An integrated dataset of daily lake surface water temperature over Tibetan Plateau

Linan Guo[1,2], Hongxing Zheng[3], Yanhong Wu[1,2]*, Lanxin Fan[1,2], Mengxuan Wen[1], Junsheng Li[1,2], Fangfang Zhang[1], Liping Zhu[4], Bing Zhang[1,2]*

5 [1]Key Laboratory of Remote Sensing Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100094, China
[2]University of the Chinese Academy of Sciences, Beijing 100049, China
[3]CSIRO Land and Water, Canberra, ACT 2601, Australia
[4]Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

Correspondence to: Yanhong Wu (wuyh@radi.ac.cn); Bing Zhang (zb@radi.ac.cn)

Abstract. Lake surface water temperature (LSWT) is a critical physical property of the aquatic ecosystem and an evident indicator of climate change. By combining the strengths of satellite-based observation and modelling, we have produced an integrated daily lake surface water temperature for 160 lakes across the Tibetan Plateau where in-situ observation is limited.

15 The satellite-based lake-wide mean LSWT in the integrated dataset includes that for the daytime, night-time and for the daily mean for the period 2000–2017. The dataset is comparable with other satellite-based LSWT products (e.g., LSWT from AVHRR and ARC-Lake) and unique for its tempo-spatial span and resolution. Calibrated and validated against the satellite-based LSWT, complete and consistent daily LSWT dataset have been reconstructed and extended to the period 1978–2017 basing on the modified air2water model. According to the reconstructed LSWT dataset, it is found that annual LSWT of lakes

20 in the Tibetan Plateau has increased significantly in the period 1978–2017 with increase rate ranging at 0.01 to 0.4 ℃ 10a⁻¹. The warming trends of the lakes are more evident in winter than in summer. The integrated dataset together with the methods introduced herein can contribute to the research community to explore water and heat balance changes and the consequent ecological effects at the Tibetan Plateau in the future researches. Data from this study are openly available via the Zenodo portal, with DOI https://doi.org/10.5281/zenodo.5111400 (Guo et al., 2021).

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1 Introduction

Lake surface water temperature (LSWT) is a critical physical property of the aquatic ecosystem and an evident indicator of climate change (Austin and Colman, 2008; Livingstone, 2003; Williamson et al., 2009). Rapid rise in water temperature has been observed in many lakes around the world, which not only reflects the changes in lake heat budget associated with global

30 warming (Bates et al., 2008;Dokulil, 2014) but also has resulted at a succession of changes in physical, chemical, and biological processes within the lake system (Hondzo and Stefan, 1993; Ke and Song, 2014; Naumenko et al., 2006; Ngai et al., 2013;

Rahel and Olden, 2008; Schindler, 2001; Woolway and Merchant, 2017; Liu et al., 2021). One of the noticeable consequences of changes in lake water temperature is the considerable change in lake ice phenology (e.g., the freezing-up and breaking-up dates of lake ice) found at mid- to high-latitude or high-altitude regions around the world during the past decades (Livingstone,

35 1997;Takacs et al., 2018;Tian et al., 2015; Prowse et al., 2011).

Lake water temperature records based on in-situ measurements are not easily available due to its costs and geographical restrictions. In the Tibetan Plateau (TP), where there are more than 1,100 alpine lakes with area larger than 1 km^2 and elevation above 4000 m, most of the lakes have no in-situ water temperature records due to its harsh nature for ground observation (Zhang et al., 2014). Satellite-based observation has been showing highly powerful in providing continuous worldwide records

40 of lake surface temperatures and has developed rapidly in recent decades with increasingly higher temporal and spatial resolutions (Schneider and Hook, 2010). At global scale, currently accessible satellite-based lake surface temperature datasets include that from the ARC-Lake (ATSR Reprocessing for Climate: LSWT & Ice Cover) (Layden et al., 2015) and the GLTC (Global Lake Temperature Collaboration) (Sharma et al., 2015). The global datasets are highly valuable in stimulating research on inland water bodies (e.g., Moukomla and Blanken, 2017; Piccolroaz et al., 2020; Torbick et al., 2016; Zhang et al., 2014).

45 The datasets however are limited for use in the Tibetan Plateau as they cover only a handful of lakes within the TP region and are temporally incomplete (Liu et al., 2019). Two other surface water temperature datasets of lakes in the Tibetan Plateau have recently been produced by Wan et al. (2017) and Liu et al. (2019) respectively using different sensors. One of the datasets bases on MODIS and provides 8-day mean surface temperature of 374 lakes for the period 2001-2015 (Wan et al., 2017), while the other bases on AVHRR and presents daytime lake surface water temperature of 97 lakes with area above 80km^2 for the

50 period 1981-2015 (Liu et al., 2019). Both the two datasets for lakes in the Tibetan Plateau, however, have quite a few missing data caused by revisit period of satellite and inconsistency in the time series due to calibration among the successive satellites. Lake surface water temperature can alternatively be derived or reconstructed basing on well calibrated modelling (Layden et al., 2016; Prats and Danis, 2019). Process-based numerical models have been used widely to investigate thermodynamics of lakes at local scales (Goudsmit et al., 2002; Kirillin et al., 2017; Launiainen and Cheng, 1998; Peeters et al., 2002; Stepanenko

55 et al., 2016), which usually requires detailed over-lake meteorological data (e.g., wind speed, humidity, cloud cover) as inputs and in-situ measurements to calibrate and validate the models (Bruce et al., 2018). For regions with scarce in-situ meteorological observations, simple statistical models (Mccombie, 1959; Webb, 1974; Sharma et al., 2008) or simplified physically based model (Piccolroaz et al., 2013) have been developed for use, which may require only air temperature as input. The air2water model proposed by Piccolroaz et al. (2013) has been tested to be an effective tool in reconstructing historical

60 LSWT (Piccolroaz et al., 2020) and in investigating LSWT responses to climate change for lakes with different morphological characteristics around the world (Piccolroaz et al., 2015; Prats and Danis, 2019; Toffolon et al., 2014). The simplified model is especially competitive and practicable for regions with limited in-situ observations to drive and calibrate a more complex process-based model.

