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Surface temperature patterns of Lagoa dos Patos, Brazil, using NOAA-AVHRR data: an annual cycle analysis

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Abstract - A processing chain for NOAA-AVHRR data can be used to retrieve lake surface water temperatures (LSWT) measurements based on a nonlinear sea surface temperature (NLSST) algorithm generally applied to open ocean conditions. This extended application has been widely used in lakes around the world and the bias of the algorithm is around 1-1.5°C. LSWT monthly average maps of surface temperature have been generated for Lagoa dos Patos, at Rio Grande do Sul State, covering the period from August/2007 to July/2008, for daytime and nighttime in order to study the annual cycle. Results show strong lake surface temperature variations within that period, and reveal an interaction with the adjacent ocean in the estuarine region. Temperatures ranged between 9.9 to 29.5 °C in daytime and from 9.9 to 27.8 ºC in nighttime. It was found that the bathymetric profile is the most significant parameter influencing LSWT salient features and the thermal dynamic of the lagoon. Knowledge of these variations gives new insights of local processes, and leads to possibilities for modeling local scale phenomena involved. The analysis procedure also provides a more realistic depiction of the distribution of the temperature than climatological maps.
Keywords: Lagoa dos Patos, surface water temperature, thermal features, cycle study.

Resumo - Padrões de temperatura superficial da Lagoa dos Patos, Brasil, utilizando dados NOAA-AVHRR: uma análise de ciclo anual. Rotinas de processamento em dados NOAA-AVHRR podem ser empregadas para estimar a temperatura superficial de lago (TSL) com base em algoritmos tradicionalmente desenvolvidos e aplicados em ambientes oceânicos. Esta extenção da aplicação tem sido largamente utilizada em diversos lagos ao redor do mundo alcançando um *bias* entre 1-1,5 °C resultante do algoritmo. Mapas mensais de temperatura da superfície da Lagoa dos Patos, RS, cobrindo o período de Agosto/2007 a Julho/2008 foram gerados para período diurno e noturno com o intuito de estudar o ciclo anual. Os resultados mostram grandes variações de temperatura dentro desse período, e revelam a interação existente com o Oceano Atlântico na região estuarina. As temperaturas variam entre 9,9 a 29,5 ºC durante o dia e entre 9,9 a 27,8 °C durante a noite. Foi verificado que o perfil batimétrico é o parâmetro mais significante influenciando as feições de TSL e a dinâmica termal da lagoa. O conhecimento dessas variações produz novas percepções sobre os processos locais, e conduz a diferentes formas de modelagem dos fenômenos envolvidos em escala local. A análise fornece também uma descrição mais realística sobre a distribuição superficial da temperatura do que mapas climatológicos.
Palavras-chave: Lagoa dos Patos, temperatura superficial da água, feições termais, estudo do ciclo.

1. Introduction

Information about the temperature of large water bodies plays an important role on interactions between earth surface and atmosphere process, as well as in navigation and fishery. For these reasons, the knowledge of the spatial and temporal heat distribution is extremely valuable. The lake surface water temperature (LSWT) acts in the physical, chemical and biological lacustrine processes, and is one of the factors that affects the climate variables; many lakes have a large enough water volume and surface to significantly influence local weather patterns due to their surface temperature (Livingstone *et al.*, 2001). Moreover, the knowledge of the LSWT can indicate the more appropriate places to catch specific fish species (Arnell *et al.*, 1996).

The Lagoa dos Patos (Fig. 1) is a lagoon located in the south-east of Rio Grande do Sul State (Brazil), where it acts as a place of convergence of freshwater arriving from several hydrographic basins. It shelters many aquatic animal species and is essential for fresh water supply to many localities along its shoreline. Nowadays the lagoon has an intense traffic of commercial ships that cruise from the State interior to the Atlantic Ocean through the Rio Grande canal. With an area of approximately 10,227 km^2, it is the largest coastal lagoon in Brazil, and the second largest in South America. However, despite its large extension, it is a shallow water body with a mean depth of about 5 m (Asmus, 1998).

