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Marine Heatwaves

Marine heatwaves are naturally occurring unusually warm ocean temperature events that can have severe impacts on marine ecosystems and socioeconomic activities.

Marine heatwaves can be driven by varying factors, including local processes, large-scale climate patterns, and human-induced global warming.

Advances in high-resolution ocean models are improving marine heatwave predictions. This is important as global warming drives more frequent and intense marine heatwaves.

Introduction

Marine heatwaves are periods of extreme warm temperatures in the oceans. They are known to have a wide range of impacts on marine ecosystems, including harmful algal blooms, coral bleaching and organism mortalities.

Marine heatwaves occur when temperatures exceed a certain statistical threshold (90th percentile) based on a reference period of 'normal' temperatures (known as 'climatology')[1]. This climatology is unique at each location in the ocean and time of the year. Marine heatwaves can therefore occur in any ocean region and during any season.

The risk that marine heatwaves pose to marine ecosystems has prompted scientists to investigate their mechanisms and trends in a warming world. Marine heatwaves have already become longer and more frequent due to rising air and sea temperatures, predominantly caused by anthropogenic emissions[2]. There is serious concern that these events will intensify even further in the future, causing more damage to our already fragile marine environment.

Giant Kelp, Sunrays, Tasmania - Photographer: Stefan Andrews, courtesy Great Southern Reef Foundation
https:greatsouthernreef.com/

The impacts of marine heatwaves

The ecological damage caused by marine heatwaves can have profound socioeconomic impacts[3], affecting important ecosystem values provided by our marine environment, such as the provision of natural resources and habitat services. Since the 1980s, the frequency and duration of marine heatwaves have been increasing in most areas of the oceans due to global warming[2], with certain regions experiencing a higher rate of increase compared to others.

Marine heatwaves have severely impacted key regions around Australia (Figure 1). Key hotspots include the ocean off:

Western Australia | The Tasman Sea.