We herein combine together the strengths of both the remotely sensed and model-based approach in producing an integrated

65 dataset on daily surface water temperature of 160 large lakes across the Tibetan Plateau for the period 1978–2017. For the

combination, the remotely sensed LSWT is used to calibrate and validate the air2water model, which is then applied to reconstruct a complete and consistent daily LSWT time series for each studied lake and extend LSWT dataset to a wider time span. The integrated dataset demonstrates potentials in investigating variabilities and changes in LSWT across the Tibetan Plateau during the past decades. It could be valuable for assessing the impacts of climate warming on the dynamics of water

70   and heat budget, water quality and aquatic biota in lakes across the Tibetan Plateau.

2 Study area

The Tibetan Plateau locates between 26°00′–39°47′N and 73°19′–104°47′E with mean elevation over 4500 m and area about 2.5×10^6 km^2. It is known as the "Asian water tower", contributing to most major rivers in Asia (Wu and Lei, 2014). The total area of lakes in the plateau is around 45,000 km^2, most of which are located at the altitudes between 4000 m and 5000 m (Yao

75   et al., 2015). Our dataset includes 160 lakes in the Tibetan Plateau covering most major lakes with area above 40 km^2 (Fig.1). All lakes were selected from Records of Lakes in China (Wang and Dou, 1998). The general properties of the studied lakes are listed in the lake_info.csv file of the dataset, which includes the names, locations and areas of the lakes.
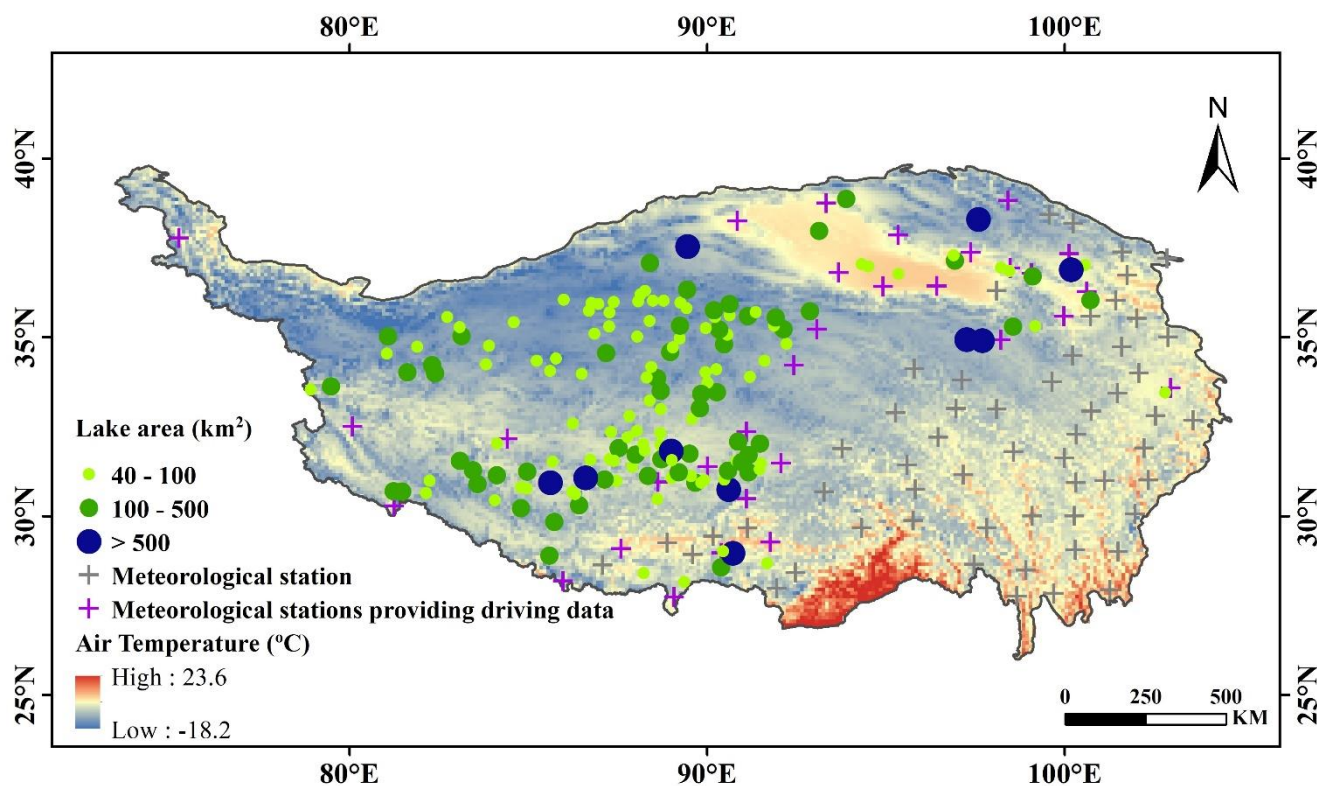
Figure 1: Locations of studied lakes in the Tibetan Plateau.