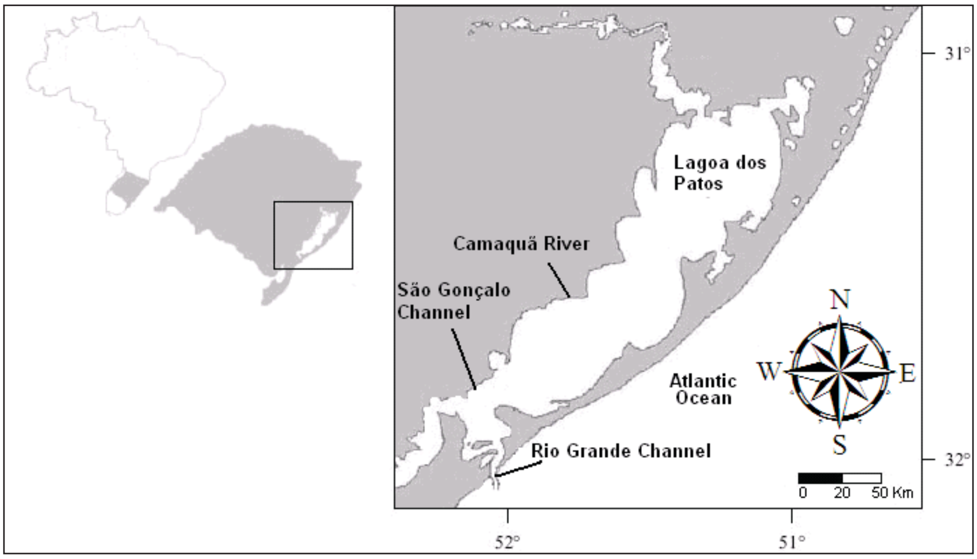

Figure 1. Localization of Lagoa dos Patos, RS, Brazil, and adjacent rivers/channels.

Many research lines have been conducted for the Lagoa dos Patos, as investigations about the distribution, spatial flow and gradients of freshwater discharges, water level, salt dispersion, sediments and pollutants that are related to local wind forces, rivers inflow, pressure and bottom morphology (Niencheski *et al.*, 1988; Möller *et al.*, 2001; Castelão & Möller, 2003; Fernandes *et al.*, 2005). However, the temperature cycle of the lagoon is not well documented. Historically, only a few *in situ* temperature measurements were made in more accessible or important places, as near cities or in ship traffic lanes. Unfortunately, the high variability found in the shore regions, and the limited ship route coverage, do not return data suitable to derive the spatial distribution of the temperature pattern in such a large lake (Schwab *et al.*, 1999). In this context, orbital remote sensing has been an effective way to study the water surface temperature of large aquatic bodies. The spatial and temporal data acquired with satellite observations are essential for a better monitoring and understanding of several meteorological phenomena, representing an enormous source of input data to weather forecast models.

The LSWT can be operationally derived from the thermal channels of many sensors, as the *Advanced Very High Resolution Radiometers* (AVHRR) aboard the meteorological satellites operated by the *National Oceanic and Atmospheric Administration* (NOAA), applying the *split-window* algorithms normally used to compute the *Sea Surface Temperature* (SST) in global scale. The algorithms generally employed are the *Multi-Channel Sea Surface Temperature (MCSST)* and the *Non-linear Sea Surface Temperature (NLSST),* widely used and improved since their development a few decades ago (Oesch *et al.*, 2005). The application of this method to derive the surface temperature of large freshwater systems, as lakes and lagoons, leads to an imprecision due to the marine physical and morphological conditions inherent to the development, where all algorithms coefficients were originally determined. Here, the coefficients within the algorithms were computed with opportunity ships data and buoys of the *National Data Buoy Center* (NDBC) in oceanic conditions, not lacustrine conditions. When the methodology used in oceans is applied in lakes or lagoons, some degradation in accuracy is expected. For the Great

Lakes (USA), for example, studies using different sensors aboard various satellites estimate a bias of about 1.0 to 1.5 K and a standard deviation around 1.0 K, based on comparisons with *in situ* data (Schwab *et al.*, 1992).

