

Chapter 15

Future Climate Change in the Caatinga

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Abstract This chapter discusses the general aspects of climate variability and climate change in South America, with a special focus on Brazil's northeast region in which the Caatinga is located. It describes the main findings reported in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC AR5), and provides a brief review of the literature addressing climate change in northeast Brazil. In addition, simulations and projections of temperature and precipitation changes provided by 24 state-of-the-art Earth System Models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset that were analyzed in the IPCC AR5 are assessed. For scenarios of future projections, the near surface air temperature should increase by at least 1 °C for the Representative Concentration Pathways (RCP) 2.6 (low radiative forcing scenario) and by 4 °C for the RCP8.5 (high radiative forcing scenario) by the end of the twenty-first century. For the Caatinga, there is a considerable spread amongst rainfall change projections of ± 1 mm day⁻¹, relative to 1961–1990, making it hard to identify any tendency in projected rainfall change. However, the RCP8.5 forcing scenario shows a slight rainfall reduction of about 0.3 mm day⁻¹ by 2100. Among the most affected regions in Brazil, the Amazon and northeast regions appear to be large hotspots. For some modeling studies, projections of the future climate show a savannization of parts of the Amazon and desertification of the Caatinga region, with potential adverse impacts on biodiversity, supply and quality of water resources, carbon storage, and the provision of other ecosystem services.

Keywords Climate change • Northeast Brazil • Caatinga • Drought • Vulnerability • Impacts

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15.1 Introduction

Earth's climate shows variabilities in almost all time scales, from the annual to the multi-decadal scale. In some of these scales, climate variability is due to the intrinsically random nature of processes or due to numerous and complex causes (often unknown or poorly understood scientifically) that make it difficult to forecast (Giorgi 2005). Therefore, the use of climate information is frequently based on statistical analysis of historical series of observed climate variables (Barros et al. 2006).

Several decades ago, the use of climate information was based on the hypothesis that the climate was stationary, at least in the decadal scale, and thus future climatic conditions could be predicted only using a robust series of observed data in previous decades (Barros et al. 2006). However, this hypothesis of climate stationarity is no longer accepted by the scientific community given abundant evidence that human activities have contributed to a rapid change in known climatic patterns (IPCC 2007, 2013).

In this context, the term 'climate change' refers to a change in the state of the climate locally or globally, which can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties (e.g., rainfall, temperature, wind), and that persists for an extended period, typically decades or longer (Giorgi 2005; IPCC 2007). Climate change may be due to natural internal processes of the climate system¹ (e.g., the occurrence of El Niño/La Niña events in the seasonal to interannual time scale) or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (Glossary of Intergovernmental Panel on Climate Change Fourth Assessment Report [IPCC AR4] [IPCC 2007]).

Since its formation about 4.6 billion years ago, Earth's climate has undergone numerous changes due to the natural variability of the climate system. These natural changes occurred mainly as a result of the following external forcings:

- Changes in the structure and composition of the Earth's atmosphere during its formation
- Continental drift
- Variations in eccentricity, axial tilt, and precession of Earth's orbit (Milankovitch cycles)
- Volcanic eruptions, which cause the release of particles into the atmosphere (especially aerosols) that can be suspended for up to several months at higher levels of the atmosphere

These factors, which are cyclic in most cases, change the radiation balance in the climate system and cause large changes in the temperature of the planet (IPCC

¹The 'climate system' consists of five major components that interact with each other: the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. The climate system changes over time because of the influence of its own internal dynamics and because of natural and anthropogenic external forcings.

2007). However, except for volcanic eruptions, these changes occur on a scale of thousands of years, which is too slow to be perceived in the lives of human beings. For this reason, the changes in climate that scientists have observed in recent decades (and which are included in the various reports of the Intergovernmental Panel on Climate Change [IPCC]) are more intense and faster than those observed for any known natural factor (IPCC 2007, 2013).

On the other hand, other external forcings that can also significantly contribute to a change in climate are those arising from human activities, such as changes in the composition of the atmosphere and land use changes,² which occur on time scales compatible with those abrupt changes observed in Earth's climate in recent decades (Meehl et al. 2007). These forcings are primarily responsible for the so-called 'greenhouse effect.' This term has been used since the nineteenth century to refer to a natural phenomenon associated with the property that some gases in the atmosphere (greenhouse gases [GHGs]) absorb and isotropically re-emit the long-wave radiation (specifically, thermal infrared radiation) emitted by Earth's surface (Meehl et al. 2007; IPCC 2007). Part of this radiation is directed back to the surface and lower levels of the atmosphere, resulting in a temperature rise of Earth's surface and the surrounding air.

GHGs are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor (H₂O), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and ozone (O₃) are the primary GHGs in the Earth's atmosphere (Glossary of IPCC AR4, [IPCC 2007]).

However, the greenhouse effect is essential to Earth. Without it, life on Earth would not be possible, because without this, the mean temperature near the surface would be about -19 °C, in contrast to the +15 °C observed (IPCC 2007). Therefore, GHGs are critical to maintaining the planet being able to house all living beings. However, in recent decades, the greenhouse effect has taken on a negative connotation, being associated with climate change and global warming. This is due to the fact that with the intense and growing GHG emissions resulting from human activities, the greenhouse effect has intensified so that a larger amount of radiation is trapped in the lower layers of the atmosphere, and, hence, the temperature of the planet increases and some changes in Earth's climate occur.

Since the industrial revolution, the concentration of GHGs has increased remarkably in the atmosphere. For example, the concentration of CO₂ increased by over

² 'Land use' refers to the total of arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The term 'land use' is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation). 'Land use change' refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land use change may have an impact on the surface albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus have a radiative forcing and/or other impacts on climate, locally or globally (Glossary of IPCC AR4 [IPCC 2007]).

35%, while the concentration of CH₄ increased by more than 2.5 times (IPCC 2007). The global increase in CO₂ concentration is mainly due to the use of fossil fuels and land use change, while the increase in CH₄ and N₂O concentrations is due primarily to agricultural and livestock practices (IPCC 2007).

The distinction between the effects caused by various external forcings and the natural variability of the climate system requires a careful comparison between the changes observed and those expected as a result of certain forcings. The studies that address this issue are known as ‘detection and attribution of climate change’ studies; they are based on thorough physical understanding of the mechanisms and feedbacks that govern the climate system and use a statistically complex and cautious treatment of the observed data (Hegerl et al. 2007; Stott et al. 2010).

Since the innumerable processes occurring in the climate system cannot be accurately reproduced in a laboratory experiment, scientists use numerical models known as climate models or Earth System Models (ESMs) to understand the possible responses and behaviors of this system when submitted to certain forcings, as well as to project the climate in the coming decades and centuries (Giorgi 2005). A climate model consists of a huge system of discretized differential equations of high complexity (transformed into a computer code containing thousands of command lines and subroutines) representing, among other things, the physical, chemical, and biological laws that govern the behavior of the climate system components (ocean, atmosphere, biosphere, etc.) and their interactions.

When the climate system is highly complex and has many processes that are still unknown or poorly understood by scientists (Giorgi 2005), climate models are approximate representations of this system. However, climate models are gradually evolving with the emergence of new scientific discoveries and new methods of analysis and measurement. This evolution can be observed, for example, through the five generations of climate models belonging to the Coupled Model Intercomparison Project [CMIP] (<http://cmip-pcmdi.llnl.gov>).

However, even though climate models are approximations of the climate system, the extent to which a model is able to reproduce the main features and the variability of the observed climate increases our confidence that this model can project future changes in climate (Torres and Marengo 2013, 2014). Moreover, despite the complexity involved in the simulation of the climate system, in large spatial scales and decadal and longer time scales it is expected that it will be possible to simulate the climate with reasonable reliability (Knutti 2008).

With the advancement of studies on climate change in recent years, the vast majority of climate scientists around the world take the fact that human activities are primarily responsible for observed climate changes for granted (IPCC 2007, 2012, 2013). Such changes are known as anthropogenic climate changes. The influence of humans in modifying both the composition of the atmosphere and the land surface of the continents during the last centuries has become so marked that some scien-

tists have established a new geological era up to the present day known as ‘Anthropocene’, a term coined by the winner of the Nobel Prize in Chemistry in 1995, Paul Crutzen.

In order to better understand and try to project the climate in the coming decades, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the IPCC in 1988. The IPCC consists of a group of hundreds of scientists from different countries around the world who meet periodically to discuss the latest research and discoveries about climate change. During these meetings, the scientists assess the current knowledge on climate change and prepare technical reports on possible impacts of climate change on humans and the planet’s biodiversity in order to assist policy- and decision-makers in the design of adaptive and sustainable measures for countries.

According to the information contained in the IPCC Fifth Assessment Report (IPCC AR5) published in 2013, scientists conclude that the warming of the climate system is unequivocal, and many of the observed changes since the 1950s are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the snow and ice have diminished, the sea level has risen, and the concentrations of GHGs have increased (IPCC 2013). Additionally, scientists conclude that it is very likely that emissions of anthropogenic GHGs affected the Earth’s climate in the twentieth century and will continue to cause further warming and changes even more markedly in this century.

