CHAPTER 5

Extreme climatic events in the ocean

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Chapter Outline

In large parts of the Northern Hemisphere, the summer of 2018 was exceptionally hot and dry. Europe, North America, and parts of East Asia were swept almost simultaneously by an exceptional heat wave that lasted several weeks, set record high temperatures, caused drought and wildfires, and affected the health of many people [1]. In contrast to earlier heat waves, such as the European heat wave in 2003, this large-scale heat wave did not catch the climate community by surprise as it has been known for more than a decade that such extreme events become more likely under global warming [2]. But it was not until recently that a similar dynamic has emerged and has been documented in the ocean with far-reaching consequences for marine ecosystems [3]. In fact some of the recently observed marine heatwaves (MHWs) revealed the high vulnerability of marine ecosystems and fisheries to such extreme temperature events in the ocean. MHWs are periods of extremely high temperatures that can last for days to months, can extend up to thousands of kilometers, and can penetrate multiple hundreds of meters into the deep ocean [4,5].

MHWs have been observed in all ocean basins over the past two decades Fig. 5.1. One of the first documented MHWs was the Mediterranean Sea 2003 MHW with sea surface temperatures up to 3°C above average [6]. Another well-documented heatwave was the Western Australian 2011 MHW. It was characterized by record high sea surface

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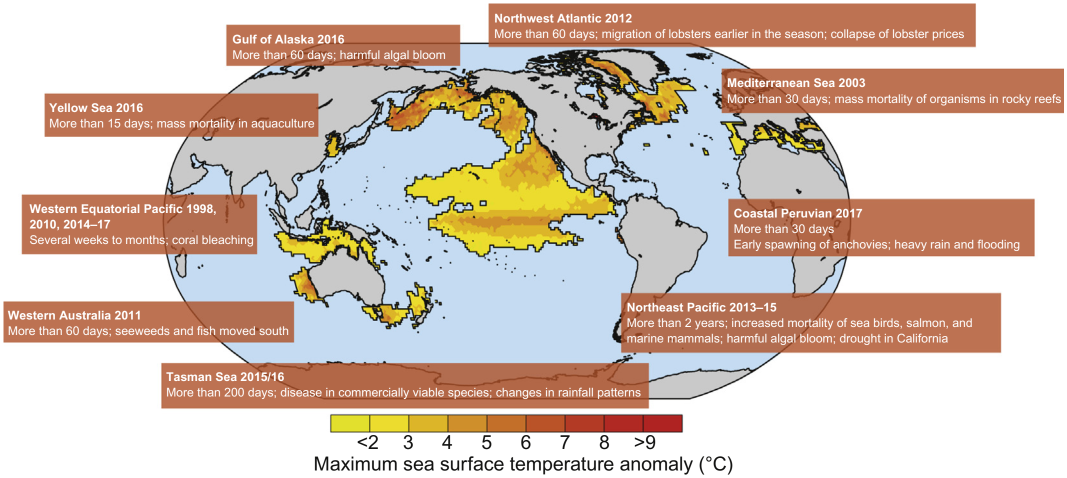

Figure 5.1
Spatial extension and maximal intensity of documented marine heatwaves over the last two decades. Yellow to red colors show the observed maximum temperature anomalies during the marine heatwaves. The orange boxes indicate the location and year of the marine heatwave occurrence and highlight the duration and some examples of observed impacts on natural and human systems. *Modified from T.L. Frölicher, C. Laufkötter, Emerging risks from marine heat waves, Nat. Commun. 9 (2018) 650. doi:10.1038/s41467-018-03163-6.*

temperatures of up to 5°C above average that persisted for more than 10 weeks in early 2011 [7]. The perhaps most famous heatwave was "The Blob" in the Northeast Pacific from 2013 to 2016 [8]. The heatwave had transiently a diameter of up to 1600 km with water temperatures of up to 6°C above average off Southern California [9]. MHWs have also been observed in the Gulf of Alaska, the Northwest Atlantic, the Tasman Sea, off the coast of Peru, and in the Yellow Sea. The western tropical Pacific including the Coral Sea has experienced multiple heatwaves (1998, 2010, 2014–17).

