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Temperature Surface of Guaíba Lake, RS, from time series of MODIS images

Temperatura de Superfície do Lago Guaíba/RS, a partir de série temporal de imagens MODIS

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ABSTRACT

The Guaíba lake is located in an area of complex weather variation and is influenced by many atmospheric circulation systems, bringing about violent occluded fronts, and, sometimes, intense precipitation. In Rio Grande do Sul, during El Niño, air temperatures and the precipitation index are higher, contrary to La Niña. Moreover, the Guaíba Lake receives water from the Guaíba's Hydrographical Region, which corresponds to 1/3 of Rio Grande do Sul State, and is thus an important water body to the metropolitan region of Porto Alegre. Methods that seek to understand the behavior of Guaíba lake surface water temperature (LSWT) may lead to relevant information to identify periods of more or less water warming, as well as the relations between LSWT, water quality deterioration and risks to human health. This paper aims to comprehend the behavior of Guaíba LSWT during periods of climatic anomalies (El Niño/La Niña). Therefore, 418 sea surface temperature (SST) images from the MODIS sensor were processed with SeaDas 7.2 software. The quarterly averages of LSWT were obtained and compared to the climatological anomalies in Equatorial Pacific Ocean. LSWT behavior is more complex in El Niño/La Niña periods. The results show that during climatic abnormality periods there are no direct relationship between the warming/cooling of Guaíba LSWT and the warming/cooling of Equatorial Pacific Ocean's SST. The precipitation indices were more significant to the behavior of LSWT during El Niño periods, but for all periods (of climatic normality and abnormality), air temperature is what most influences LSWT. This relation occurs with climatic factors of water retention time, water entry and precipitation, and air temperature. There is a major correspondence during La Niña periods with the cooling of Guaíba LSWT only for some years. On the other hand, during El Niño periods there are no correspondences of this phenomenon with the warming of Guaíba LSWT. There are only more intense oscillations in surface temperatures than during regular and La Niña periods, but with a tendency to LSWT warming.

Keywords: El Niño; La Niña; Remote sensing.

RESUMO

O Lago Guaíba localiza-se em uma área de complexa variação de tempo meteorológico, e sofre influência de vários sistemas atmosféricos ocasionando choques frontais e por vezes precipitações intensas. No Estado, durante o El Niño, as temperaturas do ar são mais elevadas e o índice pluviométrico é maior, de modo contrário à La Niña. Além disso recebe águas da Região Hidrográfica do Guaíba, o que corresponde a 1/3 do Estado do Rio Grande do Sul, constituindo-se em importante corpo d'água para a região metropolitana de Porto Alegre. Métodos que buscam a compreensão do comportamento da TSL (temperatura de superfície de lago) do Guaíba podem trazer informações relevantes para identificação de períodos de maior e menor aquecimento da água, assim como as relações entre TSL e deterioração da qualidade da água e riscos a saúde humana. Esse trabalho tem como objetivo compreender o comportamento da TSL do Guaíba em períodos de anomalias climáticas (El Niño/La Niña). Para tanto foram processadas 418 imagens de TSM (temperatura de superfície de mar), sensor MODIS, a partir do Software SeaDas 7.2, obtidas as médias trimestrais de TSL, e comparadas com anomalias climatológicas no Oceano Pacífico Equatorial. O comportamento da TSL é mais complexo em períodos de El Niño/La Niña. Os resultados mostram que nos períodos de anormalidade climática, não há uma relação direta do aquecimento/resfriamento da TSL do Guaíba com o aquecimento/resfriamento da TSM do Oceano Pacífico Equatorial. Os índices de precipitações mostraram-se mais significativos em períodos de El Niño no comportamento da TSL, mas para todos os períodos, de normalidade e anormalidade climática, a temperatura do ar é o que mais influência a TSL. Essa relação ocorre com fatores climáticos de tempo de permanência da



água, entrada de água e precipitação e da temperatura do ar. Há uma correspondência maior de períodos de La Niña com o resfriamento das TSL do Guaíba, apenas para alguns anos. Quanto ao El Niño, não há uma correspondência deste fenômeno com o aquecimento da TSL do Guaíba, o que se observa são oscilações de temperaturas superficiais de forma mais intensa, do que em períodos normais e La Niña, mas com tendência a um aquecimento das TSL.

Palavras-chave: El Niño; La Niña; Sensoriamento remoto.

INTRODUCTION

From the 1940s onwards, a concern about environmental changes caused by the intense use of natural resources, specifically in the quality of lake waters, is noted. Collins and Love (1942) examined the adequacy of water quality for uses in industry, agriculture, and for household use, and verified the effects of dissolved substances and suspended materials in water. This research served as the basis for Blakev's (2010) study by comparing air temperature data with surface water temperature data.

The temperature of a lake is an important driver of the lagoon ecosystem, and has also been identified as an indicator of global climate change (RIFFLER; LIEBERHERR; WUNDERLE, 2015). Historical data of lake temperatures include important information for studies about climate change and environmental changes that affect economy and society (GRONEWOLD et al., 2013; RIFFLER et al., 2015). Seasonal variations of phytoplankton are associated with cyclical climate and hydrology recurrences, such as in water temperature, precipitation and fluviometric level; interannual cycles are influenced by climatic (El Niño and La Niña) and anthropic (nutrient increase) disturbances (CORAZZA, 2015).

The temperature of a lake is one of the keys that determine its ecological conditions, as well as its chemical and biological processes and its hydrodynamics (TOFFOLON et al., 2014). The conditions of heat fluxes and exchanges with air, are of fundamental importance for the understanding of the hydrological cycle (MACCALLUM et al., 2011). Lakes are vital to life on the planet, acting as continental refrigerators (MACCALLUM et al., 2011).

Changes in water temperature have direct and indirect relationship with the history of organic processes (metabolism, growth, reproduction and habitat ownership), and can condition a series of environmental changes that in fact affect society.

With respect to temperature, LSWT (Lake Surface Water Temperature) is the result of heat fluxes in a lake surface (short-wave and long-wave solar radiation, sensible and latent heat exchanges), intervals of temperature inputs and outputs, groundwater, precipitation and heat transfer with mixtures of waters at different temperatures. These fluxes depend on climate variables such as solar radiation, air temperature, wind speed and direction, cloud cover and relative humidity. These fluxes can be measured with difficulty and or with significant reliability and accuracy (TOFFOLON et al., 2014). LSWT can be used to understand the processes of origin and direction of winds and their relations with upwelling events and water mass transport (OESCH et al., 2005).

The LSWT dynamics are conditioned by several factors, such as: periods of climatic normality and abnormality (El Niño and La Niña) directly interfering with local precipitation and water intake, in the same way, having an influence on cloud cover, air

temperature, winds direction and speed, modifying the annual cycle of stratification, which in tropical lakes is influenced by seasonal changes in cloud cover, interfering with radiation and wind speeds, as momentary flow effects in combination with relative humidity and latent heat fluxes (Evaporation). These variables predominate as a function of the variability of atmospheric pressure increase, which is caused by solar radiation and air temperature in tropical regions, and is relative to high latitudes. With this rise in temperatures, evaporation rates exceed the temperatures of temperate or arctic lakes at the same wind speeds, this warming of LSWT in high latitudes causes greater mixtures with deeper layers of lakes (MACINTYRE et al., 2014).

