The thermal response of a tropical reservoir to the passage of cold fronts

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Abstract: The passage of meteorological systems such as cold fronts or convergence zones over reservoirs can cause significant modifications in several aquatic variables. Cold fronts arising from Antarctic and reaching the southeast Brazil region modify the wind field basic and have important impact over physical, chemical and biological processes that act in the hydroelectric reservoirs. During the winter time these cold fronts can reach southeast Brazilian coast each six days and summer each fourteen days in average. Most part of them reaches interior of São Paulo, Minas Gerais and Goiás States. Thus, the objective of this work is to analyze the influence of cold fronts passage in the thermal stratification and water quality of the Itumbiara (Goiás, Brazil) hydroelectric reservoir. The characterization of the cold front passage over study area the GOES satellite images was used. To reach this objective a collection o meteorological (wind direction and intensity, short-wave radiation, air temperature, relative humidity, atmospheric pressure) and water temperature in four depths (5, 12, 20 and 40 m) data were used. These data were collected using an Integrated System for Environmental Monitoring called SIMA, in high frequency, 1 hour. The stratification was assessed by non-dimensional parameter analysis. The Lake Number an indicator of the degree of stability and mixing in the reservoir was used in this analysis. It was possible to observe the influence of cold fronts on meteorological and also the thermal structure of the reservoir.

Keywords: Thermal stratification, telemetric monitoring, Lake Number, physical limnology.

1. Introduction

Aquatic systems continually respond to climatic conditions (hydro-metrological processes) that vary over broad scales of space and time. The primary control of the seasonal cycle of water temperature at a given location is the seasonal cycle of incoming shortwave radiation. Superimposed on the seasonal cycle of temperature are shorter-term, irregular variations that occur in response to macro and meso-scale atmospheric disturbances such as the passage of cold fronts. A cold front is defined as the transition zone where a cold air mass is replacing a warmer air mass.

In Brazil cold fronts that affect Brazil normally begin to form in the southern part of the South American continent. Depending on their strength, some of these systems can progress northward to low latitudes, influencing great part of the country. The passage of fronts is normally associated to a drop of surface air temperature and pressure which are simultaneously accompanied by wind intensification. During the winter time these cold fronts can reach southeast Brazilian coast each six days and summer each fourteen days in average (Stech and Lorenzzetti, 1992). Most part of them reaches interior of São Paulo, Minas Gerais and Goiás States.

These modifications were identified as a key for change the physical, chemistry and biological processes in the hydroelectric reservoirs (Tundisi et al. 2004). The response of each water body to meteorological conditions is revealed firstly by the thermal structure present in the water column (Ambrosetti and Barbanti, 2001). The precise knowledge of reservoir physical dynamics results of paramount relevance for hydrobiological and water quality studies as physical control of the biotic structure in reservoirs is even more important than in natural lakes (Uhlmann, 1998). Water temperature and heat dynamics have significant influence on the water quality and ecology of lakes and reservoirs (Wetzel, 1983).

A few studies about the thermodynamics of water systems in Brazil were made such as Tundisi (1984), Henry and Barbosa (1989), Henry (1993). Tundisi et al (2004) had explored the influence of cold fronts passage in the water quality in reservoirs and describes that most important finds of the cold front passage over a Brazilian hydroelectric reservoir is the release of iron and manganese due to the possibility to increase costs of the drink water treatment.

Based on this the objective of this paper is to show the influence of the passage of cold fronts in the thermal stratification cycle of a tropical hydroelectric reservoir in Brazil

2. Material and Methods

2.1. 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 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).

