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Review

Challenge to Lake Ecosystems: Changes in Thermal Structure Triggered by Climate Change

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Abstract: Human activities, global warming, frequent extreme weather events, and changes in atmospheric composition affect the solar radiation reaching the Earth's surface, affect mass and heat transfer at the air–water interface, and induce oscillations in wind-driven internal waves. This leads to changes in the spatiotemporal characteristics of thermal stratification in lakes, altering lake circulation patterns and vertical mass transfer. However, thermal stratification structures are often overlooked. The intensification of lake thermal stratification due to warming may lead to increased release of bottom pollutants, spreading through the dynamic behavior of the thermocline to the epilimnion. Moreover, the increased heat storage is beneficial for the growth and development of certain phytoplankton, resulting in rapid transitions of the original steady state of lakes. Consequently, water quality deterioration, ecological degradation, and declining biodiversity may occur. Conventional surface water monitoring may not provide comprehensive, accurate, and timely assessments. Model simulations can better predict future thermal stratification behaviors, reducing financial burdens, providing more refined assessments, and thus preventing subsequent environmental issues.

Keywords: heat stratification; climate changing; lake ecosystem; thermocline models

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1. Introduction

Climate change, as indicated by the Sixth Assessment Report of the IPCC in 2023 [1], shows that the global mean surface temperature (GMST) for the period 2011–2020 was estimated to be 1.1 °C higher than that of 1850–1900 (with land at 1.59 °C and oceans at 0.88 °C), and is conservatively projected to rise to 1.5 °C by 2040. The intensification of warming will lead to uneven spatiotemporal distribution of water resources (increased extreme weather events [2], increased flood pressures [3], increased droughts [4], and increased frequency of transitions from floods to droughts [5]), declining biodiversity [6], threats to human health [7], agricultural impacts [8], and seasonal dynamics of microbial communities [9], all of which are expected to worsen with increasing warming levels [1], posing certain impacts on socio-economic aspects [10]. In response to the escalating risks of global warming, 'the Paris Agreement' [11] proposes to limit the increase in global average surface temperature to within 2 °C above pre-industrial levels, with efforts to keep it within 1.5 °C.

The primary driver of global warming is solar radiation, with latitude, altitude, and season determining the amount of solar radiation at the top of the atmosphere, and meteorological conditions affecting the solar radiation reaching the Earth's surface [12–14]. The average surface solar radiation is 185 W/m^2, and the average atmospheric thermal radiation is 342 W/m^2 [15]. Water vapor and CO_2 contribute 66% and 25%, respectively, to the greenhouse effect. The level of CO_2 in the atmosphere has risen from 278 ppm at the beginning of the industrial revolution to over 415 ppm today [16], The multi-year average atmospheric humidity is 6.52 g/kg [17].

Lakes and reservoirs are closely intertwined with human production and livelihoods, but they face vulnerabilities in water resource supply and algal blooms [18,19]. Natural lakes globally exceeding 10 hectares in area contain 181.9 $\times$ 10^3 km^3 of freshwater, accounting for 0.8% of the global non-frozen land water storage. Large artificial reservoirs, with a volume of 6.0 $\times$ 10^3 km^3, number over 21.2 million with an area exceeding 1 hectare. The total area of lakes exceeds 3.23 million square kilometers, representing 2.2% of the Earth's surface [20].

Due to the thermal expansion and contraction properties of water, changes in the external environment cause heat storage changes in lakes, leading to density variations and the formation of a temperature structure characterized by warmer upper layers and cooler lower layers under buoyancy forces. Strong seasonal thermal stratification divides lakes into epilimnion, metalimnion, and hypolimnion. The thermocline is where the vertical density gradient is maximal in the metalimnion [21] or where the temperature gradient is maximal within the water column [22,23]; some studies refer to the metalimnion as the thermocline [24,25]. Stratified lakes exhibit alternating periods of circulation and stratification throughout the annual cycle and are categorized, based on the frequency of water column overturn, into Polymictic, Dimictic, Monomictic, and Oligomictic types [26].

