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Diel patterns of temperature, conductivity and dissolved oxygen in an Amazon floodplain lake: description of a *friagem* phenomenon

Comportamento diário da temperatura, condutividade e oxigênio dissolvido em um lago de inundação amazônico: descrição de um fenômeno de friagem

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Abstract: Aim: The aim of this work was to study the diel stratification parameters temperature, dissolved oxygen and conductivity, providing a more detailed description of a *friagem* event. **Methods**: the mixing behavior of the limnetic water column in Lago Catalão, an Amazon floodplain lake flooded by two of the world's largest rivers (Solimões and Negro), was studied through diel profiling of temperature, conductivity and dissolved oxygen, between 2006 and 2007. Measurements were made every four hours at 1m depth intervals to the lake bottom. **Results**: The water column remained stratified during most of the year with the exception of one month with low water level, when nocturnal mixing occurred and one *friagem* event during high water (May 2007) when an isothermal temperature profile and an atypical orthograde oxygen profile were observed. **Conclusions**: The *friagem* event, a large drop in air temperatures due to the intrusion of a polar air mass in the Amazon, constitutes an important force in the dynamics of the water column, which produces a profound redistribution of dissolved gases and solutes in the system. This is the first time that the effects of the *friagem* on the mixing patterns in a lowland Amazon lake have been documented in detail. The decline in air temperature, observed during the *friagem* event destabilized the normally stratified water column, which can be associated with an environmental disturb.

Keywords: Amazon, floodplain lake, *friagem*, water column.

Resumo: Objetivo: O objetivo do presente trabalho foi estudar a estratificação diária dos parâmetros temperatura, oxigênio dissolvido e condutividade elétrica proporcionando uma descrição mais detalhada de um evento de friagem. **Métodos**: O comportamento da coluna de água no lago Catalão na Amazônia Central, que é inundado por dois dos maiores rios do mundo (Solimões e Negro) foi estudado entre 2006 e 2007, através de avaliações nictemerais da temperatura, oxigênio dissolvido e condutividade elétrica. As medições foram feitas em intervalos de quatro horas e a cada metro até o fundo do lago. **Resultados**: Observou-se em geral, uma coluna de água estratificada, com exceção do período das águas baixas e do breve período da friagem em maio de 2007, quando a coluna apresentou-se invertida em termos do oxigênio dissolvido e desestratificada em termos de temperatura. **Conclusões**: Foi possível observar que a friagem, que é um fenômeno climatológico caracterizado pela queda brusca da temperatura do ar devido às entradas de massas de ar polares na Amazônia, se constitui em uma força importante na dinâmica da coluna de água, que produz uma profunda redistribuição dos gases dissolvidos e solutos no sistema. Esta foi a primeira vez que um evento de friagem foi documentado em detalhes. O declínio na temperatura do ar, observado durante o evento de friagem desestabilizou a coluna da água normalmente estratificada, o que pode ser associado com um distúrbio ambiental.

Palavras-chave: Amazônia, lago de inundação, friagem, coluna de água.

1. Introduction

One of the most common characteristics of shallow Amazon floodplain lakes is their polimictic nature, which produces a variety of effects on the associated biological communities (Melack and Forsberg, 2001; Diehl, 2002; Thomaz et al., 2007; Almeida and Melo, 2009). These lakes are characterized by a daily cycle of stratification tied to the diurnal pattern of heat exchange and winds with the daily extent of vertical mixing defined by the seasonal variation in water depth (MacIntyre and Melack, 1984; Tundisi et al., 1984). It tends to be permanently stratified during high water periods and polimictic at low water. In Lago Calado, for example, MacIntyre and Melack (1988) observed complete daily mixing when maximum depth was less than 3 m and permanent stratification when lake depth exceeded 5m. This pattern, though, can vary between lakes depending on seasonal variations in lake morphometry. Small lakes which remain relatively deep throughout the year (> 5m) can maintain stable hypolimnia even during low water periods (Tundisi et al., 1984). Due to the consistently high water temperatures and elevated aquatic productivity in these systems, stable water columns generally result in a rapid depletion of hypolimnetic oxygen concentrations and an accompanying increase in the concentrations of methane, hydrogen sulfide and other reduced gas species (Schmidt, 1973; Crill et al., 1988; Richey et al., 1988; Aprile and Darwich, 2009).

The vertical mixing pattern in Amazon floodplain lakes can also be affected by *friagem* events, a large scale climactic phenomenon which occurs over large areas of the western Amazon during the winter months of the southern hemisphere (May – August). A *friagem* is characterized by a large drop in air temperature, lasting 1-5 days, caused by the intrusion of a polar air mass that generally passes through the Plata and Paraguay river basins before reaching the western Amazon (Hamilton and Tarifa, 1978; Marengo et al., 1997). Climactically, it has been described as a sequence of events that can reduce average air temperature in Manaus up to 5 °C, an uncommon change in a tropical equatorial region (Silva Dias et al., 2004). *Friagem* can occur several times during a single year. Culf et al. (1996) reported six *friagem* events in the Amazon during 1992, nine during 1993 and 14 events during 1994. The dates of all *friagem* events from 1983-1996 were reported by Marengo et al. (1997) and those since 1995 can be found in the Climanalise Boletim (http://www6.cptec.inpe.br/revclima/boletim/index0507.shtml) of the Instituto Nacional de Pesquisas Espaciais (INPE) of Brazil. Individual events have also been studied like the *friagem* of June 2001 in the State of Rondônia which was shown to have significant effects on the fluxes of energy and CO2 over the region. The first report of a *friagem* event in the Brazilian State of Amazonas was that of Morize in 1920 (Marengo et al., 1997), when air temperature dropped to 16 °C, resulting in the mortality of fish in lakes near Manaus. However in his book about the Amazon, Alfred Russel Wallace (1889, p.431) said

> in the month of May, some very cold days are said to occur … on the Upper Amazon and Rio Negro... Many intelligent persons have assured me that the cold is sometimes so severe that the inhabitants suffer much, and, what is much more extraordinary, the fishes in the rivers die of it.

