Academic Journal of Psychology and Education (AJPE)
Volume.14, Number 4; April-2023;
ISSN: 2836-8150 | Impact Factor: 7.87
https://zapjournals.com/Journals/index.php/ajpe/index
Published By: Zendo Academic Publishing

EFFECTS OF CLIMATE CHANGE ON INLAND AND COASTAL WATER BODIES: A REVIEW OF HARMFUL ALGAL BLOOMS

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Article Info

Keywords: Climate change, harmful algal blooms, lake temperature, precipitation, runoff, lake ice.

Abstract

Climate change poses a significant threat to the occurrence of harmful algal blooms (HABs) in both inland and coastal waters. This review paper summarizes recent research into the impact of climate change on HABs, specifically examining the relationship between climate change and three lake parameters: lake temperature, precipitation and runoff, and lake ice. The paper highlights the ways in which warming temperatures and changing precipitation patterns are causing an increase in the prevalence and severity of HABs in lakes and reservoirs. The review identifies the mechanisms through which this occurs, including changes to lake stratification, and the extension of periods of hot surface water. The paper concludes that further research is necessary to achieve a better understanding of the impact of climate change on HABs and water quality, particularly with respect to predicting future changes to HABs in a warmer climate in both inland and coastal water bodies. The significance of this research lies in the importance of addressing HABs as a growing problem that threatens not only the ecology of the world's freshwater resources but also the health and well-being of humans and aquatic life.

Introduction:

The occurrence of harmful algal blooms (HABs) is an increasing problem affecting societies worldwide. In recent years, the impact of climate change on HABs has become a pressing concern, as the environmental changes brought about by climate change exacerbate the issue. Understanding the relationship between climate change and HABs has become a focus of extensive research, with studies examining the impact of climate change on three lake parameters: lake temperature, precipitation and runoff, and lake ice. This review paper aims to summarize the recent research in this area, providing researchers with a better understanding of the impact of climate change on HABs and water quality. The paper will highlight the key mechanisms through which climate change affects HAB occurrence and severity, and will discuss ways in which further research can be undertaken

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to achieve a more complete understanding of this complex issue. Finally, the paper will emphasize the importance of addressing HABs as a pressing environmental and public health issue that requires immediate attention.

1. Indirect Impacts of Climate Change on HABs

There are several lake mechanisms that are impacted due to climate change and can influence the formation of HABs. The following subsections review recent research on three such mechanisms, lake temperature, precipitation and runoff, and lake ice. The water temperature can be a contributing factor to blooms. As blooms usually form in summer or fall, an increase in the water temperature can provide favorable conditions for the formation of HABs. Changes in precipitation and runoff due to climate change can alter the nutrient loading and runoff, including those from cities and industrial buildings. Changes in ice coverage can impact lake water temperature due to increased evaporation (due to less ice coverage) and thus impact the occurrence of HABs. In the following section, the research work on climate change impact on these three parameters is presented.

1.1. Climate Change Impacts on Lake Temperature

One of the parameters affected by climate change is lake temperature (surface as well as deep water), and it is supposed to change the frequency of HABs and their severity in the future warmer climate. There are several research papers that investigated this parameter. One of the earlier research works in this area was from Coats et al. [7]. They investigated the effects of climate variability on the thermal structure of Lake Tahoe, California-Nevada, 1970–2002, and showed that by using the observed trends in the climatic forcing variables, it is possible to explain the observed changes in the lake. They reported an increase in the volume-weighted mean temperature of the lake at the rate of 0.015° yr^{-1} between 1970 and 2002. Another study by Austin and Colman [8] found an increase in the surface water temperature for Lake Superior for the summer (July–September) period by 2.5 °C. They found this increase from the study period of 1979–2006. They attributed this increase in the surface water temperature to decreasing ice cover. Other important findings from this research paper include an increase in the periods of lake warming in the summer months due to the earlier start of the stratified season.

For one of the hottest summers in Europe, Jöhnk et al. [9] showed that summer heatwaves elevate the formation of harmful cyanobacterial blooms. Using a coupled biological–physical model, which they developed, it was shown that, in order to consider the impact of climate change on the development of harmful cyanobacteria, it is important to consider wind speed and cloudiness. Studies that focus entirely on changes in temperature, ignoring these other parameters, may significantly underestimate the impact of climate change on bloom development.

