

The drivers and the implications of marine heatwaves

John Carey, Science Writer

During the Australian summer of 2010–2011, the water off the continent's west coast got hot—really hot. Sea temperatures soared to 6 °C above normal. Researchers and fisheries managers worried about impacts on valuable species, such as abalone and scallops, and on the vast forests of kelps and other seaweeds that underpin the region's highly productive coastal ecosystem. But “no one really had any data,” recalls University of Western Australia, Perth, marine botanist Thomas Wernberg.

Wernberg had been monitoring coastal plant communities for more than a decade, so he and his colleagues decided to revisit their study sites. First up was a day trip north from Perth to Jurien Bay. The researchers were stunned by what they found. The former lush underwater meadows of strap weed, a relative of kelp, were completely gone. “We said, ‘Jesus Christ, what happened here?’” Wernberg recalls.

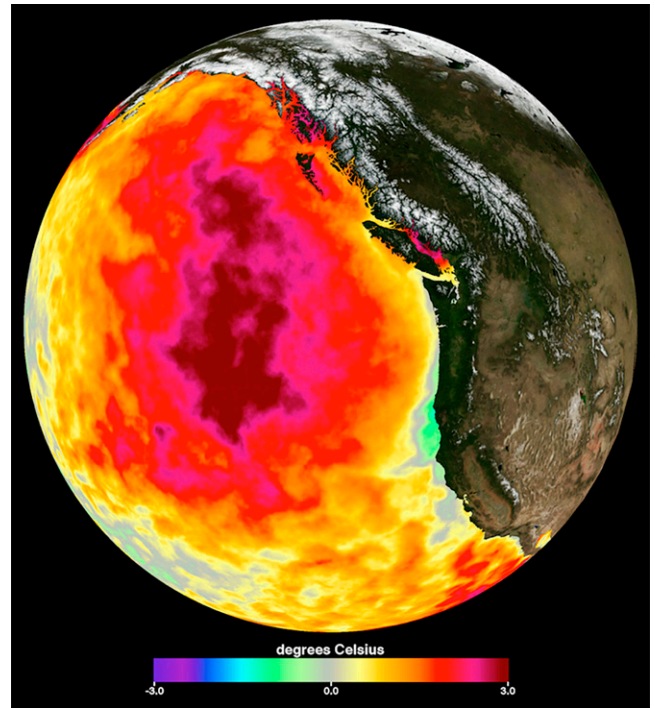
A year later, Wernberg's team ventured further north to Kalbarri to assess the productivity of the typically luxuriant kelp forests found in the coastal waters. They had another shock. “There was not a single kelp plant anywhere,” Wernberg says. “That's when we realized the huge magnitude of what had happened.” Nearly half of the kelp along more than 800 kilometers of coastline had vanished, the researchers showed—and the ecosystem had flipped to an entirely new state dominated by small turf-forming seaweeds. Abalone and scallop populations crashed. Penguin chicks died in massive numbers. The fish communities changed, with influxes of more tropical species that ramped up grazing pressure on seaweeds by 400% (1). Even now, more than a decade later, and long after sea temperatures returned to normal, Wernberg's data show that the kelp has not recovered, and shellfish populations are way down and only slowly returning to fishable levels (2).

The intense 2011 Australian coastal heatwave did more than push an entire ecosystem into uncharted waters. It also spurred the first effort to rigorously define and characterize the concept of marine heatwaves—an interdisciplinary crusade complicated by an underlying relentless uptick in temperatures as a result of climate change. In the last 10 years, “the science on marine heatwaves has exploded,” says physical scientist Dillon Amaya, at the National Oceanic and Atmospheric Administration Earth System Research Laboratories in Boulder, CO.

In more than a hundred articles, researchers have chronicled the rise and fall of ocean temperatures in scores of locations around the world, pinpointed the drivers of these heatwaves, documented the often-devastating effects on everything from plants to shellfish, and calculated a multi-billion-dollar annual toll from increasingly extreme heatwaves. Even among researchers expecting big changes owing to climate change, it's a sobering and somewhat unexpected story; the heatwaves involve temperature jumps far above the slow climb in average ocean temperature. “I think marine heatwave intensification is one of the most pervasive threats to marine ecosystems,” says benthic marine ecologist Dan Smale at the Marine Biological Association of the UK in Plymouth. “We should be really worried.”

