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# 气候变化诱导水体富营养化研究进展

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**摘要:** 对大气 $CO_2$ 浓度升高及气候变化诱发水体富营养化的驱动机制进行了综述。$CO_2$ 浓度升高促进浮游植物大量增殖;水温升高引起水体分层现象加剧,底层缺氧更加严重,沉积物营养盐释放加剧,促进浮游藻类的生长;降水变率、强降水发生的概率增加,会加剧土壤中氮的流失,导致水体营养盐浓度增加;太阳辐射减弱会导致水下光照减少,加速沉水植物的衰亡,促进浮游植物的生长,进一步恶化水下光照环境;风速降低会延长水体分层时间,提高水体稳定性,造成底层缺氧,加大沉积物营养盐的释放;台风等热带气旋引发的强风浪会促进水体中氮、磷等营养盐释放,有利于蓝藻细胞团增大,获得更大的浮力,带来的暴雨还会将周围营养盐携带入水体,促进藻类生长。以上这些气候变化主要特征还会相互作用,加大水体富营养化的发生风险,继而对整个水生生态系统产生一系列间接影响。指出了未来研究的重点:气候变化对水生生态系统的影响;气候变化主要特征之间系统相互作用的机理;内外源污染与气候变化对水体富营养化的贡献率;水生生态系统应对气候变化的对策等。

**关键词:** 气候变化;$CO_2$ 浓度;水温升高;太阳辐射;降水变率

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**Abstract:** The driving mechanisms of atmospheric $CO_2$ concentration rise and climate change induced water eutrophication were reviewed. The increase of $CO_2$ concentration can promote the proliferation of phytoplankton. The increase of water temperature will aggravate the stratification of water body, make the bottom hypoxia more serious, intensify the release of sediment nutrients, and promote the growth of planktonic algae. The change of water ice age will be conducive to the change of algae population and structure. The increase of precipitation variability and the probability of heavy precipitation will aggravate the loss of nitrogen in soil and lead to the increase of nutrient concentration in water. The solar radiation weakening will lead to the reduction of underwater light, accelerate the decline and death of submerged plants, promote the growth of phytoplankton and further deteriorate the underwater light environment. The reduction of wind speed can prolong the stratification time of water body, improve the stability of water body, cause hypoxia at the bottom and increase the release of sediment nutrients. Strong winds and waves caused by tropical cyclones such as typhoons can promote the release of nutrients such as nitrogen and phosphorus in the water body, which is conducive to the increase of cyanobacteria cell clusters and greater buoyancy. The rainstorm will also bring the surrounding nutrients into the water body and promote the growth of algae. The above main characteristics of climate change will also interact to increase the risk of water eutrophication, and then have a series of indirect effects on the whole aquatic ecosystem. The key points of future research are pointed out, which include the impact of climate change on aquatic ecosystem, the interaction mechanism between the main characteristics of climate change and aquatic ecosystem, contribution rate of internal and external source pollution and climate change to water eutrophication, countermeasures of aquatic ecosystem to deal with climate change, etc.

**Key words:** climate change; $CO_2$ concentration; water temperature rise; solar radiation; precipitation variability

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水体富营养化是指湖泊、河流、水库等水体中植物生长所需的营养物质(通常是氮、磷)浓度过高引起的生物效应[1]。湖泊在自然条件下也会发生富营养化[2],但现在常说的富营养化是指人为富营养化,其形成的原因是氮、磷等营养盐过量排入水体。大气干湿沉降中的氮、磷等营养盐输入也是导致湖泊富营养化的重要原因之一[3]。一些湖泊发生富营养化的原因与气候变化密切相关,在天山天池,气温升高、降水格局改变和夏季风动力波动对富营养化进程有重要贡献[4]。对太湖的研究发现,1987—2009 年,随着气温升高、日照减少、全球辐射和风速的降低,蓝藻水华出现的时间更早、持续时间更长[5]。春季温度增加有利于蓝藻的光合作用和生长,快速而剧烈的升温过程加大蓝藻水华形成的可能[6]。因此,研究气候变化对水体富营养化的影响,梳理气候变化对水体富营养化的驱动机制,对于弄清水体富营养化的机理,探讨水生生态系统应对气候变化均具有重要的意义。

气候变化诱导富营养化在英文文献中多表述为“climate change-induced eutrophication”或“climate-induced eutrophication”,含义是由于 $CO_2$ 等温室气体过量排放引发全球气候变化,导致气温、降水、风速、辐射等变化,继而对水体理化性质、营养盐含量、浮游植物、水生植物等产生一系列变化,从而诱发或加剧水体富营养化的过程[4]。根据政府间气候变化委员会(IPCC)报告,历史上的气候变化主要是自然气候波动引起的,20 世纪以来气候变化主要由自然波动与人类活动共同作用,特别是 20 世纪 70 年代以来,主要由人类活动引起。全球气候变化主要表现为气温升高、降水变率增大、降水分布更不均匀,同时强降水频率增加,很多地区太阳总辐射有减弱趋势,风速趋于减缓等[7]。这些波动将造成水体物理和化学性质的改变,促进藻类增殖,最终加剧富营养化的过程。

## 1 $CO_2$ 浓度升高对富营养化的驱动机制

根据 2013 年 IPCC 报告,近 50 年全球气温的变化,主要是人类活动排放的温室气体造成的[8]。大气中温室气体尤其是 $CO_2$ 浓度明显增加,工业革命前大气中 $CO_2$ 体积百分数是 $280\times10^{-6}$,截至 2021 年 2 月,全球大气平均 $CO_2$ 体积百分数已经达到 $416.5\times10^{-6}$。$CO_2$ 溶解于水体时与水进行反应形成 $HCO_3^-$,对于浮游植物来说,$HCO_3^-$ 和 $CO_2$ 都是重要无机碳源。浮游植物还可以吸收大气中 $CO_2$ 进行光合作用[9-11],$CO_2$ 利用率的变化会影响浮游植物种群的演替和分布。在富营养化过程中,用于藻类光合作用的 $CO_2$ 来源有效性是一个重要的决定因素[12],当氮、磷营养盐比较充足时,$CO_2$ 可能成为藻类生长的限制因子[13](图 1)。大气中 $CO_2$ 浓度升高有助于浮游藻类生长,可以提高浮游植物群落的光合固碳量,促进蓝藻、淡水绿藻等藻类的光合作用

