THE RESPONSE OF CARLOS BOTELHO (LOBO, BROA) RESERVOIR TO THE PASSAGE OF COLD FRONTS AS REFLECTED BY PHYSICAL, CHEMICAL, AND BIOLOGICAL VARIABLES

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ABSTRACT

This paper describes and discusses the impacts of the passage of cold fronts on the vertical structure of the Carlos Botelho (Lobo-Broa) Reservoir as demonstrated by changes in physical, chemical, and biological variables. The data were obtained with a continuous system measuring 9 variables in vertical profiles in the deepest point of the reservoir (12 m) coupled with climatological information and satellite images, during a 32-day period in July and August, 2003. During periods of incidence of cold fronts the reservoir presented vertical mixing. After the dissipation of the cold fronts a period of stability followed with thermal, chemical, and biological (chlorophyll-*a)* stratification. Climatological data obtained during the cold front passage showed lower air temperature, higher wind speed and lower solar radiation. The response of this reservoir can exemplify a generalized process in all shallow reservoirs in the Southeast Brazil and could have several implications for management, particularly in relation to the phytoplankton population dynamics and development of cyanobacterial blooms. Using this as a basis, a predictive model will be developed with the aim of advancing management strategies specially for the drinking water reservoirs of the Metropolitan Region of São Paulo.

Key words: reservoir responses, vertical structure, cyanobacterial blooms, cold fronts.

RESUMO

As respostas da Represa da UHE Carlos Botelho (Lobo, Broa) à passagem das frentes frias, refletidas pelas variáveis físicas, químicas e biológicas

Este trabalho descreve e discute os efeitos das frentes frias intermitentes na estrutura vertical do reservatório da Usina Carlos Botelho (Lobo-Broa). Esses efeitos foram demonstrados com a determinação de variáveis físicas, químicas e biológicas (clorofila-*a*). Os resultados foram obtidos com a utilização do sistema SMATER (Sistema de Monitoramento em Tempo Real) instalado na região mais profunda do reservatório (12 metros). As medidas foram realizadas durante o período de 32 dias (julho/agosto de 2003 – inverno) e foram acopladas a informações contínuas sobre a climatologia e imagens de satélite. O reservatório apresentou períodos alternados de estratificação e mistura vertical, dependendo das passagens das frentes frias e sua posterior dissipação. Imediatamente após a dissipação das frentes frias, a estabilidade térmica, química e biológica instalou-se, alterando consideravelmente a estrutura vertical do sistema. Portanto, pulsos de estratificação e mistura vertical ocorreram relacionados à passagem e à dissipação das frentes frias. A resposta desse reservatório aos efeitos da passagem das frentes frias pode ser generalizada para todos os reservatórios rasos (< 30 metros, profundidade) do Sudeste do Brasil. Essa resposta tem muitas implicações para o gerenciamento, principalmente no que se refere à dinâmica das populações fitoplanctônicas, em especial o desenvolvimento e a estabilidade de florescimentos de cianobactérias. Utilizando a base conceitual e de informações climatológicas e limnológicas, um modelo preditivo deverá ser aplicado, com a finalidade de avançar tecnologias e abordagens de gerenciamento, especialmente para os reservatórios de abastecimento de água da Região Metropolitana de São Paulo.

Palavras-chave: respostas de reservatórios, estrutura vertical, florescimentos de cianobactérias, frentes frias.

INTRODUCTION

The effect of stratification and mixing in the vertical structure of shallow reservoirs (maximum depth: 30 meters) is well documented (Straškraba, 1990, 1993). Under various wind stresses and regimes these aquatic ecosystems present several responses in their physical, chemical, and biological variables. The disturbances promoted by wind action, its force and direction have an effect on the population dynamics and species diversity of the phytoplankton (Padisak, 1992, 1993) as well as in the succession of species (Reynolds, 1992). The impact of mixing on algal growth and vertical distribution was discussed by Imboden (1992) who pointed out that the niches in aquatic systems and specially in the pelagic zone are produced by variations in the temporal, vertical, and horizontal structure of physical processes. Therefore, algal growth, succession of species, and density of phytoplankton are influenced by the extent and duration of vertical mixing and stability of the water column. Mixing and stratification promote several changes in the density structure of the water and in the distribution of chemical substances that influence growth. Also, the underwater light climate is affected by periods of mixing and stratification and their duration. The duration and quality of irradiance at the water surface depends on solar radiation and the mixing processes promoted by the external energy input of wind (Reynolds *et al.,* 1993; Reynolds, 1997).

