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Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections

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Abstract The focus of this study is to investigate the risk of aridification in the semiarid lands of Northeast Brazil, using a variety of observational information and climate change projections for the future, by means of aridity indices. We use the Budyko and United Nations aridity indices to assess the extent of areas with semi-arid and arid conditions in the present, and for the future out to 2100. Climate projections are derived from the downscaling of the HadCM3 model for the A1B scenario using the Eta regional model with horizontal resolution of 40 km. Consistent with global climate model projections from IPCC AR5, regional climate change projections suggest an increase in dryness in the region, with rainfall reductions, temperature increases and water deficits and longer dry spells, leading to drought and arid conditions expected to prevail by the second half of the 21th century. The area with arid conditions is projected to grow to cover areas currently with dry sub humid conditions, and become larger by 2100. This increase in aridity, combined with land degradation may increase the risk of desertification.

1 Introduction

Dry lands throughout the world have always undergone periods of degradation due to naturally-occurring fluctuations in climate. Drought can be caused by reduced precipitation, increased evaporation, lowering of water tables or changes in ground cover. Its major consequences include reduced agricultural production, soil degradation, ecosystem changes and decreased water catchment runoff. Over the long term, this could lead to desertification. Aridity causes a reduction in the biological and economic productivity of terrestrial ecosystems, and represents a serious threat to ecological, biogeochemical, and hydrological processes. On the other hand, human use (and abuse) of vulnerable dry land ecosystems may lead to unsustainable land management.

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In Brazil, the dry lands are mostly concentrated in the Northeast region (NEB), between 2.5° S and 16.1° S, and between 34.8° W and 46° W, with an area of about 1,542,000 km^2, representing 18.26% of Brazilian territory. It includes the states of Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe and Bahia. The region that is affected regularly by droughts in NEB was referred as the *Poligono das Secas* (Drought Polygon), and was created by the *Superintendencia do Desenvolvimento do Nordeste* (SUDENE) in 1936 and then modified in 1946, as a regionalplan to fight droughts and was based only on rainfall. It included an area of about 1,641,000 km^2. One sub-region within this Drought Polygon called *Sertão* or semiarid region in NEB, with an area of 912,200 km^2. In 2005, the limits of the semiarid region were re-defined by the Brazilian government (Brasil-MIN 2005) to include an area of 970,000 km^2, with 1133 districts and about 28 million people. This new delimitation was based on precipitation (mean anual rainfall below 800 mm), aridity index up to 0.5, and risk of drought above 60% relative to the 1970–90 climatology.

In terms of vegetation types, in the semiarid parts of Northeast Brazil, the *caatinga*, a dry, thick thorny xeromorphic vegetation type predominates in the states of Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas and Sergipe (about 412,000 km2). These states have extensive areas with farming activities. Although parts of the agricultural areas are in a process of desertification, and are no longer cultivated, they still were classified as farming areas. In addition, many areas of caatinga may have extensive pastures, which could be classified as farming; however, due to the difficulties of interpretation of the images, these areas were considered as native caatinga vegetation (Alvalá et al. 2006).

The rainfall over the area is complex, annual totals varying from 2000 mm to values less than even 500 mm between Bahia and Pernambuco. In the semiarid region the rainy period occurs between March and May, while in eastern Northeast Brazil the rain maximum occurs between June and July (Magalhaes et al. 1988; Hastenrath 1990; Xavier 2001; Nobre et al. 2006).

Droughts are part of the natural climate variability in that region, and have occurred in the past (Table 1 and Fig. 1), and according to climate change projections it is likely that drought conditions in that region may continue in the future. Brazilian news broadcasts by the press and government agencies labeled the 2012 and 2013 drought as the most severe in the last decades, and many districts in NEB states declared a state of public calamity, mainly in the semiarid portions. The Brazilian Government estimated that the drought that started in 2012 affected almost 38% of the population in the semiarid portions of NEB, approximately 9 million people.. Public drought policies somewhat diminished the problem but did not solve it.

