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A record-breaking extreme heat event caused unprecedented warming of lakes in China

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Strong evidence confirms that extreme climatic events, such as heat waves, storms and droughts, are becoming more frequent due to anthropogenic climate change[1]. These extreme events may have overwhelmingly negative impacts on lake ecosystems[2]. Specifically, by warming lake surface waters, extreme heat events are expected to influence many within-lake physical, chemical and biological processes[3]. Critically, extreme heat events can alter the lake environment in only a fraction of the time that is needed for achieving the same effect of long-term climate change[4]. In some cases, extreme heat events can exceed the resilience capacity of a lake ecosystem and lead to a loss of functionality and can even trigger catastrophic regime shifts[5]. From mid-June to late August 2022, a record-breaking extreme heat event, with the longest duration and highest intensity since recording began in 1961, swept across China[6]. The direct driver of this heat event was the Western Pacific Subtropical High, which normally sits as a smaller pressure system to the east of Yangtze River Basin. However, in summer 2022, the system was strong and hovered over Yangtze River Basin, thereby preventing cold air from the north and moisture from the Indian Ocean from reaching the region[6]. Here, we used satellite observations from 2000 to 2022 to demonstrate the effects of the unprecedented warming of China's lakes caused by this extreme event.

We found that the average air temperature (AT) across China in summer (June to August) 2022 was 24.12 °C, which was 0.75 °C higher than the base-period average between 2000 and 2021 (Figure. 1, Table S1). Specifically, AT was above 30.00 °C and 35.00 °C (threshold of high AT) for 80 and 42 days, respectively, which is 5 and 22 days more than the corresponding total cumulative yearly days from 2000 to 2021. Yangtze River Basin, Huai River Basin, Yellow River Basin and Southeast River Basin also experienced a significant increase in AT, with the summer mean temperature being 1.70 °C, 1.46 °C, 1.11 °C and 0.95 °C higher than the corresponding temperature for the period 2000 – 2021, respectively. Inland River basin experienced the warmest heat event in July, with AT reaching 40.00 ℃. Moreover, there were a total of 42 days in summer when ATs ≥ 35.00 ℃ and 80 days when ATs ≥ 30.00 °C, which is 22 days and 5 days more than during 2000 – 2021, respectively. Temperature extremes were also observed in Yangtze River Basin, with temperatures reaching 37.83 ℃ and a total of 24 and 71 days with temperatures exceeding 35.00 ℃ and 30.00 °C, respectively, which is 23 and 21 days more than the corresponding number of days observed from 2000 to 2021.

The summer average local surface air temperature (SAT) above the studied lakes in China exhibited heterogeneity in 2022 compared to that between 2000 and 2021 (Figure 1, Table S2), being extremely high in the east and relatively low over the Tibetan Plateau. Specifically, the SAT in summer 2022 was highest over Lake Dongtinghu (SAT = 30.08 °C) in Yangtze River Basin. The SAT anomalies in summer 2022 showed varying levels of increase in most lakes (n = 105, 88.24%), with an average nationwide increase of 1.20 (min: -0.60; max: 2.95) °C compared to those in 2000 – 2021. An exception to this was observed in several lakes predominately located in the Songhua and Liao River Basins (n = 14, 11.76%).

Lake surface water temperatures (LSWTs) across China during the summer of 2022 demonstrated a spatial pattern consistent with those observed in SAT (Figure. 2, Table S3). When compared to mean temperatures between 2000 and 2021, the LSWT in 2022 showed a significant increase nationwide, being 1.63 °C warmer on average. The increase in LSWT is considerably higher than the 0.75 °C increase in AT (Figure. S2). Thirty-three lakes experienced LSWT anomalies above 2.00 °C during the summer of 2022, most notably in Huai River Basin, Yangtze River Basin, Inland River Basin and Southwest River Basin. Lakes situated in the Yangtze River Basin experienced the highest LSWT of 32.24 °C in August, which was 2.20 °C higher than the average maximum LSWT during 2000 – 2021. This was followed by Huaihe River basin, where the highest temperature reached 30.33°C. Huai River Basin experienced the largest increase in LSWT (average = 2.01 °C; min: 1.89 °C; max: 2.21 °C), followed by Southwest River Basin (average = 1.81 °C; min: 0.55 °C; max: 2.44 °C), and Songhua and Liao River Basins experienced the smallest increase in LSWT (average = 0.33 °C; min: 0.12 °C; max: 0.45 °C). Seventy-four lakes (62.18%) had significantly greater LSWT increases than SAT. These lakes are mainly located in Yangtze River Basin, Huai River Basin, Inland River Basin and Southwest River Basin (Figure. S3).

The increase in average LSWT in 2022 was greatest in August, peaking at 1.78 °C, followed by July (1.38 °C), and was lowest in June (1.12 °C) (Figure. S4, Table S3). LSWT anomalies in Songhua and Liao River Basin, Hai River Basin, Pearl River Basin, and Southeast River Basin were negative in June, indicating that the summer season began later than usual in northeastern and southeastern China. Except a few lakes in Inland River Basin, lakes across the whole country were subjected to high temperatures in July, and the anomalies in Southwest River Basin reached the highest level of 2.28 °C. In August, LSWT anomalies in Songhua and Liao River Basin and Pearl River Basin started to decrease, while they were still high in other basins, up to 2.71 °C in Huai River Basin and above 2.00 °C in Southeast River Basin, Yangtze River Basin, and Southwest River Basin.

The average LSWT increase of 1.63 °C in 2022 was much higher than the cumulative increase of the past 20 years (Figure. 2, Table S4). The average rate of increase in LSWT in China from 2000 to 2021 was 0.11 °C/decade, resulting in a twenty-year average increase of 0.22 °C. There were 17 lakes with a significant increase in LSWT. All basins except Southeast River Basin exhibited a warming trend in LSWT from 2000 to 2021, with an average increase of 0.15 °C/decade, being highest in Huai River Basin with 0.36 °C/decade. Incorporating 2022 into the time series (i.e., the period 2000 – 2022), an LSWT warming trend appeared in all basins with an average of 0.24 °C/decade and up to 0.47°C/decade in Huai River Basin. The extreme heat event in 2022 had the largest impact on the LSWT trend in Southwest River Basin; thus, LSWT here changed from 0.09 to 0.24 °C/decade, followed by Southeast River Basin, changing from -0.08 to 0.05 °C/decade.

