Climate change in Brazil: perspective on the biogeochemistry of inland waters

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Abstract

Although only a small amount of the Earth's water exists as continental surface water bodies, this compartment plays an important role in the biogeochemical cycles connecting the land to the atmosphere. The territory of Brazil encompasses a dense river net and enormous number of shallow lakes. Human actions have been heavily influenced by the inland waters across the country. Both biodiversity and processes in the water are strongly driven by seasonal fluvial forces and/or precipitation. These macro drivers are sensitive to climate changes. In addition to their crucial importance to humans, inland waters are extremely rich ecosystems, harboring high biodiversity, promoting landscape equilibrium (connecting ecosystems, maintaining animal and plant flows in the landscape, and transferring mass, nutrients and inocula), and controlling regional climates through hydrological-cycle feedback. In this contribution, we describe the aquatic ecological responses to climate change in a conceptual perspective, and we then analyze the possible climate-change scenarios in different regions in Brazil. We also indentify some potential biogeochemical signals in running waters, natural lakes and man-made impoundments. The possible future changes in climate and aquatic ecosystems in Brazil are highly uncertain. Inland waters are pressured by local environmental changes because of land uses, landscape fragmentation, damming and diversion of water bodies, urbanization, wastewater load, and level of pollutants can alter biogeochemical patterns in inland waters over a shorter term than can climate changes. In fact, many intense environmental changes may enhance the effects of changes in climate. Therefore, the maintenance of key elements within the landscape and avoiding extreme perturbation in the systems are urgent to maintain the sustainability of Brazilian inland waters, in order to prevent more catastrophic future events.

Keywords: tropical limnology, biogeochemical cycles, inland waters.

Mudanças climáticas no Brasil: perspectiva sobre a biogeoquímica de águas interiores

Resumo

Embora apenas uma pequena quantidade de água da Terra esteja reservada em corpos d'água da superfície continental, esses ambientes desempenham papel importante nos ciclos biogeoquímicos, conectando a superfície à atmosfera. O território brasileiro é recortado por uma densa rede fluvial e exibe um enorme número de lagos rasos. Impactos de natureza humana têm sido intensos modificadores de ecossistemas límnicos. A biodiversidade e os processos ecossistêmicos são fortemente modulados por forças sazonais fluvial e/ou precipitação. Essas macroforçantes ecológicas respondem às mudanças climáticas. As águas interiores são ecossistemas com elevada biodiversidade, promovem transferências de energia dentro da paisagem, conectando os ecossistemas, e atuam na manutenção de fluxos de matérias – animais, vegetais, nutrientes e inóculos. Esses ecossistemas controlam o clima numa escala regional. Neste capítulo, são descritas algumas respostas dos ecossistemas aquáticos às alterações climáticas, tanto conceitualmente como analisando os possíveis cenários de mudanças climáticas em diferentes regiões no Brasil. Potenciais sinais biogeoquímicos em diferentes ecossistemas límnicos brasileiros foram identificados. Os ecossistemas límnicos são pressionados pelas atividades do uso do solo, pela fragmentação da paisagem, pelo represamento e pelo desvio de rios, pela urbanização, pela carga de águas residuais e do nível de poluentes. Essas ações perturbadoras podem alterar os padrões biogeoquímicos nas águas interiores numa escala temporal mais curta quando comparada às mudanças climáticas. A manutenção da sustentabilidade das ecossistemas aquáticos brasileiros é urgente de modo a prevenir futuros eventos catastróficos.

Palavras-chave: limnologia tropical, ciclos biogeoquímicos, águas continentais.

1. The Brazilian Inland Waters

Although only a small fraction of the Earth's water occurs as surface water bodies on the continents, this compartment plays an important role in biogeochemical cycles by channeling carbon from land to atmosphere (Cole et al., 2007). Climate drives key fluxes (e.g., evaporation, water-vapor transport, and precipitation) that determine the spatial distribution and numbers of inland water bodies. Thus, not only the availability of freshwater to both ecosystems and humans, but also mass and energy transfer (for instance, carbon flows) are highly sensitive to changes in climate.

Description of Brazilian Inland Waters – The territory of Brazil encompasses a dense river net. Among the 12 hydrographic regions, defined according to major topographical boundaries (www.ana.gov.br, 20/02/2011), the most important are the Amazon, Tocantins-Araguaia, Paraná, Paraguai and São Francisco. The Amazonas hydrographic region covers seven million km^2, of which more than 60% lies within Brazil, but extends into parts of seven South American countries. The population density of this region is very low (2.0 inhabitants/km^2) and highly concentrated in a few urban centers. Most of the Amazon Forest biome is still preserved, although in Brazil, 17% of the biome has undergone some sort of change in land cover (mainly by replacement of native vegetation for farming or cattle ranching). The Tocantins-Araguaia hydrographic region covers 967 thousand km^2, borders the Amazon basin in the northern portion of the country, and contains parts of the Amazon and Cerrado biomes within its boundaries. The region faces intense pressure for land-use changes; a substantial area of the basin is located in the eastern portion of what is called the "arc of deforestation" (Ometto et al., 2011). The population density is relatively low (8.2 inhabitants/km^2) and highly mechanized farming of sugar cane, soybeans and other grains takes place in the southern and northeast areas of the basin.

The São Francisco hydrographic region, which lies entirely within Brazil, covers 638 thousand km^2 and includes parts of three biomes (Atlantic Forest, Cerrado or savanna, and Caatinga or xeric shrub vegetation). The population density is 20 inhabitants/km^2. The Paraná hydrographic region, with an area of approximately 880 thousand km^2 in Brazil, drains to the Atlantic as part of the La Plata basin hydrographic basin. It is located in a highly developed agricultural region and is relatively densely occupied (62.1 inhabitants/km^2). The last major hydrographic region described here, the Paraguai basin, drains the largest wetland in South America, the Pantanal (140 thousand km^2), towards the La Plata Basin hydrographic net; of the total area of the basin (482 thousand km^2), 75% is within Brazilian territory. The population density is relatively low (5.2 inhabitants/km^2), and cattle ranching is the predominant land use. Six additional coastal hydrographic regions draining toward the Atlantic Ocean; and the small Uruguai hydrographic region, which is located in an agricultural area, and drains to the Atlantic toward the La Plata Basin, comprise the remainder of the Brazilian hydrological system.

