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Spatiotemporal Variations in Dianchi Lake's Surface Water Temperature From 2001 to 2017 Under the Influence of Climate Warming

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ABSTRACT Lake Surface Water Temperature (LSWT) is one of the most important biological environmental conditions that determine the biological status of lakes. It is the most important indicator that affects the decomposition of matter and the metabolism of living things, and directs the biomass production processes in lakes. Variations in LSWT are the main factor causing changes in the physical and chemical processes, as well as dynamic phenomena in lake water. In this study, MODIS (Terra) remote sensing images of 2001-2017 were used as the data source, and the LSWT of Dianchi Lake from 2001 to 2017 were extracted with the MOD11A2 LST product. Analysis was then conducted on the temporal and spatial variatons of the lakes's LSWT across the past 17 years, and the influences of climate change on LSWT. The research results show that overall, Dianchi LSWT has been on the rise over the past 17 years. This trend was especially evident in the lake's average annual daytime and nighttime temperature, which has significantly increased by about 0.12°C/yr^{-1} (P<0.002) and 0.09°C/yr^{-1} (P<0.05), respectively. Correlation analysis reveals that the correlation between air temperature and the average annual water temperature of Dianchi Lake was low, with daytime correlation coefficient being r=0.041, and nighttime correlation coefficient being r=0.012. On the other hand, average monthly air temperature presents a high correlation with monthly average water temperatures. The coefficient with nighttime monthly water temperature is r>0.82 (P<0.001), and the coefficient with daytime monthly water temperature is r>0.63 (P < 0.02).

INDEX TERMS LSWT, MODIS, temporal and spatial variation, air temperature, correlation.

I. INTRODUCTION

Lake surface water temperature (LSWT) is one of the most important factors affecting lakes' ecological environments, and a significant parameter for describing the energy state of the lake surface, which plays a vital role in maintaining balance of the lake ecosystem [1], [9], [16]. LSWT is a key physical parameter for heat balance and moisture exchange processes between lakes and their surrounding atmospheres [2], [3]. It significantly affects hydrochemical processes and dissolved gas concentrations in water, and controls biological processes and ecological conditions within the lake [4]. At the same time, compared to other water quality data parameters, LSWT is easier to monitor, and the research work can be carried out over a longer time span and across a larger spatial extent. Moreover, LSWT responds the most rapidly and sensitively to changes in external environmental conditions, such as climate changes and human activities, making it a sentinel of ecological environment changes [6], [28], [29]. In addition, lakes are not only indicators of climate change, but they also regulate the climate of watershed. Lakes also have an important influence on the formation and development of social culture, regional culture and national culture. Human social activities are often closely related to lakes and rivers [5], [32], [33].

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Over the past few decades, inland lakes around the world have experienced significant increases in water temperature [7], in 2009, Schneider et al. studied several lakes in California and Nevada, USA, and measured their LSWT at night 17 summers in a row. Through this he discovered that the LSWT of his subjects showed a serious upward trend, which was twice the increase in the minimum temperatures of the local atmosphere [8]. In 2001, Livingstone and Dokulil's study of the LSWT of eight lakes in the Perialpine region of northern Austria found that the air temperatures during all seasons were highly correlated with LSWT. From autumn to spring, the spatial consistency in the LSWT of the Central European lakes was related to the dominating influences of large-scale climate processes on weather in the North Atlantic, while during the summer, the influence of air temperature on LSWT was more regional [21]. In 2014, Guoqing Zhang et al. studied the LSWT of 52 lakes on the Qinghai-Tibet Plateau, and discovered that the main reason for the changes in water temperature was the increases in air temperature that were led by global warming (0.036 ± 0.027°C/yr^{-1}, 2001-2012). [20].

The largest plateau lake in Yunnan Province, Dianchi Lake is known as the Pearl of the Plateau and plays an important role in the local societal development. Over the past 30 years, the water quality of Dianchi Lake has deteriorated from Class II in the 1960s to inferior V, making it one of the most polluted lakes in China. Although the local government has invested a lot of manpower and resources to remedy the situation, under the dual influence of global warming and rapid urbanization, Dianchi lake remains as one of the most polluted lakes in China, with continuously aggravations in eutrophication, frequent outbreaks of cyanobacteria blooms, obvious declines in water quality, and serious damages to the water ecosystem, which especially caused harm to major biological groups such as aquatic plants, fish and algae [25]. The right water temperature is a necessary condition for cyanobacterial outbreak [10]. Therefore, exploring the temporal and spatial dynamics of the LSWT of Dianchi Lake is the key to protecting its water environment.

