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Climate change increases marine heatwaves harming marine ecosystems

ScienceBrief Review OCTOBER 2021

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This ScienceBrief Review is part of a collection on Critical Issues in Climate Change Science, relevant to inform the COP26 climate conference to be held in Glasgow (2021). Eds: Peter Liss, Corinne Le Quéré, Piers Forster. Time stamp: Published 28 October 2021. The evidence reviewed was published between 16 March 2013 to 20 August 2021. Search keywords used for the ScienceBrief Review: “climate change”, “marine heatwave”.

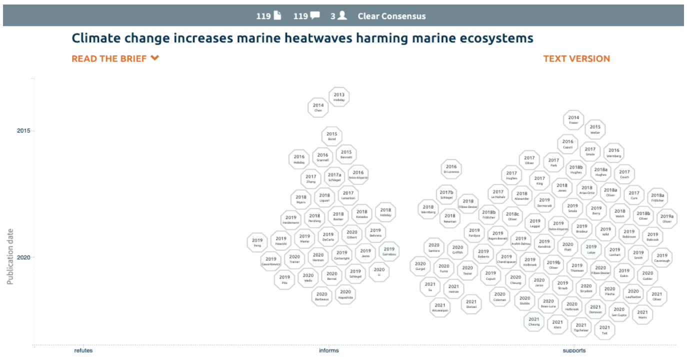
Approach. This ScienceBrief Review examines the links between climate change and marine heatwaves. It synthesises findings from more than 110 peer-reviewed scientific articles gathered using ScienceBrief. The Brief and evidence can be explored at: https://sciencebrief.org/topics/climate-change-science/marine-heatwaves.

Summary. Climate change has contributed to observed increases in the frequency, intensity and duration of marine heatwaves over recent decades. Climate models have shown that recent marine heatwaves in all oceans have been longer and more intense than can be explained by natural variability alone. These changes have caused widespread impacts on marine species with changes in distribution, loss of biodiversity, collapse of foundation species including coral, kelp and seagrass and the ecosystems they support, and declines in fisheries and cultural values. Ongoing climate change will lead to additional increases in marine heatwave frequency and intensity, further threatening marine life and the ecosystem services they provide to human societies.

Key points

The evidence shows clear consensus that human-caused climate change is causing an increase in the frequency, intensity and duration of marine heatwaves and associated impacts.

- Marine heatwaves, when defined as the daily sea surface temperature exceeding the local 99th percentile, have doubled in frequency between 1982-2016 (Frölicher et al., 2018; Collins et al., 2019) and are projected to increase further with future climate change (Frölicher et al., 2018, Oliver et al. 2019b).
- 84 to 90% of all marine heatwaves occurring between 1986-2005 have been attributed to human-caused climate change (Frölicher et al., 2018), while the likelihood of seven recent, high impact marine heatwaves increased more than 20-fold due to human-caused climate change (Laufkötter et al., 2020). It is almost impossible that the Northeast Pacific 2013-2015 marine heatwave (often called ‘the Blob’) would have occurred without human-caused global warming (Laufkötter et al., 2020).
- The ecological and socioeconomic impacts of marine heatwaves are widespread, impacting all oceans and a range of species throughout entire ecosystems. Impacts include changes to species geographic ranges and primary productivity, mass mortality, mass bleaching of coral, loss of biodiversity, declines in fisheries revenues and livelihoods, and degradation of cultural and recreational assets (Hughes et al., 2017; Smale et al. 2019; Cheung et al. 2021; Smith et al., 2021).
- Future marine heatwaves are projected to become more frequent, intense and longer by the mid-21st century under all future emissions scenarios (including those aligned with the Paris Agreement), while larger increases from high emission scenarios are projected to develop during the second half of the century (Frölicher et al., 2018; Darmaraki et al., 2019, Oliver et al. 2019b).



Snap shot of the Brief at the time of publication showing clear consensus among the evidence analysed. Click here to visit the Brief.