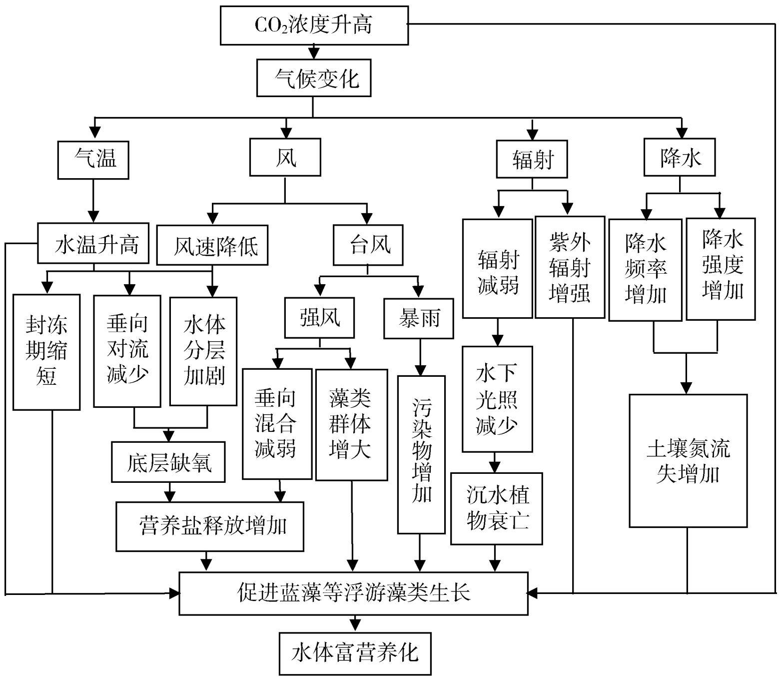


**图 1 气候变化诱发水体富营养化机制示意图**

**Fig. 1 Schematic diagram of water eutrophication mechanism induced by climate change**

与生长，使它们能够在富营养化条件下占主导地位[14]。因此，不断上升的 $CO_2$ 水平可能会加剧浮游植物的繁殖，突破碳限制导致水华暴发，特别在 pH 值低或中等且营养负荷较高的水域，这种情形更易发生。$CO_2$ 浓度增加对蓝藻的影响最为显著，蓝藻已经演化出一种非常有效的 $CO_2$ 浓缩机制，大气中 $CO_2$ 体积百分数升高将有利于蓝藻的生长[15]。目前，大气中 $CO_2$ 体积百分数已超过 $400\times10^{-6}$，据联合国成员国气候行动组织宣称，到 2100 年，若气温升高 4.0°C，大气中 $CO_2$ 体积百分数将达到 $800\times10^{-6}$，那时对水体浮游藻类的种群及结构的影响将会加剧[16]。$CO_2$ 浓度升高导致浮游植物大量繁殖，从而进一步诱发一系列相关问题，如水体缺氧和鱼类死亡，使水体浑浊度增加[17-18]，导致沉水植物持续减少，加剧富营养化的发生，水华暴发的频率可能更高[19-20]。

## 2 气候变化对水体富营养化的驱动机制

### 2.1 气温升高

全球海洋和陆地温度较工业革命前增加 0.89 ℃[5]，且有加速趋势[21]。随着气温升高，水温也随之升高[22-23]，尤其是水体表层升温更加显著，超过底层升温幅度[24]。1960—2000 年，欧洲西部的 Windermere 湖水体表层温度增加了 1.4 ℃；1950—1990 年，瑞士苏黎世湖平均水温以每 10 年 0.16 ℃的速率上升，大多数欧洲湖泊表层水温增长率为每 10 年 0.5 ~ 0.6 ℃，瑞典 Stensjön 湖更是高达每 10 年 1.6 ℃[25]；我国千岛湖地区 1980—2013 年平均气温升高 1.67 ℃，增幅为每 10 年 0.49 ℃[26]。

#### 2.1.1 水温升高增加富营养化发生概率

如图 1 所示，由于气温升高，水体温度也随之升高，引起水体分层周期延长、加剧[27]。例如，1947—1998 年，瑞士的苏黎世湖水体分层时间增加了 14 ~ 21 d；2003 年后，欧洲的莱茵河水体分层周期增加了 14 ~ 21 d[28]；芬兰一些湖泊水体分层周期延长了 30 ~ 60 d[29]。随着气候变化的持续，水体分层将更为严重，且持续时间将更长[30-31]。由于表层水体增温幅度超过底层，水体分层的加剧，将使水柱变得更为稳定，垂向对流减少，底层溶解氧（DO）浓度降低[32]。水温升高会减少大气中氧气进入水体，使水体 DO 浓度降低[33]，湖底附近 DO 会降得更低，甚至出现 DO 浓度为 0 的现象[34]。水温升高会增加水生有机体呼吸速率，进一步降低水体 DO 浓度[35]；而水体底层 DO 浓度降低，会促进水体沉积物中营养盐尤其是磷的释放，使水体营养盐浓度增加，促进水体浮游植物的生长和水体富营养化的形成[24]。

水温升高还会使水体结冰推迟，解冻提早，从而使整个水体冰封期缩短[36-37]。在俄罗斯的卡累利阿共和国的一些湖泊，1950—2009 年冰封期平均减少了 11 ~ 16 d[38]；1961—1990 年，瑞典北部一些湖泊冰封期减少了约 80 d[39]；从北欧到中欧，20 世纪 60 年代至 90 年代来水体解冻时间提前了约 30 d[40-41]。由于水体解冻提前，水体中藻类种群结构将会发生重大调整[42-43]，为一些较轻的浮游藻类生长创造了有利条件[44]，使其成为水体中的优势种[45-47]。在瑞典，自 20 世纪 90 年代开始，冬季变得更加温暖，水体解冻时间提前促进了春季浮游植物的生长，春季变暖导致夏季浮游植物生长提前，且生长期延长了至少 1 个月，一些对温度敏感的浮游植物（如蓝藻和绿藻）的春季和初夏生物量有所增加[48]。水温升高刺激水体浮游植物的生长，蓝藻暴发的风险将持续增加，富营养化发生概率也随之增高[49]。

#### 2.1.2 水温升高改变湖泊水生植物群落结构

气候变暖不仅使湖泊浮游植物种群结构发生变化，导致物种多样性下降[50]，还会改变水生植物分布深度及生长特征。水温与水生植物丰富度存在显著的正相关关系[51]，水温升高可能影响水生植物群落的物种组成、提高生产力、加快生命周期[52-53]。在较冷的水体中，水体较为清澈，透明度较高，以沉水植物为优势种，沉水植物可以从沉积物和水体中吸收养分，减少了浮游植物获取营养的机会[54]。一般而言，温度在浮游植物群落的组成和演替中起着重要作用[55-57]，全球变暖导致水温升高，水体变得较浑浊，绿藻和蓝藻等浮游藻类开始出现，浮游植物可能会取代沉水植物[58]。尤其在浅水型湖泊生态系统，水温升高可能会导致大型水生植物迅速丧失，随后浮游植物占优势[59]。高温有利于浮游植物密度的增加，尤其是蓝藻[60-61]。一旦浮游植物覆盖水面，降低了水下光照，水体可溶性磷酸盐及总氮的浓度都会因此升高，水生植物物种丰富度随之降低[62]。

### 2.2 降水变率

根据 IPCC 报告，20 世纪 30°N ~ 60°N 之间的陆地降水普遍增加，在 1951—2008 年，30°S ~ 60°S 的降水呈减少趋势[7]。除降水有变化外，气候变化也使得降水变率增大，已经观测到强降水事件大范围增加，甚至一些年降水量较少的地区也是如此。在欧洲和北美强降水发生频率显著增加，在美国，暖季降水增加最为显著；在欧洲，最显著的变化发生在寒冷季节[7]。气候变化导致降水频率、降水强度及暴雨发生频率均有所增加，使得地表径流加大，土壤侵