In recent decades, with the development of remote sensing technologies [37], [38], scholars have used a variety of remote sensing images to study the variations in LSWT and its influencing factors at different spatial and time scales. For example, Giardino and Pepe used Landsat Thematic Mapper TM to map LSWT distribution from March to July 1997 in the mountainous area of Iseoia, Italy. The root mean square error of the LSWT derived from the TM data was 0.3°C [11]. Another example would be Schneider and Hook, who used AVHRR data to analyze the nighttime LSWT of 167 large inland lakes around the world from 1985 to 2009. The data accuracy verification results showed that the water temperature deviation was 0.15°C, the standard deviation was 0.31°C, and the root mean square error was 0.53°C. Also, the average nighttime LSWT increased rapidly from 1985 to 2009, with the average temperature increase rate being 0.045 ± 0.011°C/yr^{-1}, the highest increase rate being 0.10 ± 0.01°C/yr^{-1}, and warming in regions with medium to high latitudes in the northern hemisphere being much higher than that in lower-latitude regions and the southern hemisphere [12]. Similar to the previous two examples, Simon & Tormos extracted the LSWT of two fresh water lakes in mainland France in 2009 using the single-channel correction algorithm of single-band thermal infrared Landsat data. The accuracy of the outputs were high, with the r^2 value being higher than 0.9, and the root mean square error between 1-2°C [27]. Hinkel et al. compared the LSWT produced by Landsat8 remote sensing image data with field measurements in their analysis of the LSWT of Arctic lakes. The results showed an error range of 0.11°C $\sim$ 0.46°C, with high precision [13], [18]. In 2014, Guoqing Zhang et al. used MODIS land surface temperature (LST) data to obtain the LSWT of 52 lakes on the Qinghai-Tibet Plateau between 2001 and 2012. Among these lakes, the surface temperature of 31 lakes increased, and the average heating rate was 0.055 ± 0.033°C/yr^{-1}. It was also observed that the surface temperature of nine of the lakes warmed up faster than the air temperature, and the warming of the LSWT could be attributed to the increases in local air temperature, surface temperature, and other factors. The results of precision analysis showed that the correlation coefficient between the in situ measured LSWT and the LSWT measured by MODIS was r=0.89, and the root mean square error was 4.53°C. The LSWT obtained by MODIS inversion had a high precision, and it thus helped filled in the gaps for the lack of studies on the change pattern of LSWT over longer time scales [20]. In 2017, Wei Wan & Huan Li et al. used MODIS LST's product, MOD11A2 to extract the surface temperature of 291 lakes that had areas greater than or equal to 50km^2, on the Qinghai-Tibet Plateau from 2001 to 2015, and obtained a complete LSWT data set through post-processing [6]. The dataset and the in-situ measured dataset were analyzed for accuracy testing (r=0.89), which results showed that the LSWT of the plateau lake inversion by MODIS data had high precision [24], [34].

This study will be based on MODIS data and ECMWF meteorological data, and use geospatial analysis technology as the theoretical basis. The temporal and spatial change processes of the LSWT of Dianchi Lake will be analyzed, along with the correlation between air temperature and LSWT. This study provides data support for future efforts on improving the water ecological environment, restoring the water ecosystem, and protecting the biodiversity in Dianchi Lake, and puts forward new ideas and methods for relevant research on other lakes.

II. STUDY AREA

Dianchi Lake is located in the center of the Yunnan-Guizhou Plateau (102°10'-103°40'E, 24°23' to 26°22'N, Figure 1), and in the southwest monsoon climate zone of the subtropical plateau. In this region, climate change is mainly controlled by the southwest monsoon and the tropical continental air mass. Dianchi lake has an elevation of about 1886 meters,

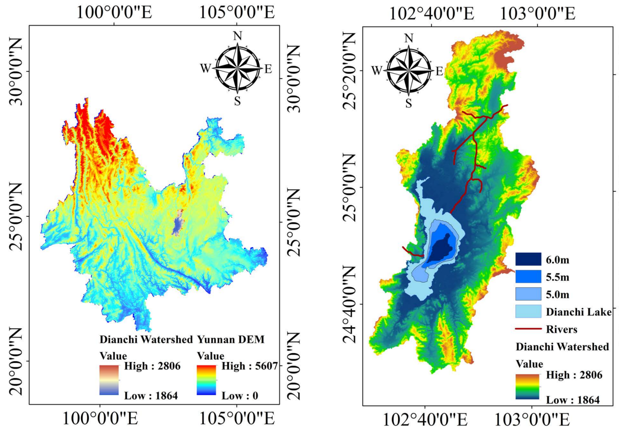

FIGURE 1. Study area, Dianchi Lake is located in the middle of the Yunnan-Guizhou Plateau, southwest of the Dianchi Lake Watershed.

an area of about 300 square kilometers, and an average water depth of about 5 meters. It is a semi-enclosed lake, with its southwestern seaport being the only water outlet. The Dianchi Lake watershed of construction area shown a significant upward trend, while the area of woodland and grassland shown a downward trend. The area of other land use types changed little (More details please refer to appendix 1 "Land use type"). Dianchi Lake plays an important role in climate regulation and has a certain impact on the social and economic development of Dianchi Lake Watershed.

III. DATA AND METHODS

A. DATA

The data source for the surface water temperature of Dianchi Lake in this study is MOD11A2 for 2001-2017, which is obtained from NASA's Earth Observing System Data and Information System (EOSDIS, https://earthdata.nasa.gov). MOD11A2 is a MOD11A1 composite surface temperature product produced every 8 days with a spatial resolution of 1km and a time resolution of 8 days. There are 46 daytime (10:30) and nighttime (23:30) surface water temperature data points produced for Dianchi Lake every year. Since the scene image (strip number 129 and line number 43) can completely cover the research area, it is only necessary to use the MODIS re-projection tool to project Dianchi Lake's MOD11A2 data in GeoTIFF format to UTM area 45.

In this study, the US Earth Resources Satellite, Landsat's remote sensing data was used to extract the boundary information of Dianchi Lake. The Landsat series's remote sensing data, which is Level L1 data with a spatial resolution of 30m, is obtained through Geospatial Data Cloud (http://www.gscloud.cn), and data from 1989 to 2017 with the lowest cloud volume is selected to extract the boundary information of Dianchi Lake. For years 2011 and prior, the sensor used is Landsat5, and for years 2013-2017, the sensor used is Landsat8.

In order to reduce the potential errors caused by fluctuations in topographic water interfaces and mixed pixels at the junctions of land and water, an 1km buffer is set when processing the lake boundary data. Since the area of Dianchi Lake is larger than 30km2, setting a buffer zone of 1km can not only minimize the surrounding land's impact on LSWT, but can also ensure that there is enough water body to invert the surface water temperature [2], [6]. The accuracy of the LSWT obtained through inversion can thus be ensured.

TABLE 1. Remote sensing image data sources and dianchi lake area.