Background. In contrast to atmospheric heatwaves, extreme temperature events that occur in the marine environment have only become the focus of significant research in the last decade, with the exception of studies on the impacts of marine heatwaves on warm water corals (e.g. Hughes et al., 2003). A 2011 extreme marine heatwave in the southeastern Indian Ocean, off Western Australia (see Box 1), initiated a wealth of new studies into the causes and impacts of marine heatwaves. Coral bleaching of the Great Barrier Reef (Hughes et al., 2018a) and other locations, is just one impact of marine heatwaves with a visible public profile. Yet extreme warming events impact a wide range of species, altering ecosystem function and provision of ecosystem services (Wernberg et al., 2016, 2018; Smale et al., 2019, Holbrook et al., 2020, Smith et al. 2021), cause mass mortality (Jones et al., 2018; Roberts et al., 2019; Piatt et al., 2020), and may also result in socioeconomic impacts to tourism and fishing (Caputi et al., 2016; Barbeaux et al., 2020; Cheung et al., 2020, 2021; Holbrook et al., 2020; Smith et al. 2021).

Marine heatwaves are often defined as anomalously warm water events of 5 days or more in duration, during which temperatures exceed the 90th percentile of locally observed long-term (i.e. 30-year) averages for a location and time (Hobday et al., 2016; Oliver et al., 2021). Though other definitions are also used. Categories I (moderate), II (strong), III (severe) and IV (extreme) are sometimes used to describe the intensity of a marine heatwave, based on multiples of the difference between the local mean and 90th percentile values (Hobday et al., 2018).

Box 1: Case study of the 2011 Western Australian marine heatwave.

During austral summer 2011, an extreme marine heatwave occurred along 1000-2000 km of the Western Australian coastline (Wernberg et al., 2013), with temperatures exceeding the long term average by +2°C to +5°C (Feng et al., 2013) for several weeks. This was caused by a strong La Niña phase of the El Niño Southern Oscillation and multi-decadal Pacific Ocean circulation trends that brought unusually strong horizontal transport of the Leeuwin Current that runs poleward along the Western Australian coast and reduced oceanic turbulent heat loss (Feng et al., 2013).

The ecological disturbances resulting from this event were widespread and long-lived, with some ecosystems not having recovered when studied 7 or 8 years later (Caputi et al., 2019; Kendrick et al., 2019; Wernberg 2021) and include contraction or relocation of species' biogeographic ranges, loss of biodiversity and widespread mortality. These disturbances have been documented for foundation species of coral (Fordyce et al., 2019), seagrass (Fraser et al., 2014; Kendrick et al., 2019; Strydom et al., 2020) and kelp (Smale & Wernberg 2013; Wernberg et al., 2013, 2016, 2018), as well as associated organisms, including invertebrates such as crabs (Chandrapavan et al., 2019), sea urchins, gastropod molluscs (Smale et al., 2017), scallops, abalone, rock lobsters, western king prawns and brown tiger prawns (Caputi et al., 2016, 2019), numerous fish species (Cure et al., 2017; Lenanton et al., 2017; Smith et al., 2019), sea snakes, dugongs, green turtles (Nowicki et al., 2019) and dolphins (Wild et al., 2019; Nowicki et al., 2019).

Observations

Marine heatwaves are caused by a range of natural physical processes driven by oceanic and atmospheric conditions, but ocean warming due to human-caused climate change increases the probability of these processes combining to produce more frequent and intense heatwaves (Oliver et al., 2018c, 2021; Holbrook et al., 2019). Marine heatwaves may arise from a combination of local and remote processes. Local processes include air-sea heat exchange, advection by mean currents and eddies, and vertical and horizontal mixing including diffusion (Oliver et al. 2021). These local processes can be modified by climate modes (patterns of large-scale oceanic or atmospheric circulation) cycling between their positive and negative phases, over periods ranging from weeks to decades (Holbrook et al., 2019, 2020). El Niño events, for example, are statistically linked to stronger marine heatwaves in the **Pacific Ocean**, as well as parts of the **Indian Ocean, Southern Ocean** and east **Atlantic Ocean** (Holbrook et al., 2019).

The observed global average frequency of marine heatwaves has doubled between 1982-2016 (Frölicher et al. 2018). The duration, extent and intensity of marine heatwaves has also increased over the last 4 decades, with evidence of increases to some metrics over longer records (Frölicher et al., 2018, Oliver et al., 2018c). Compared to the early 20th century, the average number of marine heatwave days (*defined below) over the 1982-2016 satellite period, increased +54%, with an average +34% increase in frequency, and average +17% increase in duration, based on the combination of proxy metrics, station data and satellite records (Oliver et al., 2018c).