5.1 What drives marine heatwaves?

Over land, atmospheric blocking conditions often generate prolonged periods of very high temperatures that are often amplified by soil-moisture deficits [2]. In the ocean there are many processes that may trigger heat waves. These processes are less well known and quantified than in the terrestrial realm. The most important global driver of MHWs are El Niño events [10]. During El Niño years the sea surface temperatures, in particular of the central and eastern equatorial Pacific, are anomalously warm. El Niño is the result of a strong coupling between the atmosphere and the ocean, and the weaker than normal trade winds reduce the upwelling of cold subsurface waters in the eastern equatorial Pacific. Some MHWs are triggered by atmospheric-driven perturbations, such as stable weather conditions or changes in wind patterns that can be amplified through positive feedbacks with the warm ocean water. For example, a persistent atmospheric high pressure system possibly amplified by feedback processes with the anomalous warm ocean surface water in the North Pacific may have caused "The Blob" in 2013–16 [11]. This persistent high pressure system blocked the prevailing mid-latitude westerlies and led to lower than normal rates of heat loss from the ocean to the atmosphere. The Western Australia 2011 MHW was caused by a shift in wind patterns over the Indo-Pacific Ocean that strengthened and shifted the warm Leeuwin current southward resulting in warmer than normal waters off the coast of Australia [7]. Heat waves over land and/or ocean turbulence can also induce extreme anomalies in ocean temperatures.

5.2 The warming oceans

The global ocean plays a central role in regulating climate and in mitigating climate change, because of its immense volume and the large heat capacity of seawater. In fact, the largest amount of the extra heat that has been accumulated in the Earth system due to the increase in greenhouse gas concentrations has been taken up by the ocean. Between 1970 and 2010 the ocean stored approximately 93% or 274 ZJ (1 ZJ = 10^{21} J) of the extra heat [12]. Only 7% of the excess energy is distributed within the atmosphere and the land, and has caused ice melt. As a direct result of the excess heat uptake, the ocean is warming at the surface and throughout the deeper layers. The near surface layers of the global ocean have warmed at a rate of about 0.1°C per decade since the mid-20th century [13], albeit with pronounced regional and seasonal variability and with greater warming in the world's coastal regions [14]. But also deeper layers have warmed over the last few decades and the abyssal ocean (below 4000 m) continues to warm in the Southern Hemisphere [12,15].

5.3 Increase in marine heatwaves

Superimposed onto the long-term ocean warming trend are short-term extreme hot temperature events, so-called MHWs, during which ocean temperatures are anomalously high [3,4]. Analysis of daily satellite-based measurements of sea surface temperature covering the period 1982–2016 reveal that the number of MHW days exceeding the 99th percentile, calculated over the 1982–2016 period, has doubled globally since 1982 [10,16]. In other words, MHWs that occurred twice a year in 1982 are now (i.e., year 2016) occurring four times a year. MHWs are not only getting more frequent, they are also increasing in extent, duration, and intensity. As a result of the record high sea surface temperatures in 2015 and 2016, one-quarter of the worlds' oceans experienced either the longest or most intense events since 1982 in 2015 and 2016 [4]. On a regional scale MHWs have become more common in 38% of the world's coastal oceans over the last few decades [14].

What has driven this large increase in MHWs over the last few decades? To test whether the observed multidecadal increase in the number of MHW days over the satellite data-taking period is different from what would be expected from natural variability, such as El Niño Southern Oscillation or the Meridional Overturning Circulation, Frölicher et al. [16] compared Earth system model simulations that are forced with anthropogenic climate change with simulations not including anthropogenic climate change. They found that the observed trend toward more frequent MHW days is much larger than what can be expected from natural variability alone. In fact 87% of the MHWs occurring today are attributable to human-caused global warming [16], and some recent MHWs such as the Alaskan Sea 2016 MHW [17] and the extensive warming over the Great Barrier Reef in 2016 [18] have nearly been fully attributed to anthropogenic forcing. In other words, such events are very rarely found or are absent in preindustrial climate model simulations.