Climate change can alter the inherent stratification and vertical mixing mechanisms of lakes [24,27], which are closely related to the ecological and stratification patterns within lakes. Therefore, it is crucial to pay more attention to changes in large-scale thermodynamic environments and the impacts of extreme events on temperature and humidity [28]. However, the mechanisms of climate change affecting the thermal stratification structure of lakes are highly complex, and the prediction and assessment of potential risks brought about by changes in thermal stratification are not comprehensive enough. This study aims to identify the mechanisms of climate change affecting the thermal structure of lakes and demonstrate its impact on lake ecology.

2. Lake Thermal Stratification Structure

Most studies use temperature gradient thresholds to determine the thermal structure of lakes, often employing 0.2 °C/m as the criterion [24,29–32]. Some studies define the thermocline as the water layer where the second derivative of temperature with respect to depth is zero [33]; thermocline depth is defined as the depth from the upper part of the metalimnion to the surface [24], while in some studies, it is the distance from the thermocline to the water surface [33]. In this paper, we uniformly define the former as the mixed layer depth and the latter as the thermocline depth(as shown in Figure 1). The surface mixed layer is influenced directly by surface-driven factors such as wind and convective cooling [34]. As the thermocline is close to the layer of maximum density gradient (pycnocline) [35], many studies use density gradients [36] or the first moment of density [37,38] to measure the mixed layer. Brainerd and Gregg [39] argue that it is important to match the time scales of the mixing layer with the study process, so it is necessary to distinguish between the mixed layer and the mixing layer. The former is typically the top of the seasonal thermocline, representing the maximum depth reached by the mixing layer on daily or longer time scales, while the latter is usually characterized by small changes in temperature or density. The mixing layer is also referred to as the active mixing layer, with a depth much smaller than that of the thermocline [22]. In studies that prioritize turbulence, the active mixing layer is determined by turbulent kinetic energy and Thorpe displacements [40]. For seiches studies, where the water flow direction is opposite above and below the thermocline, zero velocity points and maximum velocity gradients can also serve as indicators of the thermocline [22]. Other thermal stratification indices include thermocline thickness, defined as the difference in height between the upper and lower layers of the metalimnion, and thermocline strength, defined as the ratio of temperature difference to height difference between the upper and lower layers of the metalimnion [41].

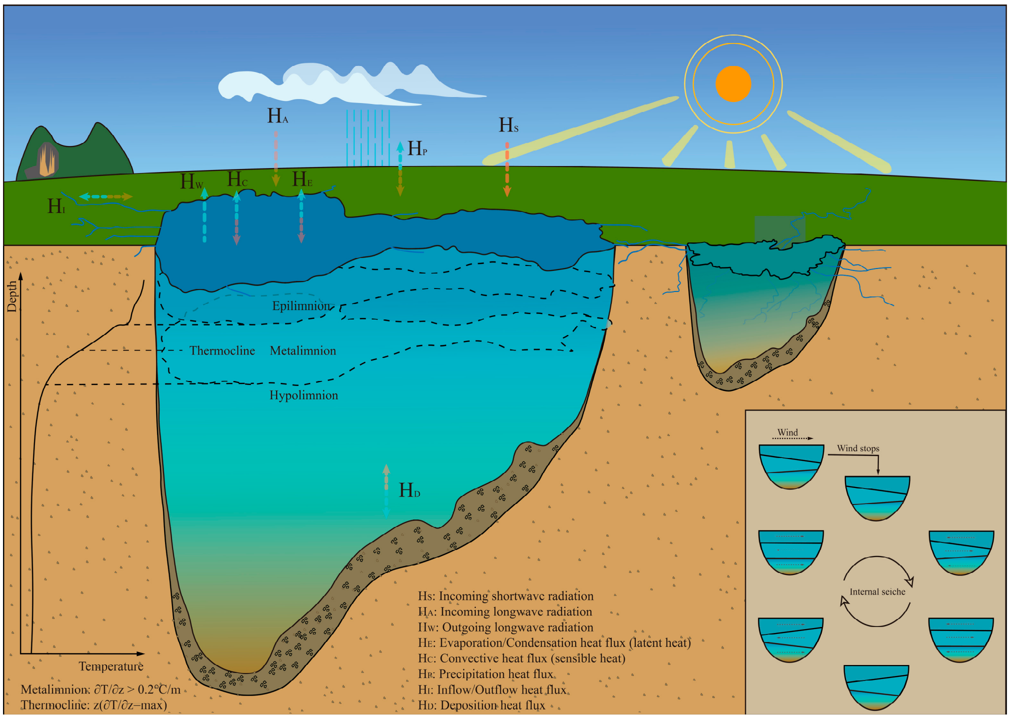

Figure 1. Schematic diagram of lake thermal stratification structure, heat budget, and internal waves.