On a time scale of a few days the passage of frontal disturbances promote transient phenomena (winds, storms) that are destabilizing agents for the water column and that influence phytoplankton distribution and succession (Legendre & Demers, 1984). Rapid light fluctuations generated by the effect of cold fronts could also affect photosynthetic capacity and the pigment system. According to Padisak *et al.* (1988) physical control plays a fundamental role in regulating the summer succession of phytoplankton in shallow lakes. During calm periods there would be a shift in selection (from physical to biological control) where blooms of *Cyanobacteria* can develop and establish themselves until next storms or disturbances.

The implications for management of these periods of wind stress and turbulence, in contrast to calm days in stratified water columns, are related with the costs of water treatment necessary to deal with toxic substances increase due to algal blooms or aggravated concentration of chemical substances or elements in the bottom or surface water such as iron and manganese.

In this paper the authors describe and discuss the impact of cold fronts measured during a one-month period on the vertical structure of a shallow reservoir in Southeast São Paulo State. The implications of this process for other shallow reservoirs in this region is discussed as well as the possible impacts on management strategies for drinking water reservoirs in the Metropolitan Region of São Paulo.

MATERIAL AND METHODS

This study was carried out at Carlos Botelho (Lobo-Broa) Reservoir a shallow (maximum depth: 12 meters) reservoir located in Southeast Brazil (São Paulo State). This reservoir has been the object of many studies over the last 33 years (Tundisi & Matsumura-Tundisi, 2003). The Fig. 1 shows the location of the reservoir and its main characteristics. Table 1 details its essential morphometric features.

A platform with a YELLOW SPRINGS 6.600 equipment was moored at a fixed station located at the deepest point of the reservoir (12 meters). The procedures for data assessment were prepared according to the SMATER (Real Time Monitoring System) developed at the International Institute of Ecology, São Carlos-SP (patent pending). Data collection in the reservoir was carried out in 2003 from July 30 to August 29.

TABLE 1
General features of Carlos Botelho (Lobo-Broa) reservoir.

Latitude	22°15'S
Longitude	47°49'W
Maximum length	8 km
Maximum width	2 km
Average width	0.9 km
Maximum depth	12.0 meters
Average depth	3.0 meters
Surface area	6.8 km^2
Perimeter	21 km
Volume	22 x 10^6 m^3
Area of watershed	227.7 km^2
Maximum altitude	940 m
Average altitude	770 m
Minimum altitude	680 m

Every 30 minutes the sensors powdered by a solar panel collected a complete profile of the water column from 0 to 12 meters. The variables collected included: *water temperature, pH, dissolved oxygen, conductivity, nitrate, ammonia, chlorophyll-a, turbidity, and redox potential.*

Climatological data obtained were: solar radiation, air temperature, and wind. These data were supplied by the Center of Water Resources and Applied Ecology of the School of Engineering, USP, located at the shore of the reservoir.

Satellite images from August 11-29 were obtained from the INPE site *http:wwww.inpe.br* and the Center for Predicting Weather and Climatic Studies (CPTEC). *http://www.cptec.inpe.br* with the GOES satellite. Images of high resolution in the visible and infrared enhance resolution for clouds.

The sequence of vertical profiles thus obtained was compared with the satellite images depicting the periods of incidence of cold fronts during this time.

RESULTS

Figs. 3, 4, and 5 show the satellite image sequence from August 11-28, 2003. These figures show the propagation and dissipation of the cold fronts in southeast Brazil, in this period.

Figs. 6 and 7 show the vertical changes in the 9 variables measured during the periods of passage of the cold fronts and after their dissipation. During periods of lower wind speed, after dissipation of cold fronts, surface heating promoted thermal stratification as can be seen from 30th July to 4th of August. Chemical stratification followed with an increase of ammonium at the bottom of the reservoir. Electrical conductivity followed the same pattern.

Thus, the impact of the cold front passage on the vertical structure of the reservoir seems clear.

During cold front, wind stress increase and solar radiaton decreases, promoting vertical circulation of the water mass at the reservoir that resulted in relatively more homogeneous water temperature, dissolved oxygen, pH, and conductivity. The results for chlorophyll a in Fig. 6 show aggregation of phytoplankton at surface layers during calm periods when water temperature stratification prevailed and also relatively more homogeneous distribution during periods of circulation.

Fig. 7 shows a detail of the propagation and dissipation of the cold front during 23, 24, 25 and 26th of August, 2003 and the respective reservoir response. It is clear the impact on the vertical structure of the reservoir as shown by the data on water temperature, dissolved oxygen and pH.

