On the spatially water surface temperature and heat flux variability over a tropical hydroelectric reservoir

E.H. Alcântara[1*], J.L. Stech[1], X. Casamitjana[2], M.P. Bonnet[3], J.A. Lorenzzetti[1], E.M.L.M. Novo[1]

[1]National Institute for Space Research, Remote Sensing Division, Brazil.
[2]Environmental Physics Group, Physics Department, University of Girona, Spain
[3]Institut de Recherche pour le Développement, France

**Corresponding author, e-mail* enner@dsr.inpe.br

ABSTRACT

Water temperature plays an important role in ecological functioning and in controlling the biogeochemical processes of a water body. Conventional water quality monitoring is expensive and time consuming. It is particularly problematic if the water bodies to be examined are large. Conventional techniques also bring about a high probability of undersampling. Conversely, remote sensing is a powerful tool to assess aquatic systems. The objective of this study was to map the surface water temperature and improve understanding of spatiotemporal variations in a hydroelectric reservoir. In this work, MODIS land-surface temperature (LST) level 2, 1-km nominal resolution data (MOD11L2, version 5) were used. All available clear-sky MODIS/Terra images from 2003 to 2008 were used, resulting in a total of 786 daytime and 473 nighttime images. Descriptive statistics (mean, maximum and minimum) were computed for the historical images to build a time series of daytime and nighttime monthly mean temperatures. The thermal amplitude and anomaly were also computed. In-situ meteorological variables were used from 2003 to 2008 to help understand the spatiotemporal variability of the surface water temperature. The surface energy budget and the depth at which the wind can distribute the heat input of a given surface were also measured. A correlation between daytime and nighttime surface water temperatures and the computed heat fluxes were made. These relationships and the causes of the water surface temperature variability are discussed.

Keywords: Remote sensing**;** water surface temperature; heat flux; mixed depth layer; thermal amplitude; MODIS.

INTRODUCTION

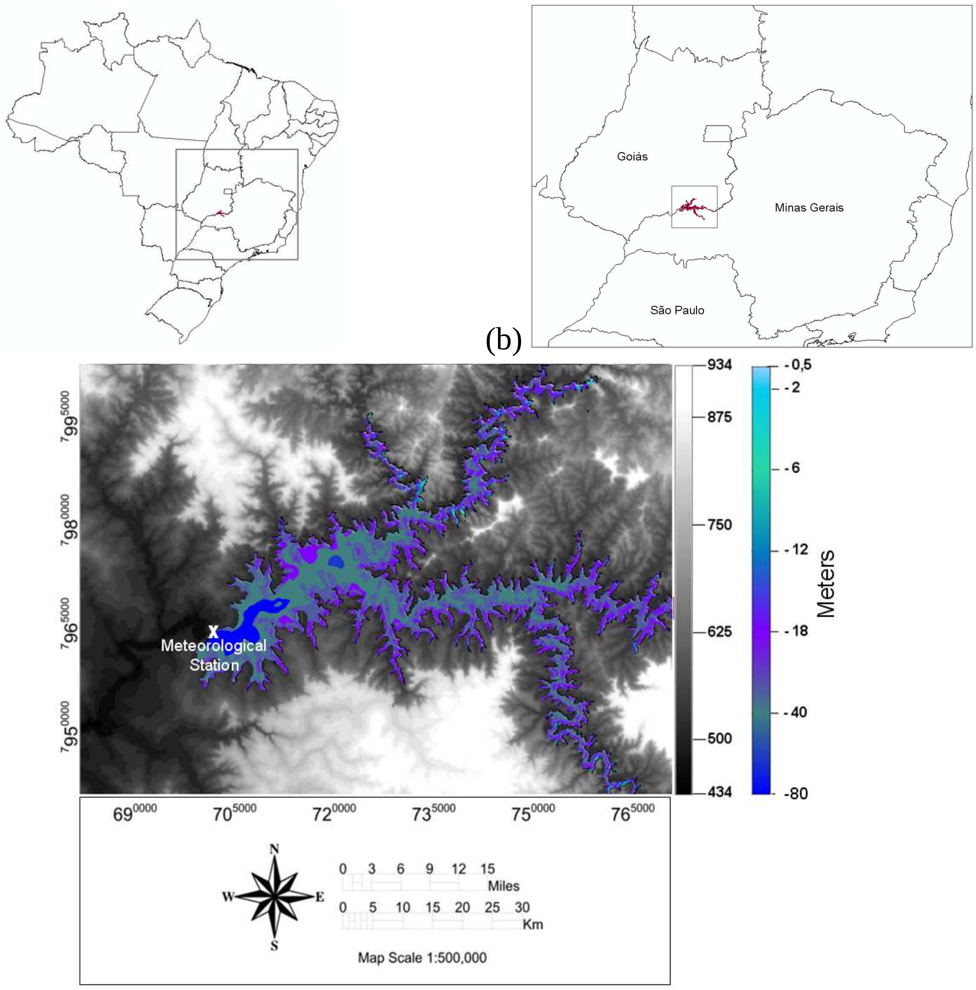
In accordance with Kimmel et al. (1990), water temperature distribution is fundamental to understanding the performance and functioning of reservoir ecosystems. Surface water temperature is a key parameter in the physics of aquatic system processes since it accounts for the water-atmosphere interactions and energy fluxes between the atmosphere and the water surface. Because it influences the water's chemistry, it also affects its biological processes (Lerman, Imboden and Gat, 1995). Moreover, temperature differences between the water and air moisture control the heat exchange in the air/water boundary layer, and as a consequence, they are crucial to understanding the hydrological cycle.

