Surface water temperature of Lake Kariba: dynamics and spatial heterogeneity

ESS 511 Master's Thesis

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Abstract

Lakes are one of the ecosystems strongly affected by the changing climate. Warming of the surface water could increase lake's stratification. This is especially relevant in case of artificial reservoirs with dams, as the quality of the water released affects the ecosystem downstream. Studying such processes is a challenge, especially in developing countries because of the lack of resources and long-term data. Remote Sensing provides both large spatial and temporal coverage. That is why we used satellite retrieved water temperature images from GHRSST project to analyze the Lake Surface Temperature (LST) of Lake Kariba throughout years 2003 to 2015. Additionally we compared LST behavior to external factors: air temperature, wind speed and bathymetry. Our aim was to describe spatial and temporal heterogeneity of LST and test the possibility of using remote sensing to identify the lake mixing periods. We found that there are clear changes in spatial distribution of temperature that correspond to general mixing and stratification periods. During 13 years of our analysis, the LST increased around 2 °C. This is higher than expected and could be caused by transition from negative to positive Indian Ocean Dipole. We also discovered that winter temperatures are driving the general increase and that LST is highest with high air temperature and low wind speed. LST increase with the distance from the inflow, but it is impossible to differentiate between the influence of the river and depth, because lake's depth also increases with distance from the inflow. However, during winter the surface pattern resembles lake's bathymetry. Therefore, although mixing periods have their reflection in Kariba's surface temperatures, the LST alone are not enough to evidence them. Overall, we find remote sensing a good tool and especially useful when analyzing general trends but with many error sources there is still place for improvement.

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1 Introduction

1.1 Changing climate

Climate change is one of the most discussed topics of today’s society. Its effects will and already have a significant impact on environment, economy and human life. We observe its results both globally and regionally. A prominent indicator of changing climate is global rising of temperatures and this rate of change shows acceleration both over seas and lands (IPCC, 2013). The change undergo also other atmospheric conditions such as absorbed incoming radiation, wind patterns, rainfalls etc. With all this, climate change is one of the greatest threats to ecosystems all around the globe (Haddout, et al., 2018).

Lakes are one of these ecosystems. Lakes also constitute significant players in forming the local climate. Similarly to the way oceans moderate climate on the global scale lakes can store and transport heat on a regional scale. Fresh water lakes provide valuable habitats for many organisms (Wetzel, 2001).

Warming climate affects lake ecosystems in many ways. Among other effects, changes in precipitation result in changes in water income and decreasing wind speeds cause decreasing evaporation and affect heat exchange. This warms up the surface waters. Such thermal changes cause changes in water density. The less dense water forms close to the surface and therefore increases stratification. As a result, lakes have reduced vertical circulation what decreases nutrient renewal and oxygen contribution in deep waters (Verburga & Hecky, 2009). This has severe consequences for the other parts of ecosystem such us fish. Let us say that overall biological, chemical and physical properties of lakes are sensitive to changing climate (Haddout, et al., 2018).

Based on satellite imagery of 167 lakes worldwide, the surface temperature of inland waters warms with a linear trend of 0.045 °C per year but in some cases reaching as high as 0.13 °C per year (Schneider & Hook, 2010). African lakes are no exception and the water warming was confirmed, among others, in Lake Victoria (Marshall, et al., 2013), Lake Malawi (Vollmer, et al., 2005), Lake Tanganyika (O'Reilly, et al., 2003; Verburg & Hecky, 2009) and Lake Kariba (Mahere, et al.; 2014; Marshall, 2017). In cases of Lake Tanganyika and Malawi increased temperatures caused enhanced stratification, however it had an opposite effect on Lake Victoria because its deep waters temperature increased more rapidly compare to surface water (Marshall, et al., 2013). This is a good example of variety of lake ecosystems. Lake stratification behavior depends not only on air temperature but it varies strongly with lake's geological settings, temperature gradient, morphometric characteristics such as depth and surface area and other external factors (e.g. increasing wind stress has a potential of counteracting thermal stratification) (Butcher, et al., 2015). Therefore, it is important to study specific lakes to understand the processes they undergo in the light of climate warming and the effects they have on local ecosystem.

1.2 Dams

Studying lake thermal behavior is especially necessary for big artificial reservoirs created by dams. A construction of a dam from the very beginning affects the local ecosystem. River flow is highly altered, land area is flooded, upstream water dynamics transform from river to lake and of course water quality and nutrient dynamics change (Kunz, et al., 2011). All physical changes that a dam causes have their biological consequences such as changing the species quantity and habitat (Lin, 2011).

Understanding processes affecting artificial lakes is crucial for water resource management. In reservoirs, vertical distribution of heat, dissolved substances, and nutrients is controlled mainly by wind-induced currents and the structure of thermocline (Elci, 2008). During warm months, solar radiation heats up the lake's surface. Warmer waters of upper layer are unable to penetrate into the deeper cold and dense waters. This results in incomplete mixing (stratification) and changes the chemistry of the deeper waters (Elci, 2008). In dams where water is taken from specific parts of the water column this could mean anoxic and colder water released downstream. Except for changing water parameters, the reservoir will also hinder the sediment particles depleting downstream waters from all nutrients that stayed in the lake. The heat trapped in the lake during summer, will mix with the deep waters in winter entering the outflow and resulting in overall colder waters in summer and warmer in winters (Baxter, 2003). These changes in nutrients, chemistry and temperature of the water downstream can result in sever biological consequences (Baxter, 2003).

The strength of lake stratification can increase because of climate change, mainly by increased temperatures and decreasing wind speeds. However, this is not the only way changing climate affects reservoirs. Scientist expect that the energy generation capacity will decrease due to reduced inflow (caused by decreasing runoff and prolonged droughts), increased water evaporation, altered timing of seasons (that could cause delays in dam operation) and increased sediment load to reservoirs (Lautze, et al., 2017).

These reservoirs are very important to the local communities especially in the developing Countries of Africa. They not only provide water source but also are the main source of renewable energy. There are already nine existing hydropower plants in Zambezi River Basin but they exploit no more than one-third of the basin's hydropower potential (Lautze, et al., 2017). As already mentioned, changing climate could cause a reduction in hydropower production due to the decrease in river flows that would follow increase in surface temperatures and evapotranspiration (IPPC, 2001).

In developing countries, there are many people whom lives depend on local ecosystems so it is important to find a balance between energy production and ecosystem exploitation. To make it possible we need to understand processes that the reservoirs undergo and cause as well as their responses to changing climate.

Finding this balance in the area of Zambezi River Basin is especially important because more than 13 dams are planned for this basin (Lautze, et al., 2017). Kariba Dam construction on Zambezi River began in 1955 with purpose of production of hydroelectric power. In 1958, the dam was closed and the accumulated waters formed Lake Kariba. The dam is 128 m high and floodgates are located in the upper part of the dam (Bollaert, et al., 2012). The water intakes are at around 462.5 and 447.5 m above sea level what usually corresponds to at least 20 m depth (Balon & Coche, 1974). Lake Kariba has changed continuously from its creation and climate change is yet another factor that can cause unpredictable consequences in this artificial ecosystem (Mahere, et al., 2014).

We hope that by improving the understanding of thermal processes in Lake Kariba we will contribute to strategies development that will help finding the balance between energy efficiency and ecosystem sustainability.

1.3 Water temperature

When studying lake processes, water temperature is one of the key parameters controlling several lake processes. However, there are a couple of issues with researching Lake Kariba. First challenge is the size of the lake. As one of the largest reservoirs, it is difficult to get enough measurements that would cover the entire lake. It is therefore easy to over or underestimate processes observed in measurement points. In addition, size makes it difficult to cover the area within a decent time span. Obtaining in situ measurements over Kariba would require significant workforce and long time.

This is especially challenging in developing countries where there is not much resources for research programs. Another issue of this part of the world is that there are not many measurements done continually in the past, making it difficult to address lake's changes thorough time and study the impact of the climate change.

Nowadays, remote sensing data is the most promising answer to these challenges. Many satellites orbit the Earth (at all times and for several decades) providing high-resolution images of water surface. A group providing the data, GHRSST, aimed at measuring surface temperature of the oceans and seas. Recently its products have been uses to study larger lakes and although not error-free it is proving a useful tool in measuring lake water surface temperature as well (e.g. Alcântara, et al., 2010). The advantages of using remote sensing is both large special and temporal coverage and their availability. Even though remote sensing has still significant error uncertainty, it allows us to expand the data series for which otherwise, we could not hope.

Satellite retrieved water temperature images provide only the data for a very shallow layer at the surface, which we will call lake surface temperature (LST). It is important to study LST because the intersection between atmosphere and water is crucial for understanding thermal processes in the lake. It is there where the difference between air and water temperature causes heat exchange and therefore controlling the energy fluxes (Alcântara, et al., 2010). As air temperatures rise, surface water will increase the heat uptake until they reach an equilibrium (Verburga & Hecky, 2009). LST influences the stability of the lake water columns, which is essential for understanding lake dynamics. Except for crucial role of air temperature in this process, it is also influenced by solar radiation, humidity, wind and lake's surface area and depth (O'Reilly, et al., 2015). Lake surface temperature plays a crucial role in stratification dynamics and therefore it is relevant for studying it, especially when recent studies indicate that this stratification becomes more stable and the thermoclines get deeper and steeper (Kraemer, et al., 2015). On the other hand, water temperature also affects the local air conditions: moisture, heat, circulation.

Overall, the influence of climate change varies from lake to lake depending on its processes and magnitude of changes in climate variables (Ogutu-Ohwayo, et al., 2016). It is therefore important to study lakes from individual perspective.

1.4 Research goals and structure

Our aim is to analyze spatial and temporal variation in Kariba's LST and to test the methodology and application of remote sensing on tropical reservoirs. We attempt to describe the LST dependence on lake's morphology and external factors and hope to outline the possibility of using remote sensing to identify lake's mixing period from LST. We first look at spatial variability of temperature through seasons and then move to analyzing the LST behavior in time. Additionally we use the collected data to study the thermal behavior differences between lake's sub-basins and the influence of the depth on corresponding LST. Then we take a look at the relationship between LST and external forcing to see how the lake's water temperature behavior changes when subjected to high or low air temperature and wind speed.

2. Methods

2.1 Study site

2.1.1 Zambezi River Basin and Lake Kariba

The focus of our research was on Lake Kariba, created in 1958 after construction of a hydropower dam on the Zambezi River. The Zambezi River Basin is the 4th largest basin of Africa. Shared by eight Countries, it covers the area of approximately 1.37 mln km^2 and is inhabited by around 40 mln people (SARDC, et al., 2012). The Zambezi River originates in the north west of Zambia, then flows through Angola, goes back to Zambia and follows its border with Namibia and Zimbabwe to reach Mozambique and its end in the Indian Ocean. Lake Kariba is located along the border between Zambia and Zimbabwe and it is the biggest artificial lake by volume in the world (Chao, et al., 2008). The lake is 277 km long (Coche & Balon, 1974) and around 20 km wide on average. The lake has a very dendritic shape and an irregular shoreline and the depth increases from the Zambezi inflow towards the dam reaching around 90 m (Coche & Balon, 1974) (Fig. 1).

Average inflow is around 60 km^3 per year (Kunz, et al., 2011) setting a residence time of 3.3 years. There are several rivers emptying into Kariba (including Sanyati River) but compared to the Zambezi River, we consider their impact on the lake as negligible.

Since its formation in 1959 Kariba is a monomictic lake (Begg, 1970), meaning that its waters mix once a year. For most of the year, during warm months, the lake is stratified and only during cold months, when the water surface temperature is equal to the one of the deep water, the lake undergoes mixing. The mixing period of Kariba falls on July – August (Begg, 1970).

Kariba Lake is divided into four sub-basins along the island chains and narrowings (Coche & Balon, 1974). Basin I is the smallest and has a surface area that is equal to 91 km^2. Its depth reaches about 37 m and forms a kind of transition from the Zambezi River to Lake Kariba. Basin II, which reaches the depth of 52 m, is still very strongly influenced by the river and its surface area is 677 km^2. Basins III and IV are significantly larger and their surface areas correspond to, respectively, 2033 and 2563 km^2. Their maximum depth is about 66 m for Basin III and 93 for Basin IV. All depths values come from Balon & Coche (1974).

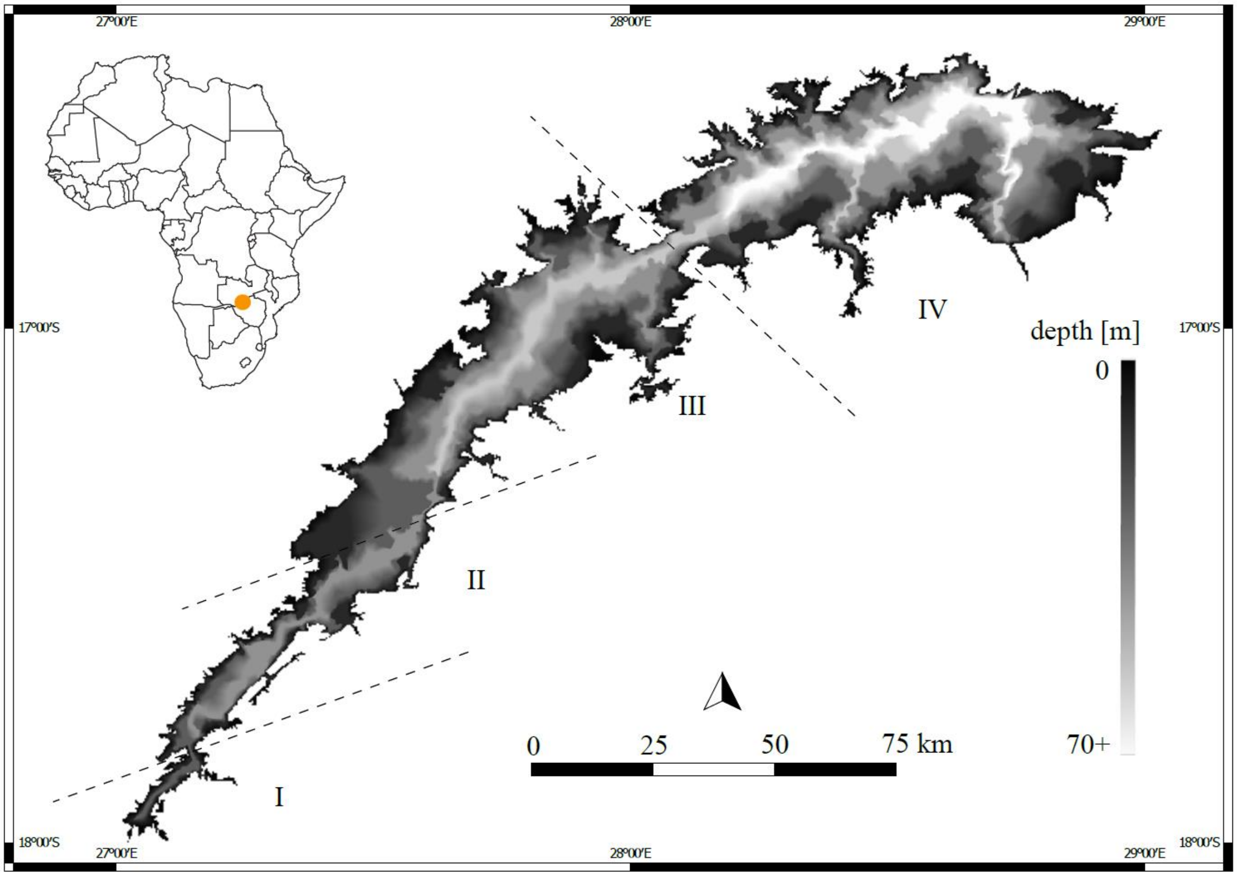

Figure 1: Lake Kariba's location and bathymetry map. The dashed lines show the division of Kariba into four sub-basins and numbers I to IV correspond to sub-basin numerology adapted from Balon & Coche (1974). First two sub-basins are shallow and have small surface area compared to sub-basins III and IV.