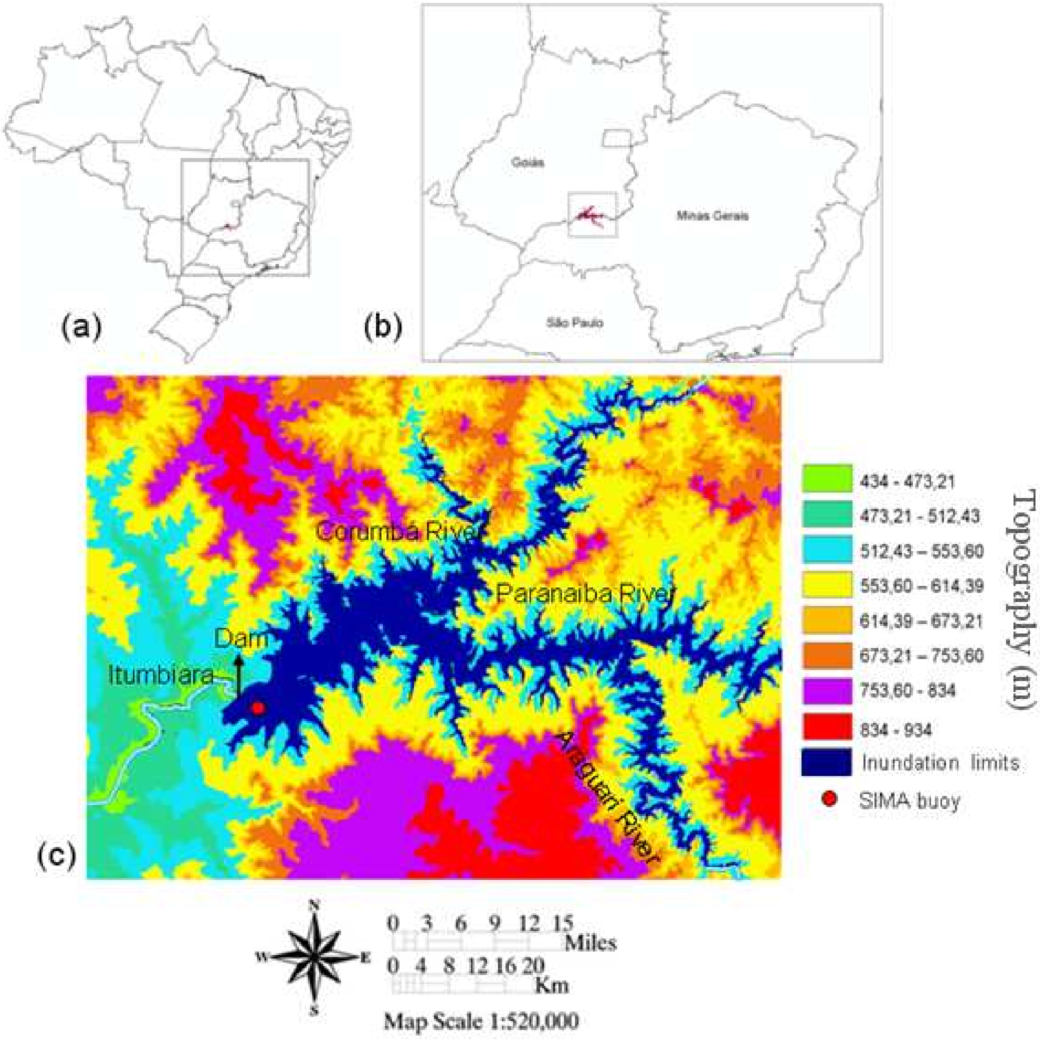
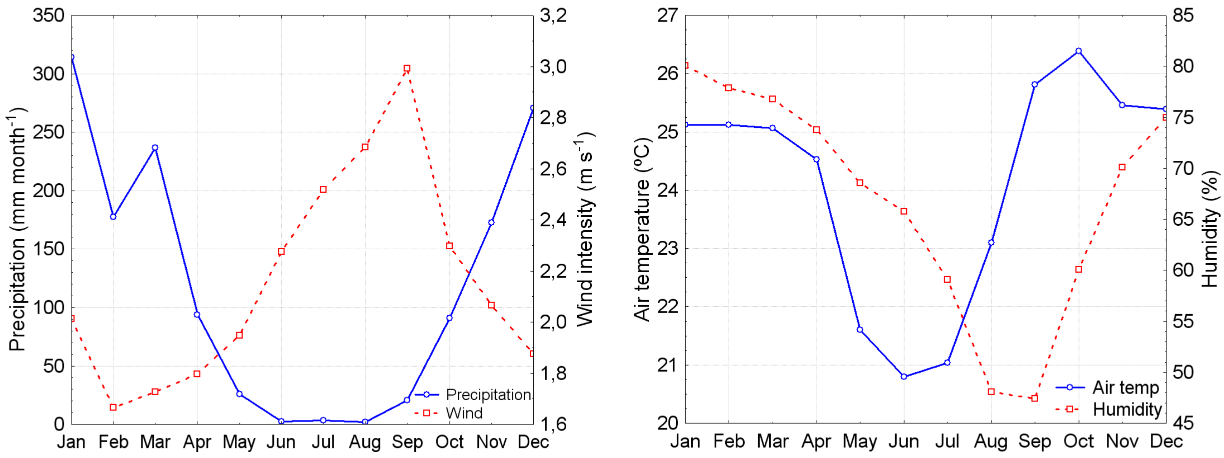


Figure 1: Itumbiara reservoir location in Brazil (a), between Minas Gerais and Goias States (b) and the topography (m) near the reservoir and the location of the moored buoy (c).

The climate in the region is characterized by an average precipitation ranging from 2.0 mm in the dry season (May - September) to 315 mm in the rainy season (October - April). In the rainy season the wind intensity ranges from 1.6 to 2.0 ms^{-1} and reaches up to 3.0 ms^{-1} in the dry season (Figure 2-a); the preferential wind direction is from southeast to northwest. The air temperature in the rainy season ranges from 25 to 26.5 ºC and breaks down to 21ºC in June as the dry season starts. The relative humidity has a pattern similar to that of the air temperature, but with a small shift in the minimum value towards September (47%). Moreover, during the rainy season the humidity can reach 80% (see Figure 2-b).



(a) (b)

Figure 2: Climate patterns of Itumbiara reservoir: average (2003-2008) monthly mean of (a) precipitation (mm month^{-1}) and wind intensity (m s^{-1}), (b) air temperature (ºC) and humidity (%).

These hydro-meteorological patterns and the operational routine for energy generation drive the water level fluctuations in the reservoir (Figure 3). The water level rising period starts in December and extends until May (with a mean period water change of $\frac{dC}{dt}$ =0.031 mday^{-1}); from May to June the water level is high (with a mean period water change of 0.006 mday^{-1}). Due to the use of water for power generation and evaporation rates, the water level recedes until November (with a mean period water change of 0.032 mday^{-1}). From November, the water reaches the low level condition until December (with a mean period water change of 0.023 mday^{-1}).

