Radiation dimming and decreasing water clarity fuel underwater darkening in lakes

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Abstract:

Long-term variability in aerosols and the associated declined incident total radiation, and anthropogenic disturbances and excessive nutrients loadings induced declined water clarity can profoundly affect the underwater light environment in aquatic ecosystems. However, the affecting mechanism and relative contribution of radiation dimming and decreasing water clarity to underwater light environment across nationwide (or worldwide) 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 data indicated that total radiation and sunshine duration decreased by 5.8% and 7.9% 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 mean SDD significantly decreased from 1.80 ± 2.19 m before 1995 to 1.28 ± 1.82 m after 2005. SDD remote sensing estimation for 641 lakes with areas ≥ 10 km² 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 average available PAR in the euphotic layer. Our results showed a more important role in underwater darkening of decreasing water clarity than radiation dimming. A meta-analysis of long-term SDD observation data from 61 various waters further elucidate a global extensive underwater darkening. Underwater darkening implies declined water quality for potable water supplies, recession in macrophytes and benthic algae, as well as declined benthic primary production, fishery production, and biodiversity.

Key words: radiation dimming, underwater darkening, Secchi disk depth, remote sensing

Introduction

Solar radiation reaching the Earth's surface is the predominate energy source to support life, with profound impacts on surface temperature, evaporation, the hydrological cycle, and the structure, function and service of terrestrial and aquatic ecosystems ^[1-5]. In the past six decades, radiation dimming have been observed worldwide, causing a decrease of 4% to 6% in surface total radiation, due to air pollution and associated increased aerosol caused by intense human activities ^[6-9]. Since the 1990's, there has been a partial recovery in Europe and North America, known as radiation brightening, due to the increase of atmospheric clear-sky transparency ^[1, 9]. However, current surface total radiation worldwide remains markedly lower than that in the 1950s, despite 20 years of radiation brightening ^[10, 11].

In China from 1960 to 1990, there was a marked dimming in surface total radiation nationwide while some studies in the 1990s reported a slight recovery in brightening ^[1, 6]. However, in the early years of 2000s there was renewed dimming, which was partially attributed to a doubling in consumption of coal in China between 2002 and 2007 ^[9, 10]. A study in 2018 indicated that the transition from dimming to brightening in China may have only occurred after 2005 based on carefully homogenized data ^[8]. In China, the high levels of air pollution have counteracted the effects of the radiation brightening since 1990, contrasting with the results from Europe and North America.

Surface total radiation, or more specifically, its photosynthetic 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 affects 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 can have a marked effect on the role of vegetation as a carbon sink [3, 12].

Although nutrient limitation is an important paradigm for aquatic plants growth in lakes, the importance of light availability is often underestimated especially for wide distribution nutrient-poor lakes [13, 14]. In aquatic ecosystems, both phytoplankton and aquatic macrophytes depend on underwater radiation amount for photosynthesis [14-16], and thus both biomass and primary production are sensitive to light availability and underwater darkening [17]. Underwater darkening could greatly induce benthic primary production decrease, food resources destruction and predatory environment deterioration for those photosensitive aquatic organisms [14, 18, 19]. However, few studies have assessed the effects of underwater darkening on aquatic ecosystems [17]. For aquatic ecosystems, the underwater darkening can be caused by a combination of radiation dimming and decreasing water clarity. In summary, water clarity is jointly determined by pure and three optically active substances including phytoplankton, non-phytoplankton particle matter, and dissolved organic matter. Therefore, any processes resulting in the 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.

Determining water clarity, Secchi disk depth (SDD), is a quick and useful way to evaluate the underwater light environment and the trophic state of aquatic ecosystems [20-22]. Traditional *in situ* SDD measurement using Secchi disk has been carried out for more than 150 years [20]. In the past decades, remote sensing is considered as 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 [23]. Many arduous efforts have been

made to develop a series of empirical, semi-empirical, and semi-analytical algorithms to estimate SDD and explore the long-term change over different inland waters using Landsat, MERIS, MODIS, etc [22, 24-27]. Decrease in water clarity has been linked to the 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 [14, 19, 28, 29]. Some previous efforts have attempted to explore long-term trends in SDD and elucidate the potential effects for many regional lakes [22, 27, 30]. However, China lacks a recent national dataset of the 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 ecosystem changes. More importantly, no published study around the world 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 that of radiation dimming. We pursue three specific objectives to: 1) quantify whether there has been a decrease in incident total radiation and sunshine duration throughout China; 2) quantify whether there has been a nation-wide decrease in lake water clarity; 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 the carbon dynamics. Our results provide a new perspective on underwater darkening and future carbon dynamics study in lakes. Considering the complex and different affecting processes of SDD for specific lake, our study has not attempted to elucidate the specific affecting factors of SDD.

Materials and methods

Surface total radiation and sunshine duration

Surface total radiation data was examined from a 53-year record from 1961 to 2013, at 116 radiation observation station in China, which was the new and complete total radiation data that we could collect. Data came from 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 (Fig. S1). The data availability was: complete data for all 53 years for 57 of the 116 stations; data 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 of total radiation in China [6-8]. Considering that sunshine duration is also 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). Sunshine duration data of 839 stations is continuing and complete for the period from 1961 to 2013.

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

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

Temporal changes in SDD were determined by comparing the values for 170 lakes in China before 1995 with those after 2005 (Table S2). These time periods were determined by the availability

of data from the first and second nationwide lake investigations, which were undertaken from the 1960s to 1980s, and 2005 to 2010, respectively. The 170 lakes in this dataset ranged from $< 1 \text{ km}^2$ to $> 4000 \text{ km}^2$ in water area and from $< 1 \text{ m}$ to $> 150 \text{ m}$ in mean depth (Table S2), covered different trophic states, and represented five previously-defined geographic lake zones in China [31-33].

The regional survey data were supplemented with more intensive SDD monitoring data over 30 to 37 years with an interval of monthly measurement 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 [33-35].

Remote sensing estimation of SDD before 1995 and after 2005

The uneven geographical distribution of *in situ* SDD data from historical investigations and the published literatures prompted us to seek data from remote sensing, from which we could estimate SDD for China's lakes. We used remote sensing data from Landsat images with 30 m spatial resolution, for two periods, 1985 to 1990 and 2005 to 2010, 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 $\geq 10 \text{ km}^2$ to reduce the uncertainty in estimates.

A total of 26321 high-quality Landsat 5 TM and 7 ETM+ scenes image of China's lakes were downloaded from the United States Geological Survey (USGS) (<http://glovis.usgs.gov/>) in summer and spring (July 1 to September 30) during two periods of 1985 to 1990 and 2005 to 2010. We selected these seasons because there is no ice cover for all China's lakes and the sky is clear in most conditions. On average, more than 2000 scenes image in every year are used, which normally meet

the need of SDD estimation for nationwide lakes. More importantly, we only compare the difference of two periods of 1985 to 1990 and 2005 to 2010 to reduce the errors and uncertainties of data as far as possible. Of course, there are some uncertainties for remote sensing data because our dataset only includes four months in summer and spring seasons. The Landsat 5 TM and 7 ETM+ images were level-1 processed, meaning 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 influence of atmospheric absorption and scattering.

To retrieve an accurate remote sensing reflectance used to estimate SDD, 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. The SDD is strongly correlated with the responses in the blue and red bands of Landsat TM/ETM+ data [36, 37]. To calibrate and validate our SDD estimation model, we used two complete independent datasets. We obtained the *in situ* SDD from 225 China's lakes covering 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 [38]. 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 falling in the SDD range of the calibration dataset.

For the large calibration dataset (887 samples), there was a highly significant power function correlation ($r^2=0.73$, $p<0.001$) between the remote sensing reflectance of red Band 3 (630-690 nm)

derived from Landsat 5 TM, 7 ETM+ and SDD. The independent validation dataset showed that the measured and estimated SDD were distributed 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 could be well used to estimate SDD of China's lakes covering SDD from less than 0.1 m to more than 10 m. Detailed information about the model calibration, validation, and assessment is found in our previous study [38]. Overall, the SDD estimation model precision in our study was accepted compared to previous similar studies [24-27].

Literature data on marked decrease in long-term SDD

Meta-analysis from the literature is a good way to summarize the available evidences to provide a more robust result than a single study. In detail, we extracted, from the published literatures, long-term SDD data for various waters including oceanic, coastal and inland waters around the world, 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").

Measurement and calculation of underwater PAR

The underwater PAR profile and SDD were synchronously measured in diverse waters, comprising 25 lakes from very clear (Lake Fuxianhu) with SDD > 6.0 m to highly turbid waters (Lake Taihu) with 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 influence of reflectance from the vessel on the underwater PAR. Measurement of underwater PAR was generally carried out between 8:30 and 17:00 on cloudless days. PAR measurements were made 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 for 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 as the PAR intensity for that depth, to minimize the effect of wind-generated waves on measurement of underwater PAR.

The diffuse attenuation coefficients for the downward irradiance, $K_d(\text{PAR})$, were determined as the slope of the linear fitting of the log-transformed profile underwater irradiance vs depth [39]. We accepted only $K_d(\text{PAR})$ values from regressions with the determination coefficient (r^2) more than 0.98. The number of depths used in these regressions was 6-30, depending on the penetration depth and water depth.

To correlate SDD with $K_d(\text{PAR})$, and calculate euphotic depth (the depth at which PAR is 1% of its value at the water surface), a dataset of 1219 SDD from < 0.1 m to > 8.0 m was used encompassing most of the range of lake water clarity observations used worldwide [22, 30].

‘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 is basically coincided with the 400 mm precipitation isoline. The statistical data in 2010 showed that the southeast region of the ‘Hu Huanyong’ Line (except for Hong Kong, Macao, and Taiwan province) covered 36.0% of the total area of mainland but gathered 94.0% of the population and contributed to 95.7% of the national gross domestic product in China. Therefore,

this line can be regarded as an important geographical, economic, social, and human activity intensity division line in China ^[40].