2.1.2 Lake Kariba bathymetry map

We studied the relationship between Kariba's water surface temperature and the lake's bathymetry. Because there was no available digital bathymetry map of Lake Kariba, we digitalized the map from Balon & Coche (1974). It contained six isobaths with values of 0, 10, 25, 40, 55, and 70 m of depth and imported them into QGIS. Since the lines were not continuous we converted them into points and then interpolated the area in between using 'Triangular Interpolation'. Our last step was to georeference the map to the right geographic projection using coordinates from Google Maps of 26 distinctive morphological features. The outcome (Fig. 1) is Kariba's digital bathymetry map where every pixel has assigned its rough depth ranging from 0 to 70 + m.

For the sake of our analysis we lowered the resolution to have the same cell size that we have for remote sensing data. Undoubtedly, our map is not free from errors, for instance, we did not mark the islands, as the resolution needed for remote sensing temperature maps was low enough to neglect them.

2.2 Remote Sensing Data

Unlike other methods, remote sensing covers the entire lake and provides information on daily time scale. Nonetheless, obtaining Sea Surface Temperature (SST) data, or in our case, Lake Surface Temperature, is not trouble-free. Observation made with infrared (IR) sensors have high spatial resolutions (1-2 km), but they are unable to penetrate through cloud cover. Microwave sensors, on the other hand, can penetrate through almost all weather conditions, but their resolution is smaller and can be disturbed by nearby land (Ray & Susanto, 2016). That is why for our analysis of lake surface temperature we used the high-resolution images from the NASA Group for High Resolution Sea Surface Temperature (GHRSST) Level 4 MUR. The objective behind this project is to produce best possible estimate of the SST by merging data from various different satellites and sensors (IR and Microwave) and in situ measurements (Donlon, et al., 2007). Therefore the error is significantly lower than when using only one type of sensors. This group also provides a corresponding error value delivered from many components including sensor errors, atmospheric conditions, etc., what makes it easier to judge the validity of the analysis.

The Multiscale Ultrahigh Resolution (MUR) analysis we used is based on nighttime skin SST (a layer of conductive diffusion-dominated water at a depth of ~10-20 µm) and subskin SST (the base of the conductive layer) observations. Data was obtained from sensors from NOAA, and Aqua and Terra satellites including the NASA Advanced Microwave Scanning Radiometer-EOS (AMSRE), the Moderate Resolution Imaging Spectroradiometer (MODIS), microwave WindSat radiometer, Advanced Very High Resolution Radiometer (AVHRR), as well as in situ observations from NOAA iQuam research. The satellite data is freely available through the data portal on the NASA website (https://podaac.jpl.nasa.gov/dataset/MUR-JPL-L4-GLOB-v4.1).

For this project, we used data for Lake Kariba from 2003 to 2015 with spatial resolution of 0.01x 0.01 latitudinal and longitudinal degrees (~1.25x1.25 km) and daily temporal resolution. Figure 2 shows the raw data obtained from the GHRSST for March the 7th 2003. In this way, we can observe the temperature pattern within the lake for every day. However, we have to point out that there are days when the measurement error is higher and the temperature pattern is disturbed.

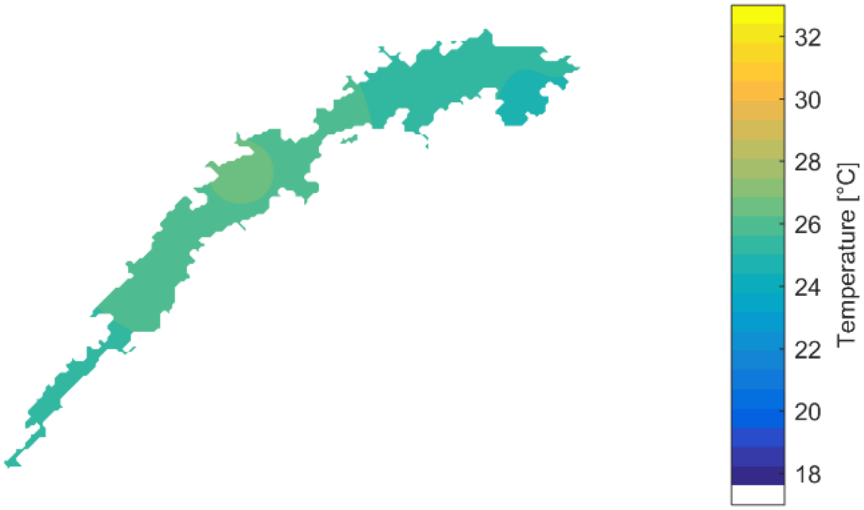

Figure 2: Raw data of lake surface temperature from Remote Sensing. The dataset contains one picture per day from 1.1.2003 to 31.12.2015 with temperature information for each cell. This particular map is from 7.3.2003 when the LST of Kariba is around 25 °C.

2.3 Local data

2.3.1 ERA-Interim reanalysis

For further analysis of LST data and its results, we studied LST dependence on external factors by comparing changes in its behavior with corresponding atmospheric conditions. As we wanted to have a full time series, we used the ERA-Interim dataset provided by ECMWF (European Centre for Medium-Range Weather Forecasts, https://www.ecmwf.int/). ERA-Interim is a global atmospheric reanalysis and it provides data from 1 January 1979 onward but for our analysis, we looked at data until 31 August 2016. Available atmospheric properties include air temperature at 2 m above the ground, solar radiation, wind speed, wind direction, precipitation and cloud cover. They are spatially distributed variables and have been averaged over the lake areas to obtain a unique time series. In our research we used air temperature and wind speed. Later on, we employed precipitation to validate the reanalysis with weather stations data.

2.3.2 Weather stations datasets

To check the reliability of ERA-Interim reanalysis we compared it with three weather stations observations: GHCN, SASSCAL WeatherNet and TuTiempo. We described them in the following paragraphs.

The Global Historical Climatology Network (GHCN) is a database that brings together weather and climate information from more than 20 sources that have been integrated and their quality has been reviewed and approved (https://rda.ucar.edu/datasets/ds564.0/). GHCN keeps records from over 100’000 stations over the world and provides daily weather variables. Every week dataset is reconstructed from these 20+ sources to ensure synchronization and high data quality. The data we considered for this project comes mainly from Livingstone in Zambia represented on Figure 3 with a red dot. This dataset includes daily precipitation and air temperature (average, maximum and minimum) from 1 January 1950 to 18 May 2017, however it is not continuous and many days have no observation recorded.

SASSCAL WeatherNet is a project run by the Southern African Science Service Centre for Climate Change and Adaptive Land Management group that deals with challenges of global changes (http://www.sasscalweathernet.org/). SASSCAL includes six countries: Angola, Botswana, Namibia, South Africa, Zambia and Germany. The weather station we took data from is located in Lusaka International Airport (represented in Figure 3 with a yellow dot) and it provided daily data from 8 October 2013 to 31 December 2017 on air temperature (average, maximum and minimum), soil temperature, precipitation, wind speed (average, maximum and minimum), wind direction, humidity, atmospheric pressure and solar irradiance.

TuTiempo is a Spanish project aimed at providing the public with knowledge, data and tools about meteorology (https://en.tutiempo.net/). This dataset contains a non-continuous record of atmospheric properties from 1 July 1962 to 30 April 2018. Some of those properties include air temperature (average, maximum and minimum), humidity, precipitation, visibility and wind speed.

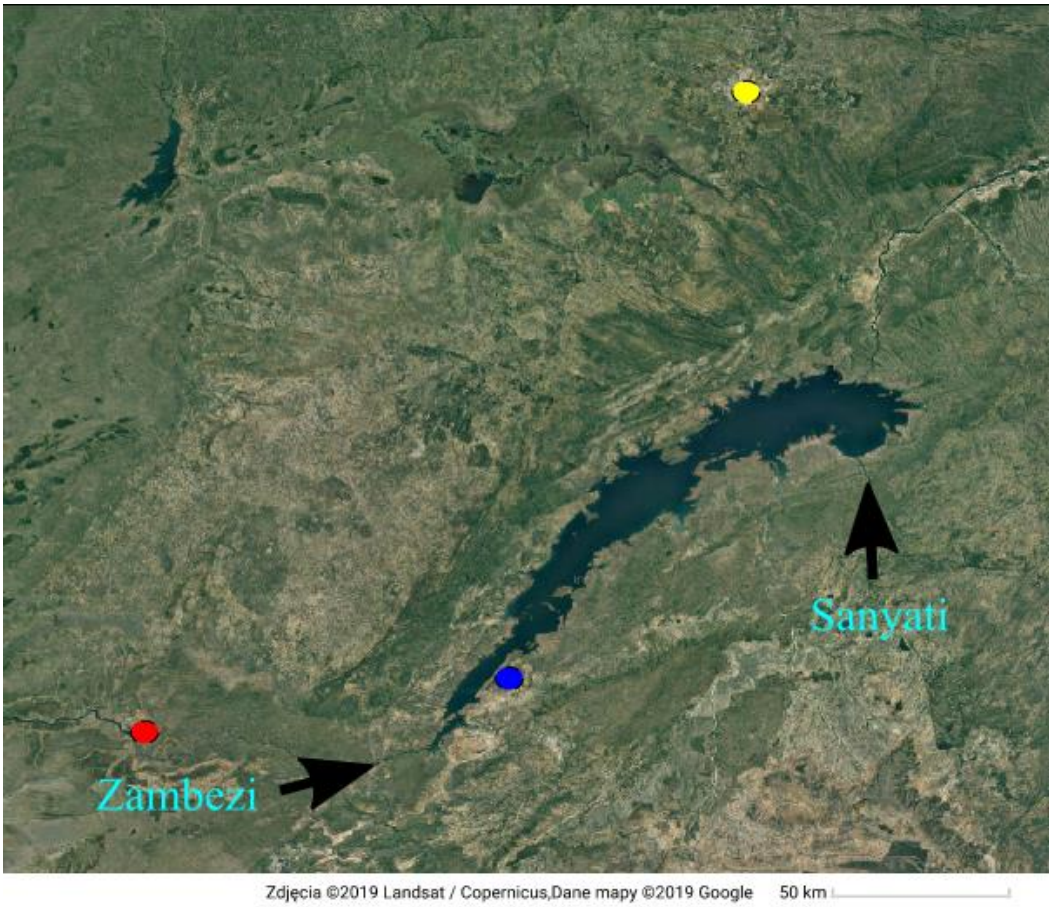

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Figure 3: Weather stations locations: GHCL in Livingstone (red), TuTiempo in Binga (blue), and SASSCAL WeatherNet in Lusaka Internation Airport (yellow). The arrows point to Lake Kariba's two main river inflows. (Source: Google Maps)

2.3.3 In situ measurements

To validate remote sensed data of surface water temperature we used a set of data measured in the northeastern part of Lake Kariba (basin IV). In situ measurements were taken in the deepest part of the lake and not far from the dam wall (unpublished database from EAWAG Research Institute, Switzerland).

3 Results

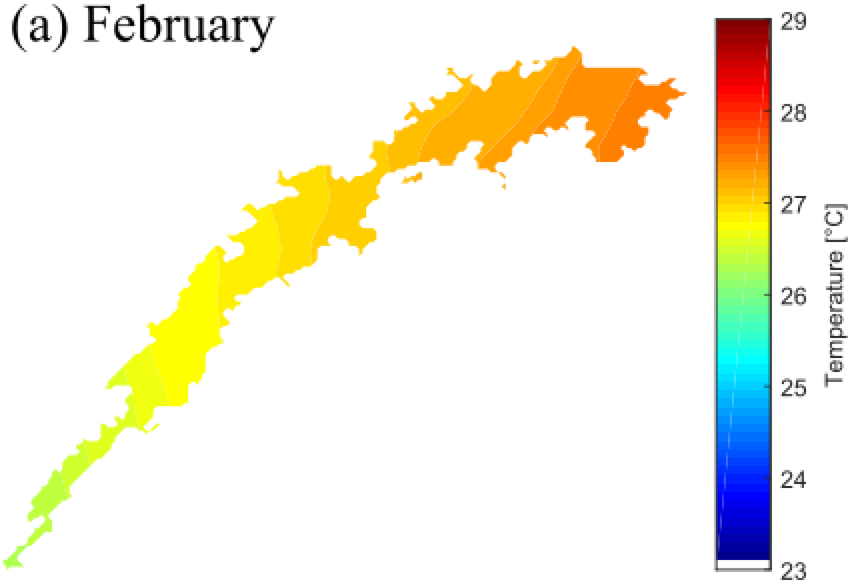
3.1 Remote Sensing

3.1.1 Lake Kariba spatial diversity of LST

To observe LST behavior in space we combined the data from all the days we had available for Februarys, which represent summertime and the data for Julys, which represent the period of winter. Depending on the season, Kariba's surface water temperature behaves differently. During summer, when lake is stratified, the water temperature is between 26 and 28 °C and increases gradually toward the northeast (Fig. 4a). There is no visible correlation to the lake's bathymetry nor any other special features. On the other hand, during winter, when the lake undergoes mixing, the average temperatures are higher toward the center of the lake leaving shallow cost areas slightly colder (Fig. 4b). This is especially prominent in the northeastern part of the lake, but observable also in the southwestern parts and it could be an indication of bathymetry influence. LSTs are about 22 °C and that corresponds to the temperature of the deep waters (Begg, 1970) making it possible for the lake to mix.

Despite the fact that the described patterns are most prominent in February and July, they can be found during the rest of the months, especially when looking at anomalies. To create the anomaly maps we took the average temperature of each month and subtracted it from the average temperature in that month for each pixel. Throughout the year most of the months have similar characteristics to February patterns, especially October till March, while May, June and July show the same temperature behavior as described before for July (Fig. 5). It seems that during the rainy season the LSTs increase gradually toward the northeast and in early months of the dry season show an influence of bathymetry. April, August and September, being transitional months between seasons, also form transitional patterns between temperatures behaviors.

(a) February



(b) July

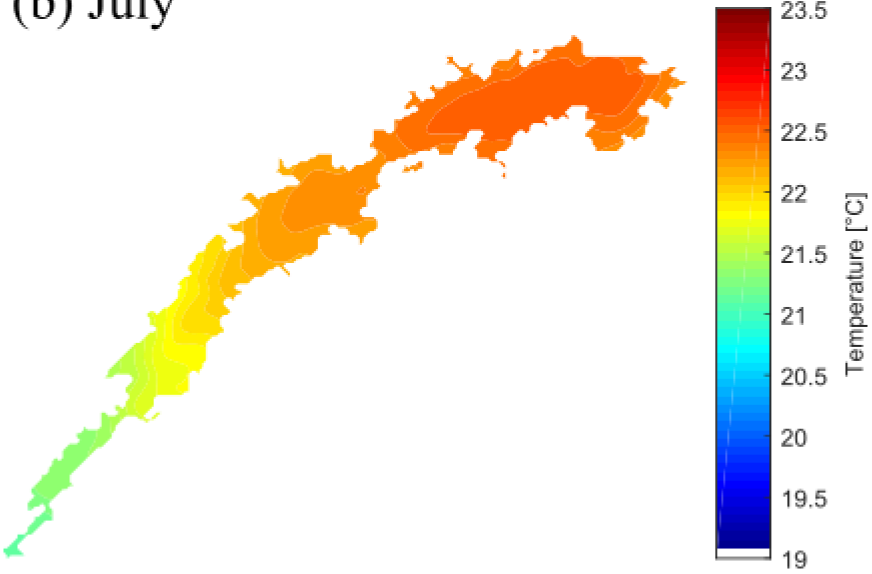


Figure 4: Lake Kariba's map of lake surface temperature for February (a), that represents summer conditions and for July (b) that represents winter. The temperatures are averaged over years from 2003 to 2015. There is a clear difference in temperature distribution between the seasons.

Overall the differences across the lake's surface temperatures are no greater than 1.6 °C and vary from + 0.4 to -1.2 °C. The average temperature falls approximately on the middle of the lake from where it increases toward east and decreases toward west. The closer to the Zambezi inflow, the colder the water gets. That is where the river influence is dominant.