Thermal infrared remote sensing applied to freshwater ecosystems has aimed to map surface temperatures (Oesch et al., 2008; Reinart and Reinhold, 2008; Crosman and Horel, 2009), bulk temperatures (Thiemann and Schiller, 2003), circulation patterns (Schladow et al., 2004) and to characterize upwelling events (Steissberg et al., 2005). However, the application of thermal infrared images to the study of surface water temperatures in hydroelectric reservoirs is scarce and, in Brazil, is being attempt for the first time.

The objectives of this paper are to map the spatial variability of the water surface temperature (WST) of a tropical hydroelectric reservoir using daytime and nighttime satellite images. Through the WST maps, the heat flux budget will be calculated and used to explain the observed patterns in the WST by the physical forcing related to the geomorphological, meteorological and hydrological context.

STUDY AREA

The Itumbiara hydroelectric reservoir (18°25'S, 49°06'W) is located in a region stretched between Minas Gerais and Goiás States (Central Brazil) that was originally covered by tropical grassland savanna. The damming of the Parnaiba River flooded its main tributaries: the Araguari and Corumbá rivers. The basin's geomorphology resulted in a lake with a dendritic pattern covering an area of approximately 814 km² and a volume of 17.03 billion m³ (Figure 1).



(a) (b)

(c)

Figure 1: Localization of Itumbiara hydroelectric reservoir in Brazil's central area (a), at the state scale (b) and at the regional scale (c) with the bathymetric map. On a regional scale, the flooded area is shown over an SRTM (Shuttle Radar Topography Mission) image.

METHODOLOGICAL APPROACH

The methodological approach was developed using the concept of disturbing influences that reservoirs are exposed to. These are described by Fischer et al. (1979) as: (1) meteorological variables, such as wind velocity, and short and long wave radiation in the area, which determine the strength of any energy transfers across the air-water interface; (2) water from the inflowing streams, which may impart kinetic and potential energy; and (3) turbulent mixing generated close to outflows, which can make some of the energy of the outflowing water transform into kinetic energy of the reservoir water. We hypothesize, then, that the heat fluxes, which are a function of the meteorological variable, could explain the spatial-temporal water surface temperature variation in the Itumbiara reservoir.