Data statistical analyses

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

Results

Radiation dimming in China

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

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

Fig. 1. Spatial patterns and comparison of linear variability slope and significance level of yearly mean sunshine duration vs year at 839 observation stations in China 1961 – 2013. Linear fitting slope (left), significance level (middle), and comparison of slope and significance level in the whole nationwide, southeastern (SE) and northwestern (NW) of the ‘Hu Huanyong’ Line (right).

Decreasing SDD in China’s lakes

The dataset from two national lake investigations and the literatures cover a large variability of SDD from 0.12 to 13.3 m from 1960s to 1995 partially demonstrating different trophic gradients from oligotrophic to hyper-eutrophic. A comparison of all 170 lakes revealed a SDD decrease in

130 lakes (76.5%), an increase in 40 lakes (23.5%) during 2005 to 2016 when compared with the 1960s to 1995. The number of lakes with a SDD decrease was more than three times that of lakes with a SDD increase. Among all 170 lakes with *in situ* SDD data (uncertainty ≤ 0.05 m), the average SDD significantly decreased by 28.9% from 1.80 ± 2.19 m from 1960s to 1995 to only 1.28 ± 1.82 m during 2005-2016 ($p < 0.05$, MW test) (Fig. 2).

Fig. 2 Spatial distribution of SDD differences during 2005-2016 compared to 1960s-1995 (a), SDD comparison before 1995 compared to after 2005 according to the five geographic lake zones and the 'Hu Huanyong' Line (b, c) based on the *in situ* dataset of 170 lakes in China; 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 represents results for lakes in the northwestern and southeastern regions of the 'Hu Huanyong' Line.

Spatially, SDD decreased more in lakes located in the Eastern Plain Lake (EPL) zone than those 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. For the 130 lakes with a SDD decrease, there was a significant decrease of 41.3% from 1.89 ± 2.12 m during 1960s-1995 to 1.11 ± 1.46 m during

2005-2016 ($p < 0.001$, MW test). In contrast, for the 40 lakes with a SDD increase, the non-significant increase was from 1.52 ± 2.40 m during 1960s-1995 to 1.84 ± 2.63 m during 2005-2016 ($p > 0.05$, MW test).

We compared the spatial distribution of remote sensing-based SDD of lakes in the five geographic lake zones during the two time periods across China with water area ≥ 10 km² (Fig. 3). There were marked decreases in SDD nationally (from 1.26 to 1.14 m by 10.1%), and significant decreases in SDD in two of the five lake zones including EPL (from 0.72 to 0.46 m by 57.8%), NPL (from 0.55 to 0.36 m by 52.8%) ($p < 0.01$, MW test), respectively, when comparing the 2005 to 2010 with the 1985 to 1990 data (Fig. 3g, 3m, 3n). In contrast, the remote sensing estimation showed a slight or marked increase in SDD for lakes in 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, 3m, 3n). This was overall consistent with results from that of the *in-situ* investigations and literature data, which showed a 22.5% decrease in SDD for 11 lakes in the TPL zone. In addition, significant decreasing trend of SDD was observed in the southeastern region while an increasing trend was found in the northwestern region along the ‘Hu Huanyong’ Line (Fig. 3g, 3m, 3n), which was consistent to the long term trend of total radiation and sunshine duration (Fig. 1).

Fig. 3 Distribution of the five geographic lake zones (a), spatial distribution of SDD remote sensing estimation for five geographic lake zones from 1985 to 1990 (b-f) and from 2005 to 2010 (h-l), mean SDD comparison for five geographic lake zones, southeastern and northwestern regions along 'Hu Huanyong' line between from 1985 to 1990 and from 2005 to 2010 (g, m, n) for

641 lakes with water area larger than 10 km² in China

The long-term, site-specific, SDD monitoring in four different trophic state lakes showed that significant decreases also occurred in the underwater light availability from 1980 to 2016. Over this period of time, a significant decrease in SDD was recorded in all of the lakes ($p \leq 0.001$) (Fig. S4). The mean decreasing rate of SDD in each of these four lakes was: Lake Fuxianhu 0.60 m/decade (1980 to 2016), Lake Qiandaohu 1.09 m/decade (1988 to 2016), Lake Erhai 0.72 m/decade (1989 to 2016), and Lake Gehu 0.28 m/decade (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. It was noteworthy that a sharp decrease of SDD was observed around 2004 in Lake Erhai due to eutrophication and the marked increase of phytoplankton biomass.

Correlation between SDD and diffuse attenuation coefficient

A highly significant correlation was found between SDD and $K_d(\text{PAR})$ ($r^2=0.935$, $n=1419$) (Fig. 4a), based on the large dataset covering SDD from < 0.08 m to > 8.0 m. This result provides strong quantitative support for calculating $K_d(\text{PAR})$ from SDD measurements. Using a power function correlation (Fig. 4a), we calculated that the mean $K_d(\text{PAR})$ values were: (i) 0.81 and 1.13 m⁻¹ before 1995 and after 2005, respectively for *in situ* observations (national investigations and literature dataset); and (ii) 1.14 and 1.26 m⁻¹ before 1995 and after 2005, respectively for Landsat 5 TM images remote sensing estimation dataset. Overall, $K_d(\text{PAR})$ values calculated from *in situ* observations were slightly lower than those calculated from Landsat 5 TM images.

Underwater darkening due to radiation dimming and decreasing SDD

Using the $K_d(\text{PAR})$ values, we calculated the underwater PAR distribution and the relative contributions of radiation dimming and decreasing SDD in euphotic zone of lakes (Fig. 4b). Based

on *in situ* field measurements and literature data, the mean euphotic depth was 5.69 m before 1995 and 4.08 m after 2005 representing a 28.3% decrease. The increase of $K_d(\text{PAR})$, from 0.81 before 1995 to 1.13 m^{-1} after 2005, resulted in a 7.49% decrease of average surface PAR in a fixed euphotic layer (1% penetration of light in the water column of 0 to 4.10 m corresponding to $K_d(\text{PAR})$ value of 1.13 m^{-1}), and a 9.60% loss of average PAR in the layer with 10% penetration of light in the water column of 0 to 2.05 m. If we consider a 5.8% decrease of surface total radiation of 2001 to 2013 compared to that of 1961 to 1970 due to radiation dimming, and assume that PAR is proportional to total radiation, we can determine 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 SDD decreasing and radiation dimming to the decrease of average surface PAR are 85.4% and 14.6% in a fixed euphotic layer (0 – 4.10 m), 81.0% and 19.0% in the layer with 10% light penetration (0 – 2.05 m). Therefore, decreasing SDD plays a more important role in underwater darkening than does radiation dimming in China's lakes.

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

Discussion

Radiation dimming

Our results show these indications: (i) in China, 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); and (ii) in China, sunshine duration decreased through 2013 (Fig. S3). Severe aerosol and air pollution over China potentially reduce both incident total radiation and sunshine duration [9, 41]. With the implementation of the “Atmospheric Pollution Prevention and Control Action Plan”, atmospheric transparency will be improved to mitigate radiation dimming. However, there are still uncertainties if the action can induce the transition from radiation dimming to radiation brightening over China, because of the influence of increased air pollution and associated dimming which may occur in neighboring, rapidly-developing countries [42, 43].

Decrease in SDD

SDD has been widely used to assess underwater light availability and water quality, and estimate phytoplankton biomass and CO₂ fluxes. For example, phytoplankton biomass, commonly expressed using chlorophyll a (Chl_a) concentration can be derived from SDD measurements, which is closely comparable to those estimated from direct *in situ* optical measurements or satellite remote sensing [28, 44].

We have now reported 28.9% and 10.1% decrease in SDD after 2005 compared with that before 1990 for national *in situ* investigation and remote sensing estimation datasets (Fig. 2, Fig. 3), respectively. Significant SDD decrease was found in the southeastern region along the ‘Hu Huanyong’ Line for both *in situ* investigation and remote sensing estimation datasets, which reflected SDD decrease was tightly linked to population agglomeration, rapid economic and social

development, and strong human activities in the southeastern region ^[40]. However, in the past 20 years, extensive lake expansion observed on the Tibetan Plateau due to the warmer and wetter climate may cause some uncertainties to elucidate the long-term trend of SDD in TPL as our remote sensing dataset showed ^[45], which requires more detailed studies in the future.

Furthermore, this decrease in SDD was accompanied by a 5.8% decrease in surface total radiation due to radiation dimming, which has led to a decrease of 10% in available PAR in the euphotic zone using national *in situ* investigation dataset. More importantly, the maximal loss of available PAR is recorded at the sub-surface corresponding to Chla and primary production maxima (Fig. 4b) ^[46]. Especially for EPL and NPL zones locating in the southeastern along ‘Hu Huanyong’ line, the highly synchronous significant decreases in total radiation, sunshine duration, and SDD have greatly resulted in underwater darkening of lakes (Figs. 1-3). In addition, because PAR is the main energy source of aquatic plants and $K_d(\text{PAR})$ is highly linearly correlated to ultraviolet radiation diffuse attenuation coefficient ($r^2=0.96$, $p<0.001$, $n=381$) (Fig. S5), we have therefore not focused on the effects of the spectral composition of light on ecosystems. Actually, ultraviolet radiation (UVR) reaching the Earth surface over China significantly decreased markedly from 1961 to 2014 ^[47], and significant declines in UVR penetration and exposure were widely observed due to browning ^[48].

Meanwhile, long-term SDD measurements and remote sensing studies have indicated that water clarity is decreasing in various aquatic ecosystems, including the coastal waters, estuaries, and lakes, due to human activities and climate change ^[18, 19, 22, 28, 49] (Fig. 5 and Table S3). For example, a 20-year comprehensive SDD dataset assembled from Landsat imagery covering more than 10,500 lakes from 1985 to 2005 indicated SDD remained stable in central and northern

sediment resuspension, and bottom and lakeshore erosion may increase in the future. Such events will lead to higher concentrations of suspended inorganic solids and dissolved organic matter in the water column [48, 53, 54], which will decrease SDD and partially counteract the endeavors of lake water clarity improvement.