3. The Impact of Climate Change on Thermal Stratification

By the year 2100, global warming is expected to increase the global average lake evaporation rate by 16% [42], leading to increased air humidity, which in turn promotes further warming [43]. Additionally, a 1 °C increase in temperature is projected to result in an annual loss of 2.28 Pg CO_2 equivalent in CH_4 and N_2O fluxes. The most direct impact of climate change stems from changes in air temperature, with near-surface air temperature being the primary influencing factor for lake surface water temperature (LSWT) [44]. For every 1 °C increase in lake surface air temperature, the lake surface equilibrium temperature rises by 0.7–0.8 °C [45]. With global warming, the average surface water temperature of lakes worldwide is increasing by 0.34 °C/decade [46]. The primary influencing factor for stratification is heat, with air temperature being significantly negatively correlated with thermocline depth [47]. With the increase in water temperature, stratification intensifies [48], leading to increased water column stability and a decrease in the frequency of lake mixing events [49]. The intensified stratification reduces the volume directly involved in heat exchange at the air–water interface, causing LSWT to increase more rapidly, sometimes exceeding air temperature [50], especially in deep lakes in cold climates [51], although water bodies in the thermal stratification period are more susceptible to mixing driven by cooling-induced convection as temperatures decrease [52].

Lake water storage is highly sensitive to climate change, with significant regional differences [49,53], and evaporation is the primary pathway for consuming available solar radiation on the Earth's surface [15], leading to increased atmospheric humidity and trapping more solar radiation. Studies have shown that a 1% increase in atmospheric relative humidity leads to a temperature rise in lakes of about 0.1 °C [45]. This positive feedback accelerates lake warming, alters lake thermal structure, and significantly impacts water levels, thereby affecting the thickness of the hypolimnion of lakes [54].

The largest component of the heat balance in lakes is typically solar radiation [55], which is influenced by seasonality, geographic location, and atmospheric composition [56,57]. Therefore, the indirect effects of atmospheric composition on lake thermal structure should not be overlooked. Similar to clouds, changes in atmospheric aerosols can alter global solar radiation [58–60]. However, aerosols generally counteract warming effects [61], and these changes do not simply add up as individual effects but rather have comprehensive effects [60]. In some regions, the impact of water vapor is greater than that of aerosols [62].

Climate change is expected to increase the frequency of windstorms [63,64], and human factors contribute to an increased likelihood of extreme weather events occurring simultaneously [65], which will enhance momentum transfer at the air–water interface of lakes and deepen the mixing layer. Precipitation resulting from these storms leads to dilution effects, influx of organic matter, and decreased turbidity, which can cause changes in stratification [66] and increased greenhouse gas emissions under flood conditions [67]. Extreme precipitation events can transport organic components between land and water via runoff [68,69], Increased runoff volume can limit the development of thermal stratification [70]. Additionally, extreme precipitation and occasional wind events are important factors affecting thermal stratification [71,72]. Wind stress counteracts buoyancy induced by density stratification, causing water to accumulate downwind and tilting the water body. If the thermocline is inclined, the shear force at the bottom of the mixing layer increases, potentially deepening it. Additionally, studies have shown that an increase in wind speed of 1 m/s can result in a decrease in lake temperature of 1 °C [45]. Wind can lead to an increase in shear force at the lower boundary of the metalimnion, enhancing the mixing and flux of important biogeochemical solutes [73], possibly even reaching sediments [74]. The depth of the winter thermocline is partially determined by wind-induced mixing [22], with each significant wind event reducing the thermocline [35]. Factors driving lake winds include thermal gradients between the lake center and shores [75] as well as pressure gradients [76]. The urban heat island effect can enhance lake–land temperature gradients, leading to more active thermal-driven local circulation [77]. Wind is strongly influenced by lake shape and large-scale wind direction [76]. Due to water's much greater density compared to air and the conservation of momentum but not energy at the air–water interface, only about 3–3.5% of wind energy is transferred to the water from the atmosphere, with 10% transferring to deeper water and the remaining dissipating as heat. Wind energy stored in waves or dissipated at the surface boundary does not reach the stratified water column, forming basin-scale internal movements. The mechanical energy reaching deep water flows is minimal (<1%), typically an order of magnitude lower than the surface [78,79], and varies 2–3 times among different lakes. Although the energy input from wind into the lake is proportionally low, compared to the lake warming rate of 0.34 °C/decade, the influence of wind on thermal structure is rapid and pronounced. Generally, wind determines the thickness of the surface layer [26], but once strong seasonal stratification is established, wind cannot substantially alter the vertical structure [78]. Wind can affect underwater light conditions [80] or generate internal waves that influence horizontal exchange in the hypolimnion of the lake [81], thereby affecting the morphology of the thermocline.