Hydrometeorological data

The daily mean air temperature (ºC), relative humidity (%), wind intensity (ms^{-1}) and precipitation (mm) from 2003 to 2008 were used for the study. These data were obtained from a meteorological station (see Figure 1 for location) near the dam. The daily mean of each variable was converted into monthly means to adequate it to the time scale of the satellite data.

Satellite data

MODIS water surface temperature (WST) level 2, 1-km nominal resolution data (MOD11L2, version 5) were obtained from the National Aeronautics and Space Administration Land Processes Distributed Active Archive Center (Wan, 2008). All available clear-sky MODIS Terra imagery between 2003 and 2008 were selected by visual inspection, resulting in a total of 786 daytime images and 473 nighttime images (Figure 2). A shoreline mask to isolate land from water was built using the TM/Landsat-5 image in order to isolate some anomalously cold or warm pixels remaining at some locations near the shoreline of the reservoir.

The WST-MODIS data were extensively validated for inland waters and were considered accurate (Oesch et al., 2005; Oesch et al., 2008; Reinart and Reinhold, 2008; Crosman and Horel, 2009).

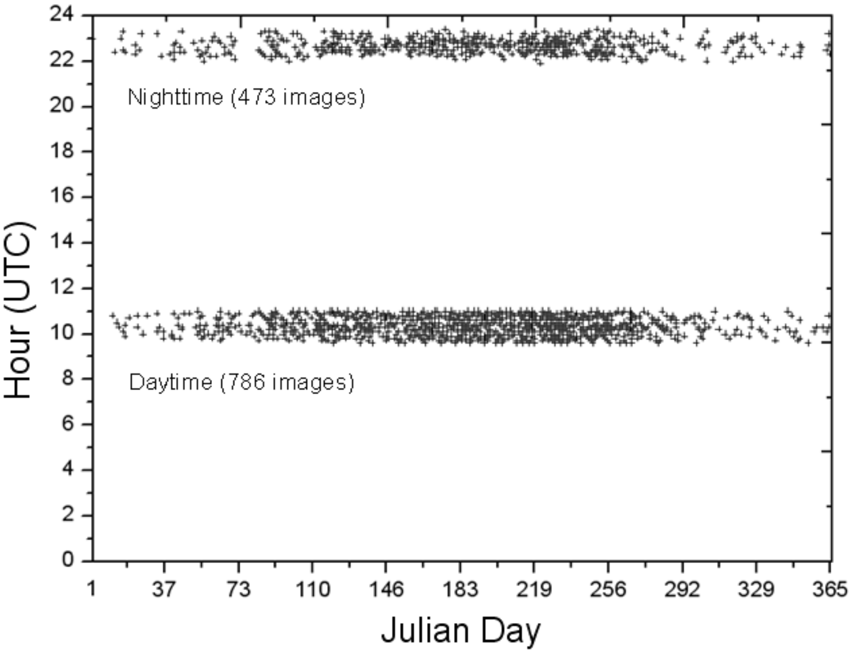


Figure 2: Acquisition date and time of all MODIS/Terra data for 2003-2008 used in this study.

WST, climatologies, anomaly maps and statistics

Maps of monthly mean daytime and nighttime water surface temperatures were produced from 2003 to 2008. The thermal amplitude was computed pixel-by-pixel by subtracting daytime and nighttime temperatures. To obtain the anomaly, the monthly mean temperatures from 2003 to 2004 were computed in a pixel-based procedure and then subtracted from each month for the entire time interval. The seasonal thermal amplitude was also analyzed. Descriptive statistics (lakewide mean, maximum and minimum) were computed for the WST maps to build a time series of daytime and nighttime monthly mean temperatures.

The surface energy budget was also calculated using the WST maps derived from MODIS/Terra.