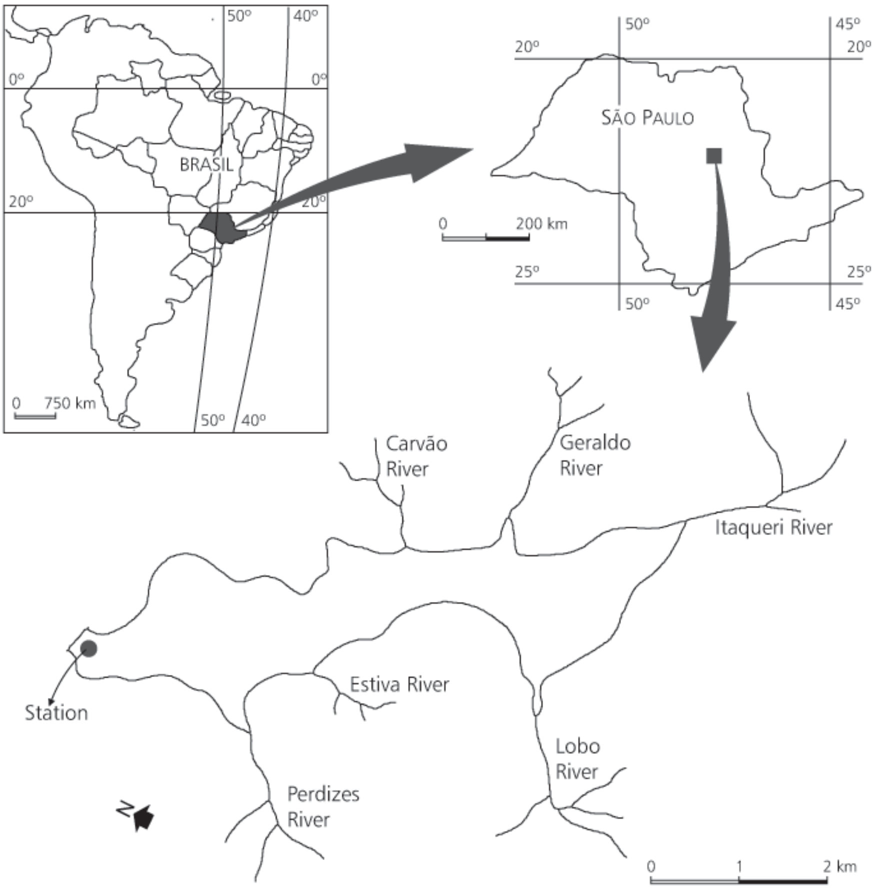

Fig. 1 — The location of Carlos Botelho (Lobo-Broa) reservoir with the sampling station.

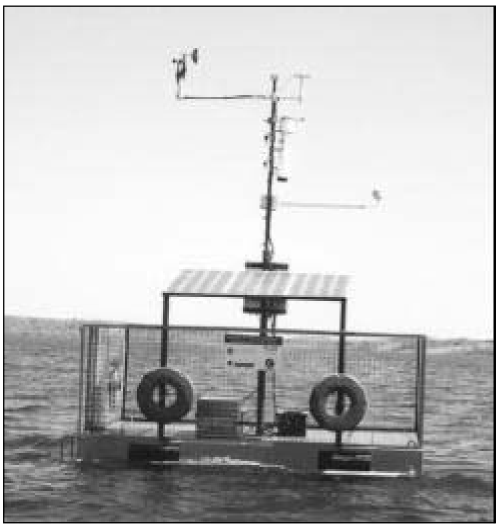

Fig. 2 — The SMATER unit consisting of a climatological station, a solar panel a data logger and a YELLOW SPRINGS 6.600 sensor (original IIE).