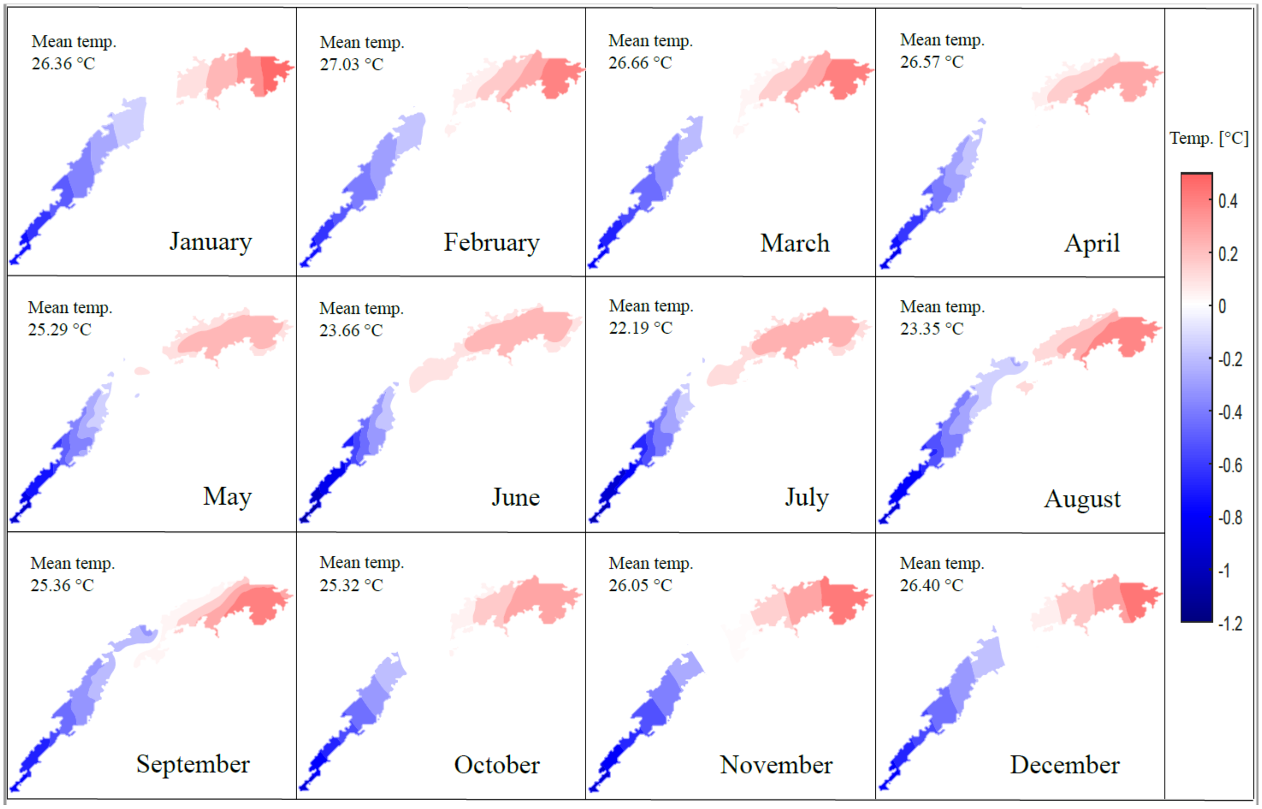


Figure 5: Anomaly maps of lake surface temperature for each month of the year averaged over years 2003 to 2015. Red and blue colors reflect respectively warmer and colder temperatures. The average temperature falls always somewhere in the Sub-Basin III.

The bathymetric shape of LST distribution corresponds to mixing periods. In May, the lake strongly shifts toward the full mixing; this mixing reaches its maximum stage in July. Afterwards re-stratification starts. Therefore, we could differentiate three types of special features: well-mixed (July-like), transitional, and stratified (December-like). Transition occurs in April, when lake starts to mix and in August and September, when waters begin to re-stratify.

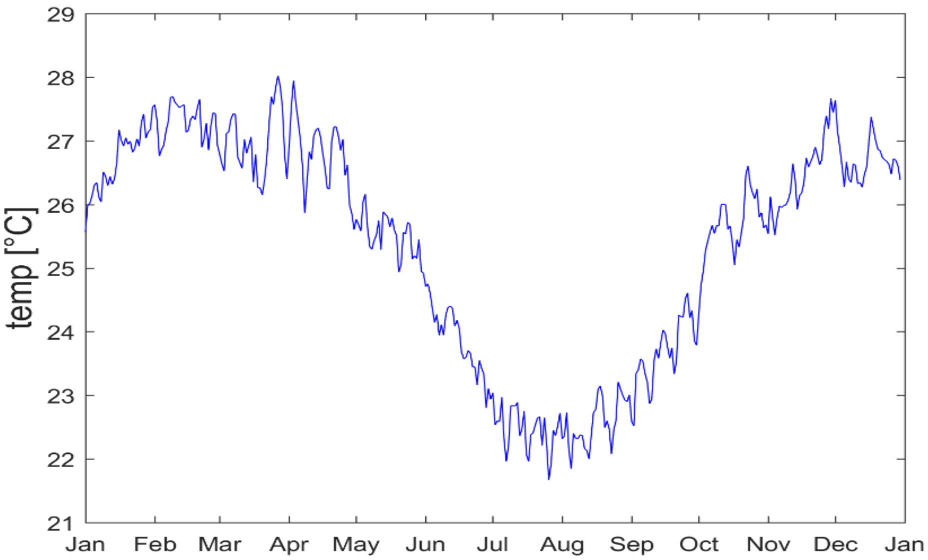


Figure 6: Overall mean year of Kariba's lake surface temperature. Data is smoothed with moving average of three months. Warmer months fall on December, January, February, and colder on July, August, September. Temperatures during summer oscillate between 26 and 27 °C, then drop and oscillate around 22 °C during winter.

Interestingly, well-mixed shape first forms in May when the temperatures are in the middle of transition from warm to cold, whereas stratification starts as soon as the LST start to increase (Fig. 6). Generally, LSTs are high during rainy seasons with their core in February, and drop in dry seasons with their core in July. Months with the coldest LSTs are July, August, and September. On average, during summer, the temperatures oscillate around 26.5 °C and during winter around 22 °C.

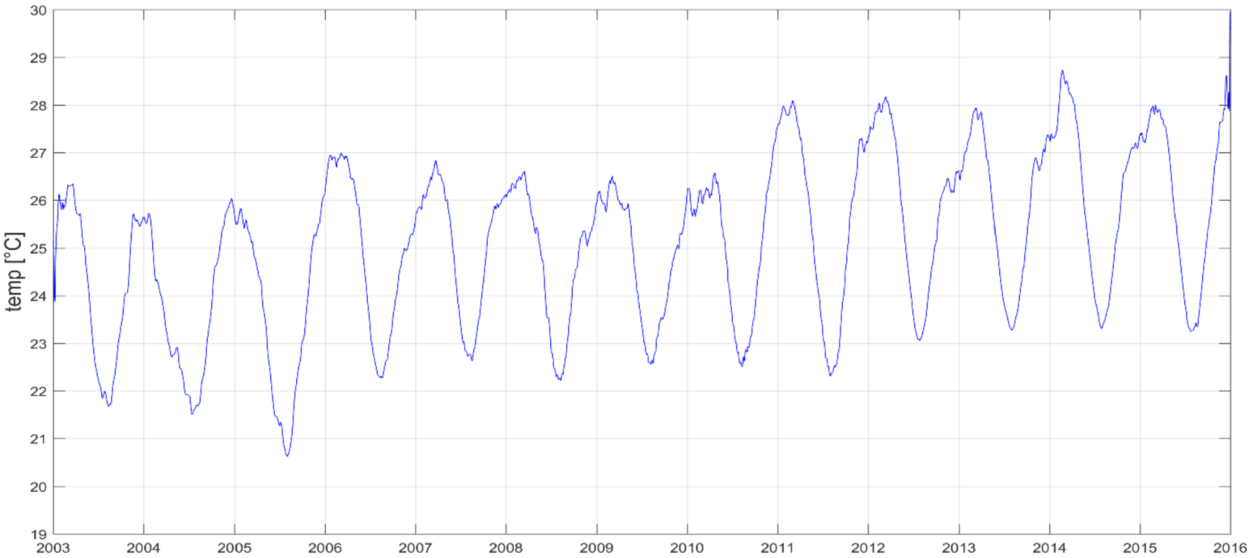


Figure 7: Overall lake surface temperature of Kariba throughout 13 years starting in 2003. Moving average of three moths is applied. The temperatures range from almost 29 °C to around 21 °C. There is a clear seasonal pattern and visible increase in LST over this time span.

3.1.1 Lake Kariba temporal diversity of LST

The remote sensing measurements of Lake Kariba between years 2003 and 2015 indicate an increase in the lake surface temperature of about 2 °C. Mostly LST stayed between 21 and 29 °C (Fig. 7). The average temperature increased first in 2006, were quite stable until 2010 and increased again in 2011. Even though in the early years of research the minimum temperature stayed below 19 °C, after 2011 the temperatures dropped below 21 °C only in 2015 (Fig. 8). Maximum temperatures exceeded 30 °C for the first time in 2011 and kept doing so in all following years. On average, the warmest year was 2014; however, the highest maximum mean temperature occurred in 2012 and reached about 31 °C. The highest LST recorded by satellites was 32.4 °C in 2013. The year with the lowest average temperatures was 2004, but again, the lowest mean temperature of around 18 °C occurred in 2011 and the coldest day recorded was in 2010 with 15.1 °C. This last value is most likely an effect of a disturbed satellite measurement. 2011 was also a year in which temperatures varied the most and in 2014, they varied the least.

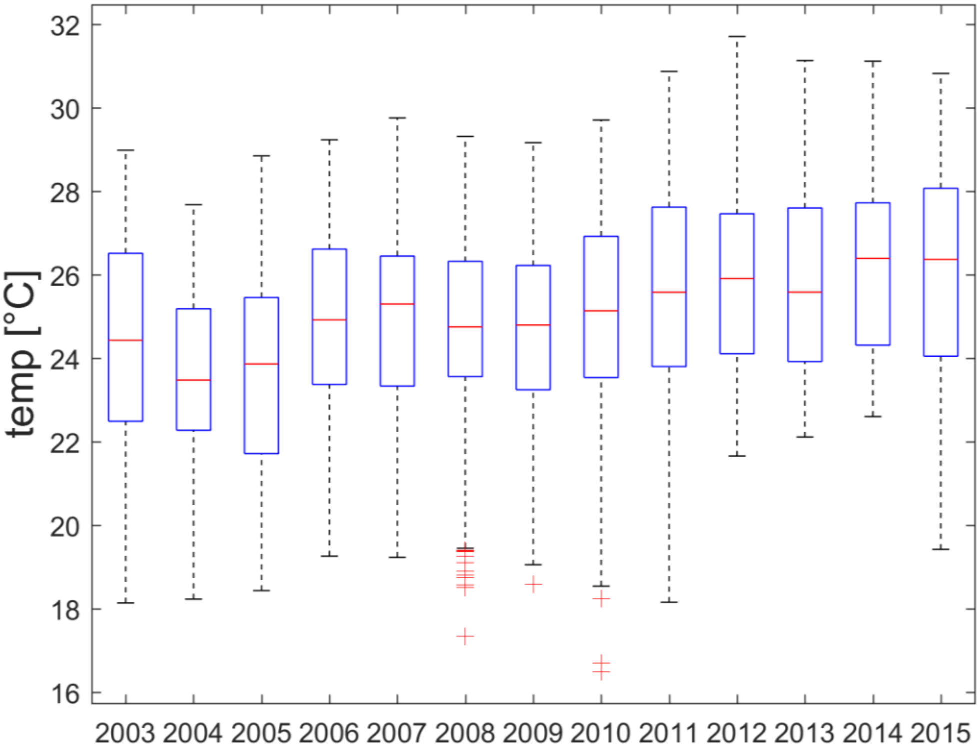


Figure 8: Box plot of Kariba's lake surface temperature distribution from 2003 to 2015. Every year is represented by one box. The red line indicates the median, the bottom and top edges of the blue box signify 25 % and 75 % of data, respectively. The whiskers reach the most extreme data points and the symbols ' + ' are used to indicate outliers.

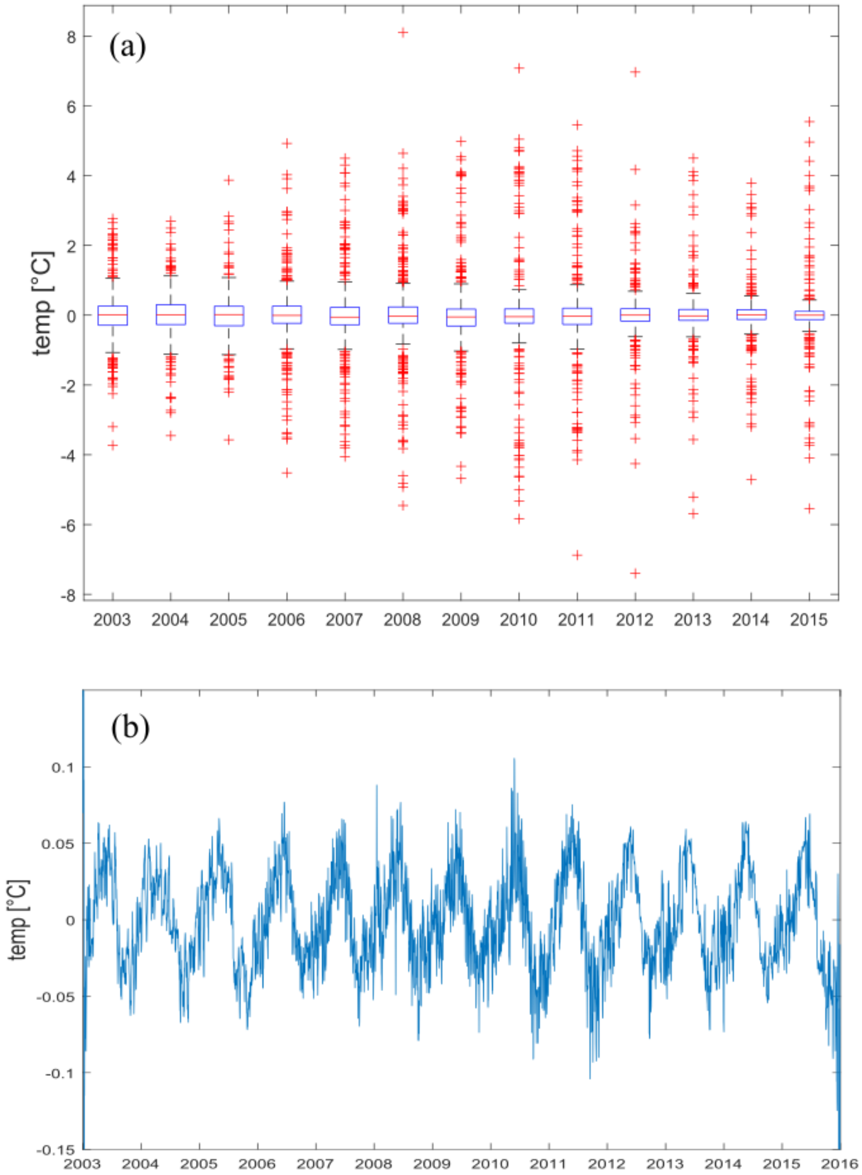


Figure 9: Box plot of temperature gradient marking the difference between each two following days (a). The red line indicates the median, the bottom and top edges of the blue box signify 25 % and 75 % of data, respectively. The whiskers reach the extreme data points and the symbols '+' indicate outliers. The majority of day-to-day temperature changes is within 1 to 2 °C, but there are many outliers in the dataset. Plot (b) shows the changes in temperature gradient throughout the change of seasons.

Figure 9 shows the temperature gradient between each two following days. Daily temperature changes usually do not exceed 1 °C; however, the dataset is full of outliers, which can reach up to 8 degrees of a difference (Fig. 9a). We believe this happens due to measurement errors. The temperature gradient was larger during early years of the research and decreased after 2011, being the smallest in 2015. Interestingly, LST changes are sharper during the core months of both dry and rainy seasons and lower in the transitional phases (Fig. 9b).