Surface Energy Budget

A study of the energy exchange between the lake and atmosphere is essential for understanding the aquatic system behavior and its reaction to possible changes of environmental and climatic conditions (Bonnet, Poulin and Devaux, 2000). The exchange of heat across the water surface was computed using the methodology described by Henderson-Sellers (1986) as:

$$\phi_N = \phi_s(1 - A) - (\phi_{ri} + \phi_{sf} + \phi_{lf}) \tag{1}$$

where ϕ_N is the surface heat flux balance, ϕ_s is the incident short-wave radiation, A is the albedo of water (=0.07), ϕ_{ri} is the Longwave flux, ϕ_{sf} is the sensible heat flux and ϕ_{lf} is the latent heat flux. The units used for the terms in Eq. (1) are W m^{-2}.

RESULTS AND DISCUSSION

Water Surface Temperature

Figure 3 shows the average monthly mean daytime and nighttime WST distributions at Itumbiara reservoir. Generally, the daytime temperatures decrease from boundary of the reservoir to the center. For nighttime, the processes is inverted. This inversion at night was observed by Sturman et al. (1999) and MacIntyre et al. (2002), who attributed this phenomenon to turbulent convection due to differential cooling. This cooling induces an effective lateral transport, replacing the water from the interior of the lake to the littoral zone (Imberger, 1985). The temperature for a given heat flux out of the water surface decreases more rapidly in the shallow water body due to the low thermal mass than in the deep regions (Wells and Sherman, 2001).

As shown in Figure 3, the spatial and horizontal variations of the daytime temperatures are at the minimum in May while the spatial horizontal variations of nighttime temperatures are the minimum during July and August. The water temperature daytime series show that January is the month with the smallest maximum temperature (26.5ºC), which starts to rise in February (30ºC). From March to July, the maximum temperature rises to around ~ 28ºC. From August to October, the temperature decreases to around ~ 7ºC. In November and December, the temperatures start to drop. The mean temperatures present the same observed patterns as the maximum temperatures.