The NEB region's rainfall exhibits marked interannual variability, with a slight decrease since the 1970s (Marengo et al. 2013). Part of this has been attributed to the sea surface temperature (SST) variations in the tropical Pacific manifested as the extremes of El Niño-Southern Oscillation (ENSO), and to the meridional SST gradient in the tropical Atlantic (Kousky et al. 1984; Aceituno, 1988; Ropelewski and Halpert 1987, 1989; Kousky and Ropelewski, 1989; Marengo and Hastenrath, 1993; Hastenrath and Greischar 1993, Uvo

Table 1 History of droughts in Northeast Brazil

Years with drought in Northeast Brazil
1583, 1603, 1624, 1692, 1711, 1723–24, 1744–46, 1754, 1760, 1772, 1766–67, 1777–80, 1784, 1790–94, 1804, 1809, 1810, 1816–17, 1824–25, 1827, 1830–33, 1845, 1877–79, 1888–89, 1891, 1898, 1900, 1902–03, 1907, 1915, 1919, 1932–33, 1936, 1941–44, 1951–53, 1958, 1970, 1979–81, 1982–83, 1992–93, 1998, 2001–02, 2010, 2012, 2013-14

The droughts years were collected from various studies (Moura and Shukla 1981; Araujo 1982; Magalhaes et al. 1988; Aceituno et al. 2012; Marengo et al. 2013), based on rainfall anomalies on the region

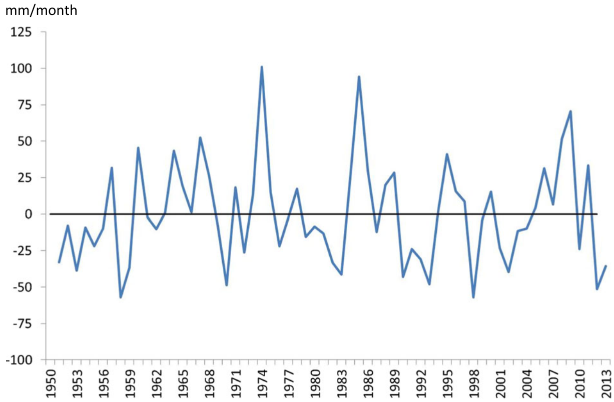

Fig. 1 Rainfall anomaly (mm month$^{-1)}$ during the peak rainy season (February–May) in Northeast Brazil from 1951 to 2013 (updated from Marengo et al. 2013]

et al. 1998, Andreoli et al. 2011, Kayano et al., 1988, Nobre et al. 2006; Aceituno et al. 2012; Marengo et al. 2013).

During drought years, the inter-hemispheric SST gradient in the tropical Atlantic is steep and the ITCZ stays far north of its normal position, while the waters of the eastern equatorial Pacific tend to be anomalously warm (Moura and Shukla 1981; Ropelewski and Halpert 1987; Uvo et al. 1998; Nobre et al. 2006; Hastenrath 2001; Marengo et al. 2013, among others). Rainfall was well below normal in 1956, 1970, 1983, 1998 and 2012–2014, of which 1983 and 1998 were El Nino years. However, not all El Niño years result in drought in NEB, since the 2012–2013 drought occurred during La Niña (Marengo et al. 2013). This drought was perhaps the worst in the last 60 years, and occurred when La Niña event was present in the tropical Pacific during austral summer, and with tropical Atlantic relatively neutral, without important SST anomalies during austral summer and fall (www.cptec.inpe.br). The drought situation extended into 2014. The 1998 drought had formerly the worse on record.

Water deficits can be considered as the consequence of delayed or deficient rainy seasons, that in combination with high air temperatures induce moisture deficiency in

the soil, lower than the minimum required by crops during austral summer and fall. According to the PROCLIMA monitoring program in the NEB region (www6.cptec.inpe.br/proclima/), there was an exacerbated water deficiency in most of the semiarid region. From October 2011 to September 2012, a large area of the NEB covering the northern part of the state of Bahia, west and central parts of the states of Pernambuco and Paraiba, and the southern parts of the states of Ceara, Piaui and Rio Grande do Norte experienced water deficiency that lasted between 80 and 90 days. During the same period in 2012–2013, the area experiencing 80–90 days with water deficiency was smaller than in 2013, and the regions that were heavily affected by droughts two years in a row were mainly northern Bahia and central and western Pernambuco. Rainfall anomaly maps from CPTEC/INPE show that during the peak of the rainy season, March-May, 2012 amounts were between 200 and 400 mm below normal, while in the same season in 2013 the anomalies varied between 100 and 200 mm below normal. Climatological rainfall for March-May varies from 200 to 700 mm over the region.

Regarding the human impacts of droughts in Northeast Brazil and other tropical regions, Aceituno et al. (2012) and Marengo et al. (2013) demonstrated the vulnerability of poor farmers to the droughts caused by strong El Niño events. While the 1877 drought, considered the worst over the climate history of the NEB region killed thousands of people, the drought of 1998 and the recent one in 2012–2013 did not cause any deaths.

