News & views

Ocean science

Marine heatwaves put into context

Mark R. Payne

An innovative metric has been devised to quantify the size and extent of the warm waters during marine heatwaves. It thus reflects how far ocean organisms might travel to find cooler conditions — a key factor in these warming events. **See p.82**

In the past few years, ocean scientists have been excited by the appearance of an entirely new subdiscipline: the study of marine heatwaves (MHWs), discrete periods of unusually warm temperatures in the ocean. Several such events have captured the attention of both scientists and the public, most notably an MHW known as the Blob[1] that occurred in the northeastern Pacific Ocean during 2013–15. High-profile impacts[2] of MHWs include the closure of fisheries, large-scale die-offs of seabirds and unusual sightings of species thousands of kilometres out of their natural range. Such effects make these heating events one of the most visible signs of an ocean under stress. On page 82, Jacox *et al.*[3] report a metric that puts MHWs into their spatial context with surrounding cooler waters, and thereby casts light on the distance by which ocean organisms might be displaced.

Progress in science is typically incremental: research papers usually 'stand on the shoulders of giants' that have preceded them. For scientists studying MHWs, however, there are no giants' shoulders to stand on. The field is therefore inventing itself from scratch, creating a dynamism and excitement that is as rare as it is fascinating to follow.

Several key developments have enabled MHWs to emerge as a field of study. The advent of user-friendly satellite-based measurements of daily sea surface temperatures provided the necessary data, and exponential increases in computational power and storage removed practical barriers to analysing these big data sets. But the crucial breakthroughs that united the field were as mundane as systematization and taxonomy[4].

The first such breakthrough was a system for defining and quantifying MHWs[5] — they are now generally defined as periods of five or more consecutive days during which ocean temperatures in a given region are in the top 10% of historical values for that time of year[2]. Next, MHWs began to be named and classified using the Hobday scale[6], in a similar way to how hurricanes are named and categorized. With these conceptual tools in hand, the results began pouring in. Systematic increases in the frequency and intensity of MHWs have been observed across all ocean regions[7] and are expected to increase dramatically in the future[8], given that the increases are linked to climate change[2].

Nevertheless, the excitement and speed of such progress have masked an important conceptual problem. Current MHW metrics are based on analyses of temperature data at individual positions in the ocean. However, working out the effect of MHWs on marine life from these physical data is complicated by the ability of some organisms to move: if an organism is too hot at one place, it will simply shift elsewhere. In some regions, cooler water might be only a few kilometres away — such as areas near frontal zones (the interfaces of distinct hydrological regions of the ocean), or near upwelling zones (where cold, deep waters are brought to the surface). In other regions, relief might be hundreds or thousands of kilometres away, as is the case in the tropics, where ocean temperatures are relatively uniform. Metrics that focus on the analysis of temperature at a single point therefore overlook the potentially crucial spatial context and extent of the MHW.

Jacox *et al.* resolve this problem by incorporating the full set of temperature data into their analysis. They define a metric that they

