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Aided by Marine Heatwaves – Harmful Agal Blooms Outbreak Situation

Binxiang Xia[1], Luote Xia[2*], Miao Zhang[1]

[1]Victoria College, Kunming, China
[2]Keystone Academy, Beijing, China
**Corresponding Author. Email: luote.xia@student.keystoneacademy.cn*

Abstract. Under climate change, marine heatwaves (MHWs) and harmful algal blooms (HABs) are increasingly becoming environmental issues in the ocean. Increasing sea temperature and human pressures are affecting marine ecosystems. Recent research indicates that MHWs are becoming more frequent, intense and long-lasting, and are associated with the increase of HABs. But most studies are limited to a specific region or event, and there is still a need for an overview of recent global outbreaks. This study examines the link between MHWs and HABs and reviews recent cases in various regions, including the Northeast Pacific, Baltic Sea and Arctic oceans. It describes how the increased temperature, stratification and nutrient conditions during MHWs provide a conducive environment for HABs. The findings reveal that HAB events are becoming more frequent, extensive, and severe, and cause severe ecological impacts including toxic production and hypoxia. This research offers a succinct review of recent MHW-HABs studies and contributes to better understanding of MHW-HABs. It can inform future monitoring and early warning systems. But more research is needed on long-term trends and multiple factor interactions, which should be the focus of future research.

Keywords: Marine heatwaves, Harmful algal bloom, Outbreak, Pacific Ocean, Baltic Sea

1. Introduction

Global environmental issues are becoming more pressing and severe. Global warming and pollution have garnered much attention. Among those, over the ocean, the largest and most complex ecosystem on Earth, global warming and human activities are placing unprecedented pressures. Recent studies have shown that marine heatwaves (MHWs) - periods of unusually warm sea temperature that last from days to months - are increasing in frequency and intensity and are helping the abnormal growth of harmful algal blooms (HABs) Harmful algal blooms (HABs) refer to the rapid proliferation of certain phytoplankton species that can produce toxins or otherwise disrupt marine ecosystems, fisheries, and human health. They are often dominated by dinoflagellates, diatoms and cyanobacteria which can produce toxic biotoxins. The development of marine heatwaves is primarily influenced by global ocean warming, atmospheric circulation patterns and reduced ocean mixing, resulting in increased sea surface temperature and increased stratification. These changes provide suitable habitats for HABs occurrence by stimulating phytoplankton growth

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and redistributing nutrients. Growing evidence suggests a close link between MHWs and HABs, with sustained warming able to speed up bloom development, change species composition, and increase the duration and extent of blooms.

However, despite numerous relevant studies conducted across the globe, few papers integrate the most recent findings. Written under the context of incremental MHWs, this essay unfolds the relationship between MHWs and HABs and the current situation of HAB outbreaks, accompanied by a partial analysis of their ecological effects on marine ecosystems. After consolidating recent case studies performed in various regions, it is concluded that harmful algal blooms have increased in frequency, intensity, and scale, shedding light on the urgent need for greater environmental attention. The aim is to aid future research with an organized and comprehensive review of the most recent MHW–HAB cases.

2. MHWs driving HABs

2.1. HABs

HABs refer to the phenomenon where algae or cyanobacteria reproduce out of control in water bodies, producing toxic or other harmful effects on the surrounding species, namely aquatic organisms and humans. In normal conditions, algae density is around 10^3–10^4 cells per liter, but during a bloom it increases to approximately 10^6–10^8 cells per liter or above [1]. When densely accumulated, these algae change the color of the water bodies to their inherent colors – commonly forming green, red, brown, or golden tides.

The harmfulness of HABs is mainly manifested through the Toxin Production and the Oxygen Depletion. Among all HABs, red tides are known for their toxicity. Mainly formed by toxic microscopic algae, such as toxin-producing dinoflagellates, red tides cause mortality among aquatic organisms, and could negatively impacts humans with higher doses. Several dinotoxins are powerful neurotoxins that directly attack the nervous system of organisms. For instance, the saxitoxin produced by Alexandrium genera blocks sodium ion channels, which hinders neural signal transmitting and causes paralytic shellfish poisoning (PSP). This paralysis the respiratory muscles in fish and other animals, leading to death [2]. On the other hand, humans could become the victims of HABs. In some blooms, such as a Karenia brevis bloom, wave action and wind could easily break the algae's cells, aerosolizing the toxins into tiny particles blowing in the air. Once contacted or breathed in by humans, the toxins might trigger asthma-like reactions [3].