Drought is an environmental hazard that affects mainly vulnerable residents of NEB, creating situations of water scarcity and risks to water and energy security. Over the long term, the process of degradation can affect the soil,impacting local agriculture in the drylands, and could be exacerbated by rainfall reductions, increased temperature, and more frequent droughts and dry spells, as shown by future climate change projections for NEB from CMIP3 models (Marengo et al. 2009, 2012; IPCC SREX 2012). These projected changes may result in a shifting of a climate regime from semiarid to arid conditions. This aridification of the NEB region, together with a deterioration of the environment due to non-sustainable land use practices may result in an increased risk of desertification in the region.

The present study focuses on an assessment of current and future aridity conditions in NEB up to 2100, using high resolution projections for climate and aridity conditions. We assess future climate change projections up to 2100, focusing on rainfall, temperature, water balance and the aridity of the region using various aridity indices.

2 Objectives

The main objectives of this study are summarized as:

- A review of region-wide hydrological characteristics during the drought in Northeast Brazil in 2012 and 2013;
- An assessment of future changes in temperature and regional water balance (precipitation-evaporation) during 2010–40, 2041–70 and 2071–2100 relative to 1961–90, from the climate change projections of the Eta-HadCM3 under the A1B emission scenario;
- An assessment of the relationships of warming and drying processes and their impacts on aridity conditions based on various aridity indices projected for the future using the Eta-HadCM3 projections under the A1B emission scenario. The climatic causes of desertification are related to prolonged and frequent droughts that affect population of the region, and the aridity índices can help in the identification of changes of climate in the region, from semiarid to arid. These índices can be useful for risk analyses.

3 Data and methodology

3.1 Rainfall

We used rainfall data sets based on station data from these Brazilian institutions: the National Institute of Meteorology (INMET), the National Water Authority (ANA), CPTEC/INPE and the Brazilian Air Force (CTA), available since 1961. The anomalies were calculated from the 1961–90 long term mean (LTM) for areas representing Northeast Brazil (38-45 W, 5-10S) for the February-May peak of the rainy season. The CPTEC/INPE data source contains rainfall data from stations from all of the Northeast Brazil states, and it is used in the monitoring of climate in the region by the PROCLIMA monitoring program. Data coverage over the region is quite good; the data are homogeneous and quality-controlled and the stations evenly distributed across the region, as shown in Fig. 1 in Alvares et al. (2014).

3.2 Climate change projections

For this study we used the climate change projections derived from the downscaling of the HadCM3 model using the Eta CPTEC regional model. The HadCM3 global model, one of the CMIP3 models (Couple Model Intercomparison Program Version 3) from the IPCC AR4 was run on an ensemble model over the twenty-first century according to the SRES (Special Report Emission Scenarios) A1B, but with each member having different climate sensitivity. The four members selected from he ensemble run to drive the Eta-CPTEC model span the sensitivity range in the global model ensemble. The Eta-CPTEC regional model nested within these lateral boundary conditions was configured with a 40-km grid size and was run over 1961–1990 to represent baseline climate, and 2011–2100 to simulate possible future changes. Results presented here focus on annual means of 2011–2040, 2041–2070 and 2071–2100 time slices.

The HadCM3 and the Eta-HadCM3 have been run for the present, 1961–90, and the ability of the regional model to reproduce present climate, the estimate of the errors and the spread of the ensemble members, was evaluated by Chou et al. (2012). The results show that the upper- and low-level large-scale circulations reproduce closely the circulation from the global model without the need of internal large-scale nudging and using a single row at the lateral boundaries, which shows the efficiency of the lateral boundary scheme. The low-level flow shows that Eta-CPTEC was able to reproduce the driver model's patterns and was able to add small-scale features that were absent in the HadCM3 fields due to its coarse resolution. The downscaled climatology of precipitation and temperature is close to CRU observations. The ensemble members from the Eta-CPTEC/HadCM3 simulations exhibit a small spread when compared against model RMSE (root mean square error). More details on the Eta CPTEC-HadCM3 model runs for the future can be found in Marengo et al. (2012).