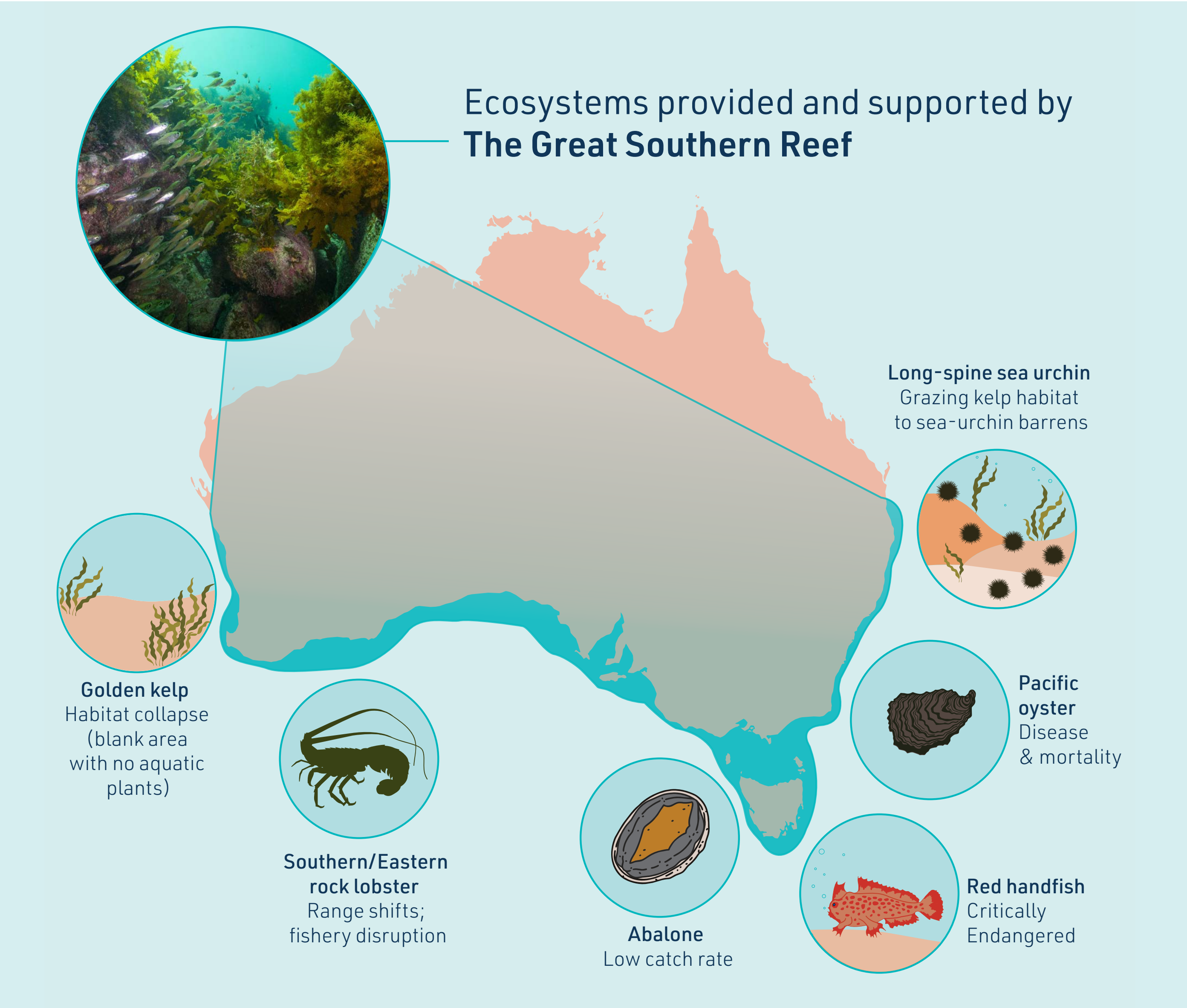
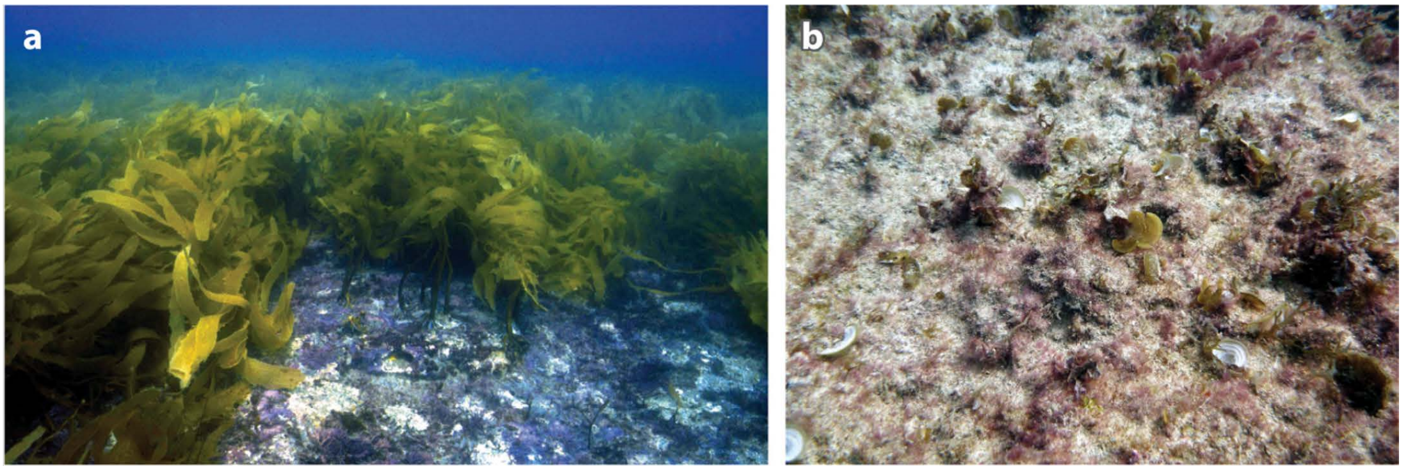