Year	Sensor type	Area (km^2)	Cloud area Percentage(%)	Image date
1988	Landsat-5 TM	301.80	0.02	Jan 26
1989	Landsat-5 TM	298.53	6.28	Mar 9
1990	Landsat-5 TM	302.25	10.38	Jan 15
1991	Landsat-5 TM	307.56	1.46	Feb 19
1992	Landsat-5 TM	303.32	0.02	Sep 1
1993	Landsat-5 TM	291.51	4.2	Dec 25
1994	Landsat-5 TM	300.49	0.24	Dec 12
1995	Landsat-5 TM	301.91	4.21	Apr 19
1996	Landsat-5 TM	303.60	0.33	Jan 16
1997	Landsat-5 TM	301.87	0.13	Mar 7
1998	Landsat-5 TM	301.83	0.35	Apr 27
1999	Landsat-5 TM	302.58	15.44	Mar 29
2000	Landsat-5 TM	299.91	5.28	Nov 26
2001	Landsat-5 TM	300.01	0.06	Mar 2
2002	Landsat-5 TM	299.81	0	Apr 6
2003	Landsat-5 TM	301.89	0.51	Feb 20
2004	Landsat-5 TM	299.65	0	Mar10
2005	Landsat-5 TM	299.88	0	Feb 25
2006	Landsat-5 TM	303.25	4.1	May 3
2007	Landsat-5 TM	301.87	0	May 6
2008	Landsat-5 TM	296.92	1.29	Apr 6
2009	Landsat-5 TM	300.48	0.02	Nov 3
2010	Landsat-5 TM	298.21	0.02	Feb 7
2011	Landsat-5 TM	298.24	0.02	Feb 26
2013	Landsat-8 OLI	294.68	3.99	May 22
2014	Landsat-8 OLI	295.15	0.07	Apr 23
2015	Landsat-8 OLI	298.74	0.1	Jan 4
2016	Landsat-8 OLI	298.61	0.15	Nov 22
2017	Landsat-8 OLI	299.83	0.15	May 1

B. METHODS

1) BOUNDARY EXTRACTION OF DIANCHI LAKE

First, radiometric calibration and atmospheric correction is performed on the original Landsat dataset to eliminate radiation errors caused by the atmosphere. Next, the boundary of Dianchi's water body from 1988 to 2017 is extracted using the Normalized Difference Water Index (NDWI). The pre-processed Landsat5 and Landsat8 images are then subjected to band calculation using equation (1), and the resulting image of the calculation is set to an appropriate threshold through visual interpretation. Finally, the boundary of Dianchi's water body is obtained through cropping the image [14]–[16].

$$NDWI = (p\,(Green) - p\,(NIR))/(p\,(Green) + p\,(NIR)) \quad (1)$$

In the above equation, p (Green) refers to the green band of the Landsat image, and p (NIR) is the near-infrared band of the Landsat image.

2) ACQUISITION OF LSWT

Due to the influence of clouds, some MODIS image data will be contaminated. In this study, the contaminated data is first replaced with null values. The average pixel value of

Dianchi Lake's surface is then obtained through the regional statistical method, and is converted to units in Celsius (°C). There are also null values and outliers among all LSWT data points, which are dealt with using interpolation. The eight-day average LSWT of Dianchi Lake from 2001 to 2017 is then calculated as an input to the monthly average, quarterly average, and annual average of Dianchi Lake's LSWT.

IV. RESULTS AND DISCUSSION

A. TEMPORAL AND SPATIAL CHANGES IN DIANCHI LAKE'S AREA

From 1988 to 2017, changes in the area of Dianchi Lake have gone through four stages. During the first stage, which was from 1988 and 1993, industrialization in Yunnan Province advanced rapidly. As a result, industrial water consumption increased sharply. A large amount of industrial water was directly extracted from Dianchi Lake, causing a reduction of about 10km2 in the area of Dianchi Lake, at a rate of 2.5km2/yr^{-1}, and with the most affected region being Caohai. During the second stage, from 1993 to 2006, the government began to control the ecological environment of Dianchi Lake. In 1993, the Caohai Dredging Project was launched [35]. The area of the dredged seabed mud was 2.83 km2, the sediment was 4.24 million cubic meters, and the capacity of Caohai increased by more than 4 million cubic meters. Through this project, the area of Dianchi Lake increased significantly at a growth rate of about 1.95 km2/yr^{-1}, resulting in an area 12km2 larger than that in 1993. The major affected areas was no longer limited to Caohai, and there were significant expansions in the areas of the outer lake waters. During the third stage, from 2006 to 2013, both Caohai and the outer waters experienced decreases in size. The area of Dianchi lake as a whole reduced by about 9km^2, and the reduction rate was about 3.89 km^2/yr^{-1}. During the fourth stage, the area of Dianchi Lake increased starting from 2014, and had increased by about 5km2 by 2017. The growth rate was about 1.25 km2/yr^{-1}, and the main area experiencing the growth was Caohai, which was directly affected by the Niulan River diversion project [36] (Figure 2).

In addition, in terms of interannual precipitation changes, Yunnan had more annual precipitation before the 1970s, but it began to decrease in the late 1970s. After the mid-1990s, the annual precipitation at first increased, and then began to decrease again after 2005. This trend also affected the area of Dianchi Lake, which then affected the LSWT as there was a direct impact between them [17], [30]. However, the lake surface area change in Dianchi is not significant, so changes in the surface area of Dianchi Lake have no considerable effect on water temperature.