3.3 Aridity indices

One of the most common approaches to measuring regional aridity is through an estimator called the aridity index. Regions where the aridity index is greater than some threshold are broadly classified as dry areas, since the evaporative demand cannot be met by precipitation. Therefore, the aridity index (AI) can be a representative indicator of regional climate, and change in the aridity index would inevitably have impacts on the hydrological cycle, water resources management, and ecosystem in the region. An aridity index is a numerical indicator of the degree of dryness of the climate at a given location. Various aridity indices have been used in the past to identify regions with potential to become arid and under risk of desertification (Beserra 2011 and references cited). The indices used in this study are:

The Budyko index. In the preparations leading to the UN Conference to Combat Desertification (UNCCD), the United Nations Environment Programme (UNEP) issued a dryness map based on a different aridity index, proposed originally by Mikhail Ivanovich Budyko (1958) and defined as follows:

$$AI_B = 100 \text{ x } (R/L*P)$$

where R is the mean annual net radiation (also known as the net radiation balance), P is the mean annual precipitation, and L is the latent heat of vaporization for water. Note that this index is dimensionless and that the variables R, L and P can be expressed in any system of units that is self-consistent.

The UNEP index. Later on, the UNEP has adopted yet another index of aridity, defined as:

$$AI_U = P/PET$$

where PET is the potential evapotranspiration and P is the average annual precipitation (UNEP 1997). Potential evapotranspiration is defined as the amount of evaporation and transpiration that would occur if sufficient water were available and is a function of temperature, vapor pressure, wind speed, and solar radiation. PET and P must be expressed in the same units, e.g., in milimetres. The boundaries that define various degrees of aridity using both índices are shown in Table 2.

Isohyet of 800 mm/year The official classification of the semiarid region of NEB was established by the Brazilian Government in 2005 (Brasil-MIN 2005). The criterion was that the semiarid region would be delimited by the 800 mm/year isoline. The aridity indices AI_B and AI_U, and the area delimited by the 800 mm/year isoline are calculated from the model output of the Eta CPTEC-HadCM3 runs, for the present (1961–90) and the future (2010–40, 2041–70 and 2071–2100) for the NEB region.

4 Results and discussions

4.1 Climate projections for the NEB region

Projections of climate change (Fig. 2a-c) suggest temperature increases in NEB, with a warming of 2 C in 2010–40, extending into the semiarid region in 2041–70 (2–4 °C) and to the whole region by 2071–2100 (above 4 °C). Precipitation (Fig. 2d-f) is projected to decrease, particularly over the western part of the region (more than 1.5 mm/day of reduction) and over the semiarid region (0.4 to 0.8 mm/day of rainfall reduction). The combination of less rainfall, lower atmospheric humidity (5 to 15% relative humidity reduction) (Fig. 3j-l) and increased temperatures determine water deficits, as shown by the P-E maps (Fig. 2g-i), where water deficit is projected for the entire region, particularly over western NEB and over the semiarid region, with a deficit after 2041 (3–4 mm/day reduction).

Consistent with the regional climate model, global model experiments have suggested that, under climate change, soil moisture and runoff would decrease in the region. From the CMIP3 models for the A1B scenario (Meehl et al. 2007) to the CMIP5 models for the RCP4.5 scenario (similar to CMIP3 A1B), annual mean shallow soil moisture and runoff show projected decreases in NEB, with at least 90% of the models agreeing on the sign of the change (Kirtmann et al. 2013). Owing to the simplified hydrological models in many CMIP3 and CMIP5 climate models, the

Table 2 Aridity degrees as shown by the AI_B Budyko and the AI_U UNEP indices

Classification	Aridity index AI_B	Aridity index AI_U
Hyperarid	$AI_B>10$	$AI_U<0.05$
Arid	$3.4<AI_B<10$	$0.05<AI_U<0.20$
Semi-arid	$2.3<AI_B<3.4$	$0.20<AI_U<0.50$
Dry subhumid	$1.1<AI_B<2.3$	$0.50<AI_U<0.65$

