

An analysis of the Lake Surface Water Temperature evolution of the world's largest lakes during the years 2003-2020 using MODIS data

José A. Sobrino*, Susana García-Monteiro and Yves Julien

Global Change Unit, Image Processing Laboratory, University of Valencia, Paterna, 46980, Spain

EDITED BY

J.C. Jiménez

Keywords:

Lake Surface Water Temperature
largest lakes
MODIS
trend

ABSTRACT

The Lake Surface Water Temperature (LSWT) evolution is analysed in ten of the largest lakes in the world: Caspian Sea, Superior, Victoria, Huron, Michigan, Tanganyika, Baikal, Great Slave Lake, Erie and Ontario. The time span selected is 2003-2020 and the satellite product, MODIS Level 3 SST Thermal IR 8 Day 4km V2019.0. Results show warming trends ranging from 0.012°C/yr. in the Victoria Lake to 0.083 °C/yr in the Baikal Lake. Results have been validated with the product MOD11L2 LSWT estimations for the years 2003-2014 in the Laurentian Great Lakes, obtaining correlations between 0.962 and a 0.998. The validation has been enlarged by considering Sentinel 3 observations from the Issyk-Kul lake, with a 0.99 correlation. The validation shows that the MODIS SST product is capable of estimating the LSWT parameter with a high precision.

1. Introduction

Lake Surface Water Temperature (LSWT) is recognized as an Essential Climate Variable (ECV) by the Global Observing System for Climate (GCOS, 2016), just as the well-known Sea Surface Temperature (SST) or Land Surface Temperature (LST). It has been proved that the behaviour of these ECVs associated to temperature condition several processes, such as the fisheries' presence and catches (Gamito et al., 2015), the alternation between rainy and dry seasons (Liu et al., 2020; Zhang et al., 2001) or the climatic oscillations dynamics (McPhaden et al., 2006; Dahlman, 2009). For this reason, it is crucial to monitor ECVs, in order to better understand these processes, among others, and be prepared to face the changes they may face.

Focusing on LSWT, it is an indicator of how climate change could affect the lake physical dynamics and aquatic ecosystems worldwide. Previous works report that warming lake temperature trends lead to changes in the water column density that are strongly correlated with an increase in average air temperatures over time, with clear effects on the thermal regime. Stainsby et al. (2011) developed a research in this field in a regional lake in Canada, whereas Lofgren and Zhu (2000) focused on the Great Lakes; the ice cover duration is shortening in German lakes (Livingstone and Adrianb, 2009); Elliott et al. (2006) tested the sensitivity of phytoplankton communities to changes in water temperature and nutrient load, predicting that cyanobacteria had the potential to dominate the phytoplankton community, with consequences on water quality. This dominance was greatest at high water temperatures.

Furthermore, the LSWT has traditionally been estimated by using in situ instruments, heterogeneous, irregularly distributed and differently calibrated (De Santis et al., 2021; Sobrino et al., 2020a). Remote sensing solves these in situ measurements disadvantages and provides continuous temporal series data, retrieved from the same sensor observations, with a given uncertainty, the identical for each observation. As a consequence, it is becoming increasingly common to find in the literature studies whose objective is to analyze the LSWT from satellite data (Ghasemifar et al., 2019; Zhang GuoQing et al., 2014; Crosman and Horel, 2009).

*Corresponding author

sobrino@uv.es (J.A. Sobrino)

ORCID(s): 0000-0003-3787-9373 (J.A. Sobrino)

<https://doi.org/10.62880/rars240001>

Received 15 January 2024; Revised 9 February 2024; Accepted 28 February 2024

Published 29 February 2024

© 2024 The Authors. Published by Recent Advances S.L. ISSN 3020-6448. This is an open access article under the Creative Commons Attribution (CC BY) license

(<https://creativecommons.org/licenses/by/4.0/>).

It is clear that LSWT is a variable to consider when studying lakes and has more implications than simple variations in lake temperatures. For this reason, we propose to develop a study that considers the most representative lakes in the world, to know their LSWT behaviour during the last years, from 2003 to 2020, by using MODIS data. The lakes selected are: the Caspian Sea, Superior, Victoria, Huron, Michigan, Tanganyika, Baikal, Great Slave, Erie and Ontario lakes.

The aim of this paper is to retrieve the LSWT of the ten lakes mentioned above by using MODIS Level 3 SST Thermal IR 8 Day 4km V2019.0 product in order to show how it functions when estimating surface temperature of freshwater extensions non-connected to the open water. Our results will be validated by a previous study focused on the Laurentian Great Lakes and which uses an LST MODIS product (Moukomla and Blanken, 2016). Furthermore, LSWT trends will be estimated to analyze the behaviour of this parameter during the last years.

2. Study Sites

Ten large lakes have been selected for developing this study: the Caspian Sea, the only saline lake included; the Superior, Michigan, Huron, Ontario and Erie Lakes, called the Great Lakes, which occupy part of the territory of the United States of America and Canada; the Victoria and Tanganyika lakes, located in the African continent; the Baikal lake in Russia and the Slave lake in Canada (Table 1) (Dumont, 1998; United States Environmental Protection Agency, 2022; Swain and Shannon, 1980; Verburg et al., 2003; Zimmerman et al., 2006).

Table 1
Metric characteristics of the ten lakes considered in the study.

Lake	Continent	Area (km ²)	Volume (km ³)	Maximum Depth (m)
Caspian Sea	Asia	371,000	78,200	1,025
Superior	America	82,100	12,100	406.3
Victoria	Africa	68,870	2,750	84
Huron	America	59,600	3,540	229
Michigan	America	58,000	4,900	281
Tanganyika	Africa	32,600	18,900	1,470
Baikal	Asia	31,500	23,600	1,620
Slave	America	27,000	1,560	614
Erie	America	25,700	489	64
Ontario	America	18,960	1,639	244

Our first study site, the Caspian Sea, is the largest lake of the world and, although it has no connections to ocean waters, its salinity is of 12.58 parts per thousand on average (Owen et al., 2024), ranging from 1 part per thousand near the Volga mouth to values over 200 parts per thousand in the Kara-Bogaz-Gol (Figure 1). This fact prevents it from being considered a purely freshwater extension.

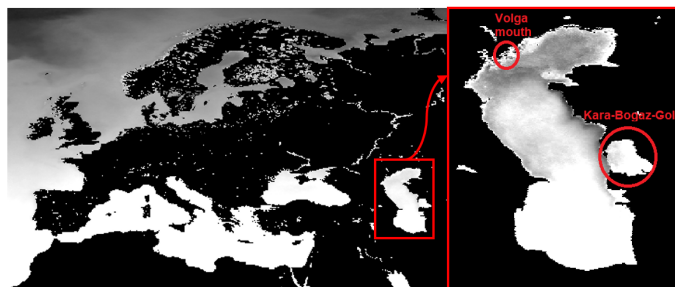


Figure 1: The Caspian Sea. Salinity varies from 1 part per thousand to 200 parts per thousand from the Volga River mouth to the Kara-Bozaz-Gol, respectively (own elaboration).