The amplitude and frequency of *friagem* events may have increased recently due to the anthropogenic reduction in forest cover which initially obstructed the flow of polar air. Certainly, there is seasonality in the occurrence of the cold fronts passage in the South American continent (Cavalcanti and Kousky, 2009). The phenomenom is known to local populations, which live on the margins of lakes and rivers and to many researchers who have referred to it in their works, as the principal cause of *Aiu*, a regional expression describing a rapid drop in surface oxygen concentrations, generally accompanied by the mortality of fish (Esteves, 1998). *Friagem* generally result in the complete destratification and mixing of the water column, bringing anoxic hypolimnetic waters, rich in H_2S and other biogenic gases, to the surface, resulting in the mortality of fish species poorly adapted to these conditions. A massive fish kill of this type was reported by Fearnside (1995) in Balbina Reservoir following a cold front which presumably destratified the water column. While the *friagem* phenomenon has been referred to in a number of limnological studies in the Amazon (Brinkman and Santos, 1974; Fearnside, 1995; Dámaso et al., 2004), a detailed analysis of its effects on the stability of the water column is still lacking. Engle and Melack (2000) attributed a sharp increase in methane concentrations in the surface waters of a central Amazon floodplain lake to deep mixing during a cold front in May of 1987. Nuñez-Avellaneda (2005), also detected a rapid cooling of surface waters in a lake along the floodplain of the Rio Putumayo in Colombia, presumably associated with a *friagem* mixing event. Tundisi et al. (1984) encountered cool surface waters in another central Amazon floodplain lake, which they attributed to an earlier *friagem* event, however the water column had already re-stratified when they made their measurements.

Hamilton et al. (1997) reported a general depletion in dissolved oxygen concentrations in lakes along the Rio Paraguay (Pantanal region) that can last for several months during the high water season, a phenomenon called *dequada* by the local populations. A similar depletion is found in the early morning hours in most Amazon floodplain during the high water period and most fish in the region have developed adaptations to deal with these moderately hypoxic conditions (Val and Almeida-Val, 1995). The *friagem* is a more severe and unpredictable climactic phenomenon of short duration whose intensity and frequency tend to be inversely proportional (Melack and Fisher, 1983). The deep mixing which occurs during these much rarer events results in: 1) trophic encounters between epilimnetic and hypolimnetic organisms (Jäger et al., 2008), 2) an increase in epilimnetic concentrations of methane and hydrogen sulfide with severe depletion in oxygen (Brinkman and Santos, 1974; Engle and Melack, 2000), 3) extensive fish mortality (Fearnside, 1995; Tundisi et al., 2010) and 4) the recycling of hypolimnetic nutrients, in the form of phosphate and ammonia, to the euphotic zone (Melack and Fisher, 1983). In lake George, Uganda, *friagem*-like events called torments have been show to be one of the principal natural factors controlling fish populations (Gwahaba, 1973). In a Brazilian southeast reservoir, Tundisi et al. (2004) observed, trough a continuous measuring of nine variables in vertical profiles, a vertical mixing of the water column. It is suspected that *friagem* events may have similar effects in Amazon. However a detailed description of the *friagem* phenomenon is still lacking for the region.

We present here results of a study of diel stratification patterns for temperature, dissolved oxygen and conductivity in an Amazon floodplain lake (Lago Catalão) during an annual flood pulse cycle. The results demonstrate the variable nature of these patterns and provide a detailed characterization of a *friagem* event observed during in May of 2007.

2. Material and Methods

2.1. Study area

Lago Catalão (Figure 1) is located on a floodplain peninsula, at the confluence of the Rio Solimões (Amazon main channel) and Rio Negro in front of the city of Manaus (3° 10' 04" S, 59° 54' 45" W). The surface area and volume of the lake vary dramatically due to fluctuations of up to 12m in water level associated with the annual river flood pulse. It ranges from a circular pool of less than a hectare at low water to an x-shaped lake at high water with the lengths of the N-S axis and NE-SW axis reaching 3.0 and 1.2 km, respectively. The lake receives water from the Rio Negro during the early rising water period and from the Rio Solimões during late rising water. The Negro is a black water river, rich in dissolved organic carbon and low in pH (<5), conductivity (8-10 µScm^{-1}) and dissolved alkalinity (<0.05 meq L^{-1}) (Sioli, 1984). In contrast, the Solimões is a white water river, with approximately neutral pH and relatively high levels of suspended solids (100-300 gL^{-1}), alkalinity (0.5-0.6 meqL^{-1}) and conductivity (60-90 µScm^{-1}) (Sioli, 1984; Devol et al., 1995). Since the lake has no significant local drainage basin, the annual water balance represents a variable mixture of water from the two geochemically distinct rivers (Brito et al., 2014; Almeida and Melo, 2009) and this complex loading regime results in a unique seasonal variation in the lake's physical and chemical characteristics.