In spite of these handicaps, studies have been conducted for a considerable number of lakes in many countries: the Great Lakes (USA) (Schwab *et al.*, 1992; Schwab *et al.*, 1999; Li *et al.*, 2001), some Canadian lakes (Bussières *et al.*, 2001), Africa (Wooster *et al.*, 2001), and Continental Europe (Thiemann & Schiller, 2003). Although the accuracy of the data cannot be confirmed without a validation with in-situ data, these numbers have a great importance to understand the spatial and temporal variations of temperature in the lagoon.

This work aims at investigate the annual pattern variability of the thermal structure of the Lagoa dos Patos employing the above mentioned methodology.

2. Materials and methods

Full resolution AVHRR-NOAA images were recorded in High Resolution Picture Transmission (HRPT) format at the receiving station at the Remote Sensing Center of the Federal University of Rio Grande do Sul (UFRGS). Images from AVHRR/3 (flown on NOOA-15 and later series satellites) contain five channels, being two channels at visible spectral bands (channel 1 at 0.58–0.68 m, channel 2 at 0.725–1.00 m) and four channels in the infrared (channel 3a at 1.58–1.64 m, channel 3b at 3.55–3.93, channel 4 at 10.30–11.30 m, and channel 5 at 11.50–12.50 m). Spatial and radiometric resolutions are 1.1 km and 10 bits, respectively. A total of 79 images from August 2007 to July 2008 were acquired. As these data were the starting point for LSWT determination, some pre-processing was done. The received data, with coordinates and calibration information appended, are radiometrically corrected and calibrated in physical units at full instrument resolution at channels 4 and 5, using the Planck function for the black body. A geometric transformation function is evaluated at every pixel on the image by using about 15 georeferenced points close to the lagoon's shores, in the WGS84 system. Subsequently, a subset focuses the region of interest. The size of the pixel in latitude-longitude was fixed as being 0.01 degree (1.1 km), according to the operational parameters found in NOAA Polar Orbiter Data User´s Guide (Kidwell, 1991). Bathymetric data for the area of interest came from Toldo Jr. *et al.* (2006).

The different water vapor absorption properties in the different channels of the AVHRR sensor are employed to correct the atmosphere effects. A slight, but not negligible distortion of the channels in the infrared spectrum is due to the atmospheric absorption, mainly from water vapor. This effect can be corrected by the split window technique, which uses the difference between channel 4 and 5. The MCSST algorithm in the equations (1), which was developed based on the work by McClain *et al.* (1985), employs the split window concept. It had been used operationally by the researchers in the eighties.

Despite it retrieves reasonable results, MCSST supposes that there is a linear relationship between two differences: the one between the actual SST and an AVHRR infrared channel equivalent black body temperature; and the difference of temperatures from satellite measurements in the split window channels (*c4-c5*). Some works, such as in Walton (1988), found b_2 and b_3 in equations (1) as having atmospheric water vapor dependence, making these coefficients to be slightly nonlinear. These limitations are overcame with the nonlinear SST algorithm, developed to improve the results, returning less scatter when comparing satellite SST against *in situ* data (Walton, 1988; Walton *et al.*, 1998).

The algorithm presently used to provide the surface temperature values was essentially the NLSST from Walton (1988) and described in Oesch *et al.* (2003):

$$\begin{aligned} NLSST &= a_1(c4) + a_2(c4 - c5)(MCSST) + a_3(c4 - c5)(q) - a4 \\ MCSST &= b_1(c4) + b_2(c4 - c5)(MCSST) + b_3(c4 - c5)(q) - b4 \end{aligned} \quad (1)$$

where:

NLSST, MCSST = non-linear and multichannel SST;

c4, c5 = channels 4 and 5 AVHRR brightness temperatures in K;

a_1-a_4, b_1-b_4 = coefficients provided by the National Environment Satellite Data and Information Service (NESDIS-NOAA);

q = ((secant of satellite's zenith angle) – 1).