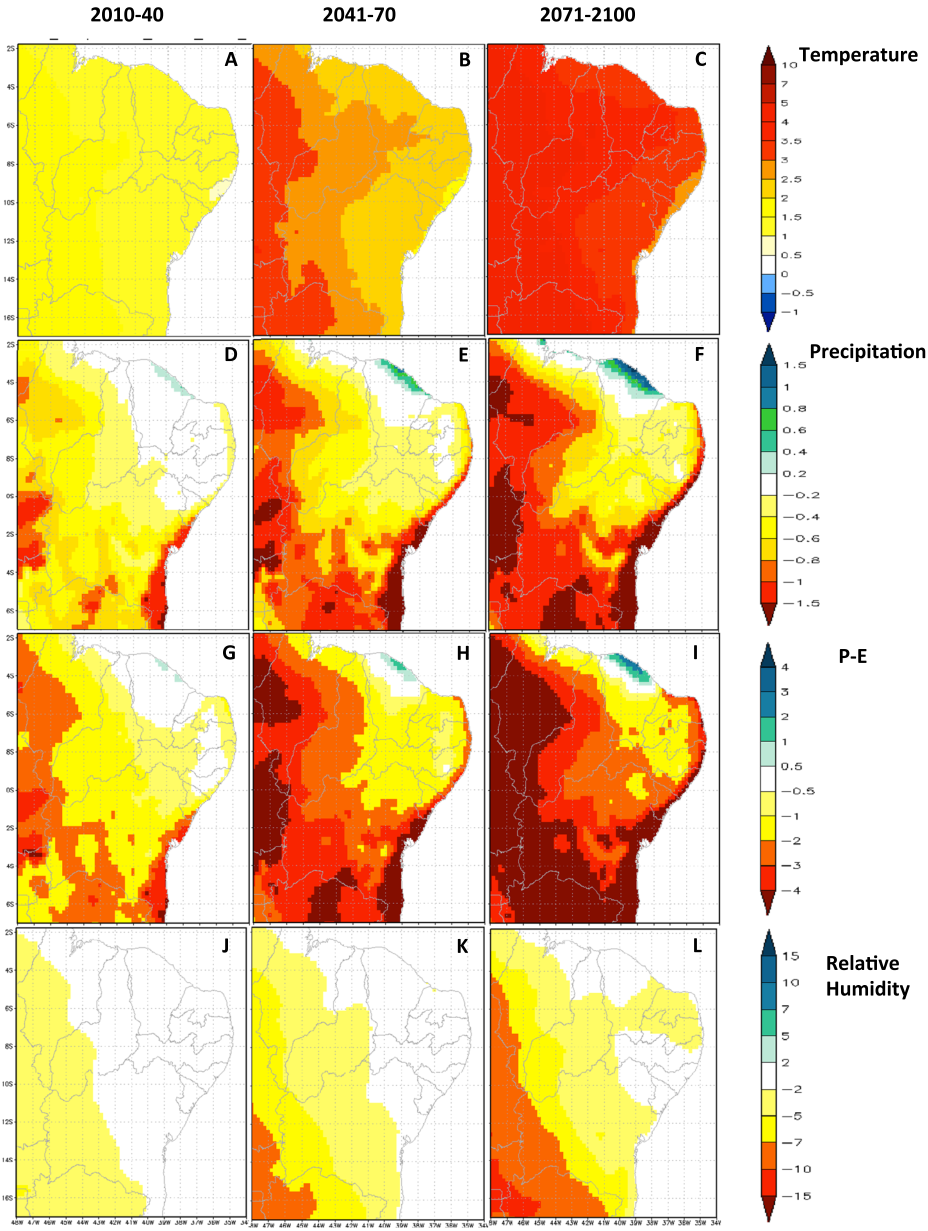

Fig. 2 Changes in anual air temperature (°C, **a**-**c**), rainfall (mm day^{-1}, **d**-**f**), precipitation-evaporation (mm day^{-1}, **g**-**i**) and relative humidity (%, **j**-**l**), derived from the downscaling of the HadCM3 models using the 40 km lat-lon Eta regional model, A1B scenario. *Left column* is for 2010–40, *center column* for 2041–70 and *right column* for 2071–2100. Changes are relative to 1961–90. *Color scale* is on the right side of the panel

projections of soil moisture and runoff have large uncertainties. In sum, global projections suggest a rainfall reduction of about 22% in NEB as well as increases in evaporation and air temperature, which determine runoff reductions in the future.