The decomposition process during the declining period of algal blooms increases the mortality of aquatic organisms in large quantity. During decomposition, as the algae debris sink to the bottom, bacteria would consume a large amount of dissolved oxygen from the bottom layer, creating "dead zones" of hypoxia. To date, more than 400 coastal "dead zones" were found globally, contributing to a total area of above 245,000 km^2 [4]. The benthic component (bottom dwellers, such as shellfish) of ecosystems is especially vulnerable. Massive mortality and defaunation of hypoxia-sensitive organisms, including clams, conches, crabs, starfish, are common.

Being naturally occurring, HABs events exhibit increased area, frequency, and duration due to human activities and environmental alterations. Increased nutrient pollution, higher temperatures, strengthened stratification and more are all driving forces.

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2.2. MHWs

MHWs are characterized by the surface temperature of the sea area being 2–5°C higher than the historical average for more than 5 consecutive days. They are marked by long duration and abnormally high temperatures, posing a serious threat to the stability of Marine ecosystems and human production activities. Global warming has caused the ocean to absorb a large amount of excess heat from the atmosphere, which is the core background for the formation of MHWs. Heat emissions from human activities, environmental pollution, abnormal fluctuations in ocean current systems, and climate events such as El Nino will further induce and exacerbate the occurrence of MHWs.

Over the past 40 years, global MHWs have shown a significant intensification trend: the number of outbreaks, extreme temperatures, duration and impact range have all been on the rise. Specifically, from 1925 to 2016, the frequency of global MHWs increased by 34%, and the average duration increased by 17%, resulting in a 54% increase in the number of annual heatwave days worldwide [5]; The average area occupied by MHWs is from a thousand to a hundred thousand square kilometers, and the scale of regional extreme cases can reach from one million to ten million square kilometers. In 2024, the ocean heatwave in the Southwest Pacific extended by 40 million square kilometers, and the sea surface temperature reached the highest level in the history of this sea area [6]. By 2025, the surface water temperature of 71% of the world's seas will reach one of the top five highs in history. The heat content of the ocean at a depth of over 2,000 meters will set a record for the ninth consecutive year. The annual average sea surface temperature will be 0.5 degrees Celsius higher than the historical data from 1981 to 2010 [7].

2.3. MHWs as a driving force for HABs

With the intensification of climate change, heatwaves are becoming more frequent, which may lead to more HAB events. MHWs render a suitable environment for algal growth.

MHWs are periods when the sea surface temperature is much higher than normal for at least 5 days. Usually, the temperature can increase by about 1–3°C, and in extreme cases even up to around 5°C [8]. Studies suggest that global warming has contributed to a large part of MHW events in recent years [8]. These heatwaves are becoming more frequent and lasting longer, which creates more suitable conditions for harmful algae growth. First, higher temperature increases the growth rate of harmful algae, because many species grow best in warm water around 20–30°C. When temperature rises during a heatwave, it becomes closer to their optimal growth range, so their population can increase quickly. Second, MHWs strengthen water stratification, meaning the surface water becomes much warmer than deeper water and vertical mixing is reduced. This creates a more stable environment where algae can stay near the surface and continuously absorb sunlight for photosynthesis. Although nutrients may sink to deeper layers, some harmful algae have special adaptations to still access them. For example, dinoflagellates can move up and down using flagella, while cyanobacteria can control their buoyancy using gas vesicles. A real example is the 2021 MHW near Japan, after which a large HAB quickly developed and expanded, and scientists found temperature was one of the main drivers [9]. Overall, nutrient pollution provides the basic resources, while MHWs provide a favorable environment, making HABs more frequent, larger, and longer lasting.

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3. Global outbreak situation

Since 1970s, global-scale observations reported increase in the frequency of harmful agal blooms (HABs). Affected relatively few countries decades ago, HABs' expansion is currently most coastal countries are threatened, facing unprecedented frequency and scale of HAB events. Between 1985 and 2019, a total of 9503 data bases available on HAB events, known as Harmful Algae Event Database (HAEDAT), has been reported by UNESCO's 2021 Global HAB Status Report [10].

Despite its global distribution today, HABs are most severe in warm, nutrient-rich, slow-moving waterbodies adjacent to dense coastal populations. There is a reported increase in HABs events in regions including Central America or Caribbean, South America, Mediterranean, North Asia, etc [10].