Another important study on the impact of climate change on the mixing of Lake Tahoe was conducted by Sahoo et al. [10]. They reported that there is a possibility that Lake Tahoe could cease to mix to the bottom after about 2060, as shown in the Geophysical Fluid Dynamics Laboratory Model (GFDL) A2 future climate scenario. The lack of mixing raises the possibility of future algal blooms. The hypothesis used for these future HABs was, that if the lake fails to completely mix continuously for more than 6 years, it will result in the depletion of the hypolimnetic dissolved oxygen concentration to zero, resulting in the release of orthophosphate and ammonium (both biostimulatory) from the deep sediments.

For Lake Tahoe, using a modified stability index (SI), Sahoo et al. [11] analyzed the impacts of climate change on thermal properties, stability intensity, length of stratification, and deep mixing dynamics. They found a lengthening of the stratification season by approximately 24 days using the water temperature records from 1968 to 2014. They performed statistical downscaling from future climate data (Geophysical Fluid Dynamics Laboratory Model (GFDL) under two different greenhouse gas emission scenarios) to prepare the forces for the lake hydrodynamic model. The two different greenhouse gas emission scenarios used were: A2, in which greenhouse-gas emissions increase rapidly throughout the 21st century, and B1, in which emissions slow and then level off by the late 21st century. For the period 2014–2098 in the future climate, the projections in the length of stratification were found to be 38 days and 12 days, respectively, for A2 and B1 scenarios, and the projections in the annual average lake stability were 30.25 kg/m^2/decade and 8.66 kg/m^2/decade, for the same two scenarios, respectively.

Another notable research paper that analyzed several decades of high-frequency subsurface water temperature data for Lake Michigan is from Anderson et al. [12]. They showed that higher subsurface temperatures and the earlier onset of summer stratification were due to a shortened winter season. This shift can have a significant impact on the ecosystem of the world's surface freshwater, which may be attributed to the shifts in the thermal regimes of large lakes. Another recent research paper based on observational data from 1966 to 2015 by Dokulil et al. [13] quantified the changes in the annual maximum surface temperature for Ten European Lakes and also the duration above a critical temperature of 20 ˚C. They showed an average rate of increase of +0.58 ˚C per decade, similar to +0.42 ˚C per decade in the annual maximum air temperature for the same period. There were variations (per decade) in the increase in lake maximum temperature between east (and0.1 ˚C) and west (+1.9 ˚C). The number of days above 20 ˚C was also noticed to be two to six times longer. These changes would have a profound impact on the lake habitat. Water temperature is inversely related to dissolve oxygen, and this increase in water temperature can have a tremendous ecological impact. As shown by Kraemer et al. [14], lake temperature change can indirectly influence the habitat available for Lake Species. They studied the impact of climate change on the shifts in the lake habitat. Woolway et al. [15] investigated the changes in lake stratification phenology across the Northern Hemisphere using a lake-climate model ensemble and long-term observational data for the period from 1901 to 2099. They found an earlier start to the stratification at about 22.0 ± 7.0 days and a later end at 11.3 ± 4.7 days by the end of the century under a high greenhouse emission scenario. The increase in the stratification would increase lake deoxygenation, which would have effects on nutrient mineralization and phosphorus release from lake sediments. Climate change has an impact on lake heat waves, which causes the extension of periods of hot surface water. The extension of the temperature of surface water can have a severe impact on lake ecosystems. The expansion of the spatial extent of lake heatwaves was noticed in a recent study by Woolway et al. [16] over the largest group of freshwater lakes on Earth, the Laurentian Great Lakes. An increase in the surface water temperature due to the lengthening of the summer season causes the development of larger heat waves. In another work, Woolway et al. [17] showed that lake heatwaves tend to be longer and hotter by the end of the century. They used satellite data and numerical models for this study. Woolway et al. [18], in another study on lake heatwaves, demonstrated that due to human effects, the probability of occurrences of severe lake heatwaves would increase substantially with a larger portion of the severe lake heatwaves studied during the satellite data-taking period having an anthropogenic contribution. The occurrence of severe heatwaves is likely to be higher (3 to 25 times) in a warmer world (1.5 ˚C and 3.5 ˚C warmer temperatures, respectively) compared to the one where there is no anthropogenic influence.