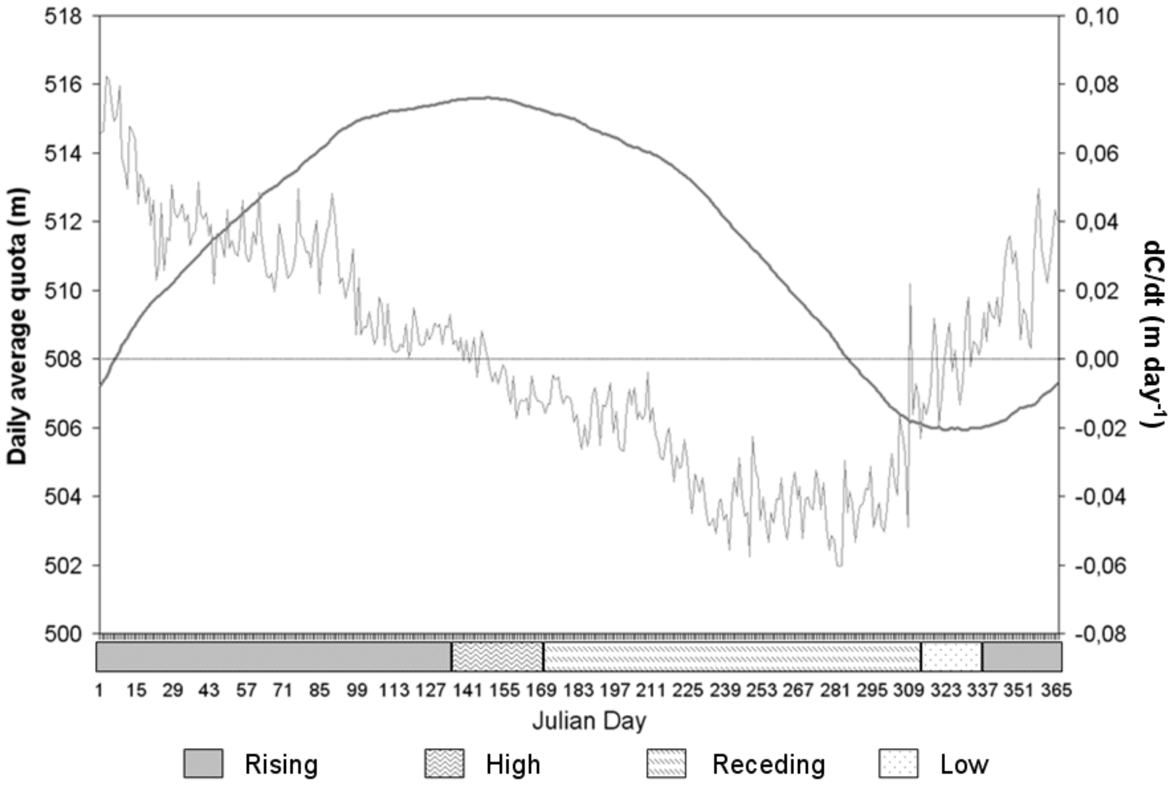


Figure 3: Daily averages (from 2003 to 2008) of water level fluctuation at Itumbiara reservoir (C) and their changer over time (t)

2.2. Satellite data

The identification of the cold front passage over the Itumbiara reservoir was made using information of the Brazilian Centre for Weather Forecasting and Climate Studies - CPTEC/INPE, a specialized centre of climate analysis. The 'CPTEC/INPE' provides for South America the track of cold front passage and then published online [http://climanalise.cptec.inpe.br/~rclimanl/boletim/]. After the identification of the possibility of the front passage near or over the reservoir, the next step was to verify the extension of this cold front using satellite data.

The data of GOES-10 (Geostationary Operational Environmental Satellite) from May 31st to June 06th 2009 (from 151 to 157 in Julian day calendar) was used to capture the track of cold front pass over the Itumbiara reservoir. Using the satellite GOES data is possible to see the extension and the hour of the cold front passage over the reservoir. The Figure 4 shows the evolution of the cold front passage over the reservoir and identifies the maximum activity of the front (Figure 4-b).

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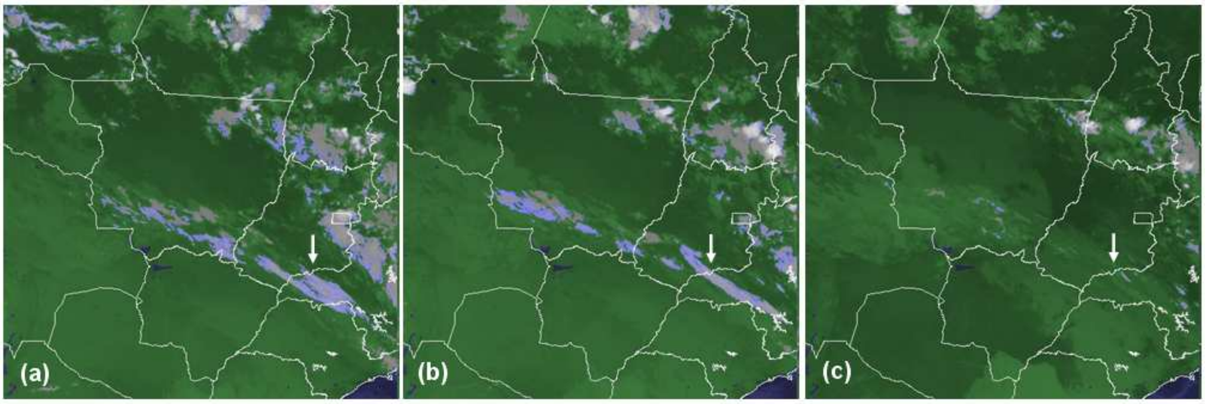

Figure 4: GOES-10 satellite data showed the evolution of the cold front passage over the reservoir: (a) 01st June 2009 at 08:00h, (b) 01st June 2009 at 09:45h (c) 01st June 2009 at 13:00h. The arrows indicate the location of the reservoir.

The identified period of cold front passage over the Itumbiara reservoir is positioned in the high water level regime, as shown in Figure 3.

2.3. Hydro-meteorological data

The meteorological (air temperature, humidity, air pressure and intensity wind) and limnological (water temperature in 5, 12, 20 and 40m depth) data from May 31st to June 06th 2009 was collected by a moored buoy called SIMA (Integrated System for Environmental Monitoring, see Stech et al., 2006; Alcântara et al. 2010) in each 1h (Figure 5).

Figure 5: Photo of SIMA installed at Itumbiara reservoir (See Fig. 1 for location).

The characteristics of the sensors used to limnological and meteorological parameters are show in Table 1.

Table 1: Characteristics of the meteorological and limnological sensors installed at SIMA.

Sensor	Manufacture	Range	Accuracy
Water temperature	Yellow Spring	-5-60 ºC	± 0.15ºC
Air temperature	Rotronic	-50 – 100ºC	± 0.2ºC
Air pressure	Vaisala	800-1060 mb	±0.3 mb
Wind	R.M. Young	0-100 ms^{-1}	± 0.3 ms^{-1}
Humidity	Rotronic	0-100 %	± 1.5 %
Shortwave	Novalynx	0-1500 Wm^{-2}	± 5%

2.4. 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}. These terms are defined as positive when directed into the water.

The incident short-wave radiation ϕ_s was calculated using the following equation:

$$\phi_s = a_1\phi_0(\sin d)^{b_1}(1-0.65C^2) \tag{2}$$

where a_1=0.79 and b_1=1.15 are two calibration parameters determined by a comparison with the radiometer data, ϕ_0=1390 Wm^{-2} is the solar constant, d is the hour angle and C is the cloud cover index, which was estimated using the Reed (1977) empirical relation.