Integrating Landscape - The hydrological cycle integrates the different components of the planet's system. Water vapor and precipitation are the components of the water cycle that directly relate the atmosphere to the biota. Studies in the Amazon basin have identified a close connection between the vegetation and rain atributtes (Andrea et al., 2002), by release of organic compounds that function as cloud nuclei; as well as evapotranspiration, a key process in transferring water from the biosphere to the atmosphere. Moreira et al. (1997) estimated the relative importance of soil evaporation and evapotranspiration for the Amazon region, indicating that evaporation accounts for 20-30% of water transfer to the atmosphere, while evapotranspiration accounts for 70-80%. The evapotranspiration process closely connects the vegetation and the atmospheric water demand. Predicted changes in the atmosphere thermodynamics, due to the increase in energy retention from the greenhouse effect (IPCC, 2007), may change the rates of water transfer from the biosphere to the atmosphere, affecting the functioning of terrestrial and aquatic ecosystems. Increased evaporation rates could heavily impact aquatic biota, mostly by reducing lake water volume. River systems could also be affected in the amount of water flow and changes in the hydrography. Coe et al. (2009) modelled changes in the hydrological cycle, which were reflected in the reduction of river discharge due to altered evapotranspiration rates when the original vegetation in the Tocantins River watershed was replaced by grassy pastures.

Climate changes in regions that are naturally stressed by low water availability will intensify ecological impacts on the aquatic systems. For instance, the Caatinga and parts of the Cerrado region may experience profound changes in the amount of precipitation, compromising the functioning of aquatic systems and the availability of water to the human population, with possible reductions in the number of small ponds in these regions.

2. Frontiers Among Ecosystems

Changing Inland Waters – The increasing rates of greenhouse gas emissions (Le Quéré et al., 2009) support the consensus that the Earth's atmospheric warming can increase the frequency of extreme events, for instance drought or heavy rainfall (Marengo et al., 2009), directly affecting the distribution of rivers, lakes and wetlands (Carpenter et al., 1992). Aside from climate changes, environmental changes such as alteration in land use and cover, dam construction, channelization of streams and rivers, and the extensive and intensive use of agrochemicals, among others, profoundly alter the structure and morphology of aquatic systems. In Brazil, the construction of dams (multipurpose, large and small hydropower) is a reality in hundreds of rivers, in most of the major drainage basins. Artificial lakes are used for a variety of purposes, e.g., irrigation, drinking water, energy production, industrial use of water, among others (Tundisi, 2008). An important effect of water retention in the continents is the reduction of sea level. The total volume of water retained in artificial lakes in all continents for the past 50 years (10,800,000 km^3) would be enough to reduce the ocean levels by about 30 millimeters (Chao et al., 2008). Another important effect of water retention in artificial lakes, especially in reservoir cascades, is the reduction of the sediment and nutrient load to estuarine regions. In addition to ecological changes, the damming of rivers has caused profound changes in the regional social dynamics.

Aside from dams, other anthropogenic alterations such as channel deviation, irrigation, and floodplain draining alter the natural dynamics and fluctuation of the water level in rivers and lakes. The ongoing transfer of the São Francisco River waters to the semi-arid region is one of the examples of potential heavy impacts on the natural dynamics of the hydrological network. In spite of the relatively small volume extracted from the river (1.4% of minimum flow, i.e., 26.4 $m^3.s^{-1}$), the scientific community has expressed concern regarding changes in the ecosystems of the receiving watersheds, and the effective social contribution to the local communities.

The hydrological pulses and changes in land use regulate functioning and interaction between biotic and abiotic components in Brazilian aquatic systems. Junk et al. (1989) described the hydrological pulse concept as the major force in rivers and floodplain lakes, which is responsible for the productivity and biological processes in these aquatic systems. Geomorphologic and hydrological conditions define the intensity and length of the flood pulses, and the precipitation regime in the watershed is an important controlling factor of high and low water in the majority of Brazilian rivers. The intensity of precipitation events, together with the land-use patterns, define the runoff intensity and transport of organic and inorganic elements from the soils to the aquatic ecosystems (Johnson et al., 2008), and these elements are crucial to the floodplain depositional areas and the metabolism of the aquatic systems. Changes in the intensity and frequency of precipitation events may contribute to higher input of nutrients (mainly nitrogen and phosphorus) from terrestrial ecosystems and their consequent enrichment in water bodies. Nutrients and light are considered the main controlling factors for primary producers in aquatic ecosystems, particularly in the tropics (Huszar et al., 2006). When present in high concentrations in aquatic ecosystems, nitrogen and phosphorus promote eutrophication, which can cause imbalances in trophic interactions, with a consequent increase in the biomass of primary and secondary producers. This increase may directly affect water quality, due to dissolved oxygen depletion and many other undesirable effects. Eventually, eutrophication results in profound and irreversible changes in aquatic ecosystems. For instance, excessive algal growth should be treated as a public-health issue, because cyanobacteria blooms, in addition to degrading water quality, can produce bioaccumulative toxic substances that are harmful to human health (Chorus and Barthram, 1999).

Changes in Land-Water Interfaces – Rivers occupy the largest areas of their basins, and are the main connections between terrestrial ecosystems and estuaries and then to the oceans. In addition to these linkages, rivers also produce and process organic matter (e.g., consumption through decomposition) through several biological and abiotic pathways (Cole et al., 2007). Shallow lakes are the most common lentic ecosystems in Brazil, and are of three main types: floodplain lakes, coastal lakes, and man-made lakes. Floodplain lakes are a prominent feature of the Amazon and Paraná River basins; they have their own peculiar features, and are strongly influenced by the flood pulse of the main river. Many coastal lakes exist, with a wide range of salinity, eutrophication and degree of connectivity to the Atlantic Ocean. Shallow man-made lakes have been constructed in many areas for irrigation, drinking-water supply, industry supply, recreation, and fishing. Deep hydroelectric reservoirs are widely dispersed over the entire country. Deep natural lakes are not in Brazil, and occur only in some particular river systems such as the Doce River, which drains to the ocean.

3. Ecological Responses of to Climate Change

Aquatic Biota Responding to Increase in Air Temperature – Water temperature is a well-studied environmental parameter, and low water temperatures are the most limiting factor for the metabolism of aquatic organisms, distribution of aquatic species, and processes in aquatic ecosystems. Increase in the mean global temperature is the main prediction of Global Climate Change (GCC), and several important outcomes of this increase are expected; such as changes in the metabolism and phenologies of aquatic organisms, including size (Daufresne et al., 2009), changes in species range (uphill or polewards migration of species adapted to warmer temperatures), extinctions (due to changes in the habitat), changes in community compositions, or genetic changes (see review by Heino et al., 2009 and references therein). For instance, although they coexist, plankton species of temperate aquatic ecosystems responded differently to warming trends, depending on whether the timing of warming matched their individual thermal requirements at critical developmental stages such as the emergence from diapause or spawning (Adrian et al., 2006; Huber et al., 2010). Other species did not change their metabolism significantly, but nevertheless increased in abundance (Adrian et al., 2007). Increases in water temperatures in temperate freshwater ecosystems are likely to favor warm-adapted freshwater fishes, for which the distribution and reproductive success may currently be constrained by temperature, rather than by cold-adapted species (Graham and Harrod, 2009).