At extreme low water in 2006 (October-November), the lake was isolated from both rivers

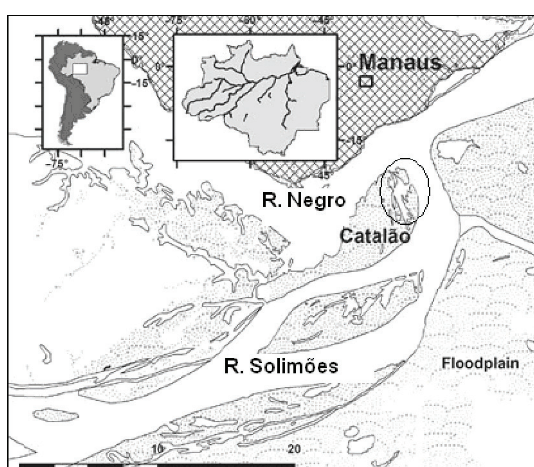

Figure 1. Map of the Amazon floodplain near Manaus, Brazil, showing the location of Lago Catalão (circled area), 3° 10' 04" S and 59° 54' 45" W. (Modified from Neves dos Santos et al., 2007).

and its area and volume were greatly reduced. The lack of advective flow from fluvial inputs in this period combined with increased physical and biological disturbance of bottom sediments due to reduced lake depth, resulted in large spatial variations in physical and chemical characteristics. Secchi disk transparency tended to be exceptionally low (~0.3m) during this uniquely lentic phase while conductivity rose to 245-425 μScm^{-1} (Almeida and Melo, 2009). By the end of November, water from the Rio Negro began to flow into the lake again resulting in a significant increase in transparency and reduction in conductivity.

The months of February – April in 2007 corresponded to the rising water period when the lake was influenced predominantly by the Rio Negro. During this phase conductivity levels dropped still further and the lake was permanently stratified. A distinct increase in the level of conductivity in the lake at the end of April marked the first inflow of water from the Rio Solimões and the beginning of the high water period. The levels of conductivity and transparency then remained relatively constant until the beginning of May when lake depth reached 12m and the flow of water from the Solimões began to increase, resulting in strong advective mixing and the homogenization of physical and chemical characteristics in the lake (Brito et al., 2014; Almeida and Melo, 2009). May was also the month when deep mixing associated with a *friagem* event was encountered.

Temporal variations in physical and chemical characteristics tended to be larger than spatial variations during the rising and high water periods in Lago Catalão (Almeida and Melo, 2009; Aprile and Darwich, 2013), as has been described for floodplain lakes in general by Thomaz et al. (2007). Peak high water, a period characterized by minimal variations in water level, occurred in June-July in 2007. The falling water period lasted from late July through September, when fluvial inputs to the lake ceased and floating macrophytes disappeared. In October, the lakes area was restricted to a central pool which drained towards the Rio Negro (Leite et al., 2006).

2.2. Sampling and data analysis

Vertical profiles of temperature, conductivity and dissolved oxygen were measured a 1 m intervals at the deepest point in the lake at 4 hour intervals during one complete diel cycle in the months of November of 2006 and February, March, April, May and August of 2007. Measurements were made with a Thermo Scientific Orion 4-Star Plus multi-sensor which was calibrated before each profile. The resolution and relative precision of the equipment are 0.01 mgL^{-1} and ± 0.2 mgL^{-1} for oxygen; 0.001 µS/cm and ± 0,01 μScm^{-1} for conductivity; 0.1 °C and ± 0.1 °C respectively. Sampling periods were chosen to represent distinct phases in the annual flood cycle of the lake (Bittencourt and Amadio, 2007), including low water (November), when the lake was isolated from the rivers, rising water (February, March and April), when water from the Rio Negro flowed into the lake, high water (May), when the Rio Solimões flow into the lake and a *friagem* event was observed and falling water (August), when the water balance was dominated by the Solimões.

Daily variations in temperature, conductivity and dissolved oxygen were represented with isolines using SigmaPlot 2001. Data that were not homogeneous or normally distributed were log-transformed [log (n+1)] and tested again to confirm normality and homogeneity. One way ANOVAs were used to detect differences for each variable between months and between hours for each month. When significant differences were detected, Tukey's t-test was used to identify the specific period where these differences occurred. Minimum differences of 1.0 °C, 10 μScm^{-1} and 1.0 mgL^{-1} were established to define vertical stratification for temperature, conductivity and dissolved oxygen, respectively.

3. Results

Significant thermal stratification (1.0–2.5 °C) persisted throughout most of the annual flood cycle in Lago Catalão, with mixed layer depths varying from 5 m during rising water (Figures 2B, C and D) to less than 2.0 m during falling water (Figure 2F). Isothermal conditions and evidence of deep mixing were only encountered at low water between 2:00 AM and 6:00 PM (Figure 2A) and at high water during a *friagem* event (Figure 2E). The highest temperatures were observed at low water and early rising water (Figures 2A and B), with surface values reaching 31.5 and 32.0 °C at 8:00 AM and 2:00 PM, respectively. In August (Figure 2F), thermal stratification was as strong as that observed during late rising water (April). However, the profile showed a more gradual temperature variation with depth, indicating a weaker density gradient and a lower stability of the water column in this period. On most dates there was evidence of a slight increase in surface temperatures around noon (at most 1.0

