ASSESSMENT OF RAINFALL VARIABILITY AND FUTURE CHANGE IN BRAZIL ACROSS MULTIPLE TIMESCALES

Assessment of rainfall variability in Brazil

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Abstract

Rainfall variability change under global warming is a crucial issue that may have a substantial impact on society and the environment, as it can directly impact biodiversity, agriculture, and water resources. Observed precipitation trends and climate change projections over Brazil indicate that many sectors of society are potentially highly vulnerable to the impacts of climate change. The purpose of this study is to assess model projections of the change in rainfall variability at various temporal scales over sub-regions of Brazil. For this, daily data from 30 CMIP5 models for historical (1900-2005) and future (2050-2100) experiments under a high-emission scenario are used. We assess the change in precipitation variability, applying a band-passfilter to isolate variability on daily, weekly, monthly, intra-seasonal, and ENSO time scales. For historical climate, simulated precipitation is evaluated against observations to establish model reliability. The results show that models largely agree on increases in variability on all timescales in all sub-regions, except on ENSO timescales where models do not agree on the sign of future change. Brazil will experience more rainfall variability in the future i.e., drier or more frequent dry periods and wetter wet periods on daily, weekly, monthly and intra-seasonal timescales, even in sub-regions where future changes in mean rainfall are currently uncertain. This may provide useful information for climate change adaptation across, for example, the agriculture and water resource sectors in Brazil.

Keywords: rainfall, variability, climate change, climate extremes, Brazil.

1. Introduction

Brazil has important physical features as well as natural and human systems, such as the Amazon, the largest rainforest in the world (Marengo *et al.*, 2018), the semiarid region of Northeast Brazil (NEB) that occupies an area of about 18 % of the area of Brazil and is the world's most densely populated dry land region (ALVALÁ *et al.*, 2017), the La Plata basin in southeastern South America, which is the fifth largest watershed in the world and an environment of great economic and demographic significance (Llopart *et al.*, 2014), and the Pantanal region, one of the worlds largest wetlands, located in a large floodplain in the center of the upper Paraguay river basin (Marengo *et al.*, 2015). Furthermore, the South America Monsoon System (SAMS) plays a vital role in the precipitation over many Brazilian regions, affecting the economy through impacts on the agriculture and hydrology sectors (Marengo *et al.*, 2012). In addition, geographic features along with remote oceanic-climatic drivers, such as El Nino Southern Oscillation ENSO and Atlantic sea surface temperatures (SST), as well as local drivers such as soil moisture and moisture recycling from vegetation, contribute to a wide variety of climate conditions and their variability over Brazil.

During recent decades Brazil has experienced extreme rainfall events on a range of time scales, with subsequent impacts on natural and human systems. For example, drought in 2005, 2010, 2015-16 (Lewis *et al.*, 2011; Marengo *et al.*, 2018) and flood in 2009, 2013 and 2014 in Amazônia (Marengo *et al.*, 2016, 2018), drought in semiarid Northeast Brazil in 2012-2017 (Brito *et al.*, 2018; Cunha *et al.*, 2018), and drought and water crisis during 2014-15 in South America's largest city, São Paulo (Nobre *et al.*, 2016). About 70% of the disasters are hydro-meteorological in nature, particularly droughts and floods (Santos, 2007). The frequency and severity of other natural disasters include flash floods and landslides have increased, affecting millions in the last decade (CEPED UFSC, 2013). For example, during the Santa Catarina floods in 2008 a landslide killed 113 people (Xavier *et al.*, 2014), Alagoas and Pernambuco experienced the most intense rainy season in 20 years affecting 1 million people, and Rio de Janeiro 2011 flash floods and landslides killed 1000 people (Marengo *et al.*, 2013). Several studies have shown that Brazil can be profoundly impacted by changes in extremes of rainfall and temperature in the present and in the future. This is mostly noted in the north, northeast and southern regions (Marengo *et al.*, 2010b, 2010a; Torres *et al.*, 2012; Christensen *et al.*, 2013; Sillmann *et al.*, 2013).