Much less is known about the effects of changing temperatures on tropical aquatic ecosystems. It is predicted that a slight increase in water temperature could enhance the metabolism of tropical and subtropical aquatic species, increasing the growth rates and accelerating reproduction in the life cycle. In this context, an increase in the water temperature could result in an increase in the fishery stocks in continental aquatic ecosystems. On the other hand, most aquatic species may be living at their optimum water temperature in tropical ecosystems, and even a small increase in water temperature could result in a decrease in fitness, which in turn may result in changes of species ranges or, in the worst scenario, in species extinctions. For instance, in a recent review of the biology of Neotropical fish species, Cussac et al. (2009) postulated that the composition of assemblages, isolation, southern limits for the distribution of species, and some morphological variation among populations are strongly related to temperature, and changes in the water temperature related to GCC would have profound effects on fish distributions and community compositions. Overall, there is little evidence but many uncertainties about the impacts of changing temperatures related to GCC on the biology of tropical aquatic species.

Effects of Changes in Precipitation Patterns on Aquatic Biota - Changes in the precipitation on local and regional scales are also expected in new climate scenarios. These changes will have great consequences for aquatic ecosystems, and consequently for the ecology of aquatic species. Climate change may have profound effects on the transport of inorganic nutrients, organic matter and suspended material from terrestrial to aquatic ecosystems, which can increase the eutrophication rate of aquatic ecosystems (Moss et al. 2011; Abe et al., 2009). For instance, model results suggest that the increase in precipitation will result in a 3.3 to 16.5% increase within the next 100 yr in phosphorus loading of Danish aquatic ecosystems, depending on soil type and region (Jeppesen et al., 2009). The increase in phosphorus concentrations and the eutrophication of aquatic ecosystems (Lacerot, 2010) would result in a shift of fish community structure toward small and abundant plankti-benthivorous fish, which would enhance the fish control on zooplankton, resulting in higher phytoplankton biomass and algal blooms, i.e., a positive feedback mechanism. Taking into account the parallel increase in water temperature, models also predicted a shift in the phytoplankton community structure and the dominance of dinoflagellates and cyanobacteria, a reduction in the size of copepods and cladocerans, and a tendency to reduce zooplankton biomass and the zooplankton: phytoplankton biomass ratio (Jeppesen et al., 2009; Lacerot, 2010). The same pattern can be expected for tropical aquatic ecosystems.

The predicted changes in turbidity related to changes in the input of suspended material can also impact tropical aquatic ecosystems and aquatic biota (Meerhoff et al., 2007). Most tropical aquatic ecosystems are shallow, and according to Scheffer et al. (1993), two possible alternative stable states of ecosystem functioning are expected: a clear-water state with low plankton primary production and the dominance of submerged aquatic macrophytes, and a turbid-water state, with high plankton primary production and the absence of submerged macrophyte banks. Differences in the community composition and abundance of different species of planktonic organisms, aquatic macrophytes and fishes are predicted for each alternative state. Changes in water turbidity drive the system from one to the other state; and aquatic ecosystems in regions where precipitation events are expected to be more intense and frequent should be dominated by the turbid-water state, while aquatic ecosystems in regions where rain events are expected to be less intense and more sporadic should be dominated by the clear-water state (Mooij et al., 2009).

Future climate-change scenarios predict rising temperatures, enhanced vertical stratification of aquatic ecosystems, and alterations in seasonal and interannual weather patterns (including droughts, storms, floods); all these changes would favor harmful cyanobacterial blooms in eutrophic waters (Paerl and Huismann, 2008, 2009; Moss et al., 2011). Therefore, current mitigation and water-management strategies, which are largely based on nutrient input and hydrological controls, must also accommodate the environmental effects of global warming in a warmer climate (Paerl and Huismann, 2009). One implication for management is that nutrient loading will have to be reduced much further if we wish to decrease the risk of cyanobacterial dominance (Kosten et al., 2012).

Submerged and free-floating plants have different effects on the spatial distribution of the main communities, the effects differing between the climate zones. In temperate lakes, submerged plants promote trophic interactions, with potentially positive cascading effects on water transparency, in contrast to the free-floating plants, and in strong contrast to the findings in subtropical lakes (Meerhoff et al., 2007). The increased impact of fish may result in higher sensitivity of warm lakes to external changes (e.g., increase in nutrient loading or water-level changes). The current warming process, particularly in temperate lakes, may entail an increased sensitivity to eutrophication, and pose a threat to the high-diversity, clear-water state. Furthermore, the increase in atmospheric CO_2 could affect submerged plant growth only under relatively eutrophic conditions and at a low community respiration rate, and alkalinity has little effect on the response of the different species (Schippers et al., 2004). When the air-water exchange is low, the proportional effect of the CO_2 increase on plant growth is higher. Under eutrophic conditions, algae and macrophytes using CO_2 and HCO_3^- may double their growth rate with higher atmospheric CO_2, while the growth of macrophytes restricted to CO_2 assimilation may increase threefold (Schippers et al., 2004). The differences in responses of the species under various conditions indicate that the elevation of atmospheric CO_2 may induce drastic changes in the productivity and species dominance in freshwater systems.

The general effects of climate change on freshwater systems will likely be to increase water temperatures, decrease dissolved-oxygen levels, and increase the toxicity of pollutants. In lotic systems, altered hydrological regimes and increased groundwater temperatures could affect the quality of fish habitat. In lentic systems, eutrophication may be exacerbated or offset, and stratification will likely become more pronounced and stronger. This could alter food webs and change habitat availability and quality. Fish physiology is inextricably linked to temperature, and fish have evolved to cope with specific hydrological regimes and habitat niches. Therefore, their physiology and life histories will be affected by alterations induced by climate change. An increase in the average precipitation or in the frequency of extreme rain events in a region can also increase the connectivity of aquatic ecosystems; and at the opposite extreme, a general decrease in precipitation in a region could result in a decrease in the connectivity of aquatic ecosystems. Connections among aquatic ecosystems are the main route of dispersal of different populations or of different species in the landscape. In this context, body size is an important attribute of aquatic species that dictates the influence or even the necessity of connections among aquatic ecosystems for organisms/species to disperse. Small aquatic species such as bacteria, phytoplankton and zooplankton move passively across the landscape through wind action and transported by large actively dispersing organisms. Because of their small size, there are no strong limits to the dispersal of bacteria, phytoplankton and zooplankton in the landscape, and the presence of a species in an aquatic ecosystem is usually regulated by local environmental factors (Fenchel and Finlay, 2004). On the other hand, large organisms such as benthic macroinvertebrates and fish have lower dispersal abilities, indicating that dispersal limitation may be more important for these groups, and the distance between aquatic ecosystems is also an important factor regulating the composition of these communities. Therefore, changes in the precipitation in a specific region could increase or decrease (depending on the amount of precipitation) the connectivity between aquatic ecosystems, and these changes should have greater effects on large aquatic organisms, such as benthic macroinvertebrates and fish, than on smaller ones, such as the plankton communities. These changes in the precipitation regime have been observed to affect some Neotropical fish communities, by formation of new communities in areas that were formerly dry, or by the loss of breeding areas and increased mortality related to decreases in the flow of the rivers and in the extent of their floodplains (Cussac et al., 2009).

