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Article

Radiation dimming and decreasing water clarity fuel underwater darkening in lakes

Yunlin Zhang [a,b,*], Boqiang Qin [a,b,*], Kun Shi [a,b], Yibo Zhang [a,b], Jianming Deng [a,b], Martin Wild [c], Lin Li [d], Yongqiang Zhou [a,b], Xiaolong Yao [a,b], Miao Liu [a,b], Guangwei Zhu [a,b], Lu Zhang [a,b], Binhe Gu [e], Justin D. Brookes [f]

[a] *Taihu Laboratory for Lake Ecosystem Research, State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*
[c] *Institute for Atmospheric and Climate Science, Zurich CH-8001, Switzerland*
[d] *Department of Earth Sciences, Indiana University-Purdue University, Indianapolis IN 46202, USA*
[e] *Soil and Water Science Department, University of Florida, Gainesville FL 32611, USA*
[f] *Water Research Centre, Environment Institute, School of Biological Science, University of Adelaide, Adelaide 5005, Australia*

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A B S T R A C T

Long-term decreases in the incident total radiation and water clarity might substantially affect the underwater light environment in aquatic ecosystems. However, the underlying mechanism and relative contributions of radiation dimming and decreasing water clarity to the underwater light environment on a national or global scale remains largely unknown. Here, we present a comprehensive dataset of unprecedented scale in China's lakes to address the combined effects of radiation dimming and decreasing water clarity on underwater darkening. Long-term total radiation and sunshine duration showed 5.8% and 7.9% decreases, respectively, after 2000 compared to 1961–1970, resulting in net radiation dimming. An *in situ* Secchi disk depth (SDD) dataset in 170 lakes showed that the mean SDD significantly decreased from 1.80 ± 2.19 m before 1995 to 1.28 ± 1.82 m after 2005. SDD remote sensing estimations for 641 lakes with areas $\geq$ 10 km^2 showed that SDD markedly decreased from 1.26 ± 0.62 m during 1985–1990 to 1.14 ± 0.66 m during 2005–2010. Radiation dimming and decreasing water clarity jointly caused an approximately 10% decrease in the average available photosynthetically active radiation (PAR) in the euphotic layer. Our results revealed a more important role of decreasing water clarity in underwater darkening than radiation dimming. A *meta*-analysis of long-term SDD observation data from 61 various waters further elucidated a global extensive underwater darkening. Underwater darkening implies a decrease in water quality for potable water supplies, recession in macrophytes and benthic algae, and decreases in benthic primary production, fishery production, and biodiversity.

1. Introduction

Solar radiation reaching the Earth's surface is the predominant energy source to support life, exerting many profound effects on the surface temperature, evaporation, the hydrological cycle, and the structure, function and service of terrestrial and aquatic ecosystems [1–4]. In the past six decades, radiation dimming has been observed worldwide, causing a decrease of 4% to 6% in surface total radiation, due to air pollution and associated increases in aerosols caused by intense human activities [5–8]. Since the 1990s, a partial recovery has been observed in Europe and North America, known as radiation brightening, due to the increase of atmospheric clear-sky transparency [1,8]. However, the current surface total radiation worldwide remains markedly lower than in the 1950s, despite 20 years of radiation brightening [9,10].

In China, a marked dimming in surface total radiation was observed nationwide from 1960 to 1990, while some studies reported a slight recovery in brightening since the 1990s [1,5]. However, in the early years of the 2000s, renewed dimming occurred, which was partially attributed to a doubling in the consumption of coal in China between 2002 and 2007 [8,9]. A study in 2018 indicated that the transition from dimming to brightening in China may have only occurred after 2005, based on carefully

* Corresponding authors.
E-mail addresses: ylzhang@niglas.ac.cn (Y. Zhang), qinbq@niglas.ac.cn (B. Qin).

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homogenized data [7]. In China, the high levels of air pollution have counteracted the effects of the radiation brightening since 1990, in contrast to the results obtained from Europe and North America.

Surface total radiation, or more specifically, its photosynthetically active radiation (PAR, 400–700 nm) is the primary driver of primary production. As PAR is proportional to total radiation, the decrease in PAR caused by radiation dimming may decrease carbon uptake of the biosphere and affect the carbon cycle. Furthermore, the gross flux of carbon taken up during photosynthesis is positively and linearly correlated with PAR, and a significant decrease in surface total radiation and PAR may exert a marked effect on the role of vegetation as a carbon sink [3,11].

Although nutrient limitation is an important paradigm for aquatic plant growth in lakes, the importance of light availability is often underestimated, particularly for the wide distribution of nutrient-poor lakes [12,13]. In aquatic ecosystems, both phytoplankton and aquatic macrophytes depend on a sufficient amount of underwater radiation for photosynthesis [13–15], and thus both the biomass and primary production are sensitive to light availability and underwater darkening [16]. Underwater darkening might substantially decrease benthic primary production, destroy food resources and result in a deterioration of the predatory environment for photosensitive aquatic organisms [13,17,18]. However, few studies have assessed the effects of underwater darkening on aquatic ecosystems [16]. For aquatic ecosystems, underwater darkening may be caused by a combination of radiation dimming and decreasing water clarity. In summary, water clarity is jointly determined by pure water and three optically active substances: phytoplankton, nonphytoplankton particulate, and chromophoric dissolved organic matter. Therefore, any processes resulting in changes in concentration and composition of three optically active substances will affect water clarity including eutrophication, pollution, browning, land use change and increased soil erosion in the catchment caused by vegetation destruction.

For determining water clarity, Secchi disk depth (SDD) is a quick and useful method to evaluate the underwater light environment and the trophic state of aquatic ecosystems [19,20]. Traditional *in situ* SDD measurement using a Secchi disk have been performed for more than 150 years [19]. In the past few decades, remote sensing is considered an important supplement or substitute to obtain an overview of the temporal-spatial patterns of SDD due to its unparalleled advantages of collecting measurements from historical and large-scale perspectives [21]. Many arduous efforts have attempted to develop a series of empirical, semi-empirical, and semi-analytical algorithms to estimate SDD and explore the long-term changes in different inland waters using Landsat, MERIS, MODIS, and other images [20,22–25]. A decrease in water clarity is associated with a reduced water quality, the loss of macrophytes and benthic algae, a decrease in primary production, decreases in habitat and fishery production, biodiversity loss, and a decrease in recreational value [13,18,26,27]. Some previous studies have attempted to explore long-term trends in SDD and elucidate the potential effects for many regional lakes [20,25,28]. However, China lacks a recent national dataset of changes in lake water clarity, which prevents a comprehensive and systematic assessment of national trends, and limits our understanding of changes in carbon source or sink dynamics and other changes in the ecosystem. More importantly, no published study from any country has examined the combined contributions of radiation dimming and decreases in water clarity on underwater darkening.