The global mean surface temperature over the last 100 years increased by approximately 0.7 °C, with most of that increase situated in the latter half of the twentieth century following the large increase in anthropogenic emissions during this period. According to climate projections for 2081–2100 relative to 1986–2005 contained in the IPCC AR5, the increase in global mean temperature is likely to be in the range of between 1 °C and 4 °C, accompanied by an increase of precipitation of around 2–6%. Moreover, these projections also indicate that most of these changes in temperature and precipitation around the world will be accompanied by more frequent extreme events such as heat waves, droughts, and heavy rains, which will cause numerous impacts on populations around the world (IPCC 2013).

Following the general context of climate change given already, Sect. 15.2 presents current climate simulations of near surface air temperature and rainfall over the Caatinga region produced by innumerable state-of-the-art ESMs. Climate simulations of precipitation and temperature are evaluated against observations to provide a measure of reliability of climate change projections and related uncertainties. Section 15.3 shows temperature and precipitation change projections covering the entire twenty-first century over the Caatinga region, as well as trends in climate extremes in the region. Finally, Sect. 15.4 presents some concluding remarks.

15.2 Present Climate Simulations Over the Caatinga Region by Earth System Models

As stated in the previous section, the current climate change projections are based exclusively on the use of climate models or ESMs, such as those belonging to the CMIP Phase 5 (CMIP5) dataset, the results of which are presented in this chapter (Table 15.1). Despite the continuous improvement of these models and the enormous growth in computing power in recent decades which enabled scientists to include numerous physical and dynamic processes and increased the spatial and temporal resolution with which they are set, the models are still being processed with spatial low resolution (of the order of hundreds of kilometers) and inadequate physical parameterizations (in part because of the difficulty of representation of some physical and dynamical processes in a low spatial scale, but also due to the

Table 15.1 List of models, approximate model horizontal resolutions, future (Representative Concentration Pathways [RCPs] 2.6, 4.5, 6.0, 8.5) and historical simulations, and number of runs in the Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset used in this chapter

Models	Resolution (latitude/longitude)	Historical	RCP			
			2.6	4.5	6.0	8.5
FGOALS-g2	$3.1^\circ \times 2.8^\circ$	4	1	1	–	1
BCC-CSM1-1	$2.8^\circ \times 2.8^\circ$	3	1	1	1	1
CanESM2	$2.8^\circ \times 2.8^\circ$	5	5	5	–	5
MIROC-ESM	$2.8^\circ \times 2.8^\circ$	3	1	1	1	1
FIO-ESM	$2.8^\circ \times 2.8^\circ$	1	1	1	1	1
MIROC-ESM-CHEM	$2.8^\circ \times 2.8^\circ$	1	1	1	1	1
GFDL-CM3	$2.0^\circ \times 2.5^\circ$	5	1	1	1	1
GFDL-ESM2G	$2.0^\circ \times 2.5^\circ$	1	1	1	1	–
Giss-E2-R	$2.0^\circ \times 2.5^\circ$	5	1	5	1	1
GFDL-ESM2M	$2.0^\circ \times 2.5^\circ$	1	1	1	1	1
IPSL-CM5A-LR	$1.9^\circ \times 3.8^\circ$	4	1	3	1	3
NorESM1-M	$1.9^\circ \times 2.5^\circ$	3	1	1	1	1
CSIRO-Mk3-6-0	$1.9^\circ \times 1.9^\circ$	10	10	10	10	10
MPI-ESM-LR	$1.9^\circ \times 1.9^\circ$	3	3	3	–	3
INMCM4	$1.5^\circ \times 2.0^\circ$	1	–	1	–	1
CNRM-CM5	$1.4^\circ \times 1.4^\circ$	1	1	1	–	1
MIROC5	$1.4^\circ \times 1.4^\circ$	1	1	1	1	1
IPSL-CM5A-MR	$1.3^\circ \times 2.5^\circ$	1	1	1	–	1
HadGEM2-CC	$1.3^\circ \times 1.9^\circ$	1	–	1	–	1
HadGEM2-ES	$1.3^\circ \times 1.9^\circ$	4	1	1	1	4
ACCESS1.0	$1.3^\circ \times 1.9^\circ$	1	–	1	–	1
EC-EARTH	$1.1^\circ \times 1.1^\circ$	1	1	1	–	1
MRI-CGCM3	$1.1^\circ \times 1.1^\circ$	5	1	1	1	1
CCSM4	$0.9^\circ \times 1.3^\circ$	6	5	5	5	5

Models are ranked by their spatial resolution (as used in Torres and Marengo 2014)

still inadequate knowledge of the processes involved such as cloud parameterization) (Giorgi 2005; Collins 2007; Räisänen 2007; Tebaldi and Knutti 2007; Annan and Hargreaves 2010; Knutti et al. 2010, 2013). Thus, the ESMs do not have a perfect representation of the current climate and do not allow for a refined spatial analysis of climate change projections, essential in studies of impact, adaptation, and vulnerability.

Therefore, given the above-mentioned problems, the first step to evaluating the climate projections in a certain region is to evaluate how climate models are representing at least the basic characteristics of the current climate in this region. Thus, this section assesses how climate models represent the climate of northeastern Brazil where the Caatinga is located.

Specifically, temperature and precipitation variables provided by 24 state-of-the-art ESMs (representing nearly 450 runs, Table 15.1) from the CMIP5 dataset (Taylor et al. 2012) that were analyzed in the IPCC AR5 are assessed. The CMIP5 climate simulations and projections analyzed in this chapter were provided by the Program for Climate Model Diagnosis and Intercomparison (PCMDI; <http://www-pcmdi.llnl.gov>). Simulations for the twentieth century are compared against the observed surface air temperature and precipitation from the CRU TS 3.0 dataset (Mitchell and Jones 2005) produced by the University of East Anglia Climate Research Unit (UEA/CRU). Hereafter, the term ‘simulation’ refers to those numerical experiments with ESMs performed to observed climate periods (e.g., 1901–2000), and the term ‘projection’ refers to those experiments relating to future periods (e.g., 2020–2100) carried out by a given climate forcing. Moreover, changes refer to the difference between the mean values of the climate variables projected for the period 2071–2100 (‘future climate’) and simulated for 1961–1990 (‘present-day’ climate). Additionally, climate simulations and projections are evaluated at seasonal means as follows: austral summer (December to February [DJF]), fall (March to May [MAM]), winter (June to August [JJA]), and spring (September to November [SON]).

The CMIP5 climate projections are performed using the new generation of radiative forcing³ scenarios called Representative Concentration Pathways (RCP) (Moss et al. 2010), and denominated as RCP 2.6, 4.5, 6.0, and 8.5, corresponding to an approximate radiative forcing by the end of the century of 2.6, 4.5, 6.0, and 8.5 Wm^{-2} , respectively, relative to pre-industrial conditions. With regard to the equivalent CO_2 concentrations, these RCPs correspond roughly to 490, 650, 850, and 1370 ppm, respectively, in 2100. Further details of the RCPs can be found, for example, in Moss et al. (2010) and van Vuuren et al. (2011).

Compared to the previous generation of climate models belonging to the CMIP Phase 3 (CMIP3) dataset, CMIP5 ESMs show slightly higher horizontal resolutions (approximately 1–3 ° of latitude/longitude) and also includes ESMs and experi-

³Radiative forcing is the change in the net, downward minus upward, irradiance (expressed in W m^{-2}) at the tropopause (boundary between the troposphere and the stratosphere) due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun (Glossary of IPCC AR4 [IPCC 2007]).

ments that are more comprehensive (e.g., including carbon cycle or decadal climate predictability experiments), which allows scientists to explore a broader spectrum of scientific questions. Moreover, some of the main improvements in the CMIP5 ESMs are the addition of interactive ocean and land carbon cycles of varying degrees of complexity, and the more complete representation of radiative forcings due to, among other things, the inclusion of more comprehensive modelling of the indirect effect of aerosols and the use of time-evolving volcanic and solar forcing in most models (Taylor et al. 2012; Knutti and Sedláček 2013; Sillmann et al. 2013a).

Northeast Brazil (NEB) has a total area of about 1.5 million km² and most of this region has a semiarid climate due to the prevailing rainfall regime (Torres and Ferreira 2011). However, while portions of the inland dry regions receive less than 600 mm of rainfall annually, the east coast receives around 2000 mm (Kousky and Chu 1978; Rao et al. 1993).

It is possible to identify different rainfall patterns in NEB. In the northern part of this region, the main rainy season occurs from March to April; in the south, the rainy season is observed from December to February; and on the east coast it occurs from May to July (Strang 1972; Rao et al. 1993). Moreover, there are regions with superimposed periods of maximum rainfall, such as the central and northeastern parts of the state of Bahia, where the maximum observed rainfall occurs from December to March, and the coastal part of Bahia, where the maximum occurs from December to May (Strang 1972; Kousky and Chu 1978). The spatial variability of annual rainfall is also high in NEB (Rao et al. 1993).