Processes versus Changes in Climate Drivers – The organic-matter metabolism of an aquatic ecosystem is understood as a balance among the production, consumption, accumulation, import and export of organic matter (Odum, 1956). The main biological processes that regulate the aquatic metabolism are related to the production and respiration of organic matter (Cole et al., 1994). Part of this organic matter can be produced in the system itself (autochthonous) or in surrounding terrestrial ecosystems (allochthonous). The amount and processing rates of organic matter in aquatic ecosystems are dependent directly on its origin and the metabolic state of the system, due to the ability to produce, e.g., nutrients such as nitrogen (N) and phosphorus (P), and to decompose, e.g., structural issues in organic molecules or metabolic constraints such as temperature. Thus, climate changes affecting rainfall and temperature have the potential to affect, directly or indirectly, the input of matter, metabolic rates and the physical and chemical structure of aquatic systems. Consequently, the ecosystem functions and feedback to the climate may also be altered.

Gross primary production (GPP) is regulated by nutrient availability, temperature, and light intensity. Ecosystem respiration (R), understood as amount of energy expended in metabolic pathways for life maintenance, depends on organic-matter availability (energy source) and is regulated by temperature (Dodds and Cole, 2007). It is clear that an increase in the input of inorganic nutrients in aquatic systems may stimulate GPP, and consequently also stimulate R due to the high availability and quality of organic matter, as a result of autochthonous production (Farjalla et al., 2006). However, the efficiency of energy processes should increase, resulting in increased net ecosystem production (NEP = GPP – R; Dodds and Cole, 2007) due to prevailing autotrophic activity (Biddanda et al., 2001). On the other hand, the input of organic matter to aquatic systems, rather than inorganic nutrients, stimulates decomposition, increasing R and decreasing the NEP.

The expected atmosphere temperature increase over the Brazilian territory (Marengo et al., 2009) may result in an increase of several degrees in water temperature. As metabolic proxies, increases in primary production and respiration are expected. However, it is not well established which of the process responses, GPP or R, will be the stronger; thus it is not easy to predict the NEP response to temperature increase. Understanding of the regulation of NEP due to climate changes is critical to understand whether or not the sediments will store or process organic matter. This issue should be addressed in future studies, to improve understanding of this dynamic in tropical areas, taking into account that: (1) the combination of high temperatures over the year and low average water-column depths will increase the homogenization of the water column and its connection with the sediment; and (2) seasonal precipitation and floodplain dynamics regulate the inputs of water, organic matter and nutrients into aquatic ecosystems, thus regulating NEP-related processes (Apple et al., 2006; Biddanda and Cotner, 2002; Thomaz et al., 2007).

The sediment is the main nutrient and organic-matter storage compartment in lakes and wetlands, and therefore is known as a long-term carbon trap in aquatic ecosystems (Tranvik et al., 2009). As most of the lakes on Earth are small and shallow, with low volume:area ratios, the metabolism of the sediment compartment is considered extremely important for the overall aquatic metabolism (Downing et al., 2006). Part of the organic matter, both dissolved (DOM) and particulate (POM), is mineralized in the water column (Farjalla et al., 2006). The other part sinks and accumulates in the sediment, where it can be stored or mineralized (Fenchel et al., 1998). Global climate change (e.g., increased or decreased rainfall) would result in increased or decreased mineralization and/or storage in the sediment. However, extreme rainfall events could also resuspend sediment, enabling it to decompose in the water column. Thus, an increase in temperature would result in increased rates of organic-matter mineralization in the water column, reducing the amount stored in the sediment (Ploug et al., 1997).

In tropical ecosystems, the organic-matter degradation processes (aerobic and anaerobic respiration and fermentation) in the sediment, which result in CO_2 or CH_4 production, are related to the amount and availability of organic matter (Conrad et al., 2010, 2011). Because organic matter in the sediment originates from the water column, changes in temperature and rainfall may affect the quality and quantity of organic-matter sedimentation, which could directly affect CO_2 and CH_4 produced in the sediment, due to changes in temperature and rainfall patterns. The temperature increase in the sediment would result in increased rates of organic-matter mineralization due to metabolic requirements (Gudasz et al., 2010), resulting in lower carbon burial/trapping in this compartment. Marotta et al. (unpublished data) recorded exponentially increased CO_2 and CH_4 production in the sediment of tropical lakes due to temperature increases, resulting in higher rates of diffusion to the atmosphere. However, CH_4 production was stimulated even more than CO_2. Thus, although CH_4 is highly oxidized in the water column (Nguyen et al., 2010), its emission to the atmosphere would increase through bubble formation, creating a positive feedback to the temperature increase.

The occurrence of aerobic and anaerobic processes in the sediment is regulated by the availability of electron acceptors, mainly oxygen, nitrate, manganese, iron and sulfate (Fenchel et al., 1998). An increase or decrease in rainfall might affect the transport of these acceptors from the drainage area to the water column and the degradation of organic matter in the sediment, respectively increasing or decreasing CH_4 production as a consequence. An eventual increase in rainfall could increase the flooded area (lakes and rivers) on Earth's surface. This increase in the volume of aquatic ecosystems would result in increased CO_2 and CH_4 emissions due to the formation of new flooded areas, resulting in another positive feedback to the global changes on the planet. An increase in rainfall periodicity could also increase the frequency of wetland and forest flooding, creating optimum conditions for the formation of biogenic gases such as CO_2, CH_4 and N_2O.

Carbon metabolism in aquatic ecosystems is frequently evaluated by the input and output rates of this element in the system, as CO_2. Organic-matter processing, such as decomposition in the sediment (CO_2 flux from the sediment to the water column), planktonic and nektonic respiration (autotrophs and heterotrophs), and photochemical degradation, will be further explored as separate topics. In general, CO_2-saturated ecosystems are considered heterotrophic, i.e., the mineralization processes are more intense than primary production (function as CO_2 sources to the atmosphere, NEP < 0). On the other hand, under-saturated ecosystems are considered autotrophic (NEP > 0), i.e., primary production rates are higher than mineralization rates (Odum et al., 2004).

Most aquatic ecosystems in the world are heterotrophic, depending on the input and decomposition of terrestrial organic matter (Cole et al., 1994; Sobek et al., 2003). Only a few systems are considered autotrophic, mainly due to nutrient inputs (e.g., eutrophication). The same pattern is recorded for important Brazilian aquatic systems, such as Amazon lakes and rivers and shallow coastal lakes (in the Atlantic Forest biome) (Kosten et al., 2010; Marotta et al., 2009; Richey et al., 2002). For instance, of 82 shallow coastal systems studied in South America (from 5 to 55° S), 80% were heterotrophic, 14% autotrophic, and only 6% had NEP close to zero (Kosten et al., 2010). Of 86 lakes, differing in shape and depth, located at different biomes and latitudes sampled in Brazil from 2005 to 2007, 87% were heterotrophic (Marotta et al., 2009).

