Marine heatwaves often wreak havoc on ecosystems and can lead to widespread coral bleaching.

HOW HEATWAVES RAVAGE THE SEAS

Sudden fevers are gripping parts of the ocean with increasing frequency. Scientists are scrambling to forecast them and prevent harm to marine life.

By Giuliana Viglione

Ten years ago, dead fish began washing ashore on the beaches of Western Australia. The culprit was a huge swathe of unusually warm water that ravaged kelp forests and scores of commercially important marine creatures, from abalone to scallops to lobster. Over the following weeks, some of Western Australia's most lucrative fisheries came close to being wiped out. To this day, some of them have not recovered.

After the crisis, scientists came together to assess the damage and try to understand what had caused the unusual warming. "This event really had such devastating consequences for marine ecosystems," says Jessica Benthuysen, a physical oceanographer at the Australian Institute of Marine Science in Perth.

Since that event, researchers have seen dozens of similar hot spells in ocean regions around the world and have now given them a name – marine heatwaves (see 'Four decades of marine heatwaves'). Although scientists have come up with a few different ways to define the events, they generally agree that they involve warm spells in surface waters of the ocean that last at least five days and reach a temperature threshold well above the normal range[1].

The effects of marine heatwaves can reverberate up the food chain, says Pippa Moore, a marine-community ecologist at Newcastle University, UK. Warm, low-nutrient water in the Northwest Pacific during a 2013–16 marine heatwave known as The Blob devastated phytoplankton growth. Then, Chinook salmon (*Oncorhynchus tshawytscha*) populations plunged, and as many as one million seabirds died in the Gulf of Alaska. Marine heatwaves have also caused massive amounts of coral bleaching in reefs around the world over the past several decades.

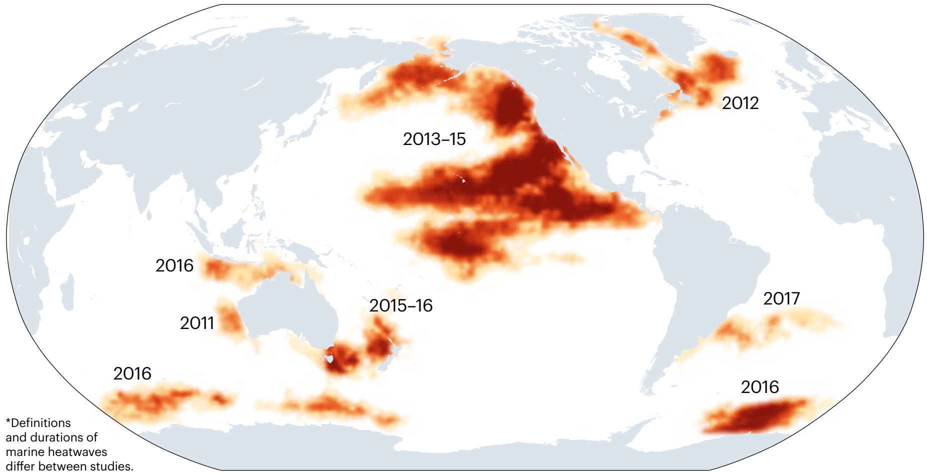
Like their counterparts in the atmosphere, marine heatwaves are getting worse: climate change is magnifying their frequency (see 'Fevered waters'), extending their length and

FOUR DECADES OF HEATWAVES

More than 30,000 distinct marine heatwaves occurred between September 1981 and December 2017, according to one study[7]. The map shows the most prominent over the past decade.

Heatwave duration (days)

0 50 >100



*Definitions and durations of marine heatwaves differ between studies.

SOURCE: REF. 7

pushing them to higher temperatures. All that puts a premium on understanding their causes and learning how to forecast them.

Such predictions would help fisheries managers decide whether to limit harvests or even close off some areas to fishing entirely. For now, forecasting methods are still in their infancy. But with fresh observational data sets, ever-improving models and global attention turned to understanding the phenomena, scientists hope to substantially improve their predictions in the coming years.

That could be a major win, say researchers, because the ocean provides hundreds of billions of dollars' worth of food and other resources, many of which are threatened by marine heatwaves. "We really need to get a handle on when and where these events are going to occur," says Hillary Scannell, a physical oceanographer at Columbia University's Lamont–Doherty Earth Observatory in Palisades, New York. That will help societies plan for what to do when marine heatwaves are heading their way, she says.

High-pressure situation

The summer of 2013–14 was a difficult one in Brazil. A severe drought devastated crops and sparked water shortages in São Paolo. At the same time, the ocean was heating up and chlorophyll concentrations — a measure of biological productivity — were dropping sharply. When Regina Rodrigues, a physical oceanographer at the Federal University of Santa Catarina in Florianópolis, Brazil, started digging into the data, she found that the drought and ocean warming had a common cause: a high-pressure atmospheric system that had sat over the southeastern part of the country for much of the summer[2].