In recent years, several studies have been conducted using projections of future precipitation change over Brazil derived from global and regional climate models (Alves and Marengo, 2010; Marengo *et al.*, 2010a; Blázquez *et al.*, 2012; Joetzjer *et al.*, 2013; Chou *et al.*, 2014a; Vera and Díaz, 2015; Gulizia and Camilloni, 2015; Sánchez *et al.*, 2015; Yoon, 2016; Cavalcanti and Silveira, 2016; Ambrizzi *et al.*, 2019; Solman and Blázquez, 2019; Díaz *et al.*, 2020). They found a consistent pattern of intense rainfall increases in southern and southeastern Brazil and more dry spells and drought in Amazonia and Northeast Brazil.

Global and regional projections based on Coupled Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012) using the high emission Representative Concentration Pathway RCP8.5 (van Vuuren *et al.*, 2011) generally agree on future regional warming over all Brazilian regions. However, there is much less agreement about mean precipitation changes. Nevertheless, on average, the models largely agree on a precipitation decrease in much of Amazonia and Northeast Brazil in the future. They also agree on increased precipitation in southern Brazil around La Plata basin (Malhi *et al.*, 2009; Chou *et al.*, 2014a, 2014b; Ambrizzi *et al.*, 2019), while there are more uncertainties over the South America Monsoon region.

Torres and Marengo (2013) evaluated the uncertainties in the projections of precipitation changes (future minus present) in South America from CMIP3 and CMIP5 models and concluded that, in general, the models were be able to reproduce the climatological patterns of precipitation, such as the seasonal mean and annual cycle. In these studies, none of the models showed an overall superior performance in reproducing the present climate. The skill of the models varied according to the region, time scale, and variables analyzed.

Changes in the variability of Brazil rainfall coupled with land use changes, notably deforestation, desertification and urbanization, would greatly increase Brazilian vulnerability to climate change. For example, extreme events combined with the mean increase in temperature, as observed during the 2005, 2010 and 2015-16 Amazon droughts, caused a decrease in river flow, an increase in tree mortality and in the number of fires (Aragão *et al.*, 2007, 2018; Marengo *et al.*, 2008; Phillips *et al.*, 2009).

In this context, it is noted that most of the studies have focused on changes of average annual or seasonal rainfall, or differences between the rainy and dry seasons. However, none of these studies have analyzed the future change of daily to interannual precipitation variability of Brazil under a high emissions scenario. Future changes in rainfall variability (intensity and frequency), may have significant impacts on Brazilian society. Therefore, describing and understanding these patterns in the long-term trends is important. In addition, despite the great environmental and socioeconomic implications, they are not yet fully explored in the literature.

A number of previous studies have examined present-day and future changes in rainfall variability on global or regional scales, primarily at the daily or monthly timescale (Lau *et al.*, 2013; Pendergrass and Hartmann, 2014). Model projections generally show increased daily and monthly precipitation variability, with an increase in both the number of dry periods (Polade *et al.*, 2015), conditional wet-period rainfall intensity (Giorgi *et al.*, 2011; Polade *et al.*, 2015), and extreme daily rainfall values (O'Gorman, 2015; Pfahl *et al.*, 2017). This increased variability is due to both warming and the plant physiological response to CO_2 (Skinner *et al.*, 2017). Recently, Brown *et al.*, (2017) introduced a framework for assessing rainfall variability change across timescales from daily to decadal. They applied this method to the Australian, Indian and East Asian monsoon regions, where they found increased variability on daily to decadal timescales. (Pendergrass *et al.*, 2017) also found a global increase in precipitation variability across a range of timescales.

