The Impact of Climate Change on Lake Color

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Abstract: Climate change's impact on lake color is a complex and great phenomenon that significantly influences the health and dynamics of water ecosystems. This review delves into the intricate relationship between climate change and changes in lake color, uncovering the underlying mechanisms driving these transformations and their broader implications. Factors associated with global warming, such as increasing temperatures, precipitation patterns, and shifting weather dynamics, directly or indirectly affect variables like nutrient input, algal bloom growth, and water clarity. Consequently, these factors ultimately shape the distinct colors observed in lakes worldwide. From green algae blooms to turbidity caused by glacial meltwater runoff, various elements contribute to alterations in lake coloration while reflecting the role played by environmental succession processes. This review paper comprehensively explains the complex interaction between climate change and lake color from climatology's perspective as well as hydrology's and ecology's perspectives. Furthermore, it emphasizes proactive measures aimed at mitigating adverse effects on freshwater ecosystems.

1 INTRODUCTION

Lake color, often taken for granted as simply a picturesque aspect of nature, holds far greater significance in the context of the changing climate. Lakes are important indicators of the health and dynamics of aquatic ecosystems, reflecting a delicate balance of environmental factors. However, with the looming threat of global warming and climate change, the hues of these water bodies are undergoing profound transformations, signaling potential disruptions to their ecological equilibrium. This shift in lake color is not merely an aesthetic alteration but rather a harbinger of underlying environmental upheavals that demand attention and action.

Climate change exacerbates global warming primarily through the emission of greenhouse gases from human activities. The Earth warms due to the greenhouse effect caused by these gases retaining heat in the atmosphere. The role of climate changes in the lake's color change remains unknown, although recent studies indicated that the climate, spatial distribution, and land cover contribute to the lake's color change. Elevated temperatures alter precipitation patterns (Oleksy et al., 2022), leading to fluctuations in nutrient and sediment inputs to lakes (Gardner et al., 2021). This nutrient influx can fuel algal blooms, altering the water's color to hues of green or brown (Leech et al., 2018). Moreover, higher temperatures accelerate chemical and biological processes within lakes, potentially affecting the composition of dissolved organic matter and the proliferation of phytoplankton, both of which influence lake color. Thus, while not directly instigating color changes, global warming indirectly influences lake color through its broader effects on climate and environmental dynamics. The color of summer lakes exhibits five distinct types of seasonality, which can be attributed to well-documented patterns of phytoplankton succession (Topp et al., 2021). The lakes' characteristics and surrounding environments are associated with the frequency at which transitions occur between these categories. Lakes situated in regions characterized by significant interannual climate fluctuations and variations in population density within their catchments tend to display lower stability compared to lakes with high inflow rates and minimal seasonal surface area variation.

Algal blooms caused by global warming can significantly impact the transparency and color of lakes. Algae blooms often lead to turbidity in the water because a large number of algae cells and the organic matter produced by the algae are suspended in the water, blocking the penetration of light. This phenomenon can make the water less transparent.

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Global warming accelerates the growth of phytoplankton and stimulates a general increase in algal blooms. Most algal blooms observed in freshwater lakes exhibit a green coloration, effectively covering the water surface. Consequently, lakes experiencing algal blooms often appear green on their surfaces. Notably, between 2000 and 2010, there was a significant rise in the occurrence of these blooms worldwide, with a median bloom occurrence value showing an increase of 44% (Hou et al., 2022). Algae such as cyanobacteria also sometimes produce toxins that cause the water to appear green, brown, or red (Leech et al., 2018). This situation is made worse because the toxins can be harmful to aquatic life and human health.

Changes in temperature can impact the lake's coloration, as rising temperatures increase dissolved organic matter (DOM) concentrations in soil, and increased precipitation leads to greater soil erosion and runoff, transporting more nutrients like nitrogen and phosphorus into the lake (Leech et al., 2018). These nutrients are essential for algae and other aquatic plant growth, leading to algal blooms and overgrowth of aquatic plants that absorb more sunlight and nutrients, causing the water to become cloudy with varying colors. Additionally, human agricultural activities contribute to eutrophication by introducing large amounts of nutrients into lakes through fertilizers, pesticides, animal manure runoff, etc., resulting in changes in lake coloration.