Although lake thermal structure responds to climate change [24], its response is more indicative of current climatic conditions rather than an accurate assessment of greenhouse gas exacerbation [82]. The stability of a lake's thermal structure can be measured using the indicators listed in Table 1; these indicators are widely adopted in the study of thermal stratification structure, but specific formulas may vary slightly among different studies. Other indicators, such as potential energy anomalies [83], can also be used as measures of stratification. Indicators for assessing the trend of global warming in lakes can include the frequency of deep ventilation [84]. Additional evaluation indicators may be necessary for assessing risks related to extreme climate impacts [85].

In general, climate change is making lake thermal structures more dynamic, and this process is accelerating. Specifically, global warming leads to intensified thermal stratification in lakes, prolonging its duration, while uneven spatial and temporal distribution of water and wind patterns brings about greater variability, with extreme weather events often lead to significant changes within a day.

Table 1. Thermal stratification stability indicators.

Indicator Name	Meaning
Brunt–Väisälä Buoyancy Frequency squared [78]	Measuring the local stability of density stratification
Richardson Number [78]	Assessing the relative strength of stability and shear flow
Schmidt Stability [86,87]	The mechanical work required to transform a stratified water column into an isothermal state
Wedderburn Number [88]	The likelihood of upwelling events under stratified conditions
Lake Number [89]	The ratio of moments related to the center of volume of the water body
Monin–Obukhov Length Scale [90]	The depth dominated by wind-induced turbulent mixing

4. How Thermal Stratification Affects Lake Ecology

4.1. The Impact of Thermal Stratification on Material Cycling and Energy Flow

The rate of thermal diffusion on a molecular level is low: heat transfer over a distance of 1 m in the vertical direction of the water body takes one month [26]. Although the flux generated by small-scale turbulent eddies, which sustain vertical mixing, is typically several orders of magnitude larger than molecular diffusion, most of the turbulent energy dissipates as heat. Therefore, thermal stratification impedes the exchange of substances and the transfer of energy between layers [91], affecting the distribution of substances in the water column and the settling of particles [92]. Additionally, thermal stratification guides mechanical energy horizontally [93], resulting in smaller differences in the horizontal direction compared to the vertical direction in lakes.

Oxygen consumption, denitrification, and hypoxic regeneration of available phosphorus are the most important processes affected by thermal stratification [81]. The stratification of dissolved oxygen generally follows the pattern of thermal stratification [94], because the primary consequence of lake stratification is the isolation of the hypolimnion [54], inhibiting vertical mass transfer [81], which makes the bottom layer prone to deoxygenation, leading to the formation of hypoxic zones [95,96]. Hypoxic events increase with depth [97], as warming of the water column not only reduces the solubility of O_2 [98] but also enhances the metabolism of organisms in the water [99], further lowering dissolved oxygen levels. Moreover, changes in the proportion of hypoxia are consistent with changes in thermal stratification stability [100]. Thermal stratification leads to a decrease in both oxygen content and the volume of oxygen-rich zones [101], and the relationship between thermal stratification and density stratification, oxygen stratification, and other chemical stratifications is complex and close [84,102–104]. Hypoxia caused by stratification promotes the release of substances such as methylmercury [105], phosphorus [106], and arsenic [107], leading to water acidification [108], while the disappearance of stratification resulting from mixing can redistribute substances such as polychlorinated biphenyls [109], resulting in complex environmental consequences.