The high evaporation rates contribute to a daily thermal mixture and stratification, characterizing tropical lakes. Stratification can also be caused by differences in cooling and processes, in which gravity currents are included by cooling in shallow or protected areas, and, consequently, fluxes away from the banks (MACINTYRE et al., 2014). Thermal stratification in tropical lakes occurs so that temperatures decrease with depth (AABERG, 2013).

LSWT, in addition to being conditioned to the annual stratification cycle, is also conditioned to factors such as El Niño and La Niña. El Niño consists in the warming of Pacific Ocean waters, while La Niña is the cooling of Pacific Ocean waters.

Climatic anomalies El Niño and La Niña are phenomena occurring in waters of Central America and East Central Equatorial Pacific (BERLATO; FONTANA, 2003; NOAA, 2007; MARENGO, 2007). These phenomena are associated with pressure fields (represented by the Southern Oscillation Index) changing the general circulation system of the atmosphere. These anomalies affect several areas of the world, accounting for the deviations from the normal climate, the so-called climatic anomalies, which last from 6 to 18 months (CUNHA et al., 2011).

In Rio Grande do Sul, under the influence of El Niño/La Niña, the average minimum temperatures tend to be higher, with an average deviation equal to or greater than 1 °C in several months of the year. As to the average maximum temperatures, these deviations do not exceed 0.5 °C (BERLATO; FONTANA, 2003).

El Niño/Southern oscillation (ENSO) is related to spatial changes in tropical convection patterns, including extreme southerly precipitation indices (ROPELEWSKI; HALPERT, 1987; MARENGO, 2007; CPETEC, 2016). During ENSO, in much of South America there is a very hot winter (BECKER, 2015).

There is a strong relationship between El Niño and La Niña with sea surface temperature anomalies, as well as precipitation and sea surface pressure anomalies (CATTO; NICHOLLS; JAKOB, 2012). During La Niña the Alisios winds of Pacific Ocean are more intense than normal (MARENGO, 2007).

In Rio Grande do Sul, the El Niño phenomenon causes humid weather, with intense to varied precipitation, fog, easterly (E) and southeasterly (SE) variable winds and declining air

temperature, in small thermal amplitudes (SARTORI, 2003). But generally El Niño tends to present higher air temperatures throughout the country (MARENGO, 2007).

Guaíba LSWT suffers great influence of air temperature and wind speed and direction. In this geographic location, State of Rio Grande do Sul, there is a complex climatic and meteorological dynamics with sudden changes of temperature caused by the entry of cold fronts and, often, shocks of air masses of different temperature and pressure causing precipitation.

The understanding of wind direction facilitates the interpretation of air origin, temperature and pressure and its influence on the LSWT. In general, the winds from Intertropical Systems influence its warming and those from Polar Anticyclones, which generally enter from the south, cause its cooling.

Winds are determined by Extratropical (polar fronts and masses) and Intertropical (tropical masses and Disturbed Currents) Atmospheric Systems. In Rio Grande do Sul there are several weather types, such as: Six Weather Types Associated to Polar Anticyclones, three Weather Types Associated to Intertropical Systems and six Weather Types Associated to Disturbed Currents (SARTORI, 2003).

The North Wind is a wind characteristic of the pre-frontal situation, with high temperatures and lasting a few hours, which enters in the northern direction of the State of Rio Grande do Sul (SARTORI, 2003; WOLLMANN, 2011), and is typical of normal regional circulation conditions. But in case of El Niño and La Niña events, they disorganize the positioning and the zonal action centers, not allowing the typical activity of North Wind in the South Region of Brazil (SARTORI, 2003). For the occurrence of typical north wind “characterized as” it is necessary that the atmospheric systems and subsystems of South America are organized so as to allow well developed frontogenesis with effective pressure gradients (SARTORI, 2003).

The understanding of the behavior of Guaíba LSWT can bring about relevant information to identify periods of higher and lower water warming, as well as the relationships between LSWT, precipitation and air temperature. This may serve as a basis to related studies. For example, to the prediction of the occurrence in Guaíba of flowering of potentially toxic cyanobacteria that cause deterioration of water quality and risks to human health (FREITAS et al., 2012; CORAZZA, 2015).

Thus, the objective of this work is to understand the behavior of LSWT in Lake Guaíba-RS, from time series of MODIS images (Moderate Resolution Imaging Spectroradiometer), and to analyze the seasonal oscillation of LSWT, in normal period and in years of El Niño and La Niña.

The use of Sea Surface Temperature images, available at Terra Satellite’s Oceancolor website, MODIS Sensor (OCEANCOLOR, 2015), presents a great potential, allowing a detailed study with great amount of images distributed evenly in extensive temporal scale. This way one can acquire a large amount of LSWT information.

The MODIS Sensor has two bands, 31 and 32, with wavelengths of 11 μm and 12 μm that are used to measure the temperature of the oceans (MODIS, 2016).

The study of Guaíba LSWT is presented as a case study, having as theoretical and methodological support the development of an epistemological structure centered around the collection

and processing of data from Oceancolor website, MODIS sensor (TSM), being complemented with data from INMET (Instituto Nacional de Meteorologia, National Institute of Meteorology), forming a data correlation system used to answer the work objectives.

MATERIALS AND METHODS

The area of study (Figure 1) is located in the Porto Alegre Metropolitan Area (PAMA), east of the State of Rio Grande do Sul, at coordinates of Longitude 51°00’38” to 51°21’34” West and Latitude 29°57’21” to 30°26’04” South. According to Secretaria do Ambiente e Desenvolvimento Sustentável (SEMA, 2015), the Guaíba basin is located in the geomorphological provinces of the Uruguayan-Sul-Rio-grandense Shield and the Coastal Plain.

The hydrographic basins of rivers Jacuí (84.6%), Sinos (7.5%), Caí (5.2%) and Gravataí (2.7%) drain into the Guaíba. The Guaíba Lake has a water accumulation basin of 1.5 billion/m³, with a length of 50 km and width ranging from 1 to 20 km (COMITÊ DO LAGO GUAÍBA, 2011).