An Interdisciplinary Agenda

Even decades before the 2011 heatwave, physical oceanographers, ecologists, fisheries researchers, and others had noted and studied episodes of unusually



Among the highest profile marine heatwaves was a huge pool of warm water in the Pacific dubbed the Blob, which first appeared in the winter of 2013. Shown here in May 2015 based on NASA data, the Blob stretched more than 2,000 kilometers along the west coast of North America and persisted for nearly 3 years with enormous ecological and economic consequences. Image credit: NASA Physical Oceanography Distributed Active Archive Center.

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high sea surface temperatures. The science, though, was held back by the lack of a unifying definition or framework, Wernberg and others realized. “The various communities didn’t necessarily speak to each other in the same language,” notes physical oceanographer Eric Oliver, now at Dalhousie University in Halifax, Canada.

So in January 2015, Wernberg, Smale, and Oliver brought together a diverse group of oceanographers, biologists, ecologists, fisheries managers, modelers, and even atmospheric physicists from around Australia and Tasmania for a three-day workshop in Perth to hash out a common language. Given that the atmospheric community already had rigorously defined extreme heat on land, “we quickly agreed not to reinvent the wheel,” says Wernberg. Instead, the group adopted the atmospheric researchers’ existing term, “heatwave,” while adjusting the definition to account for the slower responses of ocean systems. A “marine heatwave,” they concluded, is a discrete and prolonged anomalously warm event, lasting at least 5 days (and up to many months) with clear start and end times, and with temperatures in the 90th percentile compared with a 30-year-long baseline of data (3). The group didn’t neglect the details. “We spent a whole afternoon discussing whether ‘heatwave’ should be one word or two,” recalls Smale.

The workshop also laid out a clear three-part research agenda. First, quickly publish a detailed rationale for the new framework—done in 2016 (3). Second, identify the physical drivers of heatwaves. Those include higher air temperatures; more intense solar radiation; less cloud cover; a thinner mixed layer of water above the cold deep ocean waters, which heats up faster; drops in wind speed, which decrease evaporative cooling; shifts in ocean currents; the presence or absence of large-scale climate phenomena such as the El Niño-Southern Oscillation; and climate change itself, as described in a 2019 article in *Nature Communications*, led by physical oceanographer Neil Holbrook of the University of Tasmania, Australia (4).

Moreover, these drivers can interact in complex ways. A La Niña event, for example, can lock the atmosphere into a long-term persistent state where the normal prevailing winds cease blowing for weeks or months, allowing large areas of the ocean to heat up fast.

And third, the workshop noted the importance of documenting long-term trends. Poring over data from 1926 to 2016 and from Norway to California, Oliver and colleagues showed that, using the new definition, heatwaves have become longer and more intense: The number of days with heatwaves jumped 54%, with much of the increase occurring in the last couple of decades. The new extremes in temperatures have brought “major impacts...in terms of fisheries, aquaculture, and tourism,” Oliver and team reported in 2018 (5).

These efforts from the researchers Down Under helped kick-start a new era in marine heatwave research. “Australia is seen as ground zero—they’ve done some really awesome research,” says ecologist Sam Walkes at the University of California, Davis. Adds Wernberg, “It’s been a great experience to see how quickly this has been taken up once there was a concept and framework that seemed to fit.”

Major, high-profile events accelerated the pace of the work. The biggest was a mammoth pool of warm

water—2.6°C above normal—that appeared in the winter of 2013 in the Pacific Ocean. Nicknamed the Blob, it stretched for more than 2,000 km along the west coast of North America and persisted for nearly 3 years, with enormous consequences. The cod fishery, worth \$100 million per year, collapsed when krill and other food sources vanished. Lured by the warmer water, juvenile white sharks were seen “for the first time in recorded history” in Monterey Bay, CA, says Kyle Van Houtan, former chief scientist at the Monterey Bay Aquarium. Tens of thousands of dead tuna crabs washed up on San Diego beaches, kelp forests vanished, and hundreds of thousands of seabirds died, among many other impacts. After 3 years of unprecedented heat, the Blob disappeared, and many species, such as krill and crabs, have mostly recovered. (Another heatwave, dubbed the Blob 2.0, appeared in 2019—but this time in summer and of much shorter duration and with fewer ecological effects.)