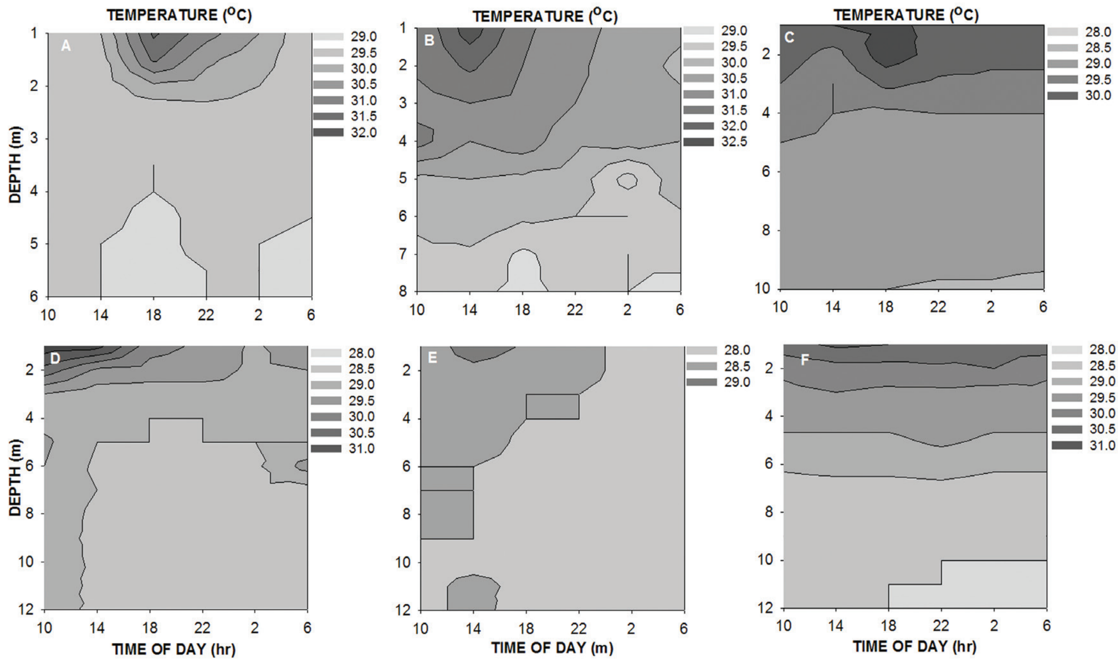

Figure 2. Daily variation in the vertical distribution of temperature in Lago Catalão during the months of: A) November; B) February; C) March; D)April; E) May and F) August.

°C). However, this only affected the first two meters, while the remainder of the water column remained stratified throughout the day. The only exceptions were during the *friagem* event in May and at low water when deep mixing was observed at night. At low water, the lake had a maximum depth of 6 m and was isothermal between 2:00 and 8:00 AM, with an average temperature of 29.0 °C. A slight increase in surface temperatures in the first 2 meters of the water column between 10:00 AM and 10:00 PM resulted in a brief period of thermal stratification and stability.

The lower temperatures observed during the month of May (Figure 2D), in both surface and bottom waters, were associated with a cold front which began the day before the measurements were made and was classified as a *friagem* event in the Climanalise Boletim (INPE, 2007). Between 2:00 and 6:00 PM on the second day of the *friagem*, the 12 meter water column was completely destratified with an average isothermal temperature of 27.8 °C, the lowest value recorded during the 24 hour cycle. A small vertical temperature difference of 0.2 °C was observed at 10:00 AM, increasing to 0.8 °C at 2:00 PM, followed by a second period of destratification between 6:00 PM and 10:00 PM.

During rising water (Figures 3B, C and D), the top 4 meters of the water column were well oxygenated while the water below this point was generally anoxic, with concentrations below 0,5 mg/L. The highest concentrations of dissolved oxygen registered in the study were encountered at the surface of the water column in April (Figure 3D) with only a slight drop in oxygen occurring at 2:00 PM on this date. In the month of May (Figure 3E), as a consequence of destratification and deep mixing during the *friagem* event, exceptionally low levels of oxygen were encountered near the surface between 4:00 PM and 2:00 AM. The lowest surface concentrations (~0.5 mg/L) were encountered between 6:00 PM and 10:00 PM while bottom concentrations varied between 2.0 e 2.5 mg/L. A different pattern was observed during the falling water period in August, (Figure 3F). Major changes in the vertical profile of oxygen were observed, indicating a net build up of oxygen near the surface during the day and consumption at night. Anoxia was not observed in the bottom waters on this date, even at the end of night. DO concentrations at all depths varied between 1.0 mgL^{-1} and 4.5 mgL^{-1}.

Conductivity was generally stratified in the water column of Lago Catalão with the values increasing gradually with depth, although the gradient was significantly reduced during the mixing events in November and May. The lowest conductivity values were observed in April when the influence of the Negro was greatest and the