1.2. Climate Change Impacts on Precipitation and Runoff

One of the earliest works related to climate change and its impact on precipitation was conducted by Barlage et al. [19]. They examined the impact of climate change and land-use changes on a regional watershed in southeastern lower Michigan. They used the output from the Hadley Coupled Climate Model (HadCM2) and land-use projections from the Southeastern Michigan Council of Government, two different time periods, 1994 to 2003 and 2090 to 2099, and two land-use scenarios, current, and future. They showed that changing climate and changing land use will increase the percentage of precipitation that results in surface runoff from 17.1% to 21.4%. The contribution from climate change was found to be 2.5%, and the increase due to land-use change was 1.6%. Burnett et al. [20], in their study on the effect of global warming on lake-effect snowfall, found an increasing trend in snowfall at lake-effect sites. They suggested that this increase was due to the result of warmer Great

Lakes surface waters and decreased ice coverage, both of which are consistent with the historically upward trend in Northern Hemispheric temperatures due to global warming. Sinha et al. [21] showed that eutrophication would increase in the 21st century due to precipitation changes. They showed that the contribution from climate-change-induced precipitation would increase total riverine nitrogen by 19 ± 14% within the continental US by the end of the century for a "business-as-usual" scenario. Wang et al. [22], in their study on the impact of climate change on the nutrients losses of two watersheds in the Great Lake region, showed that the total phosphorus loss through this century is projected to increase by 28% to 89% for the Green Lake watershed and 25% to 108% for the Walworth watershed mainly due to the combined effects of the increase in precipitation quantity, extreme storm events in intensity and frequency, and air temperature. Jeppesen et al. [23] found that there is a deep impact on phosphorus (P) loading from land to streams and also on lake eutrophication due to climate change. Their model results from Danish lakes showed an increase of 3.3 to 16.5% over the next one hundred years in the P loading-depending soil types and regions. Higher P concentrations were also seen in warm, arid lakes despite the reduced external loading due to increased evapotranspiration and reduced inflow, suggesting that in a future warmer climate, the critical loading of P can be used to indicate the good ecological state of lakes. There was also discussion on the adaptation measures, including improved P cycling in the northern temperate zone. Wrzezien et al. [24] used a global model (CCSM4) and dynamically downscaled it using the WRF (Weather Research and Forecast) model to study how the hydrologic cycle may change. They performed high spatial resolution WRF model simulations and estimated future climate conditions for

17 watersheds covering a 99% event magnitude. These watersheds are Columbia, Lower Colorado, Upper Colorado, the Upper Missouri/Yellowstone, and 12 basins draining to the western slope of the Sierra Nevada in California. They compared the historical period (1996–2005) with the mid-century (2041–2050) and the end of the century (2091–2100), The WRF/CCSM simulations projected a shift in the peaks of the streamflow for most basins in springtime. The peaks are projected to be earlier in this season. Lower Colorado watersheds were expected to experience more extreme wet days, but for Upper Colorado, the daily runoff is projected to decrease by over 30%. For northern and central Sierra Nevada, a substantial increase in the extreme runoff is projected, with the possibility of high-flow events being doubled for some basins. Zhai et al. [25] used a hydrological model (Variable Infiltration Capacity [VIC]) to differentiate hydrological impacts between two warming scenarios of 1.5 ˚C and 2 ˚C. The VIC model is forced with a representative ensemble of four global circulation models (GCMs) from the latest climate projections. This study provided a comprehensive assessment across several regions of the world and found that annual runoff is projected to increase more under a 2 ˚C change than 1.5 ˚C. An important aspect of the work was to study the impacts on population and overall gross domestic product (GDP). They found that the societal impacts on main countries in Asia are mainly associated with floods. Zakizadeh et al. [26] used a statistical downscaling model (SDSM) in their study and predicted the period from 2006 to 2100. For this work, they used another hydrological model, which is widely used, viz. the Soil and Water Assessment Tool (SWAT) model, and simulated the effects of climate change on the hydrological conditions in the Darabad watershed. They showed that under different RCP scenarios, RCP 2.6, RCP 4.5, and RCP 8.5, the surface flow and runoff are increased to 0.43, 0.44, and 0.45 m^3/s compared to the observation period (1970–2010), where this value is 0.29 m^3/s.