B. THE ANNUAL CHANGE PROCESS OF DIANCHI LAKE'S SURFACE TEMPERATURE

The daytime LSWT of Dianchi Lake was the lowest in January (Tmin = 20.4°C) and the highest in May

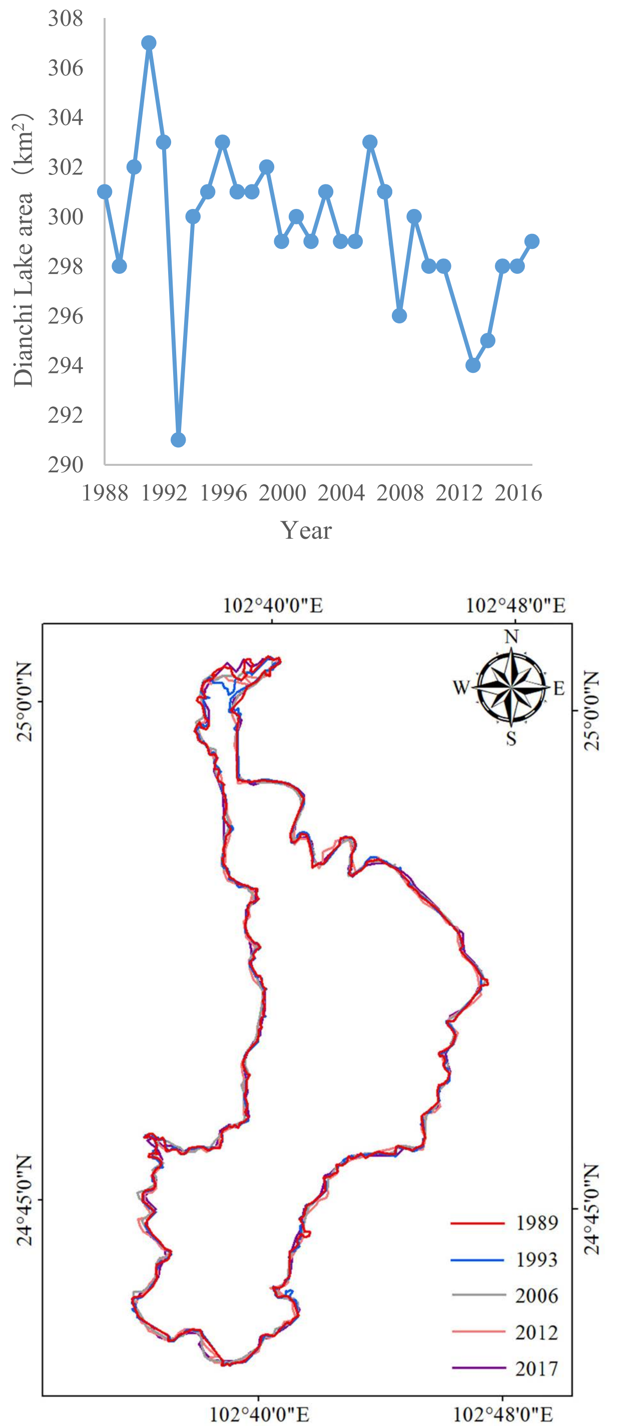

FIGURE 2. Schematic diagram of the change trend and change area of Dianchi Lake area in the past 30 years.

(Tmax = 29.5°C), with the temperature difference being about 9.1°C. The nighttime LSWT was the lowest in January (Tmin = 12.4°C) and the highest in July (Tmax = 23.6°C), with the temperature difference being about 11.2°C and larger than the daytime difference. The maximum difference between the lake's daytime and nighttime LSWT was about 9.5°C, which occurred in March, while the minimum was

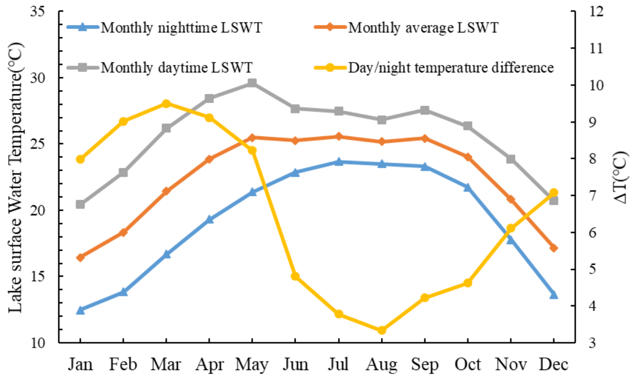

FIGURE 3. 2001-2017 Dianchi surface water temperature change trend during the year.

about 3.3°C, which appeared in August. During daytime, Dianchi Lake's LSWT increased from January to May, and decreased from May to August. From August to September, it increased by 0.7°C, and showed a downward trend from September to December. On the other hand, the nighttime LSWT showed an upward trend from January to July, and a downward trend from July to December. During both daytime and nighttime, the LSWT of Dianchi Lake rises from January to May, stabilizes between May to September, and decreases from September to December.

Figure 4 shows the characteristics of the monthly means of the water temperature of Dianchi Lake and the air temperature above the lake. The monthly mean air temperature increased significantly from January to May, and the monthly mean of LSWT showed an upward trend during the same period due to the resulting influence. In addition, because of the large heat capacity of the water body, the rising rate of Dianchi Lake's LSWT was lower than that of the average monthly temperature. The average monthly temperature was the highest in June, and decreased slowly from June to September. The average monthly LSWT did not change significantly from May to September, but experienced a decline from September to December, with September to October's trend being slightly downward, and October to December's trend being significantly downward. The difference between the lake's LSWT and the air temperature during months with changing temperatures was greater than that during months with relatively stable temperatures. Moreover, the timing for Dianchi Lake's LSWT to begin to largely decrease was about one month after when the air temperature started to decrease, which was mainly due to the large heat capacity of the water body. When the LSWT decreased, the heat dissipation process of the water body was more prolonged than the decrease process of air temperature.

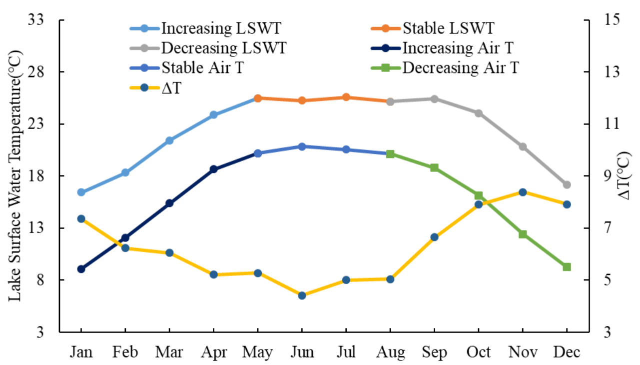

FIGURE 4. The average monthly water temperature of Dianchi Lake and average monthly air temperature from 2001 to 2017.