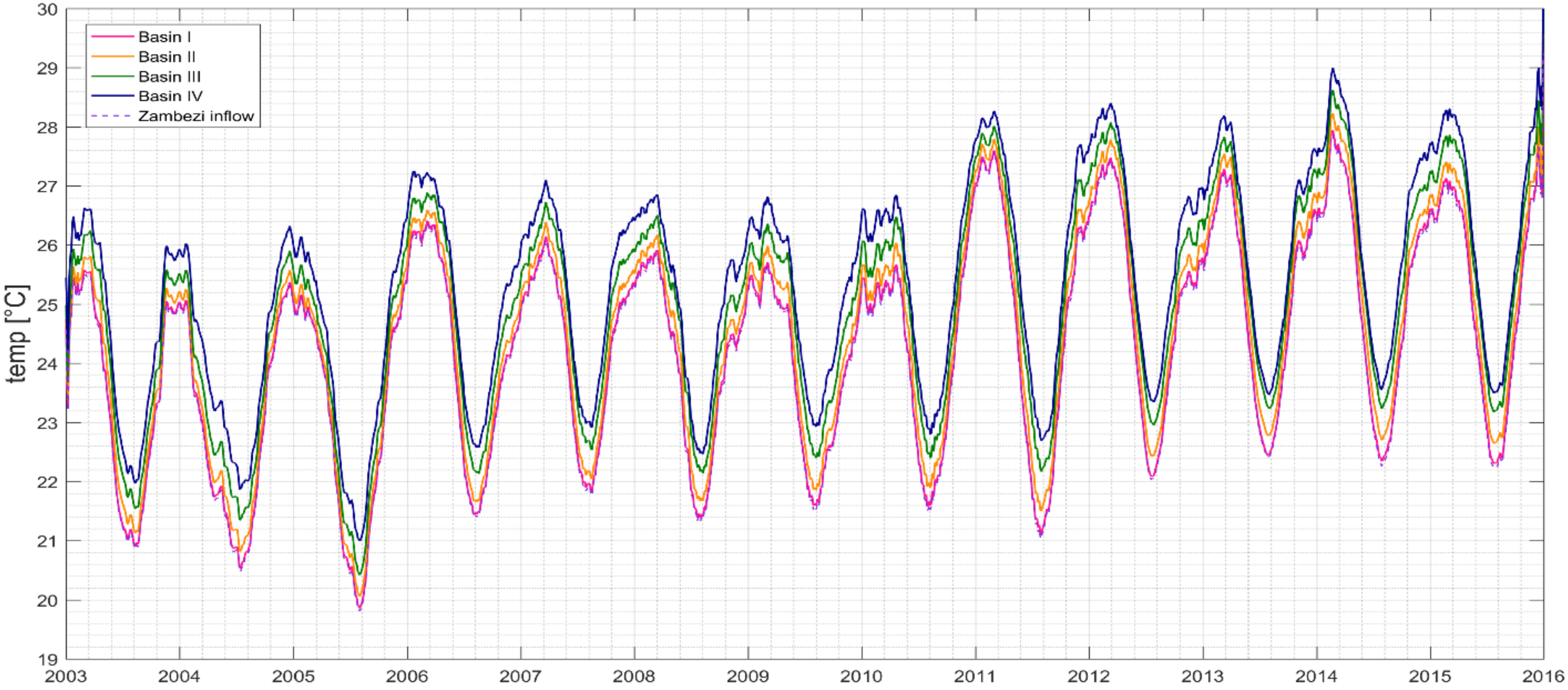


Figure 10: Mean temperature of Kariba's sub-basins (Basin I – yellow, Basin II – pink, Basin III – blue, Basin IV – green) averaged by moving average of three months. Temperatures of Basin I are the lowest and Basin IV the highest and the difference between the two is around 1 °C. Basin I is just slightly warmer then Zambezi inflow which is represented by the first pixel of the lake. The pattern of temperature change stays the same for all sub-basins.

3.2 Morphology perspective

3.2.1 Kariba's sub-basins

Lake Kariba is not a homogeneous lake and therefore is often divided into four sub-basins (Coche & Balon, 1974) (Fig. 1). We have already seen that Basin I and II are always colder, and Basin III and IV are the warmer ones. This pattern is visible throughout all analyzed years (Fig. 10). Zambezi river inflow always has the lowest temperature and is followed closely by Basin I. Basin II is about 0.25°C warmer, therefore it still lies below average temperature of the lake. Basin III is around 0.5 °C warmer than Basin II and Basin IV is again about 0.25 °C warmer. Therefore, the difference between Basin I and IV is a bit over 1 °C.

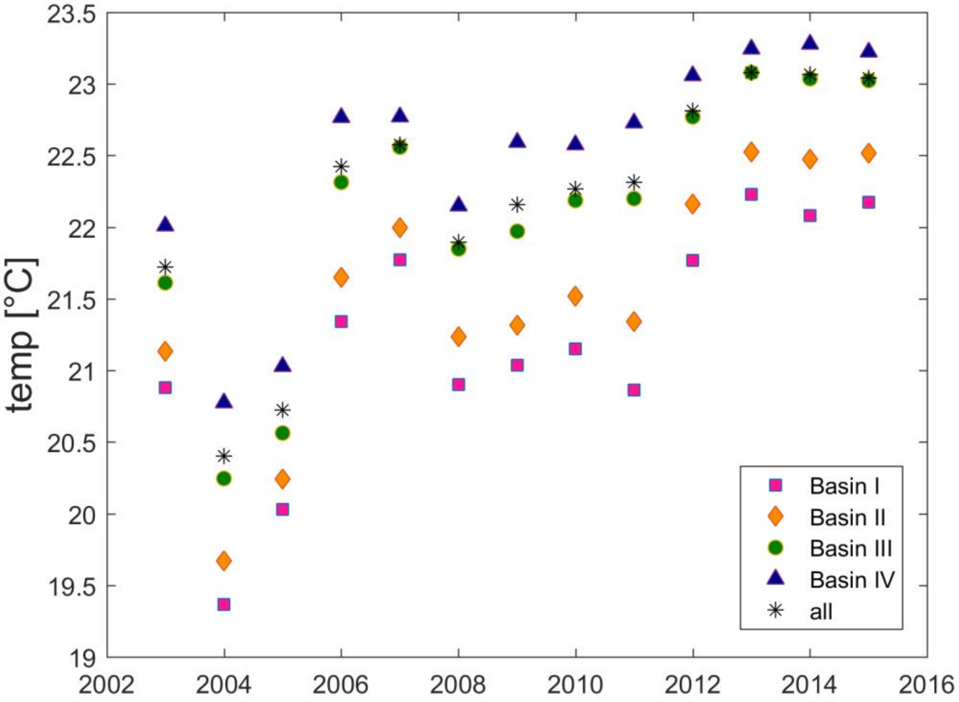


Figure 11: Yearly mean temperatures of Kariba's surface temperature and its basins. Black stars represent mean temperature of the entire lake, which falls between two largest basins: Basin III in green and Basin IV in blue.

The same pattern is maintained for the average temperature per year (Fig. 11). The average temperature of the lake is a bit above the average temperature of Basin III, which was to be expected as Basin III and IV have significantly larger surface areas. There is a clear increase in average temperatures of all basins. The differences between them usually stay proportional but are slightly larger in 2004, 2009, 2010 and 2011, and smaller in 2005 and 2013. This pattern is not sustained for maximum temperatures for which proportions change with every year (Fig. 2a).

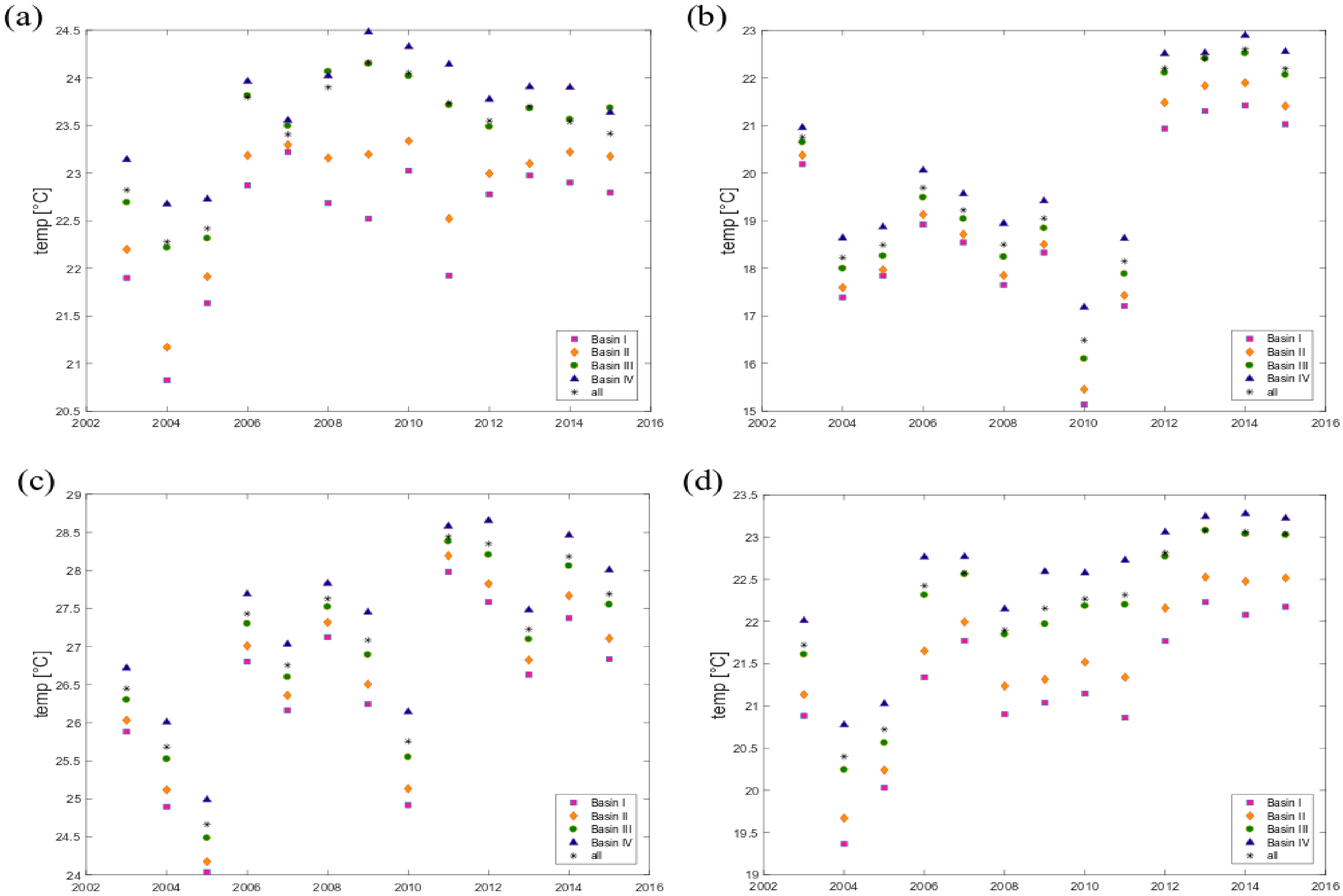


Figure 12: Yearly temperatures of lake surface temperature of Lake Kariba and its sub-basins: maximum temperatures (a), minimum temperatures (b), mean temperatures in Februarys (c), and mean temperatures in Julys (d). In 2010, the minimum temperatures drop below 16 °C but in reality they should not be below 18 °C. This could be a result of measurement error.

LSTs are spread the most in 2012 and the least in 2008. However, the latter is most likely an effect of error in measurements, because Basin II cannot be warmer than Basin IV. The same applies to year 2009. Maximum temperatures kept the increasing tendency, but their maximum happens in 2012 and decreases after. This tendency does not apply to the minimum temperatures that increase and decrease in a random manner (Fig. 12b). Here again 2008 shows an unrealistic situation when Basin IV is the coldest. Also 2010's minimum temperatures are an effect of outliers as the lake's surface temperature certainly does not drop below 16 °C (Coche & Balon, 1974). For both maximum and minimum temperatures the differences between basins are not uniform and do not show any tendencies.

Knowing that yearly mean temperatures increase with time, we analyzed how they change in correlation to seasons. Mean LST in summers do not show any tendencies, their values rise and drop randomly throughout the research years (Fig. 12c). On the opposite, during winters mean temperatures have a similar increasing pattern to the overall mean temperatures (Fig. 12d).This could mean that winter temperatures lead the year temperatures or at least that winter has a higher impact on the rest of the year, than summer.

An interesting difference is that in most years there is a time lap between reaching the lowest temperature in Basin I and IV (Fig. 13). However, it is not long and usually lasts around one day. In our research time situation that Basin I reached the lowest temperature before Basin IV happened in 2004, 2006, and 2008 to 2013. In case of 2004, 2009 and 2011 this time lap was about a day, or two long, and in the other years it took approximately a week longer for Basin IV to reach its lowest temperature. Interestingly, for the last two years (2014 and 2015), we observed a reversed situation and it was Basin IV that reached the lowest temperature first, but in both years this time lap was only a day long.

3.2.2 Kariba’s bathymetry

Kariba’s depth reaches around 90 m. Most of the lake, around 70 %, has the depth between 10 and 50 m (Fig. 14). Around 23 % is 10 m deep or shallower and only about 5 % is deeper than 70 m.

It is apparent that LSTs, as well as the lake’s depth, increase with the distance from the Zambezi inflow. We compared Kariba’s LST with the lake’s corresponding depth to see to what extend this increase is driven by bathymetry and it seems that, even though the main driving factor is the distance from the inflow, Kariba’s bathymetry has an impact as well. During summer, the distance from the inflow dominates LSTs (Fig. 15a). The further it is, the warmer the water gets.

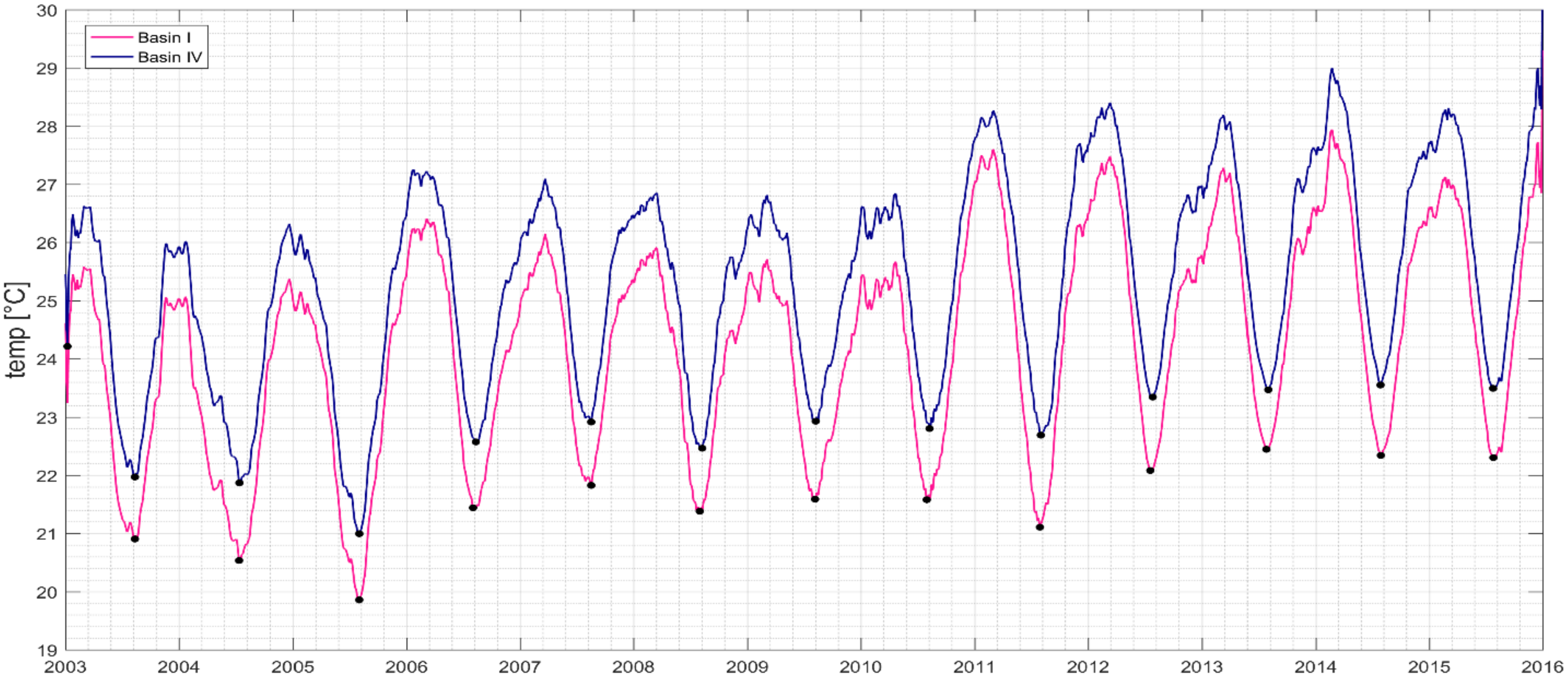


Figure 13: Comparison of lake surface temperature for Basin I (pink) and Basin IV (blue). Black dots indicate minimum peaks – the lowest temperature reached. In most years Basin I reaches its minimum temperature sooner than Basin IV.

