Special volume

Executive Summary

First National Assessment Report

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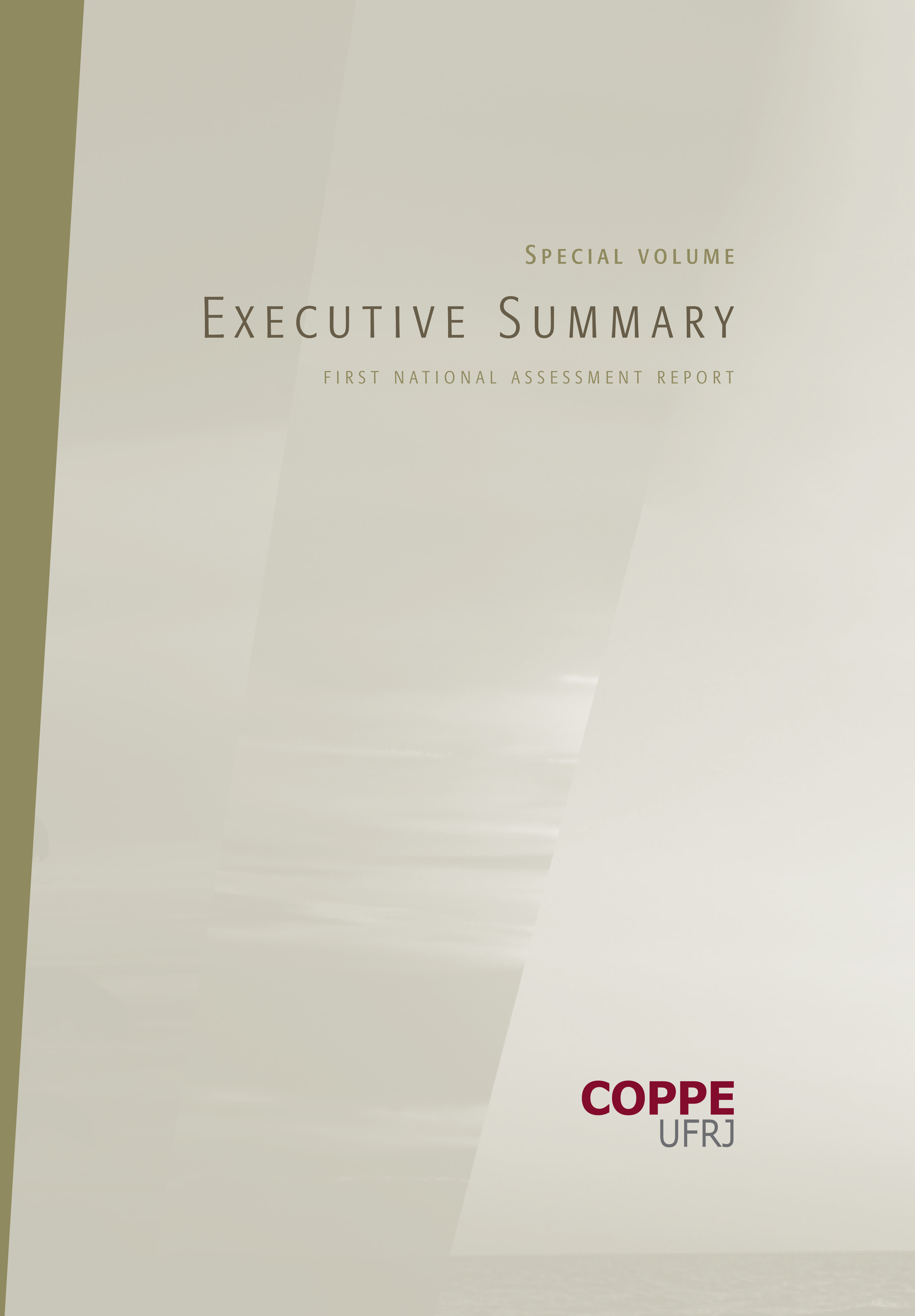

Special volume

Executive Summary

FIRST NATIONAL ASSESSMENT REPORT

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INTRODUCTION

This report includes perspectives on climate change that were derived from various scientific communities working in the context of climate science, following the strategy used by the Intergovernmental Panel on Climate Change (IPCC), which includes physical basis, impacts, vulnerability and adaptation, and mitigation.

Given the continental dimensions of Brazil and the diversity of the climatic regimes and sectors that could potentially be affected by climate variability and change, there is a need for a better understanding of the changes occurring in both global and regional climates. In this regard, and coupled with the importance of a nationalised approach to the subject, the Ministry of Science, Technology and Innovation (Ministério da Ciência, Tecnologia e Inovação – MCTI) and the Ministry of the Environment (Ministério do Meio Ambiente – MMA) together created the Brazilian Panel on Climate Change (Painel Brasileiro de Mudanças Climáticas – PBMC), which was established in September 2009.

The PBMC aims to provide scientific assessments of climate change that are relevant to Brazil, including assessments of impacts and of vulnerabilities as well as of proposed actions of adaptation and mitigation. The scientific information gathered by the PBMC is systematised through an open, objective, and transparent process for the organisation of surveys produced by the scientific community about the environmental, social, and economic aspects of climate change. The panel intends to support the process of public policy formulation and decision making to face the challenges posed by these changes and to serve as a source of reference information for society.

The PBMC presents the Assessment Reports (ARs) prepared by different scientific communities in this country that work in areas related to the environment. Following the scientific report template from the IPCC, the ARs have sought to highlight the differences in natural and anthropogenic contributions to global warming. Far from trivial, this process is based on the analysis of large amounts of observational data and the use of climate models that, although currently state of the art, still have a degree of uncertainty in their projections of future climate changes and their impacts on natural and human systems.

Regarding observational and mathematical modelling efforts of climate in Brazil, several programmes and initiatives have been implemented in recent years. From the standpoint of government programmes, the creation of the Brazilian Research Network on Global Climate Change (Rede Brasileira de Pesquisas sobre Mudanças Climáticas Globais – Rede Clima), an initiative to integrate different disciplines in the study of critical problems associated with global climate change, is noteworthy. The scientific agenda of the Rede Clima is very broad, and its actions involve dozens of research groups distributed throughout a majority of the Brazilian states. Among many other projects, the Rede Clima operates projects aimed at improving the inventory of greenhouse gas emissions in Brazil, studying the impact of smoke from fires on public health, and analysing the most effective strategies to mitigate emissions.

Another important initiative of the federal government is the establishment of the National Institutes of Science and Technology (Institutos Nacionais de Ciência e Tecnologia – INCTs), which are structured as a network of research groups. Several INCTs have scientific departments that are associated with global changes, such as the INCT of Environmental Services, the INCT of Marine Sciences, and the INCT of Adaptation of Biodiversity to Climate Change, among others. However, one of the INCTs is organised specifically around the issue of global climate change, the INCT of Global Climate Change (INCT de Mudanças Climáticas Globais – INCT-MC), which is coordinated by the National Institute for Space Research (INPE). The scientific agenda of the INCT-MC includes studies on the adaptation of the energy matrix, the role of the Amazon, the development of agricultural techniques with lower emissions, and other topics that are relevant to the impacts of climate change in Brazil.

With respect to the Amazon, an important research concentration has been developed under the Large-Scale Biosphere and Atmosphere Experiment of the Amazon (LBA), which is a programme of the MCT that is administered by the National Institute of Amazonian Research (Instituto Nacional de Pesquisa da Amazônia – INPA). The LBA studies the role of the Amazonian ecosystem relative to global changes as a natural system and has the participation of dozens of research groups in the country. Studies on carbon balance, the role of clouds in the climate system, the hydrological cycle, the meteorology of the region, the changes in land use, and other issues relevant to the Amazon ecosystem are part of the scientific focus of the LBA. The LBA has been operating successfully for the past 15 years, with a large scientific contribution in the area of global change in the Amazon. The LBA has also educated a large number of new researchers in this field.

Among the various state initiatives is the FAPESP Programme for Global Climate Change (Programa FAPESP de Mudanças Climáticas Globais – PFMCG), which was implemented by the São Paulo Research Foundation (Fundação de Amparo a Pesquisa do Estado de São Paulo – FAPESP) and is expected to last at least 10 years. The PFMCG will study a wide range of topics that are relevant to global climate change, including the process of urbanisation and emissions of greenhouse gases and their social impacts, the emissions of greenhouse gases in the cultivation of sugar cane, methods of developing a so-called "Green Economy", the effect of emissions from the process of ethanol production, climate modelling, and the role of the oceans in the Brazilian climate, among many others. The PFMCG is also funding the development of the Brazilian Model of the Global Climate System (Modelo Brasileiro do Sistema Climático Global – MBSCG), which will give the country autonomy in the field of global modelling. In recent years, Brazil has acquired the Earth System Models, which is a large supercomputer with adequate capacity to enable simulations of coupled climate models, including the cycling of carbon and other effects on the ecosystem.