We propose a new concept that radiation dimming and decreasing water clarity jointly result in accelerating underwater darkening and decreasing water clarity plays a more important role than radiation dimming. We pursue three specific objectives to: (1) quantify whether a decrease in incident total radiation and sunshine duration has occurred throughout China, (2) quantify whether a nation-wide decrease in lake water clarity has been observed, and (3) elucidate the combined or interactive effects of radiation dimming and decreasing water clarity on the underwater light environment in lakes, and discuss the implications for lake production and carbon dynamics. Our results provide a new perspective on underwater darkening and future studies of carbon dynamics in lakes. Considering the complex and different processes affecting the SDD in a specific lake, our study has not attempted to elucidate the specific factors affecting SDD dynamics.

2. Materials and methods

2.1. Surface total radiation and sunshine duration

Surface total radiation data were examined from a 53-year record from 1961 to 2013 at 116 radiation observation stations in China, which was the new and complete total radiation data that we were able to collect. Data were obtained from the archives of the National Meteorological Information Center of the China Meteorological Administration (NMIC/CMA). Detailed information on station names, codes, altitude, starting and ending years of the observation period, and linear fitting of yearly total radiation versus year is provided in Table S1 and Fig. S1 (online). Complete data were available for all 53 years for 57 of the 116 stations, data were available for at least 26 years (half the study period) for 24 stations, and for the remaining 35 stations, data were available for 20 to 24 years. These data have been widely used to trace the long-term trends in total radiation in China [5–7]. Because the sunshine duration is also an important parameter characterizing radiation dimming or brightening, we also obtained sunshine duration data from 839 meteorological stations in China, including the 116 radiation observation stations (Fig. S1 online). Sunshine duration data from 839 stations is continuous and complete for the period from 1961 to 2013.

2.2. In situ SDD measurement: nation-wide, and for four typical lakes

We next compiled three datasets from publicly available data to provide a unique insight into the long-term changes in the underwater light environment in China's lakes: *in situ* SDD measurements from investigations of national lakes and the literature, *in situ* SDD measurements from long-term studies of four lakes over the past few decades, and remotely estimated SDD during two periods from 1985 to 1990 and from 2005 to 2010.

Temporal changes in SDD were determined by comparing the values for 170 lakes in China before 1995 with the values recorded after 2005 (Table S2 online). These time periods were determined based on the availability of data from the first and second nation-wide lake investigations, which were conducted from the 1960s to 1980s and from 2005 to 2010, respectively. The 170 lakes in this dataset ranged from < 1 km^2 to greater than 4000 km^2 in water area and from < 1 m to > 150 m in mean depth (Table S2 online), covered different trophic states, and represented five previously defined geographic lake zones in China [29–31].

The regional survey data were supplemented with more intensive SDD monitoring data collected over 30 to 37 years with an interval of monthly measurements from four lakes with different trophic states and SDD ranges: Lake Fuxianhu (1980–2016), oligotrophic; Lake Qiandaohu (1988–2016), oligotrophic-mesotrophic; Lake Erhai (1985–2016), mesotrophic and Lake Gehu (1992–2016), eutrophic [31–33].

2.3. Remote sensing estimation of SDD before 1995 and after 2005

The uneven geographic distribution of *in situ* SDD data from historical investigations and the published literature prompted us to seek data from remote sensing, from which we would be able to estimate the SDD for China's lakes. We used remote sensing data from Landsat images with a 30 m spatial resolution, for two periods, 1985 to 1990 and 2005 to 2010, which are representative of conditions before 1995 and after 2005, respectively, and consistent with the time periods for the comparison of the *in situ* SDD data. Considering the 30 m spatial resolution and complex lake shoreline of some lakes, we focused on 641 lakes with water areas $\geq$ 10 km^2 to reduce the uncertainty in estimates.

A total of 26,321 high-quality Landsat 5 TM and 7 ETM + scene images of China's lakes were downloaded from the United States Geological Survey (USGS) website (http://glovis.usgs.gov/) in summer and spring (July 1 to September 30) during two periods ranging from 1985 to 1990 and 2005 to 2010. We selected these seasons because no ice covers any of China's lakes and the sky is clear under most conditions. On average, more than 2000 scene images in every year are used, which normally meet the need for SDD estimates of lakes throughout the nation. More importantly, we only compare the differences between two periods of 1985 to 1990 and 2005 to 2010 to reduce the errors and uncertainties in the data to the greatest possible. Of course, some uncertainties are inherent in remote sensing data because our dataset only includes four months in summer and autumn seasons. The Landsat 5 TM and 7 ETM + images were level-1 processed, indicating that they received uniform radiation and geometry correction. The images were then processed in two steps: (1) radiometric calibration and (2) atmospheric correction. The radiometric calibration converted the raw digital number into physically meaningful radiance or reflectance of Landsat 5 TM and 7 ETM + images; the atmospheric correction eliminated the effects of atmospheric absorption and scattering.

Based on the visible bands of the Landsat 5 TM and 7 ETM+, we used an alternative correction scheme (second simulation of satellite signal in the solar spectrum: 6S model) with the aid of Terra/MODIS aerosol information to retrieve an accurate remote sensing reflectance used to estimate SDD. The SDD is strongly correlated with the responses in the blue and red bands of Landsat TM/ETM + data [34,35]. We used two complete and independent datasets to calibrate and validate our SDD estimation model. We obtained the *in situ* SDD from 225 lakes in China ranging from shallow to deep, from small to large, and from oligotrophic to eutrophic in different months and seasons, and used 887 samples to calibrate and 246 samples to validate our SDD remote sensing estimation model [36]. For the calibration dataset, SDD ranged from 0.01 to 14.00 m, with a mean value of 1.57 ± 1.95 m. For the validation dataset, SDD ranged from 0.05 to 6.70 m with a mean value 1.51 ± 1.74 m that was within the SDD range of the calibration dataset.

For the large calibration dataset (887 samples), a highly significant power function correlation (r^2 = 0.73, P < 0.001) was observed between the remote sensing reflectance of red Band 3 (630–690 nm) derived from Landsat 5 TM and 7 ETM + images and SDD. The independent validation dataset showed the distribution of the measured and estimated SDD along the 1:1 line, with the mean relative error and normalized root mean square error of 34% and 55%, respectively, indicating that the power function model based on the red band of Landsat reflectance was suitable for estimating the SDD of China's lakes covering SDD from <0.1 m to more than 10 m. Detailed information about the calibration, validation, and assessment of the model is provided in our previous study [36]. Overall, the precision of the SDD estimation model in our study was acceptable compared to similar previous studies [22–25].

2.4. Literature data on the marked decrease in long-term SDD

A *meta*-analysis of the literature is a good way to summarize the available evidence and provide a more robust result than a single study. In more detail, we extracted long-term SDD data for various waters around the world, including oceanic, coastal and inland waters, from the published literature and compiled a dataset of changes in SDD. Specifically, we searched the Science Citation Index (SCI) Expanded database (1900–2019) and the China Academic Journals Full-text Database (1960–2019) using the topic words (‘‘Secchi" or ‘‘water transparency" or ‘‘water clarity*") and (‘‘long term" or ‘‘long-term").