Figure 5 shows the distribution of monthly mean values between 2001 and 2017. The highest monthly average LSWT appeared in August (Tmax = 28.8°C), and the lowest monthly LSWT appeared in January (Tmin = 15.2°C). The monthly average water temperatures in spring and winter were relatively concentrated on the lower end of the spectrum, while the averages in summer and autumn were more evenly distributed, with very obvious variations throughout the year. Therefore, the annual changes in Dianchi Lake's LSWT were mainly dominated by summer and autumn.

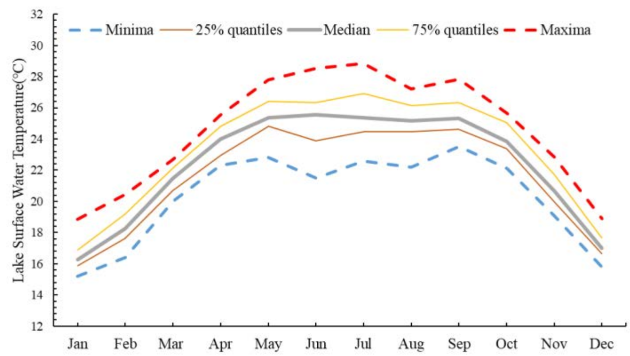

FIGURE 5. Monthly mean of surface water temperature of the Dianchi Lake during 2001-2017, the dotted line is the maximum (red) and the minimum (blue), the green line is the lower quartile, and the orange line is the upper quartile, and the gray line is the median.

C. INTERANNUAL TIME SERIES VARIATIONS IN DIANCHI LAKE'S LSWT

1) CHARACTERISTICS OF THE ANNUAL CHANGES IN DIANCHI LAKE'S LSWT

During the period of 2001-2017, the average annual fluctuations in Dianchi Lake's water temperature were not consistent across daytime and nighttime. The lowest value during the day occurred in 2009 (Tmin = 24.6°C), and the highest occurred in 2014 (Tmax = 26.8°C). The lowest value at night appeared in 2008 (Tmin = 18.3°C), and the highest value appeared in 2014 (Tmax = 19.9°C).

The annual average of Dianchi lake's LSWT increased during both daytime and nighttime. The average annual growth rate during the day was about 0.12°C/yr^{-1}, which was a significant increase ($P<0.001$). The average growth rate at night was about 0.09°C/yr^{-1}, and it was significant as well ($P<0.05$). During the day, the annual average LSWT of Dianchi Lake increased more rapidly and significantly (Figure 6).

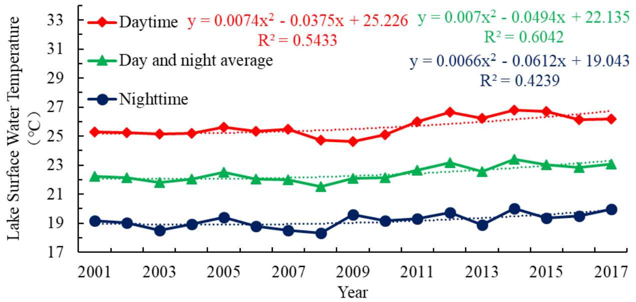

FIGURE 6. Average annual trends of surface water temperature in Dianchi Lake over the daytime and nighttime.

2) SEASONAL VARIATIONS IN DIANCHI LAKE'S LSWT

Over the past 17 years, the average LSWT of Dianchi Lake in spring during both daytime and nighttime showed a slightly upward trend, which was non-significant and had many fluctuations. In summer, Dianchi Lake's nighttime LSWT also increased slightly, with the highest value of the nighttime LSWT appearing in 2012 (Tmax = 24.9°C), the lowest value appearing in 2016 (Tmax = 21.7°C), and a maximum temperature difference of approximately 3.2°C. On the contrary, the average daytime LSWT varied greatly during summer, showing an upward trend. The lowest and highest values appeared in 2009 and 2012 respectively, and there was a maximum temperature difference of approximately 4.9°C. In autumn, Dianchi Lake's daytime average LSWT increased more obviously, with a maximum temperature difference of about 4.1°C. The lowest and highest values appeared in 2001 and 2015 respectively (Tmin = 24.1° C, Tmax = 28.2°C). Moreover, this rise was continuous (0.18°C/yr^{-1}), as well as significant ($P<0.05$). Dianchi Lake's autumn nighttime LSWT continued to show a slightly upward trend, with the maximum temperature difference being about 1.6°C. In autumn, Dianchi Lake's daytime average LSWT increased more obviously, with a maximum temperature difference of about 4.1°C. The lowest and highest values appeared in 2001 and 2015 respectively (Tmin = 24.1°C, Tmax = 28.2°C). Moreover, this rise was continuous (0.18°C/yr^{-1}), as well as significant ($P<0.05$). Dianchi Lake's autumn nighttime LSWT continued to show a slightly upward trend, with the maximum temperature difference being about 1.6°C.

D. VARIATIONS IN THE SPATIAL DISTRIBUTION OF DIANCHI LAKE'S LSWT

The spatial distribution of the annual mean LSWT of Dianchi Lake from 2001 to 2017 was obtained through Kriging interpolation, as shown in Figure 9. The results show that there was a certain level of fluctuations in the spatial distribution of Dianchi Lake's LSWT, and the overall trend was on the rise. The warming area gradually expanded to the south of

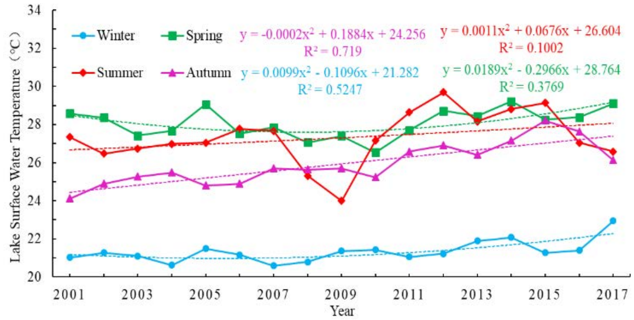

FIGURE 7. Seasonal trends in average daytime LSWT.