蚀随之加剧,大量地表径流从退化的陡坡和贫瘠的土壤流入水体,使更多有机负荷、营养盐进入水体,成为湖泊等水体外部养分输入的重要途径。沉积到湖泊沉积物中的养分逐渐成为内部释放源,在干旱季节,由于水量较少,水位急剧下降,导致水体营养盐浓度升高[5,63]。营养盐浓度增加有助于藻类暴发,大量的死亡藻类又沉积到沉积物中并成为内源性营养源的一部分[64-65]。在营养物浓度较低的水域,强降水导致湖泊外部营养盐负荷增加更加明显[25]。尤其在一些河口和沿海水域,来自河流径流的氮输入是富营养化的主要原因,随着气候变化问题将更为严重[66]。气温升高背景下强降雨事件增加,对蓝藻生长具有积极的影响[66]。意大利北部的马焦雷(Maggiore)湖自20世纪80年代后一直是一个贫营养化湖泊,但自2005年以来,马焦雷湖暴发了一系列蓝藻水华事件,可解释为对降水格局变化的响应,是气候诱导富营养化的一个重要迹象[67]。到21世纪末,受降水总量和极端降水量增加的影响,美国内陆河流的总氮负荷将增加;降水变化有可能加剧印度、中国和东南亚等地水体的富营养化[68]。

### 2.3 太阳辐射变化

#### 2.3.1 辐射减弱

光照是水生生态系统最主要的控制因素,也是沉水植物生长发育的必备环境因子[69-70]。只有在实际水深小于或等于光补偿深度的水域,沉水植物才能生长,水下光环境的恶化是导致大多数沉水植物消亡的重要原因[71]。水下光照强度受太阳辐射强度、水深、水体透明度等因素影响[72]。气溶胶颗粒可以通过吸收和散射太阳辐射来直接改变辐射平衡,从而减少到达地表的辐射量[73],由于气溶胶污染,到达中国东部的地表太阳辐射被削弱[74]。一旦地表获得的太阳辐射减弱,水下光照势必也随之减弱。光照不足的水体中,由于浮游藻类的快速繁殖进一步削减水下光照,沉水植物生长将受到抑制[75]。且浮游植物的增加,会减少大气中氧气进入水体,使得水下DO浓度进一步降低,沉积物会出现缺氧状态,使得水质恶化、富营养化过程加剧,水生生态系统陷入恶性循环[76]。

#### 2.3.2 紫外辐射增加

由于人类活动排放了大量消耗臭氧层物质(Ozone depleting substances, ODSs),导致大气平流层中的臭氧减少[77],进入地表的紫外辐射量大大增加。虽然在20世纪90年代后ODSs生产大幅减少,但直至现在并没有显著证据证实臭氧层正在恢复,全球很多地区平流层臭氧仍处于下降状态[78]。预计2040—2050年,紫外辐射强度将增加2%,南半球将达27%[79]。由于浮游植物对紫外辐射比较敏感,观测资料显示,从20世纪90年代开始全球浮游植物群落数量正逐步下降,紫外辐射的作用不可忽略[80-81]。与一般藻类相比,蓝藻为躲避高强度紫外辐射的伤害,演化了一套代谢和损伤修复机制,可抵御和修复紫外辐射的损伤[82-83]。在南美一些湖泊的研究却发现,UV-B辐射达到最强时,绿藻的种群密度增加,且叶绿素a浓度有所提高[84]。因此,地表紫外辐射增加可能增加蓝绿藻扩张的机会,对其他藻类生长产生抑制作用。

### 2.4 风的变化

#### 2.4.1 风速减弱

风在水生生态系统功能中起至关重要的作用,风对浮游植物的生长有重大影响,有时甚至起主导作用[85],如蓝细菌菌落的垂直运动和水平迁移均受风引起的水动力控制[86]。在大型浅水型湖泊中,风对浮游植物的影响可分为3个部分:对浮游植物的直接干扰影响,如对养分吸收效率和光竞争的影响;对浮游植物的间接影响,如风引起的内部养分释放;对浮游植物运输的影响,包括垂直迁移和水平漂移[87]。风速减弱可加剧富营养化的发生,因为风引起的扰动不仅影响沉积物-水界面,还强烈影响深水湖泊中的热量、氧气和养分分层[88]。风速减弱导致分层动力学发生了重大变化,不仅抑制了直接垂直混合的向下渗透,从而影响水体底层温度,还影响浮游植物的生长、养分消耗过程,以及水-沉积物界面营养盐沉积与释放过程[89]。水体分层持续时间可能从数小时到数月不等,甚至在某些湖泊中可能是永久的[89]。风在水体翻转中起重要作用,风速减弱将使水体更加稳定,分层将会更剧烈,分层时间会随之延长[90]。在爱沙尼亚的Võrtsjärv湖(平均水深2.7 m),如果年平均风速以1 m/s降低,湖泊分层天数以3.16 d/a的速率增加[89],如果风速继续降低,Võrtsjärv湖可能会分层更长的时间,从而对生态系统造成重大影响[89]。长期分层使水体底层缺氧,加速沉积物营养盐的释放,加大水体富营养化发生概率[91]。在太湖,小风浪情况更有利于蓝藻生长或漂浮,当风速低于4 m/s时,蓝藻密度和蓝藻生物量随风速增大而升高,而大风浪对蓝藻的生长或漂浮均不利[92]。随着气候变化,全球地表风速已大大下降,1979—2008年,大部分北半球中纬度地区的地面站的年平均风速下降了73%,平均每年降低0.014 m/s[93-94]。

#### 2.4.2 台风等热带气旋

通常在没有稳定分层的浅水湖泊中,沉积物-上

覆水界面经常受风扰动，风扰动主要影响沉积物的再悬浮，并导致养分释放到上覆水中，成为浮游植物生长和繁殖的养分来源，促进上层浮游植物的生长[95]。根据野外对台风等热带气旋的跟踪研究发现，台风等热带气旋对水华暴发也有显著影响[96]。首先，台风等强风浪可以引发水体垂向混合，使得底层营养盐上浮[97]。在太湖的研究中发现，台风等热带气旋引起的强风浪扰动能够提高水体中碳、氮、磷的浓度，改变水体中微囊藻的分布，并且能促使微囊藻群体迅速增大[98-100]。其次，蓝藻群体的垂直运动和水平迁移均受风致流体动力学的控制，风浪扰动增加水体中蓝藻颗粒碰撞的概率，导致蓝藻细胞团增大，使群体获得更大的浮力，中小规模或中等程度的风致扰动会引起菌落的数量、规模的增加，在风浪扰动过后迅速上浮形成表面可见的蓝藻水华[101-102]。强风浪对蓝藻菌落扩大与细胞外多糖(exopoly saccharides, EPS)的存在有关，EPS 增加了蓝藻菌落的大小和浮力并促进了菌落在水面的聚集，从而形成水华[101-102]。第三，伴随台风而来的暴雨也能在短时期内带来大量地表污染物冲刷进入水体，高强度的暴雨可能会冲走街道、建筑物屋顶、社区垃圾等，并在短时间通过地表径流进入水体，也可以将周围土壤中的营养盐冲刷进入水体[103]，为藻类生长提供的必备元素。

随着气候变化，影响我国的热带气旋变化呈现一定的规律性，且各地区差异较大。例如，1980—2014 年，影响我国的台风极端大风和台风大风年日数均显著减少，而台风极端大风年平均强度增强；引起台风极端大风的台风和台风大风频次均显著减少，但引起台风极端大风的台风在生命期和影响期的平均强度均显著增强[104]。从地区上看，台风等热带气旋表现也不尽相同，1949—2015 年 7—9 月登陆华南地区台风及热带气旋(不含热带低压)频数均有微弱上升趋势，尤其 2005—2015 年登陆华南地区的强台风有明显上升趋势[105]，而影响太湖流域台风的频次和最早影响时间变化趋势不显著，但最晚影响时间有显著推后趋势[106]。因此，热带气旋对各地区水体的影响不尽相同，在台风增强地区，台风等热带气旋诱发水体藻华暴发的风险也会增加。