1.3. Climate Change Impact on Lake Ice

Another mechanism that can have an impact on the frequency, formation, or toxicity of HABs is lake ice coverage. Variability in the winter climate may sometime be associated with lake ice [27]. Ice coverage is also considered to be important for lake and land ecosystems [28]. The reduction in ice due to climate change will result in the loss of important services for wildlife. It will also impact the people living in the neighboring regions. In this direction, Sharma et al. [29] analyzed observations for two lakes to understand climate-related changes: (a) ice freeze dates (1443–2014) for Lake Suwa, Japan, and (b) ice breakup dates (1693–2013) for the Torne River, Finland. For Suwa, Japan, they found a shift towards later ice formation. For Torne, they found earlier spring melting. Some of the other findings include (a) increasing frequencies of years with warm extremes, (b) changing inter-annual variability, (c) waning of dominant inter-decadal quasi-periodic dynamics, and (d) stronger correlations between ice seasonality and atmospheric CO_2 concentration and air temperature after the start of the Industrial Revolution. Sharma et al. [30], in another study, found that a loss of lake ice will occur within the next generation. Using observations from 513 lakes around the Northern Hemisphere, they identified lakes that are vulnerable to ice-free winters. According to their estimate, there is going to be an approximately 2-fold and 15-fold increase in the number of lakes with intermittent ice coverage at 2 and 8 ˚C, respectively, which would impact between 394 and 656 million people. Another work in the direction of climate change and lake ice coverage was from Imrit and Sharma [31]. In their work on the contribution of climate change to faster rates of loss of lake ice around the Northern Hemisphere, they showed that ice-on days would be shifted, and it would be 11 days later per century. Similarly, ice-off is 9 days earlier per century. These numbers indicate a total reduction of about 20 days per century. Furthermore, they showed that local air temperature explains the most variation in ice phenology, followed by progressive climate change and teleconnection patterns. Campbell et al. [32] found in their work over Lake George, NY, that the average duration of complete ice cover has reduced by 6 days for the period beyond 1990 compared to the period from 1912 to 1990. A modeling work using five lake models was conducted by Grant et al. [33]. Some of the findings from their work for high-emission scenario RCP 8.5 by the end of the century include (a) an increase in the annual mean lake temperatures and (b) a decrease in ice coverage. They showed that in southern, temperate latitudes in North America and in temperate latitudes across Eurasia, lakes will warm by about +4–5 ˚C by 2070–2099 relative to 1971–2000. In many boreal zones, the June–July–August Lake temperature warming exceeds the global mean surface air temperature warming by a factor of 1.5–2.0. This increase in lake temperature was attributed to a high climate sensitivity for these lakes associated with the following, (a) polar amplification of atmospheric warming and (b) local amplification due to decreased ice coverage and local stratification.

2. Climate Change and HABs

Due to the complexity of biogeochemical–climate interactions for different HAB types and locations [34], there are still large uncertainties about the precise linkages between climate change and specific HABs. Glibert et al. [35] discussed the status, advances, and challenges in the direction of HABs modeling and eutrophication. They mentioned the importance of longer time scales for planning purposes so as to prevent HAB events and mitigate their impacts. Apart from that, there are many causes for which environmental drivers of HABs are not fully understood [34,36]. In one of the recent works, Treinish et al. [37] presented results investigating atmospheric drivers from the perspective of unusually warm weather and calm winds for transient HABs in a medium-sized oligotrophic lake that occurred in early November 2020. Even though the conditions necessary for the formation of HABs are described in the literature [38], these are not sufficient conditions for the occurrence of HAB events. As far as recorded observations of HABs are concerned, there is also a miss-match between observed HAB numbers and recorded toxicity. The differences in some cases are attributed to the production of biotoxin by different phytoplankton species of the same genus, toxic and non-toxic strains within a species [39] or the environmental control (temperature, nutrient availability) of biotoxin production. There is also a possibility of a mismatch between the location where HABs are observed and the environmental drivers, which could be related to the transportation of HBAs from unobserved to observed locations [40]. There are only a few studies that exist in the direction of providing linkages between climate and HABs. On top of that, there are not many studies that have tried to include epidemiological information on HAB-related illnesses [41]. Moore et al. 2008 provided a synopsis of knowledge of climate impacts on HABs and related health impacts. They mentioned the need for long-term daily observations of physical, chemical, and biotic properties, which are continuous and co-located. Wong et al. [42] developed a simple model for the forecast of coastal HABs. They also stressed the need for observations of surface winds and solar radiation, phytoplankton species and concentration, nutrient and water chemistry profiles (CO_2 and O_2), temperature and salinity profiles, and toxins. These observations can be integrated into future modeling frameworks, and they can also be used for the verifications of model output. In one of the earlier research papers, Hallegraeff [36] reviewed climate change and HABs and mentioned that this aspect of HAB research and policy is in its infancy, with only a few publications focusing on single environmental factors (e.g., CO_2, temperature increase, stratification), single biological properties (photosynthesis, toxicity, nutrient uptake), or individual species or strains. Hallegraeff [36] highlighted that due to climate change, some species of harmful algae might become more successful in areas that are impacted by climate change compared to others which may diminish. This is due to the land runoff, water column stratification, and other parameters. In this review paper, he also mentioned that only a few long-term records exist of algal blooms at any single locality. As required for any climate change study, for studies related to the connection of HABs and climate change, a long record of data sets is required. Anderson [43] presented a perspective on HABs in a changing world. From this point of view, he looked several decades into the future, envisioning how these bloom phenomena would be affected globally. Another focus was to understand the challenges that the HAB research and management community will need to address.