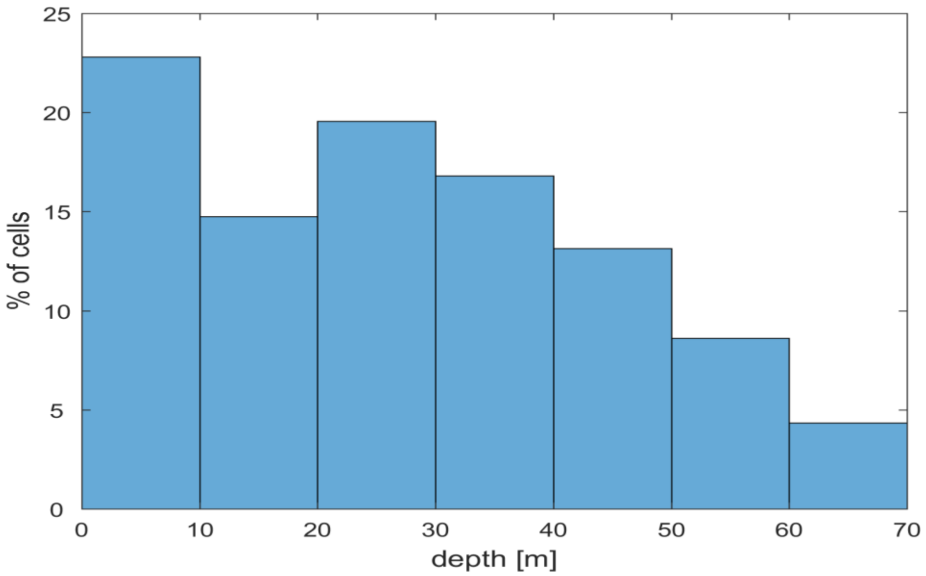


Figure 14: The percentage of numbers of cells within each range of depths in Lake Kariba. The majority of lake is between 10 and 40 m deep.

However, the difference in average temperatures only slightly exceeds 1 °C. Bathymetry has only a very small visible effect during this season by slightly cooling the deeper parts of the lake but its cooling has a magnitude of only 0.05 degree. In winter, the distance from the inflow is still the main driver but the bathymetry has a bit more influence by warming up the deeper parts (Fig. 15b). This is especially prominent in between 185 and 270 km from the inflow.

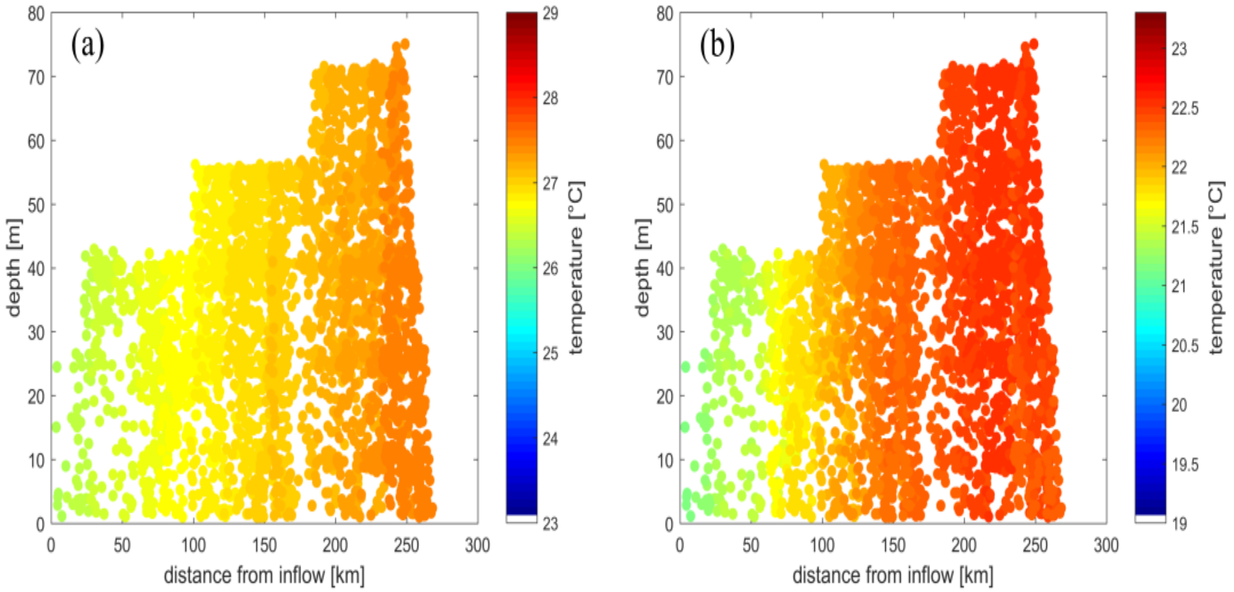


Figure 15: Lake Kariba's surface temperature dependence on distance from the inflow and depth of the specific water column during mean February (a) and mean July (b) over years 2003 to 2015. Influence of the distance is clear during both seasons.

The influence of depth varies with changing atmospheric conditions. When we consider the high air temperature (like in year 2015), in summer LST increased, as usual, with distance from the inflow, with a slight tendency for deeper regions to stay colder (Fig. 16.1). In winter of the same year, the highest LST is reached already around 150 km from the inflow and it starts decreasing again at around 250 km from the inflow (Fig. 16.3). It does not display any feature that could suggest dependence on the depth.

In the year with lowest air temperature (2004), both summer and winter share a similar pattern, where LSTs increase with distance from the inflow (Fig. 16.2 and 16.4). Not to make it an overstatement, there is a very small temperature difference between deep and shallow cells in both seasons. In winter, deeper regions have higher LSTs and in summer – lower.

On the other hand, in summer with highest wind speeds (2005) the temperature is generally uniform over all depths, slightly higher in the deepest part (Fig. 17.1). However, when winds are weaker (like in 2011) summer's LST over the wide parts of the lake are warmer in the shallower regions (Fig. 17.2). In winter with strong winds, LSTs increase smoothly with distance from the inflow (Fig.17.3). This is not the case for a year with the lowest wind speeds when Basin IV still has the highest temperatures, but they increase further with depth (Fig. 17.4).

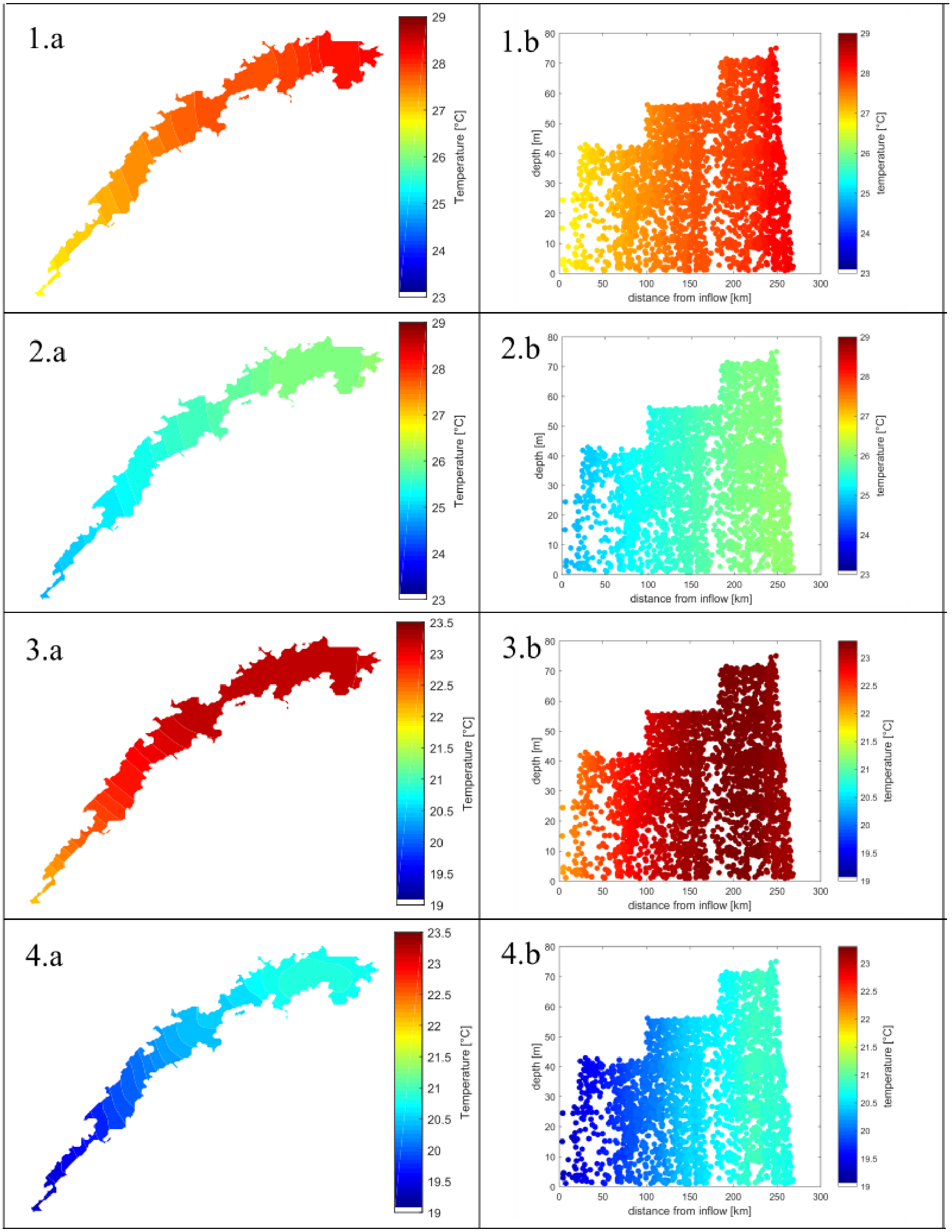


Figure 16: Lake Kariba's surface temperature map (a) and dependence on depth and distance from the inflow (b) over the years with highest (2015) and lowest (2004) air temperature. Panel 1. shows February 2015, Panel 2. February 2004, Panel 3. July 2015, and Panel 4. July 2004. The temperature scale is the same for panels (a) and (b) but the scale is different for February and July in order to catch the distinctive features of seasons.

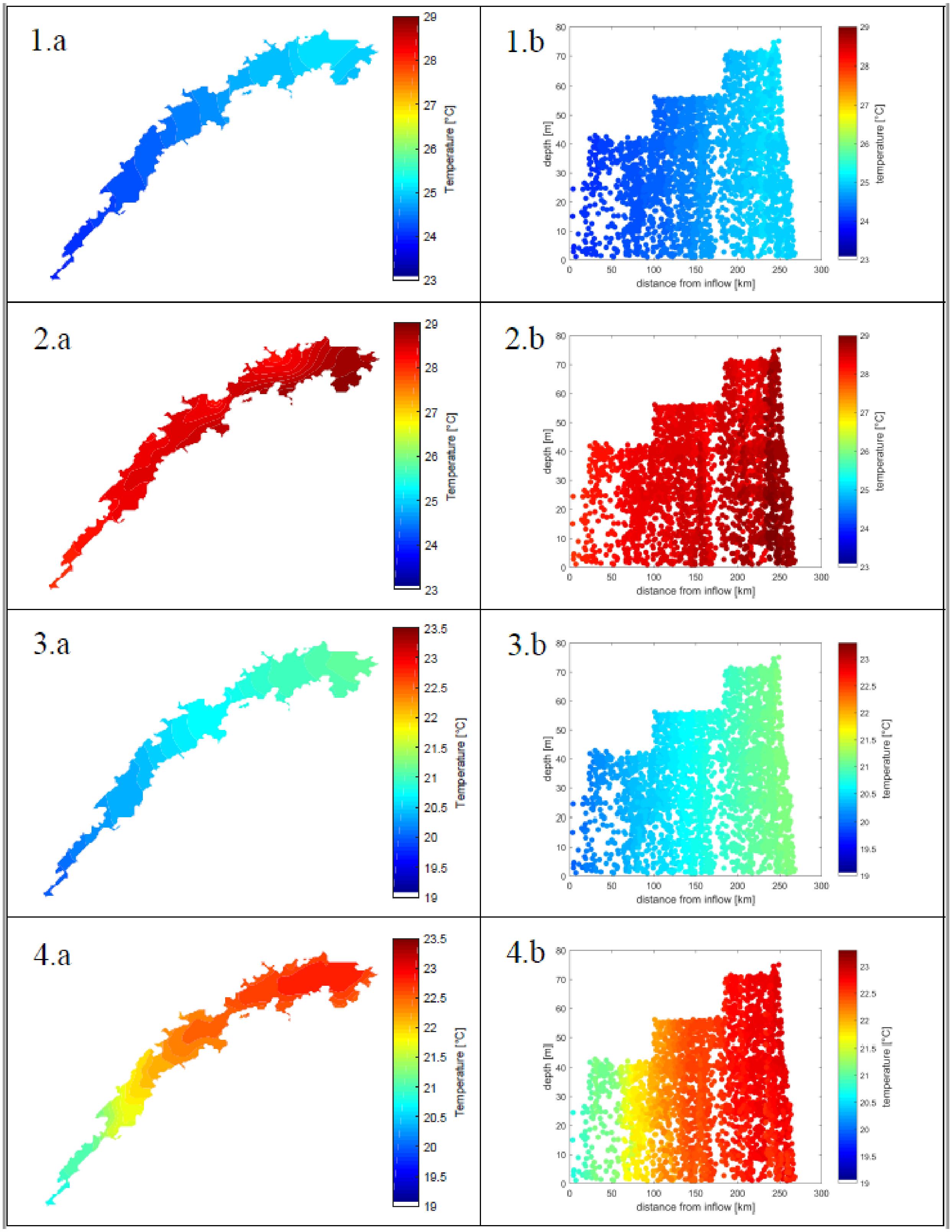


Figure 17: Lake Kariba's surface temperature map (a) and dependence on depth and distance from the inflow (b) over the years with highest (2005) and lowest (2011) wind speed. Panel 1. shows February 2005, Panel 2. February 2011, Panel 3. July 2005, and Panel 4. July 2011. The temperature scale is the same for panels (a) and (b) but the scale is different for February and July in order to catch the distinctive features of seasons.

3.3 External forces

3.3.1 Air temperature

Similar to Kariba's LSTs, air temperature above the lake is varying according to seasons. During summer months, temperatures stay above 25 and up to 33 °C and during winter, they drop down to around 17 and down to 13 °C (Fig. 18). From 2003 to 2015 air temperatures did not show any increasing nor decreasing tendencies. The year with highest overall temperatures was 2015 and with the lowest – 2004.