3 Methods

Fig. 2 shows the overall framework of our study in integrating lake surface water temperature dataset for the largest lakes across the Tibetan Plateau. The MOD11A1 product is the source data for the satellite-based LSWT, while the air temperature data from meteorological station is the source data used to drive the air2water model. The satellite-based observation is used to calibrate and validate the air2water model. The details of the procedures and methods are described in the following sections.
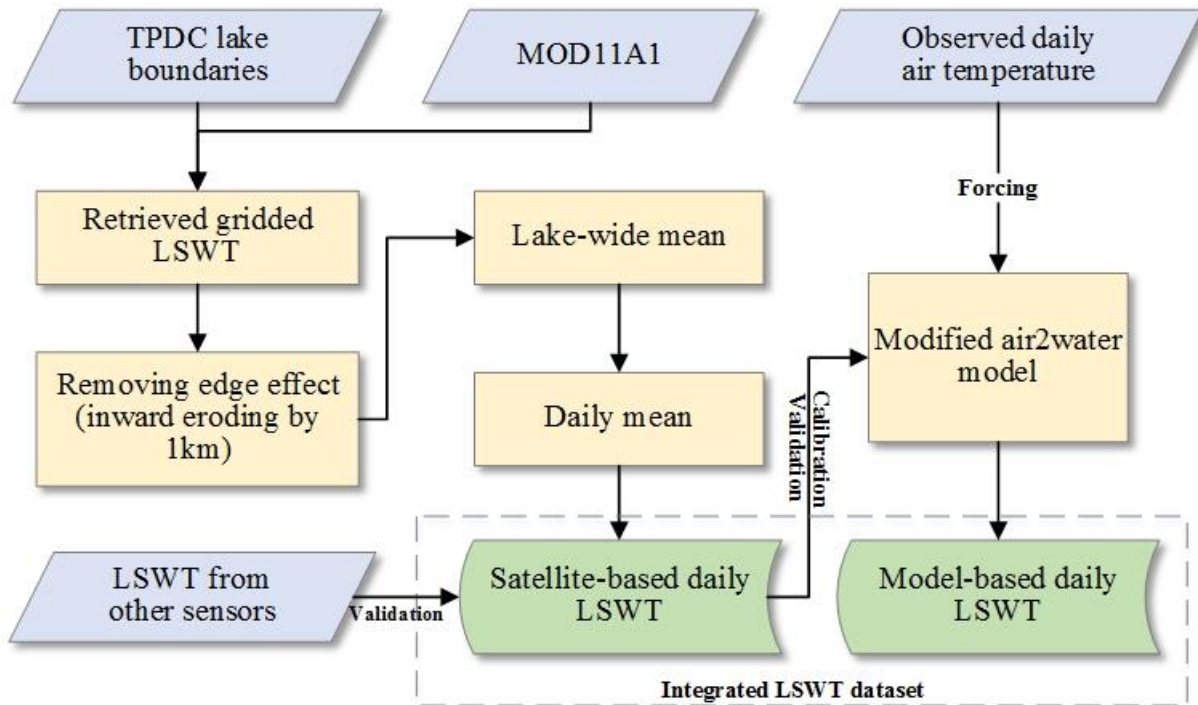
Figure 2: Framework for integrating lake surface water temperature data.

3.1 Satellite-based observation of lake surface water temperature

The first step of our effort in producing the integrated LSWT dataset is to derive the satellite-based observation from the MOD11 (version 6) provided by NASA's Earth Observing System Data and Information System (EOSDIS, https://earthdata.nasa.gov). The MOD11 is the land surface temperature and emissivity products retrieved at 1km pixels by the generalized split-window algorithm and 6km grids by the day/night algorithm mainly based on bands 31 (10.78–11.28μm) and 32 (11.77–12.27μm) of MODIS (Moderate-resolution imaging spectroradiometer) aboard the Terra and Aqua satellite, where Terra overpasses the equator at around 10:30 A.M. (10:30 P.M.) local time and Aqua at around 1:30 A.M. (1:30 P.M.). The MOD11 includes products with temporal resolutions of daily, 8-day, and monthly respectively. Different from the 8-day dataset by Wan et al. (2017), herein, we used MOD11A1 (Terra product of Land Surface Temperature/Emissivity Daily L3 Global 1km) instead of MOD11A2 to produce the daily lake surface temperature dataset. The daily product is used herein also

because it is more suitable to calibrate and validate the air2water model at the same temporal resolution. The MOD11A1 is a tile of daily Level 3 product at 1km spatial resolution corresponding to the earth locations on the sinusoidal projection.

In our dataset, the satellite observation of LSWT for a specific lake is the lake-wide mean temperature of all 1-km pixels within the lake, which is different to the temperature of the centroid pixels presented by Zhang et al., (2014) and is more consistent with our model settings. In calculating the lake-wide mean surface water temperature, pixels within a lake are identified by the boundaries of the lakes (shapefiles included in the dataset), which are mainly from National Tibetan Plateau Data Center (TPDC, http://data.tpdc.ac.cn) and cross-checked by lake boundary maps from HydroLAKES (http://www.hydrosheds.org/) (Messager et al., 2016) and Google Earth. To remove the boundary effects (i.e., where pixels could be mix of land and water), the boundaries are buffered inward by 1km. The daily surface water temperature is the mean of daytime and night-time LST in the MOD11A1. All the data processing procedures are conducted via Google Earth Engine (GEE).