Increases in LSWT may have a cascade of ecological and environmental consequences such as alterations in lake stratification and mixing regimes, water level decline, a decrease in dissolved oxygen concentrations, highly frequent cyanobacterial blooms, and loss of habitat for cold-water species[5]. Specifically, in terms of the physical environment of lakes, surface water temperature will be more responsive to extreme heat events compared to bottom waters, leading to an increase in thermal stability. Subsequently, the timing of seasonal overturn in autumn/winter will likely be delayed, leading to a prolonged summer stratification[7]. In addition, an increase in LSWT may also lead to higher evaporation rates, and thus reduce lake volumes and the spatial extent of surface water in the absence of substantial water inflows[8].

Chemical processes in lakes can be influenced, both directly and indirectly, by changes in

LSWT[9]. For instance, dissolved oxygen concentrations in lakes decrease directly due to warmer water temperatures and indirectly due to enhanced thermal stratification (e.g., increase in surface water temperature with minimal change at deeper depth). Specifically, deoxygenation in lakes can arise due to a reduction in the solubility of dissolved oxygen (i.e., due to increasing water temperature) and warming-induced changes in the strength and duration of stratification. Notably, thermal stratification can reduce the supply of oxygen from the lake surface into deeper waters, where oxygen is consumed by respiration and remineralization processes [10]. Anoxic conditions at depth can subsequently lead to nutrient release from lake sediments, accelerating eutrophication and the production and emission of potent greenhouse gases such as methane[11].

The catastrophic mortality of fish, benthic organisms and aquatic vegetation can be a direct result of LSWT increasing to extreme levels (i.e., values outside the norm)[12]. The increase in LSWT may also lead to the advancement of phytoplankton phenology, which will increase the biomass of phytoplankton before the onset of the light-dependent growth of other aquatic vegetation, potentially enlarging the area and duration of algal blooms. This may lead to a shift from a clear state dominated by aquatic vegetation to a turbid state dominated by algae[13]. In addition to these direct threats to lake ecosystems, subtle changes in physical or chemical processes within a lake as a result of LSWT modification can have significant and broader ecological impacts. The survival of aquatic life is threatened when the water level and the surface area of lakes are reduced, and oxygen is diminished[14]. Following the extreme heat event, one of the worst droughts in around 60 years occurred in Yangtze River Basin. The drought was so intense that the water levels in China's largest freshwater lake, Lake Poyanghu,

131 dropped by 55.07% from 19.43 m in June to 8.73 m at the end of August (2022).
132 Correspondingly, the water surface area plummeted from 4186 km^2 in August 2020 to 1117
133 km^2, leaving birds without habitats and aggravating fish die-off (Figure. S5)[6]. Moreover, this
134 extreme heat event directly affected the drinking water supply in Jiangxi and Hunan provinces
135 and indirectly caused a declined freshwater flow into the ocean from the Yangtze River. This
136 event triggered an extremely rare summer seawater intrusion, also known as a salty tide, which
137 led to the close of water resource in Shanghai. If this positive feedback continues, the ecological
138 balance will likely be destroyed, and the impact on aquatic life, as well as humans, could be far
139 worse than anticipated [15].

140 In summary, the extreme heat event in summer 2022 caused unprecedented warming of
141 lakes in China, with an average LSWT increase of 1.63°C, which is considerably higher than
142 the total increase in LSWT observed during the past 20 years. The effects were most apparent
143 in Southwest and Yangtze River Basins where the warming was particularly pronounced.
144 Increasing LSWT may lead to notable changes in the physical and chemical characteristics of
145 lakes, such as an intensified thermal stratification, a decline in water level, a reduction of
146 surface area, a decrease in dissolved oxygen, and an increase in greenhouse gas production and
147 emission. Furthermore, these changes may have biological consequences such as phenological
148 advancement and outbreaks of algal blooms and even catastrophic die-offs of lake biota. Given
149 that extreme events induced by global climate change are projected to be more frequent in the
150 future[10], more attention should be paid to the response of lake systems to extreme events. In
151 future research, high-frequency and real-time monitoring, experiments and modeling are
152 needed to quantify the impacts of extreme events on lake ecosystems.

Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

Weijia Wang: Conceptualization, Data curation, Methodology, Writing - original draft. **Shi Kun:** Supervision, Conceptualization, Methodology and Editing. **Xiwen Wang:** Data curation and Validation. **Siqi Wang:** Data curation, Methodology. **Dong Zhang:** Software, Validation. **Yuanyuan Peng:** Data curation, Software. **Na Li:** Data curation, Methodology, Validation. **Yunlin Zhang:** Methodology and Editing. **Yibo Zhang:** Methodology, Software, Validation. **Boqiang Qin:** Conceptualization, Validation and Editing. **R. Iestyn Woolway:** Supervision and Editing. **Jeppesen Erik:** Supervision and Editing. All authors reviewed the results and approved the final version of the manuscript.

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Figure Captions

Figure. 1. Spatial distribution of average summer air temperature between 2000 and 2021(a1) and during the summer of 2022 (a2) across China. Spatial distribution of local surface air temperature (SAT) during summer between 2000 and 2021(a3) and during the summer of 2022 (a4) across the country. (a5-a6) Anomalies of air temperature and SAT in summer 2022. (b1-b10) The temporal variation in the average summer SAT for the nine basins and the whole country.

Figure. 2. (a1) Spatial distribution of lake surface water temperature (LSWT) in summer 2022 and (a2) the anomalies of the LSWT in summer 2022 compared to those between 2000 and 2021. (b1-b10) The temporal variation in average summer LSWT for the nine basins and the whole country. Histograms show the differences in summer mean LSWT (c1) and the decadal change rate of LSWT (c2) between 2000 – 2021 and 2022 for the nine basins and the national scale.