Figure 1: Significant damage associated with marine heatwaves around the Great Southern Reef which supports the ecosystem and biodiversity around southern Australia. Source: ARC Centre of Excellence for Climate Extremes. Top left image in graphic, Kelp Forest Glassfish Wardang Island, SA - Photographer: Stefan Andrews, courtesy Great Southern Reef Foundation https://greatsouthernreef.com/

Western Australia's 2011 marine heatwave

The 2011 marine heatwave that impacted the west coast of Australia was unprecedented because of its record breaking intensity at the time. This extreme marine heatwave, which also prompted scientists to coin and use the term 'marine heatwave' for the first time in the literature, highlighted the profound impacts that marine heatwaves can cause.

Benthic (region at the bottom of the ocean) habitats play important roles across Australia's temperate reefs, known as the Great Southern Reef. They are dominated by many seaweed species that help to support rich biodiversity in the southern oceans of Australia. During the 2011 marine heatwave, important species such as the golden kelp had a 100% collapse in its canopy cover near Kalbarri[4], leading to a drastic shift in the ecosystem structure from complex kelp forests to low-structure turfs (Figure 2). This ultimately influenced local biodiversity and led to ecosystem reconfigurations. Simultaneously, there was an unprecedented loss of about 1,300 km^2 of seagrass meadows at Shark Bay in Western Australia, which was once one of the largest and most diverse assemblages of seagrasses worldwide[5]. This also resulted in a fundamental change to its composition as well as losses of important commercial species.



Wernberg T, et al. 2024
Annu. Rev. Mar. Sci. 16:247–82

Figure 2: a) Healthy golden kelp in Western Australia, b) 100% canopy cover of golden kelp in Western Australia disappeared after the marine heatwave in 2011[5]. Source: https://www.annualreviews.org/content/journals/10.1146/annurev-marine-042023-093037

Tasman Sea marine heatwaves

The Tasman Sea, between Australia and New Zealand, is a marine heatwave hotspot where sea surface temperatures have been increasing about two to three times faster than the global average rate. In the austral summer of 2015/16, the Tasman Sea experienced its longest and most intense recorded marine heatwave at the time, with sea surface temperatures reaching 3-4°C above average.

Two years later, in the summer of 2017/18, another marine heatwave occurred in the Tasman Sea, this time extending over a wider range. This marine heatwave was more intense near the ocean's surface than the 2015/16 marine heatwave. These two marine heatwaves caused severe impacts on the fisheries and aquaculture industries. In commercial aquaculture, the impacts included mortality of Pacific Oysters, reduced performance and lower growth rate of Atlantic salmon, and impaired reproduction of abalone[6]. Due to the frequent marine heatwaves, significant losses to kelp species have been observed in recent years, while there are ongoing concerns about the potential risks to the endangered red handfish.

What causes marine heatwaves?

About 90% of the heat generated by global warming is absorbed by the ocean. Although this increase in stored heat contributes to more frequent and intense marine heatwaves, it is not the primary cause of marine heatwaves. Marine heatwaves also occur naturally.

Various factors can cause marine heatwaves[7], and can be divided into two types: atmospheric and oceanic factors. These factors, whether acting alone or together, can generate marine heatwaves (Figure 3).

These factors can be caused by local processes such as air-sea interactions, or by remote influences from larger-scale climate patterns such as the El Niño-Southern Oscillation.

ATMOSPHERIC FACTORS:

Sunlight: exposure to increased sunlight warms up the ocean on sunny days with reduced cloud cover.

Heat: reduced heat transfer from the ocean to the air occurs when the winds are weak.

OCEANIC FACTORS:

Ocean layers: a shallower top layer of the ocean (called the mixed layer) allows the surface layer to heat up more easily.

Currents: more heat being transported to a specific place by warm ocean currents.

Cold water: less cold water from the deep ocean reaching the surface (known as upwelling or Ekman pumping).