For the two equations in (1), the a_1-a_4 *e* b_1-b_4 coe-fficients are routinely obtained for the operational sensor platforms by performing a regression using a match-up database of satellite retrievals and *in situ* data. There are different sets of coefficients for daytime and nighttime.

The annual cycle was covered by collecting NOAA-17 data between August/2007 and July/2008 in daytime and nighttime, at 11:30 am and 11:30 pm approximately, in local time.

Taking advantage of the fact that there are different atmospheric absorptions due to water vapor between the AVHRR channels (Anding & Kauth, 1970; Prabhakara *et al*., 1974), the methodology to exclude cloud contaminated pixels did the subtraction of the brightness temperature of channel 5 by channel 3; the difference must be equal or less than -0.6°C (Schwab *et al*., 1999). Also, pixels with temperature values less than 0°C were excluded, since they were certainly due to cloud tops. The final monthly maps were the result of averages made at pixel level, over all available images in each month.

3. Results and analysis

A total of 24 surface temperature maps of the Lagoa dos Patos were generated, along with the adjacent ocean region, to allow analysis of the interaction in the estuarine region. The maps (Fig. 2 and 3) correspond to monthly means, where the number of images used for each month changes according to their availability in the period. For better description of the temperature variability range, each monthly map has its own color palette of reference, which vary in a continuum form from blue (minimum temperature in the monthly mean) to red (maximum temperature in the monthly mean), with each map informing the monthly mean average temperature in Celsius (°C) degrees. The shoreline effects are generally border artifacts and must be neglected.