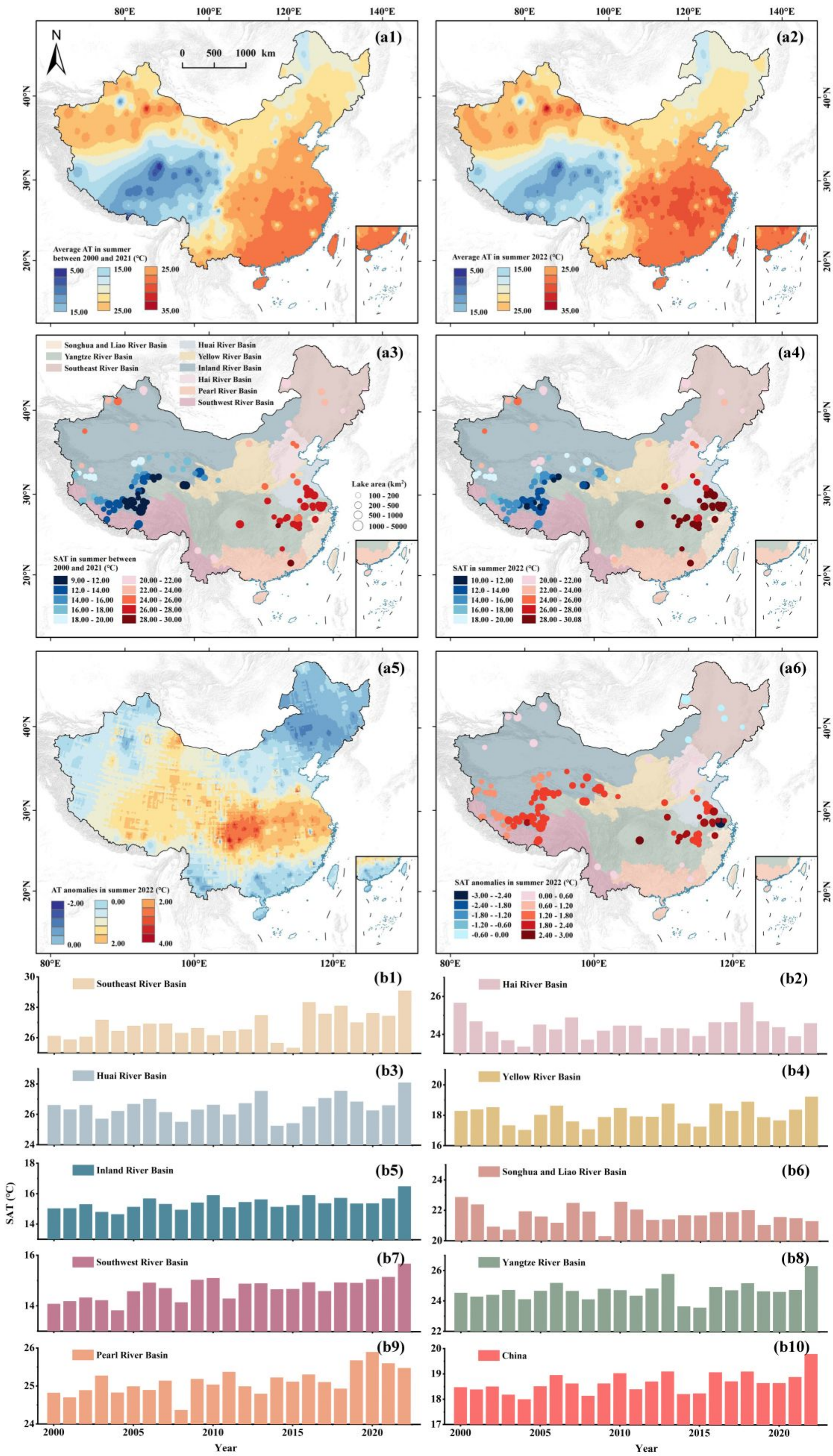
(a1)
(a2)
(a3)
(a4)
(a5)
(a6)
N
0 500 1000 km
80°E
100°E
120°E
140°E
20°N
30°N
40°N
Average AT in summer between 2000 and 2021 (°C)
Average AT in summer 2022 (°C)
Songhua and Liao River Basin
Yangtze River Basin
Southeast River Basin
Huai River Basin
Yellow River Basin
Inland River Basin
Hai River Basin
Pearl River Basin
Southwest River Basin
Lake area (km²)
100 - 200
200 - 500
500 - 1000
1000 - 5000
SAT in summer between 2000 and 2021 (°C)
SAT in summer 2022 (°C)
AT anomalies in summer 2022 (°C)
SAT anomalies in summer 2022 (°C)
(b1)
(b2)
(b3)
(b4)
(b5)
(b6)
(b7)
(b8)
(b9)
(b10)
Southeast River Basin
Hai River Basin
Huai River Basin
Yellow River Basin
Inland River Basin
Songhua and Liao River Basin
Southwest River Basin
Yangtze River Basin
Pearl River Basin
China
SAT (°C)
Year
2000
2005
2010
2015
2020

