (*60*), and between

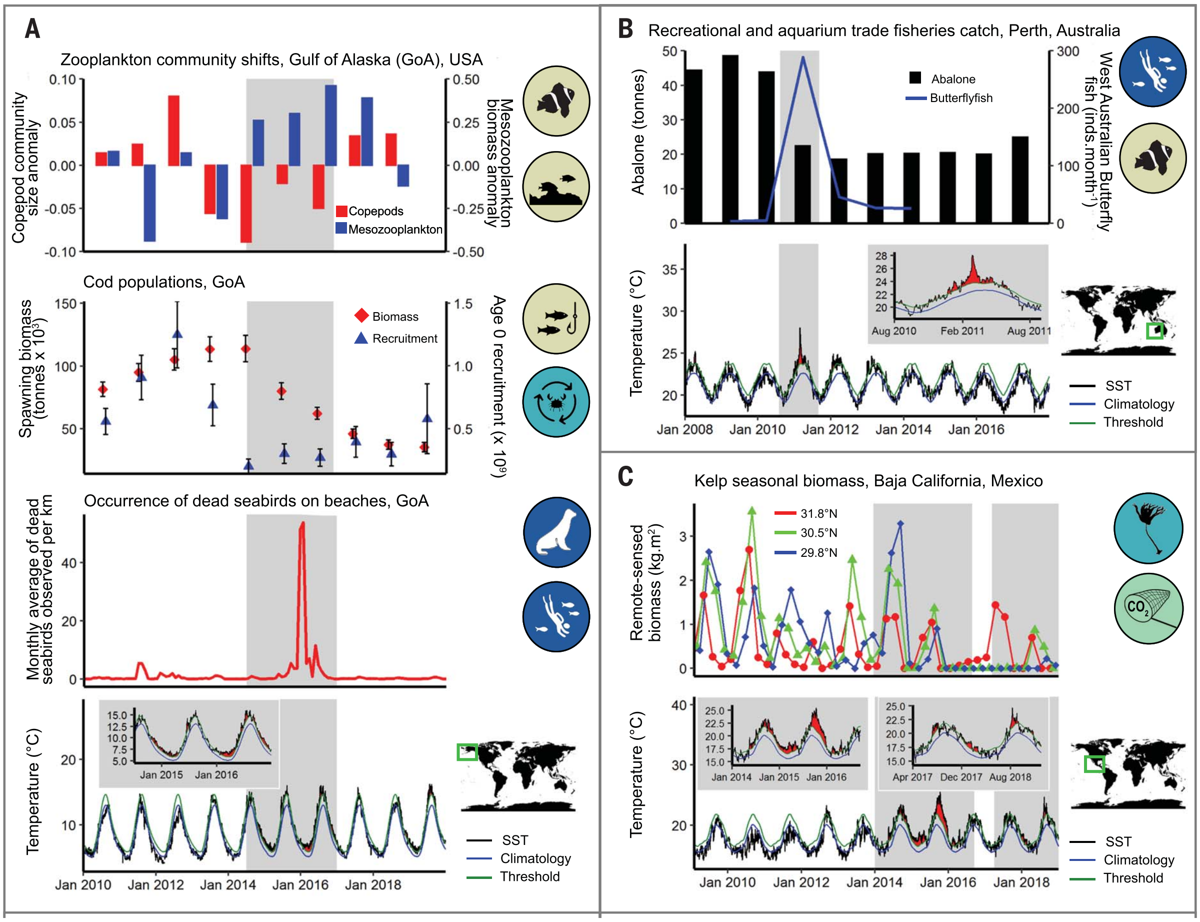

**Fig. 2. Impacts of MHWs on ecosystem services.** (**A**) Between 2014 and 2016, MHWs in the northeast Pacific led to a shift in zooplankton community in the Gulf of Alaska from lipid-rich, cold water species to smaller warm-water species [top plot; data extracted from (*100*)], reducing food supplies for groundfish. Concurrently, the spawning biomass and recruitment in cod (*Gadus macrocephalus*) decreased [second plot; data from (*48*)], and a mass die-off of fish-eating seabirds occurred due to starvation (third plot; data from https://COASST.org). Error bars represent 1 SD. (**B**) The 2011 MHW off Western Australia led to a short-term increase in butterflyfish [*Chaetodon assarius*, valuable to the aquarium trade; data extracted from (*31*)] and a long-term decrease in abalone growth, resulting in an ~50% reduction in recreational landings for at least 7 years (data from the Government of Western Australia Department of Fisheries Annual reports; https://www.fish.wa.gov.au/About-Us/Publications/Pages/State-of-the-Fisheries-report.aspx). (**C**) Giant kelp (*Macrocystis pyrifera*) off the coast of Baja California has been affected by multiple MHWs since 2014, with equatorward populations being most severely affected [data extracted from (*12*)]. The SST climatology (blue), 90th percentile (green), SST time series (black), and periods of time with identified MHWs (red fill) for each location are shown in the bottom plots. Gray shading and inset climatologies indicate the timing of respective MHWs. An event was considered a MHW if SSTs exceeded the 90th percentile for periods of ≥5 days (*41*). All circled icons are as identified in Fig. 1. Climatology timelines were generated in RStudio (*101*) using the HeatwaveR package [R Core Team, https://www.R-project.org, R package version 0.4.4, https://CRAN.R-project.org/package=heatwaveR) (*102*)].

2014 and 2017, MHWs were responsible for a global-scale coral-bleaching event (*61*) that caused habitat loss and ecosystem reconfiguration in many regions (*53*). As MHWs increase in frequency (*7*), the opportunity for recovery between successive events is further reduced, exacerbating ecosystem degradation and affecting regulating, provisioning, habitat, and cultural services, with wide-ranging socioeconomic consequences.