Additionally, human agricultural activities can contribute to lake eutrophication by introducing significant nutrients into the water, changing the lake's color. The presence of agriculture near lakes is commonly associated with lake greening phenomena (Leech et al., 2018). The application of fertilizers, the use of pesticides, and the disposal of animal dung in agricultural operations may lead to an increase in nitrogen and phosphorus levels in aquatic habitats. These nutrients stimulate the growth of phytoplankton within the lake basin, leading to an increase in algae biomass that covers the surface of the water body. Lake eutrophication often manifests as a "greening" effect caused by variations in algal biomass and total phosphorus concentration (Leech et al., 2018), which directly influence changes in lake coloration due to alterations in water transparency and the formation of a green or blue-green layer composed of phytoplankton.

Understanding the intricate relationship between climate change and lake color is imperative in comprehending the broader repercussions of environmental shifts on aquatic systems. The motivation behind this research lies in the urgency to decipher how rising temperatures, precipitation, and altering weather patterns are influencing the optical properties of lakes worldwide. By delving into this phenomenon, we aim to shed light on the mechanisms driving changes in watercolor and assess their implications for water quality and ecological health. To achieve this, the review adopts a comprehensive research framework that integrates multidisciplinary perspectives from climatology, hydrology, and ecology. Through this interdisciplinary approach, we endeavor to unravel the complexities of climate-induced alterations in lake color and their cascading effects on freshwater ecosystems.

2 FACTORS INFLUENCING LAKE WATERCOLOR

Lake watercolor is influenced by various factors, including climate, geology, and vegetation cover, which interact across various scales to impact the nature and amounts of terrestrial materials entering the aquatic environment (Yang et al., 2022). Lakes often exhibit distinct colors that differ from nearby bodies of water, and while these colors are roughly similar visually from lake to lake, there is considerable variation. However, lakes with similar dominant wavelengths in color profiles often share comparable features.

2.1 Factors Influencing Blue Lake Coloration and Regional Variations

Variations in precipitation and climate significantly impact global glacier melt. Firstly, the rate at which glaciers melt is accelerated by climate change, primarily due to rising temperatures induced by global warming. Global warming triggers the melting of permafrost and glaciers, leading to a redistribution of precipitation worldwide. The increasing temperatures cause glaciers to melt more rapidly, resulting in an initial acceleration of river flow. However, if glaciers fail to reaccumulate, their contribution to river flow may gradually diminish or cease entirely as their size decreases over time, causing a prolonged reduction in river flows. Additionally, the increased melting of glaciers could lead to the formation of glacial lakes (Zhang et al., 2011). Moreover, snowfall plays a crucial role in determining glacier mass balance and precipitation patterns are vital for snow accumulation necessary for glacier formation. When snow and ice accumulate more than they melt or evaporate in alpine regions over time, it promotes gradual glacier formation; thus, an increase in precipitation fosters glacier development. Conversely, precipitation influences the rate at which glaciers melt insufficient precipitation can expedite melting while excessive amounts can augment glacier bulk and decelerate the melting process. Furthermore, surface reflectivity modulation caused by precipitation affects glacier melt (McGee, 2020). Thin layers of snow or ice formed on glaciers reflect sunlight and impede melting rates. Glacial retreats are intensified by reduced snowfall and increased rainfall that collectively contribute to loss of glacial mass. Rising temperatures combined with changing patterns of precipitation result in extensive glacier retreats that heighten sea level rise risks while jeopardizing coastal ecosystems and livelihoods.

Blue lake coloration is largely determined by climatic and geomorphometric factors, which suggests that blue lakes typically coincide with regions of higher precipitation and cooler summer temperatures or are deeper lakes situated at higher elevations (Yang et al., 2022). Cooler summer temperatures below 19°C are associated with a higher prevalence of blue lakes, indicating a reduced likelihood of algal growth and clearer water. Moreover, the presence of winter ice cover is associated with lower summer temperatures, thereby increasing the likelihood of lakes in these regions being characterized by a blue hue approximately twice as much. The depth of a lake plays a crucial role in the functioning of its ecosystem. Ice-covered lakes are experiencing a more rapid increase in temperature compared to ambient air temperatures, with the deepest ice-covered lakes exhibiting particularly accelerated warming rates (O'Reilly et al., 2015). Furthermore, deeper lakes consistently exhibit a higher likelihood of appearing blue when compared to shallower lakes. Projections indicate that the ongoing warming trend and potential loss of winter ice cover may result in fewer blue lakes, especially in regions characterized by higher levels of precipitation.