The net longwave radiation corresponding to the outgoing flux minus the incoming flux $(LW\uparrow\downarrow = LW\uparrow - LW\downarrow)$, ϕ_{ri} is computed as given by Fung et al. (1984):

$$\phi_{\mathrm{ri}} = \varepsilon\sigma T_s^4(0.39 - 0.05e_a^{\frac{1}{2}})(1-\lambda C) + 4\varepsilon\sigma T_s^3(T_s - T_a) \tag{3}$$

where ε=0.97 is the thermal infrared emissivity of the water, σ is the Stefan-Boltzmann constant, T_s = water surface temperature (ºC), T_a = surface air temperature (ºC), λ=0.8 is the

Reed (1977) correction factor, and e_a = partial pressure of vapor (mb), which was calculated as:

$$e_a = re_{sat}(T_a) \tag{4}$$

where r is the relative humidity and e_{sat} is the saturation vapor pressure. This was calculated using the polynomial approximation of Lowe (1977).

The non-radiative energy term ϕ_{rad} accounts for the sensible heat flux and latent heat flux. The sensible heat flux was calculated as:

$$\phi_{sf} = \rho_a c_p c_H \left|\vec{V}\right| (T_s - T_a) \tag{5}$$

where ϕ_{sf} is the sensible heat flux (Wm^{-2}), ρ_a = 1.2 kgm^{-3} is the air density, c_p = 1.005x10^3 Jkg^{-1}K^{-1} is the specific heat capacity of air, c_H =1.1x10^{-3} is the coefficient of turbulent exchange and $\left|\vec{V}\right|$ = surface wind speed (ms^{-1}).

The latent heat flux was computed as follows:

$$\phi_{lf} = \rho_a c_E L \left|\vec{V}\right| [e_{sat}(T_s) - re_{sat}(T_a)] \frac{0.622}{p_a} \tag{6}$$

where ϕ_{lf} is the latent heat flux (Wm^{-2}), c_E =1.1x10^{-3} is a coefficient of turbulent exchange, L =2.501x10^6 Jkg^{-1} is the vaporization of latent heat and p_a is the atmospheric surface pressure (mb).

The energy exchange also occurs through precipitation, withdrawal of evaporated water, chemical and biological reactions in the water body, and conversion of kinetic to thermal energy. These energy terms are small enough to be omitted. Many researchers agree that omitting energy budget components with small values does not significantly affect the results (Bolsenga, 1975; Sturrock et al., 1992; Winter et al., 2003).

2.5. Lake Number - L_N

To indicate the degree of stability and mixing in the reservoir, due to the passage of cold front, the L_N was used (Imberger, 1998).

$$L_N = \frac{gS_t\left(1-\frac{Z_T}{Z_m}\right)}{\rho_0 u_* A_0^{3/2}\left(1-\frac{zg}{zm}\right)} \quad (7)$$

Where z_T and zg are the height to the center of the metalimnion and the center of area, zm is the maximum depth of the reservoir, ρ_0 is the average density of the water column, u_* is the water friction velocity, A_0 is the surface area of the reservoir (m²) and S_t (gcm^{-1}cm^{-2}) is an estimate of the stability of the reservoir calculated as (Hutchinson, 1957):

$$S_t = \frac{1}{\rho_0}\int_0^H g(h_v - zg)\rho(z)A(z)dz \quad (8)$$

Where zg can be obtained as:

$$zg = \frac{\int_0^{zm} zA(z)dz}{\int_0^{zm} A(z)dz} \quad (9)$$

The L_N characterizes the dynamic stability of a lake (Imberger and Patterson, 1990) and is a ration of moments about the center of lake volume of the wind force at the surface of the lake and the gravity restoring force to the stratification. To calculate the L_N the reservoir bathymetry are needed.

2.6. Bathymetric Data

The bathymetry of the Itumbiara reservoir was made in two campaigns, the first from 11-15th May 2009 and second from 11-16 August 2009. The depth data was collected using an echo-sound LMS-525 from Lowrance, with a GPS (Global Positioning System) coupled. The depth data was treated in accordance to Merwade (2009).

2.6.1. Area and Volume of the Reservoir

Using the bathymetric data and the quota-curve of the water level in the reservoir (mean from 1993 to 2003) the area (equation 10) and volume (equation 11) was calculated; using the first derivative analysis was possible to access the rate of quota in the reservoir. To do this the Simpson's extended method was used (Press et al., 1992) as:

$$A_i \approx \frac{\Delta x}{3}[G_{i,1} + 4G_{i,2} + 2G_{i,3} + 4G_{i,4} + ... + 2G_{i,nCol-1} + G_{i,ncol}] \quad (10)$$

and,

$$V \approx \frac{\Delta y}{3}[A_1 + 4A_2 + 2A_3 + 4A_4 + ... + 2A_{nCol-1} + A_{ncol}] \quad (11)$$

Where: A is the area (m²), Δx is the grid column spacing, $G_{i,j}$ is the grid node value in row i and column j, V is the volume (m³), Δy is the grid row spacing.

3. Results

3.1. Bathymetric Map

The result of the depth surveys shows that the reservoir presents the highest depths in the line of flooded river with depths higher than 78m during the high water level; with a littoral zone with depth less than 2m. Other deeper region is near the Dam where the depth reaches 70m (Figure 6).