The Great Lakes are the set integrated by the Superior, Michigan, Huron, Ontario and Erie lakes (Figure 2) and cover a total area of 244,360 km² as can be observed in Table 1. Due to its areal extension and depth, the Great Lakes play a large role in the surface climate of the region, influencing its dynamic over the course of the seasons (Moukomla and Blanken, 2016).

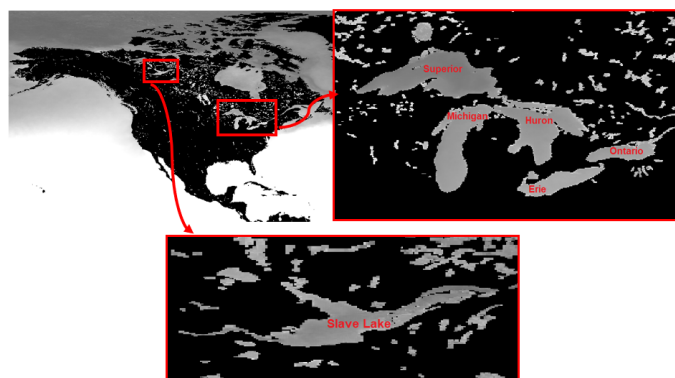


Figure 2: In the upper-left, the North-American Great Lakes: Superior, Huron, Michigan, Erie and Ontario. In the bottom, the Slave Lake

Lake Victoria is the largest freshwater lake in Africa, being the source of the Nile and providing water for domestic, agricultural, industrial and livestock purposes. Its water bathes the shores of Kenya, Tanzania and Uganda (Awange et al., 2006). The other African lake analysed, is the Tanganyika Lake, which has historically supported one of the world's more productive pelagic fisheries, specifically, provides the 25-40% animal protein supply for the populations of the surrounding countries (O'Reilly et al., 2003) (Figure 3).

The Baikal Lake, located on the Asian continent, is the oldest and deepest in the world (Figure 4). It has been designed by the UNESCO as a World Heritage Site and cited as the "most outstanding example of a freshwater ecosystem (Swann et al., 2020). There is already evidence of warming and local eutrophication of the water column (Izmeteva et al., 2016).

3. Material & Methods

3.1. Data sets

The product used in this study is MODIS Level 3 SST Thermal IR 8 Day 4km V2019.0, which is fully and freely available in <https://podaac.jpl.gov>. Images are available at a processing Level 3 for daily,



Figure 3: African lakes included in the study: Tanganyika Lake and Victoria Lake (own elaboration)



Figure 4: The Baikal Lake (own elaboration).

8-days, monthly and annual timespans. As 8-days composites are an average of the daily data available for each 8-days period, they have been considered as ideal for this work, as they allow both to save storage capacity and to reduce computational costs.

3450 images have been computed for the years 2003-2020 (1723 images associated to MODIS-Terra and 1727 images associated to MODIS-Aqua). Each image is a global dataset with a spatial resolution of 4.63 km and 8640×4320 pixels dimensions. A mask has been applied in order to consider only the area corresponding to each lake, step that will be explained with more detail in the methodology section.

The algorithm of the MODIS SST product used in this work uses seven latitudinal bands in 20° intervals from 0° to 60° and then, a single interval from 60° to the poles (Kilpatrick et al., 2019; Jia, 2019; Jia and Minnett, 2020) for setting coefficients for the different atmospheric regions at a certain month of the year. These coefficients are continuously updated and validated by the Rosenstiel School of Marine and Atmospheric Science (RSMAS) at the University of Miami (Brown et al., 1999). The product applies the long-wave algorithm, which considers MODIS bands 31 and 32 at 11μm and 12μm, respectively.

It is vital to have clear the uncertainties associated to any climatic data when developing global change studies. The product's Algorithm Technical Background Document (ATBD) establishes an uncertainty of 0.45 K at nadir and 0.56 K at 45°. Several researchers have validated the MODIS SST product at global and regional scales: Sobrino et al. (2020a) estimated the global Sea Surface Temperature (SST) with a median evaluated uncertainty of 0.10 in the period 2003-2016; Reinart and Reinhold (2008) obtained errors of 0.40°C when applying the product to Swedish lakes by using MODISTerra images and considering the period 2001-2003.

3.2. Methodology

The methodology applied is based on the one proposed by (Sobrino et al., 2020b) to estimate SST at a global level and which has been shown to be valid at regional scales too (García-Monteiro et al., 2022).

As a first step, a mask for each lake considered has been elaborated and applied, in order to include in computations only the study sites selected. Once the different regions of interest are cropped, the SST is estimated applying the methodology mentioned above.

For each lake, the monthly and annual SST have been computed as shown in Eq. 1, where SST_{lake}^t is the SST for each lake at a certain time, t ; SST_{ij}^t , the SST for each pixel ij at a time t ; m is the column pixel dimension and n , the row pixel dimension; A_{ij} , is the area of every pixel of i, j dimensions and A_{lake} , the total area of each lake, only considering cloud free pixels.

$$SST_{lake}^t = \frac{1}{A_{lake}} \sum_{i=1}^m \sum_{j=1}^n A_{ij} SST_{ij}^t \quad (1)$$

For each 8-day period, four observations are considered, Terra and Aqua, daytime and nighttime, whose passing times are the following: 10:30, 13:30, 22:30 and 01:30. For each lake, the four data average has been calculated according to Eq. 2. (Mao et al., 2017). The timespan selected starts in the year 2003 because, despite Terra provides data since 2001, Aqua was launched in 2002 and did not made data available until the year 2003. Therefore, the first complete year, with four measures per image is 2003.

$$SST_{MODIS} = \left(\frac{SST_{mean}^{(10:30)} + SST_{mean}^{(13:30)} + SST_{mean}^{(22:30)} + SST_{mean}^{(01:30)}}{4} \right) \quad (2)$$

The product ATBD assesses the pixel quality through the Quality Control variable. We have taken this information into account and only included on computations those pixels of good or acceptable quality, meaning Quality Control values of 0 and 1, respectively. Furthermore, an additional filter has been applied to results with the aim of removing outliers based on the Z-score method. Linear regressions have been used to estimate trends and develop validations. In addition, the Sen's slope method and Mann-Kendal test have been run out to estimate trends with an associated level of confidence.