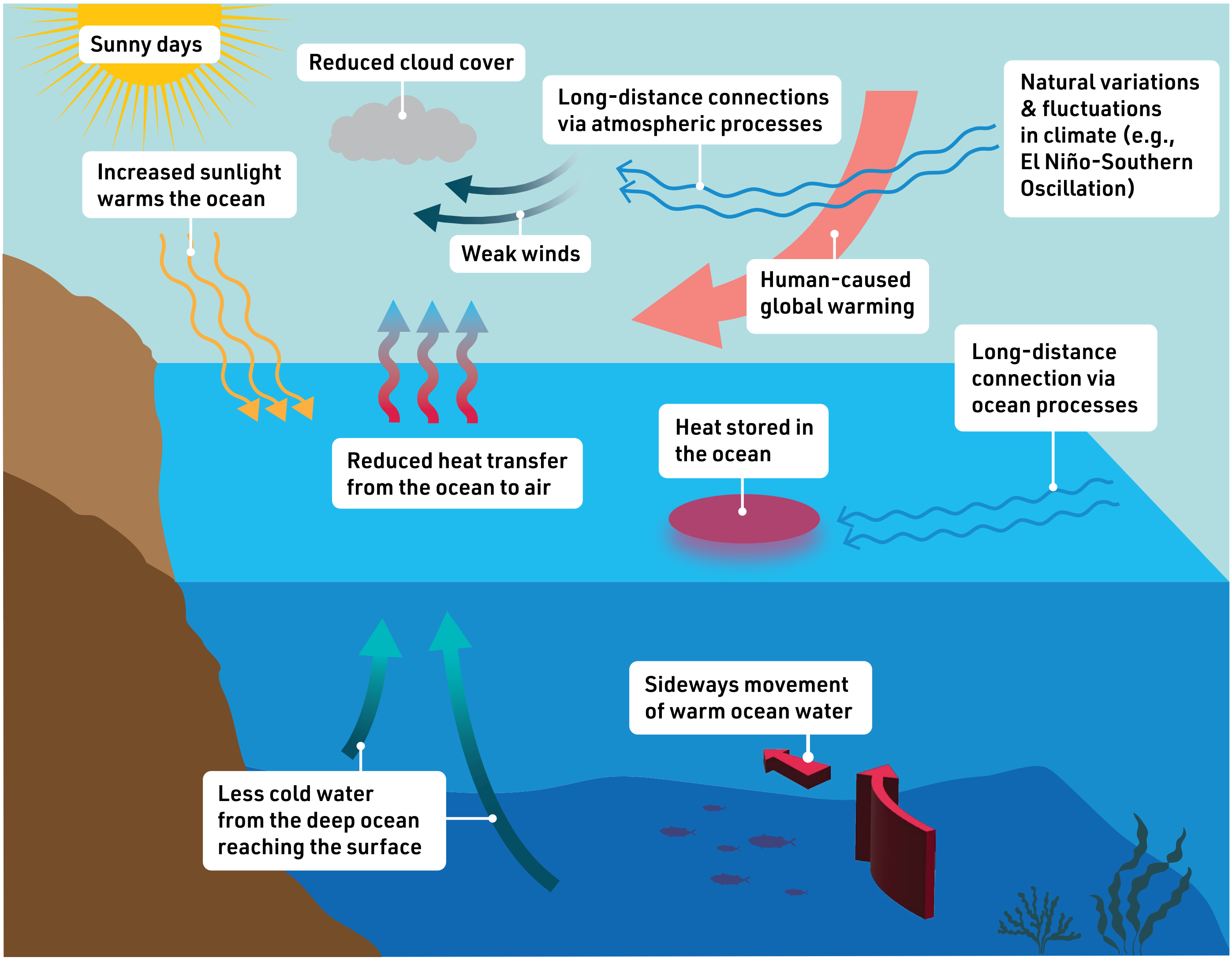


Figure 3: Physical drivers of marine heatwaves. Source: ARC Centre of Excellence for Climate Extremes, adapted from Holbrook et al., (2020).