Figure. 1

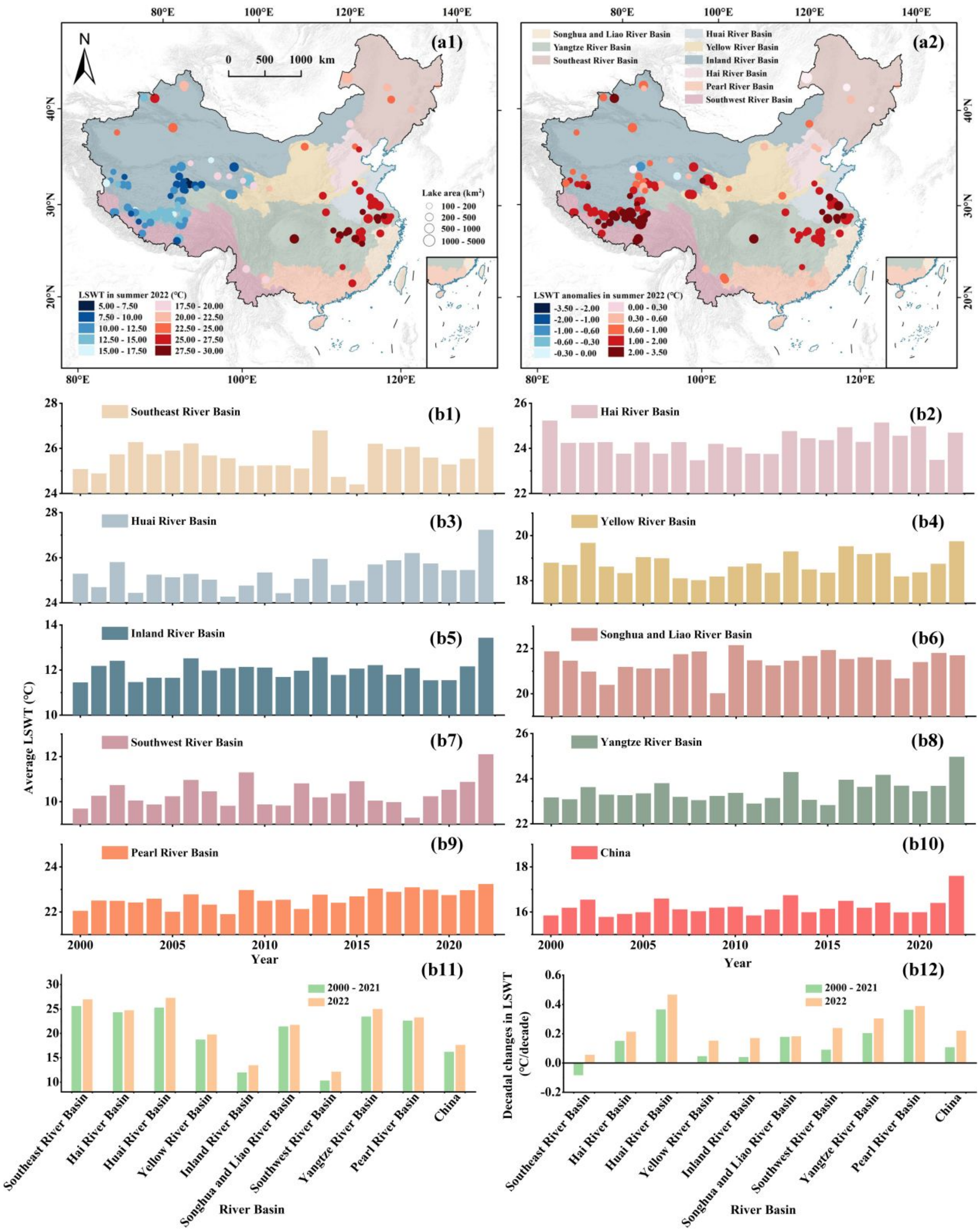
(a1)
LSWT in summer 2022 (°C)
Lake area (km²)
(a2)
Songhua and Liao River Basin
Yangtze River Basin
Southeast River Basin
Huai River Basin
Yellow River Basin
Inland River Basin
Hai River Basin
Pearl River Basin
Southwest River Basin
LSWT anomalies in summer 2022 (°C)
(b1) Southeast River Basin
(b2) Hai River Basin
(b3) Huai River Basin
(b4) Yellow River Basin
(b5) Inland River Basin
(b6) Songhua and Liao River Basin
(b7) Southwest River Basin
(b8) Yangtze River Basin
(b9) Pearl River Basin
(b10) China
Average LSWT (°C)
Year
(b11)
(b12)
2000 - 2021
2022
Decadal changes in LSWT (°C/decade)
River Basin

Figure. 2

Supplementary materials

Materials and methods

In this study, we made lake surface water temperature (LSWT) observations of large lakes in China between 2000 and 2022 from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS-terra) land surface temperature/emissivity 8-day product (MOD11A2 version 6.1) provided by NASA's Earth Observing System Data and Information System (EOSDIS, https://earthdata.nasa.gov). The daytime land surface temperature (LST) (approximately 10:30 local time), nighttime LST (approximately 22:30 local time), and corresponding quality control (QC) images were extracted from MODIS LST images after resampling to a 1 km pixel size. The average of the daytime LST and nighttime LST was taken as the daily LST for this study, before which pixels of poor quality were excluded using QC images[1]. We discard these data and set them to null if less than half the total lake pixels remained after removing those deemed poor quality. The variation between MODIS temperature products and in situ measured water temperature has been verified to be less than 2 °C[2, 3]. Meteorological data were obtained from the National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov/) by inverse distance weight interpolation of the daily site data.

Polygons provided by HydroLAKES (https://www.hydrosheds.org/pages/hydrolakes) were used to determine the lakes (≥ 100 km^2) investigated in our study. The global surface water occurrence (GSWO) dataset, which provides the probability of the presence of surface water between 1984 and 2020 at a spatial resolution of 30 m, was utilized within the lake boundaries of HydroLAKES to determine the permanent water surface extent of the studied lakes[4]. To eliminate boundary effects, i.e., pixels that may be a mixture of land and water, the boundary obtained by the above treatment was buffered inward by 1 km. Excluding lakes that dried up and bays connected to the ocean that were misidentified, 119 large lakes were confirmed for this study. Nine basin polygons in China (namely, Songhua and Liao Basin, Inland River Basin, Yellow River Basin, Hai River Basin, Huai River Basin, Yangtze River Basin, Southeast River Basin, Pearl River Basin, and Southwest River Basin) were obtained from the Resource and Environment Science and Data Center (https://www.resdc.cn/). Water levels in Lake Poyanghu was obtained from the Poyang Lake Wetland Observation and Research Station (http://pyl.cern.ac.cn/). The water surface extent data of Poyang Lake for the summer of 2000 – 2022 was obtained by modified normalized difference water index (MNDWI) and calculated using Landsat[5]. The Ostu algorithm was used to determine the threshold[6]. Due to the low temporal resolution and susceptibility to weather, we took the median value of all usable Landsat images from June to August of each year to calculate the water surface extent for Lake Poyanghu.

LSWT data from the MOD11A2 and GSWO datasets were obtained and processed through the Google Earth Engine (GEE, https://earthengine.google.com/). A lake specific LSWT in our study was calculated as the average temperature of all 1 km pixels within the lake. The original vacancies and the vacant data after quality control were filled using a random forest regression model with five input parameters: year, day of year, longitude, latitude, and elevation[7, 8]. The result of the model was satisfactory, with the error between the estimated and observed values controlled at approximately 2 °C (Figure. S1). Air temperatures (ATs) were acquired by inverse distance interpolation to 1 km spatial resolution images using station data in China from the NCEI dataset. The average local surface air temperature (SAT) was calculated similarly to LSWT, which was obtained by extracting all available pixels of each lake from the AT dataset and calculating the mean value. The anomalies in AT, LSWT and SAT were calculated as the difference between the 2022 values and the averages of 2000 – 2021. On the basis of the reconstructed LSWT, AT and SAT dataset, the long-term variation in the study area was analyzed using the Mann-Kendall trend analysis approach[9, 10].

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94 **Table S1.** Statistics of AT comparison between summer 2022 and summer 2000 – 2021 by month.