The main contributions generated by these and other research programmes will be incorporated in the First National Assessment Report (Primeiro Relatório de Avaliação Nacional – RAN1) of the PBMC. The RAN1 consists of three volumes, which correspond to the activities of each Working Group, and a volume on the Inventory Methodologies for Greenhouse Gases, prepared by the Task Force (www.pbmc.coppe.ufrj.br). This document is the Executive Summary of the main contributions of the RAN1 Working Group 1 (GT1) - Scientific Basis of Climate Change, the objective of which is to evaluate the scientific aspects of the climate system and its observed and projected changes. The structure of this document was defined previously with the Principal Authors of Chapters and is based on the scope of the PBMC-GT1. The surveys are the results of an extensive literature review that sought to emphasise the implications of the main points of the IPCC-AR4 for Brazil and to record and discuss the main scientific research published after 2007, particularly those publications that are more directly related to climate change in South America and Brazil. The set of information generated and synthesised in this summary constitutes the first contribution of Working Group 1 (Grupo de Trabalho 1 – GT1) – Scientific Basis of Climate Change for the First National Assessment Report (RAN1) of the Brazilian Panel on Climate Change.

Observational Evidence of Climate Variations

An important aspect addressed in the GT1 document is the identification of observational evidence of climate variability and changes in the geological past that contribute to a better understanding of climate variability observed in the present; additionally, the document speculates on the behaviour of the future climate, based on climate change projections for Brazil and South America.

The analyses suggest that marked changes in the circulation of the western portion of the South Atlantic occurred in the Last Glacial Maximum (from 23,000 to 19,000 years before the present - BP), in the last deglaciation (from 19,000 to 11,700 years BP), and in the Holocene (from 11,700 years BP to the present). The main changes relate to the following: (i) a decrease in the depth of the contacting areas between the intermediate and deep water masses during the Last Glacial Maximum, which was characterised by a section of the Atlantic meridional overturning circulation (also known as thermohaline circulation) that was neither significantly weaker nor significantly stronger than the current intensity; (ii) an increase in the surface temperatures of the South Atlantic during the periods of decreased intensity of the thermohaline circulation that were specific to the last deglaciation event (e.g., Heinrich Stadial 1 between 18,100 and 14,700 years BP and the Younger Dryas between 12,800 and 11,700 years BP); and (iii) the establishment of a surface circulation pattern similar to the current pattern along the continental margin of southern Brazil between 5,000 and 4,000 years BP.

Analyses have revealed that, during the Holocene, the changes in the insolation received by Earth were on an orbital timescale; additionally, these changes were the main cause of variations in the precipitation and in the tropical and subtropical ecosystems of Brazil, particularly in the regions that were under the influence of the South American monsoon system. Higher values of summer insolation in the southern hemisphere have been associated with periods of strengthening of the South American monsoon system, and vice versa. On the millennial time scale, strong and abrupt fluctuations in the temperature gradient in the Atlantic Ocean have been observed, as well as in the rainfall associated with the South American monsoon system and the Intertropical Convergence Zone. These abrupt climate changes are apparently caused by marked changes in the intensity of the Atlantic meridional overturning circulation. Periods of circulatory weakness have been associated with increases in rainfall in the tropical and subtropical regions of Brazil.

At one point, the relative sea level on the coast of Brazil was as high as 5 m above its present level (between 6,000 and 5,000 years BP), decreasing gradually until the early industrial period.

Palaeoanthracological analyses indicate that, for a long period of the Late Quaternary, fire was a major disturbance factor in the tropical and subtropical ecosystems in addition to climate, which is of paramount importance in determining the dynamics of vegetation in the geological past.

Although there are still outstanding controversies with respect to the importance of issues related to the human occupation of the Americas (e.g., the age of the first migration, the number of waves of migration that occurred, the migration paths that were used), nonetheless, it is known that all of South America was already occupied by *Homo sapiens* by approximately 12,000 years BP and that these populations already showed distinct adaptive and economic patterns among them. The apparent stability in the human occupation of Brazil was interrupted between 8,000 and 2,000 years BP, with a significant abandonment of sites and migration on a regional scale, which could be associated with marked changes in climate.

The Little Ice Age (from 1,500 to 1,850 BP) was characterised in the (sub) tropical portion of South America, which is south of the equator, by an increase in precipitation; this phenomenon was likely associated with a strengthening of the South American monsoon system and a weakening of the thermohaline circulation of the Atlantic. However, the associated climate mechanisms are not well-established, and the number of palaeoclimatic and palaeoceanographic records available in the pertinent (sub) tropical environments is particularly limited.

Moreover, there is still a very limited number of palaeoclimatic and palaeoceanographic records from Brazil and the western portion of the South Atlantic. Only in recent years were the first studies published (e.g., Cheng *et al*., 2009; Chiessi *et al*., 2009; Souto *et al*., 2011; Laprida *et al*., 2011; Stríkis *et al*., 2011) for several of these regions (e.g., the midwestern region of Brazil, the Malvinas Confluence Zone) and on relevant variables (e.g., the sea surface temperature (SST) for the Holocene and the variability in precipitation on the timescale of a decade or a century). Therefore, it is important that knowledge gaps in this area are filled in the coming years by investing in more studies and by the training of individuals in these specialised fields.

The analysis of observational results from the recent past has revealed the great impact of the interannual variability of environmental parameters, which can produce major changes in seasonal rainfall in certain regions, such as the Amazon. For example, El Niño and La Niña are major sources of interannual climate variability, in addition to the modes of variation in the tropical and southern Atlantic Ocean. Decadal variations (on a scale of 25-30 years) in the Pacific or Atlantic Oceans show smaller differences between the contrasting periods, but these variations are relevant to adaptation because of their persistence, and they may cause prolonged droughts or decades with an increased number of extreme rainfall events in several regions of South America.

The decadal variability of large-scale atmospheric and oceanic circulations has produced strong climatic variation since the mid-1970s due to the superposition of the effects of its phase change on this particular decade. Therefore, the analysis of trends in a relatively short series of climate periods, which includes periods before and after this decade, is more suggestive than conclusive. A portion of the precipitation trends identified in Brazil can be explained by the phase changes with decadal oscillations; however, it is known that part of the climate variability is already a consequence of the current global warming event. For example, certain of the trends identified are consistent with the decadal variation in annual rainfall that was produced in the second half of the last century; the decadal variation is significantly correlated not only with the SST trend but also with the Atlantic multidecadal oscillation (AMO) and the Pacific decadal oscillation (PDO). These results show negative trends in the northern and western Amazon, positive trends in the southern Amazon, positive trends in midwestern and southern Brazil, and no trend in northeastern Brazil. The increasing precipitation trend from 1950-2000 in southern Brazil and other parts of the lower Paraná/Prata River Basin, especially in the periods before and after the 1970s, appears to be interdecadal, particularly when slightly longer series are used.

To verify whether the decadal trends in precipitation are due only to the phase shift of the AMO or whether they are part of a consistent behaviour over a longer period, the following would be necessary: (i) a longer data series for precipitation and (ii) a greater consistency between these trends and the changes in the precipitation in these regions as projected by climate models. Therefore, better treatment and evaluation of the uncertainties surrounding the projected trends are required and should be combined with further development of the climate models used to generate climate projections. Similarly, it is still difficult to assess how anthropogenic changes have influenced extreme precipitation events, the variations in which could simply be related to the natural climate variability.

Temperature trend studies that use seasonal data from South America are largely limited to the period from 1960-2000. The most significant results are related to index variations based on the daily minimum temperature, which have indicated an increase in hot nights and a decrease in cold nights in most of South America with a consequent decrease in the range of daytime temperatures, especially in the spring and fall. These results are more robust for the seasons on the east and west coasts of the continent, where they have been confirmed for series over longer periods.

Although the influence of the variability of the Atlantic and Pacific Oceans on the long-term behaviour of the temperatures over South America needs to be taken into account, the influence of anthropogenic activity on the temperature extremes appears to be more likely than that found on the precipitation extremes. The huge shortage of seasonal data on vast tropical areas, such as the Amazon and midwestern and eastern Brazil, limits the establishment of accurate findings for these regions by the use of seasonal data. Recent studies have shown that factors such as changes in land use (e.g., deforestation or urbanisation) and biomass burning can influence the temperature in urban and rural areas, but the magnitude and spatial extent of these indicators of long-term influence on surface temperatures still need to be investigated. As discussed in the following sections, the effect of changing land use and urbanisation, known as an urban heat island, can be an important contributor to the increase in the average global temperature, particularly in large cities.