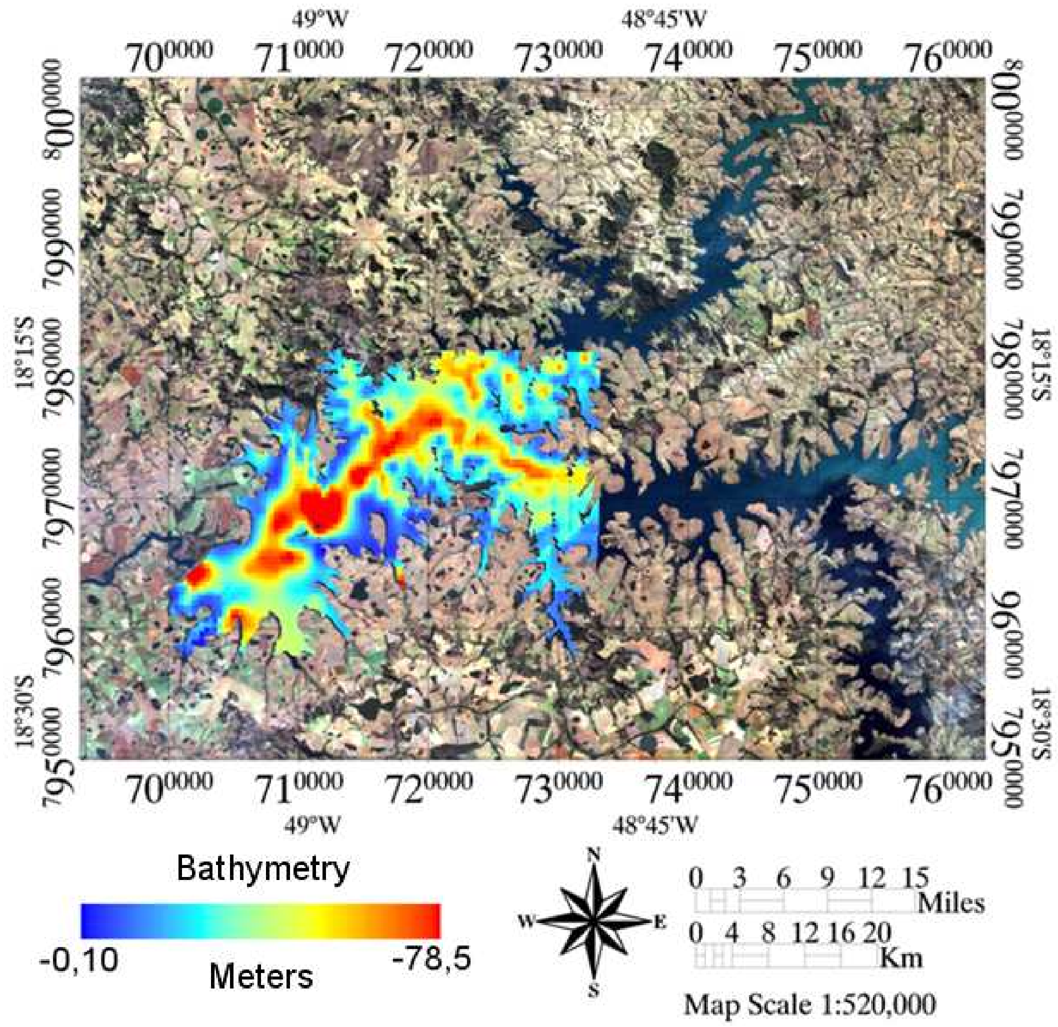

Figure 6: Bathymetric map of the Itumbiara reservoir.

3.2. Meteorological and Limnological Data

The Figure 7 shows the meteorological and limnological parameters used in this study. It is clear that during the passage of cold front the atmospheric pressure and the air temperature decrease; in the other hand the wind shows a little increase and also the relative humidity. The water surface temperature decreases after the passage of the cold front.

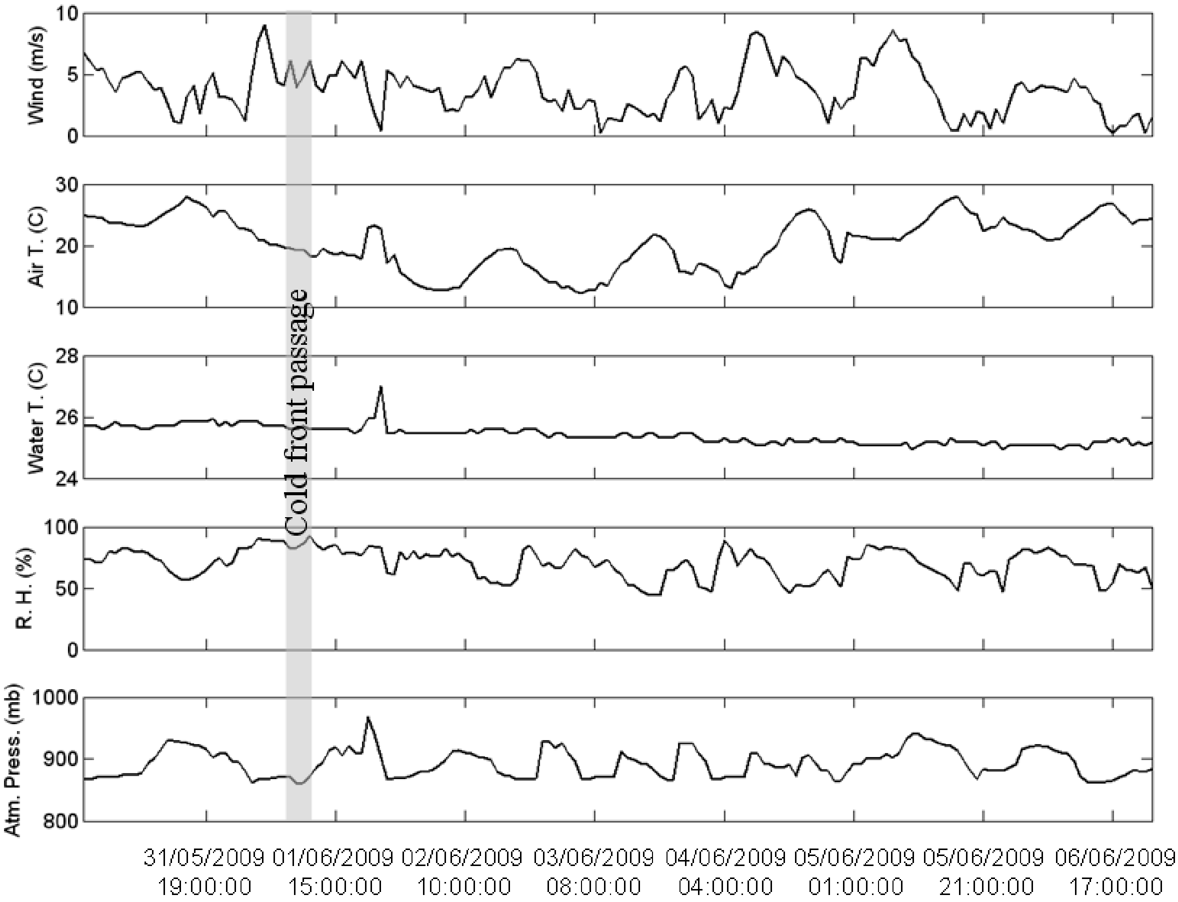

Figure 7: Meteorological (wind intensity, air temperature, relative humidity and atmospheric pressure) and limnological (water temperature) parameters collected by the SIMA buoy from May 31st to June 06th 2009.