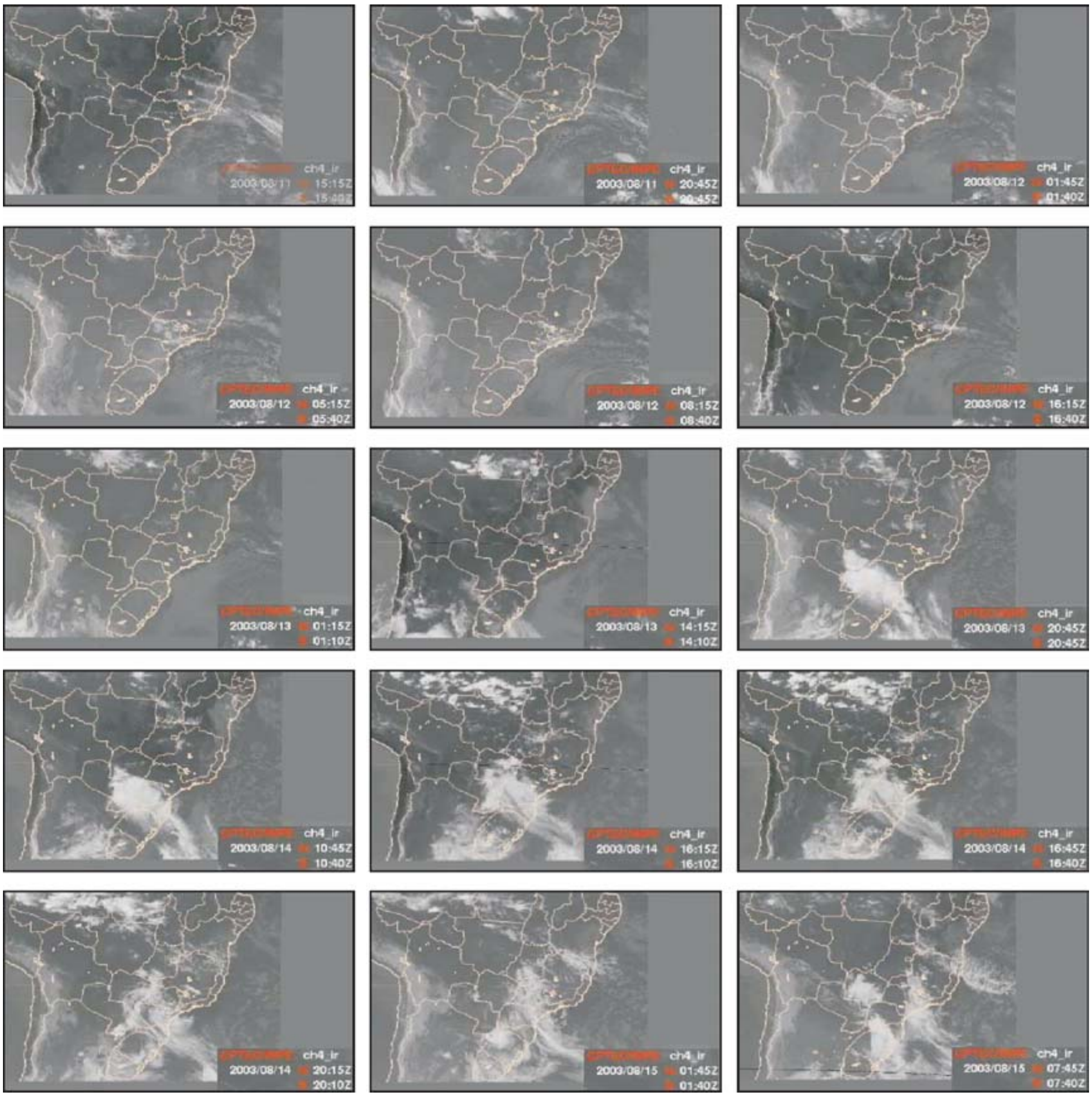

Fig. 3 — Sequences of Satellite images showing the propagation and dissipation of cold fronts from 2003/8/11 – 15:15 h to 2003/8/15 – 7:40 h.

The climatological data during this period in this figure shows lower air temperature, higher wind speed and lower solar radiation, during the cold front. Tundisi *et al.* (2002) showed the relationship between wind speed the Wedderburn number applied to Carlos Botelho (Lobo-Broa) and Barra Bonita reservoirs and the vertical distribution of phytoplankton species, particularly *Aulacoseira italica.* Chalar & Tundisi (1999) showed that during periods of calm days, with no winds, daily patterns of stratifications developed at Carlos Botelho Reservoir (Lobo-Broa). These resulted in sedimentation of Al, Fe and Al-P. Total dissolved phosphorus in the water column and the sedimentation of Fe, P, indicate a typical redox dependent P cycling. With high wind velocities the turbulence promoted water column aeration, maximal resuspension of particulate organic matter, phosphorus and vertical distribution of *Fragilaria* sp.