Reanalysed data from 1948 provide evidence of temperature increases in the lower levels of the atmosphere that are more accentuated in the tropics than in the subtropics of South America during the austral summer. In this case, the average annual temperature of the surface in the tropics has shown positive trends since then, whereas there has been a negative trend in the subtropics in certain parts of southeastern Brazil since the mid-1990s. An increase in the temperature was also recorded on the surface of the Tropical Atlantic, suggesting that changes may have occurred in the ocean-atmosphere contrast and, consequently, in the development of weather systems and climate patterns in this region. These changes may cause variations in rainfall and clouds and create feedback systems in local temperature and climate that have not been widely studied. Changes in global mean fields and SSTs, before and after the period known as the climate shift in the mid-1970s, may have played an important role in the temperature and precipitation regimes and trends and must be considered to properly evaluate the effect of global warming on South America.

There is no doubt that the global average temperature of the atmosphere has increased with accelerating intensity over the last 30-40 years, thereby contributing to global and regional climate change. However, the oceans also participate in a pivotal manner in balancing the climate due to their large spatial coverage, combined with the high heat capacity of water. The increase in the heat content of the oceans and the increase in sea level are therefore consistent indicators of the warming of the planet.

Despite the great difficulty of observing the ocean with the temporal and spatial coverage needed to better monitor and understand changes in the oceans and the results of these changes in the climate, it must be noted that great progress has been made in recent years. Remote satellite observations have been used for several decades now, and in situ observational programmes, such as Argo, have allowed for the acquisition of valuable data sets from the surface to the intermediate depths of the ocean. Recently, several efforts have been made to re-evaluate historical data to enable more reliable interpretations for longer time periods.

Based on a considerable number of papers published in recent decades, the Fourth Climate Assessment Report of the IPCC (IPCC-AR4, 2007) concluded, unequivocally, that the global ocean temperature has increased over the past 50 years and, more recently, several scientific studies have confirmed the warming of ocean waters beyond dispute. In particular, the sea surface temperature (SST) of the Atlantic Ocean has increased in recent decades. In the South Atlantic, this increase intensified during the second half of the twentieth century, possibly due to changes in the ozone layer over the South Pole and to the increase in greenhouse gases (Meehl and Arblaster, 2006; Rayner *et al.*, 2006). Consistent with this warmer climate, the hydrological cycle has also changed, reflecting changes in the salinity of the sea surface. Studies show that the subtropical South Atlantic is becoming warmer and increasing in salinity (Durack and Wijffels, 2010; McCarthy *et al.*, 2011).

Considering the oceans on a global level (i.e., the global ocean), there is clear evidence beneath the surface that the temperatures of the upper layers have increased. The reanalysis of historical data that were obtained with expendable bathythermographs (XBTs) reveals a clear warming trend in the first 700 m of the water column. Independent studies with data obtained to a depth of 2,000 m with Argo profilers also suggest a significant heating trend below 700 m. Fig. 1 (Trenberth, 2010) summarises the results of recent studies based on a broad data set, including XBT, Argo, and others, in the period from 1993-2008; the data strongly indicate that the heat content from a depth of 0-700 m in the global ocean is increasing at an average rate of 0.64 +/- 0.29 Wm^{-2} (watts per square metre) over the entire planet (Lyman *et al.*, 2010).

Fig. 1

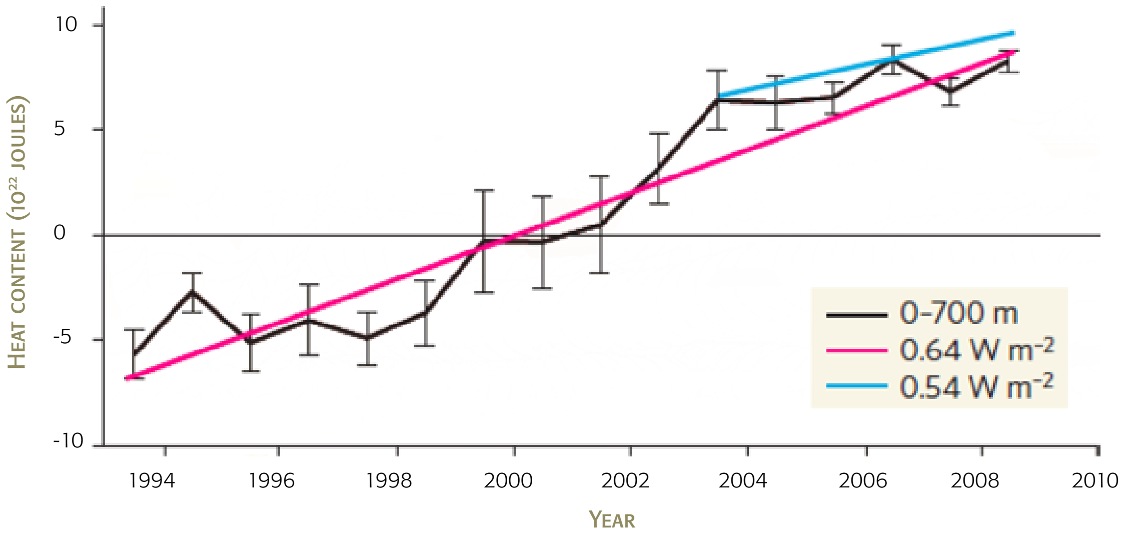

Fig. 1. The heat content variation in the layer from 0-700 m deep of the global ocean (black line). The positive trend of approximately 0.64 Wm^{-2} is a strong indicator of heating in the upper layer of the ocean. The blue line represents the heat content variation from 0-2,000 m, based on 6 years of Argo data. The rate of increase of 0.5 Wm^{-2} suggests that warming is occurring at depths exceeding 700 m (Trenberth, 2010).

The studies analysed by the IPCC-AR4 and other more recent studies and compilations also point to variations in the heat content and the rising sea level on a global scale. Variations in these properties promote changes in the characteristics of different water masses, which inevitably lead to changes in the ocean circulation patterns. In turn, changes in the circulation modify how heat and other biological, physical, and chemical properties are redistributed on the Earth's surface.

Based on several types of measurements, the average sea level is also rising. Much of the earlier projections of sea level rise, which were intended for the entire twenty-first century, will instead be met within only the first decades of the century, creating even more concerned outlooks than those released in early 2000. Variations from 20-30 cm, expected to occur over the entire century, may now be achieved before mid-century in certain locations. Significant variability in the sea level response between different regions of the globe should also be expected. Few studies based on *in situ* observations have been conducted on the coast of Brazil. Even so, rates of sea level increase along the south-southeast coast have already been reported by the Brazilian scientific community since the late 1980s and early 1990s.

The rising sea level, its rising temperature, the changes in ocean volume, the distribution of precipitation, and the concentration of CO_2 will unpredictably affect the ecological balance of marshes, depending on the extent of such changes and the local features of sedimentation and space accommodation.

Along the length of the Brazilian coast, there are several irregularly distributed, eroded stretches that are often associated with dynamic estuary environments. Several areas are densely populated coastal regions; these regions are flat and low, and their existing erosion, drainage, and flooding problems will likely be amplified in climate change scenarios.

The substantial bodies of water are changing. The subtropical gyres of the North and South Atlantic have become warmer and more saline. As a result, the second conclusion of the IPCC-AR4 and of more recent studies is that it is likely that, until the end of the last century, the Atlantic meridional overturning circulation has altered on yearly to decadal scales.

In the South Atlantic, several recent studies suggest important variations in the physical and chemical properties of the upper layers of the ocean that are associated with changes in atmospheric circulation patterns. These studies show that due to the rotational displacement of the wind toward the pole, the transport of water from the Indian Ocean to the South Atlantic, a phenomenon known as the "Agulhas leakage", has been increasing in recent years. The analysis of data obtained by remote satellite and by *in situ* measurements shows changes in the South Atlantic subtropical gyre that are associated with changes in the salinity of the upper layers. The results of observations and models suggest that the South Atlantic subtropical gyre is expanding, with a shift to the southern region of the Brazil-Malvinas Confluence (Biastoch *et al.*, 2008, 2009; Haarsma *et al.*, 2009).

Since the last publication of the IPCC-AR4 report, the greatest achievements of studies related to El Niño have been the demonstration of compelling evidence that the characteristics of this weather pattern in the Pacific Ocean have begun to change in recent decades. Current research indicates that in addition to the existence of a conventional El Niño, in which the maximum SST anomaly occurs in the Eastern Equatorial Pacific region, there is a different spatial structure, referred to as the El Niño Modoki (Ashok *et al.*, 2007) or Central Pacific El Niño (Kao and Yu, 2009; Kug *et al.*, 2009), for which the maximum SST anomalies occur in the Central Pacific. Although several studies have indicated that the El Niño Modoki has a different impact than its conventional "brother", which may include the concept of tropical-extratropical wave propagation and the changes in the Walker cell depending on the location of the tropical heating forcing (Grimm and Ambrizzi, 2009), nonetheless, investigations of its influence on South America and particularly on Brazil are still limited, possibly because these impacts should be weaker. The discovery of El Niño Modoki is related to its more frequent occurrence in the last decade versus in the past (Kug *et al*., 2009), and certain studies suggest that this anomalous warming of the tropical Pacific may be in response to increased greenhouse gases (Yeh *et al.*, 2009).