For example, the marine heatwave off Western Australia in 2011 was caused by the combination of remote driving processes associated with La Niña (a phase of the El Niño-Southern Oscillation) and local processes. During La Niña, the wind patterns favour the movement of warm water from the equator southward along the Western Australian coast, and atmospheric processes can warm ocean temperatures further, priming conditions for a marine heatwave. Locally, a series of positive feedback processes make the water even warmer. These combined factors led to this extreme marine heatwave in 2011.

Though the drivers of many major historical marine heatwaves (like the Western Australia marine heatwave in 2011) have been understood, marine heatwaves are typically caused by different drivers in different regions. Researchers are still working to fully understand each case individually.

Understanding the physical drivers of marine heatwaves is crucial for developing and improving marine heatwave prediction systems, which will allow stakeholders to take actions to minimise potential negative impacts.

Do marine heatwaves occur below the ocean surface?

Marine heatwaves can also occur below the ocean surface, known as subsurface marine heatwaves, with potentially significant impacts on marine life at both regional and global scales. For example, around the South Pacific islands, a prolonged subsurface warming event in early 2019 caused unexpected coral bleaching near Moorea, French Polynesia at depths of 40 metres[8]. Globally, 22% of upper ocean species may have experienced severe thermal stress from subsurface marine heatwaves over the past two decades, potentially altering biodiversity patterns[9]. Subsurface marine heatwaves are increasingly challenging for marine organisms, requiring greater attention.

Detecting subsurface marine heatwaves relies on direct measurements of ocean temperature from the surface to the ocean floor (Figure 4). The diverse observational methods available enable studies of subsurface marine heatwaves to focus on a single location on daily or sub-daily timescales (e.g., mooring) or broader spatial scales from 10 days to a month (e.g., Argo gridded product). However globally, subsurface observations remain sparse in time and space. The global coverage can capture long-lasting, large-scale marine heatwaves but may miss short-lived, small-scale events. To address this, methods such as high-resolution ocean models can be used.