### Economic consequences of MHWs

Conservative estimates value global ocean assets at ~US$24 trillion (*3*). For example, coral reefs are worth ~US$35.8 billion per year globally in tourism alone (*62*), Australian kelp forests ≥US$7.8 billion per year in fishing and tourism (*63*), and U.S. saltwater fishing industries generate >US$210 billion in sales annually and support 1.7 million jobs (*64*). Where economic estimates of the impacts of MHWs have been made, reported gains are typically rare and relatively small, whereas losses are common and often extensive (Table 1). In Chile, MHWs associated with the El Niño in 2016 induced harmful algal blooms, which in turn caused the largest fish farm mortality ever recorded globally, resulting in an export loss of US $800 million (*38*, *65*). Similarly, off the west coast of the United States, a combination of harmful algal blooms and loss of kelp forest habitat (both caused by MHWs) led to closures of shellfisheries in 2015, costing the economy in excess of US$185 million in that year alone (*14*, *66*, *67*). The commercial tristate Dungeness crab (*Metacarcinus magister*) fishery recorded a loss of ~US$ 97.5 million, affecting both tribal and nontribal fisheries (*67*), and Washington and Californian coastal communities lost a combined ~ US$84 million in tourist spending due to the closure of recreational razor clam (*Siliqua patula*) and abalone (*Haliotis* spp.) fisheries (*14*, *66*). By contrast, the higher temperatures were associated with an increased abundance of warmer water species such as the Pacific bluefin tuna (*Thunnus orientalis*), resulting in an increase in sports fishing charters, and the whale-watching industry saw a surge in wildlife sightings with associated economic gains from increased demand (*28*, *68*). A surprising outcome of the 2016–2017 coral reef bleaching on the Great Barrier Reef was that, despite expectations, tourism in the area was not affected. Instead, "last chance tourism" motivated visitors, saw an increase in protective attitudes toward the reef, and illustrated the potential for the loss of iconic ecosystems to mobilize the public toward tackling climate change (*69*).

Loss of biogenic coastal marine habitats are particularly costly because of their role in blue carbon sequestration and as nursery habitat for economically and culturally important species, thereby underpinning provisioning and habitat services. Estimates place the annual per-hectare ecosystem service value of seagrass and coral reefs at ~US$28,916, and US$352,249, respectively (*70*). Scaling this up, the 106,900 hectares of seagrass completely lost in Shark Bay, Western Australia, after the Ningaloo Niño (*57*) is equivalent to ~US$3.1 billion in lost ecosystem services per year, with little seagrass recovery observed after 5 years (*57*). In terms of climate regulation alone, the loss of seagrass habitat in Shark Bay, which was the largest seagrass mortality event in the world recorded to date, resulted in the potential release of between 2 and 9 Tg $CO_2$ from sedimentary carbon stocks (*21*).