According to the Rossato (2011) climatic classification for the State of Rio Grande do Sul, the Guaíba is located in an area of climatic transition. To the East it is classified as subtropical II, moderately humid with longitudinal variation of average temperatures, with greater influence of polar and tropical continental systems, with increasing interference of tropical marine climates; and to the west as subtropical III, with longitudinal variation of temperatures,

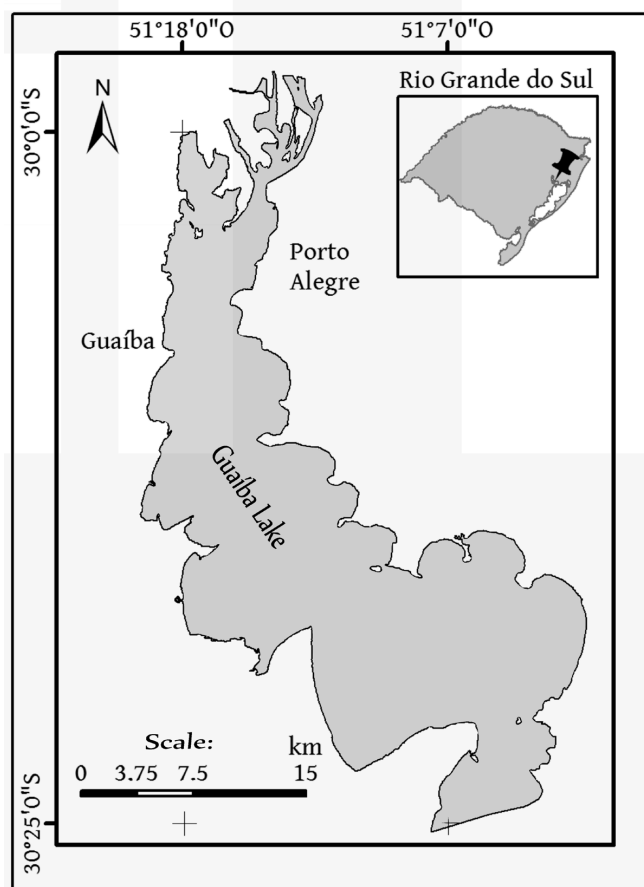


Figure 1. Location of the area of study: Guaíba Lake-RS, 2016.

with greater interference of the conjugated tropical systems, with effect of the relief, continentality, oceanicity and urbanized areas, and most precipitation is caused by frontal systems.

In order to define the appropriate methodological procedures, this study took as reference some methodological bases of CPC (2016). Based on CPC (2016), what characterizes the El Niño phenomenon is the warming of Pacific Ocean waters (at the location: 5°N-5°S, 120°E-170°W) for a period above 3 months with El Niño Oceanic Oscillation index above + 0.5 °C. The cooling of -0.5 °C, during this period, characterizes the La Niña phenomenon. Values below the 0.5 °C modulus are considered periods of climate neutrality by CPC (2016).

The materials used were obtained from the download of images of the Terra satellite - MODIS sensor (*Moderate Resolution Imaging Spectroradiometer*), from the Oceancolor website (OCEANCOLOR, 2015). These images are the product of the 8 days average of LSWT (Sea Surface Temperature), with a spatial resolution of 1 km, level 3 data (*Terra MODIS Sea Surface Temperature 11 um daytime*), (MODIS, 2016) . The file has extension “.nc” (default format for network data, matrix-oriented data standard (SEIDENGLANZ, 2012), in *binned* data - lines collected together in the read log, before actual reading (DOBBER et al., 2006).

The images were decompressed, and since they did not have projection systems, they were reprojected to WGS 84 LL and cropped using of the software SeaDAS 7.2 (NASA, 2015). The averages of all LSWT pixels (for each of the 418 images) were extracted in numerical data format, with six decimal places. With Excel 2007 software (MICROSOFT, 2007), the quarterly averages for the data tabulated (from 2000 to 2015) were calculated for purposes of comparison with the Pacific Ocean climatic anomalies table, according to CPC/NOAA methodology (2016). As it can be seen in the methodological flow chart of Figure 2, below.

The Guaíba LSWT anomaly index was calculated based on CPC/NOAA methodology (2016), for 418 images, between 2000 and 2015, according to Equation 1:

$$I=M-N \tag{1}$$

where: I= anomaly index; M= quarterly annual average; N= Guaíba General Climatological Average (general average of the respective 3 months between 2000 and 2015). Variations greater than +0.5 or lower than -0.5 ° C in relation to N were considered periods of abnormality of Guaíba LSWT.

Initially, a comparison was made between the Guaíba LSWT anomaly indices and the Pacific Ocean anomaly indices (Tables 1 and 2, respectively). Guaíba LSWT was then separated by periods (La Niña, El Niño and climatological normality), based on NOAA (2016) Table 2.

The correlation between Guaíba LSWT, in periods of climatic normality and abnormality, and data from INMET (Instituto Nacional de Meteorologia) was established. The INMET meteorological data used in the research were precipitation, wind speed, average compensated temperature, maximum and minimum temperatures of the Porto Alegre, RS Station (OMM: 83967- located at coordinates: O 51° 9' 36" e S 30° 3' 0"), and from de Santa Maria, RS Station (OMM: 83936- coordinates: O 53° 42' 0" e S 29° 42' 0") only precipitation data.

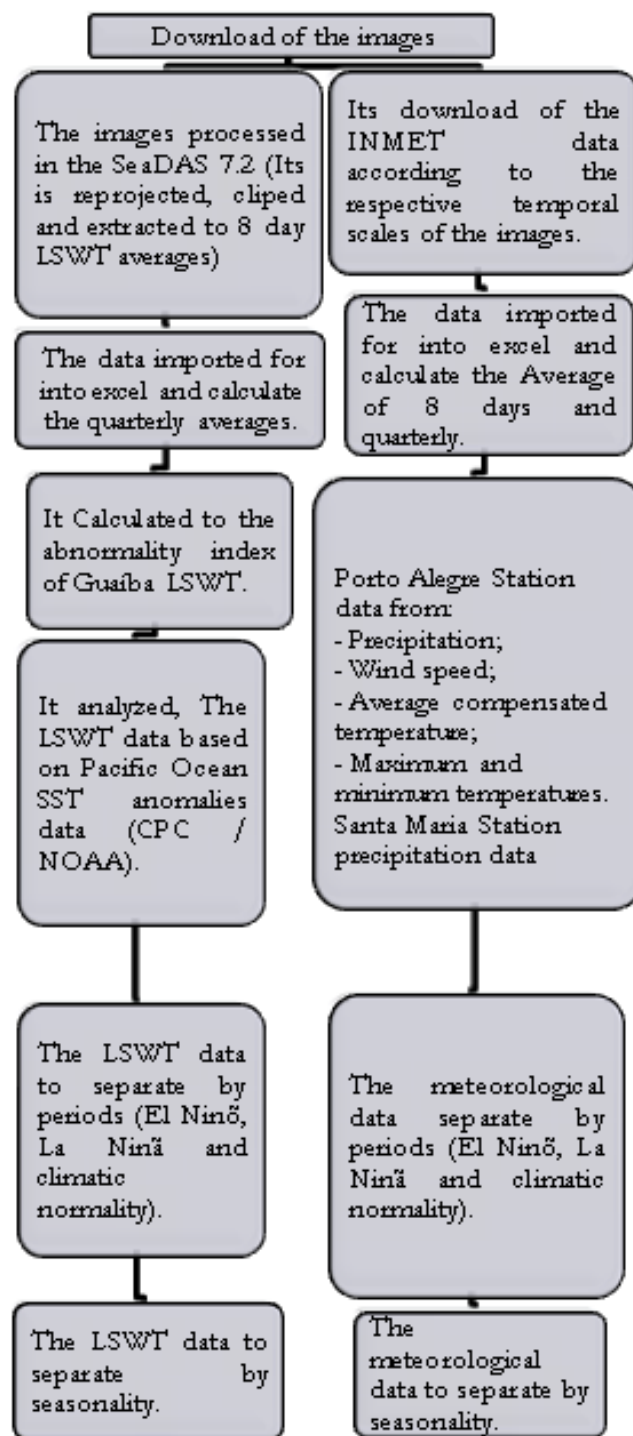


Figure 2. Methodological flow chart.