4. Result & Discussion

4.1. Validation

Our MODIS results have been validated with Moukomla and Blanken (2016) results. They estimated the Great Lakes Surface Temperature from the 6th of July 2001 and the 31st of December 2014 by merging skin temperature derived from the MODIS Land Surface Temperature (MOD11L2) and the MODIS Cloud product (MOD06L2). They validated their temperature estimations with in situ data from buoys belonging to the NOAA National Data Buoy Center, obtaining R-squared values ranging from 0.4975 to 0.9560 from regressions.

Figure 5 shows the regressions carried out considering our results respect the Moukomla and Blanken (2016) paper results. Correlations between both data sets are in the interval of 0.962-0.998, demonstrating, on one hand, that the retrievals of both products are in the same line and on the other, that our methodology is capable of generating valid SST estimations in lake water surfaces.

Our validation is extended by considering Hernández-Galindo (2022) work which uses Sentinel's 3 SLSTR data to estimate monthly LSWT of the Issyk-Kul lake, in Kyrgyzstan for the year 2020 (Figure 6). We have reproduced their methodology to estimate the lake's LSWT but using MODIS SST product data. As the SLSTR observations are made between 10 and 11 a.m., only Terra's diurnal images have been used, whose passing time is 10:30 a.m.

It must be mentioned that all the values used in this validation are from satellite retrievals and not *in situ* measurements. In this way, we are working with skin SST in every case, not bulk SST, avoiding the SST variations throughout the water column due to the SST stratification phenomenon (Minnett and Kaiser-Weiss, 2012).

The correlation between MODIS and SLSTR retrieved SST data for year 2020 is 0.99, indicating the clear symmetry between SST estimates from the two datasets. The bias is 0.33°C, lower than the MODIS SST product uncertainty at nadir established by its ATBD. The difference between standard deviation of both datasets is 0.35°C, lower than the error commented above. For this reason, we consider that MODIS Level 3 SST Thermal IR 8 Day 4 km V2019.0 product is capable of estimating LSWT at a high precision and the results shown in this paper are reliable.

4.2. Lake Surface Water Temperature in ten of the largest lakes of the world

Once the reliability of the MODIS SST product for LSWT estimations has been established, LSWT trends for the years 2003-2020 have been estimated for the Caspian Sea, Superior, Victoria, Huron, Michigan, Tanganyika, Baikal, Great Slave Lake, Erie and Ontario by both the linear and Sen's slope methods. The confidence level is offered by carrying out the Mann-Kendal test. The mean LSWT for the whole timespan is also provided (Table 2).

The MODIS Level 3 SST Thermal IR 8 Day 4km V2019.0 provides complete data (including four daily measures) from 2003 onwards. AVHRR enables a more comprehensive data period for both LST and SST variables but, in contrast, their satellites induce variability due to their orbital drift (Price, 1990; Sobrino et al., 2008; Julien and Sobrino, 2012). For this reason, MODIS time series have been selected for this study in detriment of AVHRR.

Positive trends are found in the ten lakes analysed (Table 2) for both the linear and Sen's slope trend estimation methods. The higher LSWT trend estimated is found for Lake Baikal, 0.083°C/yr at a 99.79% confidence level, whereas the lower trend is found in Lake Victoria, 0.012°C/yr. Results show a high Mann-Kendall level (> 95%) in the case of the Tanganyika and Erie lakes, with warming rates of 0.017°C/yr and 0.058°C/yr, respectively.

From the absolute LSWT values, the Tanganyika and Victoria lakes are the warmer lakes among the lakes considered and show the lower data variability through time, established by their standard deviations. These absolute LSWT are 25.76 ± 0.18°C for the Victoria Lake and 26.95 ± 0.16°C for the Tanganyika Lake. On the other hand, the colder lakes are represented by the Baikal Lake, 6.3 ± 0.6°C, and the Superior Lake, 6.8 ± 0.8°C.

In Figure 7, the annual LSWT means are shown. The higher difference between absolute annual temperatures are observed in Lake Baikal, reaching a 2.17°C variation between the years 2006 and 2020, matching with the higher warming rate estimated among the ten lakes, 0.083°C/yr. Previous studies have already documented that the high temperature increases in this lake have taken place for years: Hampton et al. (2008) estimated a 1.2°C increase during a sixty years timespan, 1946 – 2005, at a warming rate of 0.02°C/yr for this sixty years interval by using the MOD11A2 LST product. Our results imply that the trend has quadrupled for the 2003-2020 interval, indicating the magnitude of the LSWT trend for this lake,

On the other hand, the lowest annual variability is detected for lakes Victoria and Tanganyika, an expected scenario, as they are located in tropical latitudes, with a variation of 0.66°C and 0.62°C, respectively, between the lower annual mean (2008) and the higher (2020). Lower temporal variability is associated to lower warming rates: 0.012°C/yr in the Victoria Lake case and 0.017°C/yr, for the Tanganyika lake. Kraemer et al. (2015) estimated LSWT trends for the Tanganyika lake, obtaining 0.016 ± 0.008°C/yr calculated from in situ data and for the years 1985-2011. In this way, the trend remains practically constant through time.

O'Reilly et al. (2015) made the first worldwide synthesis of combined in situ and satellite data for 235 globally distributed lakes for the years 1985-2009, obtaining a mean LSWT trend of 0.034°C/yr. They pointed out that the LSWT warming rates are the result of the combination of both climatic and local characteristic and there is evidence of a rapid lake surface water warming. Our mean trend for the representative ten lakes selected is 0.038°C/yr and for a more recent period, 2003-2020. Despite the differences between O'Reilly et al. (2015) and this paper, the proximity of the trends obtained is worth noting.

Sobrino et al. (2020b) established a global SST trend of 0.019°C/yr for the years 2003-2019. Assuming this value for the present time span and attending to the Sen's slope trends estimated in this paper, seven of the ten lakes analyzed exceed this value: Caspian Sea (0.044°C/yr), Huron (0.029°C/yr), Michigan (0.029°C/yr), Baikal (0.083°C/yr), Slave Lake (0.056°C/yr), Erie (0.058°C/yr) and Ontario (0.047°C/yr). In this way, the general overview shows that lakes are warming at a higher rate than the global water surfaces.