## 3 气候变化与水体富营养化的相互作用

### 3.1 气温升高、风速降低及降水减少的协同作用

太阳辐射、水温、风速、强降水等因素均会影响水体分层[107]，继而影响水体底层 DO 浓度，进一步影响底层营养盐的释放。当风速降低时，风力对水体的混合作用减弱，水体分层也随之减弱；而水温升高，会使水体分层周期延长、加剧[27]。在太湖流域的研究发现，气温升高、风速降低、日照减少等因素是诱发太湖蓝藻暴发的重要原因，其中气温升高使蓝藻暴发的风险平均每 10 年增加约 2%，因风速降低导致蓝藻水华暴发的风险平均每 5 年增加 3.5%[108]。20 世纪 90 年代后，太湖流域气温呈上升趋势，风速呈下降趋势；降水量呈减少趋势[109-110]。气温升高为蓝藻的生长提供了热量条件，使蓝藻水华形成所需的积温时间提前；风速降低减少了对水体的搅动，有利于蓝藻上浮和聚集；降水量减少导致水体中的污染物和营养盐浓度升高，为蓝藻暴发创造了有利的水质条件；多重气候因素协同作用导致太湖蓝藻暴发越来越严重[109-110]。在福建九龙江流域，1954—2011 年风速、日照时数明显下降，未来冬季降水呈减少趋势，这些气候因素都对九龙江藻华暴发起到了一定的推动作用[111]。

### 3.2 强降水破坏水体热分层

在气温变化条件下，一些湖泊、水库会出现季节性热分层现象，但强降水能使热分层稳定性减弱[112]。气候变化背景下，热分层会有所延长，在千岛湖的研究发现，强降雨可以引发水体混合，改善水体的 DO 水平，对表层水体复氧有促进作用；中度和强降雨事件会降低水体的热稳定性，加深混合层深度，形成温跃层[113]。但强降水在破坏水体热分层稳定性的同时，也携带大量污染物进入水体，使水体污染负荷提高，大量污染物不能被快速地输移和分解，从而消耗 DO，恶化底层水体化学环境，使得水质突发性污染风险加大[114]。强降水携带的高浓度营养盐有利于藻类的生长，增加了有害藻华的发生率，同时携带的大量悬浮物质也影响水下光照，继而对水生初级生产力以及浮游植物群落结构产生影响[115]。在天目湖的研究也发现，夏季强降雨会降低水体上层 5 m 的热分层，但对 5 m 以下的热分层基本无影响。热分层期间，底层水体处于厌氧状态，底层水体氨氮浓度明显增加；热分层消失后，底层水体 DO、总磷及悬浮颗粒物浓度均增加[116]。因此，虽然气候变化引发的强降水频率增加会破坏水体热分层，但携带进入水体的污染物会导致突发性污染事件风险增大。

### 3.3 气候变化导致光照和热量错配

气候变化会导致光照和热量较历史同期出现错配现象，刘世明[117]研究发现，一般情况下春季浮游藻类以硅藻为主，后随着温度的上升，转变为绿藻，继而转为以蓝藻为优势种；但由于气候变化，气温升高导致特定温度节点较历史同期提前，但太阳高度

角度却未达到历史同期角度，导致春季虽地表获得了更高温度，但却获得了较短时间的光照及较弱光照强度，最终在较高水温与较弱光照条件下，促进了蓝藻成为优势种以及水华的形成。

## 4 结论与展望

大气中$CO_2$浓度升高促进浮游藻类大量繁殖，尤其有利于蓝藻的生长。气温升高导致水温随之升高，水体分层现象加剧，底层缺氧更加严重，加之解冻期提前，结冰期缩短，底层缺氧现象随之出现，导致沉积物营养盐释放加剧，大大增加了富营养化发生的概率。降水变率与强降水发生频率增加，地表径流增加，土壤中营养盐的流失加剧，增加了水体营养盐浓度，诱导水体富营养化的发生。由于气候变化与大气污染双重作用，太阳辐射减弱趋势明显，水下光照也随之减少，加速了沉水植物的衰亡，促进了浮游植物的生长，进一步恶化水下光照环境，加速沉水植物的衰亡，导致水体富营养化的发生。风速降低可减少浅水型湖泊沉积物再悬浮，延长水体分层时间，使得水体稳定性提高，底层缺氧现象加剧，加剧富营养化的发生。台风等强风浪扰动可促进水体中氮、磷等营养盐释放，有利于蓝藻细胞团增大，便于上浮，暴雨会促进周围营养盐进入水体，促进藻类生长。这些因素还会相互作用，加大富营养化发生风险，因此，未来研究可着重放在以下几点：

**a.** 气候变化对水生生态系统的影响。研究气候变化对水体富营养化的影响，包括温度、辐射、降水和风速等变化对水体富营养化的作用机理，对水体理化环境的影响，对浮游生物生长速度、种群、群落结构变化的影响，对水生高等植物生存、生长、分布的影响，对种群、群落结构及水生生态系统演化的影响。

**b.** $CO_2$浓度升高、气候变化（气温、降水、太阳辐射、风速等）与水生生态系统相互作用机理。如风速降低、水温升高、降水变率等对水体分层的影响；水温变化、降水波动对藻类光合作用的影响，对碳、氮、磷源吸收及利用的影响等。

**c.** 外源性污染、内源性污染、大气气溶胶沉降、气候变化影响等对水体富营养化的贡献率及其相互作用。如气候变化对大气氮、磷等营养盐沉降量等的影响；气候变化（如水温、辐射等）对水体内源性污染释放的影响；大气氮、磷沉降对内源性污染的影响。

**d.** 水生生态系统应对气候变化诱导水体富营养化问题的对策和措施。针对气候变化可能给水生生态系统带来的连锁反应，如何制定相应的对策，防控带来的不利影响。

**参考文献：**


[1] HARPER D. Eutrophication offreshwaters: principles, problems and restoration[M]. Berlin: Springer Science & Business Media, 1992.

[2] ANSARI A A, SINGH G S, LANZA G R, et al. Eutrophication: causes, consequences and control[M]. Berlin: Springer, 2013.

[3] BERGSTRÖM A K, JANSSON M. Atmospheric nitrogen deposition has caused nitrogen enrichment and eutrophication of lakes in the northern hemisphere[J]. Global Change Biology, 2006, 12(4): 635-643.

[4] LU X T, LU Y L, CHEN D L, et al. Climate change induced eutrophication of cold-water lake in an ecologically fragile nature reserve [J]. Journal of Environmental Sciences, 2019, 75: 359-369.

[5] ZHANG M, DUAN H T, SHI X L, et al. Contributions of meteorology to the phenology of cyanobacterial blooms: implications for future climate change [J]. Water Research, 2011, 46(2): 442-52.

[6] ZHANG M, YU Y, YANG Z, et al. Photochemical responses of phytoplankton to rapid increasing temperature process[J]. Phycological Research, 2012, 60(3): 199-207.