Potential effects of underwater darkening on the aquatic ecosystems

The combined effect of radiation dimming and significant decreases in water clarity in China's lakes will undoubtedly increase underwater darkening, accelerate the deterioration of underwater light availability, and could reduce macrophyte biomass and primary production; all of which could strongly influence regional carbon and nutrient cycling. Our study demonstrated that 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 [55]. Combining SDD and aquatic vegetation datasets in our previous study, an average 35.6% decrease of SDD resulted in an average 62.2% decrease of aquatic vegetation in 31 China's lakes [56]. Therefore, in the past three decades, the accelerating loss of macrophyte in China's lakes is tightly linked to lake underwater darkening [55, 56], similar to the situation in Lake Apopka (Florida, USA) [17]. However, our understanding of the driving mechanisms of lake underwater darkening on ecosystem evolution will be strengthened by further study by incorporating phytoplankton biomass and macrophyte cover changes with SDD change using data from historical investigations and remote sensing.

Although many studies have documented the effects of global warming on aquatic ecosystems around the world [57-59], no previous study has examined the effects of underwater darkening

considering both radiation dimming and decreasing water clarity. Undoubtedly, underwater darkening will cause the reduced water quality for potable water supplies and recreational demand [27, 29, 60]. Improved water clarity was associated with increased numbers of visits to lakes and lake users were willing to incur greater costs to visit clearer lakes [29]. In addition, underwater darkening has 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 less by other factors such as nutrients [14, 28, 55]. Similarly, phytoplankton primary production and fish production have been linked to underwater light availability [14]. In addition, aquatic macrophyte biomass and species richness decrease with decreasing SDD because of lower underwater light availability [16, 61, 62]. Phytoplankton production and carbon fixation are positively correlated with underwater light availability, euphotic depth, and sunshine duration [15, 63]. Underwater darkening, due to radiation dimming, decreasing sunshine duration, and water clarity, causes decreases in euphotic depth and underwater light availability, and could greatly contribute to decreases in macrophyte and benthic algal primary production [17, 64, 65] (Fig. 6). Therefore, underwater darkening potentially could impact phytoplankton and macrophyte production, CO₂ fluxes, fishery production, biodiversity and ecosystem services [18, 28, 61, 65, 66] (Fig. 6). Meanwhile, it is noteworthy that phytoplankton biomass increase and algal bloom around the water surface caused by eutrophication may partially compensate the decrease of phytoplankton primary production due to underwater darkening. However, for most unproductive natural lakes worldwide, nutrients input associated with terrestrial organic matter often causes the increase of underwater light attenuation and associated benthic production (light-limited) decrease, which may override possible positive effects of nutrients increase on pelagic production (nutrient-limited) [14, 50]. 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, more study is needed to elucidate the interactive effects of eutrophication and underwater darkening on aquatic ecosystems.

Fig. 6 Underwater darkening causes and potential effects on aquatic ecosystems in multiple ways.

(a) Scenario before 1995, (b) Scenario after 1995.

(1) Radiation dimming causes total radiation decrease reaching the water surface; (2) Water clarity decrease causes euphotic depth and underwater radiation decrease; (3) Underwater darkening will result in macrophyte, benthic algal loss, and the decrease of benthic primary production which may override possible positive effects of nutrients increase 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 fishery production and biodiversity decreases and ecosystem services loss.

In conclusions, this study documents that radiation dimming, decreasing sunshine duration, and decreasing water clarity have altogether led to accelerating underwater darkening. Decreased water clarity plays a more important role in underwater darkening than does radiation dimming in aquatic ecosystems. This could affect many vital ecological and economic issues, such as phytoplankton and aquatic vegetation production, fishery production, and biodiversity.

Acknowledgments

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Supplementary materials

Fig. S1 Spatial distribution of 839 sunshine stations and 116 radiation stations in China

Fig. S2 Spatial distribution of long-term trends of total radiation at 116 observation stations in China for 1961-2013. The numerical values represent the station numbers listed in Table S1. The red circles represent a linear fitting slope greater than 0, and the blue squares represent a linear fitting slope less than 0. The hollows in the circles and squares indicate that the linear fitting is significant ($p < 0.05$). Changes were significant for 49 of 90 stations with slope < 0 , and for 5 of 26 stations with slope > 0 . Different background color represents five geographic lake zones.

Fig. S3. Long-term trend of yearly mean sunshine duration at 839 stations in China.

Fig. S4. Long-term decreases of SDD from four typical lakes: (a) Lake Fuxianhu, very clear oligotrophic deep lake; (b) Lake Qiandaohu, very clear oligotrophic- mesotrophic deep reservoir; (c) Lake Erhai, moderately clear mesotrophic deep lake; (d) Lake Gehu, highly turbid eutrophic

shallow lake.

Fig. S5. Correlation between UVR and PAR diffuse attenuation coefficients

Table S1. Detailed information on the 116 sampling stations (province, number, name, code, and altitude), and linear fitting results of yearly total radiation vs year, and the observation period.

Table S2. Detailed information on 170 lakes (zones, province, number, name, latitude, longitude, lake area, mean water depth), the SDD from two different periods (before 1995 [most before 1990] and after 2000), and the percentage change between them (comparing after 2005 with before 1995); a decrease is shown by a downward arrow.

Table S3. Summary of linear fitting, statistical parameters from 61 long-term observations of decreasing SDD, from published literature ($n = 54$) and from the present study ($n = 7$).

Data availability

The data that support the findings of this study will be open once this manuscript is accepted for publication.

Author contributions

Y.L.Z., B.Q.Q and K.S. designed the study. Y.L.Z., K.S., Y.B.Z., J.M.D., Q.F.H., Y.Q.Z., X.L.Y., M.L., G.W.Z., and L.Z. conducted the experiments and collected, analysed the data. Y.L.Z. wrote the main manuscript text. B.Q.Q., M.W., L.L., B.H.G. and J.D.B. contributed to analyzing the data and writing and editing the manuscript. All authors discussed the results and contributed to manuscript editing.

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Supplementary Material

Radiation dimming and decreasing water clarity fuel underwater darkening in lakes

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A standard 30-cm diameter Secchi disk was used to measure the SDD. The Secchi disk is a circular black-and-white disk that is lowered into a body of water by an observer until it disappears from view, and the depth at which it is no longer visible is recorded as the transparency. *In situ* SDD measurements were carried out in 170 lakes before 1995 and after 2005 from two nation-wide lake investigations and published literature, and four special lakes for more than 25 years long-term site-specific observations. 170 lakes were distributed in five geographic lake zones in China (Fig. S2).

In addition, there were four lakes that were studied in details for the long-term (more than 25 years), site specific, *in situ* SDD measurement. Lake Fuxianhu (24°21'~24°38'N, 102°49'~102°57'E; Fig. 1) is a warm fault lake located in the middle of the Yungui Plateau in southwestern China (Yuxi City, Yunnan Province). Lake Fuxianhu is characterized by a central subtropical, plateau, semi-humid, monsoon climate. This lake has a water area of 211.0 km², a mean depth of 89.6 m, a maximum depth of 155.0 m, and a water storage of 189.0×10⁸ m³ at a water level of 1771.0 m. Lake Fuxianhu is a clear oligotrophic deep lake with a mean SDD of 6.20 m (1).

Lake Qiandaohu (29°22'-29°50'N, 118°36'-119°14'E) was originally called Xin'anjiang Reservoir and is located in western Zhejiang Province and southern Anhui Province. Lake Qiandaohu has a water area of 580 km², an average depth of 30 m, a water volume of 178.4×10⁸ m³, and a basin area of 10,480 km² when the water level is 108 m. Lake Qiandaohu is a clear oligotrophic - mesotrophic deep lake with the mean SDD of 6.39 m (2).

Lake Erhai (25°35'–25°58' N, 100°5'–100°17' E) is located in Yunnan Province, Southwest China. The lake has a water area of 249.8 km², a mean water depth of 10.5 m and a maximal depth of 21.0 m. Lake Erhai is a medium clear mesotrophic deep lake with the mean SDD of 2.75 m.

Lake Gehu (30°28'–31°42'N and 119°44'–119°53' E) is a large freshwater lake in China, which

is located in the Yangtze River Delta and has a water area of 146.5 km², a mean depth of 1.2 m. As a typical eutrophic shallow lake, Lake Gehu has experienced serious lake eutrophication, algal blooms and water quality deterioration in the past 30 years.

The Eastern Plain Lake (EPL) zone covers the municipalities of Beijing, Shanghai, and Tianjin; the provinces of Anhui, Fujian, Guangdong, Guangxi, Hainan, Henan, Hubei, Hunan, Jiangsu, Jiangxi, Shandong, Taiwan, and Zhejiang; and the Special Administrative Regions of Hong Kong and Macao. The Yunnan-Guizhou Plateau Lake (YGPL) zone covers the municipality of Chongqing and the provinces of Yunnan, Guizhou and Sichuan. The Northeast Plain Lake (NPL) zone covers the provinces of Liaoning, Jilin and Heilongjiang. The Inner Mongolia-Xinjiang Lake (IMXL) zone covers the provinces of Gansu, Shaanxi and Shanxi and autonomous regions of Inner Mongolia, Xinjiang Uygur and Ningxia Hui. The Tibetan Plateau Lake (TPL) zone covers Qinghai Province and Tibet Autonomous Region. The total number of lakes with areas >1 km² in the five zones were: EPL 634, YGPL 65, NPL 425, IMXL 514, and TPL 1055 (3).

Fig. S1 Spatial distribution of 839 sunshine stations and 116 radiation stations in China

Fig. S2. Spatial distribution of long-term trends of total radiation at 116 observation stations in China for 1961-2013. The numerical values represent the station numbers listed in Table S1. The red circles represent a linear fitting slope greater than 0, and the blue squares represent a linear fitting slope less than 0. The hollows in the circles and squares indicate that the linear fitting is significant ($p < 0.05$). Changes were significant for 49 of 90 stations with slope < 0, and for 5 of 26 stations with slope > 0. Different background color represents five geographic lake zones.

Fig. S3. Long-term trend of yearly mean sunshine duration at 839 stations in China.