5.4 Future changes

Given current trends in greenhouse gas emissions and the major challenge posed by a transformation to a fossil-fuel-free society, it is very likely that global warming will continue to increase over the next few decades [19]. It is therefore expected that MHW days will also continue to increase with unabated global warming.

Earth system model simulations suggest that if global atmospheric surface temperature were to rise by 1.5°C relative to preindustrial levels by the end of the 21st century, as has been pledged in the Paris accord, the average number of MHW days would be 16 times higher than in preindustrial times when using the 99th preindustrial percentile threshold definition (blue dots for "$>99\%$" in Fig. 5.2A) [16]. If temperature were to rise by 2°C, the number of MHW days would be 23 times larger (yellow dots for "$>99\%$" in Fig. 5.2A), and under a 3.5°C rise they would be 41 times larger (red dots for "$>99\%$" in Fig. 5.2A). In other words, MHWs occurred every 100th day at preindustrial times, under a 1.5°C rise every sixth day, under a 2°C rise every fourth day, and under a 3.5°C rise every second day. In general, the probability ratio (i.e., the relative increase in the number of MHW days) increases the most for very rare extremes (Fig. 5.2A). For example, the probability ratio is 23 for moderate MHWs (defined as the 99th preindustrial percentile) and 890 for the very rare MHWs (99.99th preindustrial percentile) under 2°C global warming. But not only the number of MHW days is increasing. The heatwaves are also becoming longer lasting and spatially more extensive. Under 3.5°C global warming, the duration of a MHW, defined as the 99th preindustrial percentile threshold, would increase to 112 days (red dots for "$>99\%$" in Fig. 5.2B) and the spatial extent would increase to 94.5×10^5 km^2—equivalent to the total area of China. As a comparison, at preindustrial times, a MHW lasted on average 11 days (black dots for "$>99\%$" in Fig. 5.2B) and had a spatial extent of 4.2×10^5 km^2, the area of Switzerland.

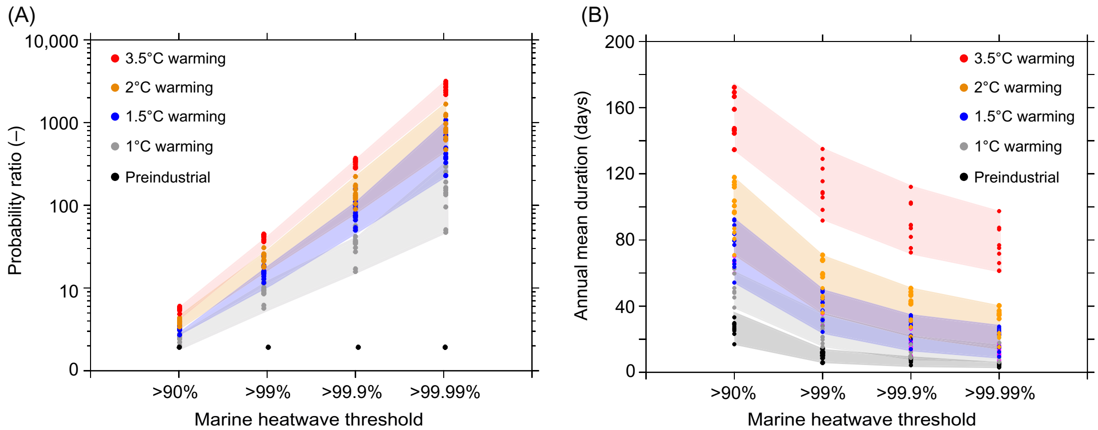

Figure 5.2
Simulated changes in the (A) probability ratio (i.e., relative increase in marine heatwave days; logarithmic scale) and the (B) duration of marine heatwaves for different global warming levels and different marine heatwave thresholds. Results are from 12 CMIP5 Earth system model simulations over the historical period and following the RCP8.5 scenario. The shaded areas indicate the maximum range and the points the individual model results should be points instead of point. *Modified from T.L. Frölicher, E.M. Fischer, N. Gruber, Marine heatwaves under global warming, Nature 560 (2018) 360–364. doi:10.1038/s41586-018-0383-9.*