Absolute LSWT and trend maps are shown in Figure 8 for the ten lakes considered. A high spatial variability for the LSWT parameter is shown,

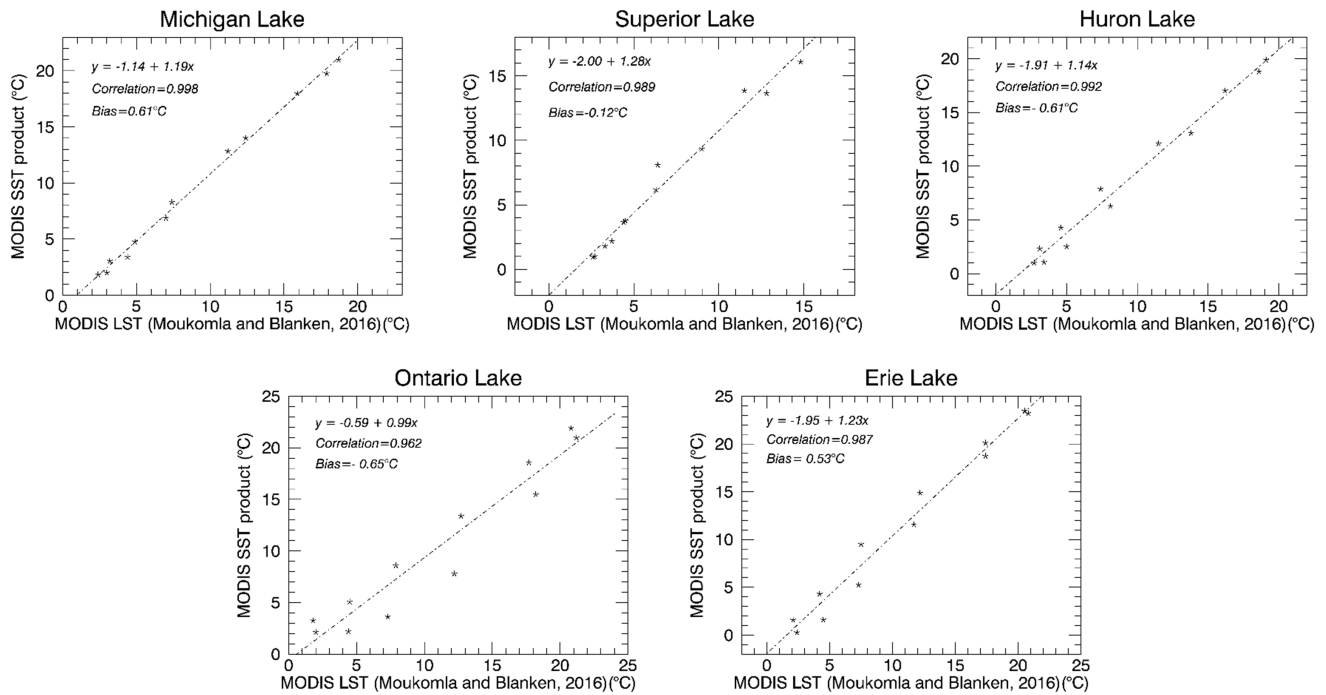


Figure 5: Results validation. MODIS SST products monthly estimations are compared with the results of Moukomla and Blanken (2016) for the Great Lakes. The timespan considered is 2003-2014. The correlation coefficients obtained ranges between 0.962 and 0.998.

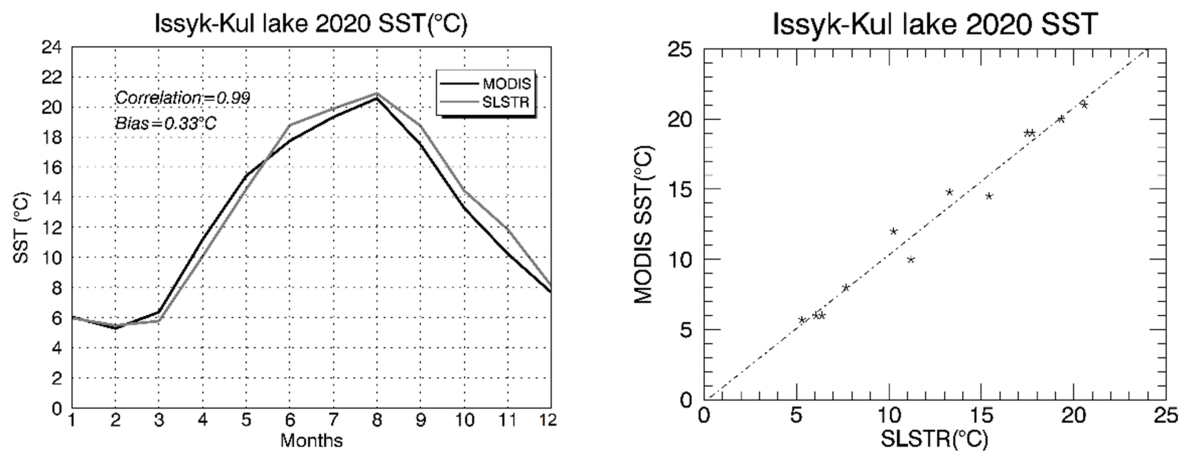


Figure 6: Monthly LSWT for the Issyk-Kul lake in the year 2020 for the MODIS and SLSTR SST estimations (left). Linear regression for both products (right).

Table 2

Annual trends estimated for the lakes analysed during the years 2003-2020 by the linear and Sen's slope methods. The results' confidence is given by the Mann-Kendal test (significant results are highlighted in bold).

Lake	Mean LSWT (°C)	Linear trend (°C)	Sen's slope (°C)	Mann-Kendal (%)
Caspian Sea	16.3 ± 0.5	0.037	0.044	87.97
Superior	6.8 ± 0.8	0.002	0.013	37.76
Victoria	25.76 ± 0.18	0.012	0.012	72.85
Huron	9.1 ± 0.6	0.031	0.029	69.37
Michigan	9.9 ± 0.8	0.025	0.029	61.64
Tanganyika	26.95 ± 0.16	0.015	0.017	96.93
Baikal	6.3 ± 0.6	0.082	0.083	99.79
Slave	6.9 ± 0.7	0.041	0.056	78.88
Erie	11.7 ± 0.5	0.043	0.058	95.53
Ontario	10.5 ± 0.7	0.043	0.047	65.64