- **Marine heatwave frequency** is between 1 and 3 annual events for most of the global ocean and this increased, on average, by +0.45 annual events per decade, during the satellite era, which is equivalent to +1.6 annual events or +5 marine heatwave days (Oliver et al., 2018c). The largest increases were in the high latitude **North Atlantic** (>50°N) and these were partly offset by decreases in the **Southern Ocean** (>50°S) (Oliver et al., 2018c).
- **Marine heatwave duration** is variable across the global ocean (Oliver et al., 2018c), with the longest recorded events being between 40 and 160 days for 80% of the ocean and exceeding 250 days in the El Niño-impacted tropical **eastern Pacific** (Sen Gupta et al., 2020). In the **northeast Pacific** the average duration is 30 days (Oliver et al., 2018c; Holbrook et al., 2019), with maximum duration exceeding 200 days (Sen Gupta et al., 2020). Comparing 2000-2016 with 1982-1998, average marine heatwave duration increased for 84% of the global ocean, increasing at +1.3 days per decade, since 1982 (Oliver et al., 2018c).
- **Marine heatwave intensity** anomaly peaks were typically between +2.5°C and +3.7°C but peaks exceeding +5°C were observed in over 5% of the global ocean, including in the tropical **eastern Pacific**, **northern Atlantic**, **northern Pacific** and **southern Indian oceans** (Sen Gupta et al., 2020). Comparing the period 2000-2016 with 1982-1998, marine heatwave intensity increased for 65% of the global ocean (Oliver et al., 2018c). Over the period 1982-2016, marine heatwave intensity (here defined with a local 99th percentile threshold) has increased by +0.07°C (-0.01°C to 0.15°C) per decade (Frölicher et al. 2018).

**In the section above, marine heatwave metrics quoted from Oliver et al. (2018c) and Sen Gupta et al. (2020) were defined by local daily sea surface temperature exceeding the seasonally varying 90th percentile for 5 days or longer.*

Ecosystem disturbance

Coral bleaching events have occurred at tropical reefs globally, with increased frequency over recent decades as the frequency of marine heatwaves has risen (Hughes et al., 2018b; Leggat et al., 2019). Persistent or severe bleaching or heat stress leads to cellular damage, reef structure change and coral mortality, which then leads to reef fish and invertebrate species mortality as habitat is lost (Fordyce et al., 2019; Robinson et al., 2019). The global average interval between coral bleaching events has reduced by around half since 1980 and is now only 6 years, which limits the likelihood of reef systems recovering between events (Hughes et al., 2017, 2018b, Eakin et al., 2019). Multiple bleaching episodes occurred during the global-scale 2014-2017 mass bleaching event (Eakin et al., 2019) and the unprecedented severity and scale of heat stress caused significant mortality and reduction of coral habitat in **Hawaii** (Couch et al., 2017), all around **Australia** (Nohaïc et al., 2017; Hughes et al., 2017, 2018a; Eakin et al., 2019, Dietzel et al., 2021), central and western **Pacific islands** (Eakin et al., 2019). Marine heatwaves have also resulted in declines of non-reef building coral invertebrates and soft corals in the Mediterranean (Garrabou et al., 2019).

Kelp forest collapse and transition to degraded turf seascapes have been associated with warming and marine heatwaves worldwide (Filbee-Dexter & Wernberg 2018), including both sides of the **North Atlantic** (Filbee-Dexter et al., 2020), the **Pacific Ocean** around **Baja California** (Arafeh-Dalmur et al., 2019; Cavanaugh et al., 2019), **British Columbia** (Rogers-Bennett et al., 2019) and **New Zealand** (Thomsen et al., 2019; Tait et al., 2021) and the **Indian Ocean** around **Western Australia** (Wernberg et al., 2013, 2016). Kelp forests provide habitat and food for a wide variety of fish and invertebrate species, so their loss can impact entire ecosystems, as well as limiting provision of ecosystem goods and services to humans, including fishing, recreation & tourism, and carbon storage (Filbee -Dexter & Wernberg 2018). In contrast, turf algae form simpler matt-like environments offering less ecosystem support (Filbee - Dexter & Wernberg 2018). The widespread distribution of changes and absence of observed recovery may be indicative of tipping points being reached, bringing regime change from kelp-dominated to turf-dominated coastlines (Filbee-Dexter & Wernberg 2018) or sea urchin barrens (Rogers-Bennett & Catton, 2019). The correlation of kelp forest collapse with warming hotspots (Filbee-Dexter et al., 2020) suggests the primary role of marine heatwaves above any compounding or secondary factors (Filbee-Dexter & Wernberg 2018; Babcock et al., 2019; Rogers-Bennett & Catton, 2019; Tait et al., 2021).