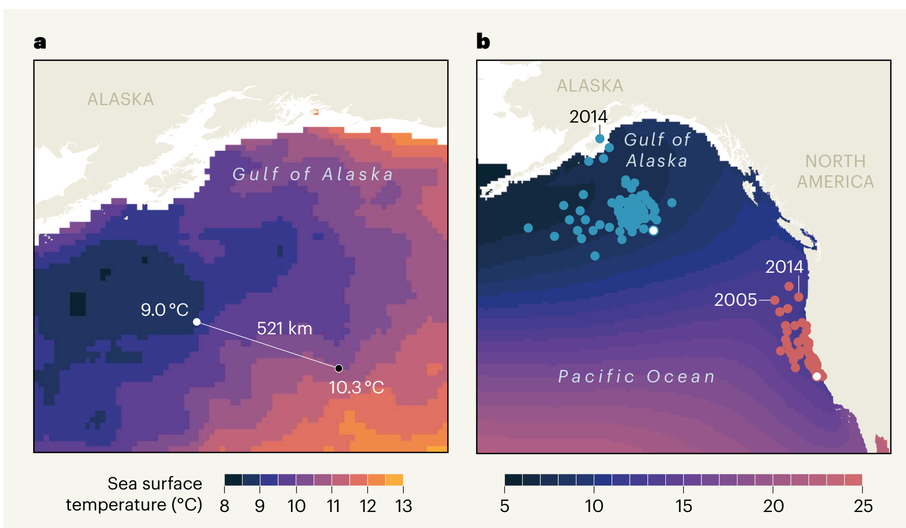

Figure 1 | How thermal displacements characterize marine heatwaves (MHWs). a, Jacox *et al.*[3] define thermal displacement during MHWs as the minimum distance from a given position that is the same temperature as or cooler than the 'normal' historical temperature at that position. Here, the normal temperature at the black circle in the Gulf of Alaska is 9.0 °C, but the MHW temperature is 10.3 °C. The minimum distance to a region at 9.0 °C or less (darkest blue regions) is 521 kilometres. Sea surface temperatures (SSTs) across the region during the MHW are indicated. White regions indicate areas covered by sea ice. (Adapted from Extended Data Fig. 5e of ref. 3.) **b**, This expanded view of the northeast Pacific shows examples of thermal displacements (red and blue circles) from two starting points (white circles) during different heatwaves, highlighting the scale of the responses: displacements for notable heatwaves during 2005 and 2014 (labelled) are more than 750 km. SSTs are mean averages for 1982–2019. (Adapted from Fig. 3a of ref. 3.)

call thermal displacement by posing the same question that bothers an overheating fish: 'How far do I have to go to find conditions that are at or cooler than normal temperatures?' In other words, this metric quantifies the availability (or lack) of cooler temperatures in the waters surrounding a given point (Fig. 1a). The authors show that historical heatwaves have thermal displacements ranging from tens to thousands of kilometres (Fig. 1b), highlighting the scale of the disruption that MHWs can bring. In many cases, these displacements are on the same scale as, or on scales even greater than, the displacements expected to become the norm by the end of the century under many climate-change scenarios[9].

Thermal displacements offer a fresh perspective when looking into the future. Projections of this metric in a changing climate combine not only the distribution of temperatures in the ocean, but also differences in the rate of warming. As a consequence, future changes in thermal displacements have a complex structure and can be either positive or negative — in contrast to projections of MHW frequency and intensity, which largely reveal uniform increases[8]. Some regions can therefore be expected to show reductions in thermal displacement due to MHWs in the future, whereas others will see increases.

Nevertheless, as with any new tool, the limitations of thermal displacement need to be understood — in particular, how this metric of ocean-temperature data relates to biological responses. For example, the habitat of a marine organism is shaped not only by temperature, but also by factors such as water depth, proximity to the coastline and the nature of the sea bed. Moreover, finding and reaching a suitable alternative habitat takes time, which means that species displacements expected on the basis of the thermal-displacement metric might not always occur, especially for short-duration MHWs. That said, Jacox and colleagues' analytical approach is flexible enough to allow species-specific constraints on habitat and movement to be incorporated. Collaborations with biogeographers, who have well-developed models[10] of the environmental niches and distribution of marine organisms, might have great potential.

It should also be noted that thermal displacement is relevant only for species that have some capacity for active movement. Many marine organisms are location-bound and cannot or will not move, such as kelp forests or parents guarding their young.

Such limitations notwithstanding, the strength of Jacox and colleagues' advance is that it diversifies the toolbox for MHW researchers. Scientists can now tailor their approach to the questions and organisms at hand, using conventional metrics when thermal tolerance at a location is the main concern, and thermal displacement when species-distribution shifts are a focus. The development of thermal displacement as a metric therefore expands our perspectives of MHWs and their potential impacts in a new direction. Discovering where this insight will lead us on the road to understanding these extreme events will be eagerly anticipated.