According to INMET (2016), the average compensated temperature is calculated based on collections performed at 12 UTC (Universal Time Coordinated) and 24 UTC, according to Equation 2.

$$T = (T_{max, k, i, j} + T_{min, k, i, j} + T_{12, k, i, j} + 2T_{24, k, i, j}) / 5 \tag{2}$$

where: the day corresponds to (k), the month (i) and the year (j). T max, k, i, j - consist in the number of observations of maximum temperatures; T min, k, i, j - consist in the number

Table 1. Comparison of LSWT anomalies above/below 5 °C between Pacific Ocean and Guaíba Lake - RS.

Quarterly anomaly	Guaíba Lake															
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
DJF	-1.1	0.2	-0.6	0.2	-1.2	-0.7	0.1	<i>0.5</i>	-0.2	-0.3	<i>0.6</i>	0.2	-0.4	-0.2	<i>1.2</i>	<i>0.6</i>
JFM	-1.7	<i>0.5</i>	0.3	0.3	-0.9	-0.2	0.3	<i>0.5</i>	-0.4	-0.3	<i>0.5</i>	0.1	0.1	-1.2	<i>0.8</i>	0.4
FMA	-1.7	<i>1.4</i>	<i>0.5</i>	-0.2	-0.6	-0.2	0	<i>1</i>	-0.7	0.1	<i>0.7</i>	-0.1	0.2	-1.1	<i>0.5</i>	0.3
MAM	-0.3	0.3	<i>0.9</i>	-0.5	-0.3	0.4	-0.7	<i>0.7</i>	-0.3	0.2	0.1	-0.2	<i>0.5</i>	-0.9	0	0.2
AMJ	0.1	<i>1</i>	<i>0.8</i>	-0.3	-0.2	<i>1</i>	-0.7	-0.2	-1.1	-0.3	-0.2	-0.3	<i>0.6</i>	-0.5	0.1	0.4
MJJ	-0.6	<i>1</i>	<i>0.6</i>	0.4	-0.5	<i>1.2</i>	0.3	-1.2	-0.8	-0.7	-0.2	-0.6	0.2	-0.3	0.4	<i>1.4</i>
JJA	-0.8	2	0.3	0.3	0.2	<i>1.1</i>	<i>0.6</i>	-1.8	-0.2	-0.8	-0.1	-1.1	<i>0.6</i>	-0.7	0.4	0.4
JAS	-1.3	<i>1.2</i>	0	-0.3	<i>0.6</i>	0.1	<i>0.6</i>	-1.1	0.3	-0.3	-0.3	-0.5	<i>0.8</i>	-0.7	<i>0.6</i>	
ASO	-0.4	<i>1.1</i>	0.2	-0.4	<i>0.6</i>	-0.6	-0.1	-0.7	-0.3	0	-0.5	-0.5	<i>1.6</i>	-0.7	<i>0.5</i>	
SON	-0.4	<i>0.7</i>	-0.5	0	0	-0.6	-0.2	0	-0.8	0.3	-0.4	-0.3	<i>1</i>	-0.2	<i>1.3</i>	
OND	0.1	0.4	-0.3	-0.7	-0.7	-0.5	0.3	-0.1	-0.6	0.3	-0.2	-0.6	<i>0.9</i>	0.4	<i>1.3</i>	
NDJ	-0.1	-0.1	-0.2	-1	-0.4	0.1	0.2	-0.2	-0.3	0.2	0.1	-1	<i>0.6</i>	<i>0.8</i>	<i>1</i>	

Source: Images of MODIS Sensor (MODIS, 2016). Values in bold are LSWT more than 5 °C below N (Guaíba General Climatological Average); values in italic and underlined are LSWT more than 5 °C above N; and in normal text are LSWT less than +/- 5 °C N.

Table 2. Comparison of LSWT anomalies above/below 5 °C between Pacific Ocean and Guaíba Lake - RS.

Quarterly anomaly	Pacific Ocean (polygon at coordinates 5°N-5°S, 120°E-170°W)															
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
DJF	-1.6	-0.7	-0.2	<i>0.9</i>	0.3	<i>0.6</i>	-0.7	<i>0.7</i>	-1.4	-0.8	<i>1.3</i>	-1.3	-0.7	-0.4	-0.5	0.5
JFM	-1.4	-0.6	-0.1	<i>0.6</i>	0.2	<i>0.6</i>	-0.6	0.3	-1.3	-0.7	<i>1.1</i>	-1.1	-0.6	-0.5	-0.6	0.4
FMA	-1.1	-0.5	0.1	0.4	0.1	<i>0.5</i>	-0.4	0	-1.1	-0.4	<i>0.8</i>	-0.8	-0.5	-0.3	-0.4	<i>0.5</i>
MAM	-0.9	-0.3	0.2	0	0.1	<i>0.5</i>	-0.2	-0.1	-0.9	-0.1	<i>0.5</i>	-0.6	-0.4	-0.2	-0.2	<i>0.7</i>
AMJ	-0.7	-0.2	0.4	-0.2	0.2	0.4	0	-0.2	-0.7	0.2	0	-0.3	-0.3	-0.2	0	<i>0.9</i>
MJJ	-0.7	-0.1	<i>0.7</i>	-0.1	0.3	0.2	0.1	-0.2	-0.5	0.4	-0.4	-0.2	-0.1	-0.2	0	<i>1</i>
JJA	-0.6	0	<i>0.8</i>	0.1	<i>0.5</i>	0.1	0.2	-0.3	-0.3	<i>0.5</i>	-0.8	-0.3	0.1	-0.2	0	<i>1.2</i>
JAS	-0.5	-0.1	<i>0.9</i>	0.2	<i>0.7</i>	0	0.3	-0.6	-0.2	<i>0.6</i>	-1.1	-0.5	0.3	-0.2	0	
ASO	-0.6	-0.1	<i>1</i>	0.3	<i>0.7</i>	0	<i>0.5</i>	-0.8	-0.2	<i>0.7</i>	-1.3	-0.7	0.4	-0.2	0.2	
SON	-0.7	-0.2	<i>1.2</i>	0.4	<i>0.7</i>	-0.1	<i>0.8</i>	-1.1	-0.3	<i>1</i>	-1.4	-0.9	0.4	-0.2	0.4	
OND	-0.8	-0.3	<i>1.3</i>	0.4	<i>0.7</i>	-0.4	<i>0.9</i>	-1.2	-0.5	<i>1.2</i>	-1.3	-0.9	0.2	-0.2	0.6	
NDJ	-0.8	-0.3	<i>1.1</i>	0.4	<i>0.7</i>	-0.7	<i>1</i>	-1.3	-0.7	<i>1.3</i>	-1.4	-0.8	-0.2	-0.3	0.6	
correlation	0.5	0.54	-0.32	0.05	0.53	0.09	0.14	0.31	0.13	0.33	0.82	-0.58	0.86	0.2	0.33	0.37

Source: Modified from NOAA (2016). Values in bold are La Niña periods; values in italic and underlined are El Niño periods; and normal text corresponds to normal climatic period.

of observations of minimum temperatures; T (12, k, i, j and 24, k, i, j) are measurements made on maximum and minimum thermometers performed at 12 and 24 UTC.