[7] STOCKER T F, QIN D, PLATTNER G, et al. Climate change 2013: the physical science basis: working group 464 I contribution to the fifth assessment report of the intergovernmental panel on climate change [M]. Cambridge: Cambridge University Press, 2013.

[8] NOAA NCEI. [DB/OL]. [2022-03-29]. https://www. $CO_2$. earth/daily-CO2.

[9] WANG B L, LIU C Q, PENG X, et al. Mechanisms controlling the carbon stable isotope composition of phytoplankton in karst reservoirs [J]. Journal of Limnology, 2013, 72(1): 127-139.

[10] 曲宝晓，宋金明，袁华茂，等. 东海海-气界面二氧化碳通量的季节变化与控制因素研究进展[J]. 地球科学进展, 2013, 28(7): 783-793. (QU Baoxiao, SONG Jinming, YUAN Huamao, et al. Advances of seasonal variations and controlling factors of the air-sea $CO_2$ flux in the east china sea[J]. Advance in Earth Sciences, 2013, 28(7): 783-793. (in Chinese))

[11] 陈崇瑛，刘再华. 喀斯特地表水生生态系统生物碳泵的碳汇和水环境改善效应[J]. 科学通报, 2017, 62(30): 3440-3450. (CHEN Chongying, LIU Zaihua. The role of biological carbon pump in the carbon sink and water environment improvement in karst surface aquatic ecosystems[J]. Chinese Science Bulletin, 2017, 62(30): 3440-3450. (in Chinese))

[12] ROST B, RIEBESELL U, BURKHARDT S, et al. Carbon acquisition of bloom-forming marine phytoplankton [J]. Limnology and Oceanography, 2003, 48(1): 55-67.

[13] KING D L. The role of carbon in eutrophication [J]. Water Pollution Control Federation, 1970, 42(12): 2035-2051.

[14] VERSPAGEN J M H, VAN DE WAA D B, FINKE J F, et al. Rising $CO_2$ levels will intensify phytoplankton blooms in eutrophic and hypertrophic lakes [J]. PLoS One, 2014, 9(8): e104325.

[15] 叶上扬,喻国良,庞红犁. 太湖蓝藻成因分析与清淤方法探讨[J]. 水资源保护, 2012, 28(2): 30-33. (YE Shangyang, YU Guoliang, PANG Hongli. Analysis of formation of blue-green algae and dredging methods in Taihu Lake [J]. Water Resources Protection, 2012, 28(2): 30-33. (in Chinese))

[16] MORABITO G, ROGORA M, AUSTONI M, et al. Could the extreme meteorological events in Lake Maggiore watershed determine a climate-driven eutrophication process? [J]. Hydrobiologia, 2018, 824(1): 163-175.

[17] ANDERSON D M, GLIBERT P M, BURKHHOLDE J M. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences [J]. Estuaries, 2002, 25(4): 704-726.

[18] GULATI R D, VAN DONK E. Lakes in the Netherlands, their origin, eutrophication and restoration: state-of-the-art review [J]. Hydrobiologia, 2002, 478(1/2/3): 73-106.

[19] MICHALAK A M, ANDERSON E J, BELETSKY D, et al. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions [J]. Proc Natl Acad Sci USA, 2013, 110(16): 6446-6452.

[20] XU H, PAERL H W, QIN B, et al. Nitrogen and phosphorus inputs control phytoplankton growth in eutrophic Lake Taihu, China [J]. Limnology and Oceanography, 2010, 55(1): 420-432.

[21] LI Q X, SUN W B, HUANG B Y, et al. Consistency of global warming trends strengthened since 1880s [J]. Science Bulletin, 2020, 65(20): 1709-1712.

[22] 付朝晖,腾威,纪媛媛. 抚仙湖水温与气象因子的关系研究[J]. 水资源与水工程学报, 2014 (2): 192-194. (FU Zhaohui, TENG Wei, JI Yuanyuan. Resarch on relationship between water temperature and meteorological factor of Fuxian Lake [J]. Journal of Water Resources and Water Engineering, 2014 (2): 192-194. (in Chinese))

[23] 夏依木拉提. 近50年天山西部内流河天然河道水温变化特征[J]. 水文, 2009, 29(2): 84-86. (XIA Yimulati. Characteristics of water temperature change of inland rivers in western part of tianshan mountains in last 50 years [J]. Journal of China Hydrology, 2009, 29(2): 84-86. (in Chinese))

[24] KOMATSU E, FUKUSHIME T, HARASAWA H. A modeling approach to forecast the effect of long-term climate change on lake water quality [J]. Ecological Modelling, 2007, 209(2/3/4): 351-366.

[25] DOKULIL M T. Impact of climate warming on European inland waters [J]. Inland Waters, 2014, 4(1): 27-40.

[26] ZHANG Y, WU Z, LIU M, et al. Dissolved oxygen stratification and response to thermal structure and long-term climate change in a large and deep subtropical reservoir (Lake Qiandaohu, China) [J]. Water Research, 2015, 75(15): 249-258.

[27] CHEN W Y, SEINER J, SUZUKI T, et al. Handbook of climate change mitigation [M]. New York: Springer Science and Business Media, 2012: 531-569.

[28] LIVINGSTONE D M. Impact of secular climate change on the thermal structure of a large temperate central European lake [J]. Climatic Change, 2003, 57(1): 205-225.

[29] ELO A R, HUTTULA T, PELTONEN A, et al. The effects of climate change on the temperature conditions of lakes [J]. Boreal Environment Research, 1998, 3(2): 137-150.

[30] DE STASIO J B T, HILL D K, KLEINHANS J M, et al. Potential effects of global climate changes on small north-temperate lakes: physics, fish, and plankton [J]. Limnology & Oceanography, 1996, 41(5): 1136-1149.

[31] KRAEMER B M, ANNEVILLE O, CHANDRA S, et al. Morphometry and average temperature affect lake stratification responses to climate change [J]. Geophysical Research Letters, 2015, 42(12): 4981-4988.

[32] RÖSNER R R, MÜLLER-NAVARRA D C, ZORITA E. Trend analysis of weekly temperatures and oxygen concentrations during summer stratification in Lake Plußsee: a long-term study [J]. Limnology & Oceanography, 2012, 57(5): 1479-1491.

[33] 王锦旗,宋玉芝,黄进. 水温升高对水体性质及水生生物的影响研究进展[J]. 水生态学杂志, 2020, 41(1): 100-109. (WANG Jinqi, SONG Yuzhi, HUANG Jin. Effects of increasing water temperature on water properties and aquatic organisms: a critical review [J]. Journal of Hydroecology, 2020, 41(1): 100-109. (in Chinese))

[34] FANG X, STEFAN H G. Projections of climate change effects on water temperature characteristics of small lakes in the contiguous U. S. [J]. Climatic Change, 1999, 42(2): 377-412.