Mark R. Payne is at the National Institute of Aquatic Resources (DTU-Aqua), Technical University of Denmark, 2800 Kongens Lyngby, Denmark.
e-mail: mpay@aqua.dtu.dk

1. Cavole, L. M. *et al. Oceanography* **29**, 273–285 (2016).
2. IPCC. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* Ch. 6.4 (IPCC, 2019).
3. Jacox, M. G., Alexander, M. A., Bograd, S. J. & Scott, J. D. *Nature* **584**, 82–86 (2020).
4. Smale, D. A. *et al. Nature Clim. Change* **9**, 306–312 (2019).
5. Hobday, A. J. *et al. Prog. Oceanogr.* **141**, 227–238 (2016).
6. Hobday, A. J. *et al. Oceanography* **31**, 162–173 (2018).
7. Oliver, E. C. J. *et al. Nature Commun.* **9**, 1324 (2018).
8. Frölicher, T. L., Fischer, E. M. & Gruber, N. *Nature* **560**, 360–364 (2018).
9. Burrows, M. T. *et al. Science* **334**, 652–655 (2011).
10. Guisan, A. & Zimmermann, N. E. *Ecol. Model.* **135**, 147–186 (2000).

Plant biology

Genetic drivers of high-rise rice

Julia Bailey-Serres & Laurentius A. C. J. Voesenek

Rice in deepwater paddy fields can survive a slow-rising flood by a remarkably rapid elongation of submerged stem sections. Two genes discovered to affect this process could aid targeted improvements in crop height and flood tolerance. **See p.109**

The height that a plant reaches during its life cycle is influenced by both its genetic inheritance and its environment. The agricultural revolution of the 1960s led to a rise in the productivity of rice (*Oryza sativa*) and wheat (*Triticum aestivum*) through the adoption of varieties with a genetic predisposition to having a short height through restrained stem elongation. This trait allows more of the carbon generated by photosynthesis to be allocated to flowers and grain production, rather than being directed to stem biomass. Moreover, these shorter, highly productive varieties are much less likely to topple over at maturity, or during driving rain, than are taller varieties. On page 109, Nagai *et al.*[1] describe the identification of genes that accelerate or decelerate stem elongation during specific phases of rice development.

The leaf blades and the floral 'spike' of grass species, including rice, develop from a compact shoot tip that expands upwards telescopically as the plant matures. This shoot tip produces a series of leaf blades that are each attached to the hollow stem by a 'collar' called a node (Fig. 1). Each node consists of a ring of tissue, including a patch of cells called a meristem that can divide to produce daughter cells; these elongate to form a stem segment called an internode[2]. The activation of this cell division and elongation process requires the growth hormone gibberellin. The number of internodes that elongate and their cumulative length determine the plant's ultimate height.

Modern rice grown in shallow paddy fields is short in stature because these plants have a defect in a gene called *SEMIDWARF 1* (*SD1*). This gene encodes the enzyme GA20 oxidase 2, which catalyses the production of highly active forms of gibberellin[3,4]. The lower stem nodes of these varieties make insufficient amounts of gibberellin to activate internode elongation. However, as these semidwarf plants transition from the juvenile (leaf producing) to the adult (flowering) phase of development, their uppermost node makes sufficient gibberellin for internode lengthening, enabling the flowers to extend above the leaf canopy. Mutations in other genes involved in the synthesis or perception of gibberellin are often responsible for the highly desired short stature of other grain crops.

More than 30% of all acreage planted with rice is susceptible to crop loss from floods[5]. The cultivation of deepwater rice allows farmers in south Asia and western Africa to integrate rice and fish farming in delta regions. Deepwater rice can escape submergence in a slow-rising flood by elongation growth of their stems at a rate of 25 centimetres per day[6].

Genes responsible for this elongating ability have been identified for the Bangladeshi deepwater rice variety C9285. One gene that is essential for this trait is a functional version of *SD1* termed $SD1^{C9285}$, which robustly produces growth-promoting gibberellins in stem nodes[7]. The aptly named *SNORKEL 1* and *SNORKEL 2* (*SK1/2*) genes further boost underwater internode elongation in this variety[8]. Plants sense submergence by means