In order to complement the analyzes, it was necessary to verify the influence of seasonality in periods of climatic abnormality (Tables 3, 4, 5 and 6), separating data from periods of climatic abnormality (based on Table 2). The influence of seasonality is very contrasting in the research area, due to having four seasons well defined.

Some LSWT images from Oceancolor (2015) website were selected as typical representative of the presence of climatic phenomena (El Niño, La Niña and Climatic Normality). For the year 2010, the most typical of the presence of climatic normality and abnormalities, we selected three images centered around the time line of the respective climatic abnormality/normality, based on Table 2.

For the spatial analysis of Guaíba LSWT, maps were elaborated in ArcGIS 10 (ESRI, 2010) with spatial resolution of 1 km (MODIS sensor). The scales of the maps were standardized,

as well as the legend, with LSWT graduations of 1 °C by 1 °C, in gray scales. Maps B and C (Figure 3) have a single legend between 15 °C and 20 °C; and Figure 3A has a graduation between 29 °C and 33°C. In Figure 3 there are no temperature classes between 21 °C and 28 °C.

RESULTS AND DISCUSSION

Relation between Guaíba LSWT and El Niño/La Niña

In general, the Guaíba Lake LSWTs correspond to the SST anomalies of Equatorial Pacific Ocean. This, however, does not necessarily occur with the same intensity, in some cases, oscillating in a more or less intense way to El Niño and La Niña phenomena. The warming of Pacific Ocean waters during El Niño does not mean that Guaíba waters will also have a greater warming. However, they will certainly present oscillations and changes in

Table 3. Guaíba LSWT behavior during the autumn, in El Niño and La Niña periods.

	Autumn		
	Normal	El Niño	La Niña
Precipitation Santa Maria	0.16	0.24	0.02
Precipitation Porto Alegre	-0.11	0.11	-0.03
Wind speed Porto Alegre	0.13	0.27	0.13
Max. Temp. Porto Alegre	0.85	0.85	0.87
Min. Temp. Porto Alegre	0.85	0.89	0.88
Average Comp. Temp. Porto Alegre	0.88	0.90	0.89

Table 4. Guaíba LSWT behavior during the winter, in El Niño and La Niña periods.

	Winter		
	Normal	El Niño	La Niña
Precipitation Santa Maria	0.00	0.01	0.19
Precipitation Porto Alegre	-0.08	0.08	0.04
Wind speed Porto Alegre	0.04	-0.02	0.24
Max. Temp. Porto Alegre	0.67	0.66	0.68
Min. Temp. Porto Alegre	0.70	0.69	0.69
Average Comp. Temp. Porto Alegre	0.73	0.73	0.75

LSWT. The highest correlations occurred in the years 2010 and 2012, with 0.82 and 0.86, respectively, as it can be observed in Figure 4.

In Guaíba, seasonal oscillations in LSWTs occur due to its geographic location. The State of Rio Grande do Sul is located in a climatic transition zone, and therefore retains the participation of Extratropical Atmospheric Systems (polar fronts and masses) as well as of intertropical ones (tropical masses and Disturbed Currents), and the former exercise the control over the weather types (SARTORI, 2003).

Table 7 shows the correlations between INMET meteorological variables (Porto Alegre and Santa Maria stations) and Guaíba LSWTs (Table 1) during El Niño periods (see Table 2, underlined values).

As can be seen in Table 7, during El Niño the correlations between LSWT and temperatures (maximum, medium and average compensated), are higher for all years. In 2007 there was an increase in the correlation between LSWT and precipitation in Porto Alegre. The lower the precipitation index, the higher the LSWT, considering a correlation of -0.45. According to Kuenzer and Dech (2013) precipitation create a cooling in water lens, resulting in a high and negative correlation.

Considering the year of 2009, it is observed that the higher the precipitation index in Santa Maria, the higher the LSWT in Guaíba, for a correlation of 0.53 (Table 7). In fact, the increase in precipitation in the State Central Region (Santa Maria), is in line

Table 5. Guaíba LSWT behavior during the spring, in El Niño and La Niña periods.

	Spring		
	Normal	El Niño	La Niña
Precipitation Santa Maria	-0.16	-0.05	0.09
Precipitation Porto Alegre	-0.21	-0.06	-0.02
Wind speed Porto Alegre	0.12	-0.07	-0.17
Max. Temp. Porto Alegre	0.86	0.82	0.86
Min. Temp. Porto Alegre	0.74	0.75	0.78
Average Comp. Temp. Porto Alegre	0.85	0.83	0.87

Table 6. Guaíba LSWT behavior during the summer, in El Niño and La Niña periods.

	Summer		
	Normal	El Niño	La Niña
Precipitation Santa Maria	0.08	0.04	0.04
Precipitation Porto Alegre	0.09	-0.02	-0.04
Wind speed Porto Alegre	-0.09	0.25	0.09
Max. Temp. Porto Alegre	0.73	0.82	0.79
Min. Temp. Porto Alegre	0.72	0.78	0.75
Average Comp. Temp. Porto Alegre	0.80	0.89	0.83

with the increase in river discharge in the Jacuí Delta (ANDRADE NETO, 2011) and with higher water temperature in the lake system. On the other hand, local precipitations cause the cooling of the water slide.

Table 8 shows the correlations between INMET meteorological variables (Porto Alegre and Santa Maria stations) and Guaíba LSWTs (Table 1) during La Niña periods (see Table 2, values in bold). Considering the temperatures (maximum, minimum and average compensated), good correlation values occur, followed by wind speed.

In La Niña periods correlations between precipitation in Porto Alegre and Guaíba LSWT tend to be negative. A single exception was the year 2012, when correlations are positive both for precipitation in Santa Maria and Porto Alegre.

Table 9 presents a comparison between the values of maximum and minimum correlations of El Niño/La Niña phenomena. It is observed that both the maximum and minimum values of precipitation data in the Santa Maria Region, as well as precipitation data in Porto Alegre, present the highest correlation values in El Niño periods.