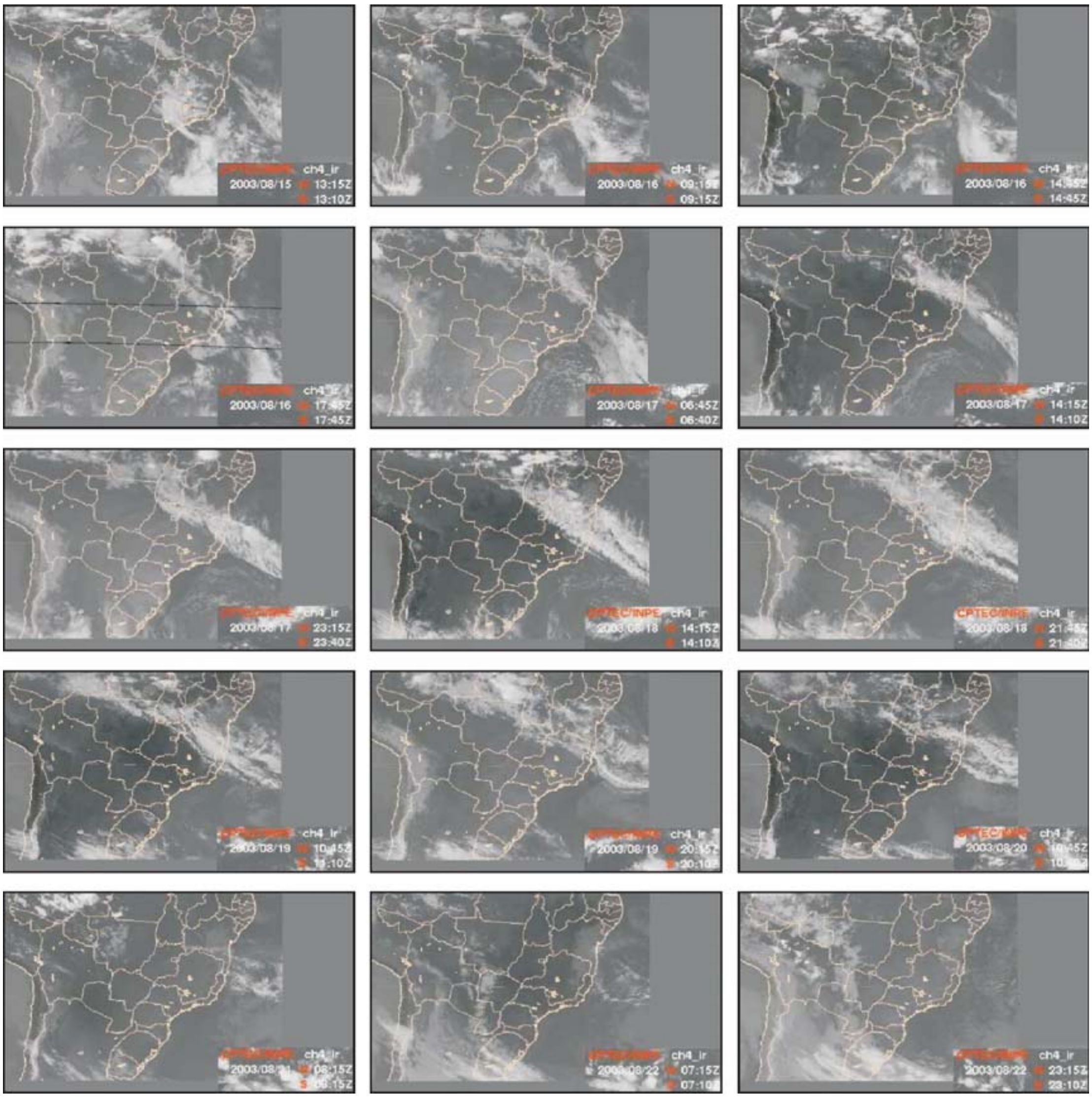

Fig. 4 — Sequences of Satellite images showing the propagation and dissipation of cold fronts from 2003/8/15 – 13:15 h to 2003/8/22 – 23:10 h.

DISCUSSION

Accordingly to Straškraba (1990) the depth of wind-induced mixing is related to the size of the freshwater ecosystem in shallow lakes. The same author pointed out that shallow lakes are hydrologically more sensitive and react biologically more strongly to hydrometeorological and water level changes. By this definition the reservoir of the Carlos Botelho (Lobo-Broa), dam can be considered shallow and respond by complete mixing of the water column to wind stresses of 5 to 10 km/h. Past work has shown (Tundisi & Matsumura-Tundisi, 1995) that the response of the reservoir as for the concentration of dissolved oxygen in the water column and distribution of filaments of *Aulacoseira italica* was strongly dependent on wind force and direction (Lima *et al*., 1978).