The current study is motivated by the opportunity to increase our knowledge about climate variability in Brazil. Specifically, the purpose of this study is to assess model projections of the future change in rainfall variability and extremes over subregions of Brazil. For this, daily data from global climate model (GCM) projections carried out as part of the CMIP5 program (Taylor *et al.*, 2012) under a high-emission scenario, Representative Concentration Pathway 8.5 (RCP8.5) are used. We assess the future change in precipitation variability by applying a band pass-filter approach (Brown *et al.*, 2017). For this, we use the method proposed by Brown et al., (2017) and apply it regionally to the daily precipitation data from observed datasets and simulated from the CMIP5 global climate model under a high-emission scenario. A fuller description of this method can be found in the next section.

2. Observations, simulations, and analysis methods

a) Observations

Various gridded observational datasets for precipitation are available in the literature and have been widely used for regional climate studies and model assessment in the study region. For instance, Carvalho et al., (2012) analyzed the South American monsoon from multiple precipitation datasets. They concluded that, in general, most of them have an adequate estimation of the major regional features mainly because they adopt the same approach based on satellite information and rain gauge observations. In this study we have used two independent gridded observational datasets as a reference because they provide high spatial resolution and long-term daily precipitation records required for the current study.

Daily rainfall time series was obtained from the INPE/CPTEC merged satellite and rain-gauge product (Rozante *et al.*, 2010) with a spatial resolution of 0.2° for the period 1998-2018 (hereafter called MERGE). The dataset combines Tropical Rainfall Measuring Mission (TRMM) satellite precipitation estimates with rain gauge observations over the South American regions using a successive correction algorithm, which provides better estimates of land surface precipitation over areas with sparse observations. The second observational dataset used is the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk *et al.*, 2014, 2015). CHIRPS is a relatively new rainfall product with a spatial resolution of 0.05°, starting from 1981 to near present. This dataset integrates satellite imagery with *in situ* rain gauge station data to create gridded rainfall time series. This dataset has a good performance in several regions of the world (Maidment *et al.*, 2015; Zambrano *et al.*, 2017; Zittis, 2018; Espinoza *et al.*, 2019; Rivera *et al.*, 2019).

b) Simulations

We also have used daily precipitation data from 30 global coupled climate models for historical (1950-2000) and future (2050-2100) under a high-emission scenario, Representative Concentration Pathway 8.5 (RCP8.5) for CMIP5 (Table 1; Taylor *et al.*, 2012). All data (models and observation) were regridded to 2.5 degree horizontal resolution, in order to perform a fair comparison across different products. All models results are from the experiment using the r1i1p1 ensemble member.

Table 1 – List of CMIP5 models used in this study

c) Analysis

The main focus of this analysis is to assess the future change in precipitation variability for 30 coupled models from the CMIP5 archive over Brazil applying a band pass-filtered technique developed by Brown *et al.*, (2017) using the following bands: “daily” (1-5 days), “weekly” (5-10 days), “monthly” (25-35 days), “intraseasonal” (30-80 days), and “ENSO” (2-8 years) to isolate variability on these time scales. For historical climate, simulated precipitation is first evaluated against observations to establish model reliability. The period 2050-2100 is used for RCP8.5 models. The present-day period is a hybrid though, to match up the same time period between models and observation. For all timescales except ENSO this is 1998-2018 for CHIRPS, Merge and models (which concatenate historical and RCP8.5 runs to get this time period). For ENSO is used 1981-2018 for CHIRPS and models.

A fast Fourier transformation was used to transform detrended data from observations and historical and future model experiments into the frequency (spectral) domain. Data detrending technique is applied to precipitation time series in order for the bandpass filter to cleanly separate different timescales of variability and avoid long-term trend introduce errors into the filtered time-series. For each frequency band of interest, all frequencies outside that band were set to zero and the remaining data were transformed back to the time domain.