Sea grasses are another foundation species that have been negatively impacted by marine heatwaves and the larger marine organisms they support, including turtles, dugong and birds, through provision of ecosystem services such as food and habitat, have also been impacted (Babcock et al., 2019; Kendrick et al., 2019; Strydom et al., 2020). Carbon storage is another ecosystem service provided by seagrass meadows (Nowicki et al., 2019) that will be reduced by seagrass meadow contraction. Extensive (-36%) loss of seagrass in Shark Bay, **Western Australia**, following the 2011 marine heatwave, is estimated to have reduced marine sediment carbon stocks between -2 and -9 million tons of CO_2, contributing +4% to +21% to Australia's land-use change CO_2 emissions (Arias-Ortiz, et al., 2018).

Marine heatwaves can cause ecosystem-level decline by reducing biomass of other primary producers, such as phytoplankton and zooplankton communities, which reduces food supply to foraging fish while simultaneously increasing their metabolic food demand, leading to starvation (Piatt et al., 2020). Consequently, declines in health (e.g. malnutrition), increased reproductive failures, or increased mortality were observed in ground fish, as well as large predatory fish, sea birds and mammals that feed on foraging fish (Piatt et al., 2020).

Attribution

A growing number of studies have quantified an increase in probability or intensity of marine heatwaves as a result of human-caused climate change, in addition to natural processes (Park et al., 2017; Walsh et al., 2018; Oliver et al., 2018a, 2021; Perkins- Kirkpatrick et al., 2019; Laufkötter et al. 2020). For example, a 5-fold increase in probability of the 2014 western **North Pacific** marine heatwave (Weller et al., 2015), and a more than 6-fold increase in intensity of the 2015/16 **Tasman Sea** marine heatwave (Oliver et al., 2017). Globally, it is estimated that 84-90% of all marine heatwaves that occurred between 1986 and 2005 are attributable to human-caused climate change (Frölicher et al., 2018). Collectively, the occurrence probabilities of the duration, intensity and cumulative intensity of the seven most severe and well documented marine heatwaves to have occurred recently, are estimated to have increased at least 20-fold due to human-caused climate change (Laufkötter et al., 2020).

Rising mean sea surface temperature is the dominant driver of increasing marine heatwave frequency and intensity, outweighing changes due to temperature variability (Alexander et al., 2018; Frölicher et al. 2018, Oliver, 2019a). Analysis indicates rising mean temperature led to higher marine heatwave frequency over two-thirds, and higher intensity over one-third, of the global ocean (Oliver, 2019a). Mean sea surface temperature is rising over most of the global ocean, while variability changes are concentrated in certain hotspots, such as western boundary currents, the equatorial **eastern Pacific** and **Mediterranean Sea** (Hobday & Pecl 2014, Oliver, 2019a). Prominent marine heatwaves commonly occur where mean warming and higher variability overlap, increasing cumulative intensity, such as in the **northwest Atlantic**, **Mediterranean Sea**, **Tasman Sea** and **Japan Sea** (Oliver, 2019a).

Future projections

Marine heatwaves are projected to continue increasing in frequency, duration and intensity under future scenarios of climate change, raising the threat to marine ecosystems and socioeconomic activities that depend upon them (Frölicher et al., 2018, Frölicher & Laufkötter, 2018; Oliver et al., 2019a, 2019b). While the extent of future impacts is dependent upon the particular greenhouse gas emission scenario, a worsening outlook is projected for marine ecosystems in all future scenarios. At +1.5^{o}C of future warming, marine heatwaves that occurred with centennial to millennial frequency in a pre-industrial climate, such as the Northeast Pacific 2013-2015 marine heatwave, are projected to occur with decadal to centennial frequency (Laufkötter et al., 2020). The outlook worsens for higher future emissions and warming scenarios (King et al., 2017; Frölicher et al. 2018; Oliver et al., 2019b). At +3.5°C of future warming relative to preindustrial levels, the number of marine heatwave days is projected to increase by a factor of at least 40. At this level of warming, marine heatwaves reach intensities of +2.5°C and have a spatial extent that is over 20 times bigger than preindustrial levels (Frölicher et al. 2018). Under high future emissions, by the late 21st century, much of the global ocean may reach a permanent state of marine heatwave, relative to a fixed preindustrial threshold (Oliver et al., 2019b).