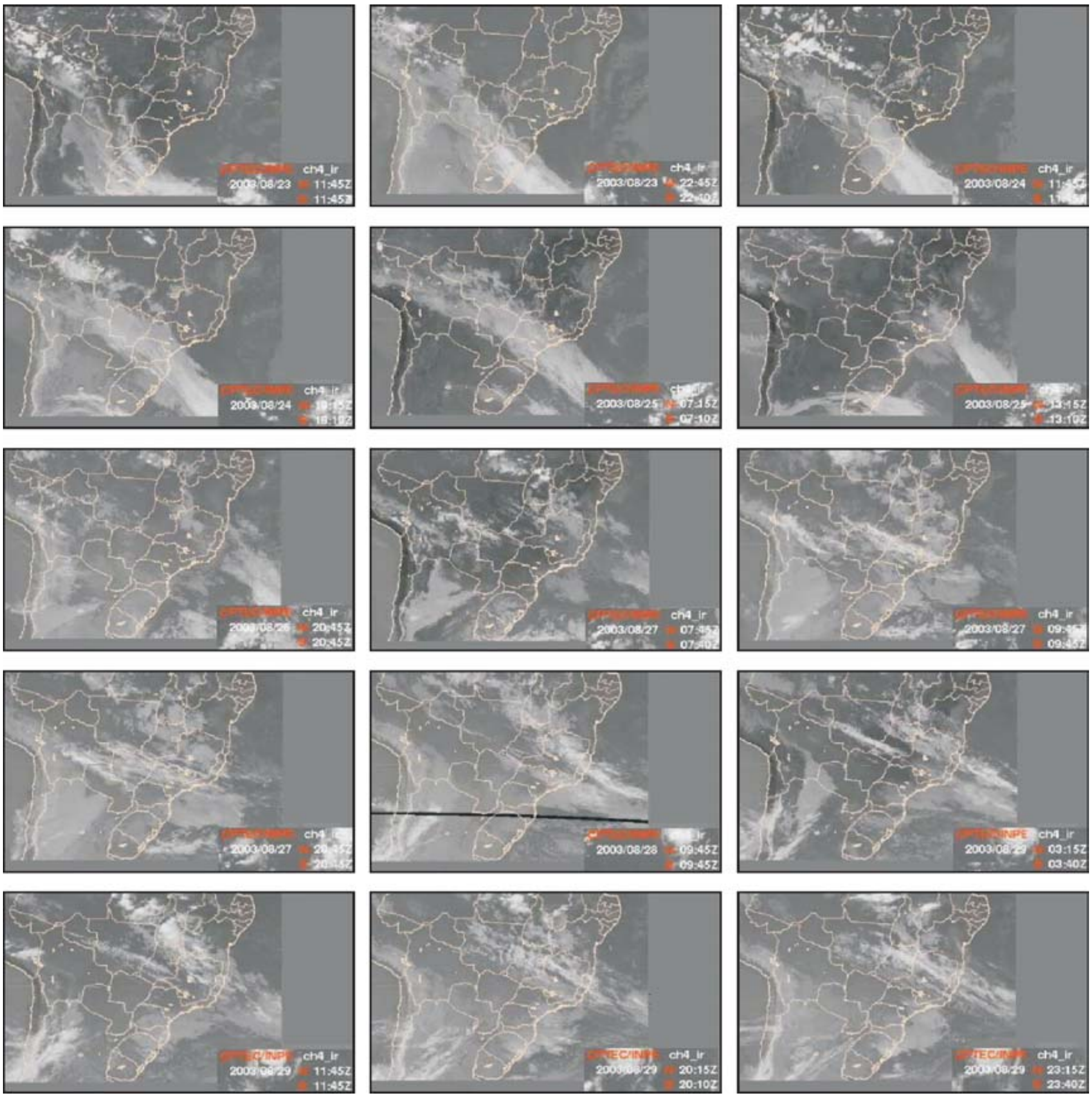

Fig. 5 — Sequences of Satellite images showing the propagation and dissipation of cold fronts from 2003/8/23 – 11:45 h to 2003/8/29 – 23:40 h.

The frequency and input of cold fronts affecting this shallow reservoir, periodically changes the structure of the water column and, as has been demonstrated in past work, the vertical distribution of the planktonic organisms. This is more common in the winter period (June, July, August, and September) when winds are important forcing functions within the system. Stech & Lorenzzetti (1992) have shown that the Southern Brazilian Bight responds to the passage of wintertime cold fronts. Accordingly to these authors "the surface wind field in the South Brazil Bight is highly influenced by the passage of frontal systems", occurring over periods of 6-11 days. Castro Filho (1985) also showed the subtidal response to wind forcing in the South Brazil Bight during the winter.