Plankton and sediment respiration are the major sources of CO_2 emission from aquatic ecosystems, and temperature is a key feature in this release, due to water saturation (physical aspects) and metabolism regulation. Assays of coastal systems showed a direct relationship between temperature and respiration rates; however, above 15 °C, which is a possible metabolic limit, local factors such as nutrient availability take effect and regulate the metabolic rates (Apple et al., 2006). In this case, it is not clear whether or not enhanced temperatures would increase CO_2 emissions over CO_2 absorption due to primary production. It is still important to consider how the biodiversity and temperature components interact and affect metabolic rates, since the latter factor might affect the former (Hall and Cotner, 2007; Hall et al., 2008). Thus, it can be suggested that warming climate in cold areas might increase biological mineralization rates; but warming climate in warmer areas might only affect spatial patterns. More studies on the respiration process in tropical areas are urgently needed in order to reach more realistic conclusions.

Photochemical degradation of colored dissolved organic matter (CDOM) can be an important mineralization process in aquatic systems, especially in tropical systems (Amado et al., 2006; Jonsson et al., 2001), since sunlight incidence is among the factors regulating it. In addition, rates of photochemical mineralization increase linearly with DOM concentration. The highest rates of photochemical mineralization were recorded in tropical coastal super-humic aquatic ecosystems (around 400 μM C d^{-1}), due to the above factors (Farjalla et al., 2009). Seasonal rainfall events regulate the input of fresh DOM into ecosystems, and its degree of degradability (Suhett et al., 2007). Besides, there is a strong synergism between these fresh DOM inputs to humic coastal lagoons in the rainy periods which is coincident with the highest sunlight incidence in the summer time. Thus, climate alterations that affect precipitation dynamics and duration, as well as the intensity of sunlight incidence on the Earth's surface may play important roles in carbon mineralization and cycling in tropical aquatic systems.

Brazilian Geographical Zones, Climate Scenarios and Conceptual Assumptions – We developed a simple conceptual model to guide the understanding of the implications of the effects of climate change for the biogeochemical features in inland waters (Figure 1). The

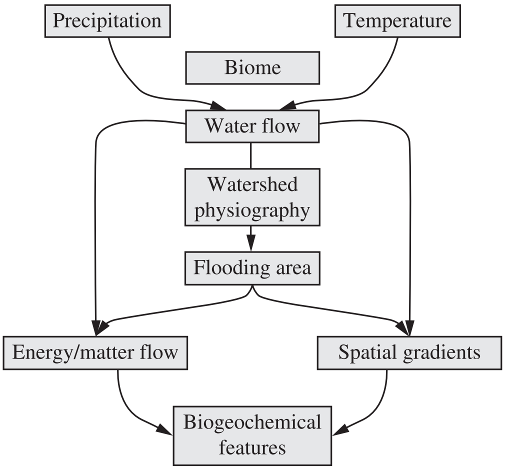

Figure 1. Conceptual model of the role of precipitation and temperature as driving forces of biogeochemical processes in aquatic environments through biome and physical filters. Basically, precipitation and temperature affect hydrological cycle in areas, according to the biome characteristics and local physical features.

predicted changes in temperature and precipitation will certainly affect hydrological fluxes in the watersheds of all terrestrial biomes. However, the magnitude and direction of these effects will depend on the vegetation cover and plant community structure of the terrestrial part of the biomes. If increased precipitation rates exceed the increased evaporation and evapotranspiration rates caused by warming, water flow through streams and rivers will increase and may interact with watershed physiography to enlarge flooded areas in lower parts of the watershed. In contrast, if precipitation decreases or does not increase enough to compensate for the increased evaporation and evapotranspiration caused by warming, water flow through streams and rivers will decrease, reducing the flooded area. The organic and inorganic substances transported by streams and rivers from terrestrial ecosystems to ponds, lakes, reservoirs and estuaries are important sources of energy and matter for inland-water organisms and biogeochemical processes. A reduction in water flow and flooded area implies a reduction in energy and matter flow from the watershed to aquatic ecosystems, slowing biogeochemical processes and making biogeochemical cycles more closed in these aquatic ecosystems. Moreover, a reduction in water flow and flooded area may decrease the length of vertical and horizontal gradients of physical conditions, resources and organisms, spatially homogenizing the biogeochemical processes in the aquatic ecosystems. Conversely, an increase in water flow and flooded area will result in increased flow of energy and matter from the watershed to aquatic ecosystems and in increased spatial heterogeneity of physical conditions, resources and organisms involved in the biogeochemical processes.

Zones vs Climate Scenarios – Brazil is a huge country, and different climate scenarios are expected for different Brazilian macro-regions, mainly related to the changes in precipitation regime (Marengo et al., 2009; Marengo et al., 2010). Overall, an increase in temperature - characterized by a decrease in the number of cold nights during winter months, and a decrease in precipitation, also during winter months - is expected for the entire country (Marengo et al., 2009; Marengo et al., 2010). Particularly in the south (subtropical areas) and in the extreme west of the Amazon region (areas of the states of Acre and Amazonas), an increase in the number of intense precipitation events is expected, while a general decrease of precipitation and an increase of consecutive days without any precipitation are predicted for the eastern Amazon (states of Tocantins, Maranhão and Pará) and for the Brazilian northeast region during the summer months (Marengo et al., 2009). In the highly populated southeast and northeast coastal areas, changes in the precipitation regime will not be particularly characterized by changes in the average amount of rainfall per month, but by changes in the frequency of precipitation events and by the increase in extreme rainfall events (storms) during the summer months (Marengo et al., 2009). These different scenarios result in several environmental driving forces in the structure and functioning of aquatic ecosystems, and therefore, conceptual models were developed for zones responding to the simulated climate scenario (Figure 2).

Zone 1 – Subtropical areas and the extreme west of the Amazon region (Figure 2a). An increase in temperature and precipitation (extreme rainfall events) would result in an increase of the water flow in the entire biome (i.e., Brazilian Pampas and Amazon rainforest), which, in turn, would extend the flooded areas in the landscape. An increase in the input of energy and matter from terrestrial to aquatic ecosystems and a decrease in spatial heterogeneity are both predicted in this model. Direct and indirect changes in the biogeochemical cycles are expected due to the increase in the water temperature, the greater input of terrestrial nutrients to aquatic ecosystems, and the homogenization of aquatic ecosystems (reduction of natural barriers by floods).