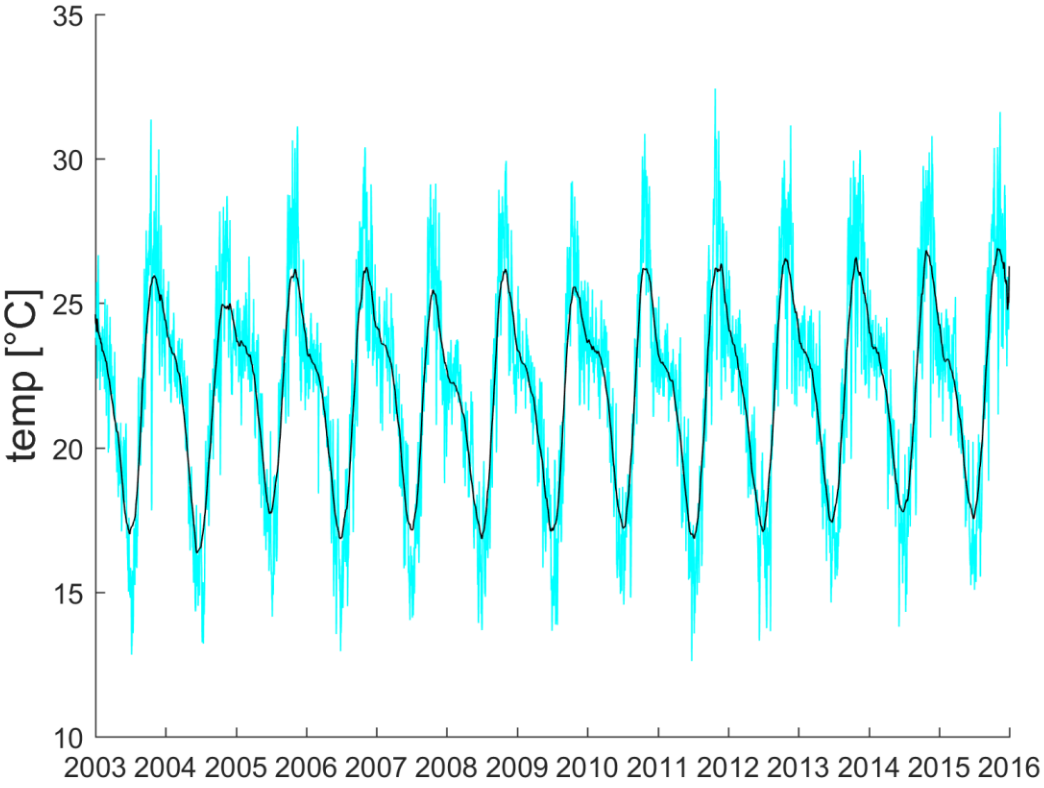


Figure 18: Mean daily air temperature over Lake Kariba through years 2003 to 2015. The black line shows the moving average of three months.

As it could be expected, the air temperatures vary more than water temperatures. Air temperatures reach their maximum well before the LSTs do (Fig. 19). Their pick happens sometime in late October or November, while LST reach their maximum only around February, March. The smallest difference was in summer 2004/2005, and the largest in 2013/2014. The same happens for the minimum temperatures but in winter this time lap is much shorter and lasts less than one month.

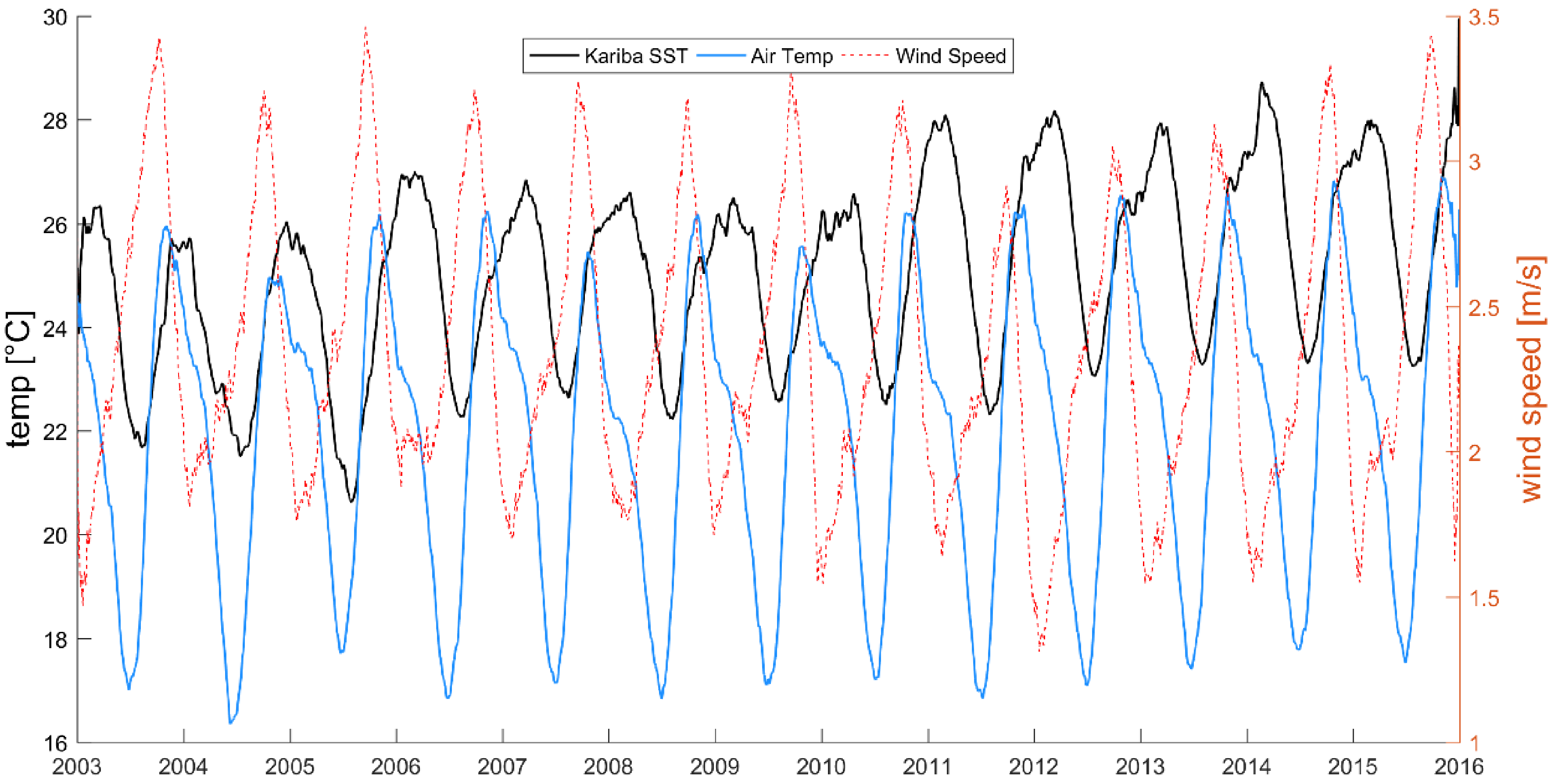


Figure 19: Comparison of surface temperature of Lake Kariba (black) with mean daily air temperature (blue) and mean daily wind speed (red) from 2003 to 2015. All data is the result of moving average of three months.

Looking at the time in a year when the LSTs start dropping and comparing it with the air temperature trend, we see that it is always around 22 °C (Fig. 20). Only in 2004 and 2005, it was higher than 23 °C and only in 2008 and 2010 were they significantly lower than 22 °C. The drop in LSTs occurs usually around March, but in 2004 it happened much sooner – already in the beginning of February. In 2010, LSTs dropped later than usually – toward the end of April.

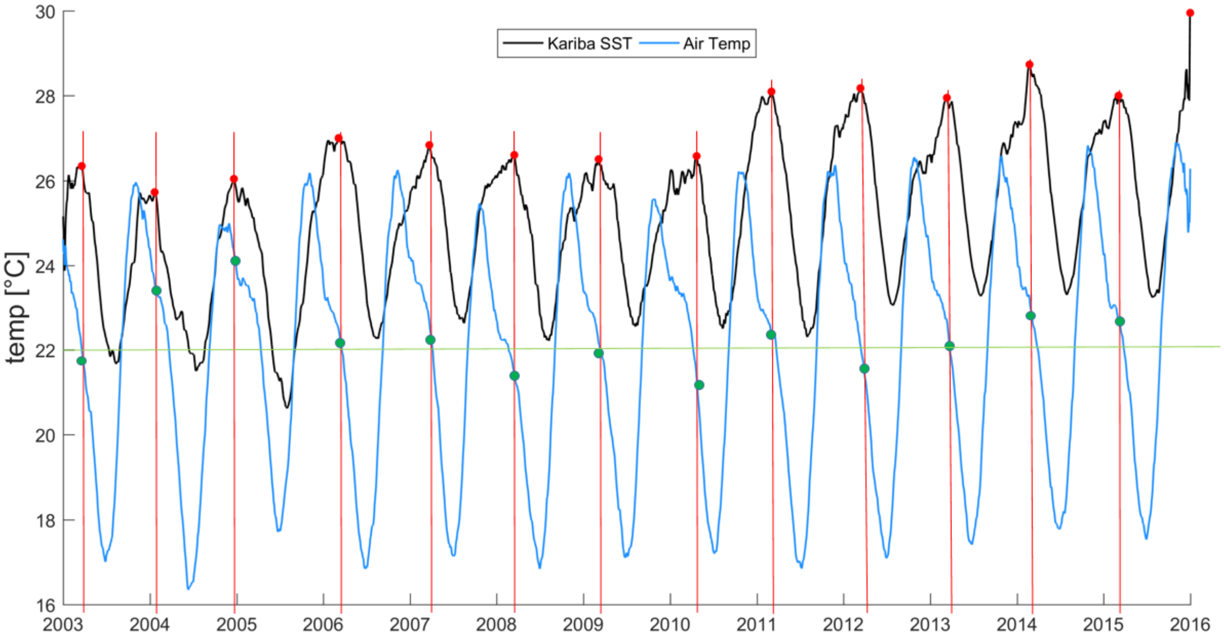
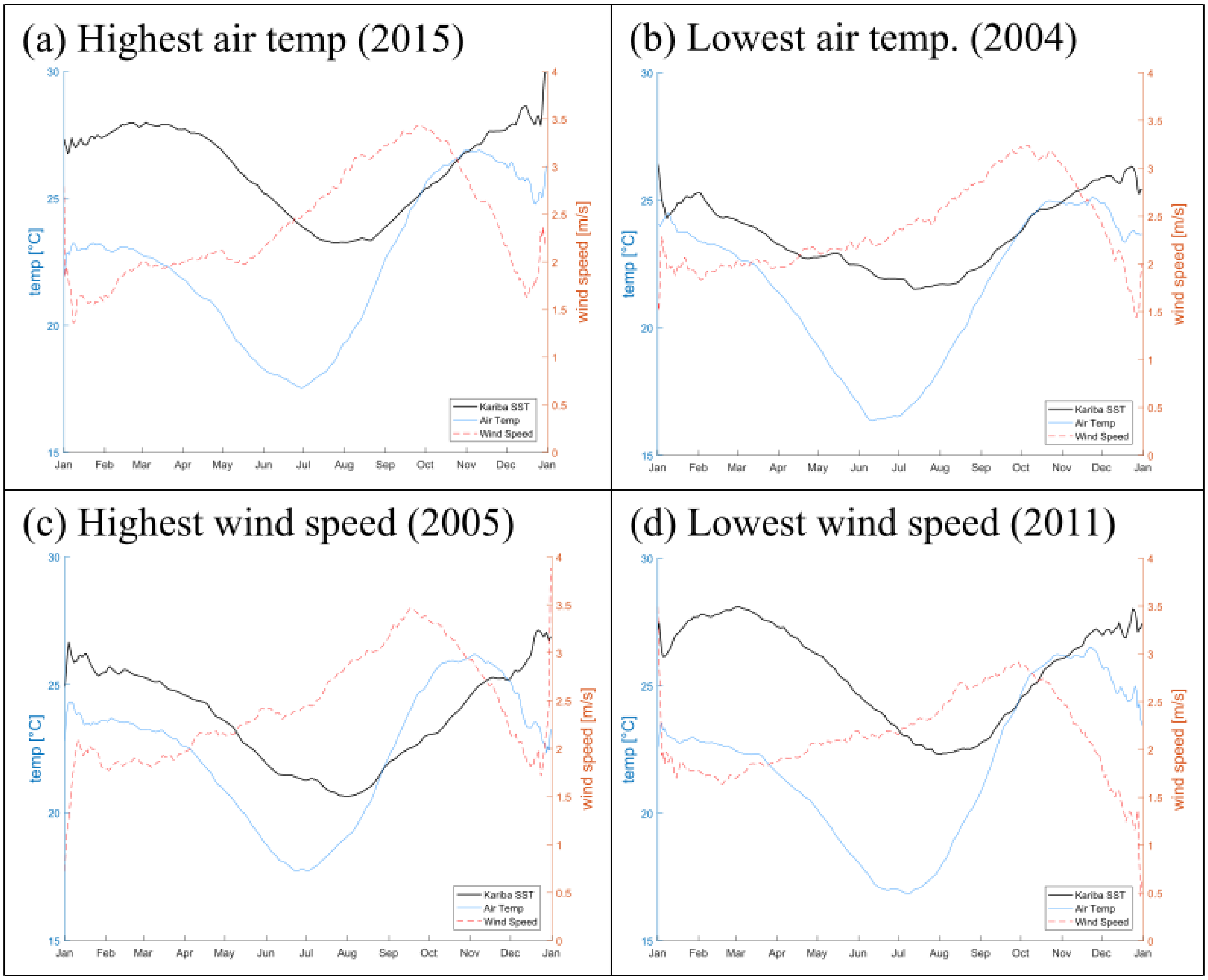


Figure 20: Lake Kariba's average surface temperature (black line) and air temperature (blue line) over the years of research. Red lines indicate the moment when the LST starts dropping and green dots show the air temperature in that moment. It seems that LST starts dropping when the air temperature drops to around 22 °C (green line).

To better understand the influence of air temperature on LSTs we looked at the years with the highest (2015) and the lowest air temperature (2004). In 2015, surface water has similar temperature pattern to the air (Fig. 21a), in 2004, it flattens significantly and never goes above 26 °C (Fig. 21b). With lower air temperatures, the drop in LSTs occurs earlier. Air temperatures influence the bathymetry reflection in LSTs distribution. During the year with higher temperatures, both February and July's water is about 2 °C warmer (Fig. 16.1 and 16.3). As usual, in Februarys water temperature increases only with distance from the inflow (Fig. 16.1 and 16.2), but the temperatures within the lake are more uniform in 2015 (Fig. 16.1). In July, bathymetry is marked stronger during the year with lower temperatures (Fig. 16.4).



(a) Highest air temp (2015)

(b) Lowest air temp. (2004)

(c) Highest wind speed (2005)

(d) Lowest wind speed (2011)

Figure 21: Comparison of Lake Kariba's surface temperature (black lines), air temperature (blue lines) and wind speed (red lines) patterns over years with highest and lowest air temperature and wind speed. Top figures show years with highest and lowest air temperature and bottom ones highest and lowest wind speed.

3.3.2 Wind speed

The winds in Kariba region generally blow from northeast, but in the second half of the year, the south-westerlies often blow over Basin IV (Begg, 1970). On average, wind speed reached around 3 to 3.5 meter per second and usually does not drop below 1.5 m/s (Fig. 19). . The highest average wind speed during the considered period was in 2005 and reached around 3.5 m/s. In very few cases can the wind reach up to 6 m/s. During our research period, the wind speed has a decreasing tendency. During the first seven years, the wind speed dropped below 1.75 m/s only once - in 2010, and after 2011, it always did. Year 2011 has the lowest, both maximum and minimum, wind speeds. After 2011, they still stayed lower compared to previous years but did increase a bit with every following year. The periods with high wind speed happen during winter months around July and with low – in summer, around January.

Again, to study wind speed influence on LSTs we looked at years with the highest (Fig. 21c) and the lowest (Fig. 21d) wind speeds. The air temperature during both years kept the same patter and was only slightly lower in 2011. During the high wind speed season the wind was almost 1 m/s faster in 2005, for the rest of the year this difference was smaller. Interestingly LSTs are much higher in the year with low wind speed. The temperature reaches up to 28 °C while in 2005, only around 26 °C. From October on in 2011 LSTs are around 27 °C while in 2005 – mostly stay at 25 °C and increase only in December.

It also seems that higher winds make the reflectance of bathymetry in LSTs pattern less visible (Fig. 17). In 2005, when the wind speed is highest, LSTs pattern shows a clear increase of temperature with the distance from the inflow of Zambezi River (Fig. 17.1 and Fig 17.3). In both seasons, only the part close to the dam of Basin IV shows a slight disturbance in this pattern with its middle being a bit warmer than coastline. In 2011, the year with lowest wind speeds, LSTs show much more diversity independent from distance from the river inflow (Fig 17.2 and Fig 17.4). LSTs pattern corresponds generally to the bathymetry. This is especially prominent in July, with surface waters being warmer over the deeper parts of the lake. Therefore, it seems that corresponding bathymetry influences the LST pattern of Lake Kariba, and that during years with low wind speed this influence is stronger.