Typically, blue lakes are located in high-elevation, steep watersheds with little vegetation and colder yearly averages. These factors lead to a limited supply of terrestrial nutrients in the lake, which reduces productivity and decreases water clarity. Lake morphology and basin area heterogeneity can also influence lake coloration. For instance, even in cold regions (with an average annual temperature below 4.5°C), green/brown lakes may occur if they are shallow (with an average depth less than 2.5 m) and have a large drainage area (greater than 12.5 km^2)(Oleksy et al., 2022). This is because small, shallow lakes generally exhibit higher productivity levels than deep lakes.

A study showed a similar pattern of blue lake color, in which increased temperature and precipitation are the important factors of bluer lake color (Cao et al., 2023). However, the study indicated that warming and wetter climates are the key characteristics linked with deep and clear lakes becoming bluer (Cao et al., 2023), in contrast to Yang et al.'s finding that the bluer lake was usually found in wetter and colder settings. The dominant wavelength of a lake in the same region can vary significantly; a yellow or brown lake may be adjacent to a blue lake. These regional variations imply that other non-spatial factors might also contribute to lake color changes (Yang et al., 2022).

The differences in the study results could be explained by the multifactors that contributed to the change in the color of lake water. The lakes in eastern China, which are mostly cultivated and urban, are shallow, cloudy, and eutrophic, and their color is mainly green and yellow (Cao et al., 2023). The cold, high-altitude regions of northern China are affected by climate change, as melted glacial water flows into lakes and increases their size. At the same time, the increase in precipitation caused by climate change not only increases the flow rate of water but also increases the clarity and decreases the greening rate of lakes at cold and high altitudes due to the lack of vegetation cover in the watershed (Cao et al., 2023).

2.2 Seasonal Variation in Lake Color

Regional drivers caused the long-term seasonal change in lake color. In recent decades, lakes in the United States' western Pacific area have tended to decrease the dominant wavelength and become bluer in color (Topp et al., 2021 & Cao et al., 2023). A study that focused more on seasonal variations investigated the periodic seasonality of the lake color changes. Four separate phenological groups were identified based on the summer color phenological characteristics of over 26,000 lakes in the United States between 1984 and 2020 (Topp et al., 2021). The median dominant wavelength of spring greening lakes is significantly lower than that of other lake types. Spring greening appears green at the beginning of summer and gradually shifts towards the blue end of the spectrum during summer and fall. From May to August, the Summer greening lake turns green before returning to a blue hue in winter. Bimodal lakes have color distribution between blue and green on the spectrum, experiencing two distinct phases of color change yearly. Aseasonal lakes show no significant seasonal color patterns with their color distribution remaining in the green part of the spectrum (Topp et al., 2021).

2.3 Impact of Agricultural Activities and Lake Turbidity on Lake Color

This section discusses the influence of agricultural activities on lake turbidity and coloration, drawing parallels between the United States and eastern China. It highlights the role of land cover and land use patterns in altering lake ecosystems, with agriculture often associated with lake greening and wetlands linked to lake turbidity. Additionally, it examines the impact of agricultural runoff, particularly nitrogen and phosphorus fertilizers, in stimulating phytoplankton growth and contributing to lake color changes. Furthermore, the section explores meteorological factors, such as temperature and wind speed, and their influence on cyanobacteria blooms in Chinese lakes, emphasizing the intricate interplay between environmental variables and lake dynamics.