This pattern observed before, during and after the passage of cold front is reflected in each component of the heat flux balance (Figure 8). During the passage of the cold front the intensity of the shortwave radiation decreases. The sensible flux tends to be higher during and after the cold front passage if compared the period before the passage. The latent flux during the passage of the cold front tends to decrease, but after the passage the latent flux tents to increase again. The heat balance before the passage of cold front is positive when shortwave act in the systems; however during the passage the balance is negative and tends to normalize with the dissipation of the front.

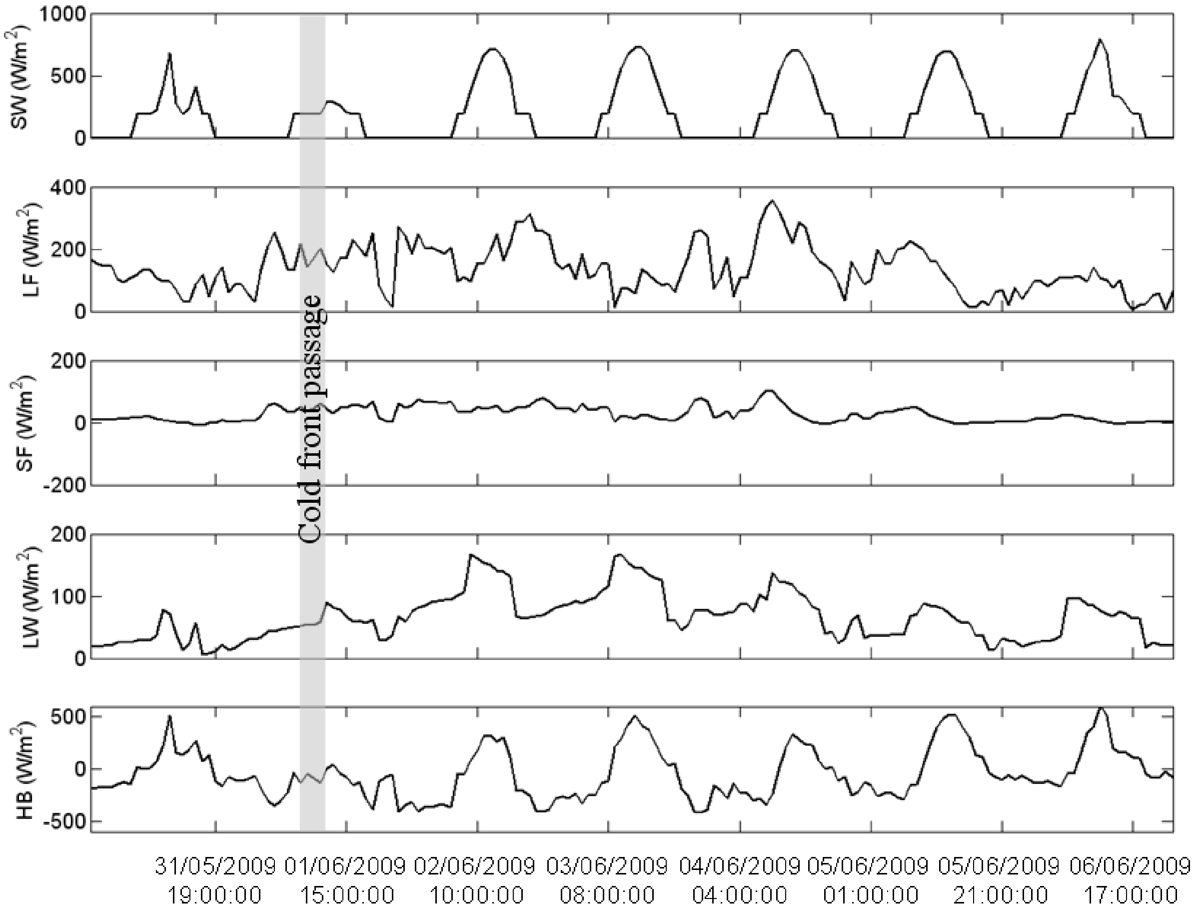

Figure 8: Heat flux components: SW – shortwave radiation, LF – latent flux, SF – sensible flux, LW – longwave radiation and HB – heat balance.

This heat content modification due to the cold front will reflect in the water column temperature and stability (Figure 9-a). Before the passage of the front the water column presented a little temperature difference between the epilimnion and metalimnion; with the passage of the cold front the water temperature of the top-most layer decrease and the difference of temperature in the water column decreases also.

The analysis of Lake Number (L_N) are show in Figure 9-b. When $L_N > 1$ there is no deep upwelling and when $L_N < 1$ the cold deep, often nutrient rich, water from the hypolimnion will reach the surface layer during the wind episode (Antenucci and Imberger, 2003). For L_N as high as 60, little turbulent mixing is expected in the hypolimnion (Hondzo and Stefan, 1996). In this case all $L_N > 1$ occurred during the daytime when the incident shortwave radiation is present, but after the passage of the cold front the values of L_N increase during the heating phase. Often $L_N < 1$ occurred during the nighttimes, the unique exception is the day during the cold passage with L_N less than 1.