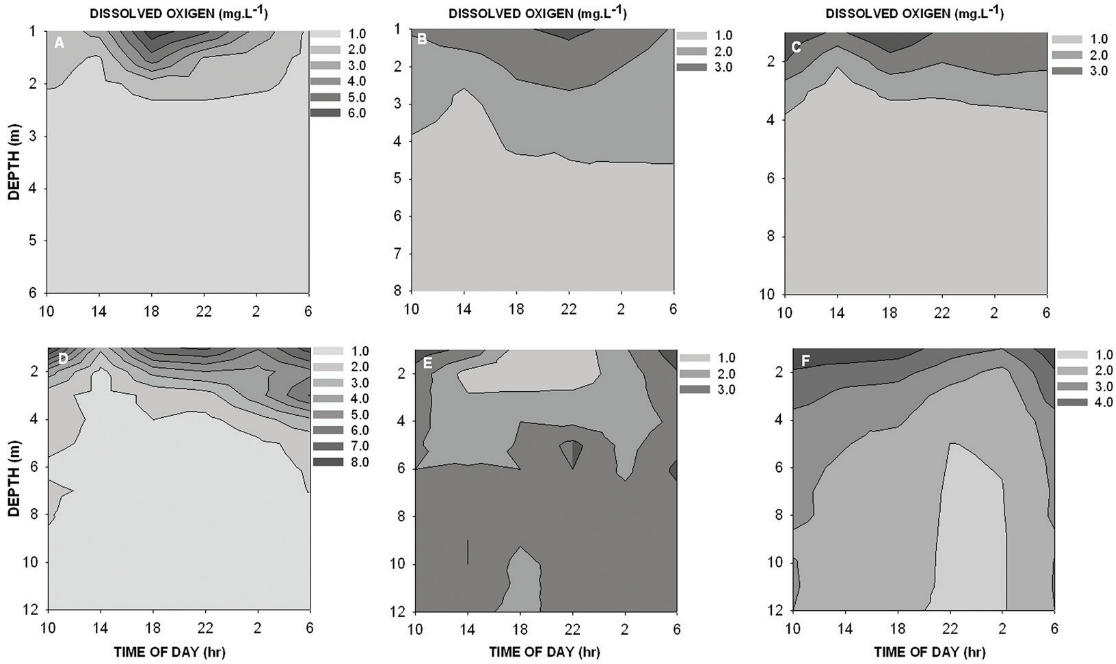

Figure 3. Daily variation in the vertical distribution of dissolved oxygen in Lago Catalão during the months of: A) November; B) February; C) March; D) April; E) May and F) August.

highest values were encountered during falling water after months of inflow from the Rio Solimões. The growing influence of the Rio Negro on the lake during the rising water period was evident from the gradual decline in conductivity values between February and April (Figures 4B, C, D), which fell from 50 to 20 μScm^{-1} in surface waters and from 90 to 45 μScm^{-1} in bottom waters. In May, conductivity in both surface and bottom waters was significantly higher (Figure 4E). The vertical distribution was also more homogeneous on this date, presumably due to deep mixing during the *friagem* event. Vertical differences ranging from 1.0 to 7.0 μScm^{-1} were observed on this date. A similar level of homogeneity was observed at low water during the nocturnal mixing period. The levels of conductivity in both surface and bottom waters were higher in August (Figure 4F), reflecting the cumulative influence of inputs from the Solimões during the high water period. The surface values at this time were similar to those in the Rio Solimões, indicating the dominance of fluvial inputs on the water balance of the lake, during this distinctly lotic phase of its flood cycle.

A significant difference in temperature regimes was encountered between months (ANOVA: F=71, p=0.000). Differences were encountered between the months of February, May and November and between these months and the remaining months. The dissolved oxygen patterns also differed significantly between months (ANOVA: F=14.6; p=0.0000), with the regimes in February and March differing from those in the remaining months. The diel variations in conductivity also varied seasonally (ANOVA: F=197, p= 0.000), with significant differences between the months of February, March and April, and between these and the remaining months.

Results from the ANOVA used to evaluate differences in the variation of temperature, oxygen and conductivity between hours on the same date are summarized in Table 1. The time intervals associated with significant differences detected by this ANOVA are summarized in Table 2.

Results from the ANOVA used to evaluate differences in the variation of temperature, oxygen and conductivity between months are summarized in Table 3. The time intervals associated with significant differences detected by this ANOVA are summarized in Table 4.

Significant differences in temperature dynamics were encountered on both seasonal and diel scales. The *friagem* event at high water had a strong influence on this result given that the temperature variation in this month differed from those in all other months and that this month also showed the greatest number of significant temperature differences during the diel cycle. In the case of dissolved oxygen, the only significant differences

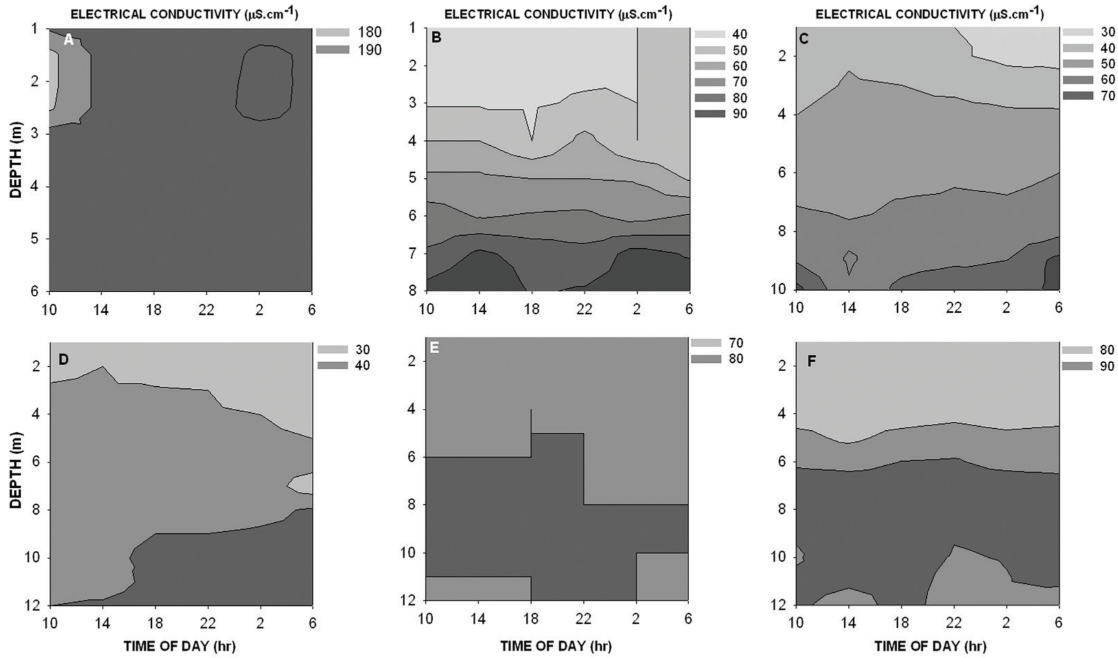

Figure 4. Daily variation in the vertical distribution of conductivity in Lago Catalão during the months of: A) November; B) February; C) March; D) April; E) May and F) August.