The maximum rainfall amount observed during the March–April period in northern NEB can be attributed to the latitudinal displacement of the intertropical convergence zone⁴ (ITCZ), which reaches its southernmost position during these months (Hastenrath and Heller 1977). The observed maximum during November–December in the southern part of the region can be attributed to frontal systems that reach low latitudes and interact with convective activity from the Amazon Basin or from the northern coast of Brazil (Kousky 1979). Several attempts have been made to explain the rainfall maximum in autumn and winter along the east coast of NEB. Yamazaki and Rao (1977) emphasized the importance of westward-propagating cloud systems, as detected in satellite images over the Atlantic Ocean. Kousky (1979) showed that rainfall in eastern NEB is influenced by breeze circulations, mainly during the night. Kousky (1979) attributed the nocturnal maximum to the formation of a convergence zone between the land breeze and the background wind field. He also noted that the land breeze is strongest during autumn and winter, when the temperature contrast between land and sea is higher than normal. Studies such as Rao et al. (1993) indicate that the position and intensity of the South Atlantic subtropical high is an important mechanism for the low-level transport of water vapor toward NEB. Torres and Ferreira (2011) identified the occurrence of easterly wave distur-

⁴The ITCZ (intertropical convergence zone) is the area encircling the Earth near the equator which represents the junction between the southeast and the northeast trades (of the Southern and Northern Hemispheres, respectively). The ITCZ appears as a band of clouds that circle the globe near the equator.

bances in the wind field, which propagated westward over the tropical South Atlantic Ocean during the austral autumn and winter. When these disturbances interact with local circulations, low-level convergence increases, causing strong rainfall on the eastern and northern NEB coasts.

Figure 15.1a–j shows the seasonal and annual precipitation observed and simulated over the Caatinga region from the average of all CMIP5 ESMs listed in Table 15.1 for the period 1961–1990. In general, the ensemble mean represents the observed climatological patterns of precipitation over the Caatinga well. However, some biases can be observed in some localities (Fig. 15.1k–o). For example, rainfall simulations show a wet bias (up to 4 mm day^{-1}) over the most of the region in austral summer and fall, but a very slight ($<1 \text{ mm day}^{-1}$) wet or dry bias in austral winter and spring.

With respect to the simulation of the near surface air temperature, the average of the ensemble is very similar to the patterns observed (Fig. 15.2a–j) and the bias does

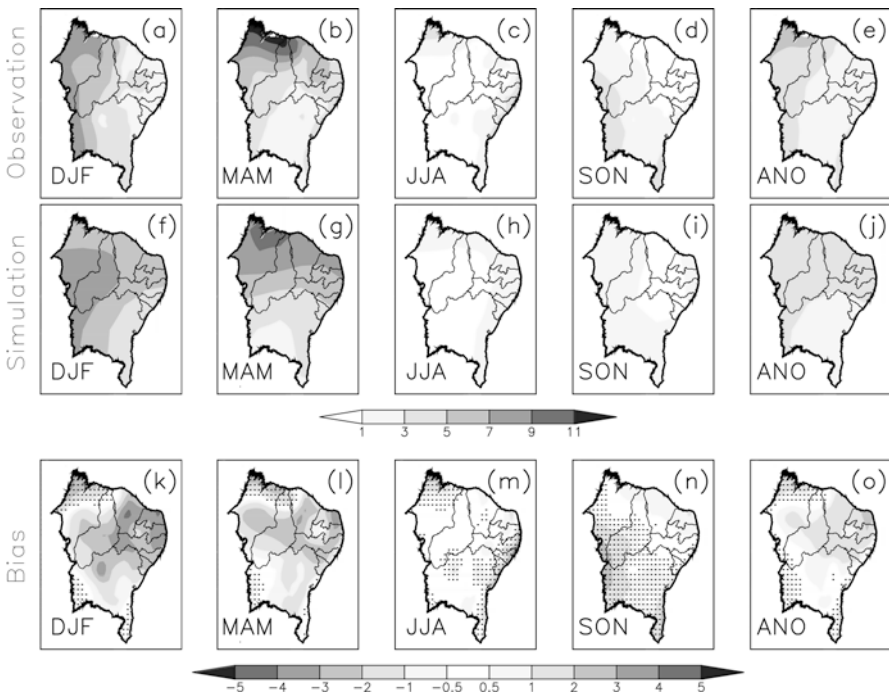


Fig. 15.1 Seasonal and annual mean precipitation from observations (a–e) and from the ensemble mean of climate models simulations (f–j) for northeast Brazil for the reference period 1961–1990. Bias (k–o) is defined as model minus observation. Dots indicate negative values. Climate simulations were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models listed in Table 15.1, and observations from the Climate Research Unit dataset (CRU 3.0 dataset; Mitchell and Jones 2005). Results are shown for the austral summer, fall, winter and spring (December to February [DJF], March to May [MAM], June to August [JJA], and September to November [SON], respectively) and annual mean (ANO). Values are in mm day^{-1} (Adapted from Marengo et al. 2016)

not exceed 1 °C in most of the region (Fig. 15.2k–o). On the other hand, the ensemble mean shows a cold bias (1–3 °C) in some parts of the Caatinga region from austral summer to winter.

The annual cycles of rainfall and temperature for the present climate are reasonable well-simulated by the ensemble mean of the ESMs, although different performances can be noticed when evaluating the individual models (Fig. 15.3). The timing of the February–April peak of the rainy season is well-depicted by the models (Fig. 15.3a), albeit with some models underestimating or overestimating the observed rainfall. The mean observed peak of the rainy season from CRU varies from 5 to 6 mm/day, while the ensemble models show 6–7 mm/day. With regard to temperature (Fig. 15.3b), the models tend to overestimate the amplitude of the annual cycle and underestimate temperatures during summer to spring (by <1 °C).

The aforementioned deficiencies in the simulation of climate conditions in the region (represented here by precipitation and temperature) may be related to numer-

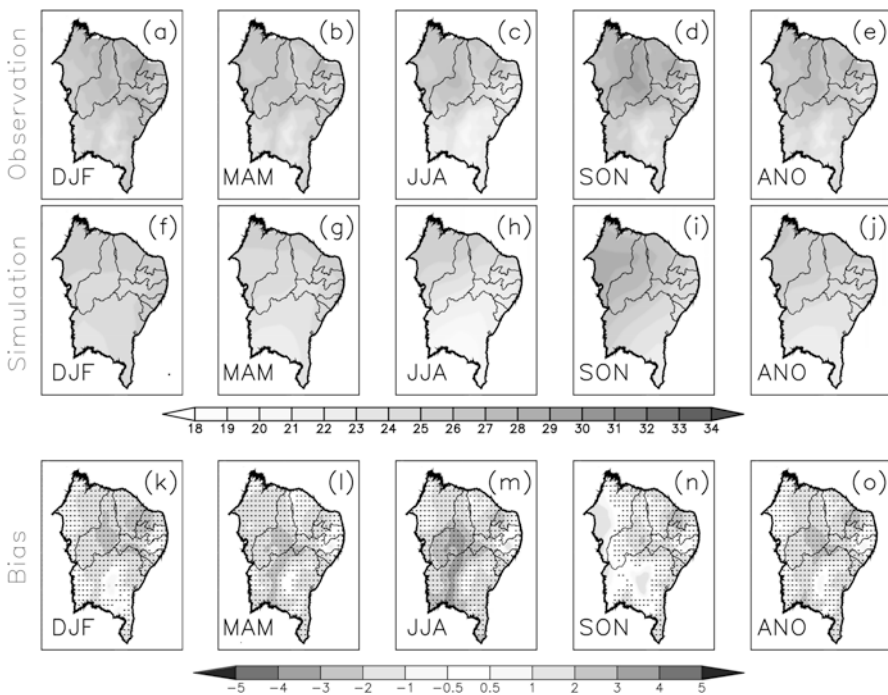


Fig. 15.2 Seasonal and annual near surface air temperature from observations (a–e) and from the ensemble mean of climate models simulations (f–j) for Northeast Brazil for the reference period 1961–1990. Bias (k–o) is defined as model minus observation. Dots indicate negative values. Climate simulations were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models listed in Table 15.1, and observations from the Climate Research Unit dataset (CRU 3.0 dataset; Mitchell and Jones 2005). Results are shown for the austral summer, fall, winter and spring (December to February [DJF], March to May [MAM], June to August [JJA], and September to November [SON], respectively) and annual mean (ANO). Values are in degree symbol missing, kindly insert in superscript position °C (Adapted from Marengo et al. 2016)