2.5. Measurement and calculation of underwater PAR

The underwater PAR profile and SDD were synchronously measured in diverse waters, comprising 25 lakes with very clear waters (Lake Fuxianhu) and SDD > 6.0 m to highly turbid waters (Lake Taihu) and SDD < 0.2 m. Down-welling PAR was measured on the sunny side of the boat, with the sensor extended 0.5 m from the boat to reduce the effect of reflectance from the vessel on the underwater PAR. Measurements of underwater PAR were generally conducted between 8:30 and 17:00 on cloudless days. PAR measurements were performed at 6–30 layers according to water depth of the different lakes.

The underwater PAR was measured using a Li-Cor 192SA underwater quantum sensor connected to a Li-Cor 1400 data logger. The Li-Cor 192SA was installed in a lowering frame, which provided stability to ensure the proper orientation of the sensor and minimized shading effects. Using the instantaneous mode of the LI-1400 data logger, three values were recorded at 1-minute intervals for each depth. Their mean value was considered the PAR intensity for that depth to minimize the effect of wind-generated waves on the measurement of underwater PAR.

The diffuse attenuation coefficients for the downward irradiance, K_d(PAR), were determined as the slope of the linear fit of the log-transformed profile of underwater irradiance vs. depth [37]. We accepted only K_d(PAR) values from regression lines with a determination coefficient (r^2) greater than 0.98. The number of depths used in these regression analyses was 6–30, depending on the penetration depth and water depth.

A dataset of 1219 SDDs ranging from < 0.1 m to > 8.0 m that encompassed most of the range of lake water clarity observations reported worldwide was used to correlate SDD with K_d(PAR) and calculate the euphotic depth (the depth at which PAR is 1% of its value at the water surface) [20,28].

2.6. Hu Huanyong Line

The Hu Huanyong Line was proposed by the famous population geographer Hu Huanyong in 1935. The line ran from the city of Aihui (Heihe) in the northeast to Tengchong County in the southwest, which basically coincided with the 400 mm precipitation isoline. According to the statistical data reported in 2010, the southeast region of the Hu Huanyong Line (except for Hong Kong, Macao, and Taiwan Province) covered 36.0% of the total area of the mainland, 94.0% of the population and contributed to 95.7% of the national gross domestic product in China. Therefore, this line has been regarded as an important geographic, economic, social, and human activity intensity division line in China [38].

2.7. Statistical analyses

All statistical analyses were performed using the Statistical Package for the Social Sciences software (SPSS 20, Chicago, IL). A significance level of $P \leq 0.05$ was considered statistically significant. For simplicity and an easy comparison, long-term trends of variations in the total radiation, sunshine duration, and SDD were determined using a linear regression analysis. The non-parametric Mann-Whitney (MW) statistical test is more suitable for non-normally distributed data and thus it may be not sensitive to the distribution type of sample data. Therefore, we used the MW statistical test to assess the significance of a shift in mean values.

3. Results

3.1. Radiation dimming in China

Marked trends in long-term yearly mean total radiation were observed at the 116 individual stations in China from 1961 to 2013 (Fig. S2 online). Total radiation decreased at 91 stations (78.4% of stations), with a statistically significant decrease recorded for 50 stations (43.1%). In contrast, an increase in total radiation was observed at 25 stations (21.6%), with a statistically significantly increase only observed at 4 stations (3.4%). For 14 of the 25 stations with increasing trends, total radiation observations were only available for the period from the 1980s to 2013, and thus the reported increases were obtained from the second half of the 53 year time span (Table S1 online). Among the 57 stations with continuous data for the 53 years from 1961 to 2013, the yearly mean total radiation decreased significantly (r^2 = 0.27, $P \leq 0.01$). Furthermore, among these 57 stations, the yearly mean total radiation in 2001 to 2013 was on average 5.8% lower than in 1961 to 1970.

A significant decrease in the yearly mean sunshine duration was also observed at 505 of 839 stations in China (60.2% of the total, Fig. 1), with a mean rate of decrease of 4.59 h/a from 1961 to 2013, when all the data from the 839 stations were pooled (r^2 = 0.68, P < 0.001, Fig. S3 online). The sunshine duration decreased by 7.9% when we compared 2001–2013 with 1961–1970, which was a greater than 5.8% decrease in the total radiation. Overall, a significantly decreasing trend of sunshine duration was observed in the southeastern region, but a nonsignificant decreasing and even slight increasing trend was observed in the northwestern region. The mean slope of the decreasing trend was 6.21 ± 3.75 and 3.03 ± 3.98 h/a in the southeastern and northwestern regions along the Hu Huanyong Line, respectively (Fig. 1).

3.2. Decreasing SDD in China's lakes

The dataset obtained from two national lake investigations and the literature covers a large range of changes in SDD from 0.12 to 13.3 m from 1960s to 1995, partially indicating different trophic gradients from oligotrophic to hyper-eutrophic. A comparison of all 170 lakes revealed a decrease in the SDD in 130 lakes (76.5%) and an increase in 40 lakes (23.5%) from 2005 to 2016 compared with the period from the 1960s to 1995. The number of lakes displaying a decrease in the SDD was more than three times the number of lakes displaying an increase in the SDD. Among all 170 lakes with available *in situ* SDD data (uncertainty $\leq$ 0.05 m), the average SDD significantly decreased by 28.9% from 1.80 ± 2.19 m from the 1960s to 1995 to only 1.28 ± 1.82 m during 2005–2016 (P < 0.05, MW test, Fig. 2).

Spatially, SDD decreased to a greater extent in lakes located in the Eastern Plain Lake (EPL) zone than in other zones (Fig. 2). The mean SDD decreased by 33.3% and 22.5% in the southeastern and northwestern regions of the Hu Huanyong Line, respectively. For the 130 lakes displaying a decrease in the SDD, a significant decrease of 41.3% from 1.89 ± 2.12 m from the 1960s to 1995 to 1.11 ± 1.46 m from 2005 to 2016 was observed (P < 0.001, MW test). In contrast, for the 40 lakes displaying an increase in the SDD, a nonsignificant increase from 1.52 ± 2.40 m from the 1960s to 1995 to 1. 84 ± 2.63 m from 2005 to 2016 was observed (P > 0.05, MW test).