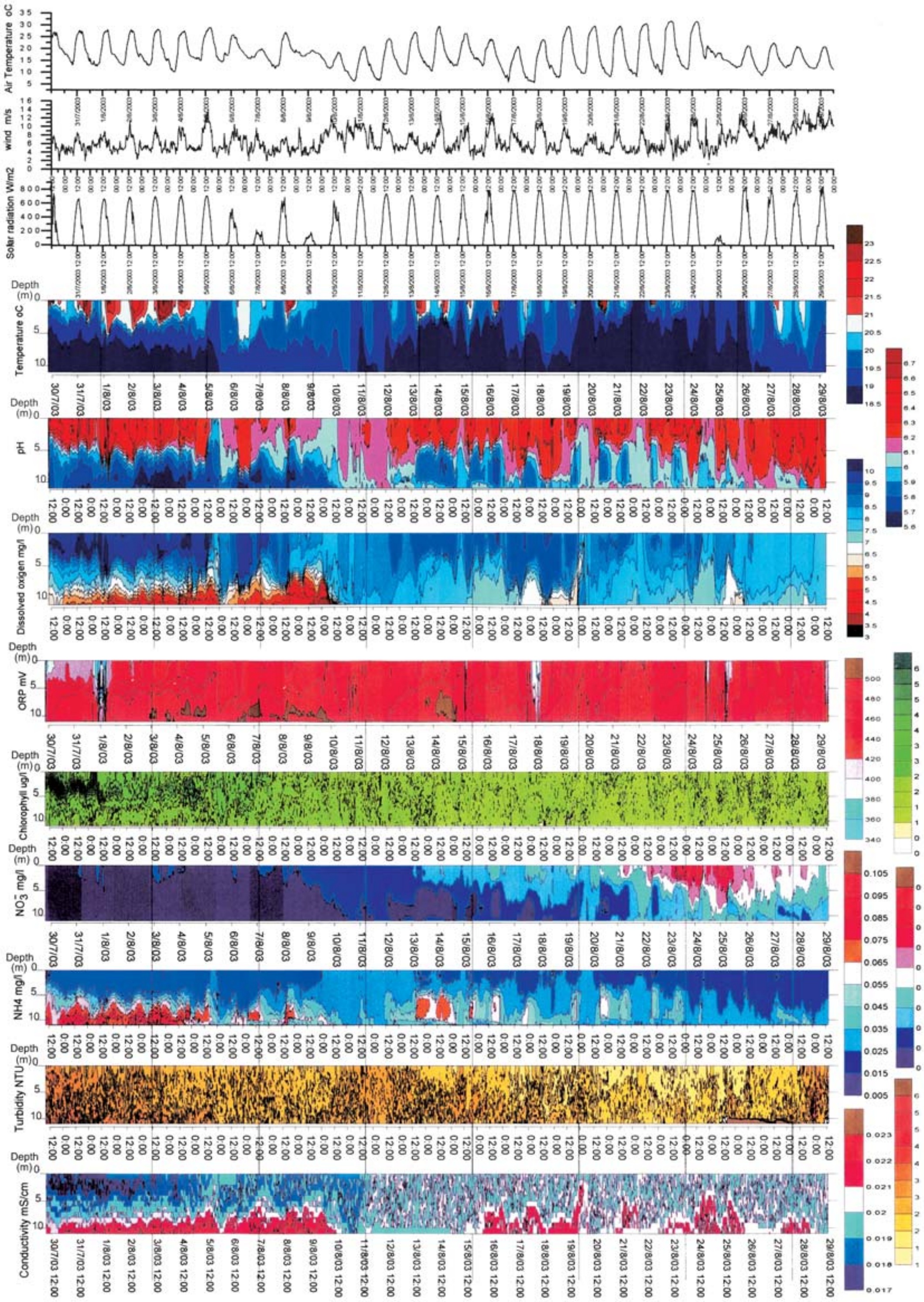

Fig. 6 — The time series of climatological data and the limnological variables measured from 2003/7/30 to 2003/8/29.