The United States exhibits a higher proportion of agricultural activities in its green and turbid lake watershed (Leech et al., 2018), mirroring the similar pattern observed in eastern China, where these watersheds are predominantly found around areas of agriculture or urbanization (Leech et al., 2018 & Cao et al., 2023). Despite geographical differences, the shared cultural environment contributes to the turbidity of lakes, resulting in their predominant green or brown appearance. The number of blue lakes in the continental United States fell between 2007 and 2012. while the number of turbid lakes increased. This change may be attributed to alterations in land cover and land use patterns surrounding the lakes. The widespread presence of agriculture in lake watersheds is typically associated with lake greening, while the prevalent existence of wetlands is often linked to lake turbidity. The increasing discharge of fertilizers, including phosphorus and nitrogen from farms, may act as a catalyst for the growth of phytoplankton, especially the blue-green algae that blanket the surface of lakes (Leech et al., 2018). The absence of dissolved oxygen in wetlands significantly hinders the breakdown of organic materials. As a result, adjacent lakes often receive higher organic matter inputs from wetlands, making the water a rich brown color.

Furthermore, it is believed that wind speed and temperature have a significant meteorological impact on cyanobacteria blooms in Chinese lakes. The study revealed that approximately 80% of cyanobacteria blooms occur in areas with calm waters, where wind speeds are below 3 m/s and temperatures exceed 16°C (Wang et al., 2023). Temperature exerts an impact on the enzymes within algae cells, facilitating their growth. Conversely, when wind speeds surpass 3 m/s, strong winds effectively hinder the accumulation of algae on the water's surface.

2.4 Effects of Turbidity on Planktonic Organisms and Radiation Absorption

Compared to blue and brown lakes, the biomass ratio of zooplankton to phytoplankton is smaller in green and turbid lakes (Leech et al., 2018). The increase in the turbid lake's color did not inhibit plankton growth. Although light attenuation is reduced due to increased turbidity (Olson et al., 2018). However, the mixing layer becomes lighter as the color increases, allowing the phytoplankton's photosynthetic cells to be still exposed to light in surface water. In green and turbid lakes, there is an average of 60% blue-green algae, which is a type of phytoplankton that forms matting on the lake's surface (Leech et al., 2018). Decreased zooplankton to phytoplankton biomass ratios may result from the presence of blue-green algae and elevated microcystin toxin concentrations in green and turbid lakes, thereby impeding zooplankton's access to food resources and reducing their ability to consume phytoplankton. However, blue and brown lakes have more algae that zooplankton can feed on. Zooplankton in these lakes may have more algae available for consumption, increasing their ability to consume phytoplankton, resulting in a higher biomass ratio of zooplankton to phytoplankton.

The consequence of glacier melting induced by global warming often results in turbid meltwater. Murky lakes, which are nourished by glaciers, can be found worldwide and significantly impact planktonic life. Glacial flour, referring to mineral-suspended particles, is consistently present in glacier-fed lakes. Glacial flour is formed when ice scrapes across bedrock, resulting in a fine powder composed of silt and clay-sized particles. Planktonic organisms are adversely affected by glacial flour due to its various characteristics. The abundance of glacial flour in the lake hinders planktonic species that rely on filter-digesting systems from obtaining food effectively. This hindrance arises from the lake ecosystem's overlapping sizes between organic and glacial particles. Furthermore, planktonic life may also consume a substantial concentration of glacial flour alongside organic particles as their source of nutrition. Consequently, significant levels of glacial flour can be found within the digestive tracts of planktonic animals, altering their ability to absorb organic matter while reducing their energy requirements for growth and reproduction (Sommaruga, 2015).

Turbidity has a major effect on radiation absorption and transmission, especially when it comes to light radiation. Over the visible spectrum and at UV wavelengths, it reduces light intensity. Moreover, turbidity influences the ability of attached algae to defend themselves against high levels of radiation. Turbidity, for example, can protect attached algae against the negative effects of light radiation, particularly UV radiation, by blocking light penetration. This occurrence reduces their exposure to light radiation and potentially mitigates damage to their photosystem. In lakes fed by glaciers where turbidity levels correlate with increased rates of light attenuation, this protective effect becomes notably apparent (Olson et al., 2018). Attached algae exhibit enhanced resistance to elevated levels of radiation in situations characterized by concentrated turbidity through regulating the absorption and dissipation of light. Consequently, in areas with high levels of radiation, turbidity serves as a transient defense mechanism for adherent algae (Nicolás and Balseiro, 2014).