Zone 2 – Brazilian Northeast and the eastern Amazon region (Figure 2b). An increase in temperature and a decrease in precipitation (increase in the number of consecutive days with no precipitation) would result in a decrease of the water flow in the entire biome (Brazilian Caatinga or Amazon rainforest), which in turn would decrease the flooded areas and the size of aquatic ecosystems. A decrease in the input of energy and matter from terrestrial to aquatic ecosystems and an increase in spatial heterogeneity (aquatic ecosystems become more isolated in the landscape) are both predicted in this model. Direct and indirect changes in the biogeochemical cycles are expected due to the increase in the water temperature, the smaller input of terrestrial nutrients to aquatic ecosystems(weaker connectivity), and the isolation of aquatic ecosystems and their communities.

Zone 3 – Southeast and coastal areas of the Northeast (Figure 2c). An increase in temperature and changes in the frequency of precipitation (increase in the number of

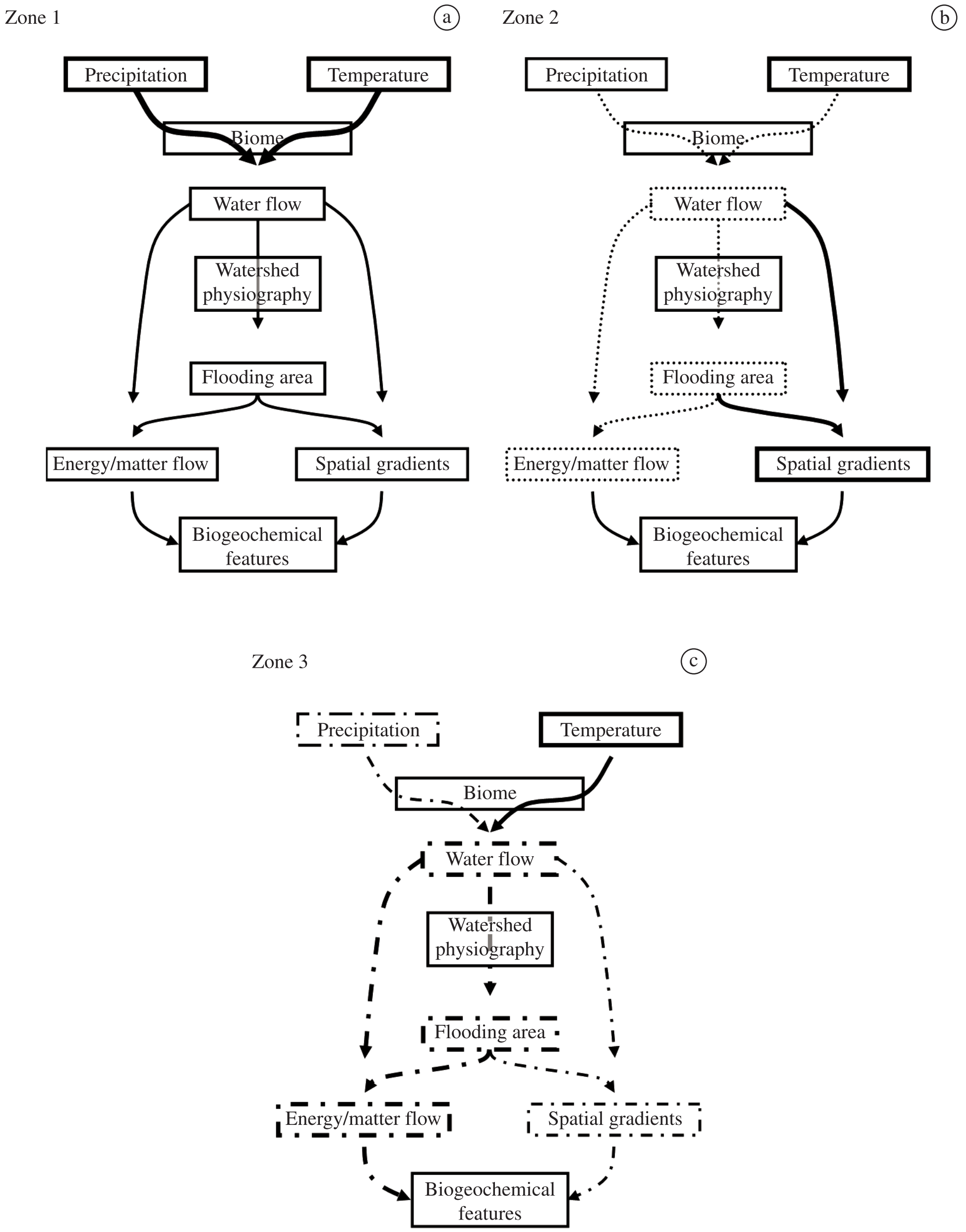

Figure 2. The conceptual model presented in Figure 1 applied to the three different projected scenarios of climate changes in Brazil by Marengo et al. 2009. (a) Zone 1 - Climate changes in the Subtropical areas and the extreme west of Amazon region (higher temperatures and higher precipitation during the summer); (b) Zone 2 - Climate changes in the Brazilian Northeast and the east of Amazon region (higher temperatures and lower precipitation) and; (c) Zone 3 - Climate changes in the Southeast and littoral areas of Northeast (higher temperatures and higher occurrence of extreme rain events; storms). The two widths of arrows indicate the degree of intensity of the referred influences; dashed lines indicate the weakest intensity of influence; full-line arrows indicate regular frequency of events (e.g. seasonal events); and Dashed-dotted lines indicate high variability in intensity and periodicity, i.e. extreme rain events (storms).

storms in the summer) would result in an increase of flood events in the biomes (i.e., Atlantic rainforest), which in turn would temporarily increase the flooded areas and the size of aquatic ecosystems. Isolated but dramatic increases in the input of energy and matter from terrestrial to aquatic ecosystems and the homogenization of aquatic communities in summer months are both predicted in this model. Direct and indirect changes in the biogeochemical cycles are expected due to the increase in the water temperature, the isolated but dramatic inputs of terrestrial nutrients to aquatic ecosystems and temporal homogenization of aquatic ecosystems, mainly in summer months.