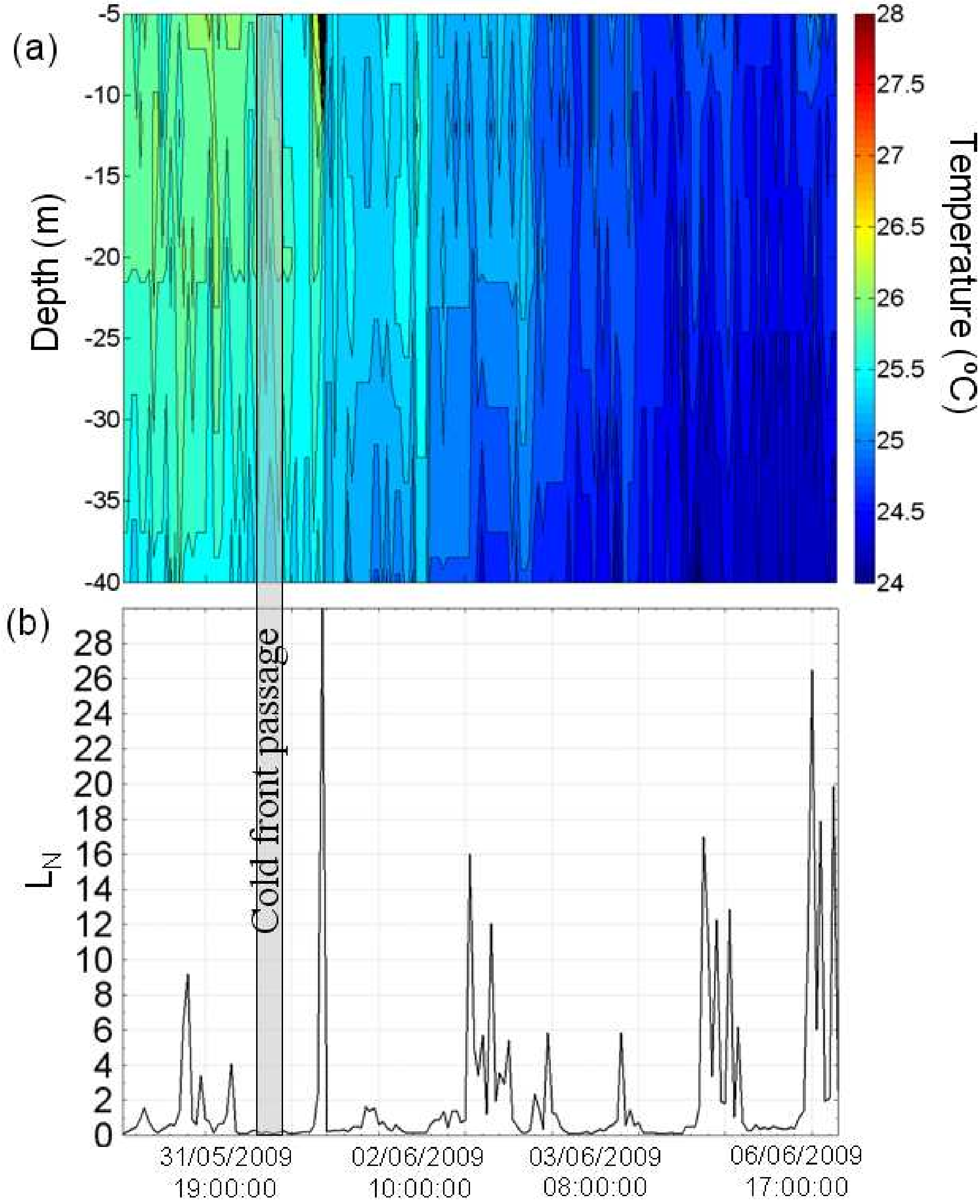

Figure 9: Thermal structure (a) and the Lake Number - L_N (b) for the Itumbiara Reservoir.

After the passage of the front the water from hypoliminion progressively cooler and the mixed layer goes up to the top layer. The fact of the L_N increases after the front passage during the daytime could be explained by the fact that during the cold front passage the water losses energy to the atmosphere and when the cold front dissipate the incident shortwave radiation heats the surface creating the condition enhancing the stability of the water column.

4. Discussion

The cold front starts acting on the Itumbiara reservoir in 31st May 2009 as was observed in the shortwave data (Figure 8). The shortwave radiation presented a variable peaks in this day, represented by the perturbation in the atmospheric boundary-layer; than during 1st June 2009 the shortwave radiation was reduced from 680 wm^{-2} to 280 wm^{-2}. This was reflected in the air temperature decrease and the increase of humidity in the reservoir (Figure 7). The showed enhanced in the sensible heat flux is due to the convection caused by decrease in the atmospheric stability. The sensible flux is proportional to the temperature difference between the water surface and the overlying atmosphere and also dependent on intensity of turbulent mixing.

In the other hand the latent flux tends to be smaller before the cold passage and higher after the passage. The turbulent exchanges of heat and water vapor over an open water surface are affected by many environmental factors. It is well known that evaporation rates over a water surface depend largely on vapor pressure deficits between water surfaces and the overlying atmosphere as well as on intensity of turbulent mixing (Henderson-Sellers, 1986). The air is always at its saturation at the interface between the water and the overlying air, and the saturation pressure in this interface is a function of water surface temperature (Hostetler and Bartlein, 1990).

The increasing in the longwave radiation after the passage of the cold front is due to the cloud cover formation. During cloud days the atmospheric longwave radiation is often the greatest source of heat at the water surface (Henderson-Sellers, 1986). Probably the observed increase in the latent heat flux could be linked with the back heat into the water by the longwave radiation.

The alterations in meteorological and heat flux data will be reflected in the heat content stored in the reservoir. The heat content (ς, cal) for given water volume stored in the reservoir can be calculated using the formulation given by Chapra and Reckhow (1983):

$$\varsigma = t\rho CV \qquad (12)$$

Where t is the water temperature (ºC), ρ is the water density (gcm^{-3}), C is the specific heat of water (calg^{-1}ºC^{-1}), and V the water volume (cm^{3}).

To transform the water temperature into heat (ς_H, cal) it has been assumed that the volume of a gram of water is 1 ml, and that the specific heat of the water is 1 cal g^{-1} ºC^{-1} (Wetzel and Likens, 2000):

$$\varsigma_H = \sum_{Z_0}^{Z_{MAX}} t_z A_z h_z \tag{13}$$

Where t_z the average temperature of the water of a unity in layer h_z (cm), and A_z is the average surface of the layer z (cm^2). Heat content results were linearly interpolated to daily values.

The Figure 10 shows the heat content evolution. In the first day before the passage the reservoir losses 81.57 cal cm^{-2} of the heat content; at the end of six days before the front passage the reservoir losses 569 cal cm^{-2}.