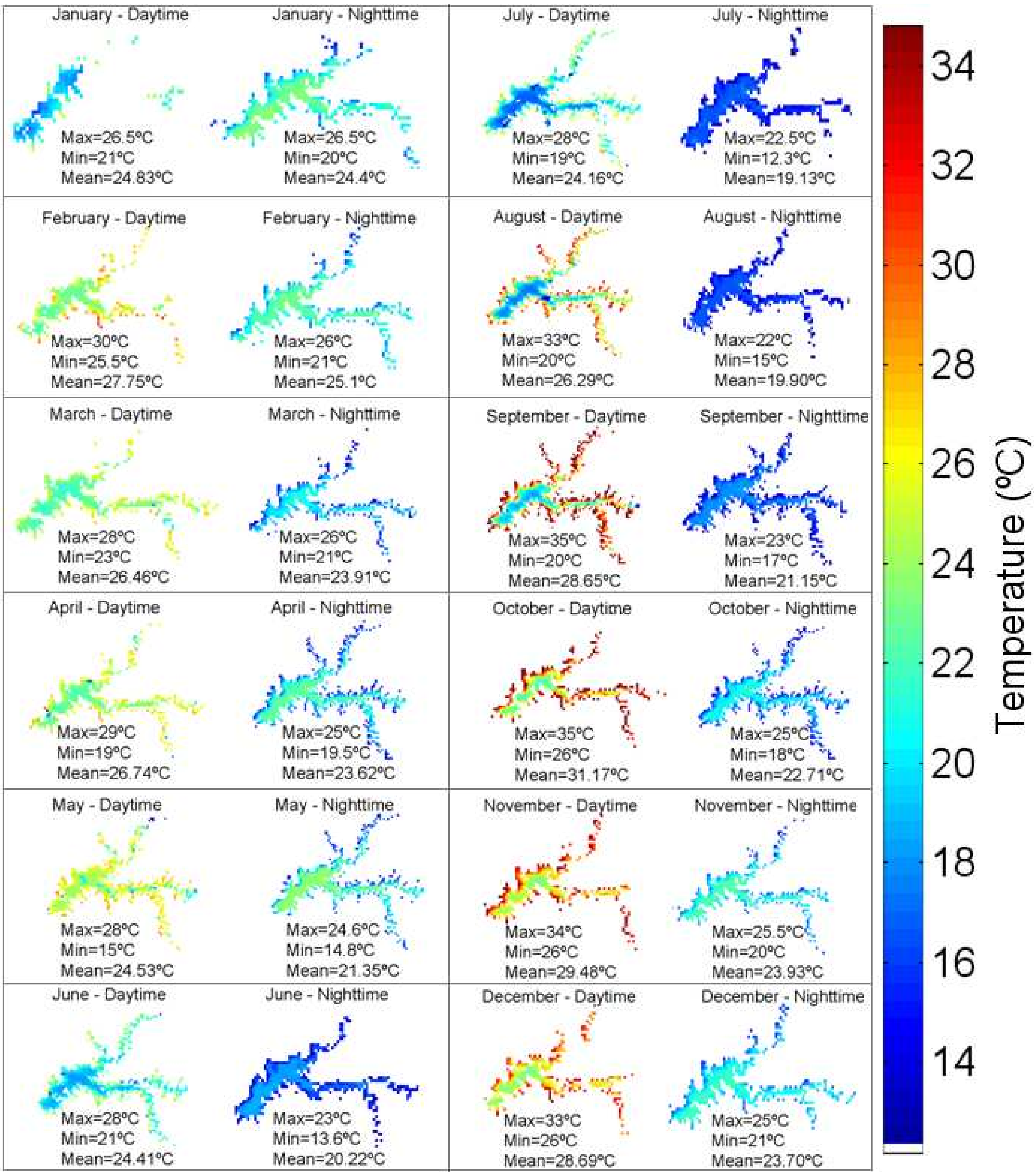


Figure 3: Monthly mean of daytime and nighttime surface water temperatures from 2003 to 2008.

Seasonal water surface temperatures

The seasonal maps were computed using the average monthly mean from 2003 to 2008 (daytime and nighttime) of the following months: summer (from December to March), fall (from March to June), winter (from June to September) and spring (from September to December). The seasonal maps of daytime were subtracted by nighttime seasonal maps to infer the seasonal thermal amplitude.

The analysis of the seasonal changes of water surface temperature shows that the differences in temperature between daytime and nighttime are negative for summer in most of the reservoir’s area (Figure 4). This means that the nighttime temperatures are higher than the daytime temperatures during the summer. The greatest differences occur in the center of the reservoir (~-6ºC).

In fall, the temperature differences are near zero, with negative differences occurring in the central part of the reservoir. However, in winter these negative differences are replaced by patches of near-zero differences in the central portion of the reservoir. In the spring, these patches of near-zero amplitude are smaller, with the occurrence of positive differences (Figure 4).