We compared the spatial distribution of remote sensing-based SDDs of lakes in the five geographic lake zones across China with a water area $\geq$ 10 km^2 during the two time periods (Fig. 3). Marked decreases in the SDD were observed nationwide from 1.26 to 1.14 m by 10.1%, and significant decreases in SDDs were observed

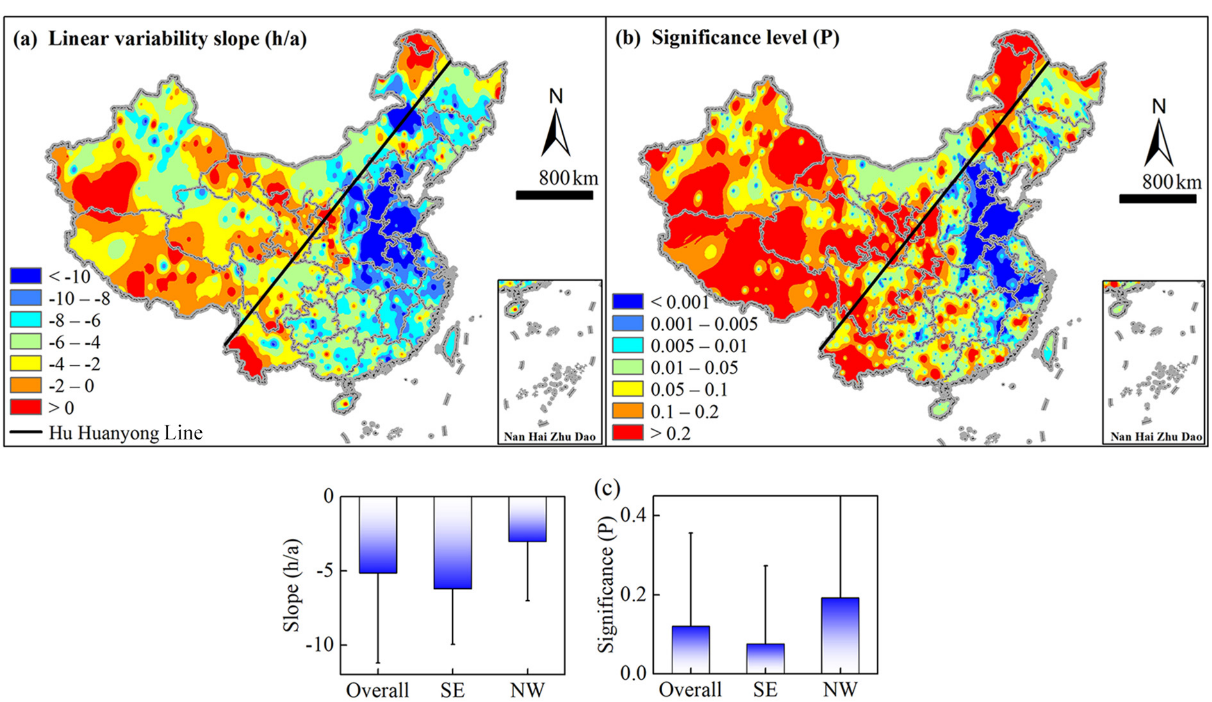

Fig. 1. Spatial patterns and comparison of the linear variability slope and significance level of yearly mean sunshine duration vs year at 839 observation stations in China from 1961 to 2013. Linear fitting slope (a), significance level (b), and comparison of slope and significance level in the whole nationwide, southeastern (SE) and northwestern (NW) regions of the Hu Huanyong Line (c).

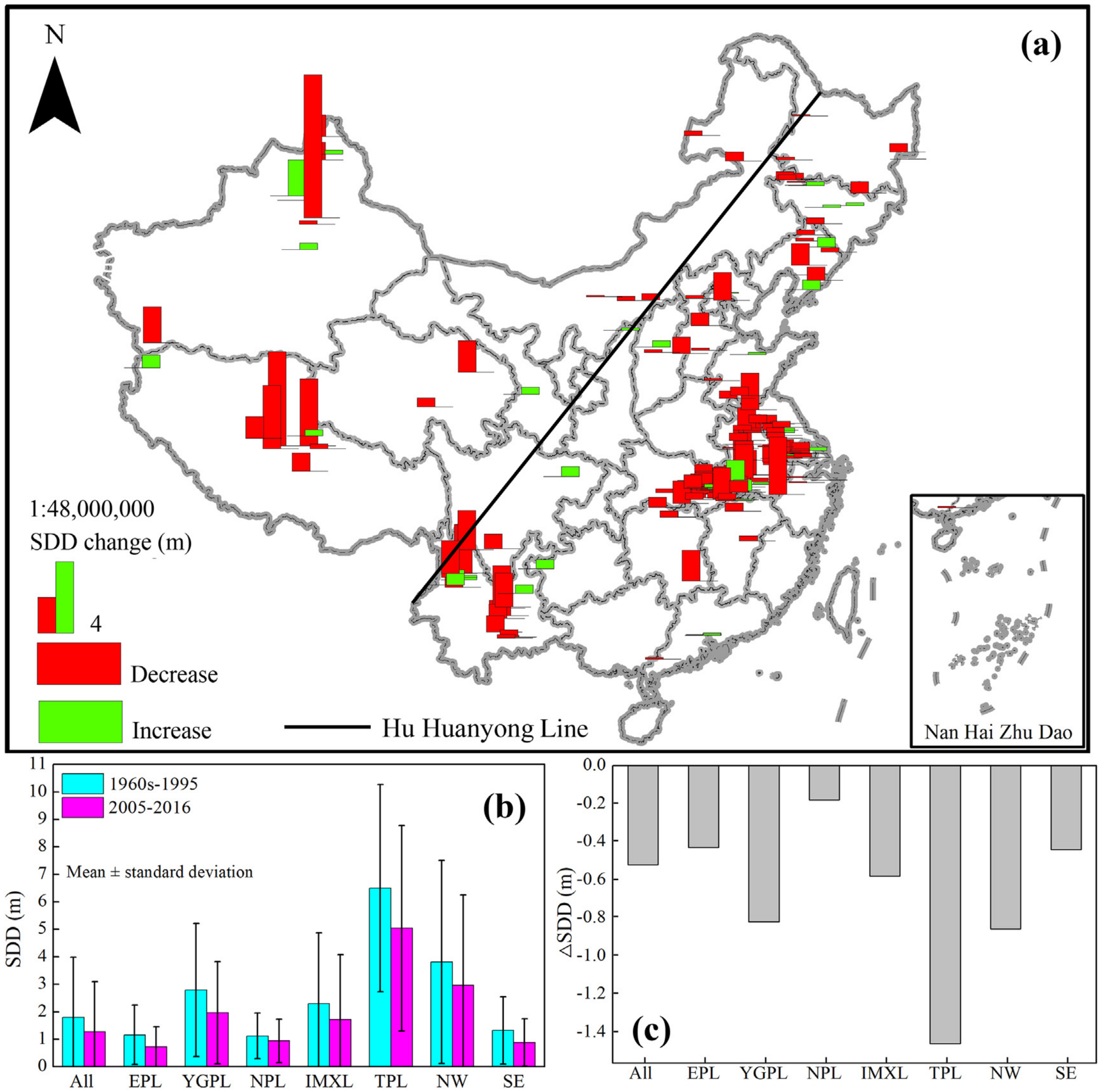

Fig. 2. Spatial distribution of SDD differences during 2005–2016 compared to the 1960s–1995 (a), comparison of SDDs before 1995 to after 2005 according to the five geographic lake zones and the Hu Huanyong Line (b and c) for the dataset of 170 lakes. All: all lakes; EPL: Eastern Plain Lake zone; YGPL: Yunnan-Guizhou Plateau Lake zone; NPL: Northeast Plain Lake zone; IMXL: Inner Mongolia-Xinjiang Lake zone; TPL: Tibetan Plateau Lake zone; NW and SE represent results for lakes in the northwestern and southeastern regions of the Hu Huanyong Line.