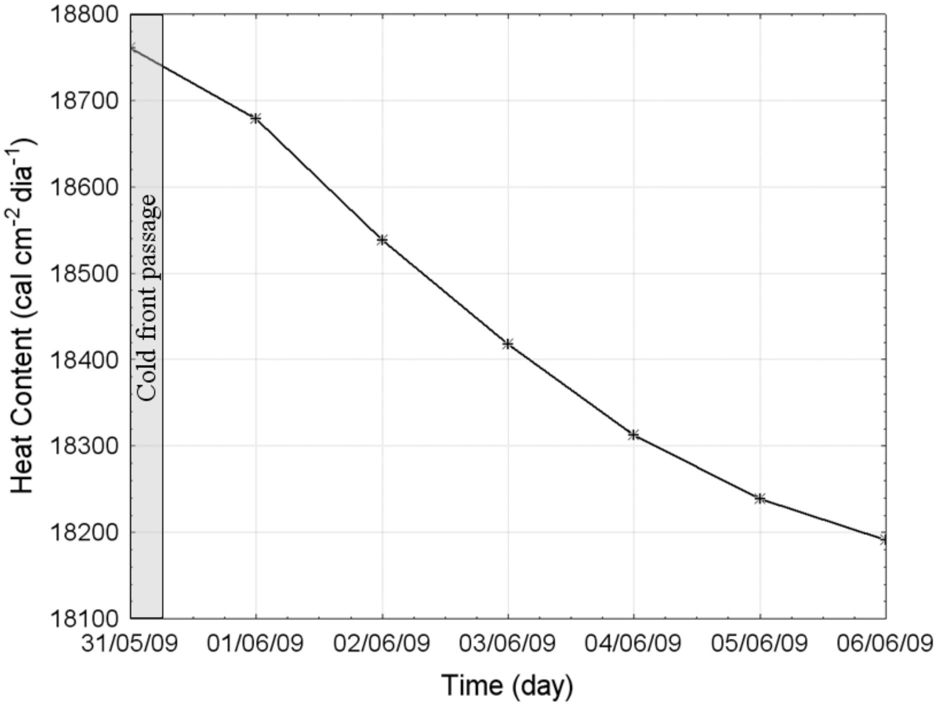

Figure 10: Heat content (cal cm^{-2} dia^{-1}) stored in the Itumbiara reservoir during the passage of the cold front.

Note that the progressively loss of energy from water to the atmosphere is associated in the first instance to the cold front passage; but when the cold front dissipate the shortwave radiation reach again their pattern value ~700 Wm^{-2}. In this case the sinking of heat is the upwelling caused by convective cooling due to the erosion of thermal stratification.

The other parameter that could be taken in consideration is the persistence of the wind action on the water surface. The autocorrelation analysis is a way of measuring linear dependence between observations of a time series (Box et al. 1994), and is suitable to measure the persistence of wind (Koçak, 2008).

The autocorrelation function applied to the wind data shows that the persistence is less than four hours (Figure 11). This result reveals that during the passage of the cold front over the Itumbiara reservoir, the wind blows over the surface area almost for four hours and then the wind become intermittent.

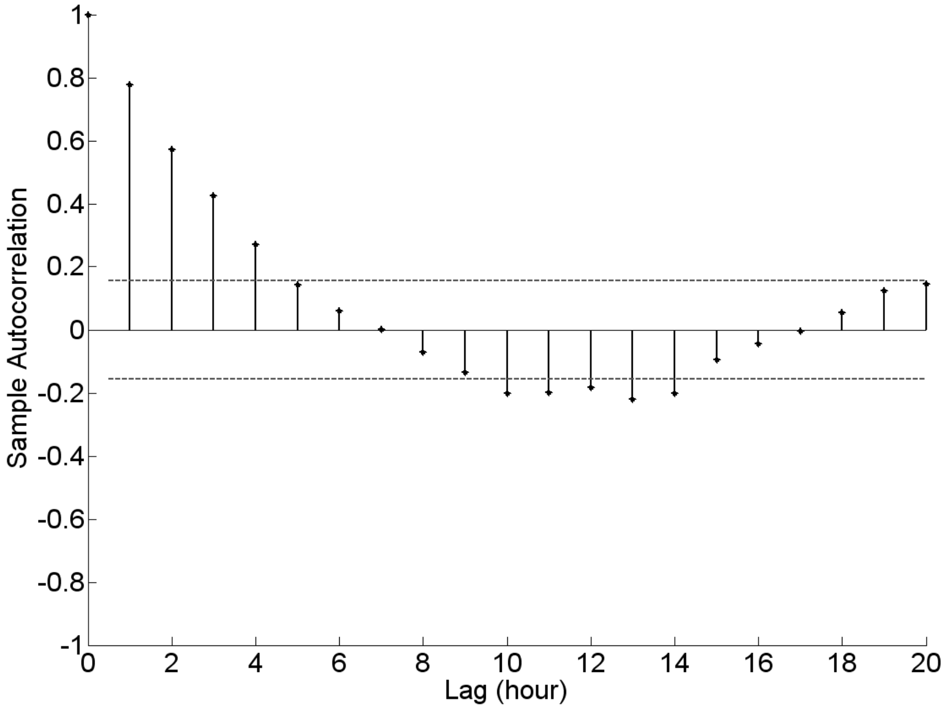

Figure 11: Wind persistence evaluation through the autocorrelation function.

The combined effect of wind persistence, decrease of the air temperature and shortwave radiation, causes an increase of latent flux (due to the difference between the air and water temperature) and sensible (due to the atmospheric instability) was the primary physical disturbance capable to decrease the upper most layer of the water column and then by convection transfer the cooling water for the subsequent layers.

5. Conclusion

This works shows the influence of cold front passage over a tropical hydroelectric reservoir in the meteorological, near-surface heat flux and consequently in the thermal structure of the water column.

The time series of meteorological and limnological variables provided a good view of the importance of meteorological systems to the stratification/mixing process in tropical reservoirs such as those studied. The passage of cold front over a region decreases the atmospheric pressure and air temperature, enhancing the relative humidity. With the formation of cloud cover the longwave radiation increase and transfer heat by turbulent convection to the water surface. The sensible flux presents a small variability but an increase occurs due to a convective turbulence caused by front passage; in other hand the latent flux decrease but insufficiently to cause a condensation, just the evaporation decreases. The upwelling events are the responsible to maintain the loss of heat after the cold front passage.

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