In addition to thermal stratification, water temperature itself can affect certain water quality indicators [110]. Other factors such as lake morphology and the Earth's rotation also interact with thermal stratification to some extent. When the interface between the thermocline and the hypolimnion exceeds the ridges at the bottom of the lake, separating the water bodies on either side of the ridge, the reduced bottom flow favors the formation of hypoxic environments [81], enhances sediment–water interface absorption, and delays the release of nutrients upward [111]. Poincaré waves increase the oxygen flux entering the hypolimnion by two orders of magnitude higher than the average molecular flux [112].

As stratification intensifies, CO_2 emissions are likely to decrease [113]. Hypoxia caused by lake thermal stratification promotes methane release [114], while the oxic oligotrophic environment existing in stratification generates aerobic methane through the decomposition of methylphosphonic acid [115]. Thermal stratification enhances the potential for denitrification and nitrification processes related to N_2O production [116]. The relationship between greenhouse gas fluxes and thermal structure is complex and requires further in-depth research. Thermal stratification makes lake environmental factors fundamentally different from those of non-stratified periods/non-stratified lakes.

4.2. The Impact of Thermal Stratification on Aquatic Organisms

Due to the influence of thermal stratification on the vertical distribution of substances and energy in lakes, the biota in the water column highly depend on these environmental factors [99,117]. Moreover, they are typically influenced by multiple environmental factors [118], and each environmental factor does not correspond one-to-one with the thermal stratification structure, leading to high variability in microbial community structure. The variability in microbial composition alters the overall functional attributes of the community [119]. Organic matter and its biological utilization will respond to the presence of thermal stratification to a certain extent [120]. There are evident interface effects on bacterial community composition [119], but the stratification of organic matter does not necessarily align perfectly with thermal stratification [121].

Algae, as primary producers in lakes and the first trophic level of the food chain, exhibit high variability in spatiotemporal dynamics, directly contributing to the overall ecological variability of lakes. Traditional Chlα-TP theory [122] and temperature control theory [123,124] only explain part of this variability, and a deeper study of algal community structure is beneficial for understanding its dynamics.

The thermal structure has a significant impact on the structure of phytoplankton communities [110]. Some studies indicate that the enhancement of thermal stratification increases phytoplankton diversity through preclusion of dominance [125] and also increases phytoplankton biomass [126]. Artificial weakening of stratification can lead to a decrease in surface phytoplankton biomass [127]. However, other studies suggest that strengthening stratification can reduce the availability of nutrients for algae, thereby decreasing biomass [128]. This contradictory result seems to make the response of algae to thermal stratification more elusive. However, in reality, phytoplankton biomass is mainly related to light, nutrients, temperature, and current species composition. Although temperature is not decisive [105,129,130], it affects those determining factors by altering the stratification structure. Lake stratification causes phytoplankton to concentrate in the well-lit and warm surface layer, while oxygen-depleted environments at the bottom, internal waves, and lake circulation cause nutrients to migrate upward from the bottom layer. The intensity of thermal stratification is positively correlated with phytoplankton species diversity and resource utilization efficiency, while it is negatively correlated with zooplankton species diversity and resource utilization efficiency [125,126]. Becker et al. used the ratio of euphotic zone depth to mixing layer depth to measure light effectiveness [131]. However, due to changes in thermal stratification, the effectiveness of light varies greatly, reaching up to 100% in summer and only 30–36% in winter. The decrease in thermocline depth and water transparency reduces the vertical distribution of underwater light intensity, causing phytoplankton to migrate upward to seek more light, reducing the average residence depth of phytoplankton. This, in turn, leads to a separation between phytoplankton and zooplankton, resulting in reduced grazing pressure and an increased likelihood of water quality deterioration [47]. Additionally, increased water column stability favors buoyant cyanobacteria that can migrate rapidly [132]. Conversely, algal blooms can increase the available potential energy (APE) in the water body, thereby promoting stratification [133]. Furthermore, algal blooms can also enhance greenhouse gas emissions from the water body [134], further exacerbating warming.