Table 1. ANOVA results: analysis of the influence of time of day for a given month on the variance of temperature, dissolved oxygen and conductivity in Lago Catalão. Significant results (p< 0.05) indicated in bold.

Month	Temperature		Dissolved Oxygen		Electrical Conductivity	
	F	P	F	P	F	P
February	1.297	0.283	1.322	0.273	0.025	0.999
March	0.641	0.670	0.674	0.645	0.040	0.999
April	**2.632**	**0.031**	1.223	0.308	0.243	0.942
May	**9.698**	**0.000**	**2.454**	**0.042**	1.148	0.344
August	0.019	0.999	**11.660**	**0.000**	0.013	0.999
November	2.279	0.057	1.199	0.319	3.604	0.060

were those encountered between hours on a given sampling date, presumably associated with metabolic patterns driven by the daily light or wind cycle. In contrast, significant differences in conductivity were encountered predominantly between months, reflecting seasonal variation in the geochemically distinct contributions of the Rio Negro and Rio Solimões.

Hydrogen sulfide gas and dead fish, often associated with *friagem* mixing events (Fearnside, 1995; Esteves, 1998; Nuñez-Avellaneda, 2005), were not detected at the surface of Lago Catalão in May. This was verified after a detailed survey of the lake surface at 6:00 PM on May 27, shortly after deep mixing had occurred and surface oxygen concentrations were severely depleted.

4. Discussion

The annual inundation pulses of the Rio Negro and Rio Solimões had a strong influence on the morphology, water balance, chemistry and mixing patterns in Lago Catalão as evidenced by the large seasonal changes in surface area, maximum depth, conductivity and diel thermal stratification patterns described here. The combined effect of contributions from these geochemically distinct sources to the water balance of the lake was best reflected by the seasonal changes in electric conductivity. Like total alkalinity, used by Forsberg et al. (1988) to investigate the water balance in 52 other Amazon floodplain lakes, conductivity is a relatively conservative parameter and thus provides a useful tracer for hydrological sources in simple mixing models. The observed seasonal trend in lake conductivity indicated a major shift in water sources from the Rio Negro during the rising water period to the Rio Solimões during high and falling water; this was previously demonstrated by Aprile and Darwich (2013) in a multiannual survey of the Lago Catalão. The seasonal variation in mixing, in turn, reflected changes in lake morphometry which determine the frequency and intensity of horizontal advection and thermal stratification together with the intensity of winds and surface heat exchange (Melack, 1984; MacIntyre and Melack, 1995; Fantin-Cruz et al., 2008).

Table 2. Results for Tukey's t-test: time periods in a given month where significant differences in temperature, dissolved oxygen and conductivity were encountered in Lago Catalão.

Temperature			
Month	Time interval		p value
	begins	end	
April	10:00	02:00	0.028
May	10:00	02:00	0.045
	10:00	06:00	0.010
	14:00	18:00	0.016
	14:00	22:00	0.001
	14:00	02:00	0.000
	14:00	06:00	0.000
Dissolved oxygen			
Month	Time interval		p value
	begins	end	
May	06:00	18:00	0.028
August	22:00	10:00	0.000
	22:00	14:00	0.001
	22:00	18:00	0.018
	22:00	06:00	0.000
	02:00	10:00	0.000
	02:00	14:00	0.001
	02:00	18:00	0.016
	02:00	06:00	0.000

Table 3. ANOVA results: analysis of the influence of month on the variance of temperature, dissolved oxygen and conductivity in Lago Catalão. Significant results ($p< 0.05$) indicated in bold.

Variable	F	P
Temperature	**12.773**	**0.000**
Dissolved Oxygen	2.439	0.060
Electrical Conductivity	**81.993**	**0.000**

Vertical mixing in the water column plays an important role in lake metabolism, promoting the recycling of nutrients to the euphotic zone and altering the redox conditions at the sediment-water interface. By redistributing oxygen and nutrients throughout the water column, vertical mixing effectively increases the habitat and food chain of benthic and pelagic organisms and the productivity of the aquatic environment (MacIntyre and Melack, 1995; Vadeboncoeur et al., 2002). Based on studies of mixing patterns in other Amazon floodplain lakes (Tundisi et al., 1984; MacIntyre and Melack, 1988; Melack and Forsberg, 2001; Aprile and Darwich, 2009), a relatively simple regional criteria has been developed to predict the frequency of complete mixing in these systems. Most lowland Amazon floodplain lakes approach isothermal conditions in the early morning hours. In lakes with maximum depths less than 4 meters, wind-induced turbulence is potentially sufficient to produce complete vertical mixing at this time.

These systems tend to be polymictic, aerobic environments with efficient nutrient recycling and elevated phytoplankton biomass and volumetric production (Schmidt, 1973; MacIntyre and Melack, 1995; Melack and Forsberg, 2001). In lakes with maximum depths ranging from 4 - 8m, nocturnal turbulence is generally insufficient to produce complete daily mixing. These lakes tend

Table 4. Results for Tukey's t-test: combinations of months for which significant differences in temperature, dissolved oxygen and conductivity were encountered in Lago Catalão.