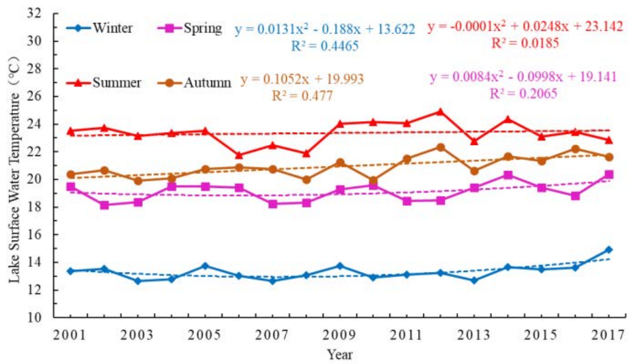

FIGURE 8. Seasonal trends in average nighttime LSWT.

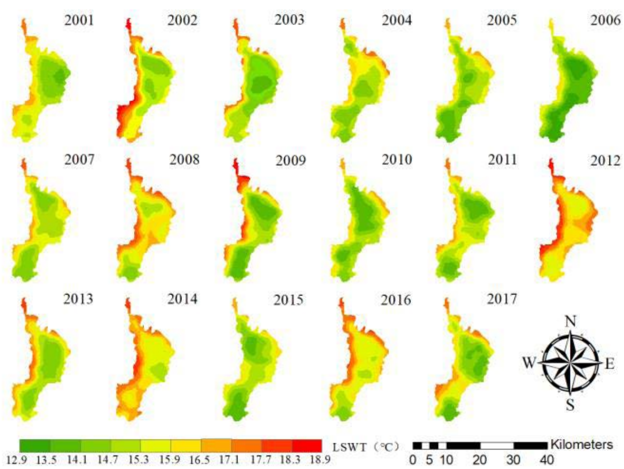

FIGURE 9. Annual mean daytime spatial distribution of Dianchi Lake's LSWT.

Dianchi Lake, and the number of regions affected gradually increased as well, especially in 2008, 2012, 2014, and 2016, when the increase of high temperature regions became more significant. In addition, changes in the lake's area also affected the temperature gradients and uniform levels within the lake [17].

The spatial distribution of Dianchi Lake's daytime annual average LSWT was consistent during 2001-2017. The high-temperature areas were mainly in the northern part of Dianchi Lake, the northeast coast, and the southwest coast. The western shore's water temperature is higher in those years (2002, 2008, 2009, 2012, 2013, 2014, 2016), and overall it is higher than the central deep area of the lake. On the other hand, the low-temperature areas were mainly in the deep-water areas in the central part of Dianchi Lake, and the temperature was lower at the center of the lake than at the lakeside. During nighttime, the spatial distribution of the annual average LSWT demonstrated opposite characteristics comparing to daytime figures (Figures 9,10). The differences between daytime and nighttime is shown in Figure 10, with the temperature difference being higher in the northern coast (Tmax = 6.42°C, Tmin = 3.97°C), and smaller in the central and southern regions (Tmax = −2.12°C, Tmin = 0.09°C). The average annual LSWT distribution during the day was mainly shaped by the fact that many rivers in the north flowed into Dianchi Lake, and that solar radiation had a greater warming impact on shallower water areas, which caused the water temperature in the northern part of Dianchi Lake to be higher. On the contrary, for deep-water areas, the hydrothermal capacity was larger and the warming impact of solar radiation was smaller, resulting in lower temperatures in the central area of Dianchi Lake.

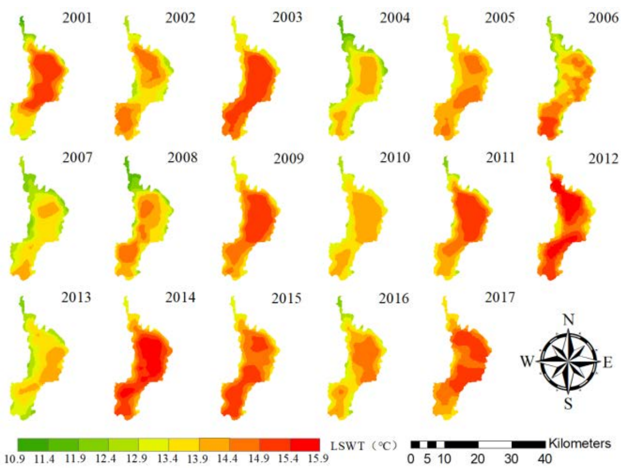

FIGURE 10. Annual mean nighttime spatial distribution Dianchi Lake's LSWT.

At night, due to the absence of solar radiation, the entire lake was in a state of heat dissipation. In deep-water areas, the heat capacity of the lake water was large and the cooling effect was small, while in the shallow-water areas, heat dissipation occurred rapidly, resulting in significant cooling-down.