3.2 Reconstructing lake surface water temperature

The satellite-based lake surface water temperature is accessible since 2000 and with missing data due to the limitation in the MODIS. To investigate the long-term changes in surface water temperature for lakes in the Tibetan Plateau and their responses to climate change, in our integrated datasets, we used a slightly modified air2water model to reconstruct the daily lake surface water temperature for the period 1978-2017 based on daily air temperature data from Dataset of daily climate data from Chinese surface stations (V3.0) provided by China Meteorological Data Service Centre of National Meteorological Information Centre (http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html).

The air2water (Piccolroaz et al., 2013) is a semi-physical model designed to simulate lake surface temperature principally based on lake surface heat balance and can be expressed as:

$$\rho c_p V_s \frac{dT_w}{dt} = A H_{net}, \tag{1}$$

where T_w is surface water temperature, H_{net} is the net heat flux per unit surface, A is the surface area of the lake, V_s is the volume of water involved in the heat exchange with the atmosphere, ρ and c_p is the density and specific heat capacity of water.

The model considers all contributions to the heat balance (H_{net}), which are represented as a function of air temperature or are parameterized (Piccolroaz et al., 2013;Piccolroaz, 2016). The original air2water model has simplified the lake heat balance by introducing eight calibratable parameters a_{1-8} with air temperature as the only required input, which can be expressed as:

$$\frac{dT_w}{dt} = \frac{1}{\delta}\left\{a_1 + a_2 T_a - a_3 T_w + a_5 \cos\left[2\pi\left(\frac{t}{t_y} - a_6\right)\right]\right\}, \tag{2}$$

$$\delta = \begin{cases} \exp\left(-\frac{T_w - T_h}{a_4}\right), & \text{for } T_w \geq T_h \\ \exp\left(-\frac{T_h - T_w}{a_7}\right) + \exp\left(-\frac{T_w}{a_8}\right), & \text{for } T_w \leq T_h \end{cases}, \tag{3}$$

where, T_a is air temperature, t_y is days of a year. $\delta = D/D_r$ is normalized well-mixed depth, where D is the depth of well-mixed surface layer (the epilimnion thickness), D_r is the maximum thickness. T_h is the deep water temperature assumed to be 4℃.

The original air2water is limited to simulate the surface temperature of open water, which results in difficulties for applications in lakes with long ice cover duration. For this sake, we assume that when the lake is completely covered by ice, the heat exchange between air and water is blocked and surface energy balance becomes:

$$\frac{dT_i}{dt} = a_9 + a_{10}T_a - a_{11}T_w + a_{12}\cos\left[2\pi\left(\frac{t}{t_y} - a_{13}\right)\right], \tag{4}$$

where T_i is the ice surface temperature, a_{9-13} have similar physical significance to $a_{1,2,3,5,6}$. To represent the state-shift of lake between open water and ice-covered, two additional parameters a_{14} and a_{15} are introduced to determine the states. The lake surface temperature T_L can be expressed as:

$$T_L = \begin{cases} T_w, & \text{for } T_L \geq a_{15} \\ T_i, & \text{for } T_L \leq a_{14}, \\ (1 - K_{ice})T_w + K_{ice}T_i, & \text{for } a_{15} > T_L > a_{14} \end{cases} \tag{5}$$

Where, $K_{ice} = \sqrt{(a_{15} - T_L)/(a_{15} - a_{14})}$ is the proportion of ice on the surface of the lake. Same as the original model, the model equations were solved numerically by using the Crank-Nicolson numerical scheme at daily time step.

The daily air temperature used to drive the modified air2water model are from 31 meteorological stations in the Tibetan Plateau (Fig.1). The air temperature above each lake is interpolated from the nearest station and adjusted by a lapse rate of 0.65℃ 100m⁻¹ (Hu et al., 2014). The model is calibrated against the derived remotely sensed LSWT described in Section 3.1 using the PSO (Particle Swarm Optimization) approach (Kennedy and Eberhart, 1995; Piccolroaz, 2016). The objective function of model calibration is the widely adopted Nash–Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970). To ensure the rationality of the calibrated model parameters, a physically consistent priori range are assigned to each parameter (Piccolroaz, 2016) and D_r is bounded by the average depth of the lake obtained from Records of Lakes in China (Wang and Dou, 1998) and HydroLAKES (Messager et al., 2016). The calibration period is set to be the period 2000-2012, while 2013-2017 is considered as the validation period. For comparison and further validation, the dataset produced by Liu et al. (2019) based on AVHRR was also used.

4 Results and discussions

4.1 MODIS-based LSWT of lakes across the Tibetan Plateau

Three subsets of lake-wide mean surface water temperature are derived and included in our integrated dataset, which are daily daytime LSWT, daily night-time LSWT and daily mean LSWT for the period 2000-2017. The lake surface water temperature derived from the MOD11A1 is compared against two satellite-based datasets released by other researches, which were based on AVHRR (Liu et al., 2019) and ARC-Lake (Layden et al., 2015) respectively.

