**Earth Surface Temperature evolution during the years 2003-2020 from MODIS data**

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ABSTRACT - *The present work shows the estimation of the surface temperature of Planet Earth with MODIS Terra and Aqua Land (LST) and Sea Surface Temperature (SST) products for the years 2003-2021. The results corroborate the temperature anomalies retrieved from climate models and show a rate of warming higher that 0.2 °C per decade. Furthermore, the MODIS surface temperature retrievals are compared with the NOAA’s NCDC air temperature estimations, showing high correlations for the global EST (0.96), LST (0.93) and SST (0.94). As an specific application, Lake Surface Water Temperature (LSWT) is estimated for ten of the largest lakes in the world by using MODIS Level 3 SST Thermal IR 8 Day 4km Version 2019.0 product at a high precision during the timespan 2003-2020. The selected lakes are the Caspian Sea, Superior, Victoria, Huron, Michigan, Tanganyika, Baikal, Great Slave Lake, Erie and Ontario lakes. LSWT trends show positive warming rates for every lake, with values ranging between 0.012°C/yr for Victoria Lake and 0.083°C/yr for Baikal Lake. Our LSWT estimations have been validated in the Laurentian Great Lakes, obtaining correlations between 0.96-0.99 respect Moukomla and Blanken (2016) research, which used the MOD11L2 LST product considering the years 2003-2014.. Despite MODIS SST product used is designed to retrieve SST by applying a specific SST algorithm, it also provides accurate information about freshwater extension and this work has demonstrated its functionality for estimating LSWT.*

Keywords - *MODIS, trend, global warming, Sea Surface Temperature, Land Surface Temperature, Lake Surface Water Temperature*

1. INTRODUCTION

The IPCC’s Fifth Assessment Report provided the scientific input into the Paris Agreement (Field et al., 2014), which aims to strengthen the global response to the threat of climate change by holding the increase in the global average temperature to well below 2 ⁰C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 ⁰C above pre-industrial levels. For this reason, estimating both Sea Surface Temperature (SST) and Land Surface Temperature (LST) in an accurate way is a priority task to achieve the IPCC’s Report objective.

Traditionally, surface temperature has been measured by using in situ instruments, which are irregularly distributed and differently calibrated (Sobrino et al., 2020a). This means that adjustments must be made in an attempt to homogenize temperature data from such varied sources. On the other hand, in situ instruments have the advantage of measuring data directly, without a column of air in between the water and instrument, as in the satellite case.

In contrast to the measurements provided by in situ sources, satellites make global and continuous observations of the planet surface (Sobrino et al., 2020b; Garcia-Monteiro, et al., 2022). by the same thermal sensor of a known uncertainty. This means no residual uncertainties are going to be carried due to different calibration methods or instrument uncertainties.

The following work aims to give an overall view of the evolution of the EST, SST and LST during the years 2003-2021, estimated from MODIS retrievals, to compare results with the NOAA’S NCDC widely used air temperature dataset and to highlight the value of satellite thermal observations in their application to climate studies.

On the other hand, Lake Surface Water Temperature (LSWT) is an Essential Climate Variable recognized by the Global Observing System for Climate (GCOS) and it is an indicator of how climate change is affecting worldwide lake physical dynamics and ecosystems Ten large lakes have been selected for developing this study: the Caspian Sea, Superior, Victoria, Huron, Michigan, Tanganyika, Baikal, Great Slave Lake, Erie and Ontario lakes in order to retrieve their LSWT, in absolute and trend terms.

LSWT will be retrieved for 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 analyse the behaviour of this parameter during the last years.

1. MATERIAL AND METHODS

2.1. Study sites (lakes)

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, 2003; United States Environmental Protection Agency, 2022; Swain and Shannon, 1980; Verburg, P. et al., 2003; Zimmerman et al., 2006).

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

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| --- | --- | --- | --- | --- |
| Lake | Cont | Area  (km2) | Vol  (km3) | Max.  depth  (m) |
| Caspian Sea | Asia | 371,0 | 78,2 | 1,025 |
| Superior | America | 82,1 | 12,1 | 406.3 |
| Victoria | Africa | 68,9 | 2,8 | 84 |
| Huron | America | 59,6 | 3,5 | 229 |
| Michigan | America | 58,0 | 4,9 | 281 |
| Tanganyika | Africa | 32,6 | 18,9 | 1,470 |
| Baikal | Asia | 31,5 | 23,6 | 1,620 |
| Slave | America | 27,0 | 1,6 | 614 |
| Erie | America | 25,7 | 489 | 64 |
| Ontario | America | 18,9 | 1,639 | 244 |

* 1. Data sets

The SST product used in this study is MODIS Level 3 SST Thermal IR 8 Day 4km V2019.0, which is freely available in https://podaac.jpl.gov. 8-days composites 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 8640x4320 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 20⁰ intervals from 0⁰ to 60⁰ and then, a single interval from 60⁰ to the poles (Kilpatrick et al, 2019; Jia, 2019; Jia and Minett, 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 and Minnett, 1999). The product applies the long-wave algorithm, which considers MODIS bands 31 and 32 at 11 μm and 12 μm, respectively (Goddard Space Flight Center, 2014).