The main cause of the Blob, Amaya says, was the “Ridiculously Resilient Ridge,” as he mentions in a 2016 article (6)—a high-atmospheric-pressure ridge in the northeastern Pacific Ocean that persisted throughout 2013 and 2014. The stalled atmospheric pattern stilled the usual winds, allowing water temperatures to climb.

More recently, researchers have pinpointed the causes of other heatwave events, such as shifting currents that have raised temperatures off the coast of Maine. And researchers have begun to explore the phenomenon of “bottom heatwaves,” where warm surface water gets pressed downward until it hits the seafloor up to 200 meters deep. Those bottom heatwaves, surprisingly, can be even hotter and longer-lasting than the corresponding surface temperature extremes, says Amaya. His recent work shows how bottom heatwaves can occur when waves of higher sea levels can “slither” up the West Coast of the United States. The extra weight from these waves can push down the thermocline (the boundary between warm surface water and cool deeper water) far enough that it actually hits bottom. The impacts on marine life are expected to be big, says Amaya, because most bottom-dwelling organisms can’t move much to avoid the extra heat.

Economic Toll

Ecological carnage aside, researchers also have calculated large economic and social costs attributed to marine heatwaves around the world. Although there can be scattered benefits, such as a potential new squid fishery in the Pacific Northwest or a boost to the lobster industry in Maine from warmer waters, researchers have calculated the overall toll at billions of dollars per year—in addition to the ecological carnage. In Chile, for example, heatwaves linked to the El Niño in 2016 triggered harmful algal blooms that wiped out fish farms, causing a loss of fish exports estimated at \$800 million (7).

Acknowledging these enormous costs, researchers are looking for ways to limit the future damage, says Oliver. One key notion: figuring out how to forecast heatwaves weeks or months in advance, giving fisheries managers and others time to prepare. Because warmer water lowers the reproductive success of sardines, for example, the allowable catch could be reduced before a heatwave strikes. Or oyster farms

2005**2013**

A marine heatwave off the west coast of Australia decimated kelp populations. Image credit: Thomas Wernberg (University of Western Australia).

could harvest earlier, before a heatwave killed their stock. Amaya's latest research shows "significant prediction skill 6 to 8 months in advance," he says (8).

More controversial is whether to step in to help nature cope with both the gradually rising temperatures from climate change and the spikes from heatwaves. Perhaps more heat-tolerant varieties of kelp could be bred and seeded in the wild to replace what's being lost, thus preserving the species' crucial role as habitat creators, food source, and potentially large carbon sink. "For some, this is ethically contentious, but we are trying to understand ahead of time whether this could be a potential tool in the toolbox," Wernberg explains.

Meanwhile, there's a growing debate about the original landmark definition of marine heatwaves, given the inexorable rise in ocean temperatures resulting from climate change. If heatwaves are defined as extremes relative to a 30-year past average, then "in the future, everything is a heatwave, because the ocean will be several degrees warmer than today," says Amaya. It may be better, then, to define a heatwave as an extreme compared with the

current average temperature, he says: "Otherwise, it will become difficult to distinguish future marine heatwaves as discreet events."

That may make sense from a physical oceanographers' perspective, where the crucial issue is variations from the current average conditions, acknowledges Oliver. But he and other authors of the original definition argue that many ecosystems will suffer when temperatures climb above the historical baseline, regardless of whether or not the rise comes from planetary warming or a temporary extreme. "That's why the debate doesn't have a singular answer," Oliver says. Perhaps the next step should be refining the definition of marine heatwaves for the contexts of particular ecosystems, depending on how adaptable they are and on how much harm they experience from sudden heatwaves compared with long-term temperature increases.

These questions and considerations are about more than just semantics. The answers will help map out future work in an urgent area of study. The debate, Oliver says, is "opening up a whole avenue of research that needs to be done."

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