The band-pass filtering was performed separately on each observational/model grid-point, and the standard deviation of each band-pass filtered time-series was calculated at each grid-point. The standard deviations were then spatially averaged over several key areas of Brazil, as highlighted in Figure 1 during the peak rainy season and following domains: (NAZ) northern Amazon (JFMAM, 5^oS-5^oN, 70^oW-45^oW), (SAZ) southern

Amazon (NDJFM, 12.5^{o}S-5^{o}S, 70^{o}W-45^{o}W), (NEB) northeast Brazil (FMAM, 15^{o}S-2^{o}S, 45^{o}S-34^{o}W), (SAM) South America Monsoon (NDJFM, 20^{o}S-10^{o}S, 55^{o}W-45^{o}W), (LPB) La Plata Basin (NDJFM, 35^{o}S-20^{o}S, 65^{o}W-45^{o}W). These regions were used in several previous regional syntheses of observed and model projection analyses (Marengo *et al.*, 2003; Raia and Cavalcanti, 2008; Nobre *et al.*, 2016; Alves *et al.*, 2017). These areas were selected because they exhibit a well-identified seasonal cycle of precipitation and represent sub-continental regions of broadly climatic coherency in all the domains and reflecting the relevance of these areas to the studies of the Brazilian biomes, climatic, hydrological, and social systems.

3. Results

Several studies have evaluated the performance of CMIP5 models in simulating precipitation variability over South America for the present-day (Yin *et al.*, 2012; Jones and Carvalho, 2013b; Knutti and Sedlacek, 2013; Torres and Marengo, 2013). The climate model performance to represent the mean climate variability is discussed compared to observed (MERGE and CHIRPS datasets), and the CMIP5 ensemble mean precipitation for the historical period (Figure 2).

The results show that the multi-model ensemble reproduces the observed climatology features of precipitation over South America, such as spatial variability of the precipitation over central South America reasonably (Figure 2a-c). However, even with substantial progress made during the last decade in the development of climate models, the results show systematic errors (dry biases) in simulating precipitation variability over the Amazon and La Plata remains in CMIP5 models. Similar results were also noted by previous studies (Jones and Carvalho, 2013b; Gulizia and Camilloni, 2015). The dry-day fraction (Figure 2g-i) patterns are smoothed in the ensemble mean compared to the observations patterns, especially across NEB and SAM regions. Also, for conditional wet-day rainfall (days with rainfall > 1mm/day), the multi-model ensemble tends to underestimate intense rainfall (Figure 2j-l).

While the focus is on band-pass-filtered analysis over several key areas of Brazil, first we present a broader geographical perspective, showing the future changes in mean rainfall, unfiltered daily rainfall variability, dry-day fraction and conditional wet-day intensity in the models (Figure 3). The dry-day threshold is 1mm/day. The wet-day intensity is the mean precipitation on days with rainfall above the dry-day threshold. The rainfall variability on all timescales is defined using the standard deviation. The dry-day fraction (%) is the percentage of days in each season that have rainfall less than the dry-day threshold.

In general, model projections show that precipitation changes will occur in rainfall amount, intensity, and frequency. Some regional differences are noted, with some areas having significant increases, and others decrease. A wetter mean climate is projected for southern Brazil, and a drier mean climate for the Amazon and northeastern Brazil. Despite model disagreement on mean rainfall changes over many parts of Brazil, there is strong model agreement on an increase in the standard deviation of daily precipitation across all of Brazil, though the reason for this may differ by region. There are widespread increases in the intensity of wet days for the period 2050-2100 as compared to present-day in southern Brazil, and even in areas where significant decreases in rainfall are projected, like northeast Brazil (Figure 3d). On the other hand, the percentage of dry days is projected to increase more than 8 %/year, a result the models agree on (Figure 3c) in parts of northern Brazil. The multi-model mean changes indicate that southern Brazil will have higher rainfall variability (Figure 3b and d), as well as high mean rainfall amounts (Figure 3a) in future climate.

The analysis is now extended to assess the skill and projected changes by climate models to simulate the rainfall variability for a range of time scales from daily to ENSO. The variability over each of the Brazil selected areas was calculated using band-pass-filtered daily anomalies for 50 years of the historical (HIST) and future climate (RCP8.5) simulations, following the method described in section 2 and for wet season months only (January-May, JFMAM, for northern Amazonia (NAZ), February-May, FMAM for northeast Brazil (NEB), and November-March, NDJFM for southern Amazonia (SAZ), South America Monsoon (SAM) and La Plata basin (LPB).