Changes in the variability of the SST in the South Atlantic may be associated with disturbances originating in the central and eastern Equatorial Pacific. These changes in SST patterns may favour above-average or average precipitation over northern and northeastern Brazil and more rain in southern and southeastern Brazil. For example, recent results by Rodrigues *et al.* (2011) suggest that El Niño events are responsible for the development of SST anomalies in the Atlantic, which in turn determine, along with changes in atmospheric circulation caused by El Niño, the pattern of rainfall over Brazil, although the uncertainties in these results are considerable. During El Niño Modoki, the Atlantic Ocean shows positive SST anomalies in the tropical South Atlantic and negative anomalies in the subtropical South Atlantic (Fig. 2). This pattern sets the negative phase of the South Atlantic dipole mode. Of the 11 negative phases of the South Atlantic dipole that occurred from 1950-2005, 9 were during El Niño Modoki years. Moreover, during El Niño Modoki, the tongue of cold water in the Atlantic does not develop, and the SST anomalies in the tropical North Atlantic are negative, establishing the negative phase of the meridional mode. These SST anomalies in the tropical Atlantic allow the Intertropical Convergence Zone (ITCZ) to move south, bringing rain to northern and northeastern Brazil. The occurrence of conventional (or canonical) El Niños, in turn, coincides with negative SST anomalies in the Tropical South Atlantic and positive anomalies in tropical North Atlantic, which restrain the ITCZ from moving south and stimulating rain in the northeast. It should be noted that the patterns of rainfall over Brazil in El Niño years are opposite to those in canonical years of El Niño Modoki (right panels in Fig 2).

Generally, droughts in the south/southeast have been accompanied by heavy rains in the north/northeast during the La Niña years. In the most recent La Niña events, in 2007-08 and 2010-11, a reversal of these patterns was observed, at least in south/southeastern Brazil. Because the most extreme climate events in Brazil are related to El Niño and La Niña, any changes in the behaviour of the El Niño Southern Oscillation (ENSO) are extremely important. If the increased frequency of El Niño Modoki events due to global warming continues, according to Rodrigues *et al*. (2011), there will be more frequent development of: (i) negative phases of the South Atlantic dipole mode (i.e., the hot equatorial pole and the cold subtropical pole), (ii) warm SST anomalies in the equatorial Atlantic, and (iii) cooler or neutral SST anomalies in the Tropical North Atlantic, which feature a negative phase of the meridional mode (i.e., a negative meridional SST gradient). Several observational studies have indicated a positive trend in the amplitude of ENSO events, which are a suggested cause of global warming (Zhang *et al*., 2008a; Kim and An, 2011). These analyses have been complemented by numerical experiments involving Coupled General Circulation Models, including the burden of an increased concentration of greenhouse gases (An *et al*., 2008). Despite these additional efforts, whether the increasing trend of the ENSO range is due to global warming or natural variability of the global climate system remains highly uncertain (Collins *et al.*, 2010). With respect to La Niña, there are still no predictions, and the effect may be opposite. The last La Niña events of 2008-09 led to droughts in the Amazon (Marengo, 2010; Lewis *et al.*, 2011), whereas the heavy rains and floods recorded in the Amazon in 2011-12 also happened during a La Niña event.

The drought of 2005-06 was once considered to be an event that occurs once every 100 years (Marengo *et al*., 2008), but in 2010, there was another drought of comparable magnitude that affected other areas of the Amazon (Lewis *et al*., 2011; Marengo *et al*., 2011a). All of these events have reinforced the hypothesis that such extreme events are likely to become more frequent and intense with future climate changes (Cox *et al.*, 2008).

Fig. 2

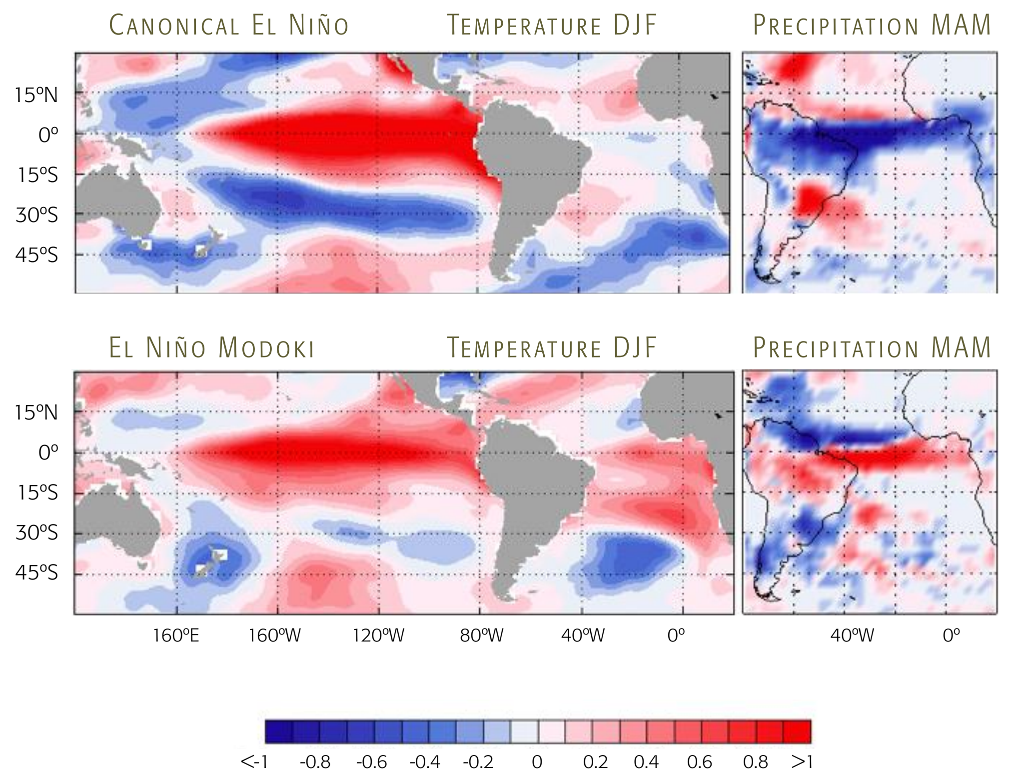

Fig 2. SST anomalies (°C) in December-January-February (DJF) and precipitation anomalies (mm day^{-1}) in March-April-May (MAM) for the canonical El Niño (top panels) and for El Niño Modoki (lower panels). DJF is the season of the year in which El Niño events reach their peak (mature stage), and MAM is the rainy season over the north/northeast, when these events have the largest influence on rainfall in Brazil. Adapted from Rodrigues *et al*. (2011).

NATURAL AND ANTHROPOGENIC RADIATIVE FORCINGS

The climate is controlled by several factors, called climate agents, which may be part of the natural climate system or which may originate from human activities (i.e., anthropogenic contributions). A certain climate agent may contribute to warming the planet, such as the increase in greenhouse gas concentrations caused by anthropogenic emissions, whereas another agent may tend to cool it, such as increasing cloud cover. It would be useful for decision makers to know the quantitative influence of each climate agent; for example, knowing the contribution of each agent to variations in the surface temperature of either the planet or of Brazil, alone. The difficulty in quantifying the role of each climate agent stems from deficiencies in the observational network, a lack of understanding of the complex climate processes and the limitations of climate models. In particular, the lack of long-term observations in Brazil is a strong limiting factor to the ability to diagnose and quantify the role of different agents operating on the Brazilian climate.

The concept of radiative forcing, as defined in Panel S1, is necessary to compare and quantify the effects of different types of climate agents that alter the balance of atmospheric radiation. A positive radiative forcing means that a particular climate agent tends to warm the planet, whereas negative values indicate a tendency to decrease the temperature. The radiative forcing of a climate agent can be expressed as a heat flux and has units of Wm^{-2} (watts per square metre). For example, if a climate agent represents a radiative forcing of +2 Wm^{-2}, this statement indicates that the agent adds 2 Wm^{-2} to the climate system and therefore puts more energy into the system and tends to warm the planet. Radiative forcing can be expressed in climate models as the additional amount of energy per unit area over time, and these climate models can calculate the increase or decrease in temperature change that a particular radiation balance may cause. The numerical quantification of the intensity of radiative forcing allows the decision maker to visualise the most significant climate agents, to rank them in the order of their relative magnitudes, and to evaluate the disruption that each climate agent causes globally or in a particular region.

In addition to independent climate agents, there are situations of interdependence between agents, called feedback processes, which make efforts to quantify the ultimate climatic effect of a certain agent even more complex. Several climate agents can influence the hydrological cycle, such as water vapour, surface albedo, the amount of aerosols, and the thermodynamic conditions of the atmosphere, among others. It has been observed in the Amazon that the smoke emitted from fires can alter the microphysics of cloud formation and development. This effect can reduce the incidence of rain in the region. When this effect occurs, the reduced rainfall can favour the occurrence of an even greater number of fires and thus establish a positive feedback cycle. In such feedback loops, the relationships of cause and effect are complex.