[35] ELSHEMY M. Climate change impacts on water resources in semiarid regions: case study of Aswan high dam

reservoir[M]. Berlin: Springer, 2013.
[36] KARETNIKOV S G, NAUMENKO M A. Recent trends in Lake Ladoga ice cover[J]. Hydrobiologia, 2008, 599(1):41-48.
[37] ROBERTSON D M, RAGOTZKIE R A. Changes in thermal structure of moderate to large sizes lakes in response to change in air temperature[J]. Aquatic Sciences, 1990, 52(4):360-380.
[38] EFREMOVA T, PALSHIN N, ZDOROVENNOV R. Long term characteristics of ice phenology in Karelian lakes[J]. Estonian Journal of Earth Sciences, 2013, 62(1): 33-41.
[39] KORHONEN J. Long-term changes in lake ice cover in Finland[J]. Water Policy, 2006, 37(4/5):347-363.
[40] GEORGE D G, MABERLY S C, HEWITT D P. The influence of the North Atlantic Oscillation on the physical, chemical and biological characteristics of four lakes in the English Lake District[J]. Freshwater Biology, 2004, 49(6):760-774.
[41] WEYHENMEYER G A. Synchrony in relationships between the North Atlantic Oscillation and water chemistry among Sweden's largest lakes[J]. Limnology & Oceanography, 2004, 49(4):1191-1201.
[42] ADRIAN R, DENEKE R, MISCHKE U, et al. A long-term study of the Heiligensee (1975-1992) evidence for effects of climatic change on the dynamics of eutrophied lake ecosystems[J]. Archiv Fur Hydrobiologie, 1995, 133(3):315-337.
[43] ADRIAN R, WALZ N, HINTZE T, et al. Effects of ice duration on plankton succession during spring in a shallow polymictic lake[J]. Freshwater Biology, 1999, 41(3): 621-634.
[44] SMITH B, AASA A, AHAS R, et al. Climate-related change in terrestrial and freshwater ecosystems[M]. Berlin: Springer Berlin Heidelberg, 2008:221-308.
[45] GEORGE D G, HARRIS G P. The effect of climate on long-term changes in the crustacean zooplankton biomass of Lake Windermere UK[J]. Nature, 1985, 317(6037): 536-539.
[46] GEORGE D G, HEWITT D P, LUND J W, et al. The relative effects of enrichment and climate change on the long-term dynamics of *daphnia* in Esthwaite Water, Cumbria[J]. Freshwater Biology, 2010, 23(23): 55-70.
[47] HYENSTRAND P, BLOMQVIST P, PETTERSSON A. Factors determining cyanobacterial success in aquatic systems: a literature review[J]. Arch Hydrobiol Spec Issues Advanc Limnol, 1998, 51:41-62.
[48] WEYHENMEYER G A. Warmer winters: are planktonic algal populations in Sweden's largest lakes affected? [J]. Ambio, 2001, 30(8):565-571.
[49] 邓建明，秦伯强. 全球变暖对淡水湖泊浮游植物影响研究进展[J]. 湖泊科学，2015，27(1):1-10. (DENG Jianming, QIN Boqiang. A review on studies of effects of climate change on phytoplankton in freshwater sytsem[J]. Journal of Lake Science, 2015, 27(1):1-10. (in Chinese))
[50] SORVARI S, KORHOLA A, THOMPSON R. Lake diatom response to recent Arctic warming in Finnish Lapland[J]. Global Change Biology, 2002, 8(2): 171-181
[51] NETTEN J J C, VAN ZUIDAM J, KOSTEN S, et al. Differential response to climatic variation of free-floating and submerged macrophytes in ditches[J]. Aquatic Botany, 2011, 56(9): 1761-1768.
[52] LESSARD J A L, HAYES D B. Effects of elevated water temperature on fish and macroinvertebrate communities below small dams[J]. River Research & Applications, 2010, 19(7):721-732.
[53] HABIB S, YOUSUF A R. Impact of elevated water temperature on phytophilous macroinvertebrate community of an eutrophic lake in Kashmir Himalayas[J]. International Journal of Current Research, 2015, 6(2): 5181-5183.
[54] NETTEN J C, ARTS G H P, GYLSTRA R, et al. Effect of temperature and nutrients on the competition between free-floating *Salvinia natans* and submerged *Elodea nuttallii* in mesocosms[J]. Fundamental and Applied Limnology, 2010, 177(2):125-132.
[55] YE C, SHEN Z, ZHANG T, et al. Long-term joint effect of nutrients and temperature increase on algal growth in Lake Taihu, China[J]. Journal of Environmental Sciences, 2011, 23(2):222-227.
[56] NEIL J M O, DAVIS T W, BURFORD M A, et al. The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change[J]. Harmful Algae, 2012, 14:313-334
[57] PAERL H W, PAUL V J. Climate change: links to global expansion of harmful cyanobacteria[J]. Water Research, 2012, 46(5):1349-1363.
[58] MOSS B, KOSTEN S, MEERHOFF M, et al. Allied attack: climate change and eutrophication[J]. Inland Waters, 2011, 1(2):101-105.
[59] MCKEE D, ATKINSON D, COLLINGS S E, et al. Response of freshwater microcosm communities to nutrients, fish, and elevated temperature during winter and summer[J]. Limnology and Oceanography, 2003, 48(2):707-722.
[60] KOSTEN S, HUSZAR V L, BÉCARES E, et al. Warmer climates boost cyanobacterial dominance in shallow lakes[J]. Global Change Biology, 2012, 18(1): 118-126.
[61] HARRIS J M, VINOBABA P, KULARATNE R K A, et

al. Spatial and temporal distribution of cyanobacteria in Batticaloa Lagoon [J]. Journal of Environmental Sciences, 2016,47(9): 211-218.

[62] FEUCHTMAYR H, MORAN R, HATTON K, et al. Global warming and eutrophication: effects on water chemistry and autotrophic communities in experimental, hypertrophic, shallow lake mesocosms [J]. Journal of Applied Ecology, 2009, 46(3): 713-723.

[63] LU X, SONG S, LU Y, et al. Response of the phytoplankton community to water quality in a local alpine glacial lake of Xinjiang Tianchi, China: potential drivers and management implications [J]. Environmental Science: Processes & Impacts, 2017, 19 (10): 1300-1311.

[64] 王寿兵,屈云芳,徐紫然. 基于生物操纵的富营养化湖库蓝藻控制实践[J]. 水资源保护, 2016, 32(5):1-4. (WANG Shoubing, QU Yunfang, XU Ziran. Algal bloom control in eutrophic lakes and reservoirs based on biomanipulation[J]. Water Resources Protection, 2016, 32(5):1-4. (in Chinese))

[65] 朱喜,李贵宝,王圣瑞. 太湖蓝藻暴发的治理[J]. 水资源保护, 2020, 36(6):106-111. (ZHU Xi, LI Guibao, WANG Shengrui. Treatment of blue algae outbreak in Taihu Lake[J]. Water Resources Protection, 2020, 36(6):106-111. (in Chinese))

[66] LU X T, LU Y L, CHEN D L. Climate change induced eutrophication of cold-water lake in an ecologically fragile nature reserve[J]. Journal of Environmental Sciences, 2019, 75: 359-369.

[67] MORABITO G, ROGORA M, AUSTONI M, et al. Could the extreme meteorological events in Lake Maggiore watershed determine a climate-driven eutrophication process? [J]. Hydrobiologia, 2018, 824(1): 163-175.

[68] SINHA E, MICHALAK A M, BALAV J. Eutrophication will increase during the 21st century as a result of precipitation changes[J]. Science, 2017, 357(6349): 405-408.