The thermocline of large, stratified lakes continuously oscillates along the sloping lakebed, creating a spatially variable internal slope zone. These internal seiches result in rapid changes in temperature and dissolved oxygen, with fish responding primarily to temperature changes over most other stimuli. According to Charles C. Coutant's hypothesis of thermal niche–dissolved oxygen extrusion [135], the high variability in temperature and dissolved oxygen poses a threat to fish [97], subsequently affecting their distribution [135–137].

The changes in the physical and chemical properties of thermal stratification affect the distribution, abundance, and diversity of microorganisms, benthic organisms, and fish within it. The scale of these changes may range from annual to monthly [138] or even shorter periods [36,96].

4.3. The Overall Response of Lake Ecology

The response of lake thermal structures to climate has been verified in multiple regions worldwide [139–143], showing a complex interactive mechanism with the highly dependent lake ecology, as illustrated in Figure 2. This mechanism exhibits significant variations among lakes. Conducting whole-lake experiments to artificially control lake stratification is quite valuable for studying the overall dynamics of lakes [105]. The environmental variables encompassed by climate change synergistically impact lakes; the physical and chemical conditions of lakes also collectively affect carbon sequestration, thereby leading to changes in overall lake productivity [144], different species' behaviors result in significant ecological structural differences [145], and rapid environmental changes can lead to a transformation of the overall stability of lakes.

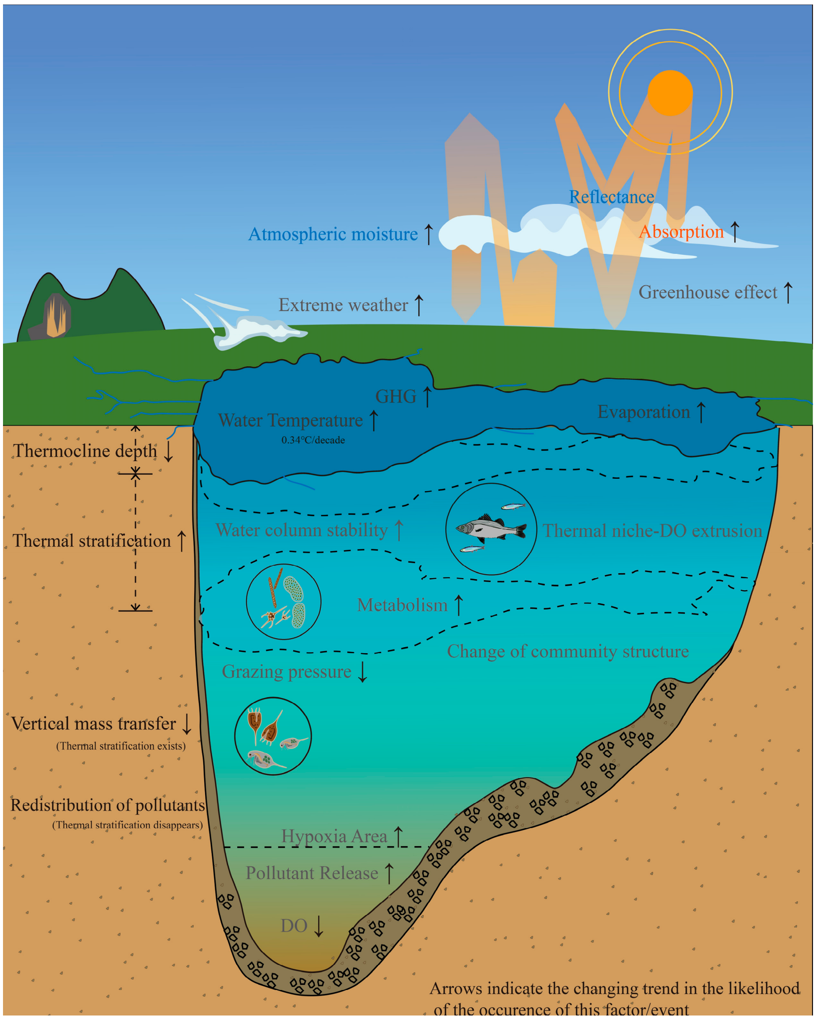

Figure 2. Lake ecosystem's holistic response mechanism to climate change.