In Brazil, the most significant climatic effects functioning on scales of tens to hundreds of years are the

PANEL S1 – DEFINITION OF RADIATIVE FORCING

The radiative forcing due to a climate agent is defined as the net difference in irradiance within the different compartments of the atmosphere (e.g., the upper atmosphere or the surface) between a reference state and a disrupted state due to the climate agent. The reference state may be the absence of the climate agent or its impact during a given time period, for example, in the Industrial Revolution (ca. 1750), as adopted by the Intergovernmental Panel on Climate Change - IPCC (Forster *et al.*, 2007).

radiative effects of clouds, the radiative forcing of greenhouse gases, forcing due to changes in land use, and aerosol particles (smoke) emitted by anthropogenic sources. Table S1 shows a compilation of the results from the scientific literature that address the main radiative effects of climate agents in Brazil.

Clouds exert a natural radiative effect and play an important role in climate regulation, but their properties can be altered by human action (e.g., the indirect effects of aerosols, changes in surface properties, changes in vertical profiles of temperature, etc.). These changes may involve either feedback processes, with possible impacts on the hydrological cycle, which may cause changes in water availability, or frequency of the occurrence of extreme precipitation events, such as severe storms. The compiled results demonstrate that clouds are the most important climate agent from the viewpoint of the radiation balance in the Amazon, reducing the radiation to the surface by as much as 110 W m^{-2} and contributing approximately +26 W m^{-2} of radiative forcing back to the top of the atmosphere. It should be noted that the included studies consider how the vertical distribution of the clouds plays a key role in the results: high clouds tend to have a warming effect on the planet, whereas low clouds tend to cool it. Thus, it is important to note that these results cannot be automatically extrapolated to other regions, particularly those with cloud patterns and surface characteristics that differ from those in the Amazon region.

Aerosol particles, which are emitted in large quantities in fires, can absorb and reflect solar radiation. This direct interaction between aerosols and solar radiation defines the so-called direct aerosol radiative forcing. Several studies have quantified this forcing as a result of anthropogenic aerosols, especially in the Amazon. A weighted average of several compiled results yields a radiative forcing of -8.0 ± 0.5 W m^{-2}, which indicates that, on average, the smoke emitted in fires contributes to cooling the surface, partially counteracting the warming caused by anthropogenic greenhouse gases. It is very important to note, however, that aerosols and gases have very different time and spatial scales: whereas greenhouse gases tend to spread fairly uniformly over the planet and typically have an average life of tens to hundreds of years, aerosols emitted in fires in the Amazon spread over much of the South American continent and have an average life span of a few days, after which they are removed from the atmosphere and deposited on the surface. It is also important to emphasise that the aerosol particles emitted in fires contain large amounts of so-called black carbon, which is a smoke constituent with a high capacity for the absorption of solar radiation. These particles heat up the air by absorbing a portion of the solar radiation; they play an important role in changing the vertical profile of the atmospheric temperature by inhibiting convection, which is an important mechanism in the formation and development of clouds.

Anthropogenic changes in land use, such as the long-term urbanisation process of Brazilian city development or the conversion of forests for agriculture in the Amazon region, result in changes in surface properties, such as the albedo, which is the reflectivity of the surface. In general, in the Amazon, the darker surface (forest) has been replaced by brighter surfaces (e.g., crops, pastures, etc.), which suggests that a greater fraction of sunlight is now reflected back into space. This effect is known to be significant for the Amazon region, where albedo changes have been observed in deforested areas: these changes have resulted in anthropogenic radiative forcing of approximately 7.3 ± 0.9 W m^{-2}. It should be noted that this value is similar to that of the radiative forcing of anthropogenic aerosols; however, it is important to note that deforestation in the Amazon has a virtually "permanent" character (i.e., in general, the majority of degraded areas do not return to their former condition as a primary forest), whereas biomass-burning aerosols have an average life span of days. These observations indicate the need to conduct further studies on this forcing, which originates in the processes of changing land use; such studies should particularly include the effects of historic urbanisation and agricultural expansion at the national level and at various time scales.

Aerosols also interact with clouds and modify their properties. The modified clouds, in turn, interact strongly with radiation, thus defining the indirect radiative forcing of aerosols (i.e., as mediated by the interaction of aerosol particles with clouds). The estimates of radiative forcing for the indirect effects of aerosols in the literature show a wide range of values. Most of the results have a negative sign, which is between approximately -9.5 to -0.02 W m^{-2} for different types of surfaces, indicating cooling climatic conditions. This is a topic that requires further studies for characterisation and independent verification, so that this component of anthropogenic forcing can be adequately studied with respect to Brazil in addition to the quantification of its wider effects in regions other than the Amazon.

To date, no scientific studies in Brazil have evaluated the radiative forcing due to aerosols of urban origin, the natural dust aerosol from Africa, or aerosols from volcanic eruptions; additionally, there have been no investigations of the formation of condensation trails by commercial aviation activities. These currently unknown radiative forcings may play a significant role and be comparable to those due to greenhouse gases. Several studies have shown the existence of significant gaps in studies of radiative forcing in Brazil. Knowing the precise magnitude of these forcings and enhancing our understanding of their impact will result in improvements in models of weather and climate. Such models are important tools for equipping political and economic decision making with respect to the climate changes that are occurring in the country.

In Brazil, a major source of greenhouse gas (GHG) emissions and anthropogenic aerosols is the burning of biomass as an agricultural practice or to change the soil cover. As an agricultural technique, fires are used to combat crop weeds and to clean fields to facilitate the harvest process, as in the cultivation of sugar cane. The use of fire to facilitate changes in land use is observed especially in the Amazon region. In the case of greenhouse gases, much of the research effort in Brazil now focuses on the development of emission inventories.

The greenhouse gases included in the official inventories are shown in Table S2, along with their main emission sources. These greenhouse gases are as follows: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Other gases that influence the chemical reactions that occur in the atmosphere are carbon monoxide (CO), nitrogen oxides (NO_x), ozone (O_3), and non-methane volatile organic compounds (NMVOCs), which may also be included in future Brazilian inventories.

Table S1 – The quantification of the radiative forcing of anthropogenic aerosols, changes in land use, and the radiative effect of clouds over Brazil and South America.

AGENT	REGION	CONDITION[a]	VALUE[b] (Wm^{-2})	DATA SOURCE	REFERENCE
Clouds	Amazon	SUR, 24h[e]	[-110;-50]	Climate model, satellite	Betts *et al*., 2009
	Amazon	SUR,24h[e]	-76	Climate model	Miller *et al*., 2011
		TA,24h[e]	+26		
Land Use	Amazon	TA	-23.7±2.8	Satellite, radiative model	Sena *et al*., 2011
		TA,24h[e]	-7.3±0.9		
Anthropogenic Aerosols Direct Effects	Amazon	SUR,24h[d]	-39.5±4.2	Remote sensor, radiative model	Procópio *et al*., 2004
		ATM,24h[d]	+31.2±3.6		
		TA,24h[d]	-8.3±0.6		
	Amazon Forest	TA,24h[e]	-16.5	Climate model, *in situ* measurements	Liu, 2005
	Tropical Atlantic	TDA,24h[e]	-1.8	Satellite, radiative model	Kaufman *et al*., 2005
		ATM,24h[e]	+2.9		
	South America	TA,24h	[-8; -1]	Climate model, satellite	Zhang *et al*., 2008
		SUR	[-35; -10]		
	South America	TA annual	[-1.0; -0.2]	Satellite	Quaas *et al*., 2008
	Amazon	TA	-13.0±3.9	Satellite, Radiative model	Patadia *et al*., 2008
		TA, 24h	-7.6±1.9		
	Amazon	TA, 24h	-5.6±1.7	Satellite, Radiative model	Sena *et al*., 2011
	Forest		-6.2±1.9		
	Cerrado		-4.6±1.6		
Anthropogenic Aerosols Indirect Effects	Southern Hemisphere	TA, 24h[c] alb	-0.70±0.45	Literature Review	Lohmann e Feichter, 2005
	Global, over continents	TA, 24h[c] ind	-1.9±1.3		
	Tropical Atlantic	TA, 24h[e] alb	-1.5	Satellite, Radiative model	Kaufman *et al*., 2005
		TA, 24h[e],ind	-9.5		
	South America	TA, 24h ind	[-5; +20]	Climate model, satellite	Zhang *et al*., 2008
	South America	TA, anual alb	[-0.10; -0.02]	Satellite	Quaas *et al*., 2008
	Tropical Atlantic		[-5.00; -0.05]		
Total aerosols and clouds	Amazon	TA,24h[c]	-9.8	Climate model, *in situ* measurements	Liu, 2005
	Tropical Atlantic	TA,24h[e]	-11.3	Satellite, climate model	Kaufman *et al*., 2005
		SUR,24h[e]	-8.4		
	South America	TA,24h	[-10; +15]	Climate model, satellite	Zhang *et al*., 2008
		SUR,24h	[-35; -5]		

a) Indicates the vertical position in the atmospheric column (TA: top of the atmosphere; SUR: surface; ATM: atmospheric column) for the estimate in question, the time domain calculation (instantaneous value, average of 24 hours or annual average), and the component of the indirect effect analysis (alb: albedo; ind: total indirect effects). b) The figures in brackets indicate the minimum and maximum ranges given in the references. When available, the uncertainties presented by the authors are indicated. c) The expected temporal domain (not explicitly reported in the reference), d) the reference state with an aerosol optical depth of 0.11, and e) the reference state with an aerosol optical depth of 0.06.