Using interannual precipitation data, Britto et al. (2008), in a time frame between 1967 and 1998, of 14 Meteorological Stations, showed that in years of ENSO, there are negative and positive precipitation indices associated to the phenomenon. According

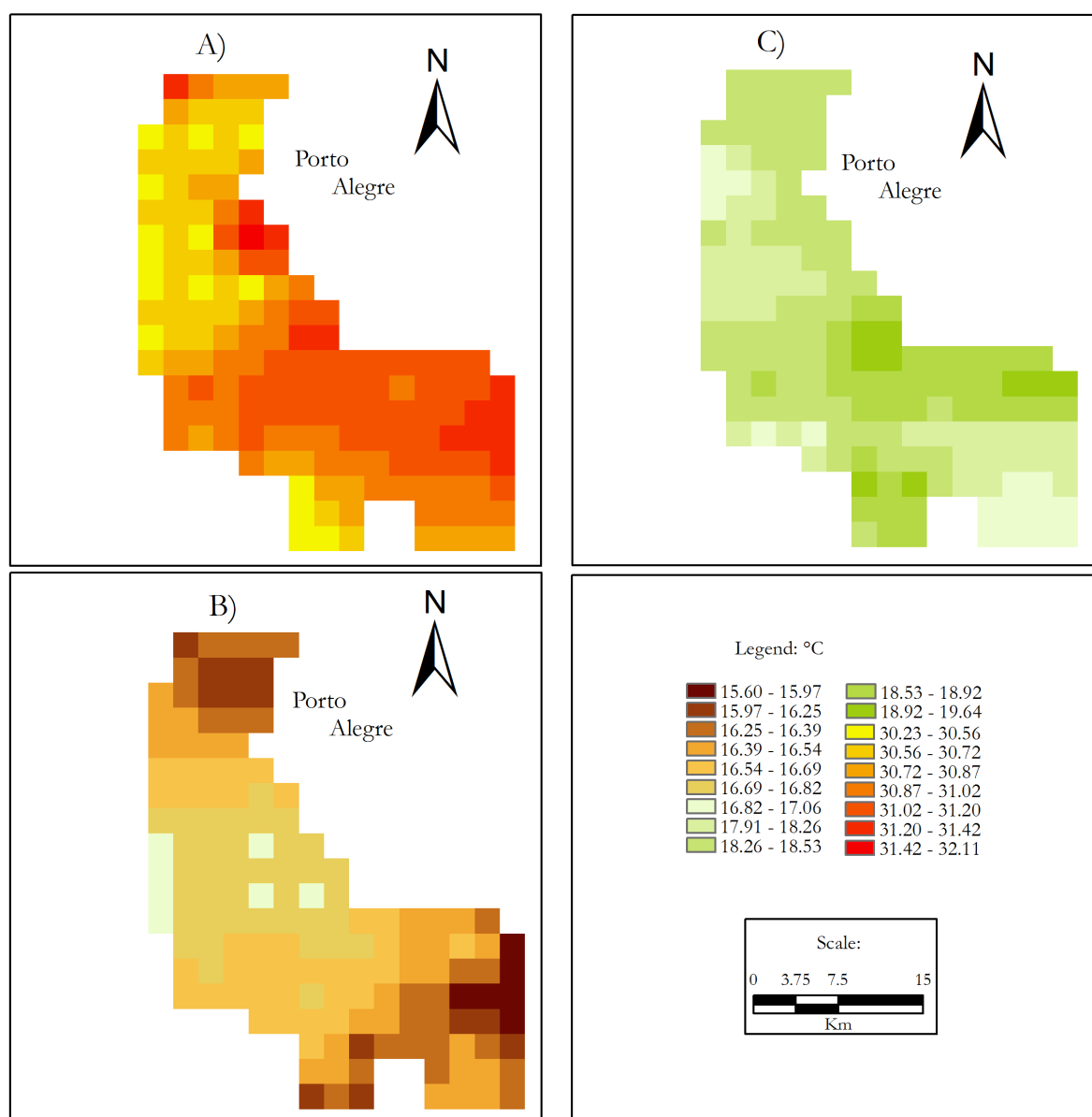


Figure 3. Guaíba LSWT behavior in 2010, in periods of climatic normality and abnormality (El Niño e La Niña). In A) February 2010; C) September 2010 e C) June.

to the authors, precipitation occurs more in the northern half of the State of Rio Grande do Sul, with totals higher than 1500 mm. In the region of Porto Alegre and Pelotas, the lowest precipitation indices are observed.

In Rio Grande do Sul, in El Niño years, hot and humid, precipitation occurs above average. In La Niña years, cold and dry, below-average precipitation is observed (BERLATO; FONTANA, 2003; BERLATO et al., 2005).

Still in Table 9, one can observe higher correlations between Guaíba LSWT and wind speed in Porto Alegre (p 0.80) and precipitation (p 0.53) occurred in the Central Region (meteorological data of the Municipality of Santa Maria), during the El Niño. It is observed that the correlation between precipitation in Porto Alegre and LSWT, during El Niño, is -0.45, occurring a LSWT cooling.

Winds during La Niña are also strong conditional indicators of the increase of Guaíba LSWT (correlation of 0.53), such that,

with the increase of precipitation in Porto Alegre, they condition the reduction of LSWT (correlation of -0.37).

Seasonal behavior of LSWT: in normal, El Niño and La Niña periods

According to Table 3, 4, 5 and 6, in general, air temperature has the highest correlations with LSWT, more or less intensely, but always predominating over other factors (precipitation and wind speed). The average compensated air temperature prevails over the maximum and minimum temperature correlations.

It is observed that correlations with wind speeds are higher during the autumn in all climatic periods (El Niño, La Niña and normal), with greater expression during El Niño (0.27). Wind speed also shows an increase in correlations during La Niña in