Fig.3 shows the comparison between our MOD11A1-based LSWT against the AVHRR-based LSWT (i.e., the TPlake_Temp dataset by Liu et al., 2019) for 77 sharing lakes. It should be noted that the AVHRR-based LSWT from the TPlake_Temp is that of the daytime instead of the daily mean, hence, it is compared against our MODIS-based daytime LSWT. It is found that

the LSWT from the two sensors are highly comparable with each other for most of the studied lakes, where the NSE and R^2 between the two datasets is higher than 0.6 for more than 96% of the lakes, and the bias ranges from -3.0 to 5.6℃. It is worth mentioning that the MODIS-based LSWT would be better for investigating the long-term changes in lake surface temperature in the Tibetan Plateau as the AVHRR-based LSWT from the TPlake_Temp dataset was reported having abrupt shifts in LSWT

160 due to inconsistent calibration among the successive satellites (Liu et al., 2019).
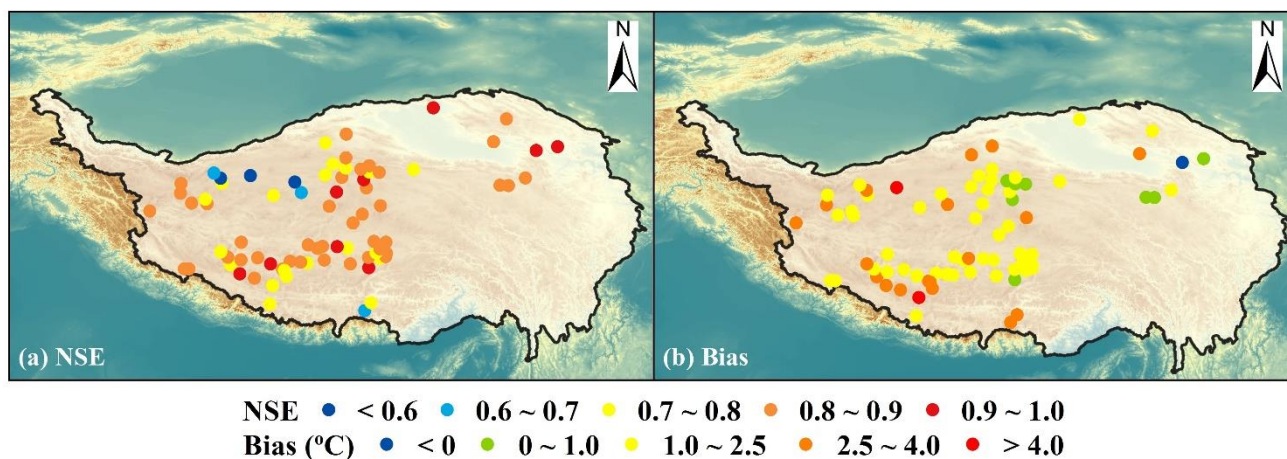
Figure 3: Comparison of LSWT from MOD11A1 and AVHRR for 77 sharing lakes.

We further compare the MODIS-based LSWT against that from ARC-Lake, where the LSWTs of daytime and night-time are averaged to present daily mean LSWT. Since the ARC-Lake LSWT product is for open water and tag temperature below 0℃ as "frozen" with value 0 ℃, in the comparison, only the period when both MODIS-based and ARC-Lake LSWT are above 0℃

165 is considered. LSWTs of 11 studied lakes are available from the ARC-Lake for the comparison. Without the consideration of the outliers which the difference between the two satellite observations are larger than 5 ℃ (around 8 % of the observations in the studied periods), as shown in Fig. 4, the two satellite-based observations of LSWT are mostly comparable with NSE>0.7 and bias ranging at -1.23 ℃ to 0.94 ℃.
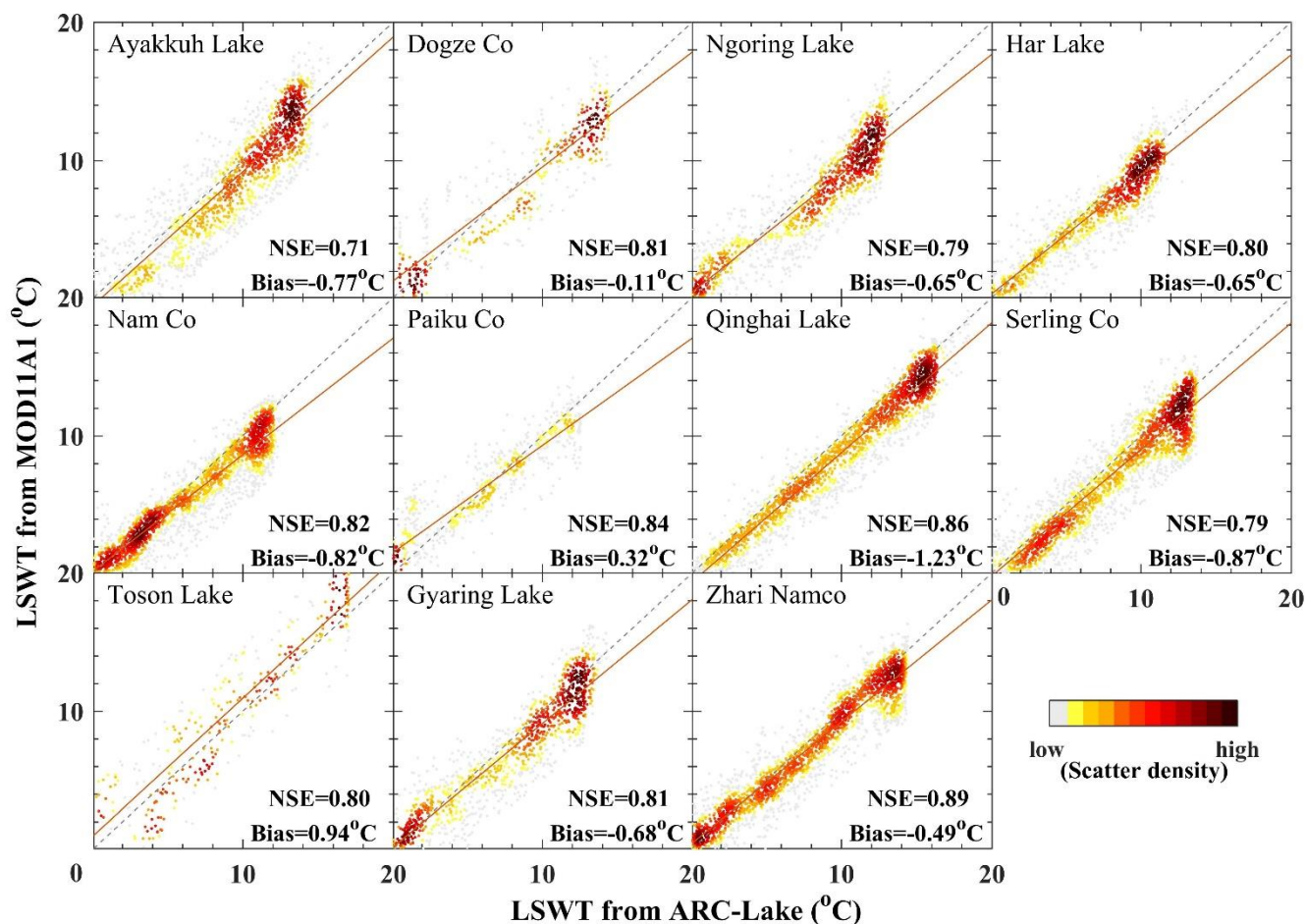
Figure 4: Comparison of LSWT from MOD11A1 and ARC-Lake for the period with LSWT>0°C. The dash line is the 1:1 line, the solid line is the linear regression line.