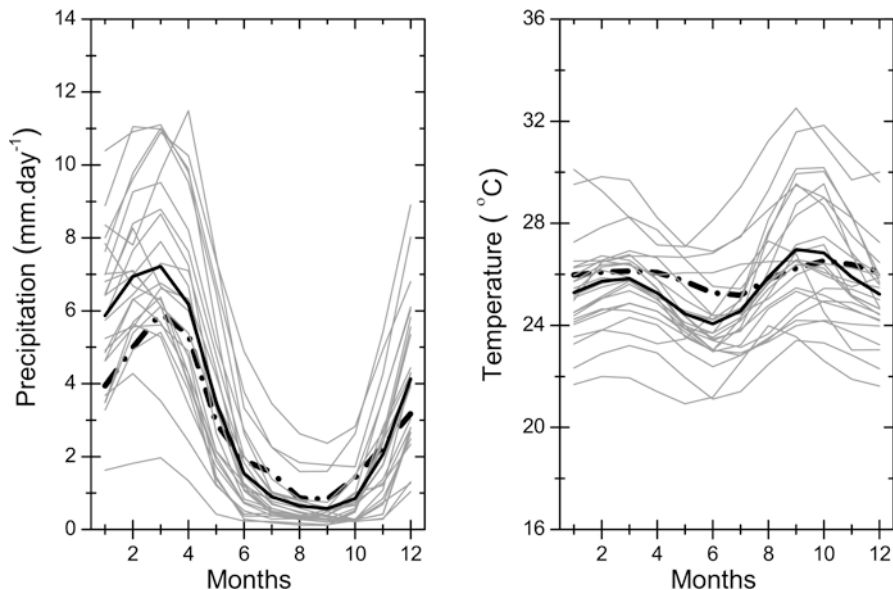


Fig. 15.3 Observed and simulated seasonal cycle of precipitation (left panel) and temperature (right panel) in the Caatinga region for the reference period 1961–1990. Climate simulations were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models listed in Table 15.1, and observations from the Climate Research Unit dataset (CRU 3.0 dataset; Mitchell and Jones 2005). In each one of the panels the thick black lines represent the ensemble model mean, the thick dash dot lines represent observations, and individual models are shown using thin lines. Values for precipitation and temperature are in mm day^{-1} and $^{\circ}\text{C}$, respectively

ous factors, among which can be highlighted: (i) horizontal resolution of ESMs is still rough and does not allow a more refined detail of the topography of the region; (ii) deficiencies in the cloud parameterization schemes; (iii) deficiencies of ESMs in properly representing the water vapor transport and moisture convergence over the region; and (iv) poor representation of biosphere–atmosphere interactions, soil moisture, and other processes in the planetary boundary layer. On the other hand, there is a large deficiency in the spatial and temporal coverage of observed data over South America, which must certainly influence the magnitude and location of the bias patterns, mainly for precipitation.

Therefore, despite the bias presented by the simulations of precipitation and temperature for the models analyzed, it can be concluded that the models could represent reasonably well the observed climatic conditions over the Caatinga region, given the complexity involved in these simulations. Therefore, these results give us good reliability for use in evaluating the projections of climate change presented in Sect. 15.3.

15.3 Climate Change Projections in South America

Several studies have identified South America as one of the regions in the world that may be deeply affected if current climate change projections are realized, especially in the tropical region of the continent (e.g., Baettig et al. 2007; IPCC 2007, 2013; Torres et al. 2012; Sillmann et al. 2013a, b; Torres and Marengo 2014). The region is vulnerable to current climate variability and extremes, mainly in the form of intense rain and floods or dry spells, and may be affected by more frequent extremes in a warmer climate (Marengo et al. 2010a, b; Rusticucci et al. 2010).

In particular, current climatic projections indicate that considerable changes may occur in the climate of Brazil during the twenty-first century (Torres and Marengo 2014; Magrin et al. 2014). Considering that in Brazil the production of food, commodities, and energy is highly dependent on climate and that a considerable part of the population is in a socially vulnerable situation (i.e., with overall low human development levels and/or living in risky areas), it is expected that climate change will likely have strong negative social impacts (Magrin et al. 2014; Darela-Filho et al. 2016). Examples of climate-driven high social and economic costs are evident in the severe drought of 2013–2015 that negatively affected water availability in large cities in southeast Brazil (Coutinho et al. 2015) and caused relentless suffering in NEB (Lindoso et al. 2014). However, while climate change mitigation has been on the agenda of the Brazilian Government for several years (IPEA 2011), effective long-term adaptation planning has lagged. This reinforces the importance of the discussion of this issue in Brazilian society so that adaptation measures for vulnerability reduction should be taken as soon as possible to avoid greater losses.

In recent years, numerous studies have examined the projections of climate change in South America, relying mainly on climate models from the CMIP3 and CMIP5 dataset (e.g., Boulanger et al. 2006, 2007; Vera et al. 2006; Vera and Silvestri 2009; Bombardi and Carvalho 2009; Seth et al. 2010; Junquas et al. 2012; IPCC 2007, 2013; Blázquez and Nuñez 2013; Joetzjer et al. 2013; Jones and Carvalho 2013; Torres and Marengo 2014). Several studies also analyzed the climate projections in the region using some downscaling methods in the results of ESMs (e.g., Nuñez et al. 2008; Urrutia and Vuille 2009; Boulanger et al. 2010; Marengo et al. 2009, 2010a, 2012; Bidegain et al. 2012; Chou et al. 2012). In general, the projections shown in those studies are in agreement with those shown in IPCC AR5 (IPCC 2013).

According to the results presented in IPCC AR5 (IPCC 2013), warming has been detected throughout South America (around 0.7 °C to 1 °C since the mid-1970s), as well as significant trends in precipitation. In addition, changes in climate variability and in extreme events have severely affected the region. Increases in temperature extremes have been identified in most of tropical and subtropical South America, while more frequent extreme rainfall in southeastern South America has favored the occurrence of landslides and flash floods (IPCC 2013).

Regarding climate projections, all studies mentioned in IPCC AR5 suggest increases in temperature and increases or decreases in precipitation for South

America by 2100. Projected warming varies from 1.7 °C (low radiative forcing scenario) to 6.7 °C (high radiative forcing scenario), where the magnitude of the major changes is located in the tropical portion of the South American continent. Rainfall changes for the region presents low confidence and varies geographically, most notably showing a reduction of 22% in NEB and an increase of 25% in southeastern South America. Additionally, projections show with medium confidence an increase in dry spells in tropical South America east of the Andes and in warm days and nights in most of this region by 2100.

Torres and Marengo (2014) identified possible hotspots of climate change in South America through an examination of the spatial pattern of the Regional Climate Change Index (RCCI) over the region by the end of twenty-first century (Fig. 15.4). The RCCI is a qualitative index that can synthesize a large number of climate model projections and is suitable for identifying those regions where climate change could be more pronounced in a warmer climate. This index is based on four variables representing climate change: change in temperature in a given specific region relative to the change in global mean temperature; change in average rainfall; and changes in the interannual variability of temperature and precipitation. All changes addressed in that study are related to projections for the period of 2071–2100 relative to 1961–1990. Torres and Marengo (2014) found that Southern Amazonia and the central-western region and western portion of Minas Gerais state in Brazil are persistent climate change hotspots through different forcing scenarios and ESMs belonging to CMIP3 and CMIP5 datasets. In general, as the scenarios vary from low- to high-level forcing, the area of high RCCI values increases and the magnitude intensifies from central-western and southeast Brazil to northwest South America. In general, the climatic hotspots identified in that study are characterized by an increase in the mean surface air temperature, mainly in the austral winter; by an increase of interannual temperature variability, predominantly in the austral summer; and by a change in the mean and interannual variability of precipitation during the austral winter. Although the Caatinga region is not identified as the most prominent hotspot in South America in that study, medium to high RCCI values can be noticed, mainly in the southern part of the region (Fig. 15.4).

15.4 Temperature and Precipitation Change Projections Over the Caatinga

The IPCC AR4 and AR5 (IPCC 2007, 2013) suggest that climate change is adversely affecting the ecosystems over the entire Earth. Projections of future climate using different global and regional climate models indicate that the distribution of the biomes around the world can be modified in the future due to increasing global warming, leading in general to increased aridity (Salazar et al. 2007; Lapola et al. 2009; Franchito et al. 2014). Expansion of subtropical desert and semi-desert zones