Table S2 – Gases that increase the greenhouse effect and their emission sources.

GHG	SOURCE
CO_2	Changes in land use and deforestation
	Burning of fossil fuels (fossil fuel use, mainly by the energy, industrial, and transportation sectors)
	Fugitive emissions (e.g., coal mining, the extraction and transport of petroleum and natural gas)
	Industrial processes (e.g., the production of cement, lime, ammonia, and aluminium)
CH_4	Changes in land use and deforestation
	Burning of fossil fuels (fossil fuel use, especially by the energy, industrial, and transportation sectors)
	Agriculture (e.g., enteric fermentation, the management of livestock manure, rice cultivation, the burning of agricultural waste)
	Waste treatment (industrial and domestic rubbish and sewage)
	Fugitive emissions (e.g., coal mining, the extraction and transportation of petroleum and natural gas)
	Industrial processes (chemical industry)
N_2O	Agriculture (associated mainly with the management of livestock manure, agricultural soils, and the burning of agricultural waste)
	Changes in land use and deforestation
	Industrial processes (chemical industry – production of nitric and adipic acid)
	Waste treatment (domestic sewage)
HFH, PFC, SF_6	These gases do not exist in nature and are produced in industrial processes, especially for use in electrical and refrigeration equipment and in the production of aluminium.
GHG Indirect[a]	
CO	Burning of fossil fuels (fossil fuel use, mainly by the energy, industrial, residential, and transportation sectors)
	Industrial processes (e.g., the chemical, aluminium, paper, and cellulose industries)
	Agriculture (the burning of sugar cane during the harvest)
	Burning during changes in land use and deforestation
NO_2	Burning of fossil fuels (fossil fuel use, mainly by the energy, industrial, residential, and transportation sectors)
	Industrial processes
	Agriculture (the burning of sugar cane and cotton residues)
	Burning during changes in land use and deforestation
NMVOC[b]	Burning of fossil fuels (fossil fuel use, mainly by the energy, industrial, residential, and transportation sectors)
	Industrial processes (e.g., the chemical, aluminium, paper and cellulose, and food and drink industries)
	Solvent use

a) Gases that influence the chemical reactions in the troposphere and that indirectly warm the atmosphere,
b) Non-methane volatile organic compounds.

BIOGEOCHEMICAL CYCLES, BIOMASS AND WATER RESOURCES

In Brazil, profound and variable changes in the climate are expected depending on the area of the country. It is expected that these changes will affect the aquatic and terrestrial ecosystems of Brazil. In this regard, the country is one of the world's richest, with six terrestrial biomes (the Amazon, Atlantic Forest, Pantanal, Pampas, Cerrado, and Caatinga). These six biomes further include several of the world's major rivers, such as the Amazon, the Paraná, and the São Francisco, and Brazil possesses a coastline of approximately 8,000 km, containing at least seven major estuaries and the entire continental shelf.

Due to a lack of information that is spatially attuned to the scales of Brazilian biomes, analyses have been concentrated in the regions of each biome for which information is available. Although this type of limitation prevents us from making a generalisation to a particular biome, it serves as a warning about the limitations of this information at scales consistent with the vast areas of our biomes. There is a lack of critical information for certain biomes, such as the Pampas, the Pantanal, and the Caatinga. Larger volumes of information are available for the Amazon and, secondarily, for the Cerrado. Only recently have studies been conducted in the Atlantic Forest, and these studies are still concentrated in a few areas.

In the Amazon, Brazil has implemented a vast network of carbon flux measurements as part of the Large-Scale Biosphere and Atmosphere Experiment (LBA). Approximately 12 carbon flux towers are in operation, using the technique of eddy correlation to estimate the flow of carbon. Other measurements, such as the heat and water vapour fluxes, phenology, soil properties, radiation, and other important properties, are recorded in parallel. The RAINFOR network was also structured for measurements of the carbon accumulation in vegetation and has been active since the early 1990s. The results of these measurements indicate that the Amazon Forest is accumulating carbon at an average rate of 0.5 tons C ha^{-1} yr^{-1} (tons of C per hectare per year). The accumulation of carbon has a strong geographical variability, depending on the amount of soil nutrients, the rainfall, and the availability of solar radiation. It is not yet clear what mechanisms are responsible for this accumulation of carbon by Amazonian vegetation. This carbon absorption was reversed significantly during the 2005 drought, indicating that climatic variables have a strong influence on the processes that are responsible for carbon absorption by the forest. A significant impact of aerosols on carbon assimilation by the forest has also been observed through the increase in diffuse radiation caused by emissions from fires. Increases of 20-40% in carbon uptake due to the presence of moderate amounts of aerosols have been observed in Rondônia, Santarém, Manaus, and other places, with a reduction in the assimilation for amounts of aerosols above 1.5 in terms of aerosol optical thickness at 500 nm.

The largest stocks of carbon and nitrogen in the soil are found in the Atlantic Forest, followed by the Amazon and the Cerrado. Regarding the stocks of carbon and nitrogen above the ground, the Atlantic Forest and especially the Amazon stand out as having the largest stocks. Interestingly, only in the Amazon and the Pantanal are the stocks of carbon and nitrogen higher in the aboveground biomass than in the soil. In the other biomes, the largest stocks are effectively concentrated in the soils. The return of carbon to the soil through leaf fall has a much less pronounced variation among biomes. The forest systems tend to have a slightly higher transfer system in relation to herbaceous and shrub systems, but when the greater aboveground biomass contained in the forest systems is taken into consideration, the values are only minimally higher. However, the transfer of nitrogen is significantly higher in the forested systems of the Amazon and Atlantic Forest than in the herbaceous and shrub systems, such as the Cerrado and the Caatinga. Despite the large differences in soil carbon stocks, changes in the flow of CO_2 into the atmosphere tend not to be higher in certain biomes than in others, especially if the Amazon, where the CO_2 fluxes are clearly higher, is excluded (Table S3). The flux of N_2O from the soil to the atmosphere is also considered to be a loss of nitrogen from the system. In this case, the differences among the biomes are more pronounced, with the largest fluxes occurring in the Amazon, followed by the Atlantic Forest, whereas very low fluxes have been detected for the Cerrado (Table S4). In the case of Biological Nitrogen Fixation (BNF), there is no way to compare the biomes since only for a Caatinga Nitrogen input from BNF was estimated (Table S4). However, when comparing the proportion of total nitrogen derived from BNF by the legumes of the Cerrado, Caatinga and Amazonia, on average 60, 40% and 34% of the nitrogen is derived from BNF, respectively (Andrews et al. 2011). Regarding the atmospheric deposition of nitrogen, the values are similar among the biomes; in most cases, the deposition values are below those of BNF and are slightly higher compared with the N_2O flux to the atmosphere.

The most critical projection for the Amazon region is the conversion of the region to a savannah-like ecosystem. Such a profound change in the vegetation would likely cause significant losses in both soil and vegetation carbon stocks. Besides the loss of carbon, there would be other physiological and phenological changes that could result in a collapse of the Amazon rainforest, leading to the conversion of the region to a savannah-like ecosystem scenario. Such changes would be reflected not only in the carbon cycle but also in the nitrogen cycle. This scenario, however, still has many uncertainties due to the need for greater integration between the climate models and the carbon cycle models in terrestrial ecosystems. In terms of precipitation in the Amazon, the uncertainty of the forecasts also plays an important role in scenarios that might forecast the conversion of the eastern part of the Amazon to a savannah-like ecosystem.

The Atlantic Forest stocks appreciable amounts of carbon and nitrogen in its soils, especially at higher altitudes. The forecasted increases in air temperature in southeastern Brazil would lead to an increase in respiration and decomposition processes, generating an increase in losses of carbon and nitrogen to the atmosphere. The question that remains, due to a lack of information, is whether these losses would be offset by an increase in the net primary productivity of the system. In the southern grasslands of the Pampas, the soils hold a considerable stock of carbon, similar to that of the Atlantic Forest. Therefore, future forecasted temperature increases would tend to increase emissions of CO_2 to the atmosphere in this biome.

Table S3 - Carbon stocks and fluxes in major biomes.