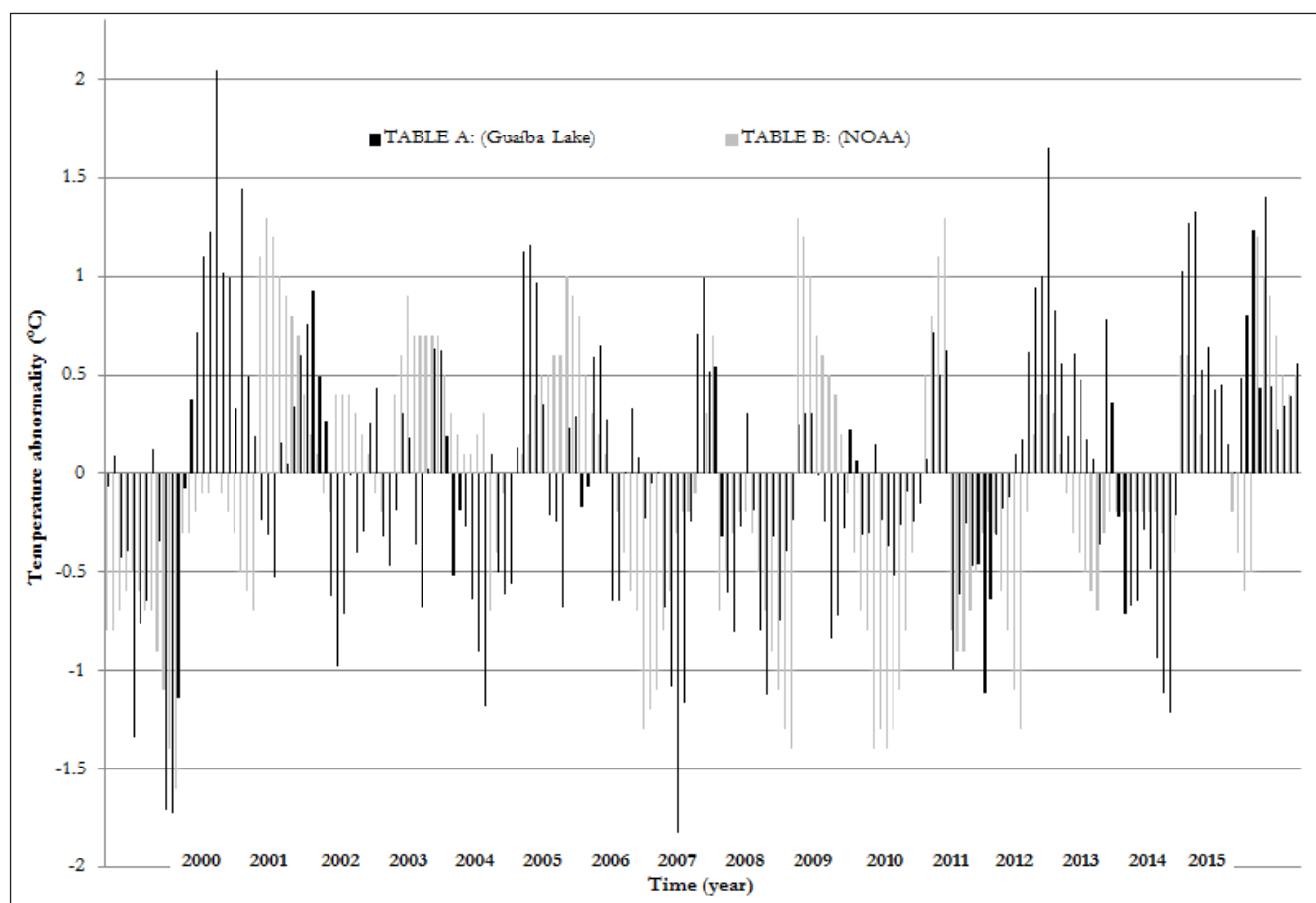


Figure 4. Oscillations of Pacific Ocean SST and Guaíba- RS LST.

Table 7. Guaíba Lake LSWT during El Niño periods, and correlation with Wind speeds, Temperatures (maximum, minimum and average compensated) considering precipitation in Porto Alegre and Santa Maria.

	Guaíba LSWT in El Niño periods (°C)									
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2015
Precipitation Santa Maria	-0.07	0.03	0.04	0.11	-0.07	-0.13	-0.27	0.53	0.17	-0.15
Precipitation Porto Alegre	-0.17	0.28	-0.25	-0.04	0.16	-0.45	-0.22	0.07	0.10	-0.29
Wind speed Porto Alegre	0.11	-0.23	0.80	0.77	-0.04	0.20	0.23	0.42	-0.14	0.80
Max. Temp. Porto Alegre	0.87	0.91	0.89	0.82	0.88	0.66	0.93	0.91	0.95	0.94
Min. Temp. Porto Alegre	0.90	0.85	0.86	0.81	0.92	0.46	0.91	0.97	0.89	0.96
Average Comp. Temp. Porto Alegre	0.90	0.96	0.90	0.85	0.92	0.64	0.94	0.96	0.94	0.96

the winter (0.24) and in the summer during El Niño (0.25). In the spring, wind speed has a correlation of 0.12 during normal periods; yet in La Niña periods it is -0.17. In El Niño periods there is no significant correlation.

Taking into account precipitation in Santa Maria and Guaíba Lake (Porto Alegre), it is observed that during the autumn in normal and El Niño periods the correlations are respectively 0.16 and 0.24 (Table 3).

During the winter (Table 4) in La Niña periods, precipitation in Santa Maria becomes significant, with a correlation of 0.19 with Guaíba LSWT. During the spring in normal periods, precipitation in Santa Maria and Porto Alegre correlates negatively with LSWT, corresponding to -0.16 and -0.21.

Through the empirical orthogonal function, Zanotta et al. (2013) verified a variation in LSWT in the north of the Patos Lagoon, and in the Guaíba area a strong relation with bathymetry.

Table 8. Guaíba LSWT during La Niña periods, and correlations with meteorological variables of Santa Maria and Porto Alegre.

	Guaíba LSWT in La Niña periods (°C)						
	2000	2008	2007	2010	2011	2012	2013
Precipitation Santa Maria	0.13	0.27	-0.23	-0.19	0.05	0.28	0.10
Precipitation Porto Alegre	-0.07	-0.22	-0.20	-0.38	-0.03	0.22	-0.16
Wind speed Porto Alegre	0.01	-0.01	0.40	0.53	0.39	0.44	0.45
Max. Temp. Porto Alegre	0.88	0.91	0.93	0.91	0.92	0.88	0.90
Min. Temp. Porto Alegre	0.91	0.88	0.93	0.88	0.96	0.88	0.95
Average Comp. Temp. Porto Alegre	0.92	0.93	0.95	0.92	0.96	0.90	0.94

Table 9. Maximum and minimum values of correlations between El Niño and La Niña.

	La Niña		El Niño	
	Max.	Min.	Max.	Min.
Precipitation Santa Maria	0.28	-0.23	0.53	-0.27
Precipitation Porto Alegre	0.22	-0.38	0.28	-0.45
Wind speed Porto Alegre	0.53	-0.01	0.80	-0.23
Max. Temp. Porto Alegre	0.93	0.88	0.95	0.66
Min. Temp. Porto Alegre	0.96	0.88	0.97	0.46
Average Comp. Temp. Porto Alegre	0.96	0.90	0.96	0.64

But there are also other factors that interfere in LSWT, such as the lake retention time and wind direction. These factors are definers in warming or cooling by wind (LUZ et al., 2015), as well as the removal of bottom sediments in areas of small depths and the formation of waves during occurrences of strong winds (BENDATI et al., 2000).

In periods of floods, level variations are less sensitive to wind speed, yet in normal or dry periods, winds of approximately $7\text{m}\cdot\text{s}^{-1}$ can produce oscillations greater than 50 cm (NICOLODI et al., 2010).

The year 2010 is typical of the presence of all El Niño, La Niña and Normal phenomena (Table 2), being used as the basis for selecting the most representative images, and giving rise to the maps of Figure 3A-C, Where the LSWT variation is observed. According to Curtarelli (2012) data collected by medium resolution optical sensors such as MODIS have great potential to provide information and parameters used in models.