Fig. S4. Long-term decreases of SDD from four typical lakes: (a) Lake Fuxianhu, very clear oligotrophic deep lake; (b) Lake Qiandaohu, very clear oligotrophic- mesotrophic deep reservoir; (c) Lake Erhai, moderately clear mesotrophic deep lake; (d) Lake Gehu, highly turbid eutrophic shallow lake.

Fig. S5 Correlation between UVR and PAR diffuse attenuation coefficients

Table S1. Detailed information on the 116 sampling stations (province, number, name, code, and altitude), and linear fitting results of yearly total radiation vs year, and the observation period.

Province	Number	Station name	Station code	Altitude	Linear slope	r^2	p	n	Trend	Observation period
Anhui	1	Heifei	58321	27	-651.69	0.053	0.098	53	Decrease	1961-2013
	2	Tunxi	58531	142.7	1161.43	0.130	0.099	22	Increase	1992-2013
Beijing	3	Beijing	54511	31.3	-2233.18	0.622	0.000	53	Significant decrease	1961-2013
Fujian	4	Fuzhou	58847	84	-249.23	0.012	0.427	53	Decrease	1961-2013
	5	Jianou	58737	154.9	-3916.79	0.225	0.026	22	Significant decrease	1992-2013
Gansu	6	Minqin	52681	1367.5	746.69	0.078	0.043	53	Significant decrease	1961-2013
	7	Dunhuang	52418	1139	-691.76	0.124	0.010	53	Significant decrease	1961-2013
	8	Lanzhou	52889	1517.2	-1494.55	0.227	0.001	44	Significant decrease	1961-2004
	9	Jiuquan	52533	1477.2	-301.45	0.014	0.613	21	Decrease	1993-2013
Guangdong	10	Guangzhou	59287	70.7	-783.95	0.101	0.021	53	Significant decrease	1961-2013

	11	Shantou	59316	2.9	-239.32	0.007	0.564	53	Decrease	1961-2013
	12	Shaoguang	59082	121.3	-4490.88	0.599	0.000	30	Significant decrease	1961-1990
	13	Zhongshan	59485	33.7	-6847.23	0.474	0.000	26	Significant decrease	1965-1990
	14	Guilin	57957	164.4	-621.01	0.050	0.108	53	Decrease	1961-2013
Guangxi	15	Nanning	59431	121.6	-277.90	0.016	0.365	53	Decrease	1961-2013
	16	Beihai	59644	12.8	507.95	0.024	0.505	21	Increase	1993-2013
	17	Guiyang	57816	1223.8	14.97	0.000	0.966	53	Increase	1961-2013
Guizhou	18	Zunyi	57713	843.9	-3165.40	0.492	0.000	30	Significant decrease	1961-1990
	19	Weining	56691	2237.5	-602.60	0.043	0.269	30	Decrease	1961-1990
	20	Haikou	59758	63.5	-342.22	0.015	0.380	53	Decrease	1961-2013
Hainan	21	Sanya	59948	419.4	-1867.44	0.249	0.018	22	Significant decrease	1992-2013
	22	Xisha	59981	4.7	479.51	0.004	0.770	22	Increase	1992-2013
Hebei	23	Leting	54539	10.5	-1889.37	0.363	0.003	22	Significant decrease	1992-2013

	24	Zhengzhou	57083	110.4	-641.83	0.095	0.024	53	Significant decrease	1961-2013
	25	Anyang	53898	62.9	-1510.73	0.149	0.035	30	Significant decrease	1961-1990
Henan	26	Gushi	58208	42.9	-1839.18	0.272	0.000	53	Significant decrease	1961-2013
	27	Yancheng	57186	60.8	-2591.79	0.099	0.090	30	Decrease	1961-1990
	28	Nanyang	57178	129.2	-557.82	0.042	0.338	24	Decrease	1990-2013
	29	Haerbin	50953	142.3	-171.18	0.007	0.542	53	Decrease	1961-2013
	30	Jiamusi	50873	82	137.26	0.004	0.658	53	Increase	1961-2013
Heilongjiang	31	Hehei	50468	166.4	357.70	0.022	0.292	53	Increase	1961-2013
	32	Mohe	50136	433	-552.87	0.009	0.689	21	Decrease	1993-2013
	33	Fuyu	50742	162.7	319.94	0.008	0.696	21	Increase	1993-2013
	34	Wuhan	57494	23.6	-1890.25	0.234	0.000	53	Significant decrease	1961-2013
Hubei	35	Yichang	57461	133.1	-705.76	0.086	0.034	53	Significant decrease	1961-2013
Hunan	36	Chansha1	57679	44.9	-3128.41	0.403	0.000	26	Significant decrease	1961-1986

	37	Changsha2	57687	68	-101.67	0.001	0.899	27	Decrease	1987-2013
	38	Jishou	57649	208.4	718.75	0.026	0.475	22	Increase	1992-2013
	39	Changning	57874	116.6	3554.58	0.099	0.153	22	Increase	1992-2013
Jilin	41	Changchun	54161	236.8	-568.37	0.084	0.036	53	Significant decrease	1961-2013
	42	Yanji	54292	257.3	-75.11	0.001	0.789	53	Decrease	1961-2013
	40	Huaian	58141	14.4	-1597.45	0.133	0.114	21	Decrease	1993-2013
Jiangsu	43	Nanjing	58238	35.2	-981.34	0.140	0.006	53	Significant decrease	1961-2013
	44	Lvsi	58265	3.6	-1238.87	0.074	0.222	22	Decrease	1992-2013
	45	Ganzhou	57993	133.1	-856.22	0.172	0.002	53	Significant decrease	1961-2013
Jiangxi	46	Nanchang	58606	46.9	-1491.25	0.292	0.000	53	Significant decrease	1961-2013
	47	Lushan	58506	1164.5	-5646.62	0.506	0.000	30	Significant decrease	1961-1990
Liaoning	48	Shenyang	54342	49	-783.86	0.130	0.008	53	Significant decrease	1961-2013
	49	Fengcheng	54494	72.6	-771.98	0.009	0.627	30	Decrease	1961-1990

	50	Dalian	54662	91.5	-210.90	0.004	0.649	53	Decrease	1963-2013
	51	Chaoyang	54324	174.3	-57.06	0.001	0.861	53	Decrease	1963-2013
	52	Erlianghaote	53068	963.1	-115.27	0.004	0.652	53	Decrease	1961-2013
	53	Yijinhualuoqi	53545	1329.3	-1921.76	0.180	0.017	31	Significant decrease	1961-1991
	54	Tongliao	54135	178.7	-214.21	0.005	0.627	53	Decrease	1961-2013
	55	Hailaer	50527	649.6	-1032.85	0.355	0.000	53	Significant decrease	1961-2013
Inner	56	Tumotezuqi	53464	1020.3	-6950.26	0.687	0.000	21	Significant decrease	1971-1991
Mongolia	57	Xilinhaote	54102	1003	1484.29	0.246	0.014	24	Significant increase	1990-2013
	58	Suolun	50834	499.7	-1075.68	0.058	0.278	22	Decrease	1992-2013
	59	Ejinaqi	52267	940.5	-468.57	0.055	0.294	22	Decrease	1992-2013
	60	Hailiutu	53336	1288	4179.78	0.314	0.007	22	Significant increase	1992-2013
	61	Dongsheng	53543	1461.9	-734.41	0.060	0.272	22	Decrease	1992-2013
Ningxia	62	Yinchuan	53614	1110.9	-1046.72	0.433	0.000	53	Significant decrease	1961-2013

	63	Guyuan	53817	1753	888.31	0.093	0.107	29	Increase	1985-2013
	64	Geermu	52818	2807.6	-745.96	0.272	0.000	53	Significant decrease	1961-2013
	65	Xining	52866	2295.2	-1492.75	0.242	0.000	53	Significant decrease	1961-2013
Qinghai	66	Yushu	56029	3716.9	-1420.61	0.137	0.006	53	Significant decrease	1961-2013
	67	Gangcha	52754	13301.5	-1518.60	0.206	0.039	21	Significant decrease	1993-2013
	68	Guoluo	56043	3719	-1345.84	0.044	0.360	21	Decrease	1993-2013
	69	Jinan	54823	170.3	-1217.61	0.256	0.000	53	Significant decrease	1961-2013
	70	Yantai	54765	46.7	342.40	0.006	0.668	31	Increase	1961-1991
Shandong	71	Jining	54915	40.7	139.44	0.001	0.908	28	Increase	1963-1990
	72	Juxian	54936	107.4	-1179.91	0.172	0.044	24	Significant decrease	1990-2013
	73	Fushan	54764	53.9	-765.00	0.069	0.239	22	Decrease	1992-2013
	74	Taiyang	53772	778.3	-2003.20	0.420	0.000	53	Significant decrease	1961-2013
Shanxi	75	Houma	53963	433.8	-1746.69	0.510	0.000	53	Significant decrease	1961-2013

	76	Datong	53487	1067.2	-1438.20	0.286	0.000	53	Significant decrease	1961-2013
	77	Xi'an	57036	397.5	-1922.94	0.394	0.000	45	Significant decrease	1961-2005
Shaanxi	78	Yan'an	53845	958.5	-683.19	0.023	0.482	24	Decrease	1990-2013
	79	Ankang	57245	290.8	-382.06	0.007	0.700	24	Decrease	1990-2013
Shanghai	80	Longhua	58367	2.8	-2722.01	0.569	0.000	30	Significant decrease	1961-1990
	81	Shanghai	58362	5.5	218.65	0.004	0.778	23	Increase	1991-2013
	82	Chengdu	56294	506.1	-2491.40	0.709	0.000	53	Significant decrease	1961-2003
	83	Emeishan	56385	13047.4	1617.30	0.413	0.000	53	Significant increase	1961-2013
Sichuan	84	Mianyang	56196	522.7	-417.17	0.020	0.412	36	Decrease	1978-2013
	85	Panzhihua	56666	1190.1	1026.94	0.015	0.584	22	Increase	1992-2013
	86	Ganzhi	56146	13393.5	-397.13	0.017	0.587	20	Decrease	1994-2013
	87	Hongyuan	56173	3491.6	1432.98	0.132	0.116	20	Increase	1994-2013
Tianjin	88	Tianjin	54527	3.5	-1555.36	0.313	0.000	53	Significant decrease	1961-2013