When referring to errors, the product’s Algorithm Technical Background Document (ATBD) establishes an uncertainty of 0.45K at nadir and 0.56K at 45⁰. Several researchers have validated the MODIS SST product at global and regional scales: Sobrino et al. (2020a) estimated de 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 0.40⁰C when applying the product to Swedish lakes by using MODIS-Terra images and considering the period 2001-2003.

For LST retrieval, the product selected is MOD11C2 (MODIS-Terra) and MYD11C2 (MODIS-Aqua), 8-days composites at 0.05º resolution. Uncertainties range between 0.88K and 1.63K depending on the observation angle and water vapour content (Wan, 2004). A total of 3497 images have been processed (1748 images from MODIS-Terra and 1749 images from MODIS-Aqua).

* 1. 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).

SST means are estimated by following equation 1, where is the SST for each area considered at a certain time, *t*;, the SST for each pixel *ij* at a time *t*; *m* is the column pixel dimension and *n*, the row pixel dimension; *Aij*, is the area of every pixel of *i,j* dimensions and *Alake*, the total area of each lake, only considering cloud free pixels.

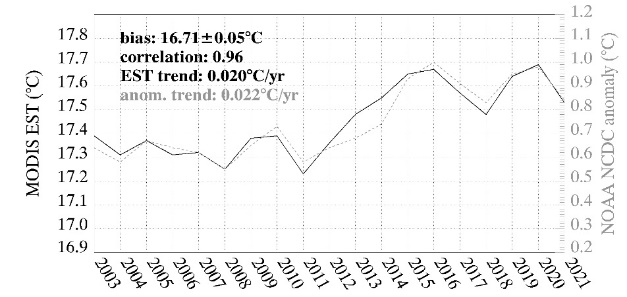
For each 8-day period, four observations are considered, Terra and Aqua, daytime and nighttime, whose passing times are the following: 10:30, 13:30, 22:30 and 01:30. For each pixel, the four data average has been calculated according to Eq. 2. (Mao et al., 2017). The timespan selected starts in the year 2003 because, despite Terra provides data since 2001, Aqua wan 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.

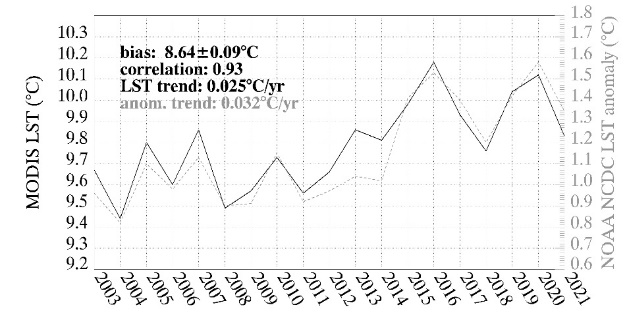
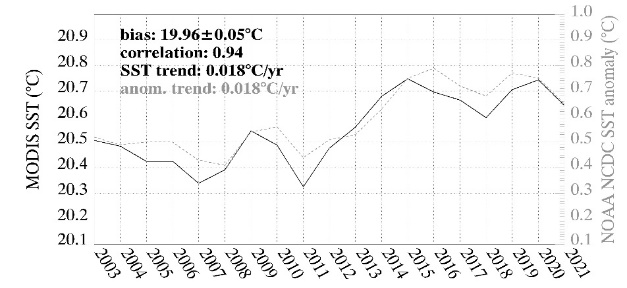
The product ATBD assesses the pixel quality through the Quality Control variable. We have taken this information into account an only included on computations those pixels of good or acceptable quality, meaning Quality Control values of 0 and 1, respectively. Furthermore, an additional filter has been applied to results with the aim or 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.

For each lake, monthly and annual SST means have been computed as shown in Eq. 1 A mask for each lake considered has been elaborated and applied, in order to include in computations only de study sites selected. Once the different regions of interest are cropped, the SST is estimated applying the methodology mentioned above.

1. RESULTS & DISCUSSION
   1. Earth Surface Temperature

MODIS EST, SST and LST global estimations are compared with NOAA’ NCDC air temperature merged land-ocean, land and ocean surface temperature measurements in figure 1.