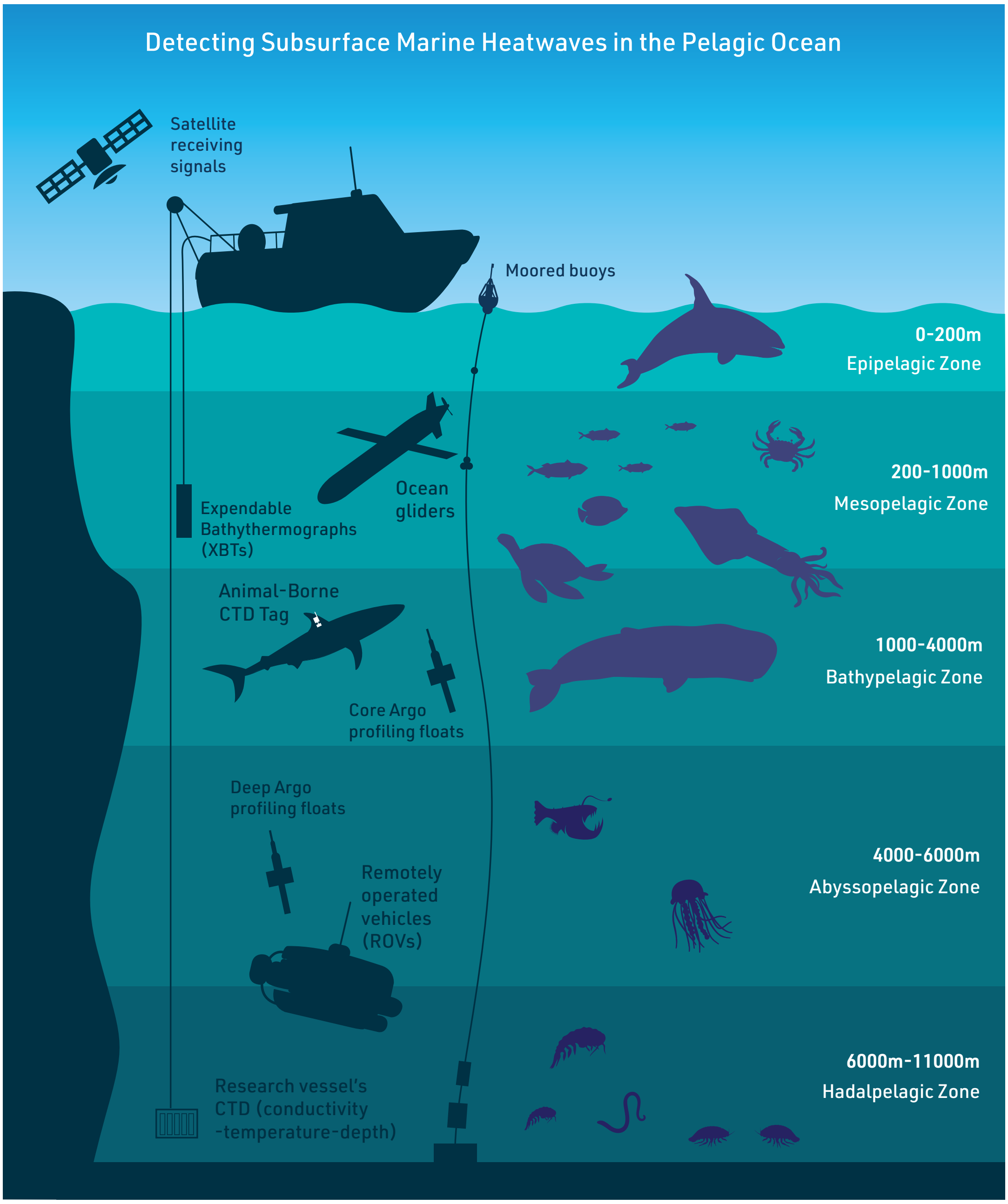


Figure 4: Diagram of in-situ instruments for subsurface marine heatwave research, and the effects of subsurface marine heatwaves on marine life at different depths. Source: ARC Centre of Excellence for Climate Extremes.

Subsurface marine heatwaves exhibit different vertical temperature structures depending on various ocean processes. They can be categorised into three classes by these vertical structures, based on daily ocean temperature observations taken from a mooring off Sydney over a 28 year period (Figure 5) .

- Shallow marine heatwaves, confined to the surface layer, are typically driven by air-sea heat fluxes under conditions of intense atmospheric warming or reduced cooling.
- Sub-merged marine heatwaves occurring at depth or near the ocean bottom, are linked to stronger surface cooling and the downward movement of warm water driven by winds.
- Deep marine heatwaves extending through the entire water column are often associated with deep, warm coastal currents.

Research into the mechanisms of subsurface marine heatwaves in various coastal and open-ocean regions is ongoing. Meanwhile, the effects of these events on coastal and open-ocean environments, including changes in ocean carbon, dissolved oxygen, and their impact on marine ecosystems requires further investigation.