3.1. Northeast Pacific Ocean

A typical case occurred along the coasts of northern California and Oregon in the Pacific Ocean. From 2014 to 2016, a persistent MHW occurred in the northeastern Pacific. The unusually high sea temperature created suitable conditions for the growth of the toxic diatom Pseudo-nitzschia australis. As a result, this species rapidly expanded northward and formed a large HAB. This alga can produce the neurotoxin domoic acid. During the 2015 MHW in the northeastern Pacific, a large HAB caused by Pseudo-nitzschia australis occurred along the west coast of the United States. This event became the largest recorded domoic acid event on the west coast of North America. Monitoring studies found that the concentration of particulate domoic acid in some areas reached up to 19,978 ng/L, indicating that large amounts of toxin were concentrated in algal cells. This level was much higher than the typical level in this region [11]. This case shows that MHWs can promote the spread of harmful algae and increase toxic bloom events by changing sea temperature and ecological conditions.

3.2. North Atlantic & North Pacific

In the North Atlantic and North Pacific oceans, long-term warming has been observed in many regions since the 1980s. A study used high-resolution sea surface temperature data from 1982 to 2016 to analyze HABs. The results showed that ocean warming significantly increased the growth rates and bloom duration of two toxic algae, Alexandrium fundyense and Dinophysis acuminata [12]. In many regions of the North Atlantic, especially between 40°N and 60°N, HABs have expanded and become more frequent. In some parts of the North Pacific, new bloom events have also appeared in recent years. The study concluded that sea surface temperature is a key factor controlling the distribution and intensity of HABs, and ocean warming is increasing risks to marine ecosystems and human health.

3.3. Baltic Sea

Another typical case occurred in the Baltic Sea region. Over the past several decades, the sea surface temperature of the Baltic Sea has shown a clear warming trend. Monitoring data show that from 1990 to 2022, sea surface temperature increased at a rate of about 0.58 °C per decade. This continuous warming makes summer sea temperatures higher and strengthens water stratification and warm conditions [13]. Such a warm and stable water structure provides favorable conditions for the large-scale growth of phytoplankton, especially cyanobacteria, and is associated with frequent HAB

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events. In some years, these blooms can cover large areas during summer and last for several weeks, which can affect water quality and marine ecosystems.

In addition, eutrophication is one of the main environmental problems in the Baltic Sea. Excessive inputs of nitrogen and phosphorus from human activities increase phytoplankton growth and lead to more frequent algal blooms [14]. Nutrient enrichment can also reduce water clarity and contribute to oxygen depletion in deeper waters, further increasing ecological stress in the region.

3.4. Arctic and subarctic oceans

Another case occurred in the Arctic and subarctic oceans. In recent years, ocean warming, and sea ice loss have changed the marine environment in this region. A study measured algal toxins in bowel samples collected from 205 bowhead whales over 19 years. These whales are filter feeders and can act as indicators of the whole food web. The results showed that algal toxins were widely present in the Arctic marine ecosystem [15]. The study also found that toxin levels were strongly related to environmental factors, including ocean heat flux, open water area, wind speed, and atmospheric pressure. Higher heat flux and larger open water areas were associated with higher toxin concentrations. This suggests that ocean warming and changing environmental conditions can increase the risk of HABs and toxin accumulation in Arctic food webs.

4. Conclusion

This paper talks about how MHWs (MHWs) affect HABs (HABs) and their big influence on marine ecosystems. After looking at many studies and cases from different sea areas, I found some key points. First, MHWs have gotten worse in recent years. Their frequency, intensity, and the area they cover are all increasing. These high-temperature events create perfect conditions for harmful algae to grow fast. Also, when MHWs happen, the seawater becomes more layered, and nutrients from deep water come up, giving algae more "food". Together with human-caused problems like water being too rich in nutrients, this makes HABs break out more often and spread to more places. Second, HABs brought by MHWs hurt marine ecosystems a lot. The toxins from algae kill many fish and shellfish, and these toxins can even get into the food chain and harm humans. Besides, when algae die, they use up lots of oxygen in the water, forming "dead zones" where no marine life can survive. The cases in the Northeast Pacific, Baltic Sea, and other sea areas all show these bad results. This paper sorts out the relationship between MHWs and HABs and their global situation. It hopes to help future researchers find better ways to warn about and stop HABs. But it's not perfect —for example, it doesn't study the long-term changes of MHWs and HABs deeply enough, and the coupling effects of multiple factors (like MHWs, ocean currents, and pollution) also need more research. These will be important things for us to study later.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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