4.2 Reconstructed LSWT by air2water

The reconstructed LSWT by the slightly modified air2water model is compared and validated by the MODIS-based LSWT. As shown in Fig.5a and 5b, the spatial pattern of the long-term mean annual lake surface water temperature from the reconstructed LSWT is close to that based on MOD11A1 with overall NSE=0.977 and R^2=0.987. For the period 2000–2017, NSE and R^2 of most lakes (>90%) are both above 0.8 with bias ranging at ±0.55°C. The bias for the validation period (2013–2017) is relatively higher than that for the calibration period (see Fig. S1 in the Supplementary). Although there is a tendency showing that NSE is relatively higher for lakes with lower altitude and higher latitude, model performance is found weakly related to altitude and latitude of the lakes (see Fig. S2 in the Supplementary). The results indicate there is no substantial systematic bias in the reconstructed LSWT. The modified air2water model hence is reliable in reconstructing LSWT for lakes at different altitude or latitude zones. However, it should be noticed that uncertainties exist in the reconstructed LSWT due to

the uncertainties not only in the calibrated model but also in the air temperature inputted to the model. As mentioned in Section 3.2, the daily air temperature above the lakes are that interpolated from the nearest meteorological stations with elevation

185   adjustment, where the performance of the interpolation would be affected by the density and locations of the stations. Currently, the available meteorological stations are concentrated on the east part of the TP (Fig.1), which may result at higher uncertainties of the reconstructed LSWT for lakes in the western TP. As shown in Fig.5c and 5d, though there is no significant difference in model performance with respect to the locations of the lakes, it is worth exploring further in the future research the effects of the interpolation approaches on the simulation of LSWT.