Tibet	89	Lasha	55591	3648.9	-1604.63	0.155	0.004	53	Significant decrease	1961-2013
	90	Changdu	56137	3315	-591.98	0.028	0.233	53	Decrease	1961-2013
	91	Naqu	55299	4507	310.78	0.003	0.716	53	Increase	1961-2013
	92	Ge'er	55228	4278.6	2486.62	0.069	0.093	42	Increase	1972-2013
	93	Ruoqiang	51777	887.7	-663.74	0.091	0.029	53	Significant decrease	1961-2013
	94	Hetian	51828	1375	-773.74	0.134	0.007	53	Significant decrease	1961-2013
Xinjiang	95	Kuche	51644	1081.9	-2567.35	0.695	0.000	30	Significant decrease	1961-1990
	96	Kasha	51709	1289.4	-1056.17	0.157	0.003	53	Significant decrease	1961-2013
	97	Wulumuqi	51463	935	-968.37	0.269	0.000	53	Significant decrease	1961-2013
	98	Yining	51431	662.5	-677.42	0.070	0.056	53	Decrease	1961-2013
	99	Tulufan	51573	34.5	-1670.08	0.542	0.000	53	Significant decrease	1961-2013
	100	A'ertai	51076	735.3	-257.98	0.023	0.282	53	Decrease	1961-2013
	101	Hami	52203	737.2	-1205.00	0.320	0.000	53	Significant decrease	1961-2013

	102	Tangcheng	51133	534.9	-459.82	0.005	0.751	21	Decrease	1993-2013
	103	Yanqi	51567	1055.3	1072.51	0.056	0.300	21	Increase	1993-2013
	104	Akesu	51628	1103.8	-2018.98	0.175	0.060	21	Decrease	1993-2013
	105	Tengchong	56739	1654.6	96.58	0.003	0.694	53	Increase	1961-2013
	106	Kunming	56778	1888.1	605.40	0.085	0.034	53	Significant increase	1961-2013
Yunnan	107	Jinghong	56959	582	255.34	0.017	0.355	53	Increase	1961-2013
	108	Zhaotong	56586	1949.5	-302.73	0.005	0.719	30	Decrease	1961-1990
	109	Lijiang	56651	2380.9	-350.17	0.035	0.181	53	Decrease	1961-2013
	110	Mengzi	56985	1300.7	-5.43	0.000	0.989	53	Decrease	1961-2013
	111	Hangzhou	58457	41.7	-29.61	0.000	0.936	53	Decrease	1961-2013
Zhejiang	112	Zixi	58467	4.5	-2165.33	0.130	0.051	30	Decrease	1961-1990
	113	Hongjia	58665	4.6	-1552.36	0.156	0.069	22	Decrease	1992-2013
Chongqing	114	Chongqing	57515	351.1	-3303.19	0.552	0.000	26	Significant decrease	1961-1986

115	Wanxian	57432	186.7	-2533.67	0.614	0.000	30	Significant decrease	1961-1990
116	Shapingba	57516	259.1	849.11	0.080	0.154	27	Increase	1987-2013

Table S2. Detailed information on 170 lakes (zones, province, number, name, latitude, longitude, lake area, mean water depth), the SDD from two different periods (before 1995 [most before 1990] and after 2000), and the percentage change between them (comparing after 2005 with before 1995); a decrease is shown by a downward arrow.

Lake Zone	Province	Number	Lake name	Latitude	Longitude	Area (km²)	Mean water depth (m)	First lake investigation		Second lake		SDD change (%)
								(before 1995, most		investigation (after		
								before 1990)		2005)		
								SDD	Reference	SDD	Reference	
								(m)	(m)	(m)	(m)	
								(m)	(m)	(m)	(m)	
EPL zone	Anhui	1	Lake Anfengtang	32.2667-32.3333	116.6333-116.7333	36.4	2.67	0.40	(4)	0.35	Dataset 1	-12.5
		2	Lake Baidanghu	30.7833-30.8500	117.3167-117.4500	39.7	3.06	1.90	(4)	0.53	Dataset 1	-72.4

3	Lake Bohu	30.0667-30.2500	116.3167-116.5500	180.4	4.41	1.80	(4)	0.48	Dataset 1	-73.6
4	Lake Caizihu	30.7167-30.9667	117.0167-117.1500	172.1	1.67	3.30	(4)	0.77	Dataset 1	-76.8
5	Lake Chaohu	31.4167-31.7167	117.2667-117.8333	769.6	2.69	0.28	(4)	0.27	Dataset 1	-2.5
6	Lake Chengdongu	32.2000-32.3667	116.3000-116.4667	120.0	1.50	0.25	(4)	0.42	Dataset 1	68.9
7	Lake Gaotanghu	32.5667-32.7333	117.1167-117.2167	49.0	1.73	0.60	(4)	0.20	Dataset 1	-66.7
8	Lake Huayuanhu	32.9167-33.0333	117.7500-117.8833	34.0	1.35	0.60	(4)	0.38	Dataset 1	-36.1
9	Lake Huangdahu	29.9333-30.1333	116.2333-116.5500	299.2	3.94	2.20	(4)	0.70	Dataset 1	-68.2
10	Lake Nanyihu	31.0500-31.1667	118.8333-119.0333	148.4	2.25	0.65	(4)	0.48	Dataset 1	-26.9
11	Lake Nvshanhu	32.8333-33.0333	117.9667-118.2333	104.6	1.71	0.85	(4)	0.16	Dataset 1	-81.8
12	Lake Ppganghu	30.5500-30.7000	117.0667-117.2167	60.0	1.52	2.65	(4)	0.53	Dataset 1	-80.2
13	Lake Shenjinhu	30.2500-30.4667	116.9667-117.2333	78.5	1.26	0.26	(4)	0.38	Dataset 1	46.2
14	Lake Tuohu	33.1500-33.2833	117.7500-117.8500	40.0	1.20	1.50	(4)	0.37	Dataset 1	-75.6
15	Lake Wabuhu	32.3833-32.5500	116.8000-117.0167	163.0	2.42	0.20	(4)	0.19	Dataset 1	-6.8

		16	Lake Wuchanghu	30.2333-30.3333	116.6000-116.8833	100.5	3.43	1.00	(4)	0.42	Dataset 1	-57.9
		17	Lake Xiangjian	33.1000-33.2000	117.2500-117.7500	45.0	0.93	0.60	(4)	0.33	Dataset 1	-45.0
		18	Lake Yihu	32.7667-32.8333	118.9833-119.0667	18.0	1.70	0.27	(5)	0.52	Dataset 1	91.4
		19	Lake Taipingh	30.3486-30.4036	118.0073-118.0213	94.0	40.00	3.30	(6)	3.10	(7)	-6.1
EPL zone	Beijing	20	Guanting Reservoir	40.2806-40.3857	115.6038-115.7909	238.0	10.00	1.02	(8)	0.84	(9)	-17.6
		21	Miyun Reservoir	40.4396-40.5538	116.8257-117.0352	180.0	30.00	2.50	(10)	2.54	(11)	1.6
IMXL Zone	Gansu	22	Liujiaxia Reservoir	35.7579-35.8998	103.1800-103.2242	130.0	31.00	1.39	(12)	1.78	(13)	28.1
EPL zone	Guangdong	23	Lake Liuhuahu	23.1385	113.2461	0.3	1.57	0.20	(4)	0.33	(14)	65.0
		24	Lake Liwanhu	23.1228	113.2238	0.2	1.20	0.31	(4)	0.42	(15)	35.5
		25	Lake Luhu	23.1499	113.2770	0.2	2.50	0.38	(4)	0.37	Unpub data	-2.6
		26	Gaozhou Reservoir	22.1444	111.0135	42.0	26.00	1.91	(16)	1.82	(17)	-4.7
YGPL zone	Guizhou	27	Lake Caohai	26.8167-26.8833	104.2000-104.3000	25.0	2.40	0.64	(4)	1.17	(18)	82.8
EPL zone	Hebei	28	Lake Baiyangdian	38.7167-39.0333	115.6000-116.0167	366.0	2.84	1.50	(4)	0.79	Dataset 1	-47.3

NPL zone		29	Lake Hengshuihu	37.5833	115.6167	75.0	2.51	0.62	(19)	0.50	Dataset 1	-19.4
		30	Pingwang Reservoir	37.5474	114.332	NaN	4.70	1.40	(20)	0.50	Unpub data	-64.3
	Heilongjiang	31	Lake Lianhuan	46.5000-46.8333	123.9833-124.2500	556.1	2.14	0.45	(4)	0.28	Dataset 1	-37.8
		32	Lake Maoxinhu	45.5500-45.6000	124.3833-124.5167	23.0	2.50	0.76	(4)	0.44	Dataset 1	-41.7
		33	Lake Xingkaihu	44.5333-45.3500	131.9667-132.8500	4380.0	6.28	0.20	(21)	0.22	Unpub data	10.0
		34	Lake Jingbohu	43.7667-44.0500	128.6167-129.0500	91.5	12.90	1.80	(16)	1.18	(22)	-34.4
		35	Lake Zhalonghu	47.1983-47.2083	120.2228-120.2274	3.6	1.00	1.25	(4)	0.75	(23)	-40.0
		36	Lake Wudalianhu	48.6666-48.7833	126.1000-126.2500	16.4	NaN	0.68	(4)	0.61	(24)	-10.3
		37	Lake small Xingkaihu	45.2667-45.3667	132.3333-132.7667	136.0	1.65	0.75	(4)	0.29	(25)	-61.3
	EPL zone	38	Lake Baoanhu	30.2000-30.3000	114.6500-114.7667	48.0	3.40	1.49	(4)	0.63	Dataset 1	-58.1
		39	Lake Changhu	30.3667-30.5333	112.2500-112.5000	129.1	1.90	1.00	(4)	0.80	Dataset 1	-20.0
		40	Lake Chidonghu	30.0667-30.1500	115.3667-115.4500	26.8	3.50	0.94	(4)	0.33	Dataset 1	-65.4
		41	Lake Cihu	30.2096-30.2183	115.0219-115.0369	10.0	1.75	0.66	(4)	0.30	Dataset 1	-54.5