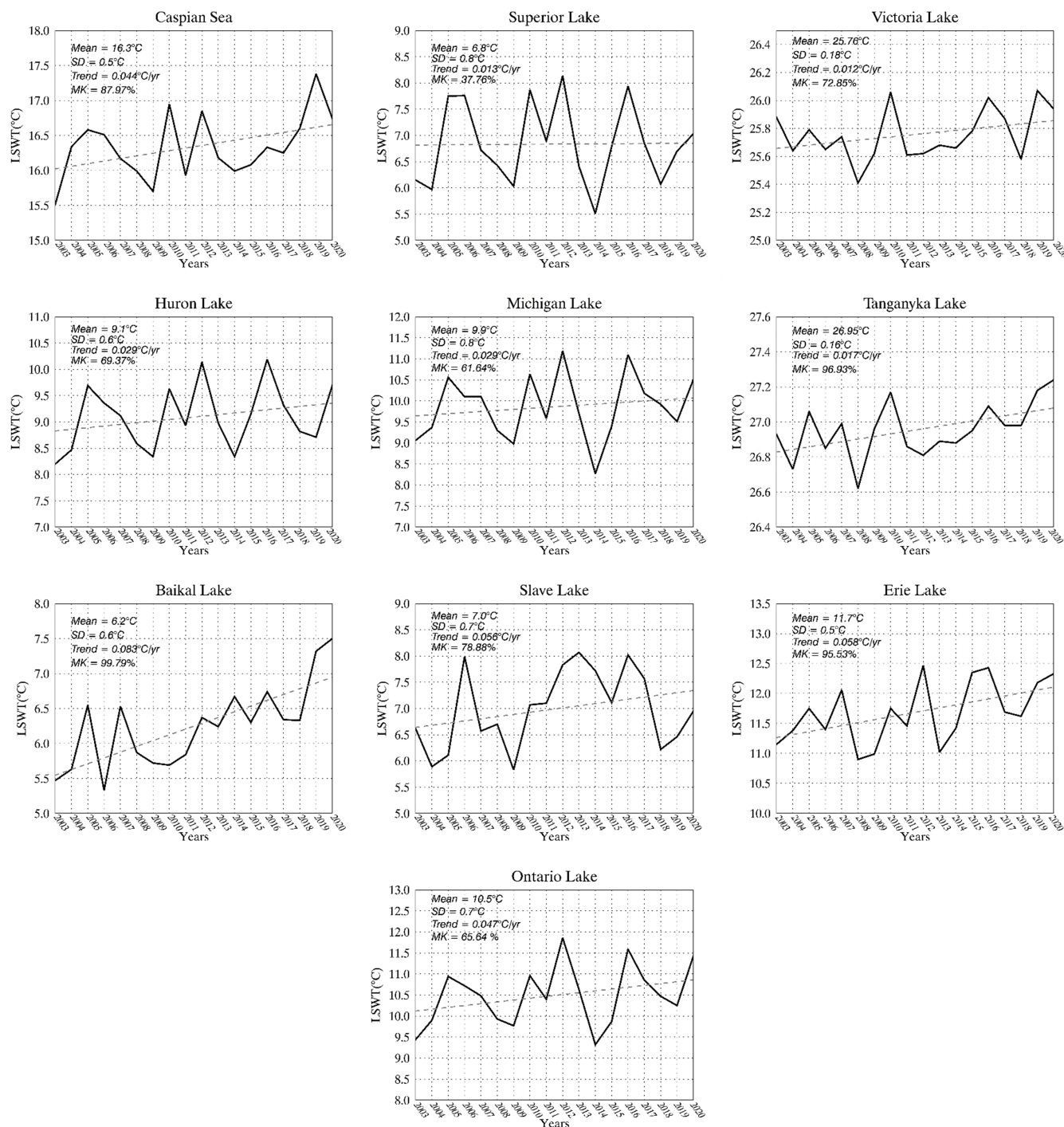


Figure 7: Annual LSWT during the timespan 2003-2020 for the ten lakes considered in the study: Caspian Sea, Superior, Victoria, Huron, Michigan, Tanganyika, Baikal, Slave Lake, Erie and Ontario.

with a more intense warming effect near the lake's shore, effect which is clearly observed for the Superior and Huron Lakes.

The 8-days LSWT have been averaged into monthly mean temperatures associated to the period 2003-2020 to detect temperature and trend variability by months. In Table 3, the mean LSWT, standard deviation, trend and Mann-Kendal confidence level are shown for each month.

The common behavior for lakes located in the Northern Hemisphere (NH) is to reach the maximum LSWT in the summer months of July and August, as it is clearly observed in the case of the Caspian Sea,

Superior, Huron, Michigan, Baikal, Great Slave Lake, Erie and Ontario lakes. In the Southern Hemisphere, the maximum monthly averages are associated to March in the Tanganyika Lake and to April in the Victoria Lake. The Tanganyika Lake has the highest estimated monthly temperature associated: $27.8 \pm 0.3^{\circ}\text{C}$. As it is expected, matching with the annual results, these lakes show the lower monthly standard deviations.

On the other hand, the minimum monthly values take place in January, February, or March for the NH lakes and in July for the SH lakes, denoting the well-known reverse seasonality between hemispheres. The minimum

Table 3

Monthly absolute LSWT and trends estimated for the lakes analysed during the years 2003–2020 by the linear and Sen's slope methods. The results' confidence is given by applying the Mann-Kendall test.