In the current scenario of global climate change, there is much more uncertainty regarding changes in rainfall than increases in temperature. It is expected, though, that some parts of Brazil will become drier while others will become wetter. These changes will certainly cause modifications in the distribution of streams, lakes and flooded areas throughout the country. On one hand, the increase in temperature combined with the reduction of rainfall in the semi-arid region will increase the already critical lack of water in this region. The number of lakes and temporary streams may thus be reduced, as well as the volume of water in artificial lakes (ponds). On the other hand, there might be an expansion in flooded areas and an increase in the number of lakes and streams in regions that become more humid. Such an expansion will potentially occur as soon as the increase in rainfall causes an increase in rivers flows. Nevertheless, foreseeing the distributions of freshwater systems in wetter regions is a difficult task, because evapotranspiration may also increase with temperature, compensating for part of the excess rainfall and affecting the water balance of drainage basins. So far, the only feasible generalization pertains to the low-rainfall scenario predicted for the Northeast and the eastern Amazon, where river flow will be reduced. Because the semi-arid drainage basins of Northeast Brazil are more sensitive to reduced rainfall and water flow, this region will tend to be more severely affected by climate change compared to the humid eastern Amazon. Shifts in rainfall regime may affect erosion and sediment transport, especially in regions of variable rain loads. Moreover, rain in the semi-arid Northeast is usually torrential and restricted to only a few days of the year. Intense rains, even if they are less frequent, cause soil erosion, widen river channels and increase the sediment load transported by the rivers. These effects are intensified by the reduction in plant cover, especially in riparian forests which are naturally scarcer in dry than in wet regions. One may conclude that the Brazilian semi-arid region is more vulnerable to extreme events of precipitation than are the humid parts of the country. This is why some researchers suggest that semi-arid freshwater ecosystems may show early signs of global change.

4. Potential Biogeochemical Signals in Ecosystems

Changes in the precipitation regime are one of the main consequences of global climate changes in tropical areas. For instance, an increase in overall precipitation is expected in some areas, such as the western Amazon region, while in other areas such as the Brazilian Southeast, an increase in the number of extreme rain events (but not followed by an overall increase in the total amount of rain) might be observed in the near future. Floods will be more frequent and severe in the rainy months, and the human population will have to cope with these new environmental conditions.

4.1. Connectivity among systems

The west of Amazon region is thinly dense-populated area but most of its population lives near water. These ecosystems are subject to seasonal flood events (known as flood pulse), and both the aquatic organisms and human population are adapted to the flood pulse. Ecosystem processes, nutrient release and storage, and the balance of elements between aquatic ecosystems, terrestrial ecosystems and atmosphere change among flood-pulse periods (Silva et al. 2010). The expected increase in the intensity of floods events would increase the homogeneity of aquatic ecosystems with respect to the aquatic communities and ecosystem processes, favor the expansion of waterborne diseases, and result in substantial losses by local population.

In contrast, the Southeast of Brazil is the most populated area in the country and, its aquatic ecosystems are most subject to human pressures. Severe environmental and social consequences have already been observed in this region, resulting from increases in the number of extreme rain events, together with the dense population in the area. In particular, coastal lakes, which are located close to the ocean, have undergone many human-driven impacts, such as eutrophication, coastal landfills and the disruption of natural sand barriers that separate these lakes from the ocean (Esteves et al., 2008). Furthermore, coastal lakes will be strongly affected directly and indirectly by climate changes, in one hand due to inland interactions and, in the other hand, due to ocean interactions.

The increase in the number of extreme rain events would intensify the problems with overflow of coastal lakes in the densely occupied floodplain areas. Increases in the time span and intensity of the overflow would result in more instances of human disruption of natural sand barriers, which, in turn, greatly impact the structure and functioning of coastal lakes (see review by Esteves et al., 2008). In these areas, aquatic environments will also be affected by the increase of sea water level. This increase of sea water level, combined with the increase in extreme rain events will result in a rise in the groundwater level, increasing the area of coastal lakes and wetlands. The extent of those newly flooded areas will be determined by the amount of sea-level increase and the local topography. The connectivity and exchange of organic matter and nutrients between coastal forest systems such as the Atlantic Forest, which includes Restinga vegetation, with aquatic environments will considerably intensify changes in the biogeochemical cycles in those areas.

An increase in sea level will also increase the salinity in coastal aquatic environments, as predicted by the IPCC report (IPPC, 2007). An increase in salinity can significantly change the community structure and ecological functions of coastal aquatic environments. Some aquatic species may not tolerate this increase and may disappear from some environments, leading to changes in aquatic biodiversity. An increase in salinity could also be expected to directly affect aquatic macrophytes, because most of their species cannot tolerate higher salinities and the existing aquatic macrophyte communities would probably be replaced by other macrophytes, benthic algae, or even mangrove vegetation.

4.2. Hydroelectric reservoirs

Increases in rain and temperature are expected in areas with numerous hydroelectric reservoirs. To date, it is known that these reservoirs are able to emit great amounts of carbon, such as CO_2 and CH_4, to atmosphere (Roland et al., 2010). The main regulating factors of these emissions are the age of the flooded area and temperature. The younger the flooding and the higher the temperature, the higher is the emission (Fearniside, 2008; Santos et al., 2008; Barros et al., 2011). An increase in rain intensity raises the water level in the reservoirs, flooding new areas, and also the input of organic matter from the watershed basin, causing an increase in the aquatic metabolism. One direct effect would be changes in oxygen profiles, which would affect the dynamics of all biogeochemical cycles in hydroelectric reservoirs, such as increased heterotrophic metabolism, resulting in higher degrees of net heterotrophy (CO_2 evasion). Decreases in the dissolved-oxygen content would certainly increase methane production and emission, as methane oxidation would probably decrease.

4.3. Patterns of flood pulse

The flood pulses of Amazon and Pantanal basins are already being affected by changes in rain intensities. Higher and lower precipitation, respectively, in the west and east part of Amazonia, and many uncertainties in the Pantanal wetland have been projected. If the water level increase, it is reasonable to think about expanding of flooded areas and raising lake and river water levels. Increases in water level combined with an increase in temperature, may change oxygen distribution in the water column increasing flooded soil and the anoxic fraction in lakes, and consequently causing an increase in CH_4 production and emission and decreased CH_4 consumption. The expansion of flooded areas may also cause increases in CH_4 production and decreases in CH_4 consumption, because more soil will be flooded and will become anoxic. The increase in flooded areas may also cause an increase in N_2O emissions, because increases in soil oxygen in the flooded areas will increase the denitrification of stored nitrate. Therefore we can expect an increase of GHG emissions, in a positive-feedback mechanism, if changes in the flood pulses increase in water level.

4.4. Nutrient loading and eutrophication

Higher temperature and lower rainfall are reliably predicted for the semi-arid region of the Brazilian Northeast and eastern Amazonia. This will include the low-latitude coastal hydrographic regions, and the lower parts of the São Francisco basin and the eastern Amazon rivers. Eutrophication, water salinization and loss of habitats are expected. High levels of nitrogen and phosphorus are usually observed in regions with higher population density, related to untreated sewage loading in the water bodies such as those in the eastern Brazil (Abe et al., 2006). Increased eutrophication and the projected increased temperature will foster the already frequent cyanobacterial blooms at least in the semi-arid region (Bouvy et al., 2002; Brasil, 2011), impairing the quality of drinking and irrigation water. Global warming and eutrophication in fresh waters may mutually reinforce the symptoms they express and thus the problems they cause (Moss et al., 2011).