### Interpreting the impacts of MHWs in the context of the SDGs

Contextualizing biological responses within the framework provided by the SDGs further highlights the socioeconomic impacts of MHWs. Clearly, MHWs affect our ability to protect life below water (SDG 14), but there are multiple other SDGs that are interlinked with the impacts of these extreme warming events. Most responses relating to fisheries or aquaculture hinder our ability to achieve zero hunger (SDG 2) or decent work and economic growth (SDG 8), with local effects sometimes having global impacts. For example, the Peruvian anchovy (*Engraulis ringens*) is by far the most caught fish species globally (*71*). Anchovies are almost exclusively processed into fishmeal and fish oil, which are used extensively in aquaculture and livestock feeds, with Peru providing as much as 50 and 33% of total global fishmeal and fish oil production, respectively (*72*). An intense MHW associated with the 1997–1998 El Niño and lasting ~8 months caused a temporary range shift in anchovies, ultimately leading to a decrease in landings from 7.5 million tons in 1996 to 1.2 million tons in 1998 (data from FishStatJ, available at www.fao.org/fishery/statistics/software/fishstatj/en), affecting availability of fishmeal and fish oil worldwide and resulting in a reduction in global fishmeal production alone by ~25% (data from seafish, available at www.seafish.org/document/?id=1b08b6d5-75d9-4179-9094-840195ceee4b).

Coastal and island communities globally rely heavily on human-ocean interactions for income, further highlighting the impacts of MHWs on SDGs 2 and 8. For example, in Southeast Asia, a MHW in 2010 caused a coral-bleaching event costing >US$49 to 74 million (based on 2010 USD values) in SCUBA-related tourism, (*73*), and likely impacts on artisanal fisheries. Further, >10% of the Tasmanian Pacific oyster (*Magallana gigas*) industry workforce lost their jobs within months of Tasmania's first outbreak of Pacific oyster mortality syndrome (POMS), which was linked to the Tasman Sea 2015–2016 MHW (*74*). The Tasmanian POMS outbreak also affected SDG 12 (manage responsible consumption and production) by preventing the movement of spat (juvenile oysters) from Tasmania to seed the Australian oyster industry, affecting production in ~300 farms (*75*).

Mortality events associated with MHWs in the Mediterranean Sea have been widely recorded, particularly for habitat-forming filter- or suspension-feeding invertebrates such as cnidarians, sponges, and bivalves, thereby reducing water quality and local biodiversity (*24*). Widespread losses of vast seagrass habitats have been linked with MHWs in Western Australia and the Mediterranean (*44*, *57*), reducing natural carbon sequestration capacity and, thus, the likelihood of meeting SDG13 (climate action). Similarly, kelp forests generally support a significant standing stock of carbon (*76*) and their loss exemplifies impacts of MHWs on SDG13.

### Adaptation, mitigation, and resilience

Human societies are beginning to adapt to the impacts of MHWs to protect ecosystem services and limit socioeconomic consequences. Local industries in several areas have responded to limit economic losses from MHWs in the short-term. For example, during MHWs in North and South America, fisheries efforts were refocused to target transiently abundant species (*27*, *35*, *77*). Longer term, fishermen are developing aquaculture programs as a secondary source of income (*78*) and governments are encouraging diversification to focus on fisheries species expected to increase in abundance with climate warming (*79*). Approaches also include increasing demand for previously rare or undesirable species through marketing efforts such as renaming and rebranding (*80*). Although shifting to newly arrived species might ease short-term fishery disruption, it may also slow the population growth of these shifting species such that larger catches are delayed for many years. Different exploitation pathways should be explored with ecosystem models to aid fishery decision makers. Furthermore, aquaculture industries are responding globally to MHWs by considering climatic extremes when selecting new aquaculture sites, for example, by using remote sensing data (*81*, *82*), by adjusting stock practices to reduce the likelihood of exposure to extreme climatic events (*83*), by regulating geographic production based on temperature-related lice and disease outbreaks (*82*), and by selective breeding for disease-resistant aquaculture strains (*75*).