		2000 – 2021				2022			
		Mean AT (℃)	**Max AT (℃)**	**Number of days above 30 °C (d)**	**Number of days above 35 °C (d)**	**Mean AT (℃)**	**Max AT (℃)**	**Number of days above 30 °C (d)**	**Number of days above 35°C (d)**
June	**Southeast River Basin**	26.03	32.27	10.82	0.00	25.89	33.33	7.00	0.00
	Hai River Basin	23.34	32.75	5.77	0.09	24.17	35.89	11.00	1.00
	Huai River Basin	24.79	32.60	6.00	0.09	26.99	35.67	16.00	1.00
	Yellow River Basin	19.29	32.28	5.05	0.05	20.95	34.44	14.00	0.00
	Inland River Basin	21.01	36.80	23.64	4.45	22.29	39.89	28.00	15.00
	Songhua and Liao River Basin	20.28	30.64	1.45	0.00	19.74	31.61	1.00	0.00
	Southwest River Basin	18.10	33.52	15.14	0.50	17.79	32.11	5.00	0.00

	Yangtze River Basin	22.20	33.03	10.41	0.00	22.97	32.83	16.00	0.00
	Pearl River Basin	27.10	32.65	14.95	0.00	26.89	31.72	13.00	0.00
	China	22.46	36.91	24.50	4.68	23.08	39.89	28.00	15.00
July	Southeast River Basin	28.60	33.80	21.41	0.09	29.89	35.72	25.00	3.00
	Hai River Basin	25.15	33.20	8.64	0.09	25.18	32.78	7.00	0.00
	Huai River Basin	27.00	33.54	10.95	0.05	27.67	33.67	14.00	0.00
	Yellow River Basin	21.16	33.14	8.23	0.14	21.32	33.94	7.00	0.00
	Inland River Basin	23.07	38.21	27.77	10.68	23.69	40.00	30.00	16.00
	Songhua and Liao River Basin	22.91	31.23	2.14	0.00	23.40	29.11	0.00	0.00
	Southwest River Basin	18.45	32.98	10.36	0.09	19.36	33.44	14.00	0.00
	Yangtze River Basin	24.48	34.62	22.32	0.50	25.78	36.39	25.00	5.00
	Pearl River Basin	27.90	33.35	17.50	0.00	28.59	34.78	22.00	0.00

	China	24.30	38.25	28.50	10.73	24.99	40.00	30.00	16.00
August	**Southeast River Basin**	28.17	33.11	16.68	0.09	29.86	35.56	26.00	5.00
	Hai River Basin	23.65	31.18	3.09	0.00	23.93	33.22	12.00	0.00
	Huai River Basin	26.31	32.55	7.09	0.05	27.83	35.06	21.00	1.00
	Yellow River Basin	19.59	31.77	4.27	0.00	21.09	34.44	14.00	0.00
	Inland River Basin	21.49	36.70	23.27	4.91	21.59	39.11	22.00	11.00
	Songhua and Liao River Basin	21.27	29.94	0.86	0.00	20.31	30.61	2.00	0.00
	Southwest River Basin	18.21	31.98	7.18	0.00	19.42	32.00	9.00	0.00
	Yangtze River Basin	23.90	34.53	17.32	0.86	26.93	37.83	30.00	19.00
	Pearl River Basin	27.54	32.92	16.05	0.00	27.85	34.78	15.00	0.00
	China	23.35	36.80	24.00	5.05	24.31	39.11	30.00	19.00
Summe	**Southeast River Basin**	27.60	34.01	48.91	0.18	28.55	35.72	58.00	8.00

r	**Hai River Basin**	24.05	33.48	17.50	0.18	24.43	35.89	30.00	1.00
	Huai River Basin	26.03	34.00	24.05	0.18	27.50	35.67	51.00	2.00
	Yellow River Basin	20.01	33.62	17.55	0.18	21.12	34.44	35.00	0.00
	Inland River Basin	21.86	38.45	74.68	20.05	22.52	40.00	80.00	42.00
	Songhua and Liao River Basin	21.49	32.03	4.45	0.00	21.15	31.61	3.00	0.00
	Southwest River Basin	18.25	33.92	32.68	0.59	18.85	33.44	28.00	0.00
	Yangtze River Basin	23.53	35.05	50.05	1.36	25.23	37.83	71.00	24.00
	Pearl River Basin	27.51	33.50	48.50	0.00	27.78	34.78	50.00	0.00
	China	23.37	38.45	74.68	20.05	24.12	40.00	80.00	42.00

Table S2. Statistics of average SAT comparison between summer 2022 and summer 2000 – 2021 by month.

	2000 – 2021				2022			
Basin	**June**	**July**	**August**	**Summer**	**June**	**July**	**August**	**Summer**
Southeast River Basin	24.50	28.12	27.68	26.77	25.32	30.70	31.32	29.11
Hai River Basin	23.42	25.51	24.22	24.38	23.66	25.84	24.32	24.61
Huai River Basin	25.06	27.52	26.74	26.44	27.36	28.39	28.59	28.11
Yellow River Basin	17.02	19.10	17.94	18.02	18.44	19.35	19.95	19.25
Inland River Basin	14.45	16.20	15.36	15.33	15.55	17.11	16.86	16.51
Songhua and Liao River Basin	20.60	23.12	21.32	21.68	20.11	23.59	20.23	21.31
Southwest River Basin	14.17	15.19	14.57	14.64	14.75	16.23	16.06	15.68
Yangtze River Basin	22.91	25.79	25.10	24.60	24.01	27.05	27.88	26.32
Pearl River Basin	24.80	25.42	25.08	25.10	24.21	26.50	25.74	25.48
China	17.54	19.55	18.70	18.59	18.55	20.49	20.36	19.80

100 **Table S3.** Statistics of LSWT comparison between summer 2022 and summer 2000 – 2021 by
101 month.

		2000 – 2021		2022	
		Mean LSWT	**Max LSWT**	**Mean LSWT**	**Max LSWT**
June	**Southeast River Basin**	23.37	25.14	22.97	25.52
	Hai River Basin	23.19	25.41	22.46	25.36
	Huai River Basin	24.09	26.48	26.17	28.10
	Yellow River Basin	17.26	27.16	18.29	28.32
	Inland River Basin	10.12	25.71	11.54	28.74
	Songhua and Liao River Basin	20.07	23.71	20.06	24.38
	Southwest River Basin	9.65	20.49	10.61	18.78
	Yangtze River Basin	21.88	27.60	22.74	28.96
	Pearl River Basin	21.87	26.18	21.44	26.05
	China	19.05	27.60	19.59	28.96
July	**Southeast River Basin**	26.65	28.16	28.80	29.33
	Hai River Basin	25.26	27.12	26.04	27.05
	Huai River Basin	26.07	28.44	27.31	28.87
	Yellow River Basin	19.82	28.14	20.07	27.78
	Inland River Basin	12.85	27.50	14.24	29.28
	Songhua and Liao River Basin	22.74	25.33	23.56	25.75