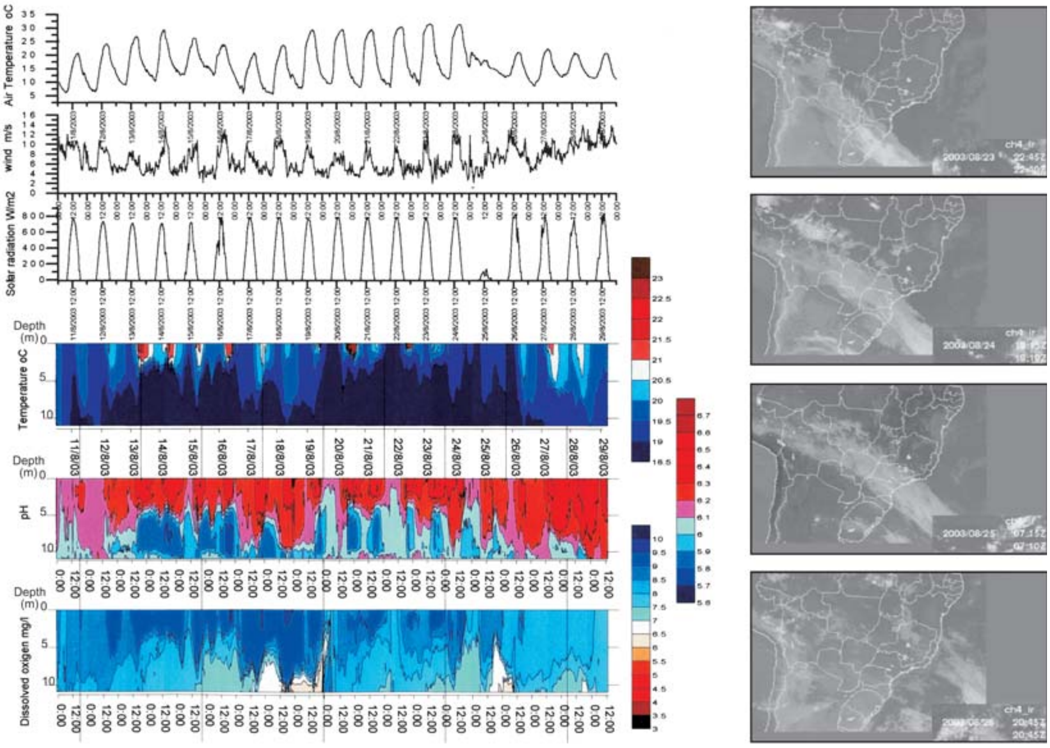

Fig. 7 — A detail of the time series of 3 limnological variables and the sequence of cold fronts from 23th to 26th of August, 2003 showing the changes on the climatological variables, water temperature, dissolved oxygen, and pH.

The results shown in this paper seem to confirm this effect of cold fronts on shallow reservoirs. During cold fronts, mixing occurs. At the more calm periods during the intermediate phases there is surface heating and stratification. Although these results applied only to Carlos Botelho (Lobo-Broa) Reservoir, they may represent a general response of shallow reservoirs in the southeast Brazil, particularly in São Paulo State.

Reynolds (1999) discussing the seasonality and phytoplankton selection in reservoirs emphasize that in shallow warm water reservoirs the dominance of *Cylindrospermopsis* sp. can be permanent as well as another low diversity steady state plankton dominated by the cyanobacteria *Microcystis aeruginosa.* With high energy incomes and heavy nutrient inputs either from the watershed or by internal load, the tendency in these reservoirs is the dominance of *Mycrocystis* sp. This however will not prevail during continuous mixing and permanent wind action such as occurs in the cold fronts.

São Paulo State has many shallow reservoirs; especially in the Metropolitan Region of São Paulo, there are 23 reservoirs utilized for water storage for drinking purposes (Tundisi, 1990a, b.; Tundisi 1993). These shallow reservoirs change states in their water quality as a result of stratification and vertical circulation impacts. When this occurs, changes in water quality are expected. When there is stratification, the frequency of cyanobacterial blooms, mainly *Microcystis aeruginosa* or *Microcystis* sp*.,* increases.

With circulation and mixing, iron and manganese can be released after a period of reducing conditions in the bottom, promoted by the stratification, resulting in increased costs of water treatment for drinking purposes. A study on the correlation between cold front frequencies, reservoir response, and water quality changes is in progress. Of particular interest in this case is the frequency of cyanobacterial blooms related to cold front impacts and mixing processes in the reservoirs.

The results obtained may ultimately lead to a predictive model for use as a tool for management of reservoirs, especially those utilized for drinking water in the São Paulo Metropolitan Region. Any negotiation for water uses in the Metropolitan Region of São Paulo, must take into account water quantity and water quality. With this results it is important to consider the predictive capacity given by the interaction of cold fronts with reservoir water quality, that will reflect costs of treatment and water availability (Tundisi *et al.,* 1998).

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