BIOME	Stocks (Mg C ha^{-1})			LEAF LITTER (Mg C ha^{-1} yr^{-1})	CO_2 SOIL RESPIRATION (Mg C. ha^{-1} yr^{-1})	ECOSYSTEM NET EXCHANGE (Mg C. ha^{-1} yr^{-1})
	SOILS	BIOMASS ABOVE THE SOIL	BIOMASS BELOW THE SOIL			
Amazon	85–100[e]	95-250	100[e]	2-7	12-17	-0.11 a -0.5
Atlantic Forest	190 – 280[e]	90-130	20-29[a]	2,6-4	3.6	
Pantanal	11.2 –15.8[b]	7.4-100.0	36.1[d]	2.5-5.2	6.5	-1.0 a -1.3
Cerrado	72-120[e]	10-35	15[f]	1-4	6-8	-0.1 a -0.3
Caatinga	25[b]	15-25	3-6[e]	1.0-3.0	2-10	
Pampa	68[c]					

a) to a depth of 10 cm; b) to a depth of 20 cm; c) to a depth of 30 cm; d) to a depth of 40 cm; e) to a depth of 1 m; f) to a depth of 2 m.

Table S4 - Nitrogen stocks and fluxes in the main Brazilian biomes.

BIOME	Stocks (Mg N ha^{-1})			LEAF LITTER (Kg N. ha^{-1} yr^{-1})	BNF (Kg N. ha^{-1} yr^{-1})	N_2O (Kg N. ha^{-1} yr^{-1})	ATMOSPHERIC DEPOSITION (Kg N. ha^{-1} yr^{-1})
	SOIL	BIOMASS ABOVE THE SOIL	BIOMASS BELOW THE SOIL				
Amazon	1[a]	1.4-2.7	9[c]	60-180	ND	2-7	4
Atlantic Forest	14-20[c]	0.8-1.6	0.25-0.4[a]	90-170	ND	1-4	1-6
Pantanal	0.5-1.9[a]			64-208	2.6	22.2	7.3
Cerrado	4.6[e]	ND	0.1[d]	13	ND	BDL	4
Caatinga	2.5[b]	0.3-0.6	0.05-0.1[c]	20-60	3-11	ND	5
Pampa							

BLD: below the limit of detection for the measuring system; ND: not determined; a) to a depth of 10 cm; b) to a depth of 20 cm; c) to a depth of 1 m; d) to a depth of 8 m.

The balance between herbaceous and woody vegetation is an important aspect of the physiognomy of the Cerrado. Woody vegetation has more recalcitrant nutrient stocks in the form of deep roots and stems, whereas herbaceous vegetation is more readily decomposed by fire. In theory, areas where droughts last longer favour an increased incidence of fire, which, in turn, favours the emergence of herbaceous vegetation, resulting in major changes in the functioning of the Cerrado. The primary productivity of the Cerrado could potentially be reduced in the face of such a projected climate change for this biome. A temperature rise is likely to result in a reduction of the photosynthetic process in plants of the Cerrado, implying a possible reduction in their biomass. Additionally, in the dry season, the Cerrado becomes a source of carbon for the atmosphere. Therefore, an increase in the duration of the dry period also implies a reduction in the primary productivity of the Cerrado. A similar increase in the duration of the dry period could potentially bring about an increased vulnerability to fire in the Cerrado. The increased incidence of fires would then result in decreases in the biomass and the nutrient stocks due to runoff, deep erosion, particle transport, and volatilisation.

In general, there have been studies on the possible effects of climate change on water resources in Brazil. The most important watersheds in the country, according to their hydrological and ecological attributes, are those of the Amazon, Araguaia-Tocantins, Paraná, Paraguay, and São Francisco basins. These basins cut through regions that could be affected differently by changes in temperature and precipitation (i.e., rain volume and frequency), with different effects on the availability of water for human use versus the maintenance of ecological processes. Regionally, an increase in extreme events associated with the frequency and volume of precipitation is also forecasted. Across the country, the scenarios point to reduced rainfall in the winter months, as well as in the summer in the eastern Amazon and in northeastern Brazil. Likewise, the frequency of rain in northeastern Brazil and eastern Amazon (such as Pará, part of Amazonas, Tocantins, and Maranhão states) could decrease with an increasing frequency of consecutive dry days. This scenario would impose serious stress on the already-scarce water resources in the northeast. In contrast, the country could experience an increased frequency and intensity of heavy rainfall in the subtropical region (the south and southeastern regions of Brazil) and in the far western Amazon. The limited nature of available climate information in certain regions of Brazil makes it impossible to identify trends in climate and the occurrence of extremes, thus hindering the exploration of future scenarios.

SHORT AND LONG TERM ENVIRONMENTAL CHANGES: PROJECTIONS AND UNCERTAINTIES

Future climate scenarios are projections generated by climate models that take into account changes in land use or the concentrations of greenhouse gases. The latter are represented by different socioeconomic scenarios of global emissions of greenhouse gases (GHGs) proposed by the IPCC. The main results of scientific consensus for regionalised climate projections involving the different biomes in Brazil are presented below; in particular, these results consider the early (2011-2040), middle (2041-2070), and late periods (2071-2100) of the twenty-first century.

Generally, our climate projection skills are relatively more advanced in the north/northeast (Amazon and Caatinga) and southern regions (Pampas) of Brazil but relatively poorer in the midwest and southeast (Cerrado, Pantanal and Atlantic Forest). As shown in Fig. 3, the **consensus forecasts for the Brazilian biomes**, which are based on the scientific results of global and regional climate modelling, are as follows:

AMAZON A 10% decrease in rainfall distribution and a temperature increase of 1-1.5 °C by 2040, maintaining the downward trend by -25% to -30% in rainfall and the temperature increase from 3-3.5 °C in the period between 2041-2070; at the end of the century (2071-2100), the changes are more substantial, with significantly less rain (reduced by -40% to -45% in the rainy season) and significantly hotter temperatures (increased by 5-6 °C). Such changes in climate, when associated with global changes, may jeopardise the Amazon rainforest biome in the long run (by the end of this century). Nevertheless, only changes in the concentration of greenhouse gases were considered for these projections, which also failed to consider **deforestation**. Resulting from intensive land use activities, the issue of deforestation represents a more immediate threat to the Amazon. In this context, we emphasise that Brazil already has an efficient system for monitoring deforestation in the Amazon, operated by the National Institute for Space Research (INPE), which uses advanced remote sensing systems to quantify the deforested area in the Amazon in real time and on an integration scale of one year. The success that Brazil has had in reducing its deforested area represents an important breakthrough for the country. In 2004, an area of approximately 27,000 km^2 was deforested in the Amazon. In 2011, the deforested area was reduced to approximately 6,200 km^2. There are disagreements about which public policies are most effective for considerably reducing deforestation in the Amazon, and consequently, for reducing the emissions of greenhouse gases as a result of deforestation in Brazil. However, Brazil's success in this area is undeniable and the question of how the continued reduction of the deforested area can be maintained is important, in part to insure that Brazil achieves its targets for reducing emissions of greenhouse gases, which have been officially admitted and disclosed to the international community. Numerical modelling studies have suggested that if deforestation reaches 40% in the region, drastic changes will likely occur in the hydrological cycle, with a 40% reduction in rainfall during the months from July to November, which would prolong the duration of the dry season in addition to causing an increase of 4 °C in surface temperatures. Thus, when the regional changes due to the effects of deforestation are combined with those of global change, they indicate conditions that are conducive for the prevalence of Cerrado vegetation. The potential for the "savannisation" of the Amazon tends to be more critical in the eastern region.

CAATINGA An increase of 0.5-1 °C in air temperature and a decrease between -10% and -20% in rainfall are expected during the next three decades (until 2040), with gradual increases in temperature from 1.5-2.5 °C and decreases between -25% and -35% in rainfall patterns over the period from 2041-2070. At the end of the century (2071-2100), the projections indicate significantly warmer conditions (temperature increases from 3.5-4.5 °C) and worsening of the regional water deficit, with a reduction of almost half (-40 to -50%) of the rainfall distribution.

CERRADO Over the next three decades (until 2040), an increase of 1 °C in air temperature is forecast, with a decrease of -10% to -20% in precipitation. By mid-century (2041-2070), the air temperature is expected to increase by 3-3.5 °C, and a reduction in rainfall of -20% and -35% is expected. At the end of the century (2071-2100), the predicted temperature elevation reaches values from 5-5.5 °C, and the decrease in rainfall distribution is more critical, with a decrease between -35% and -45%.

PANTANAL An increase of 1 °C in temperature and a decrease in rainfall patterns between -5% and -15% are expected by 2040, maintaining the trend of reduced rainfall values between -10% and -25% and a temperature increase of 2.5-3 °C by mid-century (2041-2070). At the end of the century (2071-2100), there will be a predominance of intense heating (temperature increase by 3.5-4.5 °C), with a marked decrease in rainfall patterns of from -35% to -45%.