	Southwest River Basin	10.23	20.77	12.51	22.02
	Yangtze River Basin	24.36	29.67	25.85	30.44
	Pearl River Basin	22.83	27.52	24.37	29.73
	China	21.20	29.67	22.53	30.44
August	**Southeast River Basin**	26.65	27.88	29.00	29.40
	Hai River Basin	24.37	26.31	25.57	27.68
	Huai River Basin	25.49	27.56	28.20	30.33
	Yellow River Basin	19.02	26.69	20.86	28.42
	Inland River Basin	12.88	26.25	14.49	29.32
	Songhua and Liao River Basin	21.29	24.20	21.47	24.09
	Southwest River Basin	10.96	20.98	13.15	22.18
	Yangtze River Basin	24.00	29.36	26.30	32.24
	Pearl River Basin	23.02	27.21	23.89	27.95
	China	20.85	29.36	22.55	32.24
Summer	**Southeast River Basin**	25.56	28.33	26.92	29.40
	Hai River Basin	24.27	27.44	24.69	27.68
	Huai River Basin	25.22	28.65	27.23	30.33
	Yellow River Basin	18.70	28.49	19.74	28.42
	Inland River Basin	11.95	27.62	13.42	29.32
	Songhua and Liao River Basin	21.37	25.60	21.69	25.75
	Southwest River Basin	10.28	21.45	12.09	22.18

Yangtze River Basin	23.41	30.04	24.96	32.24
Pearl River Basin	22.57	27.72	23.23	29.73
China	20.37	30.04	21.55	32.24

104 **Table S4.** Comparison of rate of change in SAT and LSWT in 2000 – 2021 with 2000-2022

105 for the nine basins and China.

	Rate of SAT change (°C/decade)		Rate of LSWT change (°C/decade)	
Basin	**2000 – 2021**	**2000 – 2022**	**2000 – 2021**	**2000 – 2022**
Southeast River Basin	0.23	0.30	-0.08	0.05
Hai River Basin	0.63	0.75	0.15	0.21
Huai River Basin	0.11	0.12	0.36	0.47
Yellow River Basin	0.18	0.31	0.05	0.15
Inland River Basin	0.07	0.20	0.04	0.17
Songhua and Liao River Basin	0.29	0.36	0.18	0.18
Southwest River Basin	-0.16	-0.21	0.09	0.24
Yangtze River Basin	0.43	0.47	0.20	0.30
Pearl River Basin	0.13	0.24	0.36	0.39
China	0.32	0.32	0.11	0.22

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Table S5. Slope and *p*-value of the linear relationship of the change in the summer average of LSWT and SAT during 2000 – 2022.

	SAT		LSWT	
Basin	**Slope**	***p*-value**	**Slope**	***p*-value**
Southeast River Basin	0.02	$P < 0.01$	0.08	$P < 0.01$
Hai River Basin	0.02	$P < 0.01$	0.01	$P < 0.01$
Huai River Basin	0.05	$P < 0.01$	0.03	$P < 0.01$
Yellow River Basin	0.01	$P < 0.01$	0.02	$P < 0.01$
Inland River Basin	0.02	$P < 0.01$	0.04	$P < 0.01$
Songhua and Liao River Basin	0.02	$P < 0.01$	-0.01	$P < 0.01$
Southwest River Basin	0.02	$P < 0.01$	0.05	$P < 0.01$
Yangtze River Basin	0.04	$P < 0.01$	0.03	$P < 0.01$
Pearl River Basin	0.04	$P < 0.01$	0.03	$P < 0.01$
China	0.02	$P < 0.01$	0.03	$P < 0.01$

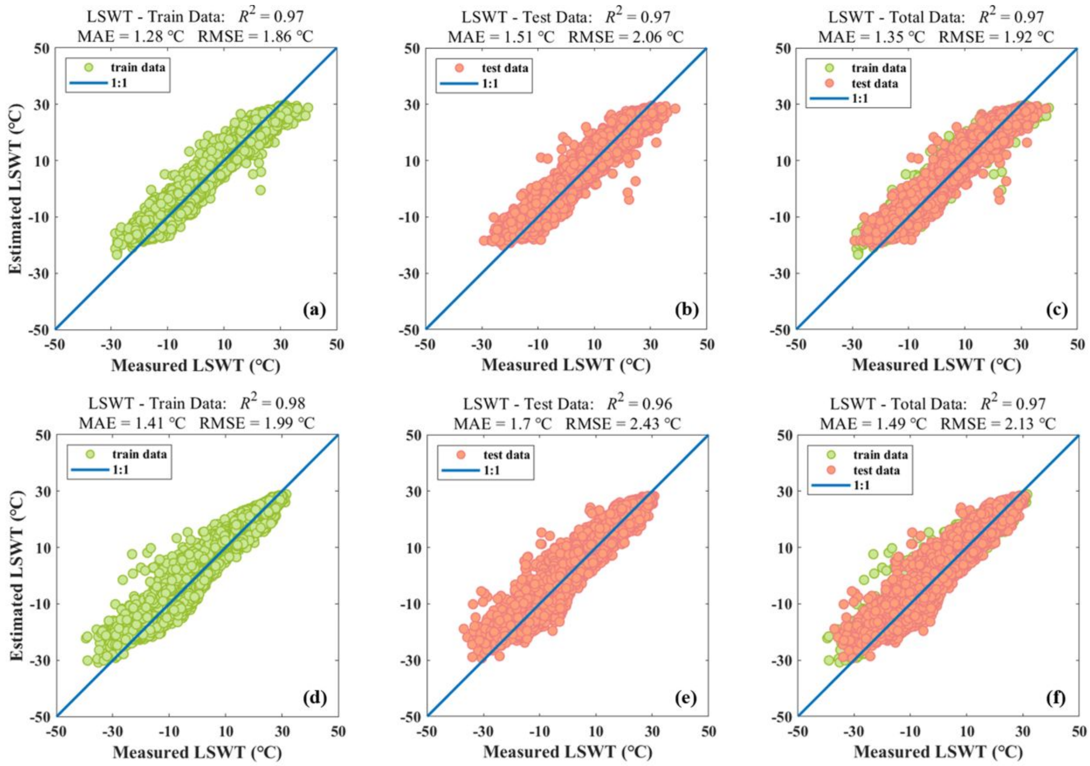

Figure S1. Performance of the random forest regression model for LSWT supplemented with missing data (daytime (a-c), nighttime (d-f)). The green circle represents the training dataset, and the red circle represents the test dataset.