Is there a significant correlation between lake water quality/ecology and thermal stratification structure, such that we can extract some empirical relationships from it? In other words, can we simply describe the consequences of lake thermal stratification as "getting better" or "getting worse"?

The increase in lake thermal gradients causes more particles to be trapped in the metalimnion [146], potentially leading to the enrichment of certain pollutants or nutrients in the upper layers. When this nutrient-rich environment overlaps with the well-lit and warm conditions of the surface, it is beneficial for increased productivity. This overlap is influenced not only by thermal stratification but also by factors such as declining water levels, which can increase this overlap [147]. If stratification is further intensified, causing a decrease in the overlap of these two environments, it is unfavorable for increasing productivity. Similarly, intensified stratification also makes it difficult for substances from the lake bottom to reach the surface. Therefore, the strengthening of thermal stratification does not always lead to serious consequences and, to some extent, is beneficial for surface water quality and ecology. Thus, we cannot simply consider the strengthening of thermal structure as negative for lakes, but it poses a risk for most polluted lakes affected by long-term human activities. There exists a critical point between these extremes, which varies from lake to lake.

5. Thermal Stratification Models

To study the impact of climate change on lakes and extract more universal patterns of change, it is best to utilize a richer dataset [19,35,66,148]. This requires comprehensive hydrological and water quality monitoring data. However, deploying too many devices can impose an economic burden. Adopting a space-for-time substitution approach may not necessarily be a good substitute for predicting the effects of climate change, as lakes at different altitudes or latitudes may not exhibit similar responses [45]. Therefore, it is necessary to abstract this mechanism using models. There have been many studies on thermal stratification models, with the primary heat flux modules typically calculated using the following formula [149,150] (the meanings of the variables are as shown in Figure 1), ensuring that the increase in lake heat is positive. However, not all modules are utilized in every study [151]. For instance, lakes without inflowing rivers do not require the H_I module, and the H_D module may be omitted due to the typically very small heat flux from sediments (≈0.1 [W/m^2]) [93]. Shortwave radiation contributes the most, and simulations of net longwave radiation flux are insensitive to wind. The calculation of latent and sensible heat fluxes is greatly influenced by wind data [152]. For lakes prone to ice formation, the situation becomes even more complex.

$$H_{net} = H_S + H_A + H_W + H_E + H_C + H_P + H_I + H_D, \ [\mathrm{W/m^2}] \tag{1}$$

Thermal stratification has been studied since 1948 when Munk and Anderson [153] began researching one-dimensional models of the thermocline due to its small horizontal differences and prominent vertical features. While two-dimensional and three-dimensional models provide more spatial and temporal details [154–156], they also incur higher computational costs [81]. The synchronous development of thermal stratification models in oceans and lakes has led to a high degree of similarity between basic formulas [157], and hence ocean models are often used in lake studies [95]. The fundamental principles of thermal stratification models are almost identical [158] and can be broadly categorized into finite difference models (eddy diffusion models [153,159], k-ε turbulence closure models [160]), models concerning the mixing layer [161,162], self-similarity theory models [163], and Bulk formulations models [164]. Adjusting parameters tailored to specific lakes can improve model results [165]. Different models have their own strengths and weaknesses depending on the research objectives [166], and selecting the appropriate model can address many practical issues [167]. Moreover, coupling various models can compensate for the shortcomings of individual models [32,168]. For example, current models mostly simplify heat transfer at the bottom of lakes. For lakes with geothermal energy, their thermal structure is more complex, requiring the use of more sophisticated models [169].