This type of long-lasting high-pressure system is associated with a phenomenon known as atmospheric blocking, and it's one of the most common drivers of marine heatwaves — and heatwaves over land, too. Atmospheric blocking leads to sparse cloud cover and relatively calm winds. The lack of clouds allows more solar radiation to reach the ocean and warm it; at the same time, the still air inhibits mixing and evaporation. All these factors can lead to a build-up of heat in the upper ocean. And that can shift the wind patterns in ways that intensify or prolong the warming.

In a study[2] published in 2019, Rodrigues and her team found that about 60% of marine heatwave events in the southwestern part of the Atlantic Ocean — including the 2013–14 event — were the result of high-pressure systems that originated somewhere over the Indian Ocean, thousands of kilometres away. These systems then moved through the atmosphere towards South America. But because atmospheric blocking relies on so many factors, it's a complex phenomenon to recreate in a numerical model. "It depends on so many aspects of the climate system that it's really hard to get it right," Rodrigues says.

These seemingly disconnected, far-flung regions are linked through 'teleconnections'. Rodrigues likens them to tossing a stone in a lake and watching the ripples spread outwards. In her study, she found that the process generally starts when air near Earth's surface warms and rises. Convection above the Indian Ocean pokes the atmosphere, she says, causing atmospheric waves that reach South America and result in a marine heatwave. This interconnectedness of the climate system complicates predictions. Rather than just modelling a specific, small region of interest in the ocean, researchers have to account for processes happening around the globe.

Teasing apart the climatic conditions that lead to a marine heatwave is a painstaking process, says Robert Schlegel, a data scientist at Sorbonne University's Villefranche Sea Institute in France. Schlegel is among the researchers turning to statistical and machine-learning methods to try to understand the main causes of the ocean's heatwaves.

"The surface is just the tip of the iceberg of the marine heatwave."

Deep drivers

Sometimes, the drivers of a marine heatwave hide in the ocean itself. That happened with the event off Western Australia, when the southward-flowing Leeuwin Current grew stronger. As the current intensified, it carried larger-than-usual quantities of warm water from the Indian Ocean, bathing hundreds of kilometres of coastline in a months-long heatwave[3].

A similar pattern caused a 2015–16 marine heatwave in the Tasman Sea between Australia and New Zealand that set records for its duration and intensity in that part of the ocean. A 2017 study[4] traced that event back to a strengthening of the East Australian Current, which brings warm tropical waters to those countries' shores. Such ocean-driven events can penetrate much deeper into the ocean than do their atmosphere-driven counterparts, says Neil Holbrook, an ocean and climate scientist at Australia's University of Tasmania, who co-authored the paper.

These deeper events pose a unique challenge to climate scientists. Almost all of the current understanding of marine heatwaves is restricted to what happens in the surface ocean, where researchers can use satellite instruments to map the temperature and track events in near-real time. But beneath the surface is a world of complex currents. "We can see and define the heatwave on the surface," says Sofia Darmaraki, a physical oceanographer at Dalhousie University in Halifax, Canada. "But the surface is just the tip of the iceberg of the marine heatwave."

There are relatively few observational networks tracking conditions beneath the surface. Floats and buoys provide data in some regions, but they are completely missing in others. Understanding how subsurface heat anomalies develop, persist and evolve is one of the biggest open questions in marine-heatwave research. And because the vast majority of the ocean's inhabitants reside below the surface, this is a critical frontier for scientists to explore, Scannell says. "We haven't really fully understood how the subsurface marine heatwaves impact the ecosystems."

Benthuysen and other researchers in Australia are trying to fill in some of those gaps, using a strategy known as event-based sampling. The country's Integrated Marine Observing System (IMOS) and its partners maintain a fleet of ocean gliders – underwater, remotely pilotable instruments – that are on standby. When a marine heatwave develops, the IMOS team can mobilize quickly to get its gliders in the water to collect key data about temperature and salinity.

One test came early this year when waters off Western Australia began to warm again. The researchers used a glider to track the development of what turned out to be the strongest marine heatwave in that part of the ocean since the devastating event a decade earlier. The glider swam more than 500 kilometres and captured the cooling effect of a tropical cyclone that tore through the waters in early February. In March and April, the team deployed two more gliders off the coast of Tasmania to help map the extent of a persistent heatwave in the Tasman Sea. That pair revealed that the temperature anomalies were higher in the ocean's subsurface than in its uppermost waters.

The researchers say that data collected by these gliders could help to improve predictions from dynamical forecasting models, which simulate the physics of processes in the ocean and atmosphere. "Collecting near-real-time data and ensuring that those could go into short-term models definitely has a lot of promise to help people make decisions and communicate what might be happening," Benthuysen says.

Limited forecasts

Forecasting efforts around the world are currently unable to predict the extremes very far in advance, says Alex Sen Gupta, a climate scientist and oceanographer at the University of New South Wales in Sydney. "The science of ocean forecasting is quite a long way behind the science of weather forecasting."