Lake	Parameter	January	February	March	April	May	June	July	August	September	October	November	December
Caspian	T (°C)	8.7	7.5	8.2	11.9	17.93	23.4	26.4	26.56	22.6	17.77	13.33	10.4
	SD (°C)	0.6	0.5	0.7	1.2	1.05	1.2	0.9	1.09	0.6	1.01	1.08	0.9
	Trend (°C/yr.)	0.016	-0.001	0.066	0.032	0.06	0.105	0.103	-0.033	0.011	-0.042	-0.053	-0.002
	MK (%)	63.69	3.02	96.28	48.04	83.9	92.49	98.3	52.84	26.69	65.64	83.9	9.05
Superior	T (°C)	2.2	1	0.9	1.7	3.6	8	13.9	16.1	13.8	9.5	6.2	3.8
	SD (°C)	0.6	0.6	0.7	0.8	0.9	1.3	2.2	1.6	1.6	1.2	0.8	0.5
	Trend (°C/yr.)	-0.007	0.005	-0.004	-0.023	-0.023	0.025	0.06	0.013	-0.005	0.026	-0.03	0.011
	MK (%)	23.82	20.92	3.02	32.31	50.48	12.05	65.64	15.02	20.92	32.31	69.37	29.52
Victoria	T (°C)	25.9	26.1	26.2	26.3	26.1	25.5	25	25.04	25.41	25.76	26	25.96
	SD (°C)	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.15	0.14	0.16	0.2	0.18
	Trend (°C/yr.)	-0.011	0.028	0.02	0.022	0.013	0.025	0.023	0.01	0.016	-0.006	0.007	0.004
	MK (%)	45.57	82.75	63.69	40.42	69.38	93.11	97.92	91.89	99.01	43.05	71.16	17.99
Huron	T (°C)	2.3	1.1	1.1	2.5	6.3	13	18.9	20.06	17.28	12.3	7.9	4.5
	SD (°C)	0.6	0.5	0.7	0.9	1.4	1.3	1.5	1.02	1.06	1.2	0.9	0.8
	Trend (°C/yr.)	0.004	0.03	0.107	-0.001	0.075	0.008	0.056	0.03	0.007	0.05	-0.023	0.023
	MK (%)	3.02	61.64	23.82	6.04	59.54	3.02	45.55	32.31	23.82	77.46	37.77	40.41
Michigan	T (°C)	3.07	1.9	2	3.37	6.98	13.93	19.94	21.14	18.18	13.04	8.33	4.91
	SD (°C)	0.6	0.63	0.86	1	1.46	1.55	1.76	1.24	0.95	1.28	0.95	0.71
	Trend (°C/yr.)	0.012	0.027	0.013	-0.009	0.04	0.01	0.094	0.02	0.026	0.027	-0.05	0.035
	MK (%)	29.52	57.37	20.91	37.76	48.04	3.02	69.36	37.76	32.31	48.04	65.64	63.68
Tanganyika	T (°C)	27.25	27.53	27.78	27.69	27.37	26.54	25.8	25.85	26.48	27.02	27.16	27.18
	SD (°C)	0.24	0.28	0.36	0.33	0.38	0.28	0.2	0.16	0.16	0.16	0.24	0.17
	Trend (°C/yr.)	0.005	-0.001	0.003	0.014	0.035	0.017	0.028	0.02	0.018	0	0.019	0.016
	MK (%)	15.03	6.04	17.99	52.85	97.7	65.68	99.87	98.94	95.93	0	92.52	89.69
Baikal	T (°C)	0.95	-0.37	-0.25	0.16	1.94	5.76	13.06	14.82	10.76	6.44	3.87	1.98
	SD (°C)	0.38	0.69	0.26	0.28	0.55	1.09	1.9	1.64	1.27	0.54	0.36	0.26
	Trend (°C/yr.)	0.008	0.65	-0.003	0.016	0.061	0.132	0.218	0.21	0.132	0.036	0.034	0.018
	MK (%)	37.77	9.04	35.08	95.54	99.11	99.43	98.62	98.89	96.28	75.98	96.62	75.99
Slave	T (°C)	-0.4	0.04	0.11	0.39	1.22	6.19	14.16	14.12	9.77	5.64	2.59	0.83
	SD (°C)	1.64	0.38	0.33	0.21	0.28	1.56	1.41	1.41	1.24	0.75	0.43	0.77
	Trend (°C/yr.)	-	-	-	-0.004	-0.024	0.141	0.054	0.12	0.033	-0.025	0.008	-
	MK (%)	-	-	-	37.78	91.19	91.17	52.83	86.04	40.41	57.37	29.52	-
Erie	T (°C)	1.62	0.43	1.66	5.24	11.46	18.55	23.36	23.63	20.46	15.25	9.68	4.59
	SD (°C)	0.85	0.49	1.03	1.3	1.34	1.04	1.24	0.97	0.94	1.26	1.05	1.16
	Trend (°C/yr.)	0.034	0.037	0.026	0.015	0.002	-0.029	0.378	0.789	0.07	0.093	-0.006	0.054
	MK (%)	45.56	95.93	37.76	26.68	12.04	26.69	83.9	37.76	78.88	91.18	9.04	55.14
Ontario	T (°C)	3.33	2.19	2.22	3.61	7.75	15.24	21.16	22.08	18.98	13.66	8.62	5.27
	SD (°C)	0.59	0.6	0.85	1.03	1.92	1.58	1.55	0.97	1	1.15	0.85	0.79
	Trend (°C/yr.)	0.013	0.024	0.024	0.032	0.038	0.015	0.114	0.035	0.063	0.077	0.015	0.041
	MK (%)	35.06	57.37	65.65	52.83	23.82	15.02	86.04	43.01	87.96	94.66	9.04	45.56

monthly value is registered for the Baikal lake in February, $-0.4 \pm 0.3^\circ\text{C}$. According to Moukomla and Blanken (2016), surface temperature below 0°C may correspond to ice cover, which could be for liquid water surfaces by the sensor. Changes from minimum to maximum values are gradual through the months.

Stability in absolute LSWT values terms is observed in two pair of months: July and August for the Caspian Sea, Victoria, Tanganyika, Slave and Erie lakes and February and March for the Superior, Victoria, Huron, Michigan, Baikal, Slave and Ontario lakes. These relative stable values are identified with minimum and maximum annual values. Changes from minimum to maximum LSWT values are gradual through the months.

5. Conclusion

Lakes are freshwater enclosed extensions in which there is no exchange with open waters. For this reason, the initial hypothesis of this work was that they could suffer to a greater extent from the effect of global warming. Results show positive LSWT trend for the ten lakes considered: the Caspian Sea, Superior, Victoria, Huron, Michigan, Tanganyika, Baikal, Great Slave Lake, Erie and Ontario lakes.

Furthermore, when considering the current SST warming rate, established in $0.018^\circ\text{C}/\text{yr}$ for the whole sea surfaces, seven of these ten lakes exceed this trend. The sample size is limited enough to prevent generalizing that LSWT is warming at a higher rate than SST, but it can be affirmed that the LSWT of seven of the largest lakes of the world is increasing at an accelerated rate. The highest LSWT is found for Lake

Baikal, with $0.083^\circ\text{C}/\text{yr}$, nearly five times the global SST trend, whereas the lowest trend is associated to Victoria Lake, with $0.012^\circ\text{C}/\text{yr}$.

LSWT trends have also been calculated by months for each lake with the aim of detecting possible monthly variability. Results show that warming rates are not homogeneous throughout the year, and they are accentuated during the Northern Hemisphere summer months (June–July–August) for all the lakes, matching, as well, with the higher absolute LSWT values of the Northern Hemisphere lakes.

The MODIS Level 3 SST Thermal IR 8 Day 4 km V2019.0 achieves SST retrieval by applying a specific SST algorithm. However, it also provides information about freshwater extension and this paper has demonstrated its functionality in this type of ecosystems. The validations carried out show correlations between 0.96 and 0.99 with results provided by previous literature.

Remote sensing is a valuable technology which provides homogeneous and periodic data from the whole Earth's surface. Its main disadvantage is the impossibility of collecting data below clouds. This weakness is overcome by the satellite temporal resolution that means 4 passes per day. The low uncertainty of results confirms its reliability, strengthened by the validation that has been carried out.

The LSWT is positioned as a parameter of climatic interest, already recognized as an Essential Climate Variable by the World Meteorological Organization, which reflects global warming in an amplified way. As for other ECVs, such as SST, the LSWT must be continuously monitored, as it is an indicator of the behaviour of the surface temperature of the planet.