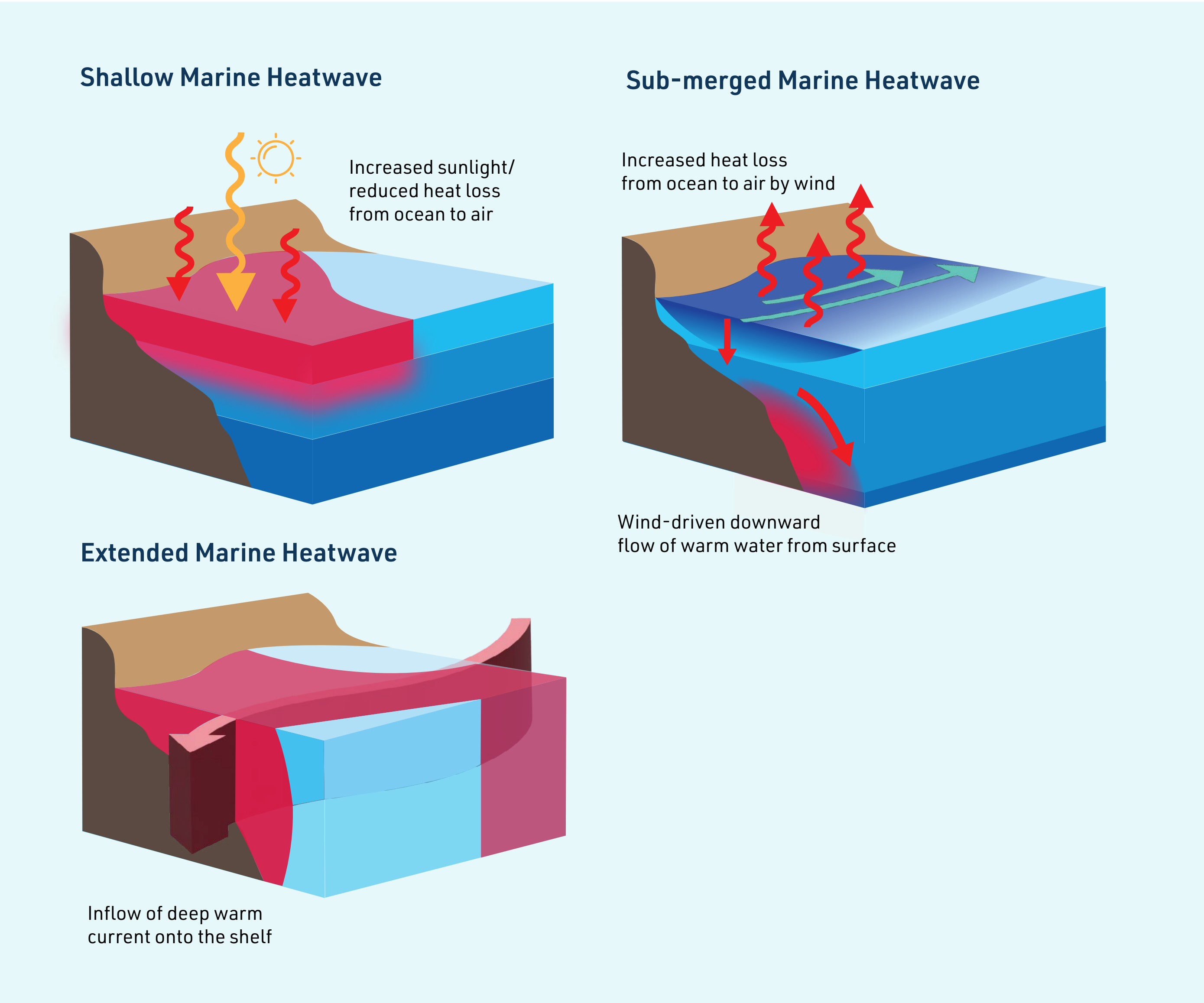


Figure 5: Schematic of the three marine heatwave classes and their divers in the Eastern Australian coastal region off Sydney. Source: ARC Centre of Excellence for Climate Extremes. Adapted from Schaeffer et al. (2023)[10].

Model simulations and forecasts of marine heatwaves

Predicting marine heatwaves requires an understanding of how various physical factors and processes interact over time. Short-term forecasts (several days) may benefit from understanding local air-sea interactions. Longer-term forecasts (weeks to months) depend on ocean conditions such as the thickness of the upper ocean layer, and the heat content stored in the ocean, with warm ocean currents playing a role. Long-term predictions (months to multiple years) are influenced by climate patterns like the El Niño-Southern Oscillation and planetary-scale oceanic waves which can enable forecasts many months in advance. These 'teleconnections' can help predict marine heatwaves, including off Western Australia.