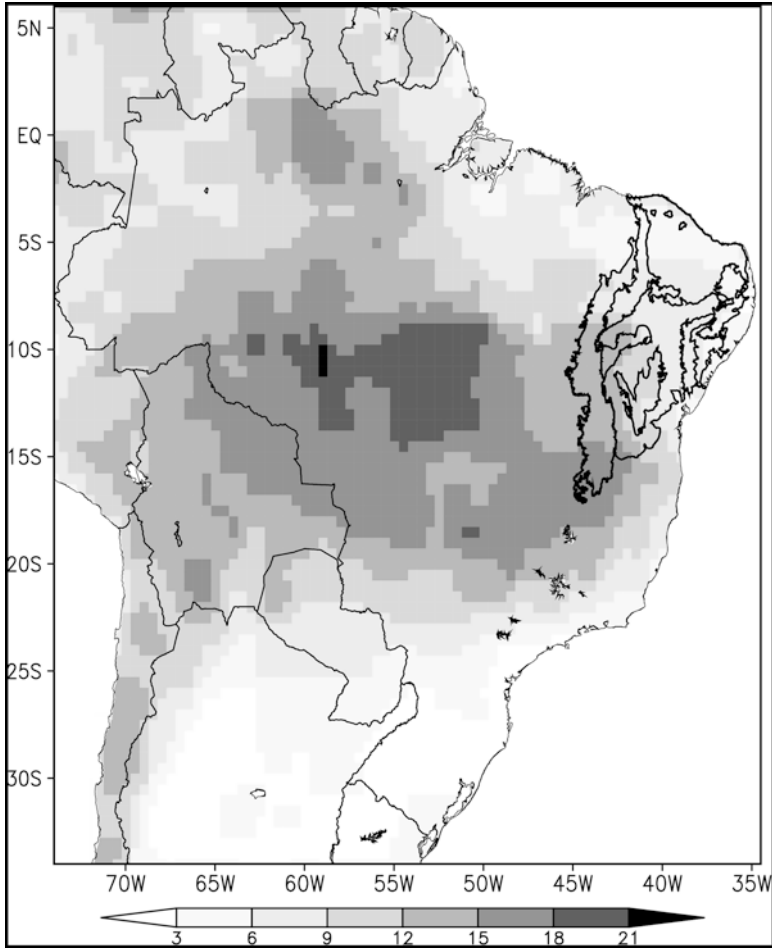


Fig. 15.4 Regional Climate Change Index (RCCI) for South America using climate projections of the Coupled Model Intercomparison Project Phase 5 (CMIP5, analyzed in the Intergovernmental Panel on Climate Change [IPCC] Fifth Assessment Report [IPCC AR5]) dataset by the end of the twenty-first century (2071–2100) under different Representative Concentration Pathways (RCPs). Darker colors indicate those areas where climate change may be more prominent. The Caatinga boundary is indicated by thick black lines. Values are dimensionless (Adapted from Torres and Marengo 2014)

and a reduction of the tropical rainforest and boreal forest can occur due to the increased GHGs concentration (IPCC 2007, 2013; Franchito et al. 2014).

The semiarid region of NEB is already vulnerable to the current interannual climate variability, and global and regional climate change projections indicate that the region will be deeply affected by a precipitation deficit and increased aridity in the next century, with negative consequences for the Caatinga (Salazar et al. 2007; Lapola et al. 2009; Franchito et al. 2014; Marengo and Bernasconi 2015; Vieira

et al. 2015; Marengo et al. 2016). Rainfall variability, land degradation, and desertification are some of the factors that combined could make NEB one of the world's most vulnerable regions to climate change, with potential adverse impacts on the rich species diversity and water resources (IPCC 2012, 2014).

The time series of annual near surface air temperature and precipitation anomalies over the Caatinga region for the historical simulations and projections under the four RCPs from the CMIP5 models listed in Table 15.1 are shown in Fig. 15.5. Regarding to the historical simulations, it is possible to identify a temperature increase of about 0.8 °C from 1901 to 2000, but there is no apparent tendency of change in the mean annual rainfall. For scenarios of future projections, the near surface air temperature should increase by approximately 1.3 °C (0.5–1.9 °C) for the RCP2.6 (low radiative forcing scenario), and by 4.4 °C (2.7–6.2 °C) for the RCP8.5 (high radiative forcing scenario) by the end of the twenty-first century, relative to the reference period 1961–1990.

Regional precipitation changes depend on regional forcings and on how climate models simulate their local and remote effects (Marengo et al. 2016). Thus, this variable has a high degree of complexity in its simulation and future projections show a high degree of uncertainty. For the Caatinga region (Fig. 15.5), there is a considerable spread among rainfall change projections of ± 1 mm day⁻¹, relative to 1961–1990, making it hard to identify any tendency in projected rainfall change. However, the RCP8.5 forcing scenario shows a slight rainfall reduction of about 0.3 mm day⁻¹ by 2100 (Fig. 15.5).

Figures 15.6, 15.7, 15.8, and 15.9 evaluate the spatial distributions of the CMIP5-derived projections of temperature and precipitation changes over NEB by the late twenty-first century relative to the reference period 1961–1990. The ensemble mean of all CMIP5 ESMs project a temperature increase varying between 1 and 2 °C in the RCP 2.6 to above 5 °C for the RCP8.5, in which the warming is slightly more intense in austral winter and spring (Fig. 15.6). Furthermore, it is possible to observe a clear east–west gradient in the patterns of changes, in which the highest values lie more to the west of the region. Regarding projections of rainfall changes (Fig. 15.8), trends vary both spatially and seasonally. For the austral summer (DJF), the ensemble mean of all ESMs shows rainfall increases that vary from 0.5 mm day⁻¹ (for the RCP2.6) to 1.0 mm day⁻¹ (for the RCP8.5), in which the highest values are located in the north/northwest of the region. During the austral fall (MAM), the model ensemble shows a rainfall increase in the north and decrease in the south part of the region in the order of 0.5 mm day⁻¹ for RCPs 2.6, 4.5, and 6.0, while for RCP8.5 the entire region shows a rainfall decrease of 0.5 mm day⁻¹. For the austral winter (JJA) and spring (SON), the model ensemble shows rainfall reductions between 0.1 and 1 mm day⁻¹ for the entire region.

As an approximated indicator of temperature change uncertainty, the standard deviation for the different ESM projections used in this study is shown in Fig. 15.7 as a measure of ensemble spread. Temperature projections show larger spread over the western part of NEB; however, the standard deviation does not exceed 1 °C for almost the entire region. Regarding precipitation, the signal agreement from all

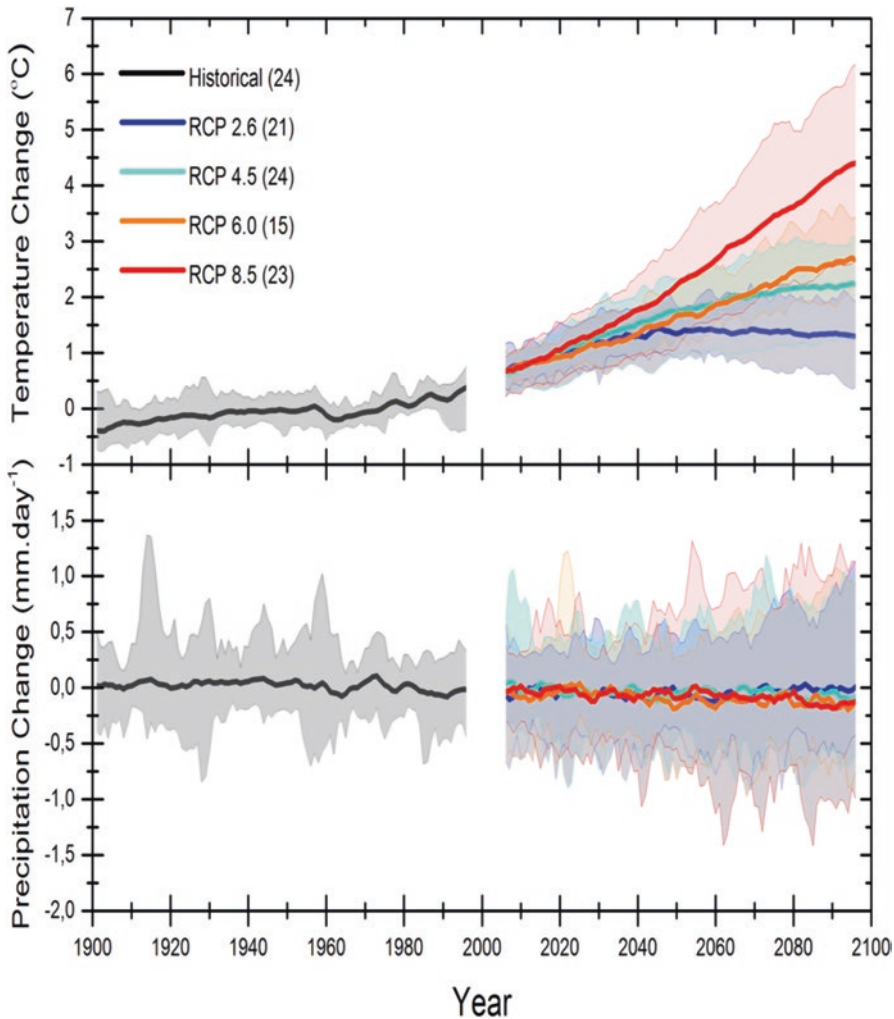


Fig. 15.5 Time series of temperature (upper panel) and precipitation (lower panel) anomalies over the Caatinga region for the historical simulations (left) and projections (right) under different Representative Concentration Pathways (RCPs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models listed in Table 15.1. The number of models used in each group is shown in brackets. Anomalies are relative to the reference period 1961–1990. Shaded areas represent the dispersion among CMIP5 models. All time series have been smoothed using a 5-year moving average for better visualization. Values of precipitation and temperature are in mm day⁻¹ and °C, respectively

models used in this study are employed as a measure of uncertainty (Fig. 15.9). In general, for all RCP scenarios, 60–80% of the models agree with rainfall increases in austral summer in the northern part of NEB, 60–80% agree with rainfall reductions in austral fall, and between 80% and 90% of the models show rainfall reduc-