Ralston and Moore [44] presented a comprehensive review assessing harmful algal bloom (HAB) modeling in the context of climate change. They reviewed both physical as well as statistical modeling methodologies that are currently being used, along with approaches for representing climate processes and time scales of HAB model projections. In the direction of a process-based model, they presented several recommendations, namely, explicitly representing key physical and biological factors in HAB development, including evaluating HAB responses to climate change in the context of the broader ecosystem; using ensemble approaches and scenario planning to quantify and convey model uncertainty; downscaling methods to downscale global climate models (because of the coarse spatial horizontal model resolution) to the coastal regions that are most impacted by HABs. The role of long-term observations in evaluating HAB models is also critical for assessing long-term trends associated with climate change. Hallegraeff et al. [45], in their study related to the global increase in algal blooms, attributed the reported increase in harmful algae events to the intensified monitoring efforts associated with increased aquaculture production. They mentioned that there is no empirical support for broad statements regarding increasing global trends. They suggested that there is a need to understand these trends at a regional scale and also for more specific species.

3. Discussion and Conclusions

This paper presents a literature review of the recent research on climate change impact studies on harmful algal blooms and discusses this challenging problem. This review is divided into indirect impact viz. climate change impact on lake temperature, lake ice coverage, precipitation and runoff, and the direct impact of climate change on HABs
(Table 1).

Table 1. Summary of cited research papers and main conclusions.

Climate Change Impact On-	Cited Research Papers	Combined Key Conclusions from the Cited Research Papers

Lake Temperature	Coats et al. (2006) Austin and Coleman (2007) Jöhnk et al. (2008) Sahoo et al. (2013a) Sahoo et al. (2015) Anderson et al. (2021) Dokuli et al. (2021) Kraemer et al. (2021) Woolway et al. (2021) Woolway et al. (2021b) Woolway et al. (2022)	1. 2. 3. 4.	Surface water temperatures of specific lakes are increasing. Increase in subsurface water temperature as well as shortened winter season. Climate change impacts lake heat waves which cause the extension of periods of hot lake surface water. Lakes are becoming more stratified in future climate. Some research works reported lengthening of the stratification season.
Precipitation and Runoff	Barlage et al. (2002) Burnett et al. (2003) Sinha et al. (2017) Wang et al. (2018) Jeppesen et al. (2009) Wrzezien et al. (2020) Zhai et al. (2020) Zakizadeh et al. (2021)	1. 2. 3. 4.	Generally, there is an increase in precipitation and runoff, which can lead to more nutrient loading in future climate. Some watersheds show an increase in the runoff, whereas some of the watersheds show a decrease in the runoff when historical period is compared to the mid and end of the century. An increase in the observed lake effect snowfall under global warming. An increase in total phosphorus loss through this century due to climate change.
Lake ice	Magnuson and Lathrop (2014) Sharma et al. (2016) Sharma et al. (2019) Imrit and Sharma (2021) Campbell et al. (2020) Grant et al. (2021)	1. 2. 3.	Generally, there is a reduction in ice duration due to various factors, including lake temperature. Decrease in ice-cover by the end of the century under high emission RCP8.4 scenario. Ice-on days are going to be delayed, whereas ice-off is going to be early.
Harmful Algal Blooms	Wells et al. (2015) Glibert et al. (2010) Hallegraeff, (2010) Raine, (2014) Treinish et al. (2020) Trainer et al. (2012) Anderson et al. (2019) Moore et al. (2008) Wong et al. (2007) Ralston and Moore (2020) Anderson (2012) Hallegraeff et al. (2021)	1. 2. 3.	Uncertainties in the linkage of climate change and HABs. Need for long-term continuous observations of physical, chemical, and biotic properties to study the impact of climate change on HABs. Modeling pathways include ensemble approaches and scenario planning.

The research papers on the indirect impact of climate change examine the mechanisms that can affect lake ecology, whereas the direct impact summarizes the research papers on climate change's effect on HABs. Furthermore, it would be useful to refer to the crossreferences within the cited papers to understand the current state of knowledge on the subject of the impact of climate change on specific mechanisms. It would also help to provide a direction towards formulating future research to understand better how climate change will affect HABs.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Not Applicable.

Acknowledgments: The author would like to thank C.M. Kishtawal, Space Applications Center, Ahmedabad, India, for his valuable comments. I would like to thank the anonymous reviewers for their comments which has improved the manuscript.

Conflicts of Interest: The author declares no conflict of interest.

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