Figure 4 shows a set of box plots of the standard deviation of daily rainfall anomalies in each of the time bands for the spread of model variability in the HIST simulation (blue boxes), the RCP8.5 simulation (pink boxes) and the difference RCP8.5 minus HIST (grey boxes) as well as for observational gridded datasets from CHIRPS (red squares) and MERGE (blue squares) observations overlaid on the HIST box plots. Note that the value for the ENSO time band is multiplied by 5 in Figure 4 for more precise visualization.

On short time scales (daily (1-5 days) and weekly (5-10 days)) the models show most substantial variability in their respective wet seasons over all regions and, as a whole, there is a lack of model agreement in rainfall variability, with the observations lying outside the interquartile range, particularly in daily rainfall variability and in the northern Amazonia. On the other hand, the model variability and observations show reasonably good agreement at the weekly, monthly (25-35 days) and intra-seasonal (30-80 days) time bands for all regions investigated in this study, i.e, we note that the observation values fell within the inter-quartile range of GCMs.

This result may be because CMIP5 ensemble have shown improvements to the simulation of regional patterns of precipitation compared to previous generation of climate models (Sperber et al., 2013), particularly due to substantial improvement in representations of sub-grid scale processes, such as convection (Neale et al., 2008) or representation of cloud physics (Khairoutdinov et al., 2005), in conjunction with an increase in atmospheric resolution (Ploshay and Lau, 2010; Delworth et al., 2012). It is also likely to be because the models are better able to capture large-scale patterns of circulation and variability than individual smaller scale synoptic and convective rainfall events (Flato et al., 2013). However, although the previous results suggest with confidence that models reproduce regional rainfall variability on a wide range of time scales, several studies have shown that GCMs don’t simulate rainfall variability well on daily-to-weekly time scales, particularly in the tropics (Westra et al., 2014).

These results pose a challenge for interpreting the sign of projections of changes in mean rainfall due to future climate change because this suggests that the coarsest-resolution models do not replicate mesoscale circulations induced by regional features that are associated with convective precipitation and subgrid convection parameterization schemes (Watson *et al.*, 2017). Furthermore, it is essential to note that the lack of adequate and robust observational information on precipitation, especially over northern Amazonia, also poses great difficulties in validating climate model outputs. Another possible cause of the aforementioned model-observation disagreement may be the horizontal resolution differences, since the biases usually are highly sensitive to model spatial resolution.

There are significant regional differences. For instance, southern Amazonia (Figure 4b) has more variability compared with northern Amazonia (Figure 4a) and this difference is associated with the annual cycle of rainfall where rainfall in northern peaks in March-May and that in southern peaks in December-February. These differences are also associated with land atmosphere interactions and sea surface variability over both the Atlantic and Pacific oceans (Marengo *et al.*, 2001; Fu and Li, 2004). More recent, Espinoza *et al.*, (2019) also show climatic differences between regions, for instance, while southern Amazonia exhibits negative trends in total rainfall and extremes, the opposite is found in Northern Amazonia.

Strong interannual rainfall variability is a major climatological feature in northeast Brazil (NEB). It is influenced by the SST in the tropical Pacific and Atlantic oceans (Marengo *et al.*, 2020). Furthermore, the mean precipitation during the wet season (FMAM) is primarily influenced by north-south displacements of the Intertropical Convergence Zone (ITCZ) (Hastenrath, 2012). In Figure 4c, the variability for the NEB rainy season is shown. It is interesting to note that a large model spread is observed for all timescales. Another feature noted is reasonable agreement between models and observations for all except mean and ENSO time-scales. Concerning median change (gray boxes), for NEB, coherently positive values were found for all time scales, indicating an increase in rainfall variability. On the other hand, some models do project a decrease in rainfall variability for the NEB.