The growing concerns about the threats posed by marine heatwaves underscore the need for better simulation and forecasting using high-resolution ocean models[10]. Compared to other models, high-resolution models can capture small-scale oceanographic processes such as eddies, fronts, and currents that are often missed by lower-resolution models. These processes are critical to the development and evolution of marine heatwaves, affecting their intensity, duration and spatial extent. Marine heatwaves can vary significantly over short distances. High-resolution models enable the analysis of these localised influences, providing more accurate information for specific regions. This is crucial for coastal communities, fisheries, and conservation efforts that rely on precise predictions.

Researchers from the ARC Centre of Excellence for Climate Extremes (the Centre) have been working on understanding marine heatwave predictability and developing forecast models. Recent achievements include the development of high-resolution ocean models. It has been shown that ACCESS-OM2, a global ocean model, represents marine heatwaves with high accuracy[11]. Additionally, ACCESS-S2, which is a multi-week to seasonal prediction system, is currently being used to provide preliminary forecasts of marine heatwaves several months in advance by Australia's Bureau of Meteorology.

The most costly impacts of marine heatwave events, both ecologically and economically, are concentrated in nearshore, relatively shallow seas. Global ocean and climate models are not very reliable near the coast because their coarse resolution prevents them from simulating ocean currents and processes smaller than about 50 km in scale.

Regional ocean models, which incorporate data from global models and simulate complex ocean processes at much higher resolutions, are shedding new light on the key factors that cause marine heatwaves in sensitive shallow marine ecosystems. These include small ocean eddies that can inject heat from the deep ocean into coastal seas. Researchers from the Centre have developed tools to apply these regional model simulations. Their current products include a software package to help researchers easily set up a regional model scheme[12].

Marine heatwaves in a warming world

In 2023, global average sea surface temperatures reached new highs resulting in a record area of global marine heatwave coverage. The global oceans experienced an average daily marine heatwave coverage of 32%, well above the previous record of 23% set in 2016 relative to the recent baseline[14]. The key drivers of the 2023 marine heatwave were likely a combination of a strong El Niño event and human-induced global warming, which widely increased global ocean temperatures, and other large scale climate drivers, including the Indian Ocean Dipole and the North Atlantic Oscillation, which caused regional increases in ocean temperatures.

While limiting anthropogenic emissions to curtail global warming and the associated rise in marine heatwaves remains a priority, researchers are considering the ecological implications if the Paris Agreement targets are not met. It is likely that many marine species will not be able to adapt to an increasingly warming world. Yet, sustained higher global ocean temperatures are also leading to the increased resistance of some marine species to higher temperatures[15], which are adapting to the 'new normal'. If ocean temperatures keep rising, the global oceans may reach a permanent marine heatwave state with respect to the current climatology and as a result, there are pressures to update the marine heatwave baseline to reflect the ecological risks[11]. This is one of the many ways a changing climate brings a new way of thinking about our current systems.

Conclusion

Marine heatwaves are naturally occurring unusually warm ocean temperature events. They can severely influence marine ecosystems and the socioeconomic activities associated with them. Marine heatwaves are caused by varying factors, such as intense sunlight, weakened wind, warm ocean currents, long-distance influence from larger climate patterns like the El Niño-Southern Oscillation and human-induced global warming. Subsurface marine heatwaves, which affect deeper parts of the ocean, are gaining attention due to their unique drivers and widespread ecological effects.

Worryingly, marine heatwaves will likely become more intense and frequent as global average temperatures keep rising, thus becoming an increasing threat to marine ecosystems. Advances in high-resolution models are improving our ability to predict marine heatwaves accurately, which help provide a "preparation window" for taking actions and adapting in advance to minimise the potential impacts. Efforts to curtail global warming by reducing greenhouse gas emissions remain a priority so that the risks of marine heatwaves can be reduced. At the same time, more research into the drivers of marine heatwaves, their predictability, and their ecological impacts is also important to better help us prepare for the future.

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