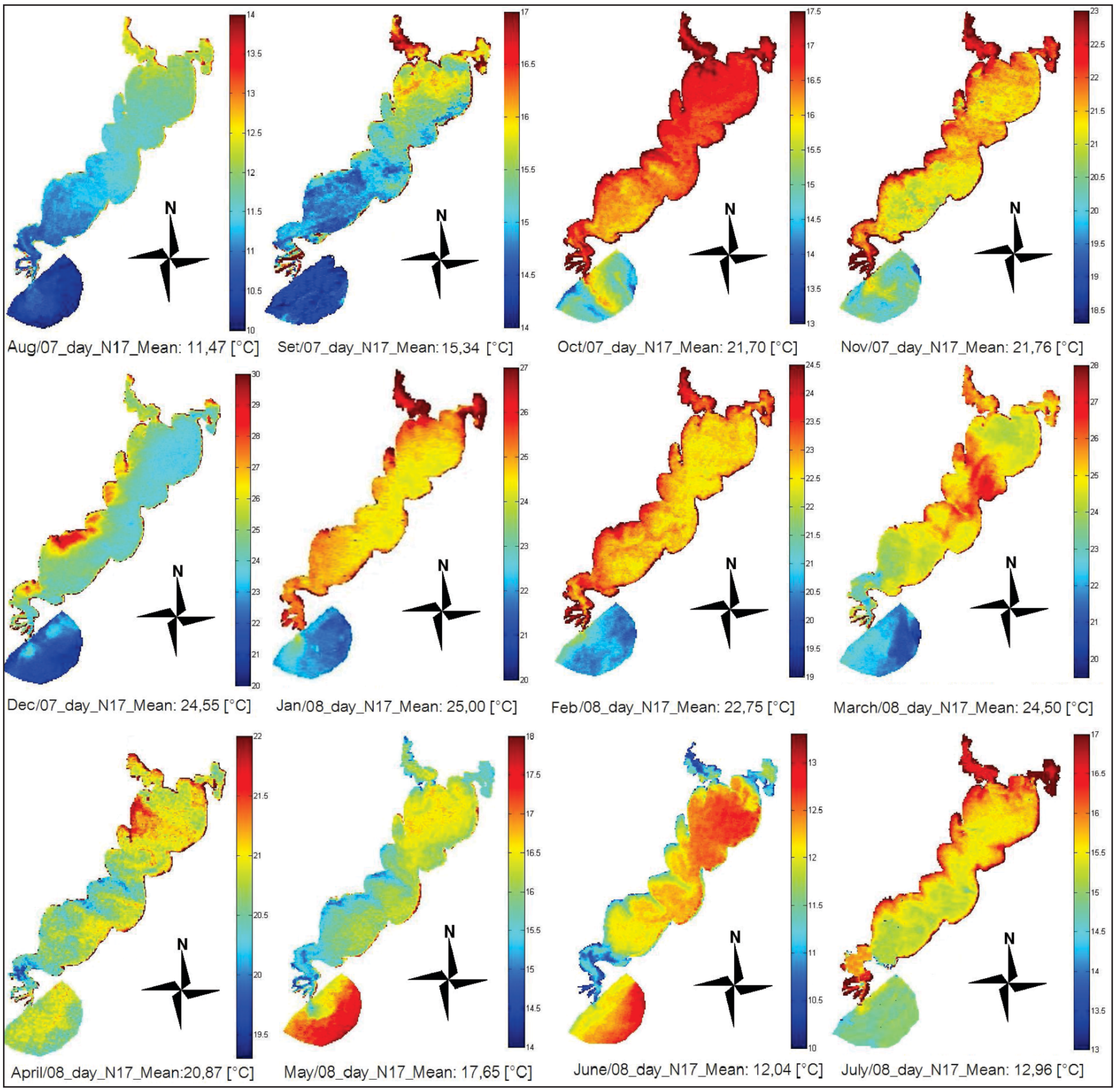

Figure 2. LSWT monthly diurnal variation between August/2007 and July/2008.