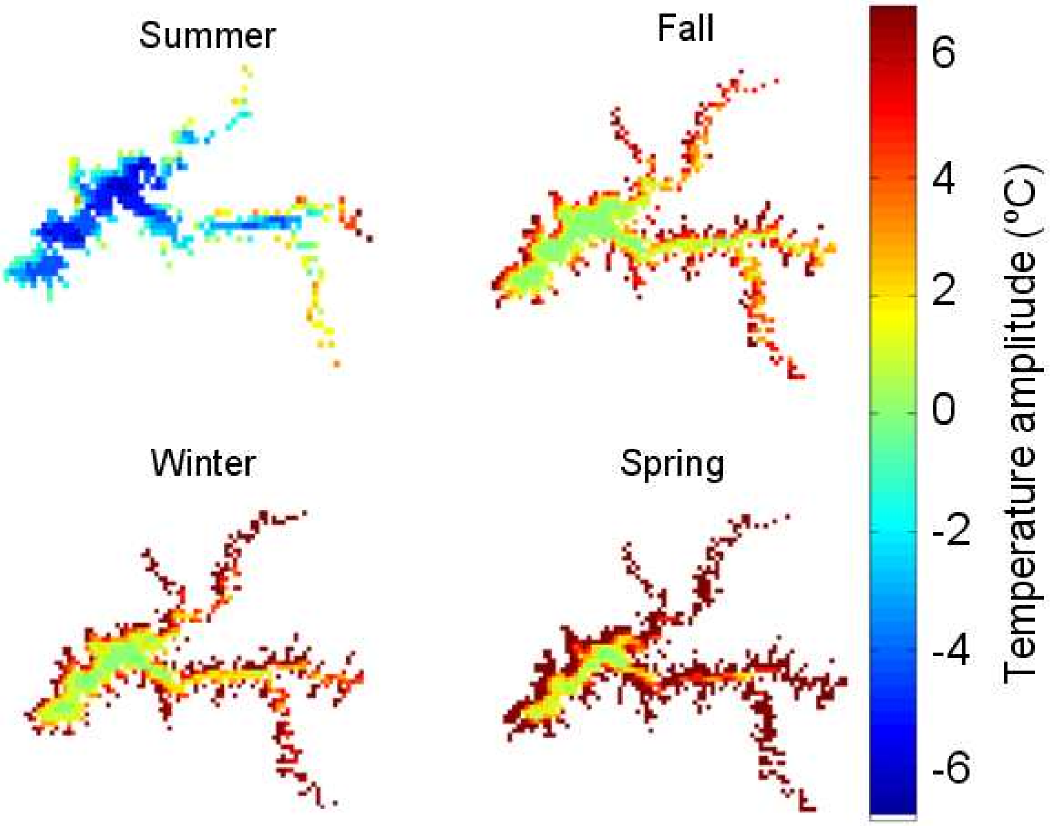


Figure 4: Monthly mean water surface temperature differences between daytime and nighttime over the seasons.

In conclusion, the temperature differences between the border and the central water body of the reservoir are positive from summer to spring. This is due to the low depth of these areas, which is less than 1 m. During spring, the highest positive temperature differences can occur (~6ºC). The nighttime temperatures can be higher than daytime temperatures during summer and fall. However, this is more pronounced in summer than in fall. The energy fluxes were computed to understand this variability observed in the results.

Surface energy budget for daytime and nighttime

The spatially effective surface heat balances are show in Figure 5. For January, February and April the northwest section of the reservoir gains more heat than the southeast section. This is because the preferable wind direction is from southeast to northwest as the wind drives the warm masses into the littoral zone by advection. For March, the southwest heats more than the northeast. During May, the greatest area of the reservoir loses heat, and only a small area in the main body of the reservoir gains heat. From June to July, heat loss dominates the whole reservoir, and the northwest losses are lower than the southeast losses. From August to December, the reservoir heats from the littoral zone to the center of the reservoir; but in October, it presents the greatest heat gradient between the littoral zone and the center of the reservoir.