42	Lake Dayehu	30.0667-30.1333	115.0333-115.1833	68.7	2.30	1.20	(4)	1.11	Dataset 1	-7.3
43	Lake Dongxichahu	30.7-30.7167	113.6167-113.8167	24.3	1.60	0.80	(4)	0.55	Dataset 1	-31.3
44	Lake Hutouhu	29.9167-30.1167	114.1500-114.3333	114.7	2.90	1.61	(4)	0.55	Dataset 1	-65.8
45	Lake Hanyangxihu	30.4667-30.5667	113.8333-113.9500	12.7	3.40	0.77	(4)	0.84	Dataset 1	9.4
46	Lake Honghu	29.6333-29.9833	113.1833-113.4667	344.4	1.91	1.74	(4)	0.50	Dataset 1	-71.3
47	Lake Huamahu	30.2667-30.3667	115.0000-115.0667	10.3	1.80	0.50	(26)	0.53	Dataset 1	5.0
48	Lake Liangzihu	30.0833-30.3000	114.3500-114.6500	304.3	4.16	2.23	(4)	1.61	Dataset 1	-27.7
49	Lake Sanshanhu	30.2667-30.3667	114.7333-114.8333	24.3	2.80	0.82	(4)	0.48	Dataset 1	-41.5
50	Lake Taibei hu	29.9333-30.0167	115.7667-115.8333	25.1	3.20	0.45	(4)	0.44	Dataset 1	-1.9
51	Lake Tangxunhu	30.3833-30.4833	114.3167-114.4833	36.6	1.85	0.42	(4)	0.50	Dataset 1	18.0
52	Lake Wanghu	29.8500-29.9000	115.3333-115.4167	42.3	3.70	1.00	(4)	0.71	Dataset 1	-29.2
53	Lake Wuchangdonghu	30.5167-30.6000	114.3500-114.4667	33.7	2.80	0.64	(4)	0.45	Dataset 1	-29.7
54	Lake Wuhu	30.7833-30.8333	114.4667-114.5500	21.2	2.60	1.50	(4)	1.06	Dataset 1	-29.3

		55	Lake Xilianghu	29.8500-30.0333	114.0000-114.1667	72.1	1.94	1.77	(4)	1.41	Dataset 1	-20.5
		56	Lake Yanxihu	30.5333-30.6167	114.4500-114.5167	11.8	1.90	0.76	(4)	0.55	Dataset 1	-28.3
		57	Lake Zhangduhu	30.6167-30.7000	114.6667-114.8000	35.2	1.20	1.50	(4)	0.42	Dataset 1	-72.2
		58	Lake Longganhu	29.8667-30.0833	115.3167-116.2833	316.2	3.78	2.15	(4)	0.59	Dataset 1	-72.8
		59	Lake Houguanhu	30.4667-30.5667	113.9833-114.1500	34.4	1.14	1.90	(4)	1.15	(27)	-39.5
		60	Lake Qingshanhu	30.3007	115.0447	1.1	1.35	0.34	(4)	0.30	(28)	-11.8
		61	Lake Yanglanhu	30.3878	114.8969	1.7	1.50	0.30	(4)	0.41	(29)	36.7
		62	Lake Mushuihu	30.5439	114.2255	3.6	1.30	0.25	(4)	0.44	(27)	76.0
		63	Fuqiaohe Reservoir	31.1759-31.2692	114.8362-114.8728	96.0	5.60	1.50	(30)	1.40	(30)	-6.7
		64	Bailianhe Reservoir	30.6128	115.5540	41.3	NaN	1.35	(12)	2.63	(31)	94.8
		65	Longping Reservoir	30.1811	115.9150	NaN	NaN	1.60	(12)	2.20	(31)	37.5
EPL zone	Hunan	66	Lake Beiminh	29.7000-29.7667	111.8500-111.9167	14.5	2.80	0.96	(32)	0.43	Dataset 1	-55.7
		67	Lake Datonghu	29.0833-29.2667	112.4333-112.5833	114.2	2.89	0.67	(33)	0.38	Dataset 1	-44.0

		68	Lake Dongtinghu	28.7333-29.5833	111.8833-113.0833	2432.5	6.39	0.85	(4)	0.48	Dataset 1	-43.6
		69	Dongjiang Reservoir	25.7408-25.9458	113.3109-113.4416	160.0	50.80	5.20	(34)	3.50	(35)	-32.7
NPL zone	Jilin	70	Lake Chaganhu	45.1667-45.3500	124.0667-124.4500	347.4	1.56	0.12	(4)	0.17	Dataset 1	38.3
		71	Kulipao	45.3725	124.4768	NaN	NaN	0.24	(36)	0.18	Dataset 1	-26.3
		72	Xiaohuangpao	45.6683	123.7285	42.0	2.25	0.72	(37)	0.28	Dataset 1	-60.7
		73	Xinmiaopao	45.1667-45.2167	124.4333-124.5833	31.0	2.00	0.20	(4)	0.41	Dataset 1	104.0
		74	Yueliangpao	45.6500-45.6000	123.7000-124.0333	206.0	2.30	0.54	(12)	0.28	Dataset 1	-48.1
		75	Lake Songhuahu	43.5234-43.7089	126.8449-127.1072	554.0	35.00	1.10	(4)	1.26	(38)	14.5
		76	Lake Jilinnanhu	43.8525	125.3077	0.9	2.00	0.36	(16)	0.49	(39)	36.1
		77	Longtou Reservoir	42.9920	125.0904	2.7	7.00	0.75	(40)	0.42	(41)	-44.0
EPL zone	Jiangsu	78	Lake Baimahu	33.1500-33.3167	119.0500-119.1833	108.0	0.97	1.15	(4)	0.67	Dataset 1	-42.0
		79	Lake Chenghu	31.1667-31.2333	120.8000-120.8667	45.0	1.83	0.54	(42)	0.46	Dataset 1	-15.1
		80	Lake Dazhonghu	33.13333-33.1833	119.7833-119.8500	28.0	1.02	0.65	(4)	0.55	Dataset 1	-15.4

81	Lake Gaoyouhu	32.7000-33.0667	119.1000-119.4167	674.7	1.44	0.63	(4)	0.24	Dataset 1	-61.8
82	Lake Gehu	31.4833-31.7000	119.7333-119.8833	146.5	1.19	1.01	(4)	0.26	Dataset 1	-74.0
83	Lake Guchenghu	31.2333-31.3000	118.8833-118.9500	24.5	1.56	2.07	(4)	1.10	Dataset 1	-46.9
84	Lake Hongzehu	33.1000-33.6667	118.1667-118.8667	1576.9	1.77	0.72	(4)	0.26	Dataset 1	-63.2
85	Lake Kunchenghu	31.5500-31.6000	120.7167-120.7667	18.0	1.78	0.63	(43)	0.80	Dataset 1	27.0
86	Lake Luomahu	34.0000-34.2333	118.0667-118.3000	260.0	3.30	2.55	(4)	0.54	Dataset 1	-79.0
87	Lake Sanjiu	31.3667	119.8000	23.2	1.85	0.70	(4)	0.30	Dataset 1	-57.1
88	Lake Shaobohu	32.5000-32.6667	119.3833-119.5000	77.0	1.10	0.73	(4)	0.30	Dataset 1	-58.9
89	Lake Shijiuhu	31.3833-31.5500	118.7667-118.9333	210.4	4.08	0.60	(4)	0.87	Dataset 1	44.4
90	Lake Taohu	31.5000-31.6667	119.5000-119.6667	89.0	1.10	1.03	(4)	0.31	Dataset 1	-69.9
91	Lake Yangchenghu	31.3500-31.5000	120.6500-120.8500	119.0	1.40	1.33	(4)	0.73	Dataset 1	-45.0
92	Lake Taihu	30.9333-31.5667	119.9000-120.6000	2338.0	2.12	0.53	(4)	0.39	Dataset 2	-26.4
93	Lake Wulihu	31.5151-31.5351	120.2322-120.2555	8.6	2.00	0.51	(4)	0.45	Dataset 2	-11.8

EPL zone	Jiangxi	94	Lake Xuwuhu	32.0692	118.7984	3.7	1.50	0.27	(16)	0.20	(44)	-25.9
		95	Lake Shouxihu	32.4226	119.4226	1.7	1.50	0.70	(4)	0.35	(45)	-50.0
		96	Lake Deshenghu	32.9167-32.9500	119.8333-119.9500	15.0	0.67	0.65	(4)	0.30	(46)	-53.8
		97	Lake Wugonghu	31.5500-31.600	120.7167-120.7667	18.0	2.60	0.70	(4)	0.63	(46)	-10.0
		98	Lake Baoyinghu	31.1667-31.2333	120.8000-120.8667	192.1	1.13	1.05	(4)	0.84	(47)	-20.0
		99	Lake Chihu	29.7333-29.8333	115.6167-115.7333	80.4	2.80	2.50	(48)	0.76	Dataset 1	-69.5
		100	Lake Nanbeihu	29.6333-29.7000	116.2000-116.2667	24.7	4.65	0.50	(4)	0.40	Dataset 1	-20.0
		101	Lake Poyanghu	28.4000-29.7667	115.8167-116.7667	2933.0	5.10	0.85	(4)	0.41	Dataset 1	-51.4
		102	Lake Qilihu	29.6500-29.7000	115.9167-115.9500	16.2	2.20	0.40	(4)	0.45	Dataset 1	12.5
		103	Lake Saichenghu	29.6500-29.7000	115.7500-115.9167	61.3	2.24	0.70	(4)	0.51	Dataset 1	-26.8
		104	Lake Taibohu	29.9500-30.0333	116.6667-116.7667	20.7	5.00	1.00	(4)	0.33	Dataset 1	-66.7
		105	Lake Gantanghu	29.7177	115.9869	2.4	1.40	0.56	(16)	0.22	(44)	-60.7
		106	Hongmen Reservoir	27.4745-27.4833	116.7983-116.8952	69.6	17.50	1.57	(49)	1.30	(50)	-17.2