The predictive capability of models themselves is inherently limited, and complex environmental variables can cause significant interference. For instance, lake warming induced by elevated air temperatures can be reduced by 10% due to changes in other meteorological variables [45]. The influence of data on models is evident; although in situ measurements are crucial for models, they cannot be the sole input [78]. Moreover, the major data gap lies in the lack of monitoring of lake surface weather conditions, as differences in land-water physical properties will lead to variations in precipitation, wind, temperature, and other factors [170,171]. Investing more resources in monitoring the physical hydrology of lakes could lead to the development of a more reliable model. Low-frequency monitoring of lakes makes it challenging to understand the rich dynamics and variability of the lake area [22,97], necessitating improved temporal resolution for rapidly occurring events [39]. Parameter estimation values and their uncertainty converge as the number of measurements increases [148,152], and conventional monitoring lacks comprehensive data, such as groundwater monitoring data [170]. Combining satellite data [140,172] and field observations, with machine learning [49,173] can significantly enhance the capabilities of models.

6. Conclusions and Future Prospects

The undeniable trend of global warming is accompanied by an increase in greenhouse gas concentrations, leading to changes in atmospheric composition, rising temperatures, alterations in precipitation patterns, and increased frequency of extreme weather events (such as strong winds, rapid temperature changes, and intense precipitation). Anthropogenic climate forcing has contributed to the rise in global concurrent extreme weather events, enhancing the complexity of environmental factors. Based on existing knowledge, changes in the spatiotemporal patterns of factors such as air humidity, temperature, solar radiation, wind, precipitation, and runoff lead to changes in lake heat flux and internal wave oscillation patterns directly or indirectly, thereby altering the thermal structure of lakes. The diverse stratification of lakes, through its influence on the energy and biogeochemical cycles of lakes, transmits these changes to the entire lake ecosystem. In-depth research in this area holds immense potential for understanding the dynamic behavior of lake heat.

In most cases, the strengthening of lake stratification promotes the growth of phytoplankton, especially in nutrient-rich lakes, which increases the risk of algal blooms or leads to higher levels of certain pollutants being released. However, for certain pollutants, intensified stratification will confine them to the hypolimnion, necessitating a more cautious assessment of the effects of changes in thermal stratification structure.

Currently, research on thermal structure tends to focus on fundamental studies of small-scale turbulence or practical applications. Future research should aim to develop devices capable of monitoring sporadic and extreme mixing events, integrating simulations of small-scale turbulence with basin-scale hydrodynamic models. Against the backdrop of climate change profoundly altering stratification dynamics, basic knowledge of the spatiotemporal distribution of small-scale turbulence in lake stratification is crucial for predicting thermal stratification evolution. Predictions of lakes are often based on historical data and experiential judgments, while on-site monitoring typically focuses only on surface water. Even if there are monitoring efforts targeting the vertical profiles of lakes, they often provide data with low spatiotemporal accuracy due to cost considerations. However, thermal structure is highly correlated with lake water quality and ecology, and it is also highly influenced by meteorological conditions. Therefore, models using real-time meteorological data can rapidly assess thermal structures to prepare for sudden changes before they occur in lakes. Accurate prediction of atmospheric environmental elements is a prerequisite for the accurate simulation of thermocline models. However, the current lack of monitoring methods and inadequate monitoring accuracy make it difficult to fully grasp the variables in the environment. The lack of meteorological data is often the main obstacle limiting the in-depth study of lake thermal stratification, necessitating greater investment in obtaining high-precision meteorological data. Other research methods, such as stoichiometry and isotopes, can enrich our understanding of the mechanisms underlying lake ecosystem responses. Of course, we can also conduct whole-lake manipulation experiments in smaller lakes to study overall changes and validate the entire mechanism. Based on the understanding that "we can derive empirical models/mechanisms from the response of lake ecosystems to climate", the current application of machine learning in lake simulations holds great potential. Altitude, latitude and longitude, depth, and the degree of human activity in the watershed can be distilled into relatively reliable empirical relationships. The distinct mechanisms between large and small lakes make it difficult to extrapolate research findings from small lakes to large ones and the converse is also true. Therefore, it seems that studying in combination with models tailored to local conditions is a better approach.

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