ATLANTIC FOREST Because this biome covers areas from the south to the southwest to the northeast of Brazil, the forecasts indicate two distinct regimes. Northeast Portion (NE): A relatively low temperature increase of 0.5-1 °C and a decrease in rainfall of approximately -10% are predicted by 2040, with the warming trend maintained from 2-3 °C and rainfall decreased to between -20% and -25% by mid-century (2041-2070). Towards the end of the century (2071-2100), conditions of intense heat are expected (an increase of 3-4 °C) and a decrease of between -30% and -35% in regional rainfall patterns. South/Southeast Portion (S/SE): By 2040, projections indicate relatively low increases in temperature from 0.5-1 °C, with an approximate 5% to 10% increase in rainfall patterns. In the middle of the century (2041-2070), the trends of gradual temperature increases of 1.5-2 °C will continue, as well as a 15% to 20% increase in rainfall, and these trends are increased at the end of the century (2071-2100) with climate patterns that are 2.5-3 °C warmer and with 25% to 30% more rain.

PAMPAS In the period up to 2040, prevailing regional climate conditions are forecast to be between 5% to 10% wetter and 1 °C warmer, and the warming trend is expected to continue with temperature increases from 1-1.5 °C and rainfall increased by between 15% and 20% by mid-century (2041-2070). At the end of the century (2071-2100), the projections are more severe, with an increase in temperature of 2.5-3 °C and rainfall that is 35% to 40% above normal.

Due to the high degree of vulnerability of the northern and northeastern regions of Brazil, it is noteworthy that the most troubling projections for the end of the century are for the Amazon and Caatinga, whose warming air temperature trends and decreases in regional rain patterns would be greater than the overall average variation. In terms of attributing physical causes, it is suggested that this climate-related reduction in rainfall is associated with changes in the patterns of general atmospheric circulation. More specifically, the anomalously warm tropical oceans over the Pacific and Atlantic, which are expected in a future scenario of global warming, may affect the pressure gradient between the continent and the ocean, thereby modifying the system of global (Hadley and Walker cells) and regional winds (low-level jets east of the Andes). These pressure gradient changes would induce a reduction in the transport of moisture to the mainland, with a prevalence of downward atmospheric circulation over the tropical regions of Brazil, inhibiting the formation of convective clouds and explaining conditions of rainfall predicted to be well below normal.

Fig. 3

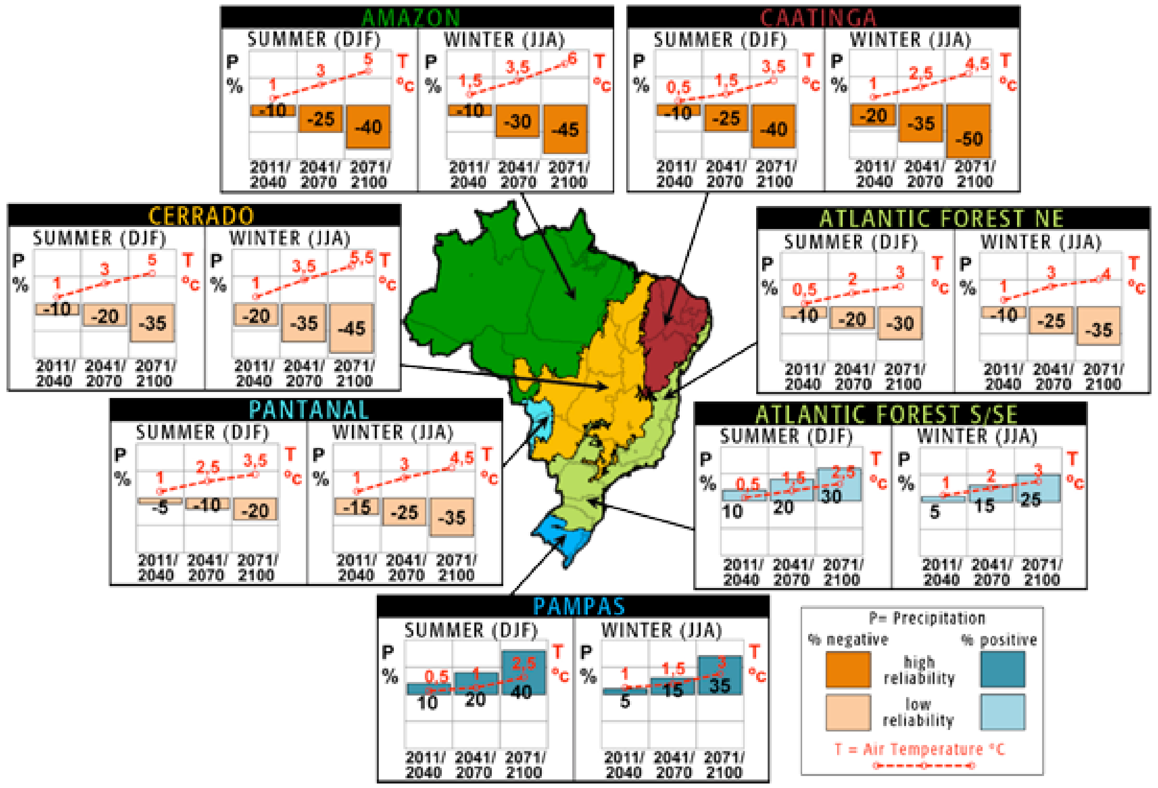

Fig 3: Regionalised climate projections in the Amazon, Cerrado, Caatinga, Pantanal, Atlantic Forest (northeast and south/southeast areas), and Pampas biomes for the early (2011-2040), middle (2041-2070), and late (2071-2100) twenty-first century, based on the scientific results of global and regional climate modelling. The regions with different colours on the map indicate the geographical areas of the biomes. The legend is at the bottom right corner. Source of information: CCST INPE.

The last decade has been marked by substantial improvements in the development of Earth system modelling approaches, with the introduction of more complete formulations of physical, chemical, and biological processes, including their complex interactions. These theoretical advances have been systematically incorporated into models of the global climate system, which have been facilitated by significant technological advances in computer simulation.

Still, it appears that the environmental and climate projections generated by climate modelling bring different levels of uncertainty, whose major categories are as follows:

Uncertainty about emissions scenarios: Global emissions of GHGs are difficult to predict because of the complexity of socioeconomic factors, such as demographics, the composition of the sources of power generation, land use activities, and the overall direction of human development; **Uncertainty about the natural variability of the climate system**: The physical and chemical processes of the global atmosphere are chaotic in nature, so the weather can be sensitive to minor changes (non-linear variations), which are difficult to measure both in observational data and in models; and **Uncertainties related to the models**: The ability to model the global climate system is a major challenge for the scientific community, and the limiting factors include the incomplete representation of several processes, such as global and regional carbon balances, the role of aerosols in global energy, the representation of biogeochemical cycles, anthropogenic factors in the ocean and atmosphere, and the role of fire and biomass burning. Conversely, even though the same emissions scenarios are used, different models produce different projections of climate change, thus providing another source of uncertainty, which can be evaluated by the application of ensembles of global and regional models.

In general, the results of the models tend to capture the behaviour of the present climate well (20th century), and thus, despite the uncertainties, the projections of future climate change over the twenty-first century are plausible. Therefore, such projections constitute innovative and valuable information for mitigation purposes, such as the planning of adaptation actions and the mitigation of impacts and vulnerability for the societies living in the various Brazilian biomes. Taking into account the different projections that imply potential impacts on natural and human systems (socio-economic and environmental), it is possible to analyse the expected impacts of climate change on various sectors of Brazil and to plan and make decisions to define adaptation strategies and mitigation policies.

The best available scientific tool for the generation of detailed projections of environmental change is dynamic downscaling (regionalisation), a technique that consists of using a regional climate model nested in a global climate model. This methodology provides greater detail of the climate scenarios provided by global models, which generally have low spatial resolution and lower computational cost. Several dynamic downscaling activities have been developed in Brazil and South America over the past 5 years. The first experiments used three regional models (HadRM3P, Eta, and RegCM3-CCS), the simulations of which were performed with the same boundary conditions as the global model HadAM3P from the UK, and generated the current climate scenarios and projections of future climate over South America (SA); however, these projections of the future climate were focused only on the end of this century (2071-2100) (Marengo et al., 2010). More recent experiments have been conducted with an enhanced version of the Eta regional model, which was developed in Brazil, using the boundary conditions from the global model HadCM3 for the period of 2010-2100 (Marengo et al., 2011b). The results of this work have been used in studies of sector impacts and vulnerability to climate change in Brazil. The authors point out, however, that the projections of these models differ in the regions where the greatest warming is projected to occur (above 8 °C); for example, maximum temperatures could be located both in the eastern Amazon and in the western Amazon, depending on the regional model used. According to these authors, the greatest uncertainties are associated with numerical projections of changes in rainfall. In this regard, current developments in climate modelling and environmental monitoring emerge as privileged strategies that may enable a better understanding of these uncertainties and thus the potential ability to reduce them.

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