Ecosystem disturbance

The projected rise in marine heatwave frequency, duration and intensity will have an increased impact on marine ecosystems, particularly species with reduced mobility, including foundation species such as coral, kelp and seagrasses (Smale et al. 2019) and populations of species that live near the upper limit of their thermal tolerance (Collins et al., 2019). Despite some species showing greater resilience to marine heatwaves, widespread species mortality and the decline of ecosystems are possible future outcomes (Straub et al., 2019). In the **northwest Pacific Ocean**, by 2050 under a high future emissions scenario (RCP8.5), future marine heatwaves are projected to double the magnitude of the impact of long-term changes to mean climate on fish stocks, particularly in terms of reduced biomass, which will impact the fishing industry (Cheung et al., 2020). In the **Indian ocean** off **Western Australia**, a four-fold increase in marine heatwave frequency is projected to reduce the reproductive output of green turtles by -20%, while also reducing food availability (Stubbs et al., 2020).

Marine heatwaves will amplify reductions in fish stocks and food availability, already predicted due to long-term climate change. The global average impact of marine heatwaves on future fish stocks is projected to be a reduction in biomass of 77% of fish and invertebrate species targeted by fisheries and a -6% reduction (range = -1% to -22%) in maximum catch potential under a high emissions (RCP8.5) scenario (Cheung et al., 2021). These changes in biomass and fish catch due to marine heatwaves will be in addition to the projected climate change-induced long-term changes in fisheries catch and biomass by 2050, (Bindoff et al., 2019; Lotze et al. 2019). The increased frequency of marine heatwaves will further reduce future food supply, revenue and employment in the majority of maritime countries, especially those most susceptible to future climate change and with high dependency on wild-capture fisheries, such as Small Island Developing States, countries in southeast Asia and Africa (Cheung et al., 2021; Tigchelaar et al., 2021).

This ScienceBrief Review is consistent with the IPCC Sixth Assessment Reports (AR6 WG1) Chapter 9.2 (2021) **and Special Report on the Ocean and Cryosphere in a Changing Climate** Chapter 6.4, which assessed with *high confidence*§ that the observed increasing occurrence of marine heatwaves with rising frequency, intensity and duration, are *very likely*§ the result of human-caused climate change. Future increases in magnitude are also assessed as *very likely*§, varying by future emissions scenario and region, and yielding severe and persistent impacts on marine ecosystems.

§*See an explanation of IPCC calibrated language.*

References

The full Brief and references can be explored on ScienceBrief with the following link: https://sciencebrief.org/topics/climate-change-science/marine-heatwaves, where the search filter can be used for e.g. Author name or keyword.

Suggested citation. Wernberg, T., Smale, D.A., Frölicher, T.L. and Smith, A.J.P. (2021): ScienceBrief Review: Climate change increases marine heatwaves harming marine ecosystems. In: Critical Issues in Climate Change Science, edited by: P. Liss, C. Le Quéré, & P. Forster. https://doi.org/10.5281/zenodo.5596820.

Acknowledgements.

This ScienceBrief Review was supported by the European Commission via projects 4C, VERIFY and COMFORT (grant no. 821003, 776810 and 820989). TW was supported by the Australian Research Council (DP190100058). DAS was supported by a UKRI Future Leaders Fellowship (MR/S032827/1), TLF was supported by Swiss National Science Foundation (PP00P2_198897). The authors thank N. L. Bindoff for reviewing an earlier version of this review.

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ScienceBrief is supported by the University of East Anglia (UEA). The platform was initiated with funding from the UK NERC International Opportunities Fund (NE/N013891/1). The ScienceBrief platform is developed by Anthony Jude De-Gol.

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