Seasonal changes in Dianchi Lake's LSWT are shown in Figure 12. The spatial distribution of daytime quarterly mean LSWT was similar to that of the annual average (Fig. 12.a). During nighttime, the average LSWT was characterized by lower temperatures in the coastal region and higher temperatures in the central region of the lake (Fig.12.b). During both daytime and nighttime, the seasonal average LSWT was the highest in summer and the lowest in winter. The difference between the spatial distribution of daytime and nighttime LSWT was higher in the lakeside area (Tmax = 7.8°C, Tmin = 5.92°C) and lower in the central area of the lake (Tmax = 2.47°C, Tmin = 1.23°C) (Fig. 12.c). The spatial distribution pattern could be mainly attributed

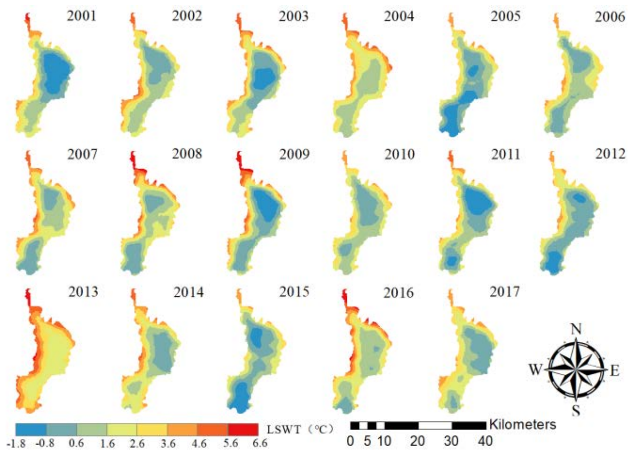

FIGURE 11. Annual mean LSWT difference between daytime and nighttime.

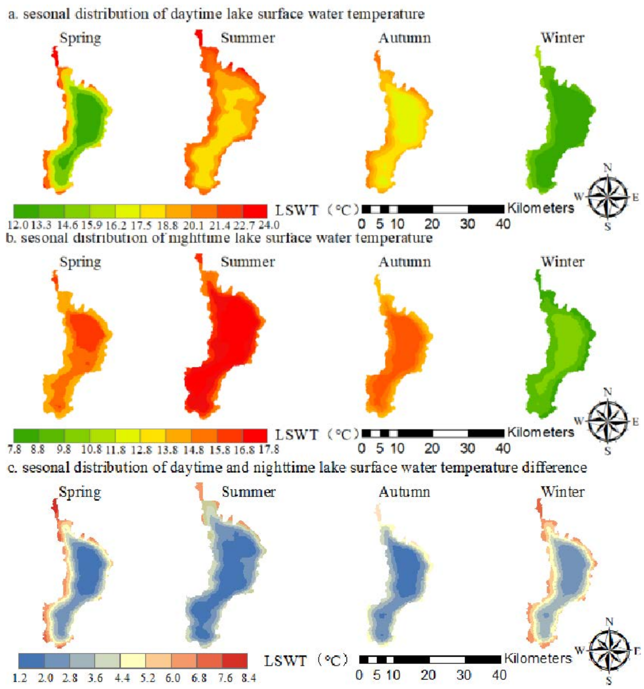

FIGURE 12. Quarterly mean water temperature on the surface of the Dianchi Lake in daytime and nighttime, and temperature difference between day and night.

to the different effects inflowing streams from the north and solar radiation had on the deep-water area and shallow-water areas, as well as the different nighttime heat dissipation rates between the different regions. In addition, regional differences in how lake temperature responds to climate warming also affects the process of LWST changes [31].

E. TEMPERATURE CHANGE PROCESSES AND THE CORRELATION BETWEEN AIR TEMPERATURE AND DIANCHI LAKE'S LSWT

Figure 14 shows the comparison between the annual average LSWT of Dianchi Lake and the local air temperature. The annual average LSWT during both daytime and

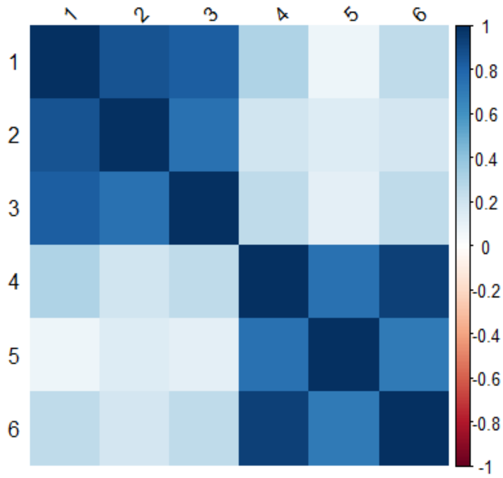

FIGURE 13. Correlation analysis between the highest, lowest and average surface water temperature of Dianchi Lake and the air temperature in day and night.

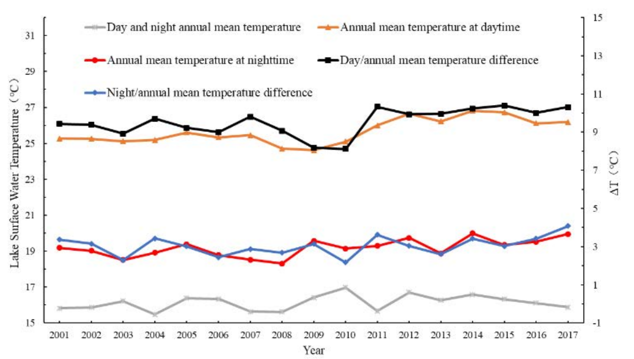

FIGURE 14. Comparison of mean annual surface water temperature of Dianchi Lake and air temperature.

nighttime was higher than the air temperature. The maximum daytime temperature difference was 10.3°C (2017), and the minimum was 8.1°C (2010). The maximum nighttime temperature difference was 4.0°C (2017), and the minimum was 2.1°C (2010)

The trend testing results show that the annual average air temperatures in the Dianchi Lake Watershed has been increasing at a rate of about 0.02°C/yr^{-1}, which did not pass the significance test (P>0.05), and was thus identified as a non-significant change. The average air temperature in the Dianchi Lake Watershed showed a downward trend in winter, and a decline rate of about 0.01°C/yr^{-1}. This result did not pass the significance test either (P>0.05), and was thus also a non-significant change. In spring, the average air temperature showed an upward trend, and its rate of increase was about 0.03°C/yr^{-1}, which again did not pass the significance test (P>0.05), and was a non-significant increase. The average air temperature in summer and autumn showed an upward trend, and the rise rate was about 0.03°C/yr^{-1} in summer and 0.05°C/yr^{-1} in autumn. These two trends passed the significance test (P<0.05) and were thus categorized as significant increases.