[69] 邹丽莎, 聂泽宇, 姚笑颜, 等. 富营养化水体中光照对沉水植物的影响研究进展[J]. 应用生态学报, 2013, 24(7) : 2073-2080. (ZOU Lisha, NIE Zeyu, YAO Xiaoyan, et al. Effects of light on submerged macrophytes in eutrophic water: research progress[J]. Chinese Journal of Applied Ecology, 2013, 24(7): 2073-2080. (in Chinese))

[70] SCHWARZ A M, DE WINTON M, HAWES I. Species-specific depth zonation in New Zealand charophytes as a function of light availability[J]. Aquatic Botany, 2002, 72(3/4): 209-217.

[71] 严俊, 王颖, 王一博, 等. 基于光补偿深度的白洋淀沉水植物修复技术[J]. 环境工程学报, 2020, 14(10):2853-2865. (YAN Jun, WANG Ying, WANG Yibo, et al. Remediation technology of submerged plants in Baiyangdian Lake based on light compensation depth [J]. Chinese Journal of Environmental Engineering, 2020, 14(10):2853-2865. (in Chinese))

[72] 摆晓虎, 曹特, 倪乐意, 等. 洱海水体光学特性的季节变化及其影响因素分析[J]. 水生态学杂志, 2016, 37(2):10-16. (BAI Xiaohu, CAO Te , NI Leyi , et al. Seasonal variation of water column optical parameters in Lake Erhai, China [J]. Journal of Hydroecology, 2016, 37(2):10-16. (in Chinese))

[73] JING S. All-sky direct radiative effects of urban aerosols in Beijing and Shanghai, China [J]. Atmospheric and Oceanic Science Letters, 2015, 8(5):295-300.

[74] YANG X, ZHAO C, ZHOU L, et al. Distinct impact of different types of aerosols on surface solar radiation in China [J]. Journal of Geophysical Research Atmospheres, 2016, 121(11):6459-6471.

[75] 徐德瑞, 周杰, 吴时强, 等. 夏季东太湖光合有效辐射衰减特征及其对沉水植物恢复的指示[J]. 湖泊科学, 2021, 33(1): 111-122. (XU Derui, ZHOU Jie, WU Shiqiang, et al. Attenuation characteristics of photosynthetically active radiation in summer eastern Lake Taihu and implications for submerged plants[J]. Journal of Lake Sciences, 2021, 33(1): 111-122. (in Chinese))

[76] PHILLIPS G, WILLBY N, MOSS B. Submerged macrophyte decline in shallow lakes: what have we learnt in the last forty years? [J]. Aquatic Botany, 2016, 135: 37-45.

[77] HEGGLINN M I , FAHEY D W , MCFARLAND M , et al. Twenty questions and answers about the ozone layer: 2014 update [R]. Geneva: World Meteorological Organization, 2015.

[78] BALL W T, CHIODO G, ABALOS M, et al. Inconsistencies between chemistry: climate models and observed lower stratospheric ozone trends since 1998[J]. Atmospheric Chemistry and Physics, 2020, 20(16): 9737-9752.

[79] TAALAS P, KAUROLA J, KYLLING A, et a1. The impact of greenhouse gases and halogenated species on future solar UV radiation doses [J]. Geophysical Research Letters, 2000, 27(8):1127-1130.

[80] HEIDEN J P , VLKNER C , JONES E M , et al. Impact of ocean acidification and high solar radiation on productivity and species composition of a late summer phytoplankton community of the coastal Western Antarctic Peninsula[J]. Limnology and Oceanography, 2019, 64: 1716-1736.

[81] TONG S , HUTCHINS D A , GAO K. Physiological and biochemical responses of Emiliania huxleyi to ocean acidification and warming are modulated by UV radiation

[J]. Biogeosciences, 2019, 16(2):561-572.
[82] CONNELLY S J, MOELLER R E, SANCHEZ G, et al. Temperature effects on survival and DNA repair in four freshwater cladoceran *Daphnia species* exposed to UV radiation[J]. Photochemistry and Photobiology, 2009, 85(1):144-152.
[83] SINGHA S P, HÄDERA D P, SINHAB R P. Cyanobacteria and ultraviolet radiation (UVR) stress: mitigation strategies [J]. Ageing Research Reviews, 2010, 9(2): 79-90.
[84] CABRERS, LÓPEZ M, ATARTAR OTTI B. Phytoplankton and zooplankton response to ultraviolet radiation in a high-altitude Andean Lake: short- versus long-term effects[J]. Journal of Plankton Research, 1997, 19 (11):1565-1582.
[85] PAERL H W, VALDES L M, PEIERLS B L, et al. Harding anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems [J]. Limnology and Oceanography, 2006, 51 (1/2) : 448-462.
[86] QIN B Q , YANG G J , MA J R, et al. Spatiotemporal changes of cyanobacterial bloom in large shallow eutrophic Lake Taihu, China[J]. Frontiers in Microbiology, 2018: 00451.
[87] WANG H, ZHANG Z Z, LIANG D F, et al. Separation of wind's influence on harmful cyanobacterial blooms[J]. Water Research, 2016, 98 (1):280-292.
[88] CHURCHILL J H, KERFOOT W C. The impact of surface heat flux and wind on thermal stratification in portage Lake, Michigan [J]. Journal of Great Lakes Research, 2007, 33(1):143-155.
[89] WOOLWAY R I, MEINSON P, NÕGES P, et al. Atmospheric stilling leads to prolonged thermal stratification in a large shallow polymictic lake [J]. Climatic Change, 2017, 141(4):759-773.
[90] CYR H. Winds and the distribution of nearshore phytoplankton in a stratified lake[J]. Water Research, 2017, 122(1):114-127.
[91] KO C Y, LAI C C, HSU H H, et al. Decadal phytoplankton dynamics in response to episodic climatic disturbances in a subtropical deep freshwater ecosystem [J]. Water Research, 2017, 109(1):102-113.
[92] 孙小静, 秦伯强, 朱广伟,等. 风浪对太湖水体中胶体态营养盐和浮游植物的影响[J]. 环境科学, 2007, 28 (3): 506-511. (SUN Xiaojing , QIN Boqiang, ZHU Guangwei, et al. Effect of wind-induced wave on concentration of colloidal nutrient and phytoplankton in Lake Taihu [J]. Chinese Journal of Environmental Science, 2007, 28(3):506-511. (in Chinese))
[93] VAUTARD R, CATTIAUX J, YIOU P, et al. Northern hemisphere atmospheric stilling partly attributed to an increase in surface roughness[J]. Nature Geoscience, 2010, 3(11):756-761.
[94] MCVICAR T R, RODERICK M L, DONOHUE R J, et al. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: implications for evaporation[J]. Journal of Hydrology, 2012, 416: 182-205.
[95] ZHU G, QIN B, GAO G. Direct evidence of phosphorus outbreak release from sediment to overlying water in a large shallow lake caused by strong wind wave disturbance [J]. Chinese Science Bulletin, 2005, 50(6):577-582.
[96] WU T, QIN B, ZHU G, et al. Dynamics of cyanobacterial bloom formation during short-term hydrodynamic fluctuation in a large shallow, eutrophic, and wind-exposed Lake Taihu, China[J]. Environmental Science and Pollution Research, 2013, 20(12): 8546-8556.
[97] 张亚锋, 王旭涛, 殷克东. 南海台风引发藻华的生物机制[J]. 生态学报, 2017, 38(16): 5667-5678. (ZHANG Yafeng, WANG Xutao, YIN Kedong. Biological mechanisms of typhoon-induced blooms in the South China Sea [J]. Acta Ecologica Sinica, 2017, 38 (16):5667-5678. (in Chinese))
[98] 王玉兵, 杨桂军, 秦伯强, 等. 台风对太湖微囊藻群体大小的影响[J]. 环境工程学报, 2016, 10(7): 3961-3966. (WANG Yubing, YANG Guijun, QIN Boqiang, et al. Effect of typhoon on the size of microcystis colonies in Lake Taihu[J]. Chinese Journal of Environmental Engineering, 2016, 10(7): 3961-3966. (in Chinese))
[99] 刘颢, 杨棢, 高光, 等. 台风过程中太湖藻类富集区氨基酸的变化特征[J]. 生态环境学报, 2019, 28(8): 170-179. (LIU Hao, YANG Bei, GAO Guang , et al. Characteristics of amino acids during the process of typhoon in algal rich areas of Lake Taihu[J]. Ecology and Environmental Sciences, 2019, 28(8): 170-179. (in Chinese))
[100] 王寿兵,徐紫然,张洁. 大型湖库富营养化蓝藻水华防控技术发展述评[J]. 水资源保护, 2016, 32(4): 88-99. (WANG Shoubing, XU Ziran, ZHANG Jie. A review of technologies for prevention and control of cyanobacteria blooms in large-scale eutrophicated lakes and reservoirs[J]. Water Resources Protection, 2016, 32 (4): 88-99. (in Chinese))
[101] LI W, QIN B Q. Dynamics of spatiotemporal heterogeneity of cyanobacterial blooms in large eutrophic Lake Taihu, China[J]. Hydrobiologia, 2019, 833(1): 81-93.
[102] QIN B Q, YANG G J, MA J R, et al. Spatiotemporal changes of cyanobacterial bloom in large shallow Eutrophic Lake Taihu, China [J]. Frontiers in Microbiology, 2018, 9: 00451.