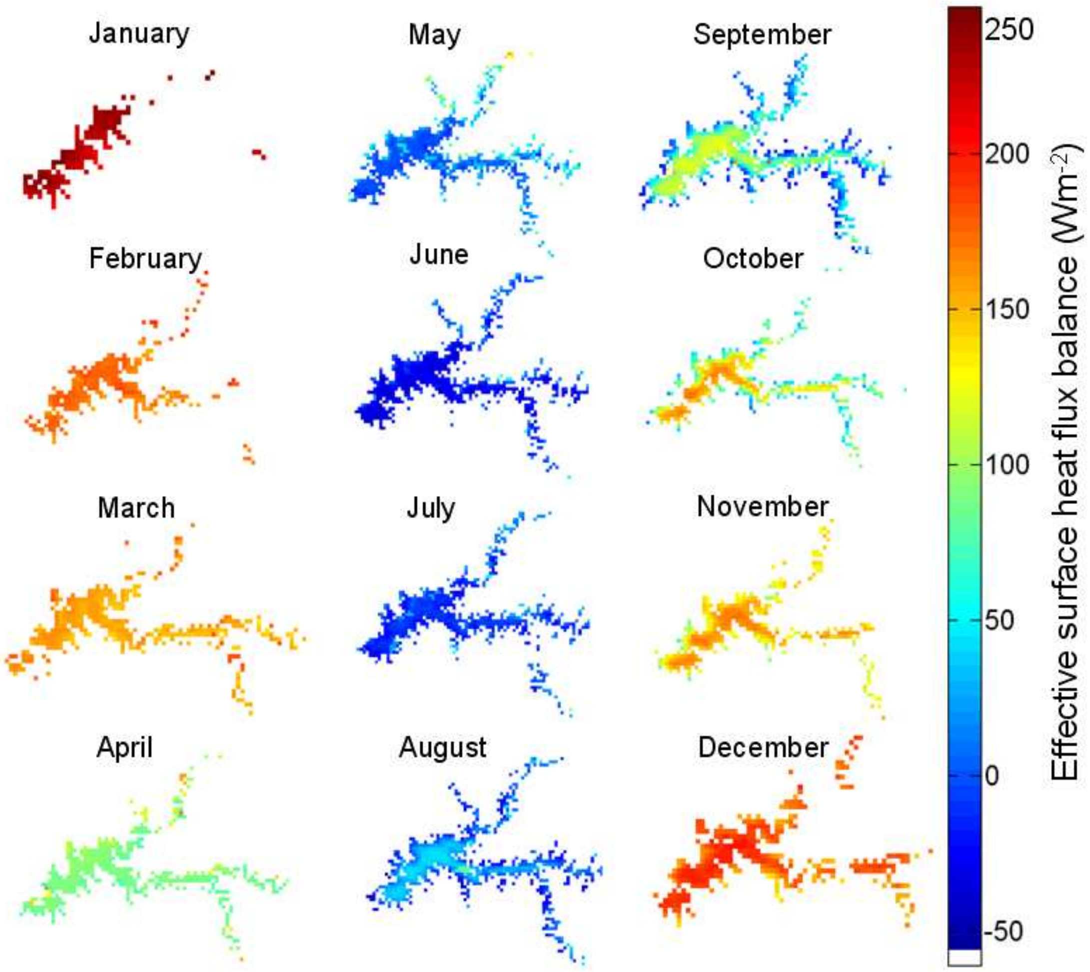


Figure 5: Spatially effective surface heat flux balance (Wm^{-2}) over the Itumbiara reservoir.

CONCLUSIONS

The objective of this study was to map the surface water temperatures and improve understanding of spatial and temporal variations in the Itumbiara hydroelectric reservoir. Our hypothesis of how meteorological and heat fluxes would affect the water surface temperature was developed and tested. The main conclusions are:

During the daytime, the water surface temperature heats from the center to the littoral zone. During nighttime, the processes invert due to the turbulent convection caused by differential cooling. The temperature, for a given heat flux out of the water surface, decreases more rapidly in the shallow water due to the low thermal mass. The seasonal analysis shows that, during summer, the water surface temperature is warmer than during nighttime. The interannual anomalies are higher in January and smaller in June for daytime and nighttime.

The reservoir gained heat from January to May and from August to December. It lost heat from May to August. The period of heat gain was also the period when the reservoir had a high potential to stratify, and during heat loss, it had the potential to mix. A difference exists between the heat balance near the dam and river confluences.

The statistical model shows that, for water surface temperatures measured at daytime, only the incoming shortwave radiation is needed for the model. For nighttime, it needs the longwave radiation, latent heat flux and sensible heat flux. The nighttime water surface temperature is more complex to model than the daytime surface temperature.

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