NPL zone	Liaoning	107	Caihe Reservoir	42.2187-42.2512	123.9866-124.0819	17.0	35.30	1.16	(12)	1.00	(51)	-13.8
		108	Dahuofang Reservoir	41.8069-41.9491	124.0872-124.3211	110.4	19.20	1.71	(12)	2.25	(51)	31.6
		109	Biliuhe Reservoir	39.8143-39.9097	122.4612-122.5343	56.0	13.00	1.81	(52)	2.35	(51)	29.8
		110	Tanghe Reservoir	41.0048-41.0684	123.3159-123.3636	44.4	16.30	3.03	(12)	1.82	(51)	-39.9
		111	Huanren Reservoir	41.29244-41.3776	125.5478-125.6327	98.7	12.50	1.82	(53)	1.59	(51)	-12.6
		112	Qinghe Reservoir	42.5362	124.2176	46.0	13.70	1.04	(54)	0.76	(55)	-26.9
		113	Shuifeng Reservoir	40.6241-40.4644	120.9620-125.3929	357.0	25.00	2.68	(12)	2.75	(56)	2.6
		114	Tiejia Reservoir	40.0573-40.0955	124.1415-124.1595	21.6	11.90	2.48	(12)	1.76	(57)	-29.0
IMXL zone	Inner Mongolia	115	Hasuhai	40.5733-40.6366	110.9321-110.9955	29.7	1.70	0.88	(58)	0.64	Dataset 1	-27.3
		116	Daihai	40.4667-40.6167	112.5500-112.7833	133.5	7.41	1.20	(4)	0.85	(59)	-29.2
		117	Lake Hulunhu	48.5000-49.3333	116.9667-117.8000	2339.0	5.92	0.48	(4)	0.22	(60)	-54.2
		118	Wuliangsu hai	40.7833-41.0500	108.7167-108.9500	233.0	1.12	0.90	(16)	0.82	(61)	-8.9
TPL zone	Qinghai	119	Lake Qinghaihu	36.5333-37.2500	99.6000-100.7833	4340.0	17.90	5.00	(4)	3.27	(62)	-34.6

		120	Lake Elinghu	34.7500-35.0833	97.5167-97.9167	610.7	17.60	3.50	(4)	3.00	(63)	-14.3
EPL zone	Shandong	121	Lake Dongpinghu	35.7167-36.1167	116.0333-116.3000	148.0	1.59	0.83	(4)	0.72	Dataset 1	-13.2
		122	Lake Nansihu	34.4500-35.3333	116.5667-117.3500	1097.6	1.46	0.92	(64)	0.50	Dataset 1	-45.5
		123	Lake Matahu	37.0500-37.0667	118.0333-118.1500	58.9	2.08	0.24	(4)	0.35	(65)	45.8
		124	Zhoucun Reservoir	34.9500	117.6833	8.5	9.80	1.45	(66)	0.98	(67)	-32.4
IMXL zone	Shanxi	125	Fenhe Reservoir	38.0491-38.1243	111.8545-111.9214	32.0	6.50	1.27	(12)	1.63	(68)	28.3
		126	Lake Jinyanghu	37.7631	112.4987	4.8	4.00	0.80	(12)	0.64	(57)	-20.0
IMXL zone	Shaanxi	127	Hongjianzuo	39.0667-39.1333	109.8333-109.9333	60.3	8.20	0.69	(4)	0.83	(69)	20.3
EPL zone	Shanghai	128	Lake Dianshanhu	31.0667-31.200	120.8833-12.0167	63.7	2.50	0.55	(4)	0.42	Dataset 1	-23.9
YGPL zone	Sichuan	129	Lake Qionghai	27.7833-27.8667	102.2667-102.3500	31.0	10.32	2.13	(4)	1.32	Dataset 1	-38.0
		130	Shengzhong Reservoir	31.5453-31.5938	105.7597-105.6734	56.0	18.20	2.20	(70)	2.76	(71)	25.5
EPL zone	Tianjin	131	Yuqiao Reservoir	40.0206-40.0268	117.5670-117.5997	86.8	4.74	2.55	(16)	1.00	(72)	-60.8
TPL zone	Tibet	132	Namucuo	30.5000-30.9333	90.2667-91.0500	1961.5	NaN	9.00	(4)	8.00	(73)	-11.1

		133	Selincuo	31.5667-31.9500	88.5500-89.3500	1628.0	NaN	7.50	(4)	2.30	(73)	-69.3
		134	Cuoe	31.4167-31.7000	88.5333-88.8333	269.0	NaN	11.50	(4)	8.00	(73)	-30.4
		135	Dazhecuo	31.8167-31.9833	87.4167-87.6500	244.7	NaN	7.20	(4)	6.00	(73)	-16.7
		136	Bangongcuo	33.4333-33.9667	78.4167-79.9333	604.0	NaN	13.30	Unpub data	14.00	(73)	5.3
		137	Bangdacuo	34.9-35	81.4833-81.6500	106.5	NaN	1.30	Unpub data	1.30	(73)	0.0
		138	Zigetangcuo	32.0000-32.1500	90.7333-90.9500	191.4	NaN	6.70	(4)	3.00	Unpub data	-55.2
		139	Qixiangcuo	32.4-32.5167	89.8667-90.0667	149.0	NaN	1.95	(4)	2.30	Unpub data	17.9
		140	Cuona	31.9167-32.1333	91.4167-91.5500	182.4	NaN	4.50	(4)	4.25	Unpub data	-5.6
IMXL zone	Xinjiang	141	Lake Caiwobao	43.5	87.9	30.0	4.18	0.40	(74)	0.22	Dataset 1	-45.0
		142	Lake Jilihu	46.8500-47.0000	87.3333-87.5333	174.0	9.90	2.80	(4)	1.83	Dataset 1	-34.6
		143	Lake Sailimuhu	44.5000-44.7000	81.0833-89.6000	453.0	46.40	8.50	(4)	10.50	(75)	23.5
		144	Lake Bositenghu	41.8167-42.1333	86.6833-87.4500	992.2	8.08	1.74	(76)	2.10	(77)	20.7
		145	Lake Hanasihu	48.0500-48.2333	86.9833-87.1167	44.8	120.10	3.00	(4)	1.80	Dataset 1	-40.0

		146	Buluntuohai	47.0333-47.4167	87.0333-87.5833	753.0	8.00	2.40	(4)	2.60	(78)	8.3
		147	Moguhu Reservoir	44.4524-44.4758	85.9187-85.9339	31.2	4.30	0.64	(16)	0.65	(79)	1.6
		148	Fukangtianchi	43.8833	88.1333	4.9	60.00	9.00	(4)	1.10	Dataset 1	-87.8
		149	Lake Akesaiqinhu	35.2456	79.7935	165.8	7.75	3.00	Unpub data	1.00	(73)	-66.7
		150	Lake Dianchi	24.6667-25.0333	102.6000-102.7833	298.0	2.93	1.00	(80)	0.56	(81)	-44.0
		151	Lake Fuxianhu	24.3500-24.6333	102.8167-102.9500	211.0	89.60	7.10	(4)	4.35	(81)	-38.7
		152	Lake Xingyunhu	24.2833-24.3833	102.7500-102.6000	34.7	5.30	1.60	(4)	0.81	(81)	-49.4
		153	Lake Yangzonghai	24.8500-24.9667	102.9667-103.0167	31.7	19.50	4.50	(4)	2.62	(81)	-41.8
YGPL zone	Yunan	154	Lake Yilonghu	23.6333-23.7000	102.5000-102.6333	38.0	2.40	1.85	(4)	0.95	(81)	-48.6
		155	Lake Datunhai	23.3833-23.4500	103.2833-103.3333	12.3	3.70	0.78	(4)	0.37	(81)	-52.6
		156	Lake Erhai	25.6000-25.9667	100.1000-100.3000	249.0	10.17	3.35	(4)	1.38	(81)	-58.8
		157	Lake Chenghai	26.4500-26.6333	100.6333-100.6833	77.2	25.70	4.10	(4)	1.42	(81)	-65.4
		158	Lake Luguhu	27.6833-27.7500	100.7500-100.8333	48.4	40.30	10.37	(4)	8.20	(82)	-20.9

		159	Lake Changqiaohai	23.4000-23.4500	103.3333-103.4000	10.7	3.74	0.60	(4)	0.50	(81)	-16.7
		160	Lake Qiluhu	24.1333-24.2167	102.7167-102.8167	36.9	4.03	1.60	(83)	0.50	(81)	-68.8
		161	Lake Qingshuihai	25.5833-25.6167	103.1000-103.1167	7.2	20.00	2.02	(4)	2.50	(81)	23.8
		162	Lake Cibihu	26.1335-26.1861	99.9252-99.9594	8.4	0.96	3.40	(80)	3.65	(84)	7.4
		163	Lake Haixihai	26.2778-26.2810	99.9554-99.9693	3.8	10.00	4.00	(4)	2.90	(84)	-27.5
		164	Yunlongtianchi	25.8704	99.2794	1.2	8.50	1.10	(4)	1.92	(84)	74.5
		165	Lake Jianhu	26.4868-26.4892	99.9342-99.9356	4.8	4.50	2.60	(4)	0.79	(84)	-69.6
		166	Lake Gejiuhu	23.3699	103.1562	0.8	2.00	0.90	(83)	0.69	(85)	-23.3
EPL zone	Zhejiang	167	Lake Dongqianhu	29.8667	121.5667	21.0	2.00	0.66	(4)	0.68	Dataset 1	3.5
		168	Lake Hangzhouxihu	30.2333-30.2667	120.1333-120.1500	5.7	1.84	0.51	(4)	0.45	(86)	-11.8
		169	Lake Jiangxijianhu	29.9667	120.2333	2.4	2.77	0.67	(4)	0.61	(87)	-9.0
		170	Lake Qiandaohu	29.4188-29.7184	118.7085-119.1952	570.0	30.00	8.17	Dataset 2	5.00	Dataset 2	-38.8

Dataset 1: The second national lake investigation, from 2006 to 2010

Dataset 2: Long-term (more than 20 years) site-specific observations in Lake Fuxianh, Lake Qiandaohu, Lake Erhai and Lake Taihu,

Unpub data: Unpublished data

NaN represents no data.