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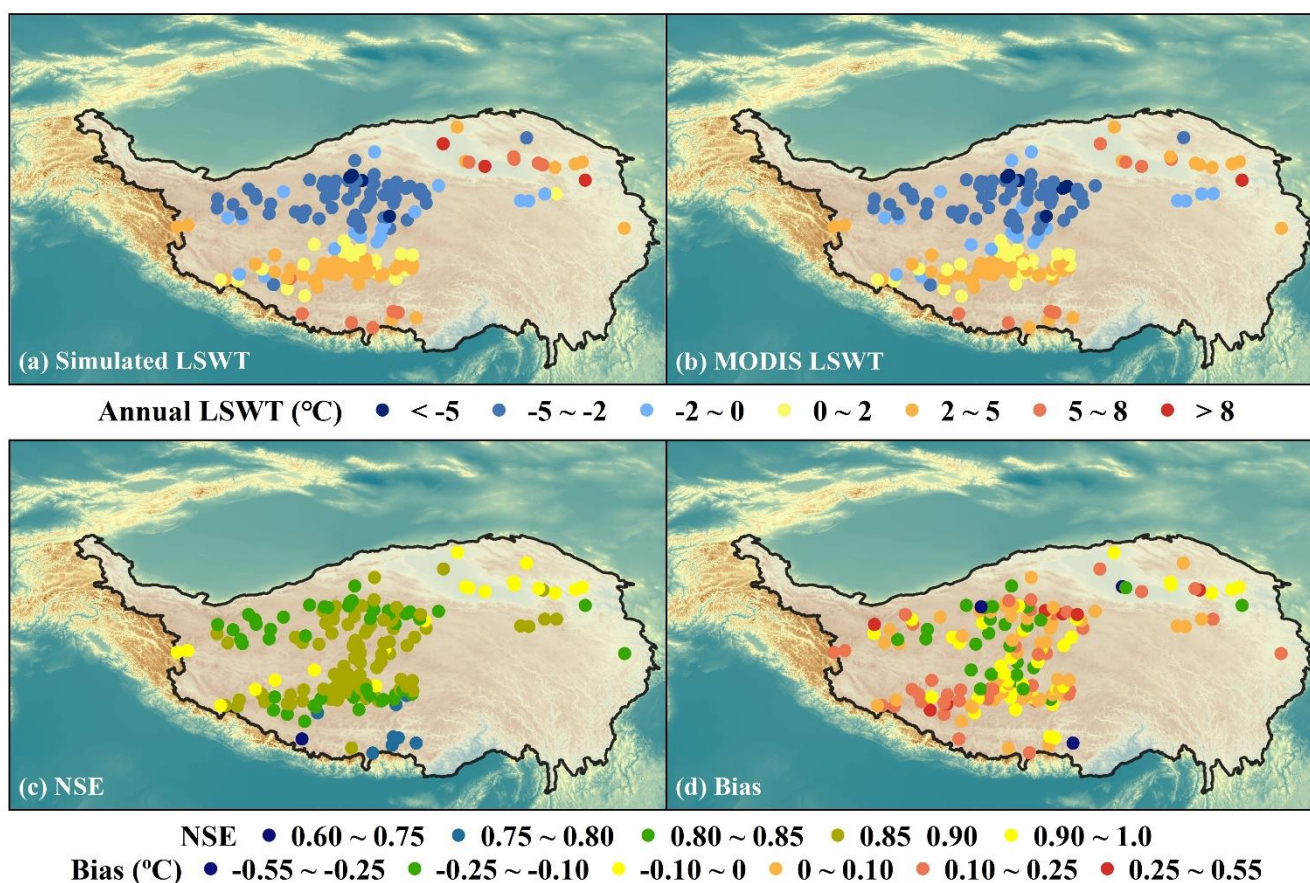
Figure 5: Spatial comparison between MOD11A1-based (a) and reconstructed (b) annual mean LSWT and spatial distribution of model performance evaluated by NSE (c) and bias (d).

4.3 Long-term trends of LSWT in the Tibetan Plateau

195   On the basis of the reconstructed daily LSWT dataset, the long-term changes of surface water temperatures of lakes across the Tibetan Plateau are detected by using the Mann-Kendall trend analysis approach (Kendall, 1955; Mann, 1945). As shown in Fig.6, for the period 1978–2017, most of the lakes (except for Lake Beidao and Lake Changhong) showed significant increasing

trends in annual LSWT with increasing rate ranging at 0.01 to 0.47 ℃ 10a^{-1}. Lakes with the highest increasing rate are found

locating at the northwest of the Tibetan Plateau. The increase in LSWT is more evident in the winter season (December–

200 Feburary). Except for Lake Kuhai Lake, the LSWTs of all the other lakes increase significantly at a rate ranging at 0.06 and

0.96 ℃ 10a^{-1}. In summer (June–August), while most of the lakes (125 out of 160) show significantly increase in LSWT, the

LSWTs of 13 lakes locating at the northern part of the TP decrease insignificantly. The lakes with decreasing trend in summer

LSWT could be because that the warming climate has been leading to more melting glacier water flowing into the lakes in the

season. The cooling effect of melted glacier water, however, needs further exploration in the future research.