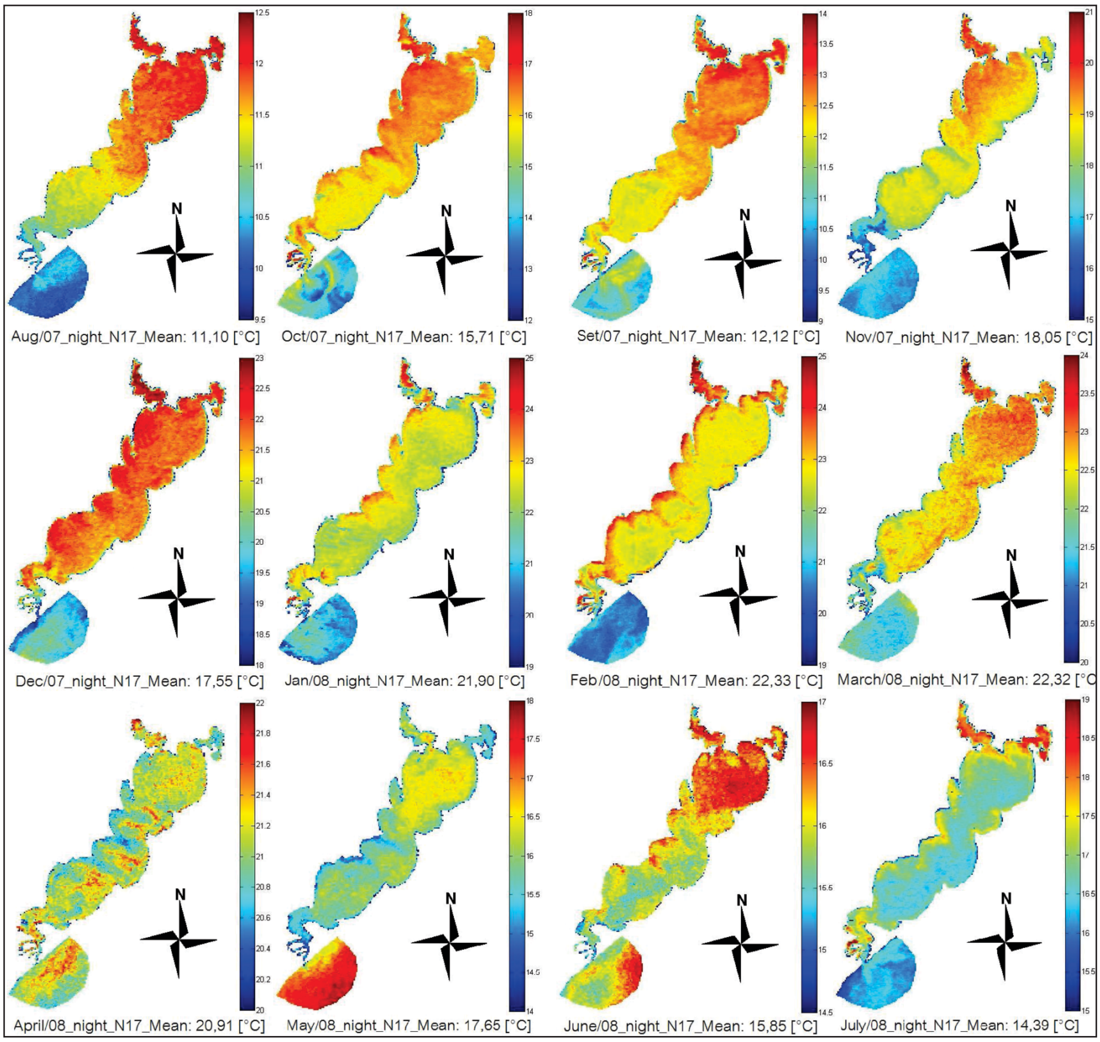

Figure 3. LSWT monthly night variation between August/2007 and July/2008.

As can be seen from the maps, the monthly average of TSL of the Lagoa dos Patos from August/07 to July/08 vary during the night from 9.9°C in August to 24.8°C in February, and during the day from 9.9°C in August to 29.5°C in December. The spatial variation of temperatures in daytime is greater than in nighttime period: the average of this variation reaches 4.7°C during the day and 2.7°C during the night. This is an evident effect of solar heating. The spatial variability, especially when comparing the daytime summer months like December (20-30°C) and January (20-27°C) with winter months like June (10-13.5ºC) and July (13-17ºC), expresses the stronger seasonal temperature range dependence.

The thermal patterns found within a lagoon are due to the complex internal circulation, which is related to bathymetric, meteorological and seasonal parameters, along with wind patterns and input of external fresh water from regional basins (Oesch *et al.*, 2003). Among these factors, it is found that the bathymetric profile and the interaction with regional basins are the most significant factors influencing LSWT and the thermal dynamic of the Lagoa dos Patos. It is worth noting that all the quoted parameters act in the thermal description of the lagoon surface. However, as we can see, the bottom morphological aspect and the input of external fresh water from regional basins and rivers are dominant in the characterization of the thermal features. In fact, according to Xie *et al.* (2002), there is a thermal inertia which is proportional to the bottom depth and determines the warming rate of the water: deep water temperatures vary much more slowly than shallow waters. The cited study found that bathymetric-control mechanism predicts a strong association between LSWT and bottom topography distributions. The bathymetric map of the Lagoa dos Patos indicates a number of salient thermal patterns having a spatial correlation with the bottom topography (Fig. 4).