LSWT can directly reflect long-term climate change and respond quickly to climate change, and increases in air temperature is the direct cause of increases in LSWT [2], [6]. The increase in temperature is the direct cause of the increase in surface water temperature on the lake [20], [22]. Lager water bodies can help regulate the climate in the surrounding area, which is closely tied to the changes in the LSWT of the water body [19], [23], [26]. Therefore, this study analyzes the correlation between air temperature and Dianchi Lake's LSWT at different time scales. The results of correlation analysis show that the correlation coefficient between the annual average temperature in the Dianchi Lake Watershed and the annual average LSWT of Dianchi Lake during daytime is r=0.04, which signifies a very low correlation. The correlation coefficient between the annual average temperature of the Dianchi Lake Watershed and the nighttime LSWT of Dianchi Lake is r=0.01, which indicates an even smaller correlation, with neither of them passing the significance test (Figure 13). The correlation between the seasonal mean air temperature and the quarterly mean value of Dianchi Lake's LSWT is also low. The coefficient between the mean air temperature in winter and the daytime winter LSWT is r=0.24, and does not pass the significance test. The coefficient between mean air temperature in winter and the nighttime winter LSWT is r=0.03. The coefficient between the spring air temperature and the spring daytime LSWT is r=−0.05. Note that only during spring daytime, the air temperature is negatively correlated with the lake's LSWT. The coefficient between air temperature and spring nighttime LSWT is r=0.24, and the correlation is low. The correlation coefficients between air temperature and summer daytime LSWT is r=0.35, and with summer nighttime LSWT it is at r=0.34, which are higher than those in winter and spring. The correlation coefficient between air temperature and autumn daytime LSWT is r=0.48, and with autumn nighttime LSWT it is at r=0.65, with the latter passing the significance test (P<0.05), making it a significant correlation. The correlations between the monthly mean air temperature and the monthly average LSWT of Dianchi Lake during both daytime and nighttime are high, with a correlation coefficient of r>0.63 for daytime, and r>0.81 for nighttime. Both passed the significance test, indicating significant correlations.

V. CONCLUSION

In this study, MOD11A2 (version 6) remote sensing image data was preprocessed, and Landsat data was used to extract the boundary of Dianchi Lake during the studied time range. The eight-day average of the lake's LSWT during daytime and nighttime, its monthly mean, quarterly mean, and annual mean over the past 20 years were obtained, along with temperature data of the Dianchi Lake Watershed, which was from ECMWF meteorological data. Analysis of the trends in the changes in Dianchi Lake's LSWT showed that during daytime, there has been an upward trend in LSWT from 2001 to 2017 (Trend = + 0.12°C/yr^{-1}), and it was a significant increase. During nighttime, Dianchi Lake's annual

LSWT has also been increasing (Trend = + 0.09°C/yr^{-1}), which also passed the significance test, making it a significant increase. The lake's seasonal LSWT during daytime increased as well, and it increased significantly in autumn and winter (TrendAutu = +0.18°C/yr^{-1}, TrendWin. = +0.07°C/yr^{-1}). At night, Dianchi Lake's LSWT increased (TrendSpr. = +0.05°C/yr^{-1}, TrendSum. = +0.02°C/yr^{-1}, TrendAutu. = +0.1°C/yr^{-1}, TrendWin. = +0.04°C/yr^{-1}), and the average nighttime LSWT in autumn has significantly increased. During daytime, the monthly average LSWT was down in April and August (TrendApr = −0.04°C/yr^{-1}, TrendAug = −0.03°C/yr^{-1}), yet it was a non-significant decline. It showed an upward trend during the rest of the year, especially in October and November. The monthly average LSWT at night showed a downward trend in February, April, and July (TrendFeb = −0.01°C/yr^{-1} TrendApr = −0.009°C/yr^{-1}, TrendJul = −0.001°C/yr^{-1}), which were non-significant declines, and the measurement showed an upward trend in other months. The spatial analysis results showed that the area subject to LSWT increases has expanded in the past 20 years from the coast of Dianchi Lake to the center of the lake, and from the north to the south of the Lake. The expansion was more significant in shallow-water areas than in deep-water areas. Correlation analysis between air temperature and LSWT showed that the annual average temperature had a low correlation with both daytime and nighttime LSWT, with no correlations passing the significance test. During daytime, the seasonal LSWT was not significantly correlated with the average air temperature. The correlation between LSWT during nighttime in spring, summer, and winter and the mean of each season did not pass the significance test, while the LSWT in autumn was significantly correlated with the mean air temperature in autumn ($P<0.005$). The correlations between the mean monthly LSWT and the monthly mean air temperature during both daytime and nighttime were high, with both passing the significance test, and indicating a significant correlation. These results signified that air temperature is a key factor affecting the changes in the monthly average LSWT of Dianchi Lake. Because LSWT of the lake is affected by many factors, from a longer time scale, factors other than air temperature may have a more significant influence on LSWT, resulting in low correlations between the LSWT of Dianchi Lake and air temperature, from either an annual or a seasonal standpoint. However, it is safe to conclude that the annual average and seasonal average air temperatures and the LSWT of Dianchi Lake show different degrees of upward trends, and climate warming surely causes LSWT of Dianchi Lake to increase by a certain extent. Future work involves extending this study to other lakes over the Yunnan-Guizhou Plateau to analyze the LSWT changes of Yunnan-Guizhou Plateau lakes in the past 17 years and the inferences for region climate changes.

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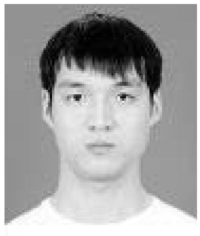

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