4.5. Transport of organic matter to the ocean

Riverine impoundments, which are used for a variety of purposes in human society, substantially change the nutrient balance in an ecosystem and nutrient export to the ocean. It is relatively well established that soil erosion is presently accelerating, due to the intensification of land use and also due to increased deforestation in many parts of the world, consequently increasing the sediment load in rivers. Contrariwise, as a result of river impoundments and river-diversion schemes in some regions, sediment flux to the coastal zone has decreased, which may have drastic effects on coastal biogeochemical cycling. The increase of nutrient load because of inadequate soil management and the greater retention of nutrients in rivers because of impoundments will be affected by changes in the precipitation pattern in a given region. The predicted reduction of precipitation in regions with important river systems (for instance, the São Francisco and the Araguaia) might slow nutrient export to downstream ecosystems and to the coastal zones. On the other hand, in southeast Brazil where river systems of several magnitudes are regulated by impoundments, the predicted increase in the amount of precipitation and the frequency (and intensity) of extreme events may affect dam management, allowing higher flow of water from the impoundments and increasing nutrient transport to downstream regions. However, cascade reservoir systems may buffer the amount of nutrients flowing through the system, despite the larger water input from precipitation.

4.6. In system water movement

The projected changes in precipitation patterns suggested by Marengo et al. (2009) in southern and central Brazil describe higher frequencies of extreme events (more precipitation in a given period). The amount of flooding associated with this kind of event is critical to both hydroelectric reservoir management and to the biogeochemical cycles within these systems. Physical drivers are determinants for biological processes in the water, and therefore changes in the intensity of these drivers will necessarily alter the dynamics of organic-matter production and processing. For instance, higher influx of inorganic particles from the watershed to the surface water bodies might change the distribution of light in the water column, but more importantly, will increase the input of organic matter and nutrients to the system (if soil-management practices in the watershed remain the same). Also, the higher energy associated with the water flow might cause substantial water mixing, which in combination with the processes described by Roland et al. (2010) of anoxic water movement in the reservoirs, would increase the fluxes of carbon dioxide and methane to the atmosphere.

Table 1. Results of the effects of temperature increases simulation in Brazilian regions and its effect on CO_2 concentrations in aquatic ecosystems according to Marotta et al. (2009).

		Current scenario		Predicted scenario		
Region	**Sub-region**	**Temperature* (°C)**	**CO_2 (µatm)**	**Temperature (°C)**	**CO_2 (µatm)**	**Increase (%) CO_2**
Northeast	Semi-arid	25-27	18958	28	20417	7%
	Coastal	23-25	17500	26	18958	8%
	South	21-23	16042	24	17500	8%
North	North	25-27	18958	28	20417	7%
	Centre-south	23-25	17500	26	18958	8%
	South	25-27	18958	28	20417	7%
Center-east	North	25-27	18958	28	20417	7%
	Center-west	23-25	17500	26	18958	8%
	East	21-23	16042	24	17500	8%
	Extreme east	19-21	14583	22	16042	9%
Southeast		19-25	16770	26	18958	12%
South		15-21	13125	22	16042	18%

Source: www.climabrasileiro.hpg.ig.br

4.7. Increase in temperature and CO_2 pattern

Recent studies have demonstrated the effect of temperature in raising CO_2 concentrations in tropical lakes (Marotta et al., 2009; Kosten et al., 2010). An exponential regression was recorded between temperature and CO_2 concentrations in Brazilian tropical lakes from several latitudes and biomes ($N = 367$; $p < 0.001$, $R^2 = 0.82$; Marotta et al., 2009). Using the model proposed by Marotta et al. (2009), the increase in air temperature predicted for the period between 2071-2100 (Marengo et al., 2009) in a high-CO_2 emission scenario (IPCC), and a coefficient of water increase due to air temperature increase of ¼ (according to the specific heat of air and water), we can estimate CO_2 concentrations in lakes. For instance, the model would predict an increase in air temperature from 26 to 32 °C in the central Amazon, which would result in an increase of 5% of pCO_2 in aquatic systems of that region. In contrast, an increase in air temperature from 18 to 21 °C in the south would result in a 4% increase of pCO_2 in the aquatic systems. The predictions for the other areas are presented in Table 1.

All the proposed scenarios agree in predicting increased temperature in the entire Brazilian territory, which intuitively indicates greater CO_2 emissions to the atmosphere. However, we must point out that temperature increases would affect both heterotrophic and autotrophic metabolisms, and the latter is also dependent on nutrient availability. Thus, we could argue that temperature increases combined with eutrophication in the current scenario could generate a positive feedback, trapping CO_2 in aquatic systems. Using chlorophyll *a* concentrations as a measure of productivity, Kosten et al. (2010) recorded a negative relationship with the CO_2 concentration ($p < 0.001$; $r^2 = 0.19$).

5. Final Remarks

There is great uncertainty regarding possible future changes in the climate and aquatic ecosystems in Brazil. Patterns of changes in the intensity and fluctuation of flows can be predicted given the available climate simulations for the current century. Similarly, changes in the water temperature and volume (flow) are predicted to affect the aquatic biota in Brazil.

The existing environmental changes, including land use, landscape fragmentation, damming and diversion of water bodies, urbanization, wastewater load, and level of pollutants place greater pressures on aquatic systems in the short term than do climate changes. In fact, many profound environmental changes will enhance the effects of changes in climate. In this contribution, we have indicated some likely effects on aquatic systems and aquatic biota related to increase in nutrient loads in several regions, combined with changes in precipitation patterns and vegetation cover, which could, for instance, increase risks to human health from harmful cyanobacterial blooms. Changes in water temperature and changes in the physical structure of water bodies (dams, water diversion, changes along shoreline), could drastically affect the metabolism (i.e., respiration) and dispersal of aquatic organisms, carbon fluxes, and the toxicity and distribution of pollutants.

In addition to their crucial importance to humans, inland waters are extremely rich ecosystems, harboring highly diverse biotic communities, promoting landscape equilibration (linking ecosystems, maintaining animal and plant flows in the landscape, and transfer of mass, nutrients and inoccula), affecting and determining the regional climate through hydrological-cycle feedbacks. The maintenance of key elements of the landscape and preventing extreme perturbation in the systems are urgently required in order to maintain the sustainability of Brazilian inland waters. Furthermore, we point out that special attention should be given to the new Forest Policy in Brazil. The new proposed legislation may imply in reduction in conservation requirements in riparian vegetation. Effects of such decision could be catastrophic to ecological system as to the physical environment with climatic feedbacks on carbon balance and hydrological systems. For instance, increased water flow would directly affect downstream ecosystems function and structure with great consequences to water quality and biogeochemical cycles (e.g. eutrophication, carbon emission). Besides, the replacement of the riparian vegetation for cattle-feeding grass or agricultural products, such as soybean, would expose high quality organic matter to decomposition processes enhancing carbon emissions even higher.

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