[103] FU X, LIU J, MEI C, et al. Effect of typhoon rainstorm patterns on the spatio-temporal distribution of non-point source pollution in a coastal urbanized watershed[J]. Journal of Cleaner Production, 2021, 292:126098.
[104] 陆逸, 朱伟军, 任福民, 等. 1980—2014 年中国台风大风和台风极端大风的变化[J]. 气候变化研究进展, 2016, 12(5):413-421. (LU Yi, ZHU Weijun, REN Fumin, et al. Changes of tropical cyclone high winds and extreme winds during 1980-2014 over China [J]. Advances in Climate Change, 2016, 12(5):413-421. (in Chinese))
[105] 姚才, 罗小莉, 张成扬, 等. 7—9 月登陆华南台风气候变化特征及大尺度环流系统分析[J]. 气象研究与应用, 2019, 40(1):3-8. (YAO Cai, LUO Xiaoli, ZHANG Chengyang, et al. The climatic changes of landfall typhoons in South China in July-September and the associated large-scale circulation [J]. Journal of Meteorological Research and Application, 2019, 40(1): 3-8. (in Chinese))
[106] 崔婷婷, 王银堂, 刘勇, 等. 影响太湖流域的台风演变规律分析[J]. 水文, 2012, 32(2):54-58. (CUI Tingting, WANG Yintang, LIU Yong, et al. Analysis of change trend of typhoon impacting Taihu Lake basin [J]. Journel of China Hydrology, 2012, 32(2):54-58. (in Chinese))
[107] 赵林林, 朱广伟, 陈元芳, 等. 太湖水体水温垂向分层特征及其影响因素[J]. 水科学进展, 2011, 22(6): 844-850. (ZHAO Linlin, ZHU Guangwei, CHEN Yuanfang, et al. Thermal stratification and its influence factors in a large-sized and shallow Lake Taihu [J]. Advances in Water Science, 2011, 22(6):844-850. (in Chinese))
[108] 黄国情, 吴时强, 周杰, 等. 太湖蓝藻生境对气候变化的响应[J]. 水利水运工程学报, 2014 (6):39-44. (HUANG Guoqing, WU Shiqiang, ZHOU Jie, et al. Response of blue-green algae habitat in Taihu Lake to climate change [J]. Hydro-Science and Engineering, 2014 (6):39-44. (in Chinese))
[109] 王成林, 潘维玉, 韩月琪, 等. 全球气候变化对太湖蓝藻水华发展演变的影响[J]. 中国环境科学, 2010, 30(6):822-828. (WANG Chenglin, PAN Weiyu, HAN Yueqi, et al. Effect of global climate change on cyanobacteria bloom in Taihu Lake [J]. China Environmental Science, 2010, 30(6):822-828. (in Chinese))
[110] 商兆堂, 任健, 秦铭荣, 等. 气候变化与太湖蓝藻暴发的关系[J]. 生态学杂志, 2010 (1):55-61. (SHANG Zhaotang, REN Jian, QIN Mingrong, et al. Relationships between climatic change and cyanobacterial bloom in Taihu Lake [J]. Chinese Journal of Ecology, 2010 (1):55-61. (in Chinese))
[111] 刘光生, 赵超, 郑丽云. 九龙江流域气候变化特征及对藻华暴发的影响[J]. 水电能源科学, 2015(6):35-38. (LIU Guangsheng, ZHAO Chao, ZHENG Liyun. Characteristics of climate change and its impact on algal bloom in Jiulongjiang basin [J]. Water Resources and Power, 2015(6):35-38. (in Chinese))
[112] 曾康, 黄廷林, 马卫星, 等. 金盆水库汛期高浊水径流的潜入及热分层水体水质响应[J]. 中国环境科学, 2015(9): 2778-2786. (ZENG Kang, HUANG Tinglin, MA Weixing, et al. Water-quality responses of the intrusion of high-turbidity runoff to the thermal stratified Jin-pen Reservoir during flood season [J]. China Environmental Science, 2015 (9): 2778-2786. (in Chinese))
[113] LIU M, ZHANG Y, SHI K, et al. Effects of rainfall on thermal stratification and dissolved oxygen in a deep drinking water reservoir [J]. Hydrological Processes, 2020, 34: 6903
[114] 曾康, 黄廷林, 马卫星, 等. 暴雨径流对分层水库水质的影响[J]. 环境工程学报, 2016, 10(9):4979-4986. (ZENG Kang, HUANG Tinglin, MA Weixing, et al. Impact of storm runoff on water quality of one stratified reservoir [J]. Chinese Journal of Enviromental Engineeing, 2016, 10(9):4979-4986. (in Chinese))
[115] ZHANG Y, QIN B, SHI K, et al. Radiation dimming and decreasing water clarity fuel underwater darkening in lakes[J]. Science Bulletin, 2020, 65(19):1675-1684.
[116] 孙祥, 朱广伟, 笪文怡, 等. 天目湖沙河水库热分层变化及其对水质的影响[J]. 环境科学, 2018, 39(6): 2632-2640. (SUN Xiang, ZHU Guangwei, DA Wenyi, et al. Thermal stratification and its impacts on water quality in Shahe Reservoir, Liyang, China [J]. Environmental Science, 2018, 39(6): 2632-2640. (in Chinese))
[117] 刘世明. 温度与光照错配对春季藻类生长及演替的影响[D]. 南京:南京农业大学, 2014.

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