Early management intervention and shifts in management approaches can also help to limit the impacts of MHWs. For example, after a US$38 million loss from the lobster price crash caused by the 2012 MHW in the northwest Atlantic, processing capacity was expanded and a proactive management system was applied, which included quotas determined by climatological forecasts (*35*, *84*). Such efforts to increase the resilience of the fishery proved effective during a subsequent MHW in 2016, when the shift in management approach led to a gain of US$108 million (*39*, *77*). Similarly, in many regions, the combination of stock assessments and flexible harvesting strategies allow management to intervene early to reduce MHW impacts, and a variety of approaches, including quotas, fisheries closures, and restocking, have been implemented to facilitate species recovery and stabilize stocks after MHWs (*39*, *51*). For example, low female spawning biomass identified during stock assessments in 2019 led to the closure of the Gulf of Alaska Pacific cod federal fishery in 2020. Removing fishing pressure for a season enabled the cod population to begin recovering and helped to ensure that adequate prey were available for the endangered western stock of the Steller sea lion (48). However, consistent with increasing MHWs, the United States has seen a significant rise in federal fishery disasters related to climate warming over the past 30 years (*85*), suggesting that whereas proactive management can prove beneficial, it may be more effectively used in combination with other mitigation strategies.

Natural populations may also be showing resilience to MHWs, with emerging evidence suggesting that moderate climatic events affect population genetics (*86*). For example, the 2011 Ningaloo Niño caused substantial changes to the genetic structure of kelp forests in the southeast Indian Ocean, with a loss of genetic diversity (*87*) and an increase in warm-affiliated genotypes (*88*, *89*), consistent with genomic evidence for adaptive changes to increased temperature tolerance (*90*). Therefore, moderate MHWs are likely to accelerate selection for heat tolerance. Similarly, coral populations exposed to previous MHWs and extreme temperature variation show increased resilience to warming events (*91*).

It remains uncertain whether marine protected areas (MPAs) can buffer the impacts of extreme climatic events in a warming ocean (92). Evidence certainly indicates that warming events occurring inside MPAs have comparable, or sometimes even greater, impacts as events in nonprotected areas [(92) and references therein]. This is partly because, historically, climate change and extreme climatic events have not been considered during the design and implementation phases of MPAs (92). MPAs are more likely to buffer the impacts of MHWs if climate change responses are considered in their design. Planning larger networks of no-take MPAs may provide some protection for species tracking their thermal niches compared with smaller, isolated MPAs. Likewise, targeting locations with steep depth (and therefore often temperature) gradients or strong upwelling may offer climatic refugia. Furthermore, examining relevant scales of spatial variability in sea temperature may identify climatic refugia for the foundation species that underpin biodiversity (92, 93). Certainly, resilience to and recovery from MHW events vary spatially, and what drives this is not yet well understood but may be related to local environmental conditions (58, 94). For example, giant kelp populations off Bahia Tortugas, Mexico, close to the equatorward range edge of the species, have shown greater resilience to and more rapid recovery from multiple MHWs compared with populations both north and south of this location (94, 95), suggesting that this area could serve as an important refuge for giant kelp and its associated communities (and therefore should be prioritized in designs of future MPAs). Regardless, MPAs are likely to be more effective at mitigating the impacts of MHWs if combined with other management tools such as restoration or stock enhancement (96).

## Future directions

Efforts to improve mechanistic understanding of the physical drivers of MHWs will undoubtedly lead to better climatological forecasting and predictions (39), which in turn will provide opportunities to implement mitigation measures. It is clear that MHWs induce both direct (e.g., coral reef bleaching reduces tourism) and indirect (e.g., loss of kelp forests results in lack of nursery grounds for fisheries species, which leads to reduced landings) impacts on ecosystem services, which can last from weeks to decades or more. The realization that heritable genotypic variation likely underpins responses to MHWs opens the possibility to harness "future-proof" populations through selective breeding and assisted evolution of resilience (97, 98). However, current knowledge of (direct or indirect) biological impacts of MHWs is lacking for many species and populations, which limits our capacity to safeguard marine resources against future extreme climatic events (99). Moreover, understanding of how MHWs interact with other stressors, such as oxygen, nutrient, and light availability, to affect marine organisms, populations, and ecosystems remains limited. MHWs have intensified over the past century largely due to anthropogenic climate change and will continue to do so as warming intensifies further, with wide-ranging consequences for marine ecosystems globally (11). There is a pressing need to develop a toolbox of adaptation and mitigation measures, including improved climatological forecasting, proactive resource management, and enhanced resilience, in response to increasing MHW impacts in the coming decades.

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