Temperature	February	March	April	May	August	November
February		**0.037027**	**0.001585**	**0.000141**	**0.017546**	0.414997
March	**0.037027**		0.856025	**0.000946**	0.999723	0.831446
April	**0.001585**	0.856025		**0.022867**	0.953350	0.194256
May	**0.000141**	**0.000946**	**0.022867**		**0.002104**	**0.000154**
August	**0.017546**	0.999723	0.953350	**0.002104**		0.668095
November	0.414997	0.831446	0.194256	**0.000154**	0.668095	
Electrical Conductivity	**February**	**March**	**April**	**May**	**August**	**November**
February		0.420608	**0.000143**	**0.013890**	**0.005452**	**0.000141**
March	0.420608		**0.001219**	**0.000176**	**0.000152**	**0.000141**
April	**0.000143**	**0.001219**		**0.000141**	**0.000141**	**0.000141**
May	**0.013890**	**0.000176**	**0.000141**		0.999421	**0.000141**
August	**0.005452**	**0.000152**	**0.000141**	0.999421		**0.000141**
November	**0.000141**	**0.000141**	**0.000141**	**0.000141**	**0.000141**	

to mix irregularly and develop anoxic hypolimnia. Lakes deeper than 8m tend to be oligomictic with permanent anoxic hypolimnia, nutrient-depleted epilimnia and low phytoplankton biomass and volumetric production (Schmidt, 1973; Melack and Fisher, 1990; Melack and Forsberg, 2001). The mixing patterns in individual floodplain lakes tend to vary seasonally due to large fluctuations in lake depth associated with the river flood pulse. Polymictic conditions are common at low water while oligomixis predominates at high water (Tundisi et al., 1984; MacIntyre and Melack, 1995; Lewis Junior, 1996). *Friagem* events are exceptions to this rule, causing intense surface-cooling and strong density currents which promote complete mixing even in deep lakes at high water (Melack and Fisher, 1990).

With the exception of the *friagem* event in May, all of the diel temperature patterns observed in 2007 indicated a regime of permanent stratification, similar to that described by Aprile and Darwich (2013) during the high water period. The general pattern described by MacIntyre (1993) included: 1) windless conditions and high incident radiation resulting in the warming surface waters in the morning, 2) increased winds and continued warming in the afternoon and 3) surface cooling combined with moderate winds at night resulting in the vertical mixing of surface waters to a depth defining the daily mixed layer (Imberger, 1985), The depth of the daily mixed layer varied from 5m at late rising water to 2m at falling water. The development of this daily mixed layer basis was ecologically important since in guaranteed the intermittent access of the phytoplankton distributed in this layer to the euphotic zone (Diehl, 2002), which according Brito et al. (2014) varies in depth from 1.6 to 2.6m in Lago Catalão.

The concentration of dissolved oxygen in the water column of Lago Catalão reflected the balance between planktonic production, community respiration and atmospheric exchange. Concentrations were generally higher near the surface, reflecting oxygen gains from photosynthesis and atmospheric exchange which are insignificant at greater depths. However, there was no consistent difference in concentrations between day and night. The surface waters in Amazon floodplain lakes are generally sub-saturated in oxygen due to an abundance of allochtonous organic inputs and the predominance of aerial photosynthesis in aquatic plant communities (Melack and Fisher, 1983; Richey et al., 1988; Melack and Forsberg, 2001). Surface waters in Lago Catalão also tended to be sub-saturated in dissolved oxygen with the lowest values occurring at low water, the highest occurring at high and falling water and an average concentration of 1.5 mgL^{-1} or approximately 20% saturation. Super-saturation was only observed once near the surface in April. Significant levels of oxygen were generally restricted to the top 5 meters of the water column which corresponded to the maximum daily mixed layer. A predominance of bacterial consumption, combined with consistently high temperatures and an abundance of organic substrates resulted in anoxic conditions throughout most of the year in waters below this depth.

In November of 2006, when maximum depth was reduced to 6m, oxygen remained stratified throughout most of the diel cycle with concentrations peaking during the day and declining at night. Complete mixing apparently occurred at 6:00 AM when oxygen concentrations were uniform throughout the water column. This behavior is consistent with the general pattern of irregular mixing with anoxic hypolimnion, expected for lakes with maximum depths between 4 and 8m.

During the early rising water period, as water from the Rio Negro flowed into the lake, the levels of oxygen in the daily mixed layer (<5 m) were significantly lower than those encountered in other periods. This could reflect the increased oxygen consumption which commonly occurs at the terrestrial-aquatic transition zone in floodplain environments, as terrestrial plants, buffalo feces, and other organic materials, entrained by rising waters, begin to decompose (Junk et al., 1989). Similar depletions have been observed in river and floodplain environments in the Pantanal region (Hamilton et al., 1997; Hamilton, 2002) and Australia (Ford et al., 2002) at this time. The values registered here in open water environments were presumably higher than those which occurred in littoral environments where metabolic activities were expected to be more intense (Brito et al., 2014), when the lake was near maximum depth and the influence of the Negro was greatest. The super-saturated values registered in surface waters on this date were inconsistent with the results of Tundisi et al. (1984) and Devol et al. (1995) who found the lowest oxygen levels in Amazon floodplain lakes when they approached maximum depth, but are consistent with the results of Aprile and Darwich (2009) who detected supersaturation in the epilimnion of the Lago Tupé. These anomalously high values were probably caused by a phytoplankton bloom which was observed on this date. The lack of a clear increase in surface oxygen values during the day on most dates indicates that photosynthesis is not the dominant source of oxygen in this system. Melack and Fisher (1983) found similar results in a study of the diel oxygen balance of lago Calado, a floodplain lake near Catalão, and concluded that atmospheric exchange and not photosynthesis was the principal source of oxygen in this system. While we did not measure photosynthetic inputs directly, the lack of clear diel trend in surface oxygen concentrations suggests that atmospheric exchange is also the principal source of oxygen in Lago Catalão.