Additionally, both South America Monsoon (SAM) (Figure 4b) and La Plata basin (LPB) (Figure 4e) areas overall show similar rainfall variability characteristics for all-time bands. However, there are significant regional differences in the intensities and variability (interquartile range), particularly among mean, daily (1-5 days) and weekly (5–10 days) time scales. Frontal systems and the South Atlantic Convergence Zone (SACZ) (Raia and Cavalcanti, 2008; Jones and Carvalho, 2013a) particularly affect the rainfall variability within the rainy season in the SAM, between December and February. On the other hand, the LPB is associated with incursions of frontal systems and Mesoscale Convective

Complexes (MCCs) (Silva and Berbery, 2006). It is also noteworthy that the main feature of rainfall variability in these regions occurs in a dipole pattern because, when it is wet over the SAM region, the LPB is relatively dry, and vice-versa, which appears in all timescales, from intraseasonal to interdecadal (Grimm and Saboia, 2015). In general, the models are able to simulate the observed rainfall variability for various time bands, although the model rainfall variability may be somewhat underestimated at daily and weekly timescales. The median change (gray boxes) in SAM and LPB rainfall variability is positive for almost all time scales, indicating that rainfall variability is increased in more than half of climate models. Negative values at the lower tail are present for all time scales, especially in the SAM region, indicating that some models project reduced future rainfall variability.

Though this study provides a clear picture of how rainfall over Brazil will respond to climate change and offer robust policy-relevant climate projections, there remain many outstanding issues that illustrate the need of future work to address them. These include the impact of internal variability (Hawkins and Sutton, 2009), potential effects of different stressor, such as land-use change and fires (Spracklen *et al.*, 2018), ocean-atmosphere feedbacks (Cai *et al.*, 2020) and high-resolution simulations, based on Regional Climate Models (RCMs) (Giorgi *et al.*, 2012) and Convection-Permitting Models (CPMs) (Coppola *et al.*, 2020), which could lead to a better representation of both the spatial patterns and magnitudes of mean climate and climate extremes, especially in regions of strong surface heterogeneity.

Figure 5 illustrates similarities and differences in rainfall variability change for each of the Brazilian sub-regions. Overall, all projected changes are fairly similar across different regions, i.e., an increase in rainfall variability, generally about 10% for all study regions and for all time scales, which is consistent with previous studies that found climate models generally project large rainfall changes over the twenty-first century under global warming (Brown *et al.*, 2017; Pendergrass *et al.*, 2017). While significant inter-model uncertainty in the future projections is observed on the daily and weekly time scale, models project an increase in the median change in variability for all sub-annual time bands in most regions – in other words, rainfall variability is increased in the majority of models for all timescales except "ENSO" variability. Despite ENSO variability being a key feature for Brazilian climate (Grimm, 2011) there is also no consistent signal of

ENSO precipitation change, consistent with Power and Delage (2018). Similarly, there is no consistent signal of mean precipitation change in most regions.

In summary, the results varies with regions, however, model projections indicate that the response of precipitation variability due to global warming could be substantially increased in most of the sub-regions (Figure 5), leading to an increase in extremes over the coming century (Figure 3). This is consistent with previous research showing projected hydroclimatic changes (Junquas *et al.*, 2012; Collins *et al.*, 2013; Hegerl *et al.*, 2015; Ambrizzi *et al.*, 2019) which can have multiple and significant impacts on the hydrological cycle and a variety of sectors (Magrin *et al.*, 2014).

4. Summary and Conclusions

This study assesses the rainfall variability and future change across Brazilian regions from the model projections of climate change available through the CMIP5 under the RCP8.5 scenario for a range of time scales from daily to ENSO. Band-pass-filtering was used to isolate variability on each time scale, and the range of model rainfall standard deviations was calculated for historical (HIST) and future (RCP8.5) climates.