Lake zones:

EPL, Eastern Plain Lake zone, covering Shanghai, Beijing and Tianjin municipalities, Hong Kong and Macao Special Administrative Regions, and Taiwan, Jiangxi, Hunan, Hubei, Anhui, Henan, Shandong, Zhejiang, Jiangsu, Hainan, Fujian, Guangdong and Guangxi provinces.

IMXL, Inner Mongolia-Xinjiang Lake zone, covering Inner Mongolia, Xinjiang Uygur and Ningxia Hui Autonomous Regions, and Gansu, Shaanxi and Shanxi provinces.

NPL, Northeast Plain Lake zone, covered Liaoning, Jilin and Heilongjiang provinces.

TPL, Tibetan Plateau Lake zone, covering Qinghai province and Tibet Autonomous Region.

YGPL, Yunnan-Guizhou Plateau Lake zone, covering Chongqing Municipality, and Yunnan, Guizhou and Sichuan provinces.

Table S3. Summary of linear fitting, statistical parameters from 61 long-term observations of decreasing SDD, from published literature ($n = 54$) and from the present study ($n = 7$).

Nr.	Name	SDD observation method	Linear fitting	r^2	p	n	Years	Reference
1	Black Sea	<i>In situ</i>	$y=-0.090x+191.392$	0.305	<0.001	58	1955-1998	(88)
2	Little St. Germain Lake	<i>In situ</i>	$y=-0.051x+104.201$	0.351	<0.005	22	1991-2013	(89)
3	Baia River	<i>In situ</i>	$y=-0.023x+46.510$	0.333	≤ 0.05	12	1992-2007	(90)
4	Baltic sea + North sea	<i>In situ</i>	$y=-0.049x+103.291$	0.677	<0.001	72	1903-1998	(91)
5	Mattawoman Creek	<i>In situ</i>	$y=-0.007x+14.224$	0.180	<0.05	25	1986-2010	(92)
6	Clear Lake, Iowa	<i>In situ</i>	$y=-0.010x+19.671$	0.441	<0.005	18	1896-2000	(93)
7	Lake Modre	<i>In situ</i>	$y=-0.246x+497.822$	0.451	<0.005	19	1989-2010	(94)
8	Bohai Sea	Remote sensing	$y=-0.176x+356.944$	0.862	$=0.071$	4	1969-2008	(95)
9	Lake Okareka	<i>In situ</i>	$y=-0.051x+\Delta$	0.515	>0.05	18	2000-2017	(96)
10	Crystal lake	<i>In situ</i>	$y=-0.127x+263.233$	0.681	<0.001	27	1981-2011	(97)

11	Lurefjorden	<i>Calculation from beam</i>	$y=-0.0012x+13.746$	0.220	<0.001	72	1935-2007	(98)
12	Lake Tahoe	<i>In situ</i>	$y=-0.214x+448.543$	0.392	<0.001	34	1968-2001	(99)
13	Grane Langso	<i>In situ</i>	$y=-0.123x+251.521$	0.699	<0.001	24	1951-1994	(100)
14	Gulf of Finland	<i>In situ</i>	$y=-0.039x+84.791$	0.933	<0.001	18	1944-1994	(101)
15	Lake Giles	<i>In situ</i>	$y=-0.379x+776.890$	0.635	<0.001	27	1988-2014	(102)
16	Lake Lacawac	<i>In situ</i>	$y=-0.068x+141.496$	0.267	<0.01	27	1988-2014	(102)
17	Lake Annie	<i>In situ</i>	$y=-0.249x+501.517$	0.764	<0.001	25	1984-2008	(103)
18	Lake Okeechobee	<i>In situ</i>	$y=-0.007x+15.161$	0.388	<0.001	27	1973-2000	(104)
19	Emiquon Preserve	<i>In situ</i>	$y=-0.192x+386.474$	0.678	<0.05	7	2008-2014	(105)
20	Wadden Sea	<i>In situ</i>	$y=-0.052x+109.382$	0.279	<0.005	31	1977-2013	(106)
21	Jordan	<i>In situ</i>	$y=-0.247x+508.650$	0.484	<0.005	18	1991-2008	(107)
22	Spanish Mediterranean	<i>In situ</i>	$y=-0.094x+203.397$	0.477	<0.001	20	1973-1992	(108)
23	Conesus Lake	<i>In situ</i>	$y=-0.038x+79.315$	0.794	<0.001	12	1901-2014	(109)

24	Lake Væng	<i>In situ</i>	$y=-0.058x+117.710$	0.725	<0.001	17	1998-2004	(110)
25	Deep Bay, Hong Kong	<i>In situ</i>	$y=-0.044x+88.563$	0.543	<0.05	9	1998-2006	(111)
26	Lake Nakaumi	<i>In situ</i>	$y=-0.029x+58.585$	0.663	<0.001	37	1932-2003	(112)
27	Lake Donghu	<i>In situ</i>	$y=-0.029x+58.788$	0.736	<0.001	18	1979-1996	(113)
28	Chesapeake Bay	<i>In situ</i>	$y=-0.022x+46.374$	0.562	<0.001	25	1985-2009	(114)
29	Lake Plotycze	<i>In situ</i>	$y=-0.044x+89.483$	0.391	<0.01	16	1995-2012	(115)
30	Seto Inland Sea	<i>In situ</i>	$y=-0.072x+149.169$	0.832	<0.001	16	1950-1992	(116)
31	Kytai Lake	<i>In situ</i>	$y=-0.091x+183.860$	0.668	<0.005	10	2004-2013	(117)
32	Lake Peipsi	<i>In situ</i>	$y=-0.005x+11.971$	0.562	<0.001	56	1955-2010	(118)
33	Lake Kasumigaura	<i>In situ</i>	$y=-0.017x+35.037$	0.573	<0.001	20	1988-2007	(119)
34	Pärnu Bay	<i>In situ</i>	$y=-0.018x+36.995$	0.417	<0.001	48	1959-2010	(120)
35	California Current System	<i>In situ</i>	$y=-0.112x+244.813$	0.230	<0.05	26	1969-2007	(121)
36	Indian Sundarbans	<i>In situ</i>	$y=-0.272x+564.958$	0.971	<0.001	18	1980-2007	(122)

37	Marsdiep	<i>In situ</i>	$y=-0.008x+17.561$	0.257	<0.05	24	1974-2000	(123)
38	Lake Vörtsjärvi	<i>In situ</i>	$y=-0.010x+20.472$	0.234	<0.01	28	1978-2007	(124)
39	Lake Ladoga	<i>In situ</i>	$y=-0.007x+17.350$	/	/	/	1905-2003	(125)
40	Menai Strait	<i>In situ</i>	$y=-0.029x+58.963$	0.368	<0.001	22	1962-1988	(126)
41	Palić Lake**	<i>In situ</i>	$y=-0.004x+7.236$	0.395	<0.001	26	1977-2006	(127)
42	Nyanza Gulf	<i>In situ</i>	$y=-0.013x+26.138$	0.899	<0.05	5	1927-1998	(128)
43	26 boreal lakes	<i>In situ</i>	$y=-0.043x+90.227$	0.304	<0.05	18	1992-2009	(129)
44	Garcas Reservoir	<i>In situ</i>	$y=-0.094x+188.338$	0.602	<0.05	8	1997-2004	(130)
45	Lake George	<i>In situ</i>	$y=-0.221x+448.978$	0.281	<0.05	15	1981-1998	(131)
46	Lake Constance	<i>In situ</i>	$y=-0.035x+75.128$	0.156	<0.05	34	1975-2015	(132)
47	Římov Reservoir	<i>In situ</i>	$y=-0.013x+29.831$	0.182	<0.05	32	1983-2014	(133)
48	Great Barrier Reef	Remote sensing	$y=-0.020x$	/	<0.005	10	2002-2012	(134)
49	28 lakes in the Adirondack Park	<i>In situ</i>	$y=-0.063x+\Delta$	0.48	<0.005	17	1994-2012	(135)

50	Lake Maninjau	<i>In situ</i>	$y=-0.145x+294.47$	0.59	<0.005	13	2001-2019	(136)
51	Lake Malawi	Remote sensing	$y=-0.052x+117.94$	0.05	>0.05	9	2003-2011	(137)
52	West Yellow Sea	Remote sensing	$y=-0.164x+337.45$	0.43	<0.01	15	2002-2016	(138)
53	Lake Changdang	<i>In situ</i>	$y=-0.073x+146.464$	0.879	<0.005	7	1997-2010	(139)
54	10 lakes, Taihu catchment (excluding Lake Taihu)	<i>In situ</i>	$y=-0.011x+23.176$	0.232	<0.05	20	1991-2010	(140)
55	Lake Fuxianhu	<i>In situ</i>	$y=-0.060x+125.178$	0.418	<0.001	36	1980-2016	This study
56	Lake Qiandaohu	<i>In situ</i>	$y=-0.109x+223.931$	0.346	<0.001	29	1988-2016	This study
57	Lake Erhai	<i>In situ</i>	$y=-0.072x+146.471$	0.678	<0.001	32	1985-2016	This study
58	Lake Liangzihu	<i>In situ</i>	$y=-0.078x+158.727$	0.643	<0.001	16	2001-2016	This study
59	Lake Dainchi	<i>In situ</i>	$y=-0.008x+15.724$	0.321	<0.001	30	1982-2016	This study
60	Lake Taihu	<i>In situ</i>	$y=-0.005x+9.611$	0.156	<0.05	25	1992-2016	This study
61	Lake Gehu	<i>In situ</i>	$y=-0.028x+57.432$	0.953	<0.001	30	1985-2016	This study

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