*Figure 2. MODIS and NOAA’S NCDC air temperature comparison for EST, SST and LST.*

For EST, the linear trends estimated are of 0.0202±0.0008⁰C/yr for MODIS EST and 0.022⁰C/yr for NOAA NCDC anomalies Results show a high correlation between MODIS EST estimations and NOAA NCDC air temperature global data, interpolated from in situ sources, with a 0.96 value. MODIS EST trend has also been estimated by the Sen’s slope method, obtaining 0.020⁰C/yr, as for the linear method, with a confidence level of 99.9%, showing the high potential of MODIS thermal infrared satellite data as a source of input data for global surface temperature estimations and for global change studies

In the LST case, The correlation is of 0.93 between both data sets with a significance higher than 99.9%. Linear trends are defined as 0.025±0.001⁰C/yr for the MODIS LST and 0.032⁰C/yr for the NOAA’S NCDC anomalies. As for EST, the Sen’s slope trend has also been calculated, with a similar resulting value, 0.023⁰C/yr and a Mann-Kendall significance of 99.7%.

For the SST variable, The correlation between NOAA NCDC anomalies and MODIS retrievals is 0.94, slightly improving the LST results. The SST trend is 0.018⁰C/yr in both cases, confirmed by the Sen’s slope method with a 99.7% of confidence. The trend uncertainty for the MODIS linear estimation is 0.0008⁰C/yr.

Global surface temperature trend maps, as well as the Mann-Kendal significance map, are shown in figure 2. The global trends are 0.020⁰C/yr for EST, 0.018⁰C/yr for SST and 0.023⁰C/yr for LST, given at a confidence level higher than 99%.

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| --- |
| **Sen’s slope trend** |
|  |
| **Mann-Kendal test** |
|  |

*Figure 2. Sen’s slope trend and Mann-Kendal confidence level in maps*

For the LST variable, positive trends are found for large areas of the central and Eastern Europe, Scandinavia and Siberia. In the American continent, peninsulas of California and Florida, and in northeastern Brazil and Patagonia. Negative trends appear mainly in the Indian Peninsula and in eastern longitudes of Antarctica.

In the SST case, negative trends are found in the North Atlantic Ocean, Greenland, in the North Pacific, the Sea of Japan, the Yellow Sea and in the Southern Ocean. On the other hand, positive trends are irregularly distributed along NH low and mid-latitudes and in the Atlantic and Pacific Oceans, next to the North American and Australian Continent and the Arctic Circle.

* 1. Lake Surface Water Temperature 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 3 shows the regressions carried out considering our results respect the Moulomla 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.

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*Figure 3. Results validation. MODIS SST products monthly estimations are compared with the results of Moukomla and Blanken (2016) for the Great Leaks. The timespan considered is 2003-2014. The correlation coefficients obtained ranges between 0.962 and 0.998.*

* 1. 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, 0.083⁰C/yr at a 99.79% confidence level, whereas the lower trend is found in Lake Victoria, 0.012⁰C/yr. Results show a high Mann-Kendall level (>95%) in the case of the Tanganyka and Erie lakes, with warming rates of 0.017⁰C/yr and 0.058⁰C/yr, respectively.

From the absolute LSWT values, the Tanganyka 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±0.18⁰C for the Victoria Lake and 26.95±0.16⁰C for the Tanganyka Lake. On the other hand, the colder lakes are represented by the Baikal Lake, 6.3±0.6⁰C, and the Superior Lake, 6.8±0.8⁰C.

*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).*

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| --- | --- | --- | --- | --- |
| Lake | Mean LSWT (⁰C) | Linear trend (⁰C) | Sen’s slope  (⁰C) | 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 |

Sobrino et al. (2020b) established a global SST trend of 0.019⁰C/yr for the years 2003-2019. Assuming this value for the present timespan and attending to the Sen’s slope trends estimated in this paper, seven of the ten lakes analysed exceed this value: Caspian Sea (0.044⁰C/yr), Huron (0.029⁰C/yr), Michigan (0.029⁰C/yr), Baikal (0.083⁰C/yr), Slave Lake (0.056⁰C/yr), Erie (0.058⁰C/yr) and Ontario (0.047⁰C/yr). In this way, the general overview shows that lakes are warming at a higher rate than the global water surfaces.

1. CONCLUSIONS

The comparison between the planetary MODIS Earth Surface Temperature (EST) presented in this work and the NOAA-NCDC air temperature data shows a correlation coefficient of 0.96 between the two databases, demonstrating the high potential of thermal infrared satellite data to provide accurate data for climatic and meteorological studies. Satellite data are essential in the monitoring of SST, LST and EST as a solid source of continuous data in space and time.

The global EST trend is 0.020 °C/yr, 0.018°C/yr for SST trends and 0.025°C/yr for the LST parameter. SST shows less variability in time than LST and a higher influence on EST, as sea surface extension dominates over the land surface extension. This proceeding has covered not only the trends observed from satellites but also the current estimations of air temperature. We consider that satellite data used be used to estimate anomalies of the average temperature of the Earth’s surface and be included in the IPCC assessment reports

When referring to lakes, they 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 form 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 0.018⁰C/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 0.083⁰C/yr, nearly five times the global SST trend, whereas the lowest trend is associated to Victoria Lake, with 0.012⁰C/yr.

The MODIS Level 3 SST Thermal IR 8 Day 4km 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.

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