All ocean regions will experience an increase in MHW days. The regional differences are caused by the heterogenous warming of the ocean surface. The largest changes are projected to occur in the Arctic Ocean and the western tropical Pacific. In the Arctic Ocean, the number of MHW days will increase 50-fold, in the western tropical Pacific even 70-fold. In the Arctic Ocean, the retreat of sea ice leads to an overproportional increase in temperature and therefore MHW days. In the western tropical Pacific, the seasonal and annual changes in sea surface temperature are small, and a relatively small increase in sea surface temperature can lead to a large increase in MHW days. In the Southern Ocean, however, only a small increase in MHW days is projected. There, the water upwells from very deep and cold layers and therefore the water at the surface does not warm up rapidly.

Interestingly, the number of MHWs is increasing more rapidly than the number of heat waves over land, even though the land generally warms more than the ocean. The reason is that the temperature variability is much smaller in the water than in the atmosphere. The probability of MHWs, therefore, increases disproportionally to comparatively small temperature increases [3].

A comparison between satellite measurements and model projections of MHWs suggests that the models adequately represent the trend in the number of MHW days over the last 35 years [16]. However, models have difficulties in simulating the duration and the spatial extent of the heatwaves, possibly caused by the relatively coarse resolution of the ocean (and atmosphere) models. The horizontal resolution of the ocean models is typically about 100 km and therefore too coarse to resolve mesoscale processes that may be critical to improve the representation of the duration and spatial extent of MHWs. To run long simulations with such global high-resolution, coupled ocean–atmosphere models enormous computational resources would be needed which are not yet available.

5.5 Impacts

Recent MHWs have had profound impacts on marine organisms (Fig. 5.1). Warm-water corals, for example, are an ecosystem that reacts very sensitively to elevated ocean temperatures. The prolonged MHW from 2014 to 2017 in the tropics and subtropics caused mass bleaching of corals, the third global-scale event in the past two decades. The heat stress during this event caused bleaching at 75% of global reefs and mortality at 30% [20].

Apart from the strong impact on corals, MHWs also strongly impacted other ecosystems. Reported biological impacts range from geographical species shifts and widespread changes in species composition to harmful algal blooms, mass stranding of mammals and mass mortalities of particular species. The Western Australia 2011 MHW, for example, led to a collapse of the temperate kelp forest off Australia and also to a shift in community composition with an increase in herbivorous tropical fishes that prevent the reestablishment of the kelp forest [21]. In several cases MHWs also strongly affected the fishery industry and tourism. The Northeast Pacific 2013–15 MHW, for example, caused a coast-wide harmful algal bloom [22] and the closing of beaches and commercially important fisheries and aquaculture industry [23].

5.6 Outlook

Whereas the long-term changes in ocean temperatures and the associated rise in sea level have been subject to intensive research for decades, with the exception of tropical coral reef systems, little focus has been given to MHWs and their impact on natural and human systems. The abovementioned examples demonstrate that a range of organisms and ecosystems can be impacted by MHWs with cascading risks for other natural and human systems. As MHW days are predicted to increase with continued global warming, it is therefore likely that this will result in profound impacts on natural and human systems. Especially organisms that are sessile and which cannot adapt to higher temperature will face very high risk of impacts.

Observations and model simulations also demonstrate that other drivers such as deoxygenation and acidification are putting additional stress on marine organisms and ecosystems [24]. Of particular concern are “Compound Events” [25], which correspond to extreme events with multiple concurrent and consecutive drivers (e.g., MHWs co-occurring with very low oxygen and pH levels) resulting in extreme consequences for marine ecosystems. Although there are a few studies on individual compound events in the ocean, the underlying drivers and the degree to which they can be represented in current climate models are currently unknown, making it difficult to design appropriate adaptation strategies. In order to better understand the impact of such compound events on individual organisms and entire ecosystems, continued interdisciplinary collaborations are needed.

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