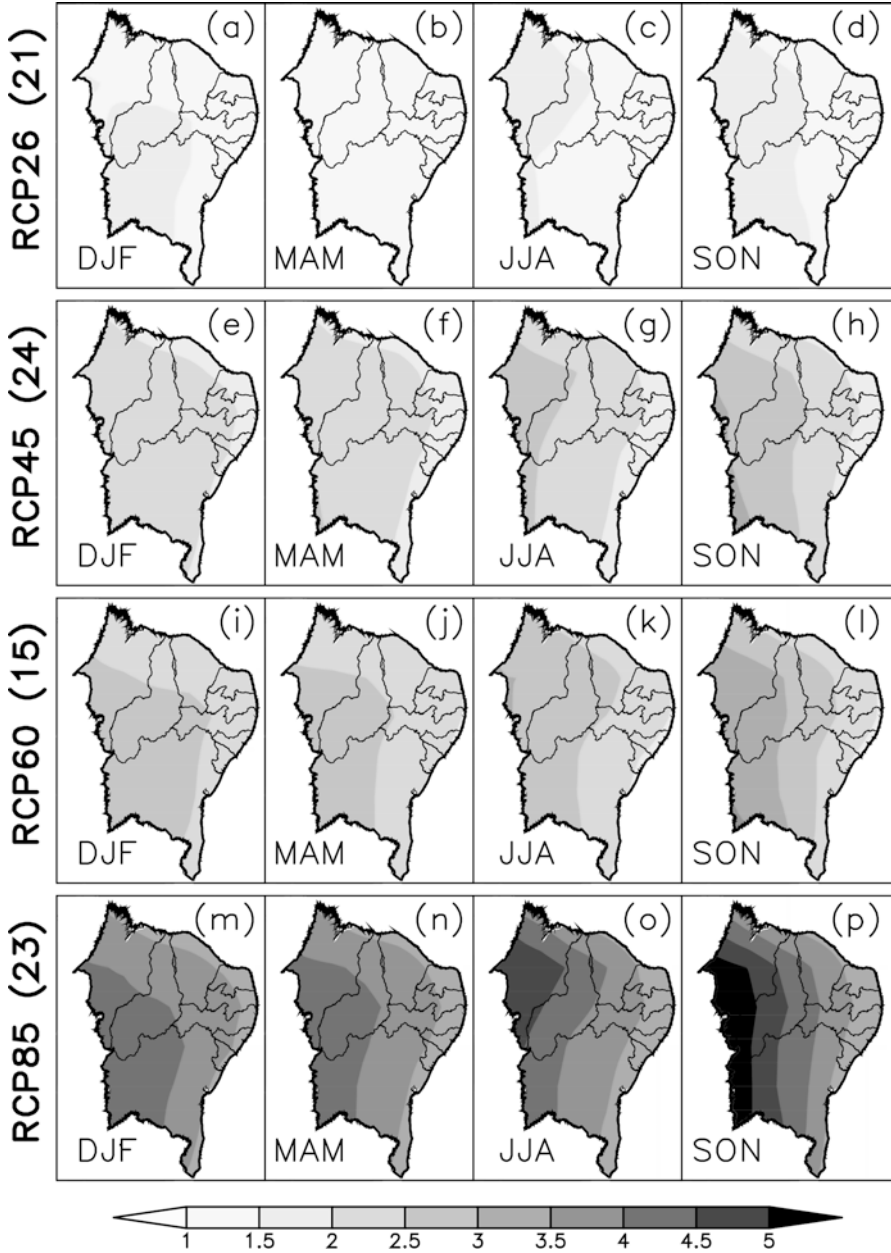


Fig. 15.6 Projections of near surface air temperature change ($^{\circ}\text{C}$) for 2071–2100 relative to the reference period 1961–1990 under the four Representative Concentration Pathways (RCPs) scenarios over northeast Brazil. Results are shown for the austral summer, fall, winter, and spring seasons (December to February [DJF], March to May [MAM], June to August [JJA], and September to November [SON], respectively). The number of models used in each forcing scenario is shown in brackets

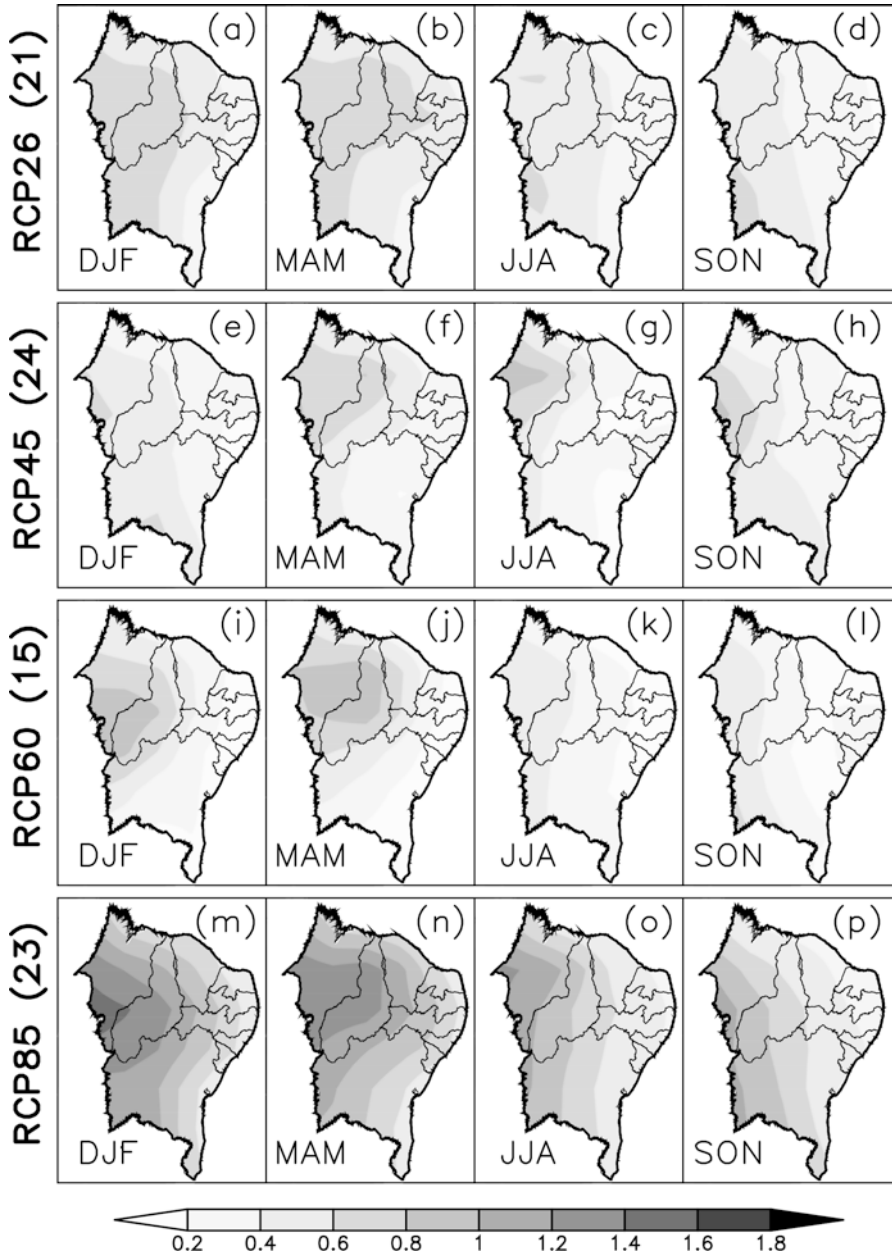


Fig. 15.7 Standard deviation ($^{\circ}\text{C}$) among the different Earth System Models (ESMs) projections for the temperature change results shown in Fig. 15.6. Results are shown for the austral summer, fall, winter, and spring seasons (December to February [DJF], March to May [MAM], June to August [JJA], and September to November [SON], respectively). The number of models used in each forcing scenario is shown in brackets