In Figure 3A (T20100412010048, where, T means satellite TERRA, 2010 the year, 041 the Julian day of the initial image, 2010 the year and 048 the Julian day of the final image), relative to the second week of February and the effect of El Niño, LSWT is observed above $29\text{ }^{\circ}\text{C}$, reaching $33\text{ }^{\circ}\text{C}$ on the eastern margins near the urban area of Porto Alegre.

In Figure 3B (T20101692010176), relative to the third week of June, a period of short climatic normality, a cooling with LSWTs below $17,16\text{ }^{\circ}\text{C}$ is verified. There is a more homogeneous spatial distribution of LSWTs, varying between $15\text{ }^{\circ}\text{C}$ and $17.15\text{ }^{\circ}\text{C}$, with the exception of the margins. The lowest LSWTs occur in the east margin and the highest ones in the west margin.

According to Curtarelli (2012), the surface heat fluxes obtained by means of the MODIS product for water surface temperature show that sensible and latent heat losses can be up to 4 times higher during the occurrence of cold fronts.

In Figure 3C (T20102572010264), relative to the third week of September and La Niña phenomenon, LSWT warms up again, between $16\text{ }^{\circ}\text{C}$ and $19\text{ }^{\circ}\text{C}$. It presents larger spatial variations of non-uniformly distributed LSWTs, but the highest temperatures are in the central region of the Guaíba.

According to Paz et al. (2005), regarding water circulation among the Lake areas, the “interaction” between the navigation channel and the external regions is very small, prevailing two main kinds of water circulation, which have barely been “mixed”.

Certainly with the effect of air temperatures, due to seasonality, it is observed that, in Figures 3B and 3C, the lowest LSWTs are located to the north and southeast of the Guaíba water mass. In contrast, in Figure 3A the areas with higher LSWTs are located to the north and southeast. In fact, the winter is conditioning a greater cooling of the water body. The seasonality information evidences the difference of LSWTs between the images.

Water entry is acting so as to intensify the warming/cooling process of the water body, as well as in the southeastern portion, a place with less water flow and low depth, the greater water retention allows it to be more affected by the action of air temperature and wind direction (PAZ et al., 2005; LUZ et al., 2015). According to Curtarelli (2012), the passage of cold fronts affects hydrodynamics, thermal structure and mixing regimes, which may result in changes in water quality

According to Nicolodi et al. (2010) the waves incident in Guaíba follow the patterns and intensity of the winds and have the potential to generate turbulence next to the bottom. According to Rovira (2006 apud ANDRADE NETO, 2011), the hydraulic properties of river flow are not the only responsible for sediment concentration, but also the sediment supply, the intensity and spatial distribution of rains, runoff rates and volumes, and the distances from flash flood locations to the main channel. According to Paz et al. (2005), in the water circulation pattern of Guaíba Lake, the influence of the discharge of forming rivers and the oscillation of Patos Lagoon level predominate.

Based on Tables 3, 4, 5 and 6, LSWTs are between $14\text{ }^{\circ}\text{C}$ and $33\text{ }^{\circ}\text{C}$, with large oscillations among this range of LSWTs as a function of seasonality, depth, precipitation, flow speed, increase in water entry, air temperature, winds, periods of climatological abnormality and normality.

The decrease of water entry in Guaíba Lake, during La Niña, increases water retention time in Guaíba Lake, allowing local meteorological factors to act more intensely in the definition of LSWTs. In El Niño, there is a greater action of pluviometric regimes coming from other regions (mainly during the autumn), making the entry of water at different temperature act more intensely in the definitions of LSWTs.

It is observed that there is a positive correlation between Guaíba LSWT and precipitation in Santa Maria. El Niño increases subtropical high pressure systems, causing the stagnation of polar fronts (SARTORI, 2003), which leads to an increase of precipitation indices in the State. These abnormalities in pluviometric precipitation are distributed in an anomaly gradient in the southeast-northeast direction (BERLATO; FONTANA, 2003). It rains more in the Central Region of the State of Rio Grande do Sul (Santa Maria) than in Porto Alegre (Lake Guaíba). This water entry becomes significant in the control of Guaíba LSWT, since the Santa Maria region is relatively close to some springs of the Jacuí River, which corresponds to 84.6% of the Guaíba Basin (DMAE, 2016).

In some El Niño/La Niña periods, wind speed has positive correlations with Guaíba LSWT. El Niño and La Niña events disorganize the zonal action centers and positioning, not allowing the typical activity of North Wind in the South of Brazil (SARTORI, 2003).

It is observed that precipitation increases in Porto Alegre (Guaíba Lake) have negative correlations with Guaíba Lake LSWT. In fact, precipitation causes a cooling of LSWT. The most intense precipitations create a cooling in the water lens, and consequently a stratification in the LSWT skin (KUENZER; DECH, 2013), mainly during the spring in periods of climatic normality.

On January 26, 2011, there was the emergence of green algae that left the Guaíba waters green (ZH Notícias, 2011). This was a La Niña period. Equatorial Pacific Ocean waters were colder than normal (NOAA, 2007; MARENGO, 2007), causing a reduction in the amount of precipitation in the State of Rio Grande do Sul (BERLATO; FONTANA, 2003).

Wind speed becomes an aggravating factor in the minimum and maximum peaks of Guaíba LSWTs during La Niña (in winter periods) and El Niño (in summer periods). During the autumn, precipitation becomes more significant in the control of LSWTs in El Niño and normal periods. During the spring, precipitation correlates negatively with normal periods.

It cannot be said that the intensity of El Niño and La Niña has the same intensity and significance on Guaíba LSWT. The variation of ± 5 °C in equatorial Pacific Ocean, not necessarily has the same correspondence with Guaíba LSWT. When analyzing the year 2013, for example, corresponding to a period of climatological normality, Lake Guaíba LSWTs were mostly with values -5 °C lower during most of the year.

CONCLUSIONS

In order to define the behavior of Guaíba LSWT, atmospheric climatic factors are not locally and directly proportional to the magnitude of LSWT. A very important factor in the changes in the LSWT field is water entry, mainly from the Jacuí River.

During El Niño there is an increase in water entry. In contrast, during La Niña, the water entry in the Guaíba lagoon system decreases, affecting Guaíba LSWT. In El Niño, the correlations between LSWT and temperatures (maximum, medium and average compensated), are higher for all years.

The decrease of water entry in Guaíba Lake, during La Niña, increases water retention time in Guaíba Lake, allowing local meteorological factors to act more intensely in the definition

of LSWTs. In El Niño, there is a greater action of pluviometric regimes coming from other regions (mainly during the autumn), making the entry of water at different temperature act more intensely in the definitions of LSWTs.

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Authors contributions

Glenio Antonio da Luz: Elaboration of the text, application of the methodology, treatment of the data, analysis and discussion of the results.

Laurindo Antonio Guasselli: Advisor, reviewer, analysis and discussion of results.

Daniela Rocha: Treatment, extraction of the data and information of MODIS images.