in two of the five lake zones, including the EPL from 0.72 to 0.46 m by 57.8% and NPL from 0.55 to 0.36 m by 52.8% ($P < 0.01$, MW test), when we compared the data obtained from 2005 to 2010 with the data recorded from 1985 to 1990 (Fig. 3g, m, and n). In contrast, the remote sensing estimation showed a slight or marked increase in SDDs for lakes in the YGPL (from 1.15 to 1.17 m by 1.8%), IMXL (from 1.02 to 1.10 m by 7.1%), and TPL zones (from 1.64 to 2.02 m by 19.0%, Fig. 3g, m, and n). This finding was generally consistent with the results from the *in situ* investigations and published data, which showed a 22.5% decrease in SDDs for 11 lakes in the TPL zone. In addition, a significant decreasing trend of SDDs was observed in the southeastern region, while an increasing trend was observed in the northwestern region along the Hu Huanyong Line (Fig. 3g, m, and n), consistent with the long-term trends of total radiation and sunshine duration (Fig. 1).

The long-term, site-specific, SDD monitoring in four lakes with different trophic states revealed significant decreases in the underwater light availability from 1980 to 2016. Over this period, a significant decrease in the SDD was recorded in all of the lakes ($P \leq 0.001$, Fig. S4 online). The following mean rates of decrease in the SDD in each of these four lakes were recorded: Lake Fuxianhu 0.60 m/10 a (1980 to 2016), Lake Qiandaohu 1.09 m/10 a (1988 to 2016), Lake Erhai 0.72 m/10 a (1989 to 2016), and Lake Gehu 0.28 m/10 a (1985 to 2016). Based on a linear fitting, decreases of 29.1%, 42.2%, 57.3%, and 83.2% occurred in Lake Fuxianhu, Lake Qiandaohu, Lake Erihai, and Lake Gehu, respectively. Notably, a substantial decrease in the SDD was observed at approximately 2004 in Lake Erhai due to eutrophication and the marked increase in the phytoplankton biomass.

3.3. Correlation between the SDD and diffuse attenuation coefficient

A highly significant correlation was observed between the SDD and K_d(PAR) ($r^2 = 0.935$, $n = 1419$, Fig. 4a), based on the large dataset covering SDDs from < 0.08 m to greater than 8.0 m. This result provides strong quantitative support for calculating the K_d(PAR) from SDD measurements. Using a power function correlation (Fig. 4a), we calculated the mean K_d(PAR) values of (1) 0.81 and 1.13 m^{-1} before 1995 and after 2005, respectively, for *in situ* observations (national investigations and literature dataset); and (2) 1.14 and 1.26 m^{-1} before 1995 and after 2005, respectively, for the remote sensing estimation dataset obtained from Landsat images. Overall, K_d(PAR) values calculated from *in situ* observations were slightly lower than the values calculated from Landsat images.