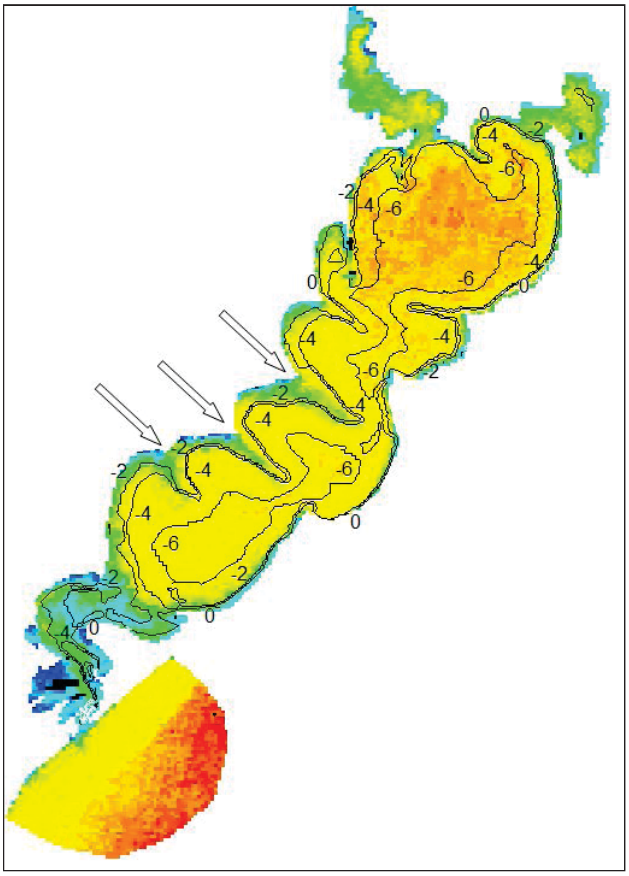

Figure 4. Thermal map June 18, 2008 (daytime) overlapped with the lagoon bathymetry (isobaths every 2 m). Arrows indicate the regions where bathymetric profile induces the thermal patterns.

Depending on the map, the effect is more or less evident but, in general, it can be noticed that the surface temperatures of some shallow areas are spatially different compared to the rest of the lagoon. Whether it is colder or warmer depends on the thermal dynamic around the period. Especially at daytime, some cool patterns near the center-west region can be seen (arrows at Fig. 4) related to bathymetric influence. In the monthly maps, the phenomena is more visible in May/08 and June/08 in daytime, and May/08 and Nov/07 at nighttime; this same kind of pattern can be found, but with warmer waters, at Jan/08 and Feb/08 nighttime.

On the other hand, it can be noticed that another phenomena also causes considerable influences on the thermal surface pattern, mainly on the west portion of the lagoon. This aspect can be reasonably related to near-shore warmer water arriving from the adjacent basins (mainly Camaquã river and São Gonçalo channel). This can explain the west near-shore warmer patterns found in Dec/07, as well as in other months, where the same fact is observed less clearly. In fact, the mean annual input of freshwater from the basins to the lagoon is extremely large and reaches 2400 m^3/s; significant variations in this value are generally tied with “El Niño” and “La Niña” events (Vaz *et al.*, 2006). It must be noted that the image collection used to compute the Dec/07 mean was made with just three images, due to large presence of clouds in this month. It is also worth noting that, because the cloud condition is crucial to derive LSWT from remote sensing optical images, the image data collection used to compute the monthly average LSWT are not necessarily correspondent for daytime and nighttime. This can cause differences in the patterns found for the two periods (e.g., Dec/07 daytime and nighttime are spatially different).

Concerning the thermal system relationship between the ocean and the lagoon through Rio Grande channel, in general, it is observed that the areas further north have greater temperature values compared with the areas to the south and, except for a few months, the lagoon is warmer than the ocean. The launch of lagoon waters into the sea is shown by the temperature difference in some images, highlighting the traditional plume formed in the adjacent coastal region currently being studied by numerical models (Marques *et al.*, 2009). The reverse phenomena (input of sea water into the lagoon) can also occur, but as the satellite temperature measured is from the skin layer, the effect is masked since seawater tends to flow beneath the lagoon freshwater because of its density difference (Wright & Friedrichs, 2006).

4. Conclusions

In this work we analyzed and discussed the thermal patterns found in an annual cycle (Aug /2007 to July/2008) for Lagoa dos Patos/RS. Analyzing the results presented by the thermal maps and the bathymetric lagoon profile, which presented strong spatial correlation, we concluded that the morphological description, through the prominences, characterizes the physical constraints leading to restrict water circulation, causing the thermal patterns found on the surface. Moreover, the also strongly noticeable patterns found on the west region in some months were clearly recognized as due to the basins/rivers inflow.

The remaining factors (e.g., local winds, tidal regime, and internal currents) were not deeply analyzed in this work. Despite the fact that we assumed here that they have no significant influence in the thermal features presented, it would be of great value to study a possible relationship. Some referenced works (e.g., Niencheski *et al.*, 1988; Möller *et al.*, 2001; Castelão & Möller, 2003; Fernandes *et al.*, 2005), as well as additional meteorological data, would bring information on physicochemical parameters which could be used to improve and further develop such studies.

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