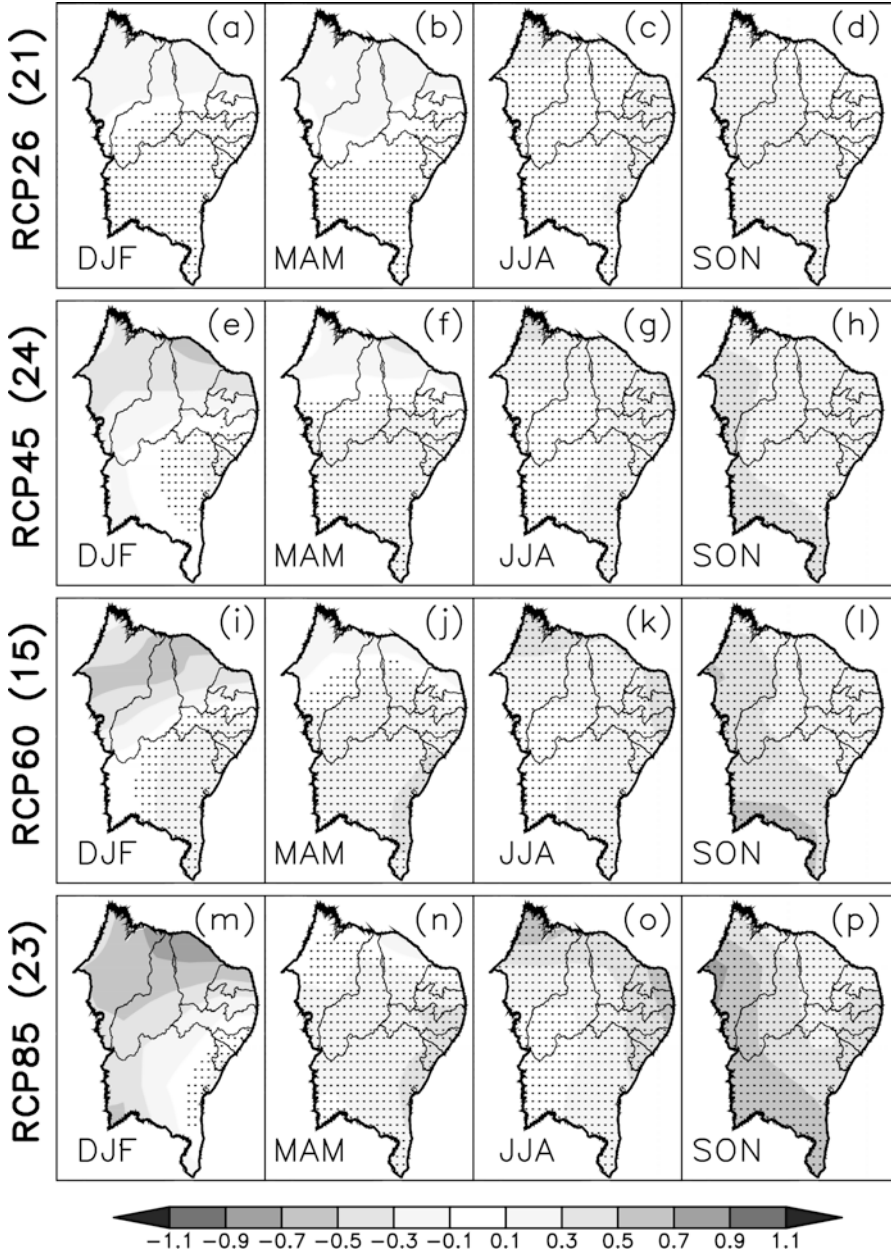


Fig. 15.8 Projections of precipitation change (mm day^{-1}) for 2071–2100 relative to the reference period 1961–1990 under the four Representative Concentration Pathways (RCPs) scenarios. Results are shown for the austral summer, fall, winter, and spring seasons (December to February [DJF], March to May [MAM], June to August [JJA], and September to November [SON], respectively). Dots indicate negative values. The number of models used in each forcing scenario is shown in brackets

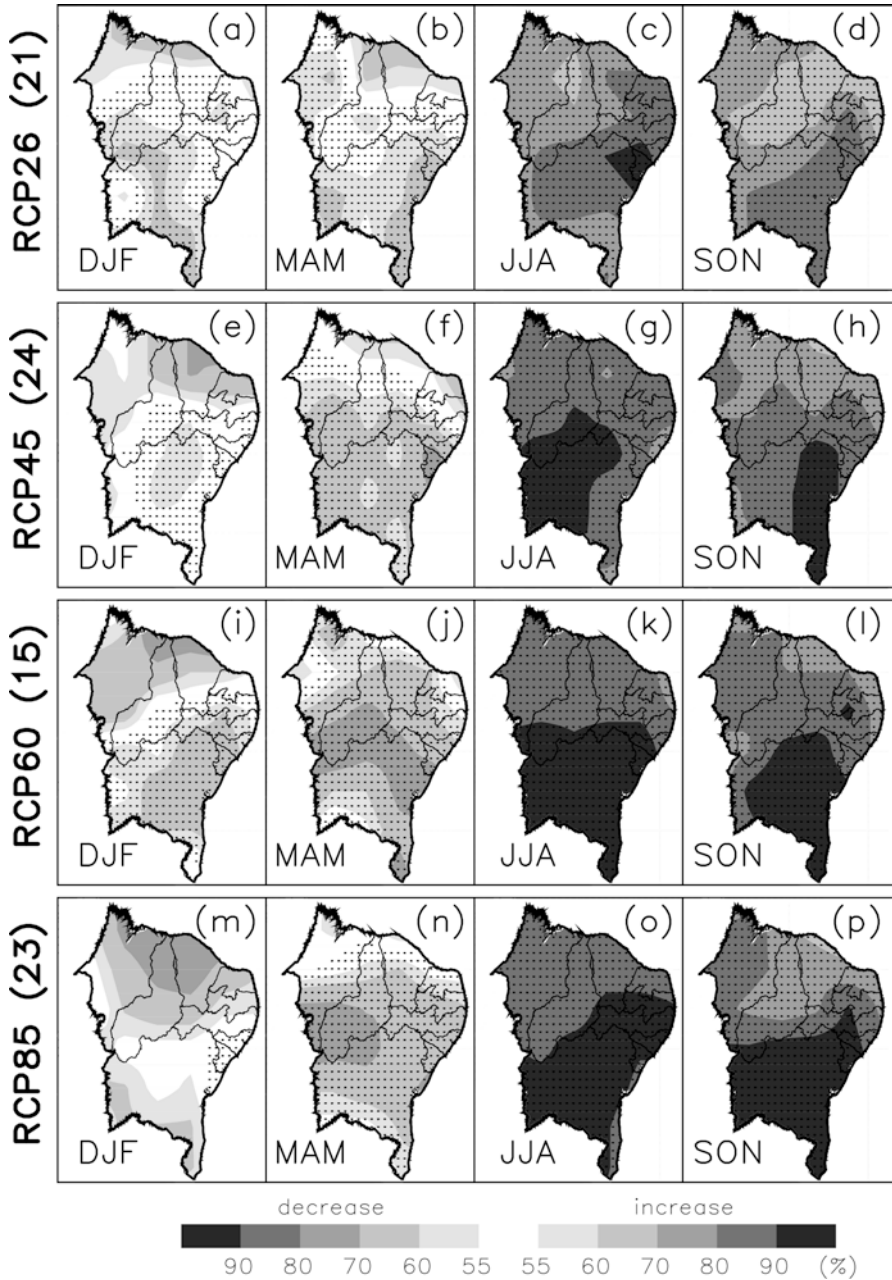


Fig. 15.9 Agreement (%) among the different Earth System Models (ESMs) for the signal of those projected precipitation change shown in Fig. 15.8. Results are shown for the austral summer, fall, winter, and spring seasons (December to February [DJF], March to May [MAM], June to August [JJA], and September to November [SON], respectively). Dots indicate negative values or decrease. The number of models used in each forcing scenario is shown in brackets

tions during austral winter and spring. Therefore, both Figs. 15.7 and 15.9 show that there is some degree of uncertainty in climate change projections for NEB, but with good reliability for rainfall decreases and temperature increases during the austral fall until austral spring.

15.5 Climate Extremes Trends Over the Caatinga

In addition to the changes discussed earlier in this chapter, the IPCC AR5 (IPCC 2013) also projects with medium to high confidence (based on the agreement among CMIP5 models and the consistency with other physical features of climate change) the following climatic stressors over NEB:

- Surface soils are projected to dry out;
- Both annual evapotranspiration and runoff are projected to decrease;
- Days and nights are projected to be warmer;
- More frequent intense rainfall episodes followed by dry and warm periods without rain; and
- Dry spells are projected to be longer with the possibility of droughts being triggered.

Figures 15.10 and 15.11 show some of the aforementioned climatic stressors through some climate extremes indexes computed with the CMIP5 dataset, namely: dry spells (depicted by the number of consecutive dry-days [CDD]⁵), cold days (TX10p⁶) and cold nights (TN10p⁷), and warm days (TX90p⁸) and warm nights (TN90p⁹).

The CMIP5 ensemble mean projections of CDD change for three time slices (2011–2040, 2041–2070, and 2071–2100) and four RCPs, displayed as anomalies from the reference period 1961–1990, are shown in Fig. 15.10. Dry spells are projected to increase in all time slices and forcing scenarios from eight to more than 28 additional dry days, with the highest values located in the western portion of the northeast. Results generally indicate an intensification of the patterns of change with increasing radiative forcing. In this way, the largest CDD values (from 20 to more than 28 additional dry days) are observed during 2071–2100 for RCP 8.5.

⁵Consecutive Dry Days (CDD): maximum number of consecutive days when precipitation is <1 mm.