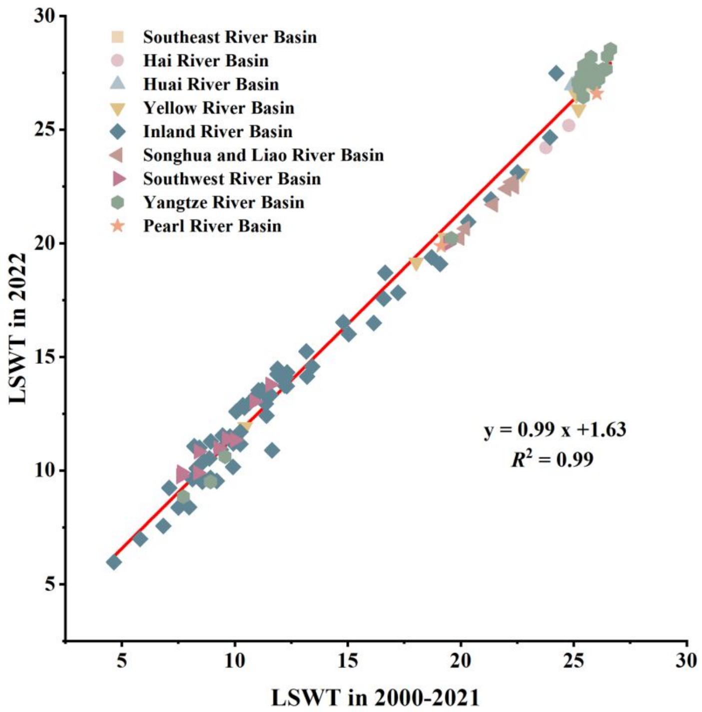

Figure S2. Basin level changes in LSWT (n = 119) from 2000 – 2021 to 2022.

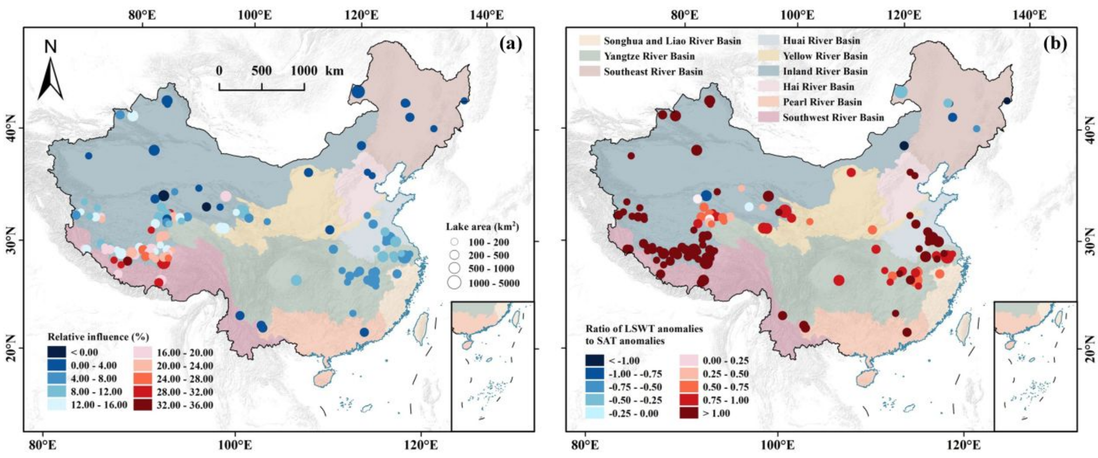

Figure S3. Relative influence of changed LSWT (2022 summer anomalies divided by average summer LSWT of 2000 – 2021) on individual lakes in summer 2022 (a), and the ratio of LSWT anomalies to SAT anomalies (b).

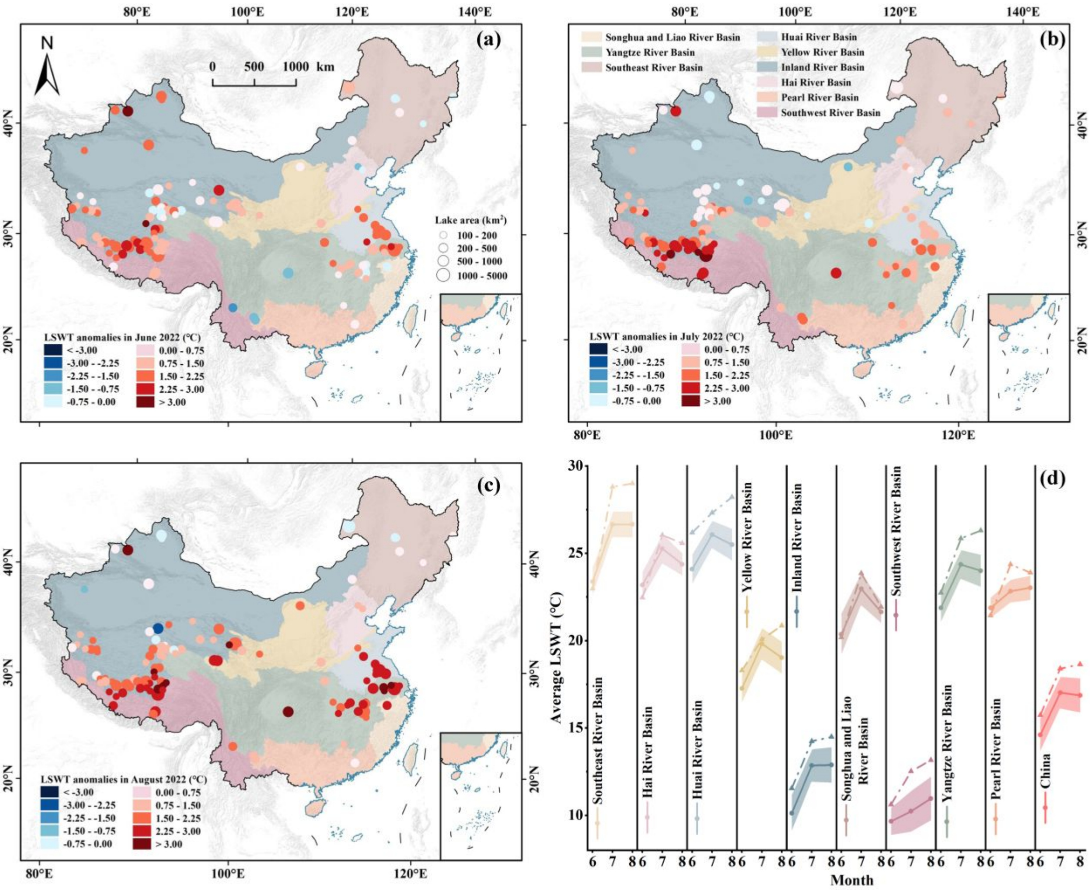

Figure S4. Spatial distribution of LSWT anomalies in June (a), July (b), and August (c) 2022, and line graph (d) of monthly average LSWT for nine basins and nationwide in summer 2000 – 2021 (solid line) and 2022 (dashed line), with standard deviation represented by the shaded region.