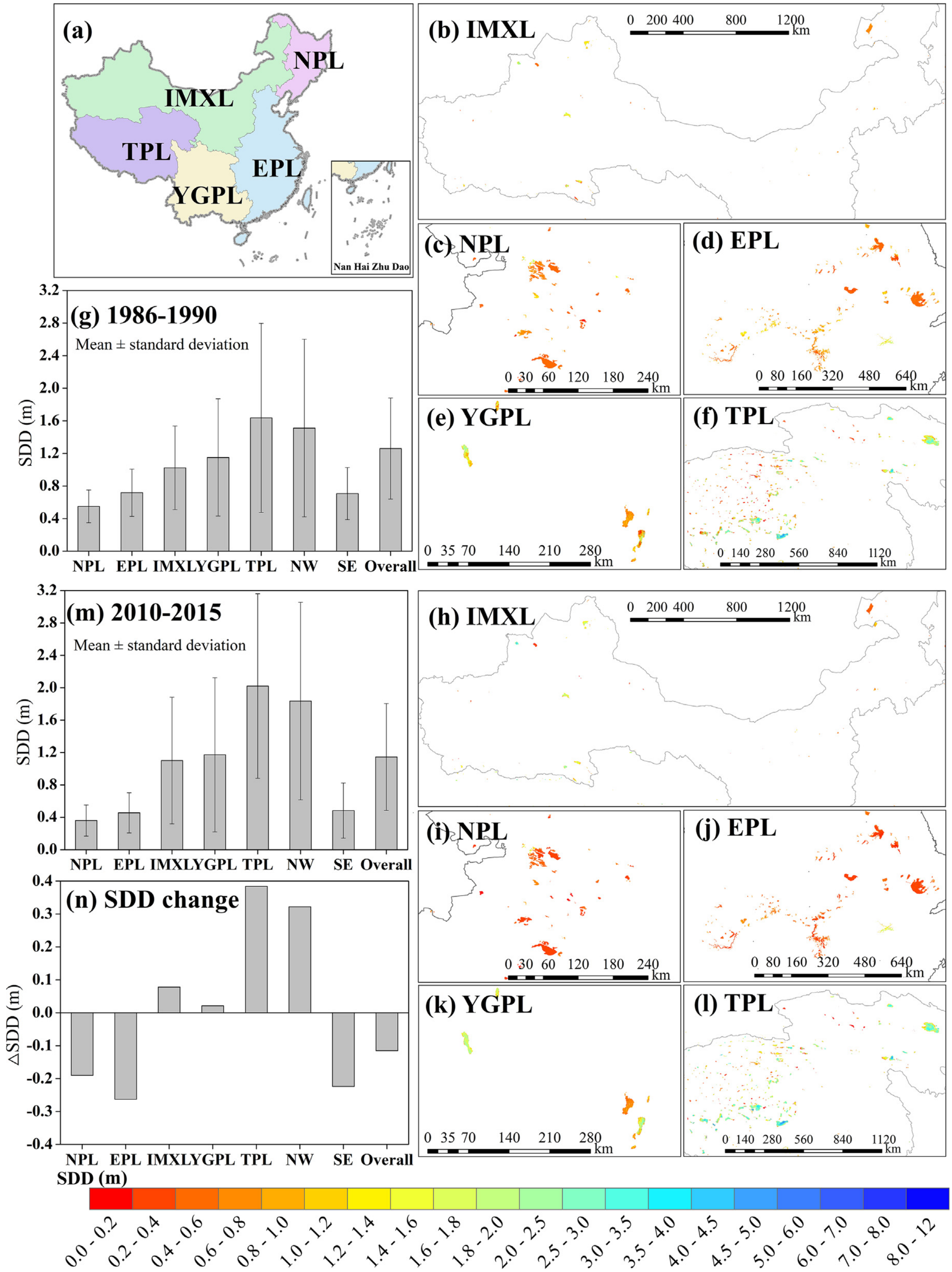

Fig. 3. Distribution of the five geographic lake zones (a), spatial distribution of SDD remote sensing estimates for five geographic lake zones from 1985 to 1990 (b–f) and from 2005 to 2010 (h–l), and a comparison of the mean SDDs for five geographic lake zones, southeastern and northwestern regions along Hu Huanyong Line between from 1985 to 1990 and from 2005 to 2010, and (g, m, and n) for 641 lakes with water area larger than 10 km^2 in China.

3.4. Underwater darkening due to radiation dimming and decreasing SDD

Using the K_d(PAR) values, we calculated the underwater PAR distribution and the relative contributions of radiation dimming and decreasing SDDs in the euphotic zone of lakes (Fig. 4b). Based on *in situ* field measurements and published data, the mean euphotic depth was 5.69 m before 1995 and 4.08 m after 2005, representing a 28.3% decrease. The increase in K_d(PAR), from 0.81 before 1995 to 1.13 m^{-1} after 2005, resulted in a 7.49% decrease in the

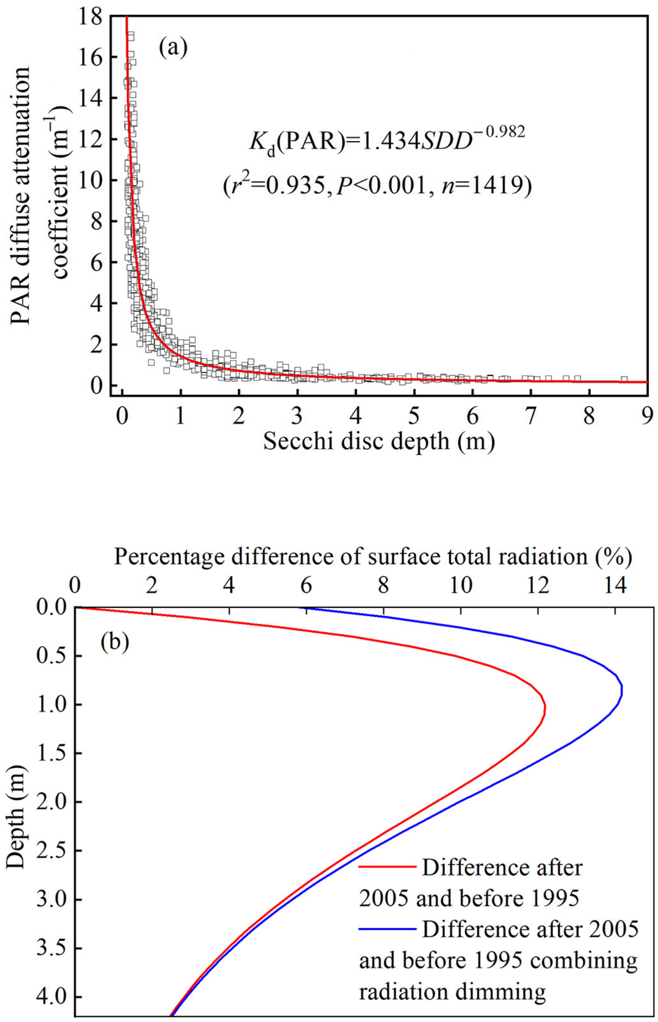

Fig. 4. (Color online) Correlation between the Secchi disk depth and PAR diffuse attenuation coefficient when both were synchronously measured (a), and depth profile of the loss of surface total radiation a fixed euphotic layer when comparing data before 1995 and after 2005 from *in situ* measurements from national investigations and published datasets (b).

average surface PAR in a fixed euphotic layer (1% penetration of light in the water column of 0 to 4.10 m, corresponding to K_d(PAR) value of 1.13 m^{-1}), and a 9.60% loss of the average PAR in the layer with a 10% penetration of light in the water column of 0 to 2.05 m. If we consider a 5.8% decrease in the surface total radiation of 2001 to 2013 compared to the value recorded in 1961 to 1970 due to radiation dimming and assume that PAR is proportional to total radiation, we calculated a 8.77% loss of average surface PAR in the euphotic layer and a 11.85% loss of average PAR in the layer with 10% light penetration (Fig. 4b). In comparison, the relative contributions of the decreasing SDD and radiation dimming to the decrease in the average surface PAR are 85.4% and 14.6% in a fixed euphotic layer (0–4.10 m) and 81.0% and 19.0% in the layer with 10% light penetration (0–2.05 m), respectively. Therefore, decreasing SDD plays a more important role in underwater darkening than radiation dimming in China's lakes.

4. Discussion

4.1. Radiation dimming

In China, the yearly mean total radiation was 5.8% lower after 2000 compared to 1961–1970, although a slight brightening was observed in a minority of stations (Fig. S2 and Table S1 online). The sunshine duration decreased through 2013 in China (Fig. S3 online). Severe aerosol and air pollution over China potentially reduce both the incident total radiation and sunshine duration [8,39]. With the implementation of the "Atmospheric Pollution Prevention and Control Action Plan", atmospheric transparency will be improved to mitigate radiation dimming. However, uncertainties about whether the action will induce the transition from radiation dimming to radiation brightening over China persist because of the effects of increased air pollution and associated dimming that may occur in neighboring, rapidly developing countries [40].

4.2. Decrease in the SDD

The SDD has been widely used to assess underwater light availability and water quality and to estimate phytoplankton biomass and CO_2 fluxes. For example, the phytoplankton biomass, which is commonly expressed as the chlorophyll *a* (Chl*a*) concentration, can be derived from SDD measurements and is similar to the values estimated from direct *in situ* optical measurements or satellite remote sensing [26].

We have now reported 28.9% and 10.1% decreases in the SDD after 2005 compared with the values recorded before 1990 for national *in situ* investigations and remote sensing estimation datasets (Figs. 2 and 3), respectively. A significant decrease in the SDD was observed in the southeastern region along the Hu Huanyong Line for both the *in situ* investigation and remote sensing estimation datasets, indicating that the decrease in the SDD was tightly linked to population agglomeration, rapid economic and social development, and intense human activities in the southeastern region [38]. However, in the past 20 years, extensive lake expansion observed on the Tibetan Plateau due to the warmer and wetter climate may have caused some uncertainties in elucidating the long-term trend of SDD in TPL, as shown in our remote sensing dataset [41], which requires more detailed studies in the future.