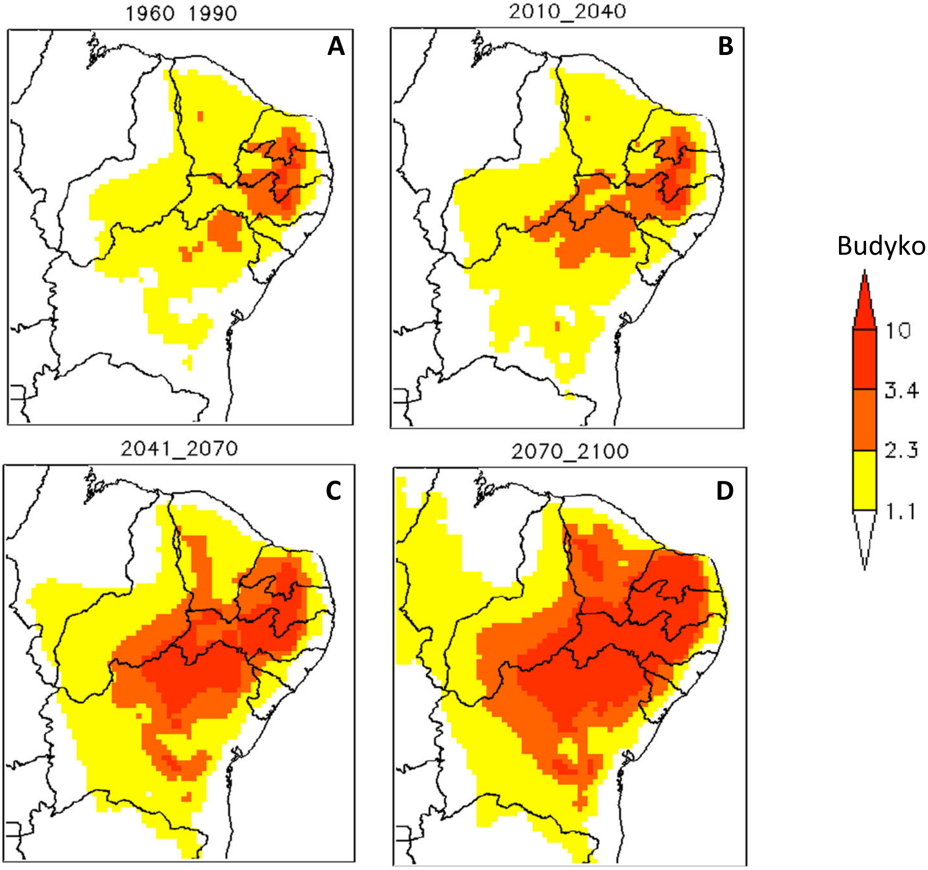

Fig. 3 Maps of aridity derived from the Budyko index, for 1961–90, 2010–40, 2071–70 and 2071–2100 derived from the downscaling of the HadCM3 models using the 40 km lat-lon Eta regional model, A1B scenario. *Color scale* is on the right side of the panel

The increases in temperature and decreases in rainfall could decrease the productivity in the short term (by 2030), threatening the food security of the poorest portions of the population (medium confidence) [Magrin et al. 2014].

Furthermore, an increase and intensification in droughts is projected for large parts of South America under RCP8.5 (Sillmann et al. 2013) including NEB, although large model uncertainties remain. Dai (2012) finds that regions such as NEB would be under severe to extreme drought conditions relative to present climate by the end of the 21st century under the RCP4.5. The multi-model impact model analysis under RCP8.5 reveals a strong increase in drought risk in this region, although uncertainties remain substantial (Prudhomme et al. 2013).

According to Magrin et al. (2014), there is medium confidence that droughts will intensify throughout the 21st century in some seasons in NEB due to reduced precipitation and/or increased evapotranspiration. The future climate change scenarios show a decrease in water availability for agricultural irrigation owing to reductions in precipitation and increases in evapotranspiration

4.2 Changes in aridity

Figures 3 and 4 show the projections of aridity derived from the Budyko and UNEP indices in the region, respectively, over the short (2010–40), medium (2041–70) and longer term (2071–2100). Figure 5 shows the areas covered by each category from both índices and the 800 mm/year isohyet for the present and future. We will focus on arid and semiarid conditions only. The Budyko index maps (Fig. 3) show an increase in the areas with semiarid and arid conditions out to 2100, occupying areas that previously were dry subhumid. This index presently shows a small region with arid conditions in the states of Pernambuco and Paraiba. By 2010–40 this arid region grows a little and by 2040–71 it covers from the northern part of the state of Bahia to the Southern part of the state of Rio Grande do Norte. By 2071–2100 the arid conditions now covers large parts of what in the present is a semiarid region, covering now a large area extending from the northern part of the state of Bahia to the southern and central part of the state of Ceara, and from the eastern part of the state of Piaui covering most of the states of Rio Grande do Norte, Pernambuco, Paraiba, Alagoas e Sergipe.

The maps from the UNEP index (Fig. 4) show an increase in the area with semiarid conditions out to 2100, anddifferently from the Budyko maps, arid conditions appear only by 2071–2100 period, in a region extending from northern Bahia, the central parts of Paraiba and Pernambuco to south central Rio Grande do Norte. Furthermore, it is noted from both indices