⁶Cold Days (TX10p): percentage of time when daily maximum temperature is less than the 10th percentile.

⁷Cold Nights (TN10p): percentage of time when daily minimum temperature is less than the 10th percentile.

⁸Warm Days (TX90p): percentage of time when daily maximum temperature is greater than the 90th percentile.

⁹Warm Nights (TN90p): percentage of time when daily minimum temperature is greater than the 90th percentile.

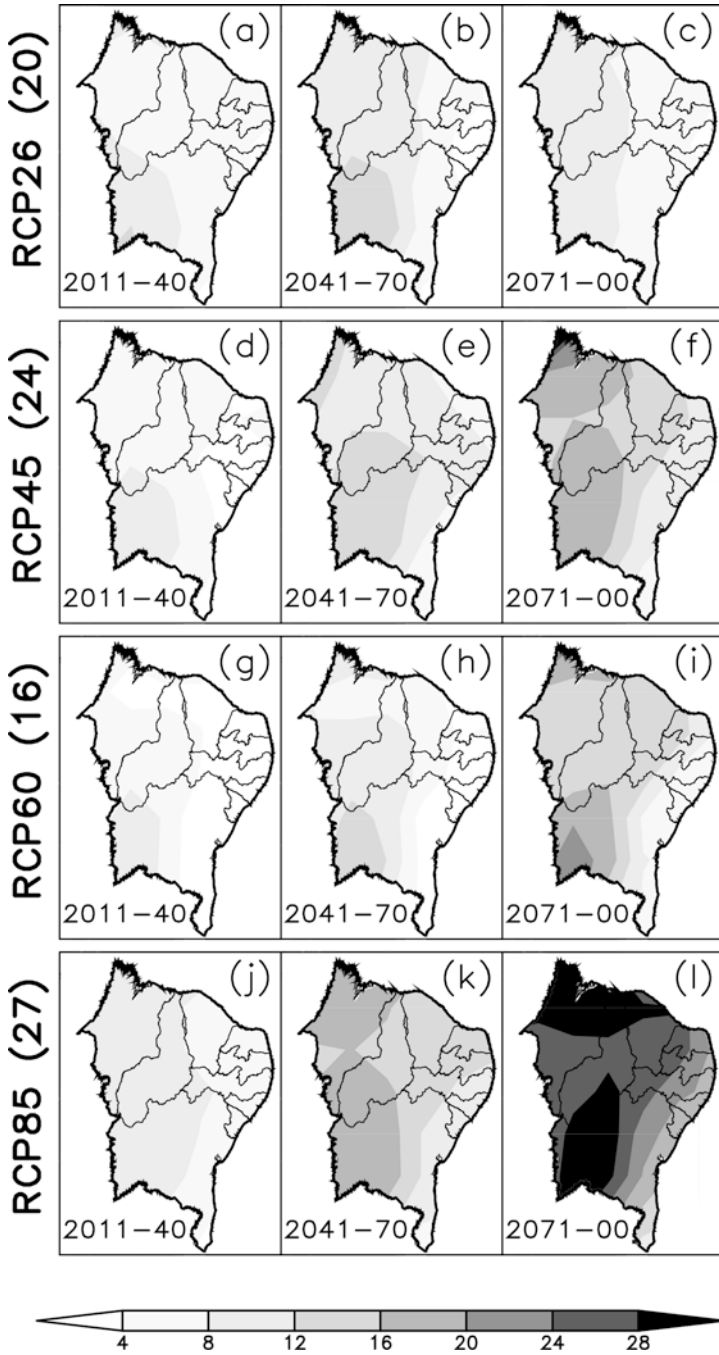


Fig. 15.10 Ensemble mean of consecutive dry days (CDD) changes projected for 2011–2040, 2041–2070, and 2071–2100 for the forcing scenarios Representative Concentration Pathway (RCP) 2.6 (a–c), RCP4.5 (d–f), RCP6.0 (g–i), and RCP8.5 (j–l), displayed as anomalies from the reference period 1961–1990. The number of models used in each forcing scenario is shown on the left (in brackets). Values are in days per year (Adapted from Marengo et al. 2016)

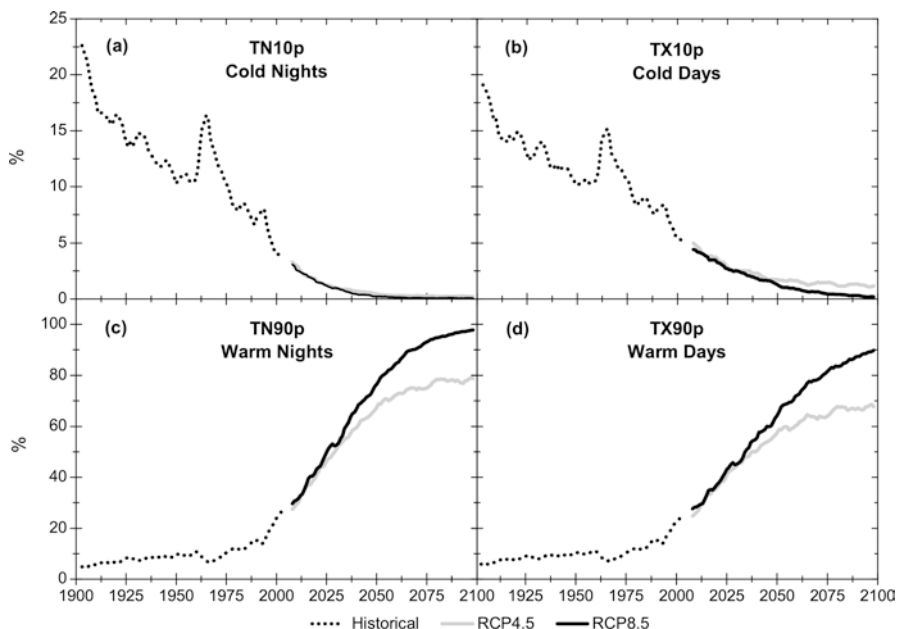


Fig. 15.11 Time series of the following extremes indexes over the Caatinga region: cold nights (TN10p), cold days (TX10p), warm nights (TN90p), and warm days (TX90p). Results represent the ensemble mean of all Earth System Models (ESMs) shown in Table 15.1. Dotted lines represent the ensemble mean for the historical period (1901–2005), and gray lines and black lines represent the ensemble mean for the forcing scenarios Representative Concentration Pathway (RCP) 4.5 and RCP8.5 (2006–2100), respectively. All time series have been smoothed using a 5-year moving average. Values are in percentage of events per year

In NEB, dry spells and drought events are part of the natural climate variability. These events have occurred in the past, are occurring in the present, and are likely to intensify in the future according to climate change projections (Marengo et al. 2016). Drought affects mainly vulnerable residents of the semiarid region, creating situations of water deficiency and risks to water, energy, and food security (Eakin et al. 2014). For example, the drought that intensified in 2012 and extended into 2015 is considered to be the most severe in recent decades and has had an impact on many districts in NEB, affecting almost nine million people (Marengo et al. 2013, 2016). Superimposing droughts upon pre-existing social–economic–political stresses place intense pressure on freshwater availability and quality in the region, and threaten its water, energy, and food security (e.g., Gutiérrez et al. 2014).

Regarding temperature extremes indices (Fig. 15.11), the ensemble mean of all CMIP5 ESMs shows a large tendency to decrease the number of cold nights and days and a relatively less pronounced tendency to increase the number of warm nights and days for the historical period (1901–2005), which have already been found in several observations studies in South America (e.g., IPCC 2007, 2012, 2013; Marengo et al. 2009; Rusticucci et al. 2010; Sillmann et al. 2013a, b). For the

future projections (2006–2100), results generally indicate an intensification of the tendencies observed in the historical period and intensification with increasing radiative forcing. All these results are consistent with the expected changes due to increasing GHG emissions and consequently global warming.

15.6 Concluding Remarks

According to the latest reports of the IPCC, warming of the climate system is unequivocal, and many of the observed changes since the 1950s are unprecedented over decades to millennia. The largest contribution to these changes is attributed to the human influence in the climate system, mainly through the increase in the atmospheric concentration of CO₂ since the 1750s.

In Brazil, several studies based on global and regional climate projections indicate that important changes in the climate are still expected to happen in this century, with major social and economic impacts on food production, commodities, and energy, and also large impact on the region's biodiversity. The changes projected in the IPCC reports will certainly lead to a new set of risks and threats that can exacerbate existing risk situations in the country.

Among the most affected regions in Brazil, the Amazon and northeast regions appear to be large hotspots. For some modeling studies, projections of the future climate drive a savannization of parts of Amazon and desertification of the Caatinga region, with potential adverse impacts on biodiversity, supply and quality of water resources, carbon storage, and the provision of other ecosystem services. Therefore, despite the many uncertainties that remain in projections of climate change, the scientific knowledge available today is enough for decision-makers to implement mitigation and adaptation measures to prevent dangerous climate change in the region.

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