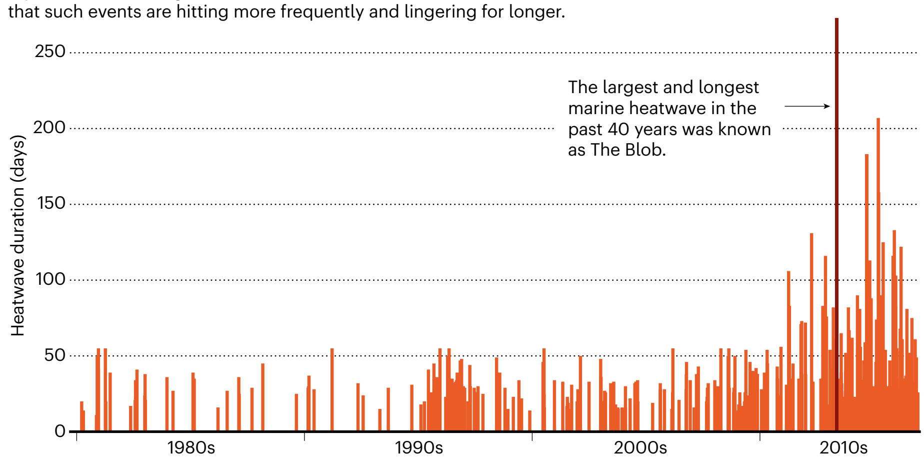
Some models might be able to predict a singular event a few days or a week ahead of time, Sen Gupta says. But beyond that, the chaotic nature of the climate system makes individual events more difficult to forecast. And for many stakeholders, the current models are not sophisticated enough or at fine-enough scales to inform the kinds of policy decision they need to make to prepare for a potential heatwave.

Jahson Alemu I, a marine ecologist at the National University of Singapore, notes that the resolution of today's predictive models is not much smaller than the island of Tobago. That makes it hard both to make decisions and to communicate risks to the public, says Alemu I, who is also director of SpeSeas, a non-governmental organization focused on marine issues in the Caribbean.

Currently, researchers tend to rely on statistical models based on past patterns to give them a sense of whether a heatwave is likely to occur over a given time period. But these models are a sort of stopgap measure until dynamical models are sophisticated enough to predict the events. "Statistical methods rely on patterns that you've seen in the past repeating themselves," says Alistair Hobday, a marine scientist at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Hobart, Australia. In a world with a rapidly changing climate, he says, such models will begin to fail. "The dynamical model is the way to go."

FEVERED WATERS

A plot of the 300 largest marine heatwaves between 1981 and 2017 shows that such events are hitting more frequently and lingering for longer.



SOURCE: REF. 7

Hobday leads a project at CSIRO to predict marine heatwaves. In December, the group released its first statistical forecast created with machine-learning techniques that examined both historical data and models of sea surface temperatures and the amount of heat stored in the upper ocean. The forecast warned of a high likelihood of a marine heatwave developing off the coast of Western Australia between January and April.

In fact, temperatures offshore did rise to abnormal highs in the beginning of the year. This year's statistical forecast was a kind of proof-of-concept, Hobday says – the team intentionally chose a large region and a long time period over which a heatwave might be expected. But next year, his team plans to release a dynamical forecast for the region that will provide a finer-scale look at marine-heatwave risks.

Worsening future

There is one type of marine-heatwave prediction that climate scientists feel confident in making: that climate change is going to intensify and exacerbate the events. As people continue to pump greenhouse gases into the atmosphere, climate models project that rising global temperatures will exacerbate nearly every measure of marine heatwaves. "You expect that extremes will increase under climate change," Holbrook says. "Things are just kind of going to get worse."

Some of these changes are already happening. Between 1925 and 2016, the number of annual marine heatwave days around the globe increased by more than 50%. And from the beginning of the satellite record in 1982, marine heatwaves have increased in intensity across nearly two-thirds of the ocean[5]. And scientists predict that those trends will continue. Several studies have shown that even under moderate warming scenarios, almost all of the ocean will experience more-frequent and longer-lasting marine heatwaves over the coming years[6,7].

Many of the extreme events over the past several decades have been made worse by climate change, too. A 2020 study[7] examining seven of the highest-impact marine heatwaves since 1981 concluded that all but one were at least partially due to human-driven warming. The researchers compared climate model simulations using pre-industrial concentrations of carbon dioxide in the atmosphere with model runs using present-day concentrations.

The results showed that some of the events were so strong that they were fully attributable to anthropogenic climate change, says Charlotte Laufkötter, a climate scientist at the University of Bern in Switzerland who led that work. "In pre-industrial times, they couldn't have occurred."

And at some point in the next century, scientists project that much of the ocean will have warmed past the temperature threshold that defines these events – plunging many parts of the world into a state of permanent marine heatwave. "If we have such strong warming," Laufkötter says, "it's not an extreme event any more. It's always there."

Giuliana Viglione is a freelance journalist in Washington DC.

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