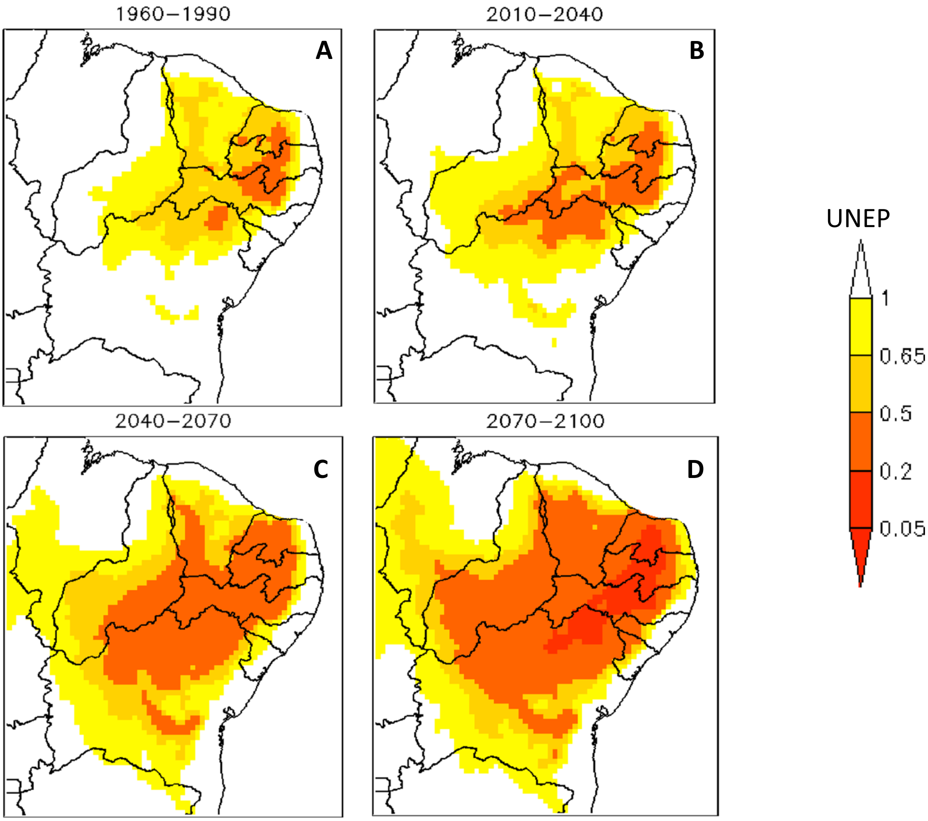

Fig. 4 Same as in Fig. 5, but for the UNEP index

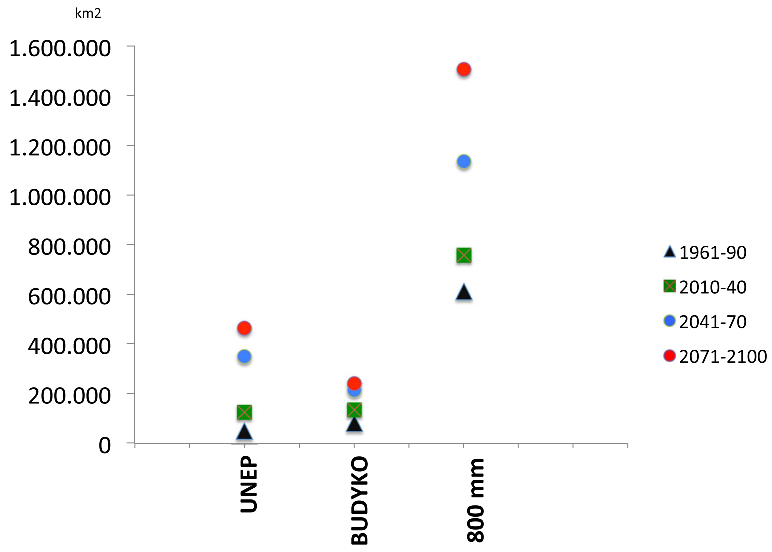

Fig. 5 Extent (km^2) of area with semiarid conditions in NEB as derived from various índices (Budyko, UNEP) and from the criterion of the of 800 mm/year isoline. Areas are indicated as simulated for the present (1961–90) and projected for the future (2010–40, 2041–70 and 2071–2100)

that the semiarid area is increasing in coverage in the future, going into the dry sub humid areas, but there are differences in the magnitude of the areas projected by both indices. The indices that use the energy (Budyko) or water balance (UNEP) methods show semiarid areas of 84,800 and 54,000 km^2, respectively for the present. In 2010–2040 the area projected to be semiarid by both indices increases by more than 200% relative to the present, while in 2041–2070 the increase in the area is about 250% for the Budyko index and 600% for the UNEP index. For the 2071–2100 period, the area projected derived from the Budyko index is 290% larger than the present, while for the UNEP index the increase is about 800% relative to the present.