Furthermore, this decrease in the SDD was accompanied by a 5.8% decrease in surface total radiation due to radiation dimming, leading to a decrease of 10% in available PAR in the euphotic zone using a national *in situ* investigation dataset. More importantly, the maximal loss of available PAR is recorded at the subsurface corresponding to Chl*a* and primary production maxima (Fig. 4b) [42]. In particular for the EPL an NPL zones located in the southeastern along the Hu Huanyong Line, the highly synchronous and significant decreases in total radiation, sunshine duration, and SDD have resulted in the substantial underwater darkening of lakes (Figs. 1–3). In addition, because PAR is the main energy source of aquatic plants and K_d(PAR) is highly linearly correlated to the ultraviolet radiation diffuse attenuation coefficient (r^2 = 0.96, P < 0.001, n = 381, Fig. S5 online), we have therefore not focused on the effects of the spectral composition of light on ecosystems. Actually, ultraviolet radiation (UVR) reaching the Earth's surface over China decreased significantly from 1961 to 2014 [43], and significant decreases in UVR penetration and exposure were widely observed due to browning [44].

Meanwhile, long-term SDD measurements and remote sensing studies have revealed decreasing water clarity in various aquatic ecosystems, including the coastal waters, estuaries, and lakes, due to human activities and climate change [17,18,20,26] (Fig. 5 and Table S3 online). For example, a 20-year comprehensive SDD dataset assembled from Landsat images covering more than 10,500 lakes from 1985 to 2005 indicated that the SDD remained stable in central and northern Minnesota, but decreasing SDD trends were detected in other eco-regions in southern Minnesota [20]. Extensive browning due to increasing amounts of dissolved organic matter was reported to significantly decrease the SDD in

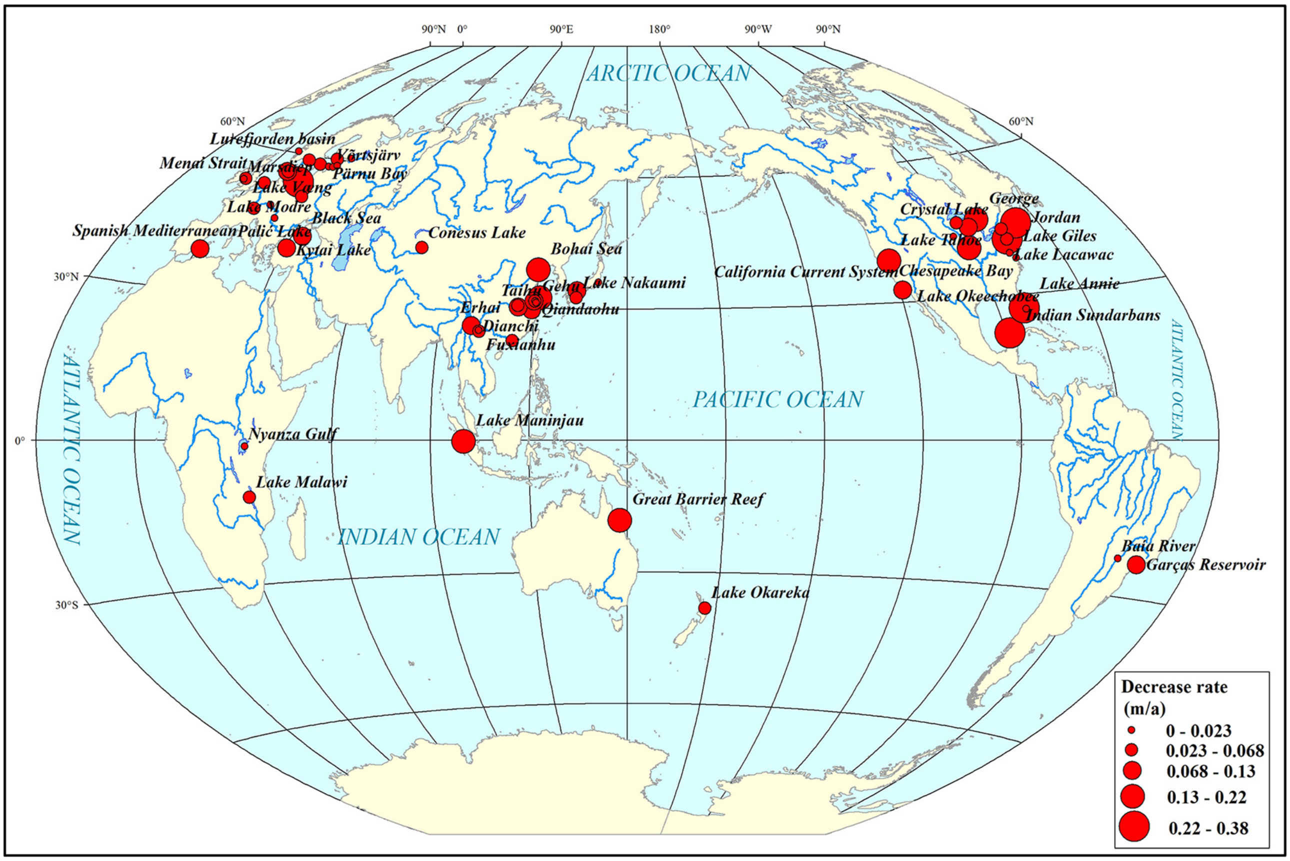

Fig. 5. Map of the world showing significant decreases in the SDD derived from long-term observations in many oceanic, coastal and inland waters from 1896 to 2019. Detailed information about the literature sources is listed in Table S3 (online).

the boreal lakes [44,45]. Therefore, underwater darkening due to decreasing water clarity in aquatic ecosystems is a global environmental problem that is accentuated in China due to the high levels of air and water pollution. In comparison, water pollution has a more important contribution to the underwater darkening of China's lakes than air pollution (9.60% vs 2.25% loss of the average PAR in the water column with 10% light penetration).

The Chinese Central government launched a "Water Pollution Prevention and Control Action Plan" (10-Point Water Plan) in April 2015 to address the water pollution crisis and improve freshwater habitats in the country. The goal is for the SDD to increase with implementation of this plan; however, scenarios from recent climate change models and observations suggest that extreme rainfall events and storms may increase during this century [46,47]. If rainfall and storms increase, turbidity due to increased levels of riverine discharge, sediment resuspension, and bottom and lakeshore erosion may increase in the future. These events will lead to higher concentrations of suspended inorganic solids and dissolved organic matter in the water column [44,47,48], which will decrease the SDD and partially counteract the endeavors to improve the lake water clarity.