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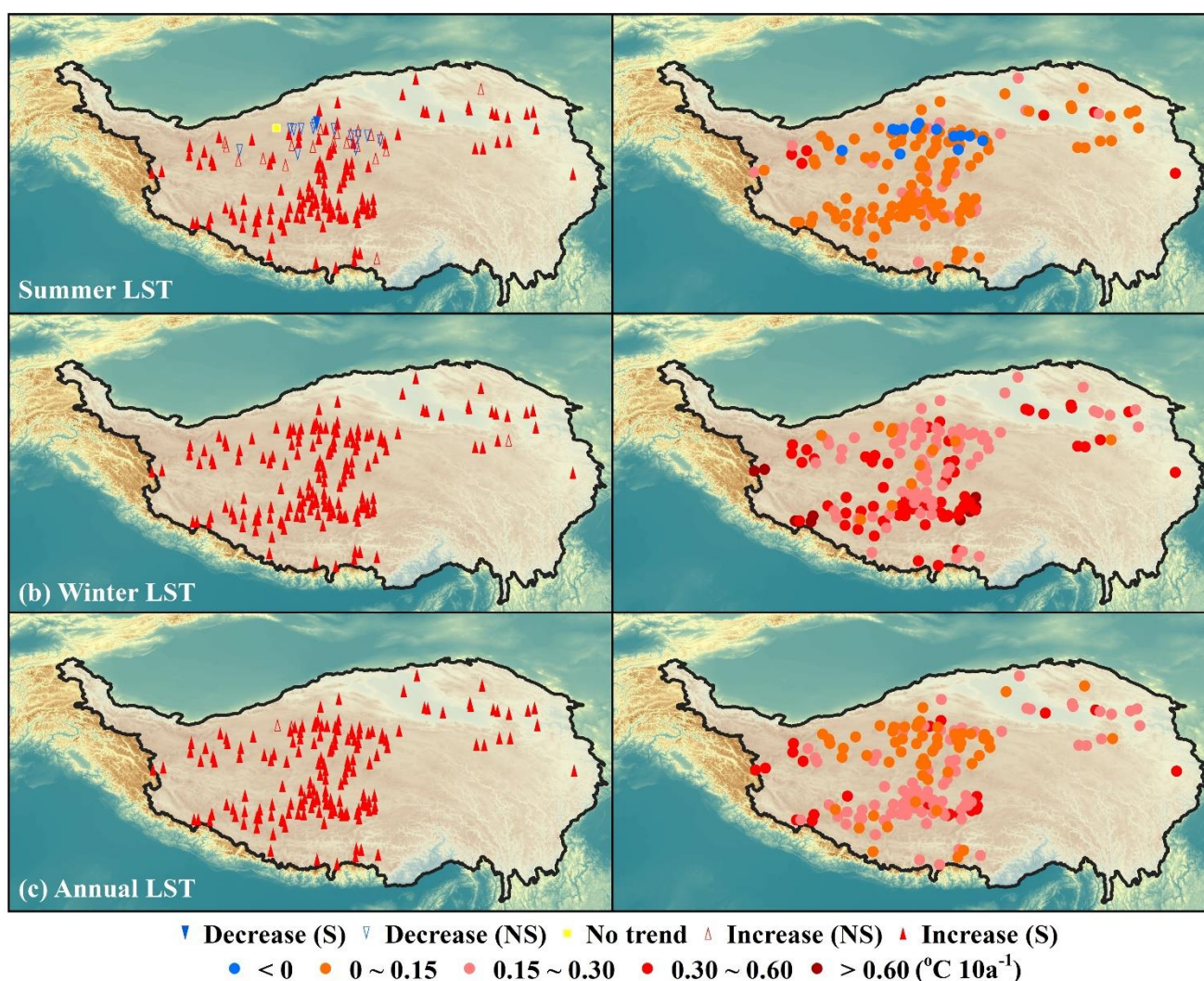
Figure 6: Long-term trends of summer (Jun-Aug), winter (Dec-Feb) and annual LSWT during 1978–2017.

5 Data availability

Table 1 gives the details of the data included in our integrated dataset. In the dataset, the properties of the lakes (including name, latitude, longitude, altitude) are listed in the lake_info.csv file. The boundaries of the lakes are provided in the ESRI shapefile format. The satellite-based observations of the LSWT are given as the MOD11A1_DT and MOD11A1_NT for the daytime and night-time lake-wide mean lake surface water temperature, while the MOD11A1_DM is the mean of them representing the daily mean surface water temperature. The time span of the MODIS-based LSWT is for the period 2000–2017. The Air2Water_DM is the reconstructed daily LSWT based on the modified air2water model for the period 1978–2017. The dataset is archived and openly accessible via the Zenodo portal: https://doi.org/10.5281/zenodo.5111400 (Guo et al., 2021). The GEE scripts are available at: https://code.earthengine.google.com/563820c56b30595de901c21aef5f0c71.

Table 1 Data descriptions.

	Data	Description	Period
	Lake boundary	Boundaries of lakes in the format of ESRI shapefile	-
	LakeInfo	Properties of lakes in the format of csv	-
Daily LSWT	MOD11A1_DT	Lake surface temperature derived from MOD11A1 daytime products.	2000–2017
	MOD11A1_NT	Lake surface temperature derived from MOD11A1 nighttime products.	2000–2017
	MOD11A1_DM	Mean of MOD11A1_DT and MOD11A1_NT.	2000–2017
	Air2Water_DM	Model-based daily lake surface water temperature.	1978–2017

6 Conclusions

An integrated daily lake surface water temperature has been produced for 160 lakes across the Tibetan Plateau by combining the strengths of satellite-based observation and model-based approaches. The satellite-based lake-wide mean LSWT is derived from MOD11A1 via Google Earth Engine, which includes that for the daytime, night-time and for the daily mean for the period 2000–2017. The dataset is found comparable with other satellite-based LSWT products (e.g., LSWT from AVHRR and ARC-Lake) but unique due to its tempo-spatial span and resolution. The satellite-based LSWT enables the calibration and validation of a simplified heat balance model (i.e., air2water) at regions with scarce ground-based observation (like the Tibetan Plateau).

The modified air2water model is found successfully in reconstructing the daily LSWT of lakes across the Tibetan Plateau by extending the LSWT time series to the period 1978–2017 and filling the time gaps in the satellite-based LSWT. The completeness and consistency of the reconstructed LSWT therefore is reliable and valuable to investigate the long-term variation and changes of LSWT in the Tibetan Plateau. According to the reconstructed LSWT dataset, the annual LSWT is found increased significantly in the period 1978–2017 with increase rate ranging at 0.01 to 0.47 ℃ 10a^{-1}. The warming trend

of the lakes is more evident in winter than in summer. The integrated dataset together with the methods introduced herein can contribute to the research community in exploring water and heat balance changes in the Tibetan Plateau and the consequent ecological effects in the future researches.

Author contributions. YW, HZ, BZ and LG conceived the research. LG, YW and HZ developed the approaches and datasets.
235 LG, MW and LF collected basic data of lakes. JL, SW checked the results. LG, HZ and YW wrote the original draft. BZ and LZ revised the draft.

Competing interests. The authors declare that they have no conflict of interest.

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