A relevant analysis by Prudhomme et al. (2013) reveals a strong increase in drought risk in NEB under RCP8.5, although uncertainties remain substantial, and drought risks are much less pronounced under RCP2.6. This difference between the magnitude of the projected semiarid area by both indices may be because the UNEP index depends on evapotranspiration, which includes the net radiation and the dryness of the air and wind speed, while the Budyko index considers mainly net radiation. Because evapotranspiration is a process controlled by both net radiation and the aerodynamic effects (wind speed and dryness of the atmosphere), the UNEP index may represent better the physics of the water balance and the water deficit linked to arid conditions.

Considering the 800 mm/year isoline as an indicator of semiarid areas, coverage within this isoline increases from the present level to include most of the state of Bahia by 2040, and after 2040 to include the northern part of the state of Minas Gerais in Southeastern Brazil, and the state of Maranhao, west of NEB. Figure 5 shows the changes in the area with semiarid conditions derived using the three criteria, the three índices suggesting an increase in the area with semiarid conditions out to 2100.

Regarding the presence of arid conditions, while the Budyko index shows arid conditions from the present on, the UNEP index shows arid conditions starting to appear only by 2071–2100, with about 85,000 km^2. This is consistent with Beserra (2011), whichshowed arid conditions by using the high resolution MRI-AGCM3 model by the end of the 21st century from the Budyko index, but not from the UNEP index.. This value of 85,000 km^2 represents in size almost the entire area of the states of Rio Grande do Norte and Sergipe combined.

The results reveal a closer relationship between the water balance and aridity/humidity index. Given the very evident regional environmental differences across Northeast Brazil, both evapotranspiration and precipitation should be considered when analyzing aridity/humidity conditions on a regional scale. Considering only a single factor would induce more mistakes and probably misdirect agricultural development and ecological structuring.

5 Conclusions

The Ministry of National Integration of Brazil estimates that more than 10 million people have been impacted by the drought of 2012–14 in the semiarid region. The extreme conditions in those years were linked to deficient rainfall and drying conditions that reduced soil water availability mainly in the semiarid region. Observed changes in rainfall and atmospheric circulation at interanual scales are consistent with the notion of an active role of colder than normal surface waters in the equatorial Pacific and the tropical Atlantic, with weak upward motion and less than normal rainfall in Northeast Brazil.

In our results, areas with the largest signal of drought increase are generally located where precipitation is projected to decrease, and increase in evaporation leads to more drought and aridity as projected by the model. Regional climate change projections suggest the increase in dryness in the region, with rainfall reductions, temperature increases and water deficits and longer dry spells, leading to drought and arid conditions, expected to prevail by the second half of the 21th century. This is consistent with global climate model projections from CMIP3 and CMIP5 for the region by 2100. In terms of observations, we have no long term soil moisture observations in the region to detect the presence of a drying trend. What we have noticed is that during drought years, as in 1998 and recently in 2012–2013, soil moisture reductions can reach the levels of deficit sufficient to affect regional agriculture.

The use of aridity indices provides a straightforward method for obtaining a first- order estimate of the effect of climate change on the water balance and water availability. This increase in aridity as derived from the UNEP index during 2071–2100, together with an increase of the extension of semiarid conditions are shown by the aridiy índices. This aridity combined with land degradation may increase the risk of desertification. The arid/drought scenario projected for most of the semiarid region of Northeast Brazil by the Eta-HadCM1 A1B scenario is similar to that projected by the MRI AGCM3.1 model and to those from the IPCC CMIP3 and CMIP5 model runs.

Dryness and aridification in the region may vary among different scenarios and models, varying between extremes, but the projected changes tend to be directed more toward drier and warmer conditions. In view of this increased risk of drought/aridity and the recognized vulnerability of people in the semiarid region of Northeast Brazil to these extremes, it is necessary to consider measures of risk management that could serve as a basis for implementing adaptation measures.

Currently, some adaptation measures are directed at efforts to store water in tanks (*cisternas*), and transportation of water by trucks (*carros pipa*), helping maintain small scale agriculture and local people's livelihoods. The most important initiative in the semiarid region, which is also part of the National Emergency Response Force for Droughts, is the construction of tanks, launched by an NGO called Articulação do Semiárido (ASA, http://www.asabrasil.org.br). With capacity for 16,000 liters of water, the tank fulfills the consumption needs of a family of five people for a dry period of eight months. Some are collectively built and used, shared by families. In total, 850,000 households, or around 4.5 million people, already have access to this technology.

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