4.3. Potential effects of underwater darkening on the aquatic ecosystems

The combined effect of radiation dimming and significant decreases in water clarity on China's lakes will undoubtedly increase underwater darkening, accelerate the deterioration of underwater light availability, and may reduce the macrophyte biomass and primary production, all of which will substantially alter regional carbon and nutrient cycling. As shown in the present study, the mean euphotic depth had decreased from 5.69 m before 1995 to only 4.08 m after 2005 in China, a decrease of approximately 1.50 m based on the national *in situ* investigation dataset. This change has been accompanied by a decrease in the maximum depth of macrophyte colonization [49]. Combining the SDD and aquatic vegetation datasets in our previous study, an average 35.6% decrease in the SDD resulted in an average 62.2% decrease in aquatic vegetation in 31 of China's lakes [50]. Therefore, in the past three decades, the accelerating loss of macrophytes in China's lakes is tightly linked to underwater darkening in lakes [49,50], similar to the situation in Lake Apopka (Florida, USA) [16]. However, our understanding of the mechanisms underlying underwater darkening in lakes on ecosystem evolution will be strengthened by further studies incorporating changes in the phytoplankton biomass and macrophyte cover with changes in the SDD using data from historical investigations and remote sensing.

Although many studies have documented the effects of global warming on aquatic ecosystems around the world [51,52], no previous study has examined the effects of underwater darkening by considering both radiation dimming and decreasing water clarity. Undoubtedly, underwater darkening will reduce the water quality for potable water supplies and recreational demand [25,27,53]. Improved water clarity is associated with increased numbers of visits to lakes and lake users were willing to incur greater costs to visit clearer lakes [27]. In addition, underwater darkening exerts many negative effects on the aquatic ecosystems. In aquatic ecosystems, the primary production of microalgae, macrophyte, and benthic algae is usually limited by light penetration and availability and, to a lesser extent, by other factors, such as nutrients [13,26,49]. Similarly, phytoplankton primary production and fish production are associated underwater light availability [13]. In

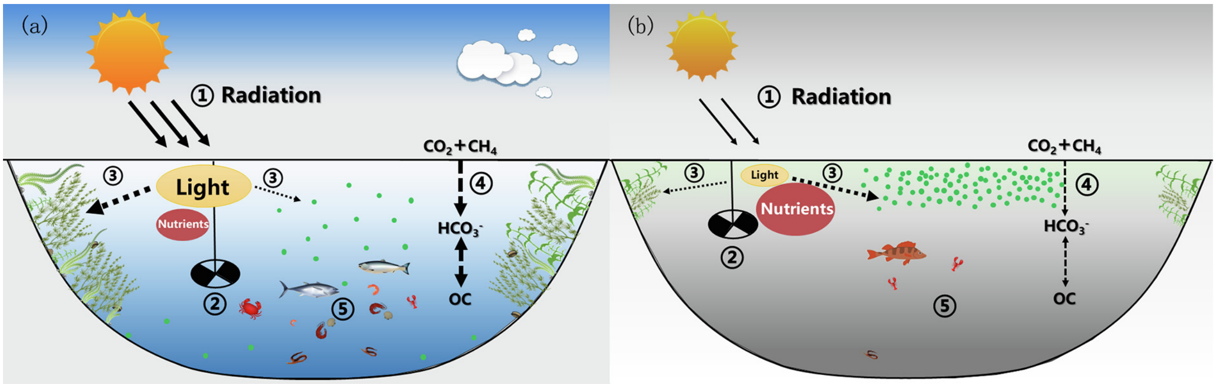

Fig. 6. Causes of underwater darkening and potential effects on aquatic ecosystems through multiple pathways. (a) Scenario before 1995; (b) scenario after 1995. ① Radiation dimming causes a decrease in the amount of total radiation reaching the water surface. ② A decrease in water clarity decreases the euphotic depth and underwater radiation. ③ Underwater darkening will result in macrophyte and benthic algal loss, and a decrease in benthic primary production, which may override possible positive effects of the increase in nutrients associated with underwater darkening on pelagic production. ④ Decreased benthic algal primary production and macrophyte loss may decrease carbon dioxide utilization and organic carbon fixation. ⑤ Underwater darkening may result in decreased fishery production and biodiversity and a loss of ecosystem services.

addition, the aquatic macrophyte biomass and species richness decrease with a decreasing SDD because of lower underwater light availability [15,49,54]. Phytoplankton production and carbon fixation are positively correlated with underwater light availability, euphotic depth, and sunshine duration [14,55]. Underwater darkening, due to radiation dimming, decreasing sunshine duration, and changes in water clarity, causes decreases in the euphotic depth and underwater light availability, and might substantially contribute to decreases in macrophyte and benthic algal primary production [16,56,57] (Fig. 6). Therefore, underwater darkening potentially affects phytoplankton and macrophyte production, CO_2 fluxes, fishery production, biodiversity and ecosystem services [17,26,54,57,58] (Fig. 6). Meanwhile, the increase in the phytoplankton biomass and algal bloom on the water surface caused by eutrophication may partially compensate for the decrease in phytoplankton primary production due to underwater darkening. However, for most unproductive natural lakes worldwide, nutrient input associated with terrestrial organic matter often increases underwater light attenuation and decreases the associated benthic (light-limited) production, which may override possible positive effects of increased nutrients on pelagic (nutrient-limited) production [13,45]. Similarly, if the substances reducing water clarity adsorb a greater proportion of UV in the surface layer, then photo-inhibition may also be reduced, which may compensate for some loss of light availability. Therefore, additional studies are needed to elucidate the interactive effects of eutrophication and underwater darkening on aquatic ecosystems.

In conclusions, this study documents that radiation dimming, decreasing sunshine duration, and decreasing water clarity have together led to an acceleration of underwater darkening. Decreased water clarity plays a more important role in underwater darkening in aquatic ecosystems than radiation dimming. Underwater darkening likely affects many vital ecological and economic issues, such as phytoplankton and aquatic vegetation production, fishery production, and biodiversity.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Yunlin Zhang, Boqiang Qin and Kun Shi designed the study. Yunlin Zhang, Kun Shi, Yibo Zhang, Jianming Deng, Yongqiang Zhou, Xiaolong Yao, Miao Liu, Guangwei Zhu, and Lu Zhang conducted the experiments and collected and analyzed the data. Yunlin Zhang wrote the main manuscript text. Boqiang Qin, Martin Wild, Lin Li, Binhe Gu and Justin D. Brookes contributed to writing and editing the manuscript. All authors discussed the results and contributed to editing the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2020.06.016.

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Yunlin Zhang is a professor at Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. His study interests cover lake optics and water colour remote sensing, lakes thermodynamics, and chromophoric dissolved organic matter biogeochemistry cycle.

Boqiang Qin is a professor at Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences, and Director of Taihu Laboratory for Lake Ecosystem Research. His study fields include hydrology, physical limnology, and aquatic ecology. Currently he focuses on dynamics of Lake Eutrophication, nutrient reduction and ecological restoration.