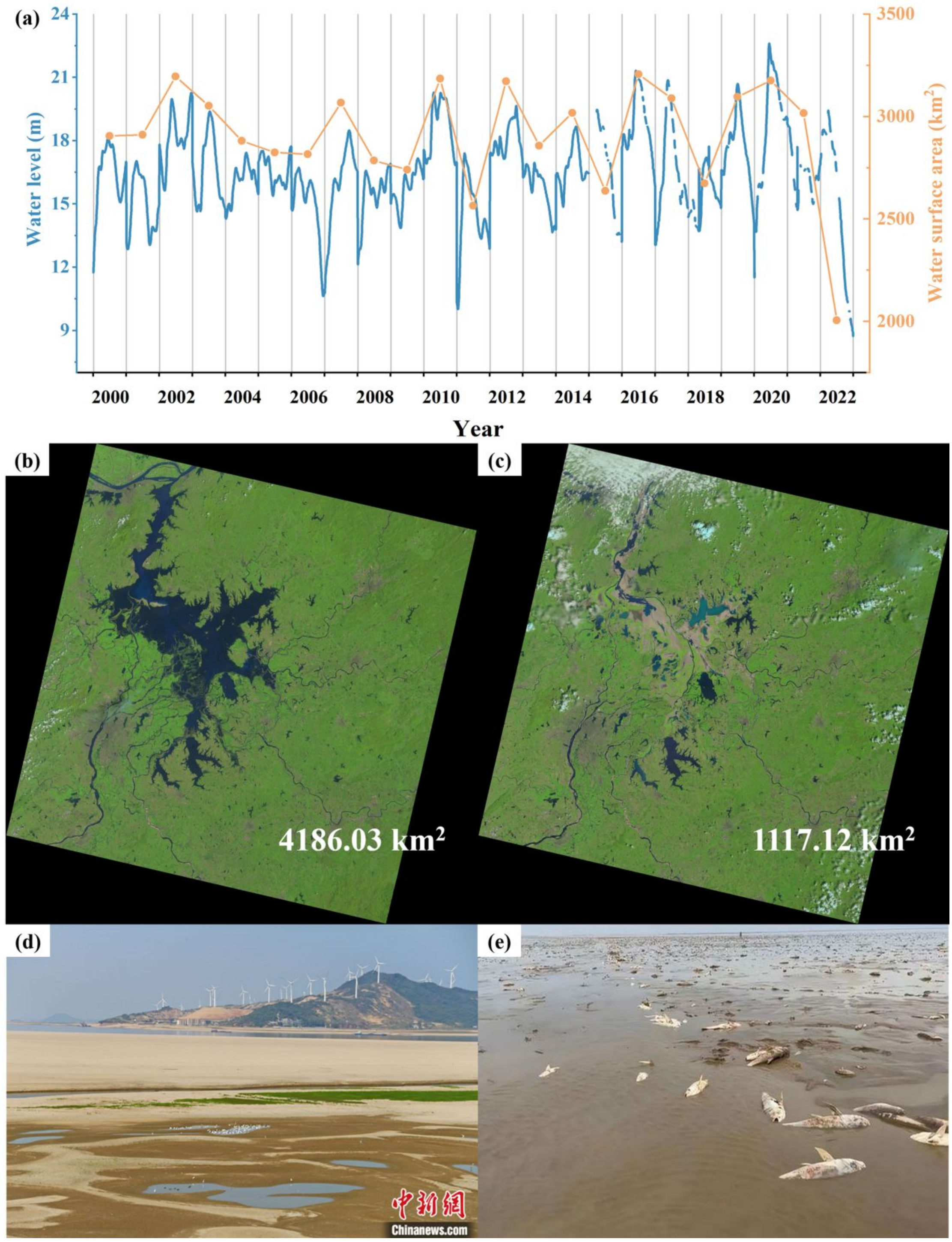

Figure S5. Variation of water level and water surface area of Lake Poyanghu in summer from 2000 to 2022 (a). Landsat images of Lake Poyanghu, the largest freshwater lake in China, on August 27, 2020 (b) and August 27, 2022 (c). Migratory birds gathering in a small puddle in the drought-stricken lake in August 2022 (d). Dead fish in drought-stricken lakebed (e). Photos

136 d and e are from reports on the China News Network (https://www.chinanews.com.cn/).

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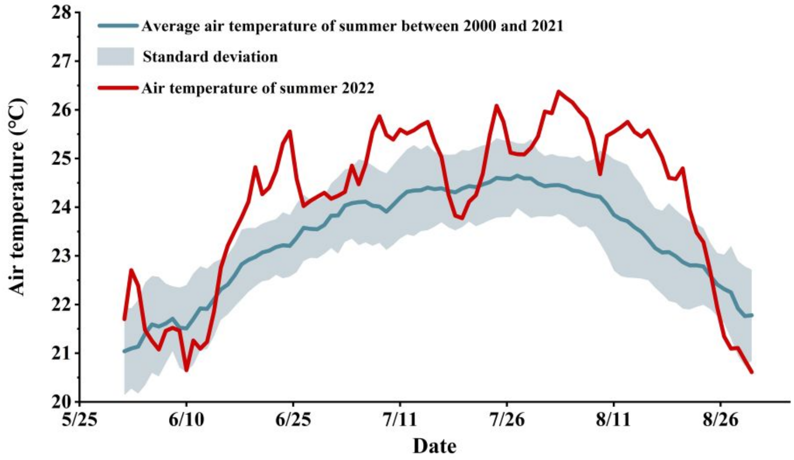
138 

139 **Figure S6.** Line graph of average AT in China in summer 2000 – 2021 (blue line) and 2022

140 (red line), with standard deviation represented by the shaded region.

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