4 Discussion

4.1 Cautious approach

In case of remote sensing, it is reasonable to apply the principle of cautious approach because there are many sources that could increase the measurement error. Atmospheric conditions significantly influence the data delivered by satellites and although our data source, GHRSST, combined several sensors in order to minimalize this influence, we cannot neglect the possibility of error. To better understand the results we looked at error maps provided together with the database by the source group (Fig. 22). Error is never higher than 0.41 °C and is uniform for the entire lake area. Higher error values occur during rainy season, which is to be expected, as the rain is the one atmospheric property that affects microwave measurements. First, in 2003-2005 error values stay higher than 0.4 °C throughout most of the year. Following 2006, the errors stay the same for rainy seasons but drop in winter months. This could be caused by the monsoon oscillation. Other source of mistake could come from the time of image taken. For example in Brazil, the difference from day to night could be as high as 8.4 °C (Alcântara, et al., 2010). This could be the reason why on some days temperature drastically drops, compared to the day before and rises up soon after as for example on August the 30th to 31st 2007 (Fig. 23). However, our dataset supposedly contains only nighttime skin. During the rainy season, the reason for this drastic temperature drop could result from quickly developing thunderstorms (Begg, 1970).

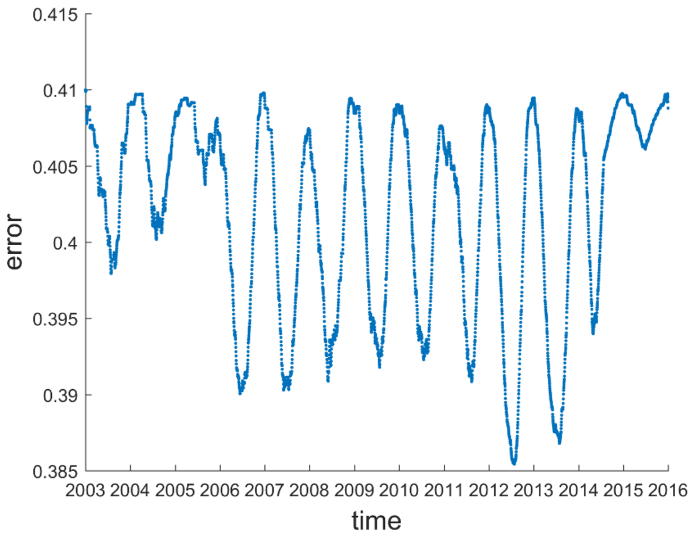


Figure 22: Remote sensing error data. The mean error overall lake surface is always below 0.41 °C. The highest errors occur at the turn of the years and drop to 0.39 °C in the middle of winter.

For a better understanding of our dataset, we compared it to the in situ measurements taken in Basin IV of Lake Kariba, around 1.5 km away from the dam wall (Fig. 24). Kariba's depth at this point is above 70 m. The overall pattern of satellite-delivered temperatures follows well the in situ ones but from 2007 to 2011, the cold season temperatures are as much as even 2 °C lower than the observed ones and in warm season around a Celsius degree lower. This difference is significantly lower in later years. In general, there are quite significant differences when looking at specific days but the overall RMSE equals 2.33 °C.

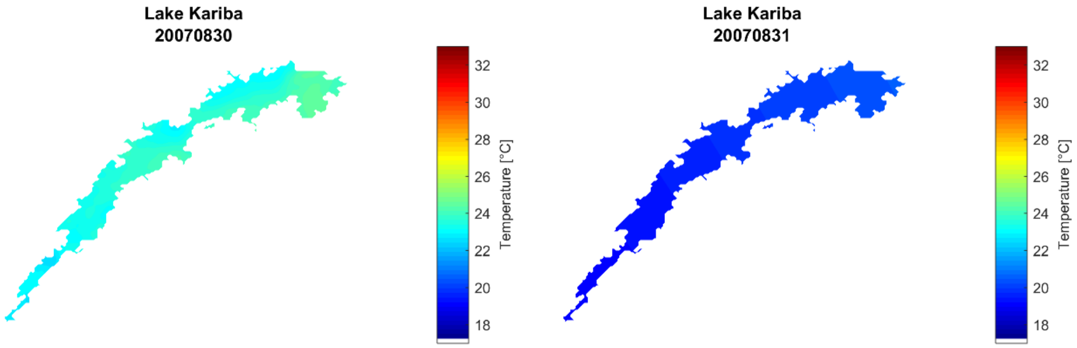


Figure 23: Lake Kariba's surface temperature maps of two following days (30.08.2007 and 31.08.2007). This temperature drop seems unlikely and could be caused either by daytime difference when taking the measurement or by other measurement error.

As a conclusion, the remote sensed GHRSST database underestimates the actual LST. The main factor causing this discrepancy is probably due to changes in the time of measurements during the day.

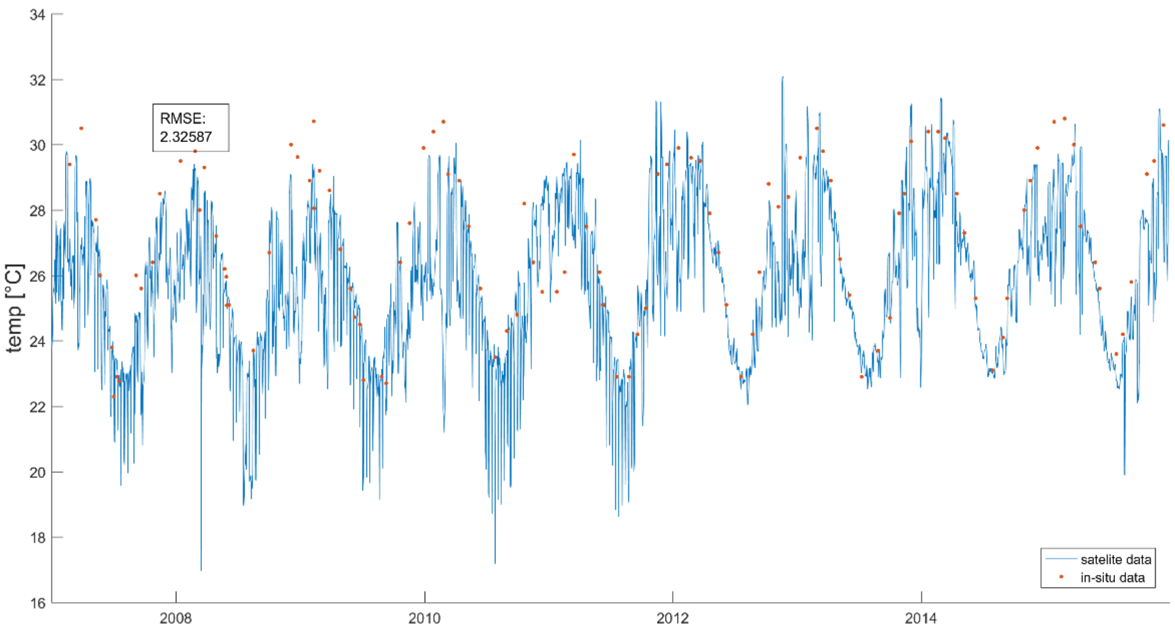


Figure 24: Remote sensing data validation with in situ measurements. The blue line represents remote sensing data and red dots show the in situ measurements of surface water temperature. The RMSE is about 2.33 °C.

We are dealing with similar problems when studying bathymetry. Even though the weather is not an issue here, we have to remember about several error sources. Firstly, the data was taken from Kunz (2011), which had been adopted from the book from 1974 (Balon & Coche, 1974). When exporting isobaths from graphic software files we experienced some shifting and in some places, the lines were overcrossing one another. We had to fix it manually and therefore created space for human error. Later, the automatic interpolation assigned a depth to each map cell and this is not necessary accurate. Lastly, georeferencing caused another shift and the shapes from bathymetry map only generally match the satellite images.

We used meteorological data from reanalysis; therefore, they are also subjected to systematic and random errors (Sun, et al., 2018). This reanalysis database is a gridded database meaning that we have one value for each cell (0.5 °lat x 0.5 °long). We have averaged the cells over the lake in order to get a unique time series of air temperature, precipitation and wind speed. When we compared it with the actual weather stations data, there were significant differences. Overall, Era-Interim reanalysis' temperatures came out underestimated. However, we must point out that the stations were located in some distance from the lake at significantly higher elevation (Fig. 3).

4.2 Spatial heterogeneity

As we expected, the LST varies across the lake and its most prominent characteristic is an increase with the distance to the inflow. Lake Kariba's surface temperature changes its horizontal behavior throughout the year. The difference between February and July patterns (Fig. 4) are prominent and most likely caused by changing weather conditions. In February the rainy season, high temperatures and low wind speeds dominate the heat uptake and cause the highest LST. A probable explanation for the LST distribution increasing with the distance from the Zambezi inflow is that the heat trapped in the epilimnion does not interact with the deeper waters. Waters in Basin I and II have strong river-like characteristic (Begg, 1970) and thus, the water there moves faster and does not have enough time to warm up. Basin III and IV, where the water stays long enough, warms up more and generate stratification which allow the water for further warming because in this situation only the uppermost layer of the lake is absorbing the heat. This is opposite to behavior of mean water column temperature, as in the last century there was a general decrease in water temperature with the distance from the inflow (Magadza, 2010). Therefore, while the mean temperature of the water column is decreasing, the surface water temperature shows the opposite trend supporting stratification. That points out to significant differences in temperature dynamics of surface water and the rest of the lake.

In July, the situation is different. Higher temperatures toward the center of the lake could be explained by the mixing process and increased wind activity. With lower air temperature the waters cool off, but together with the increased wind speed, it mobilizes the mixing of the lake's waters. As the bottom waters rarely drop below 22 °C, the heat stored in the deeper parts of the lake could be warming the surface water above. This effect is higher where the water storage in hypolimnion is greater, meaning that the water is cooling less in the deepest part of the lake.

The problem with this reasoning starts when we look at the changes in temperature horizontal patterns throughout the year (Fig.5). Spatial temperature differences across the lake is about 1.6 °C. This is a similar value to the Lake Tahoe's (Strub & Powell, 1986). However, when we attribute the horizontal distribution to the mixing and stratification periods, there is a discrepancy in timing. July-like pattern forms already in May and persists only until July, while mixing period starts only in June and lasts until August (Begg, 1970). It is hard to explain why the discussed horizontal feature would form already in May and cease in August. One might suggest a shift in seasons but according to other research, if there was an overall shift there would be a delay in cooling and not early cooling (Mahere, et al., 2014). However, in the same research the water column in May seems to be well mixed in the middle parts of the lake and remind stratify in the shore regions. In August, both the middle of the lake and the shore waters are mixed so by this month the temperature difference could again be driven more by weather conditions. This could help explain the reason of this temperature difference especially as there are no specific atmospheric condition changes during these months. The air temperature in May drops below 20 °C and remains so still in August. Wind speeds rise steadily and in May reach around 2 m/s and keep rising until October. It is also unlikely that it is a result of error fluctuation.

Based on the information we have, we suggest differentiating three phases for the lake water: well-mixed, transitional, and stratified. At the beginning of the year, the lake is stratified. Transitional phase occurs in April and detectable mixing starts already sometime in May. Mixing reaches its core in July and it weakens in August when another transitional phase takes place and waters begin to re-stratify. The lake reminds stratified until the end of the year. To confirm this we need more research on the water column.

4.3 Temporal heterogeneity

4.3.1 LST increase

Over the studied period, the LST of Lake Kariba increased around 2 °C. This is significantly higher than we expected from the overall global warming trend of 0.045 °C per year (Schneider & Hook, 2010). According to the previous research, Lake Kariba's water temperature warmed about 2 °C in 50 years from the lake's creation (Magadza, 2010); this however is an increase in value of the entire water body. This warming is significantly higher than the warming of other lakes in the region. Lake Tanganyika has a warming trend of 0.1 °C per decade (O'Reilly, et al., 2003) and Lake Malawi's surface water temperature warmed up 1 °C between 1940 and 1950 (Vollmer, et al., 2005). Higher rates of increase had two dams in South Africa - Hartbeespoort Dam and Roodeplaat Dam, on average 0.14 °C per year (van Ginkel & Silberbauer, 2007) and this agrees more with our warming of Lake Kariba. However, all these numbers correspond to waters of the entire upper layer or the top few meters (epilimnion), and not only the surface air intersection, therefore it is not the best to compare with our research and can explain the overestimation of warming for Lake Kariba.

As usual, when talking about warming we look up to the climate change. The air temperatures around Lake Kariba increased about 0.78 °C per decade (Ndebele-Murisa, et al., 2011). Interestingly throughout these 13 years, our data show no increasing nor decreasing trend in the air temperature above Lake Kariba but we observe a significant decrease in wind speed. The change that happened over year 2011 drew our attention. Although the increase of mean temperatures was in norm with previous years, the increase in both maximum and minimum temperatures was significantly higher and fell in tandem with decreasing wind speeds. It is possible that the cause of this shift is a change in monsoon regimes. Several scientists (Williams & Hanan, 2011; Ummenhofer, et al., 2017) studied the influence of Indian Ocean Dipole (IOD) and El Niño Southern Oscillation on the climate variability in East Africa. Between 2010 and 2011, there was a shift from negative to positive IOD. This could explain the warmer temperatures of Kariba and weaker winds during these years.

4.3.2 Seasonal feedback

We noticed that the mean temperature increase pattern was reflected in mean winter temperatures but not in mean summer. We suspect this is a result of a positive feedback. During warm winters, water temperatures stay higher and this could result in limited mixing. In this case some of the cold deep water stays separated from the rest of the lake. As a result, the heat stored in the epilimnion during the summer is distributed over a smaller water volume and this would keep the surface waters warmer. Therefore, the following summer starts already with higher temperatures and has a head start in warming up and temperature can increase even more. Again, warmer summer waters mean shallower mixing in the winter and this can fuel the feedback. As a result, we have winter surface temperatures driving the overall increase of Kariba's LSTs. This supports the observation that stratification pattern variation depend on meteorological condition and previous winter temperatures (Begg, 1970).

This also indicates that the stratification of the lake increases with increasing temperatures as already suggested by Ndebele-Murisa, et al. in 2011. However, according to the recent other research Kariba's response to warming temperature is similar to Lake Victoria, meaning its deep water temperatures rise higher than surface waters what results in decreased stratification rather than increased (Mahere, et al., 2014; Marshall, 2017). This was discredited by other researchers as the effect of La Niña (Ogutu-Ohwayo, et al., 2016) but having this in mind, understanding the effect of increasing LSTs, especially winter LSTs, have on lake's stratification would clearly require more research.

4.3.3 Diurnal gradient

The daily temperature changes are relatively high, especially during the first half of the research period. This gradient decreases from 2011 on. We accredit these large values to the difference in timing of taking the satellite images or other measurement related issues.

4.4 Morphology

There is a clear dependence between lake's temperature dynamics and its depth and morphology. Remote sensing of Great Lakes in North America showed that throughout autumn and winter the LSTs decreased from the coasts toward the middle of the lake (Moukomla & Blanken, 2016). Additionally, models and observations show that in the middle of the winter the LSTs are higher over the deeper waters than those over shore areas (Bai, et al., 2013). This is sensible, as the shallower waters are easier to cool down. The opposite situation takes place in May. The lake's center is colder than the coastal waters as they warm up quicker during spring warming.

We expected the same effect of bathymetry in Lake Kariba, but this was not the case. The deeper, middle part of the lake stands out only from May to July. This could correspond to the fall season when the lakes cools off. During this time, it could be that the wind speed is still not very high and therefore the bathymetry has a chance to dominate the thermal distribution. As a result, the shallower regions cool off faster. The question arises why this is not the case for August, in which waters are usually well mixed (Mahere, et al., 2014), and winter to summer transition, when the temperature pattern should be reversed. A possible explanation could be the higher wind speed, which would dominate the LSTs distribution. Another possibility is that the increased rainfall during rainy seasons affects the surface temperature warming.

We could argue that this particular LST feature that takes place from May to July, is the effect of mixing but it is for sure not the entire picture as it excludes August and to check this hypothesis, we would need to analyze entire water columns. However it is apparent that there is comparable little bathymetry reflectance in LSTs of Lake Kariba compared with other lakes.

Instead, the LSTs show strong dependence on distance from the Zambezi inflow, which dominates the most part of the year, especially rainy season. We suggest that this dependence is driven by water flow speed. As explained before the water in Basins I and II have very river-like characteristics (Begg, 1970), so the faster flowing water has less time to warm up and consequently has temperatures always lower than lake's average. Basins III and IV both have typical lake characteristics yet Basin IV is always warmer, probably also due to longer residence time. This could also be an effect of the secondary thermoclines observed in Kariba (Marshall, 2017). However, we have to point out that the depth also increases with the distance from the inflow, so it was impossible to determine to which extend it affects the thermal distribution of surface waters.