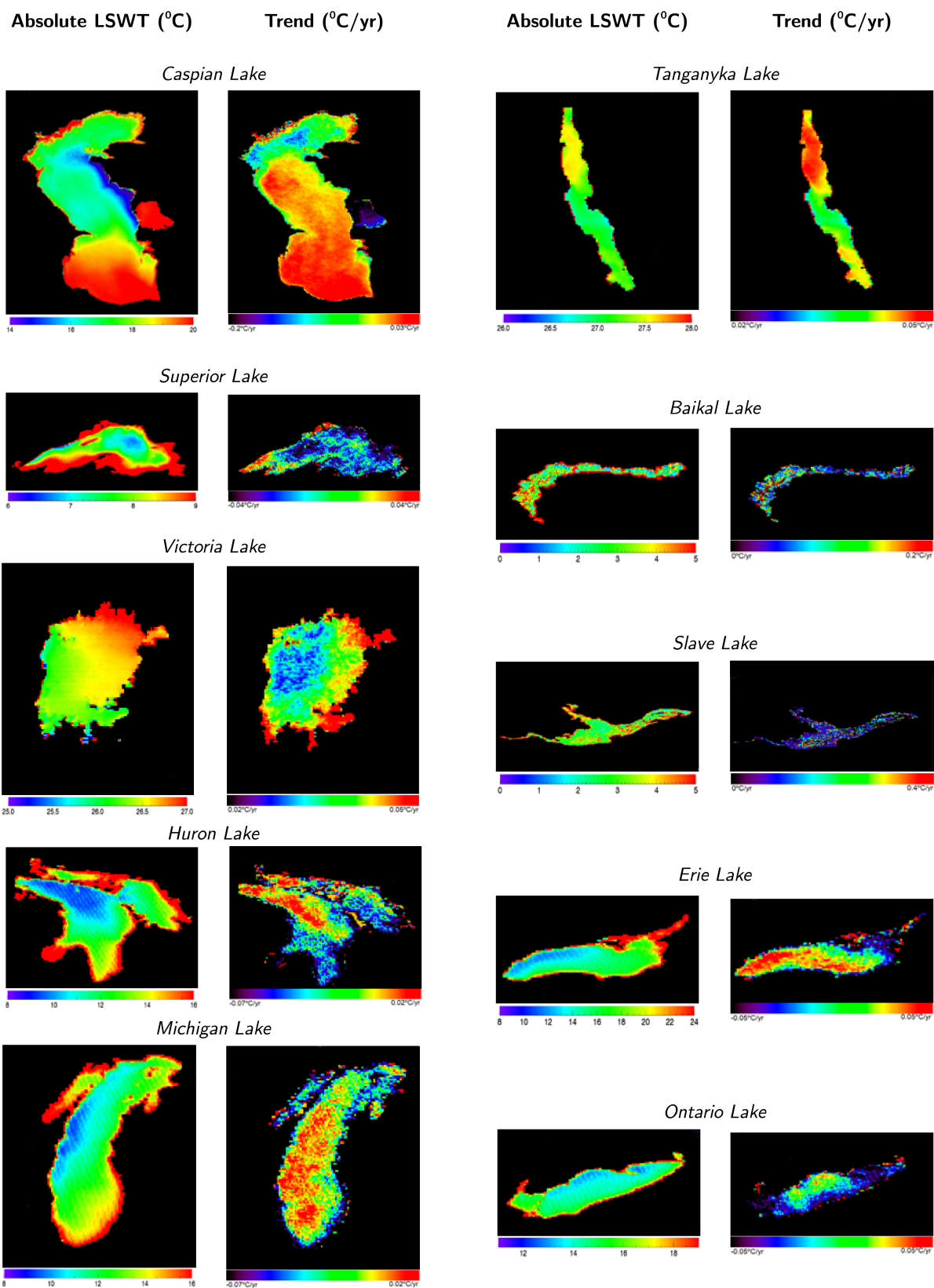


Figure 8: Absolute LSWT and trends during the timespan 2003-2020 for the ten lakes considered in the study: Caspian Sea, Superior, Victoria, Huron, Michigan, Tanganyika, Baikal, Great Slave Lake, Erie and Ontario lakes.

Author Contributions

Sobrino, J.: Conceptualization; Julien, Y., García-Monteiro, S.: Data curation; Julien, Y., García-Monteiro: Formal analysis; Sobrino, J., García-Monteiro, S.: Funding acquisition; Julien, Y., García-Monteiro, Sobrino, J.: Investigation; Julien, Y.: Methodology; Sobrino, J.: Project administration; Sobrino, J.: Resources; Julien, Y.: Software; Julien, J.: Sobrino, J.: Supervision; Sobrino, J., García-Monteiro, S.: Validation; García-Monteiro, S.: Visualization; García-Monteiro, S.: Writing – original draft; Julien, Y., Sobrino, J., García-Monteiro, S.: Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgments

The authors thank the NASA Physical Oceanography Distributed Active Archive Center team for making MODIS data freely available.

Funding

This research was funded by the *Ministerio de Ciencia e Innovación* (TIRSAT ESP2017-85770-R and PID2020-112494RB-I00 IPL-LSTM) and the *Ministerio de Universidades* (grant number FPU18/01239).