In general, a comparison of the various climate model data used in this assessment provides a consistent picture of the large-scale projected precipitation changes across Brazil. This analysis suggests Brazil will experience more rainfall variability in the future i.e., the numbers of dry periods are increased, and the intensity of rainfall when it does rain is increased. However, the number/length of wet periods are not increased, primarily over the Amazonia, northeast Brazil and La Plata basin (Figure 3) areas already pointed as socio-climatic hotspots (Torres *et al.*, 2012) .

There is also a model consensus on the change in rainfall variability at all sub-annual timescales. GCMs robustly project increased rainfall variability (measured by the mean standard deviation) from daily to intra-seasonal timescales over all study areas (Figure 5). In most regions, the increase in precipitation variability is at least as large and in many cases greater than the increase in mean precipitation, even in regions where the future change in mean rainfall is currently uncertain. Similar results are found by Pendergrass *et al.*, (2017) and are attributed to a robust emergent aspect of the water cycle that is changing as a result of anthropogenic warming.

Overall, CMIP5 model projections indicate that both the frequency and intensity of the strong ENSO events will increase under high emissions scenarios (Cai *et al.*, 2018; Wang *et al.*, 2019). However, the results show that there is no robust change in precipitation variability at ENSO timescales over Brazil, in contrast with the results of Brown *et al.*, (2017) for the Indian, East Asian, and Australian monsoon regions.

This may provide useful information to policymakers for advising some suitable adaptation and mitigation policies to cope with anticipated climate variability and climate change, especially in the agriculture and water resource sectors in Brazil as well on the risk of fire and natural disasters of hydro meteorological nature.

On the other hand, at the regional scales, in recent years there have been an increasing number of observed studies that showed the precipitation distribution, including both spatial pattern and extreme rainfall is change under the ongoing anthropogenic warming (Meehl *et al.*, 2007; Zhang *et al.*, 2013; Zhang and Zhou, 2019). These studies have also demonstrated local land surface-atmospheric processes have played an important role in driving intensity and frequency of rainfall variability at a regional scale. However, a comprehensive assessment of land surface feedbacks on climate variability and climate change in the current climate models is still a challenge, mainly due to the low spatial resolution of the models.

Thus, further work is required to investigate the local and regional drivers of these changes, for instance, land use and cover change and fire, associated with climate model improvements and long-term regional climate observations to better understand the underlying rainfall variability and change in Brazil. Further research is recommended to explore a wider set of plausible outcomes include use of high-resolution simulations, such as Regional Climate Models (RCMs) and Convection-Permitting Model (CPM), potentially providing more useful information to policymakers than is currently available for advising on suitable adaptation and mitigation policies to cope with anticipated climate variability and climate change, especially in the agriculture and water resource sectors in Brazil as well on the risk of fire and natural disasters of hydro meteorological nature.

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References

ALVALÁ RCS, CUNHA APMA, BRITO SSB, SELUCHI ME, MARENGO JA, MORAES OLL, CARVALHO MA. 2017. Drought monitoring in the Brazilian Semiarid region. *Anais da Academia Brasileira de Ciências*, 91(suppl 1). https://doi.org/10.1590/0001-3765201720170209.

Alves LM, Marengo J. 2010. Assessment of regional seasonal predictability using the PRECIS regional climate modeling system over South America. *Theoretical and Applied Climatology*, 100(3–4): 337–350. https://doi.org/10.1007/s00704-009-0165-2.

Alves LM, Marengo JA, Fu R, Bombardi RJ. 2017. Sensitivity of Amazon Regional Climate to Deforestation. *American Journal of Climate Change*, 06(01): 75–98. https://doi.org/10.4236/ajcc.2017.61005.

Ambrizzi T, Reboita MS, da Rocha RP, Llopart M. 2019. The state of the art and fundamental aspects of regional climate modeling in South America. *Annals of the New York Academy of Sciences*, 1436(1): 98–120. https://doi.org/10.1111/nyas.13932.