3 CONCLUSION

The findings presented in this paper emphasize the significance of comprehending the correlation between climate change and lake color to elucidate broader patterns in freshwater ecosystems. In conclusion, climate change has a multifaceted impact on lake color due to the complex interplay of environmental factors. The rising temperatures and changing precipitation patterns driven by global warming have resulted in altered nutrient and sediment inputs to lakes, promoting algae blooms and modifying watercolor. Furthermore, human agricultural activities contribute significantly to the eutrophication phenomenon by introducing a substantial amount of nutrients into the lake, which further affects its coloration. Regional variations in lake color reflect the influence of diverse climatic, geological, and anthropogenic factors. Typically, blue lakes are associated with lower temperatures and nutrient levels; whereas green and turbid lakes primarily result from farmland runoff and wetland discharge. A comprehensive understanding of these intricate relationships between climate change and lake color is crucial for comprehending the broader impacts on freshwater ecosystems as well as guiding effective management strategies amidst ongoing environmental changes.

REFERENCES

Oleksy, I. A., Collins, S. M., Sillen, S. J., Topp, S. N., Austin, M., Hall, E. K., O'Reilly, C. M., Yang, X., & Ross, M. R. V., Heterogenous controls on lake color and trends across the high-elevation U.S. Rocky Mountain region. Environmental Research Letters, 17(10), 104041 (2022).

Gardner, J. R., Yang, X., Topp, S. N., Ross, M. R. V., Altenau, E. H., & Pavelsky, T. M., The Color of Rivers. Geophysical Research Letters, 48(1), (2021).

Leech, D. M., Pollard, A. I., Labou, S. G., & Hampton, S. E., Fewer blue lakes and more murky lakes across the continental U.S.: Implications for planktonic food webs. Limnology and Oceanography, 63(6), 2661–2680 (2018).

Topp, S. N., Pavelsky, T. M., Dugan, H. A., Yang, X., Gardner, J. R., & Richard, M., Shifting Patterns of Summer Lake Color Phenology in Over 26,000 US Lakes. Water Resources Research, 57(5), (2021).

Hou, X., Feng, L., Dai, Y., Hu, C., Gibson, L., Tang, J., Lee, Z., Wang, Y., Cai, X., Liu, J., Zheng, Y., & Zheng, C., Global mapping reveals increase in lacustrine algal blooms over the past decade. Nature Geoscience, 15(2), 130–134, (2022).

Yang, X., O'Reilly, C. M., Gardner, J. R., Ross, M. R. V., Topp, S. N., Wang, J., & Pavelsky, T. M., The Color of Earth's Lakes. Geophysical Research Letters, 49(18), (2022).

Zhang, M., Ren, Q., Wei, X., Wang, J., Yang, X., & Jiang, Z. Climate change, glacier melting and streamflow in the Niyang River Basin, Southeast Tibet, China. Ecohydrology, 4(2), 288–298, (2011).

McGee, D. Glacial–Interglacial Precipitation Changes. Annual Review of Marine Science, 12(1), 525–557, (2020).

O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J. D., McIntyre, P. B., Kraemer, B. M., Weyhenmeyer, G. A., Straile, D., Dong, B., Adrian, R., Allan, M. G., Anneville, O., Arvola, L., Austin, J., Bailey, J. L., & Baron, J. S. Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters, 42(24), (2015).

Cao, Z., Melack, J. M., Liu, M., Tiit Kutser, Duan, H., & Ma, R. Shifts, Trends, and Drivers of Lake Color Across China Since the 1980s. Geophysical Research Letters, 50(8), (2023).

Wang, Y., Feng, L., & Hou, X. Algal Blooms in Lakes in China Over the Past Two Decades: Patterns, Trends, and Drivers. Water Resources Research, 59(10), (2023).

Olson, M. H., Fischer, J. M., Williamson, C. E., Overholt, E. P., & Theodore, N. Landscape-scale regulators of water transparency in mountain lakes: implications of

projected glacial loss. Canadian Journal of Fisheries and Aquatic Sciences, 75(7), 1169–1176, (2018).
Sommaruga, R. When glaciers and ice sheets melt: consequences for planktonic organisms. Journal of Plankton Research, 37(3), 509–518, (2015).
Nicolás Alejandro Martyniuk, Modenutti, B., & Balseiro, E. Can increased glacial melting resulting from global change provide attached algae with transient protection against high irradiance? Freshwater Biology, 59(11), 2290–2302, (2014).

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