References

- Awange, J. L. et al. (2006). *Lake Victoria: ecology, resources, environment*. Springer Science & Business Media.
- Benada, J. R. (1997). Physical oceanography distributed active archive center.
- Brown, O. B., Minnett, P. J., Evans, R., Kearns, E., Kilpatrick, K., Kumar, A., Sikorski, R., and Závody, A. (1999). Modis infrared sea surface temperature algorithm theoretical basis document version 2.0. *University of Miami*, 31:098–33.
- Crosman, E. T. and Horel, J. D. (2009). Modis-derived surface temperature of the great salt lake. *Remote Sensing of Environment*, 113(1):73–81.
- Dahlman, L. (2009). Climate variability: North atlantic oscillation. *Natl. Oceanic Atmosph. Administ. (NOAA)*.
- De Santis, D., Del Frate, F., and Schiavon, G. (2021). Analysis of climate change effects on surface temperature in central-italy lakes using satellite data time-series. *Remote Sensing*, 14(1):117.
- Dumont, H. (1998). The caspian lake: history, biota, structure, and function. *Limnology and Oceanography*, 43(1):44–52.
- Elliott, J., Jones, I., and Thackeray, S. (2006). Testing the sensitivity of phytoplankton communities to changes in water temperature and nutrient load, in a temperate lake. *Hydrobiologia*, 559:401–411.
- Gamito, R., Teixeira, C. M., Costa, M. J., and Cabral, H. N. (2015). Are regional fisheries' catches changing with climate? *Fisheries research*, 161:207–216.
- García-Monteiro, S., Sobrino, J., Julien, Y., Sòria, G., and Skokovic, D. (2022). Surface temperature trends in the mediterranean sea from modis data during years 2003–2019. *Regional Studies in Marine Science*, 49:102086.
- GCOS (2016). Global climate observation system. <https://gcos.wmo.int/en/essential-climate-variables/about>. Accessed in the 14h of February of 2022.
- Ghasemifar, E., Farajzadeh, M., Mohammadi, C., and Alipoor, E. (2019). Long-term change of surface temperature in water bodies around iran-caspian sea, gulf of oman, and persian gulf—using 2001–2015 modis data. *Physical Geography*, 41(1):21–35.
- Hampton, S. E., Izmet'eva, L. R., Moore, M. V., Katz, S. L., Dennis, B., and Silow, E. A. (2008). Sixty years of environmental change in the world's largest freshwater lake—lake baikal, siberia. *Global Change Biology*, 14(8):1947–1958.
- Izmet'eva, L. R., Moore, M. V., Hampton, S. E., Ferwerda, C. J., Gray, D. K., Woo, K. H., Pislegina, H. V., Krashchuk, L. S., Shimaraeva, S. V., and Silow, E. A. (2016). Lake-wide physical and biological trends associated with warming in lake baikal. *Journal of Great Lakes Research*, 42(1):6–17.
- Jia, C. (2019). *Satellite Infrared Retrievals of Sea Surface Temperature at High Latitudes*. PhD thesis, University of Miami.
- Jia, C. and Minnett, P. J. (2020). High latitude sea surface temperatures derived from modis infrared measurements. *Remote sensing of environment*, 251:112094.
- Julien, Y. and Sobrino, J. A. (2012). Correcting avhrr long term data record v3 estimated lst from orbital drift effects. *Remote sensing of environment*, 123:207–219.
- Kilpatrick, K., Minnett, P., and Luo, B. (2019). Validation of nasa modis r2019. 0 reprocessed sst products. In *Proceedings of the 18th International GHRSSST Science Team Meeting (GHRSSST XVIII)*, Frascati, Italy, pages 6–10.
- Kraemer, B. M., Hook, S., Huttula, T., Kotilainen, P., O'Reilly, C. M., Peltonen, A., Plisnier, P.-D., Sarvala, J., Tamatamah, R., Vadeboncoeur, Y., et al. (2015). Century-long warming trends in the upper water column of lake tanganyika. *PLoS One*, 10(7):e0132490.
- Liu, Q., Zhang, S., Zhang, H., Bai, Y., and Zhang, J. (2020). Monitoring drought using composite drought indices based on remote sensing. *Science of the total environment*, 711:134585.
- Livingstone, D. M. and Adrianb, R. (2009). Modeling the duration of intermittent ice cover on a lake for climate-change studies. *Limnology and Oceanography*, 54(5):1709–1722.
- Lofgren, B. M. and Zhu, Y. (2000). Surface energy fluxes on the great lakes based on satellite-observed surface temperatures 1992 to 1995. *Journal of Great Lakes Research*, 26(3):305–314.
- Mao, K., Ma, Y., Tan, X. a., Shen, X., Liu, G., Li, Z., Chen, J., and Xia, L. (2017). Global surface temperature change analysis based on modis data in recent twelve years. *Advances in Space Research*, 59(2):503–512.
- McPhaden, M. J., Zebiak, S. E., and Glantz, M. H. (2006). El Niño as an integrating concept in earth science. *science*, 314(5806):1740–1745.
- Minnett, P. and Kaiser-Weiss, A. (2012). Near-surface oceanic temperature gradients. *GHRSSST Discussion Doc*, 7.
- Moukoma, S. and Blanken, P. D. (2016). Remote sensing of the north american laurentian great lakes' surface temperature. *Remote Sensing*, 8(4):286.
- O'Reilly, C. M., Alin, S. R., Plisnier, P.-D., Cohen, A. S., and McKee, B. A. (2003). Climate change decreases aquatic ecosystem productivity of lake tanganyika, africa. *Nature*, 424(6950):766–768.
- O'Reilly, C. M., Sharma, S., Gray, D. K., Hampton, S. E., Read, J. S., Rowley, R. J., Schneider, P., Lenters, J. D., McIntyre, P. B., Kraemer, B. M., et al. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, 42(24):10–773.
- Owen, Lewis, Kosarev, A. N., and Leontiev, O. K. (2024). Caspian sea. *Encyclopedia Britannica*. Accessed 27 February 2024.
- Price, J. C. (1990). Using spatial context in satellite data to infer regional scale evapotranspiration. *IEEE transactions on Geoscience and Remote Sensing*, 28(5):940–948.
- Reinart, A. and Reinhold, M. (2008). Mapping surface temperature in large lakes with modis data. *Remote Sensing of Environment*, 112(2):603–611.
- Sobrino, J. A., Julien, Y., Atitar, M., and Nerry, F. (2008). Noaa-avhrr orbital drift correction from solar zenithal angle data. *IEEE Transactions on Geoscience and Remote Sensing*, 46(12):4014–4019.
- Sobrino, J. A., Julien, Y., and García-Monteiro, S. (2020a). Surface temperature of the planet earth from satellite data. *Remote Sensing*, 12(2):218.
- Sobrino, J. A., Julien, Y., and García-Monteiro, S. (2020b). Surface temperature of the planet earth from satellite data over the period 2003–2019. *Remote Sensing*, 12(2):218.
- Stainsby, E., Winter, J., Jarjanazi, H., Paterson, A., Evans, D., and Young, J. (2011). Changes in the thermal stability of lake simcoe from 1980 to 2008. *Journal of Great Lakes Research*, 37:55–62.
- Swain, W. R. and Shannon, V. R. (1980). Proceedings of the second american-soviet symposium on the use of mathematical models to optimize water quality management. *United States Environmental Protection Agency. EPA-300/9-80-033*.
- Swann, G. E., Panizzo, V. N., Piccolroaz, S., Pashley, V., Horstwood, M. S., Roberts, S., Vologina, E., Piotrowska, N., Sturm, M., Zhdanov, A., et al. (2020). Changing nutrient cycling in lake baikal, the world's oldest lake. *Proceedings of the National Academy of Sciences*, 117(44):27211–27217.
- United States Environmental Protection Agency (2022). Great lakes atlas. physical facts. <http://www.epa.gov/glnpo/physfacts.html>. Accessed in the 15th of February of 2022.

- Verburg, P., Hecky, R. E., and Kling, H. (2003). Ecological consequences of a century of warming in lake tanganyika. *Science*, 301(5632):505–507.
- Zhang, Y., Li, T., Chang, C.-P., and Wang, B. (2001). On the relationship between indian ocean sea surface temperature and asian summer monsoon. *Geophysical Research Letters*, 28(14):2843–2846.
- Zhang GuoQing, Z. G., Yao TanDong, Y. T., Xie, H., Qin Jun, Q. J., Ye QingHua, Y. Q., Dai YuFeng, D. Y., and Guo RuiFang, G. R. (2014). Estimating surface temperature changes of lakes in the tibetan plateau using modis 1st data.
- Zimmerman, M. S., Krueger, C. C., and Eshenroder, R. L. (2006). Phenotypic diversity of lake trout in great slave lake: differences in morphology, buoyancy, and habitat depth. *Transactions of the American Fisheries Society*, 135(4):1056–1067.

Publisher's Note

The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of Recent Advances S.L. and/or the editor(s). Recent Advances S.L. and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.