When we compare Basin I with Basin IV, we notice that in most years there is a time lag in reaching the lowest temperature. Until 2013, Basin I has reached the minimum before Basin IV. This lag varied in time and could be anywhere from few days up to few weeks and was especially long in 2006, 2008 and 2010. We explain that the water in shallower basins can cool down quicker and therefore reaches its minimum before the waters in deeper basins have time to cool. Interestingly, in 2014, the situation reversed itself and Basin IV reached lower temperature before Basin I. The lag was no longer than 1-2 days but as this is a very unlikely situation, it could be a result of estimation error. However if during the cooling phase the air was not cold enough, the river would not cool more than the air temperature but the lake would continue to cool down because it was still warmer than air. It is possible as the winter of 2014 was the warmest winter in our timespan.

4.5 External forcing

Variability in LST is an outcome of influence from lake properties, such as surface area and morphology, and external forcing such as air temperature, wind speed, humidity, radiation and precipitation (Schmidt, et al., 2018). These forces affect thermal distribution both horizontal and vertical. Water temperature alone cannot drive the thermal processes in lakes and is insufficient to explain stratification trends due to its nonlinear relationship to water density (Kraemer, et al., 2015). Therefore, it is important to incorporate lake's morphology but also atmospheric conditions into lake's thermal analysis, especially when studying mixing phenomena.

4.5.1 Wind speed and air temperature influence on LST

Although an increase in wind speed over large parts of Africa is expected over the next few decades (IPCC, 2014), a decrease in wind speed was observed in many regions (Ogutu-Ohwayo, et al., 2016). In Lake Tanganyika the reduction in water mixing was attributed to this decrease together with increasing air temperatures (O'Reilly, et al., 2003). The previous studies of Kariba showed that the variation in thermocline largely depends on the exposure to wind (Begg, 1970). Our research supports it showing that on temporal scale the decrease in wind speed is correlated with Kariba's LSTs increase. Kariba is a relatively shallow lake, and shallow lakes, due to their larger ratio area to volume, are more sensitive to wind stress (Ogutu-Ohwayo, et al., 2016). This could explain the higher impact of decreasing wind speed on Kariba's LST. Especially since both LST and wind speed trends had their main shift in 2011. The decrease in wind is probably the effect of the positive phase of Indian Ocean Dipole but at this point, it is impossible to say to what extend the wind speed is the driver of the shift in LST and how important is the combination of factors and response to widely understood climate change.

When we compare the influence of the wind speed and air temperature on Kariba's LST it is hard to see which one is the dominant one. The LST changes in years with highest and lowest air temperatures and wind speeds have similar magnitude. However, we notice the smoothed summer-winter LST oscillation in the year with lowest air temperature that did not happen in wind variation (Fig. 21). This could imply that the increasing air temperature favors greater variance over a year in LST.

The timing of the annual decrease in LST also speaks in favor for the dominant effect of air temperature. We observed that the LSTs start dropping around the time when air temperature reaches 22 °C. This makes sense as the deep water temperature generally stays around 22 °C (Begg, 1970). Therefore, when the air reaches this temperature there is no need for the wind factor to drive the mixing as density circulation takes over and LST starts dropping. The air temperature at which the LST start dropping is a bit higher in 2004 and 2005; this could be caused by a drought that took place over East Africa in these years following El Niño. Another possibility is the dominant factor of the influence of the previous year temperatures. As it happens, 2003 is the only year when the maximum air temperature is higher than maximum water temperature. During this year the wind speed was extremely high and the winter quite warm. This could have delayed the stratification season after summer, warming the hypolimnetic water and therefore causing following mixing to appear when the air temperature is at 23 °C rather than 22 °C.

We conclude that, at least to a certain degree, the decrease in wind speed dominates the effect on LST and it is the cause of the regime shift. The air temperature acts "from behind the curtain" and keeps increasing the LST year by year. We suggest that the wind speed is the dominant driver of

LST changes, but only until certain temperature is reached. Above this threshold, mixing takes over and air temperature becomes the dominant driver.

4.5.2 Wind speed and air temperature influence on bathymetry effect

An example of how complex thermal dynamics in lakes are is the way everything is interconnected. We conclude that the bathymetry effect on LST is not constant over time and its effect changes depending on meteorological conditions. Normally shallow waters warm up and cool off quicker (Peeters, et al., 2003). Both low air temperature values and low wind speeds in particular years make the reflection of bathymetry in LST more prominent. Change in external forcing changes the influence of lake morphology on the water temperature.

4.6 Future work

Although LSTs tell us a lot about the impact of climate change on the water and Kariba’s thermal dynamics, there is still much to do to understand this phenomenon properly. First of all, the method of measuring the LST has to be improved. It would be advisable to eliminate from the dataset the days with the largest temperature shifts compared to the previous day. The bathymetry map could be created with more recent data and modern methods that would eliminate the error of shift with the LST maps. We could extend the time series analysis and use more in situ measurements to validate both LSTs and meteorological data. It would help to understand the influence of the wind and the LST changes in response to variation in IOD and ENSO.

It would be interesting to test whether the peculiar shape of LSTs in May-July corresponds with the timing of mixing periods and how the water column during that time behaves. If there was a correlation it would be great to develop a tool allowing an identification of mixing periods though a remote sensing analysis. This would require further study of this phenomenon and the way weather conditions affect it. Maybe the combination of LST, wind speed, and air temperature would be sufficient to determine this process and predict it for the future. This would enable us to counteract the effect of deoxidized and nutrient depleted water being released downstream.

5 Conclusions

We delivered the first remote sensing derived water surface temperatures analysis of Lake Kariba and digitalized the lake's bathymetry map. Our aim was to describe Kariba's LST spatial and temporal behavior and test the possibility of using remote sensing to identify the lake mixing periods.

We found that there is a clear spatial temperature heterogeneity in the LST. Moreover, LST spatial pattern change between summer (February) and winter (July). In summer the temperature increases with the distance from Zambezi inflow, while in winter waters in Basin III and IV additionally increase toward the center of the lake. The latter pattern have been observed in other lakes and corresponds to cooling stage but unexpectedly, Kariba does not show a warming stage pattern, which should be a reverse version of the cooling one. Therefore, we suggest that this pattern could represent LST during mixing period and we differentiate between three types of phases: well-mixed, transitional and stratified. Confirming it will require more research.

Lake surface temperature of Lake Kariba has been increasing through the entire span of our research. In 13 years, the LST increased around 2 °C. The increase rate is higher than expected and higher than most of the lakes in the area. However, similar observations have been reported, especially in South Africa, so it is not an unreasonable outcome but could still be a result of measurement error. If anything, remote sensing delivered temperatures are generally lower than in situ measurements due to their different time-of-day. Increasing LST had a significant shift in 2011 that coincides with decrease in wind speed. We suggest that the forcing behind this shift is the transition from negative to positive Indian Ocean Dipole that caused lower wind speeds, which in turn contributed to increase in LST. The overall temperature increase pattern was the same as the pattern of winter temperatures. We imply that there is a positive feedback between higher winter temperatures causing general higher LSTs.

We found that there is little visible influence of bathymetry on horizontal temperature distribution. In summer, the bathymetry effect is not visible and in winter, it is just generally marked in Basins III and IV. Instead, for the most time the temperature increases with the distance form Zambezi inflow. However, since the depth also increases with the distance from the inflow we cannot disentangle the effect of bathymetry itself from the distance-related one. Generally, we explain this increase in temperature as a result of water residence time which is shorter in Basin I and II giving the water less time to warm up and to stratify.

We confirm that the atmospheric conditions affect Kariba's LST. Temperature of the surface is highest with higher air temperatures and lower wind speed. However, it is difficult to assess which factor is dominating when and how. It seems that on shorter, yearly scale, air temperature has larger impact and on longer scale, the wind is the stronger influencer. Water thermal dynamics are so complicated and interconnected it would require much more detailed analysis in order to actually prove it. Interestingly, when wind speed or air temperatures are low, LST distribution tends to be more influenced by the bathymetry and reflect the shape of Kariba's bottom. We therefore confirm that Kariba's LST depend on both lake morphology and external forcing with the latter one being the dominant drivers.

After analyzing spatial and temporal variations in Kariba LST we find remote sensing a good tool and reasonable to use especially when analyzing general patterns and tendencies. However, with many error sources there is still place for improvement.

We conclude that, although mixing periods might have their reflection in surface temperatures, the LSTs alone are not enough to identify them. Combining remote sensing with weather and climate conditions could give better results and improve our understanding of the thermal processes taking place in Kariba reservoir.

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Bibliography

Alcântara, E. H. et al., 2010. Remote sensing of water surface temperature and heat flux over a tropical hydroelectric reservoir. *Remote Sensing of Environment*, 114(11), pp. 2651-2665.

Bai, X. et al., 2013. Modeling 1993–2008 climatology of seasonal general circulation and thermal structure in the Great Lakes using FVCOM. *Ocean Modelling*, Volume 65, pp. 40-63.

Balon, E. K. & Coche, A. G., 1974. *Lake Kariba : a Man-made Tropical Ecosystem In Central Africa.*. s.l.:The Hague: Junk.

Baxter, R. M., 2003. Environmental Effects of Dams and Impoundments. *Annual Review of Ecology and Systematics.*

Begg, G. W., 1970. Limnological observations on Lake Kariba during 1967 with emphasis on some special features.. *Limnology and Oceanography.*

Bollaert, E. et al., 2012. *Physical and numerical model study investigating plunge pool scour at Kariba Dam*, s.l.: Commission Internationale des Grands Barrages.

Butcher, J. B., Nover, D., Johnson, T. E. & Clark, C. M., 2015. Sensitivity of lake thermal and mixing dynamics to climate change. *Climatic Change.*

Chao, B. F., Wu, Y. H. & Li, Y. S., 2008. Impact of Artificial Reservoir Water Impoundment on Global Sea Level. *Science*, 320(5873), pp. 212-214 .

Coche, A. G. & Balon, E. K., 1974. *Lake Kariba : a Man-made Tropical Ecosystem In Central Africa.*. s.l.:The Hague: Junk.

Donlon, C. et al., 2007. The Global Ocean Data Assimilation Experiment High-resolution Sea Surface Temperature Pilot Project. *American Meteorological Society.*

Elci, S., 2008. Effects of thermal stratification and mixing on reservoir water quality. *The Japanese Society of Limnology.*

Haddout, S., Priya, . K. & Boko, M., 2018. Thermal response of Moroccan lakes to climatic warming: first results. *International Journal of Limnology.*

IPCC, 2013. *Climate Change 2013: The Physical Science Basis.*, Cambridge: Cambridge University Press.

IPCC, 2014. *Climate Change: The Physical science basis,* s.l.: IPCC.

IPPC, 2001. *Climate change 2001: Impacts, adaptation, and vulnerability,* s.l.: Cambridge University Press.

Kraemer, B. M. et al., 2015. Morphometry and average temperature affect lake stratification responses to climate change. *Geophysical Research Letters* , 42(12), pp. 4981-4988.

Kunz, M. J. et al., 2011. Sediment accumulation and carbon, nitrogen, and phosphorus deposition in the large tropical reservoir Lake Kariba (Zambia/Zimbabwe). *Journal of Geophysical Research.*

Lautze, J., Phiri, Z., Smakhtin, V. & Saruchera, D., 2017. *The Zambezi River Basin: Water and sustainable development.* 1st Edition ed. s.l.:Routledge.

Lin, Q., 2011. Influence of Dams on River Ecosystem and Its Countermeasures. *Journal of Water Resource and Protection.*

Magadza, C. H. D., 2010. Environmental state of Lake Kariba and Zambezi River Valley: Lessons learned and not learned. *Lakes and Reservoirs: Research and Management,* Volume 15, pp. 167-192.

Mahere, T. S., Mtsambiwa, M. Z., Chifamba, P. C. & Nhiwatiwa, T., 2014. Climate change impact on the limnology of Lake Kariba, Zambia–Zimbabwe. *African Journal of Aquatic Science.*

Marshall, B. E., 2017. An assessment of climate change and stratification in Lake Kariba (Zambia–Zimbabwe). *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use.*

Marshall, B. E. et al., 2013. Has climate change disrupted stratification patterns in Lake Victoria, East Africa?. *African Journal of Aquatic Science.*

Moukomla, S. & Blanken, P. D., 2016. Remote Sensing of the North American Laurentian Great Lakes' Surface Temperature. *Remote Sensing,* 8(4).

Ndebele-Murisa, M. R., Mashonjowa, E. & Hill, T., 2011. The implications of a changing climate on the Kapenta fish stocks of Lake Kariba, Zimbabwe. *Transactions of the Royal Society of South Africa*, 66(2), pp. 105-119.

Ogutu-Ohwayo, R. et al., 2016. Implications of climate variability and change for African lake ecosystems, fisheries productivity, and livelihoods. *Journal of Great Lakes Research,* 42(3), p. ray498–510.

O'Reilly, C. M. et al., 2003. Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature.*

O'Reilly, C. M. et al., 2015. Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters,* 42(24), pp. 10,773-10,781.

Peeters, F. et al., 2003. Deep-water renewal in Lake Issyk-Kul driven by differential cooling. *Limnology and Oceanography*, 48(4), pp. 1419-1431.

Ray, R. D. & Susanto, R. D., 2016. Tidal mixing signatures in the Indonesian seas from high-resolution sea surface temperature data. *Geophysical Research Letters.*

SARDC, et al., 2012. *Zambezi River Basin - Atlas of the changing Environment. Southern African Research and Documentation Centre,* s.l.: s.n.

Schmidt, S. R. et al., 2018. Temporal and spatial scales of water temperature variability as an indicator for mixing in a polymictic lake. *Inland Waters,* 8(1), pp. 82-95.

Schneider, P. & Hook, S. J., 2010. Space observations of inland water bodies show rapid surface warming since 1985. *Geophysical Research Letters.*

Strub, T. P. & Powell, T. M., 1986. Surface temperature and transport in Lake Tahoe: inferences from satellite (AVHRR) imagery. *Continental Shelf Research,* 7(9), pp. 1001-1013.

Sun, Q. et al., 2018. A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. *Reviews of Geophysics,* Volume 56, pp. 79-107.

Ummenhofer, C. C., Kulüke, M. & Tierney, J. E., 2017. Extremes in East African hydroclimate and links to Indo-Pacific variability on interannual to decadal timescales. *Climate Dynamics,* Volume 50, p. 2971–2991.

van Ginkel, C. E. & Silberbauer, M. J., 2007. Temporal trends in total phosphorus, temperature, oxygen, chlorophyll a and phytoplankton populations in Hartbeespoort Dam and Roodeplaat Dam, South Africa, between 1980 and 2000. *African Journal of Aquatic Science,* 32(1), pp. 63-70.

Verburga, P. & Hecky, R. E., 2009. The physics of the warming of Lake Tanganyika by climate change. *Association for the Sciences of Limnology and Oceanography.*

Verburg, P. & Hecky, R. E., 2009. The physics of the warming of Lake Tanganyika by climate change. *Limnology and Oceanography.*

Vollmer, M. K. et al., 2005. Deep-water warming trend in Lake Malawi, East Africa. *Limnology and Oceanography.*

Wetzel, R., 2001. *Limnology: Lake and River Ecosystems.* 3rd ed. s.l.:Academic Press.

Williams, C. A. & Hanan, N. P., 2011. ENSO and IOD teleconnections for African ecosystems: evidence of destructive interference between climate oscillations. *Biogeosciences,* Volume 8, p. 27–40.

DATA sources:

Remote Sensing Data, GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis (v4.1), https://podaac.jpl.nasa.gov/dataset/MUR-JPL-L4-GLOB-v4.1

ERA-Interim reanalysis, European Centre for Medium-Range Weather Forecasts, https://www.ecmwf.int/

The Global Historical Climatology Network (GHCN), https://rda.ucar.edu/datasets/ds564.0/

SASSCAL WeatherNet, http://www.sasscalweathernet.org/

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Unpublished database from EAWAG Research Institute
Google Maps

Personal declaration: I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

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28.01.2019, Winterthur

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