Like alkalinity (Forsberg et al., 1988), conductivity proved to be a good indicator of the water balance in Lago Catalão, accurately reflecting the relative mixture of waters from the Rio Negro and Rio Solimões present in the lake throughout most of the year (Aprile and Darwich, 2013). The low water results (November 2006) were exceptional in this sense with conductivity values exceeding the maximum levels encountered in either river. The high conductivity in this case was probably derived from the decomposition and leaching of lake sediments and macrophytes, associated with the extensive areas of exposed lake bottom surrounding the small residual water mass at this time. The hydrological dynamics of Lago Catalão differed from the patterns described by Lesack and Melack (1995) for Lago Calado and by Forsberg et al. (1988) for 51 lakes along the central Amazon floodplain. Water in these lakes was derived predominantly from two sources, a single large river and local runoff, with fluvial inputs dominating the water balances during high water and local runoff, when significant, having a greater influence during low water. Lago Catalão differed from these systems because it received water from two major rivers and no significant inputs from local runoff, especially during the dry season, when a weak interaction with terrestrial system was observed by Aprile and Darwich (2009). In this case, the relative importance of inputs from the two rivers depended on small seasonal differences between their surface levels. The river with the highest surface level at a given time tended to dominate inputs. When this height advantage was maintained for several weeks of months the higher river also tended to dominate the water balance in the lake. In the case of Lago Catalão, the Rio Negro dominated the inflow and water balance from early rising water through late April, while the Solimões dominated from May through the end of falling water. The unique hydrological dynamics of Lago Catalão reflects it is uncommon location on a relatively isolated peninsula of floodplain at the confluence of two major rivers. Diel variations in the depth profile of conductivity also proved useful for evaluating vertical mixing patterns. Conductivity profiles tended to be highly stratified when the water column was stable (Figures 4B, C, D and F) and relatively homogeneous during the mixing events at low and high water (Figures 4A and E). Given its relatively conservative nature, conductivity profiles could therefore provide a better index of stratification than oxygen profiles, which have been used to evaluated mixing patterns in other Amazon floodplain lakes (Melack, 1984)

4.1. Friagem

Ten *friagem* events were registered in the State of Amazonas between the months of May and September in 2007, affecting predominantly the southern and southeastern portions of the state. A series of polar air masses invaded the South American continent in May causing an accentuated drop in air temperature and atypical snowfall events in the south of Brazil A total of six polar incursions occurred in this month. The second incursion was especially intense and resulted in *friagem* in the Amazonian states of Acre and Rondônia. In the last week of May, a new polar air mass advanced over the continent, producing record-low temperatures in the South of Brazil. By 22 May 2007, this air mass had extended over most of South and Central of Brazil and the southern part of Northern Brazil, where on 24 and 25 May 2007 it caused the *friagem* event we registered at Lago Catalão. No precipitation was registered in the study region during the 15 days prior to the measurements. A strong rain occurred on the night of 24 May 2007 at the beginning of the measurement series, followed by cold southern winds which continued through 25 May 2007 and then diminished by 10:00 AM the following day. The effects of this cold front were clearly visible in the diel distributions of temperature, dissolved oxygen and conductivity (Figures 2E, 3E and 4E). The lake had a maximum depth on 12 meters at the time of these measurements and would normally have been permanently stratified with an anoxic hypolimnion (Melack and Forsberg, 2001). Instead, we found an isothermal water column with anoxic surface waters, oxygenated bottom waters and a weakly stratified conductivity profile, all signs of a major deep mixing event. The daily mixed layer, established by wind-driven nocturnal turbulence, is normally limited to 5 m in this period (Melack and Fisher, 1983; Tundisi et al., 1984; MacIntyre and Melack, 1995). However, vertical mixing during a *friagem* event does not depend on winds but on density currents caused by an unstable inverted temperature profile. The cold dense surface waters produced during these events penetrate much deeper than wind driven turbulence, resulting in complete mixing, independent of water column depth.

The consequences of deep mixing at high water, after lakes have been permanently stratified for several months, can have catastrophic effects on some aquatic organisms. These massive die-offs can have important effects on the demography and population dynamics of these species (Gwahaba, 1973). The wide range of behavioral and physiological adaptations to hypoxic conditions demonstrated by regional fish communities (Val and Almeida-Val, 1995) suggests that they may also play an important role in the evolution of the Amazon's diverse aquatic fauna. The absence of fish mortality during the *friagem* event documented here may be due to the fact that anoxic conditions were restricted to the surface layer. Oxygenated bottom waters may have provided a refuge for sensitive aerobic organisms, preventing mortality in this case.

For other aquatic organisms, deep mixing can have positive consequences. The introduction of hypolimnetic nutrients to the euphotic zone, which tends to be nutrient-depleted in these lakes at high water (Setaro and Melack, 1984), can be expected to increase phytoplankton biomass and productivity (Fisher and Parsley, 1979; Vadeboncoeur et al., 2002, Trevisan and Forsberg, 2007) and increase carbon flow to higher trophic levels (Araujo-Lima et al., 1986; Forsberg et al., 1993). The oxygenation of benthic environments during extended *friagem* events can also increase the habitat, food web and productivity of aerobic organisms that can tolerate hypoxic conditions (MacIntyre and Melack, 1995; Vadeboncoeur et al., 2002).

Since *friagem*-induced deep-mixing events are linked to regional climactic patterns, they tend to occur in many lakes at the same time. The regional nature of these this phenomenon was confirmed during a high water cruise along the Amazon floodplain during July of 1984, when repeated reports of massive fish kills were obtained from living in lakes throughout the region (Forsberg, personal communication). Considering the regional significance of these events, their intensity and ecological significance as an environmental disturb, it is recommended that they be investigated in more detail. Continuous synchronous measurements of oxygen and temperature profiles in multiple lakes are needed to better characterize the spatial and temporal variability of this phenomenon and investigate its impact on floodplain ecosystems.

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