Aragão LEOC, Anderson LO, Fonseca MG, Rosan TM, Vedovato LB, Wagner FH, Silva CVJ, Silva Junior CHL, Arai E, Aguiar AP, Barlow J, Berenguer E, Deeter MN, Domingues LG, Gatti L, Gloor M, Malhi Y, Marengo JA, Miller JB, Phillips OL, Saatchi S. 2018. 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*, 9(1): 536. https://doi.org/10.1038/s41467-017-02771-y.

Aragão LEOC, Malhi Y, Roman-Cuesta RM, Saatchi S, Anderson LO, Shimabukuro YE. 2007. Spatial patterns and fire response of recent Amazonian droughts. *Geophysical Research Letters*, 34(7): L07701. https://doi.org/10.1029/2006GL028946.

Blázquez J, Nestor Nuñez M, Kusunoki S. 2012. Climate Projections and Uncertainties over South America from MRI/JMA Global Model Experiments. *Atmospheric and Climate Sciences*, 02(04): 381–400. https://doi.org/10.4236/acs.2012.24034.

Brito SSB, Cunha APMA, Cunningham CC, Alvalá RC, Marengo JA, Carvalho MA. 2018. Frequency, duration and severity of drought in the Semiarid Northeast Brazil region. *International Journal of Climatology*, 38(2): 517–529. https://doi.org/10.1002/joc.5225.

Brown JR, Moise AF, Colman RA. 2017. Projected increases in daily to decadal variability of Asian-Australian monsoon rainfall. *Geophysical Research Letters*, 44(11): 5683–5690. https://doi.org/10.1002/2017GL073217.

Cai W, McPhaden MJ, Grimm AM, Rodrigues RR, Taschetto AS, Garreaud RD, Dewitte B, Poveda G, Ham Y-G, Santoso A, Ng B, Anderson W, Wang G, Geng T, Jo H-S, Marengo JA, Alves LM, Osman M, Li S, Wu L, Karamperidou C, Takahashi K, Vera C. 2020. Climate impacts of the El Niño–Southern Oscillation on South America. *Nature Reviews Earth & Environment*, 1(4): 215–231. https://doi.org/10.1038/s43017-020-0040-3.

Cai W, Wang G, Dewitte B, Wu L, Santoso A, Takahashi K, Yang Y, Carréric A, McPhaden MJ. 2018. Increased variability of eastern Pacific El Niño under greenhouse warming. *Nature*, 564(7735): 201–206. https://doi.org/10.1038/s41586-018-0776-9.

Carvalho LM V, Jones C, Posadas AND, Quiroz R, Bookhagen B, Liebmann B. 2012. Precipitation Characteristics of the South American Monsoon System Derived from Multiple Datasets. *Journal of Climate*. American Meteorological Society, 25(13): 4600–4620. https://doi.org/10.1175/JCLI-D-11-00335.1.

Cavalcanti I, Silveira V. 2016. Changes in precipitation over the La Plata Basin, projected by CLARIS-LPB regional models. *Climate Research*, 68(2–3): 169–182. https://doi.org/10.3354/cr01388.

CEPED UFSC. 2013. *Atlas Brasileiro de Desastres Naturais: 1991 a 2012*. Centro Universitário de Estudos e Pesquisas sobre Desastres: Florianópolis.

Chou SC, Lyra A, Mourão C, Dereczynski C, Pilotto I, Gomes J, Bustamante J, Tavares P, Silva A, Rodrigues D, Campos D, Chagas D, Sueiro G, Siqueira G, Marengo J. 2014a. Assessment of Climate Change over South America under RCP 4.5 and 8.5 Downscaling Scenarios. *American Journal of Climate Change*, 03(05): 512–527. https://doi.org/10.4236/ajcc.2014.35043.

Chou SC, Lyra A, Mourão C, Dereczynski C, Pilotto I, Gomes J, Bustamante J, Tavares P, Silva A, Rodrigues D, Campos D, Chagas D, Sueiro G, Siqueira G, Nobre P, Marengo J. 2014b. Evaluation of the Eta Simulations Nested in Three Global Climate Models. *American Journal of Climate Change*, 03(05): 438–454. https://doi.org/10.4236/ajcc.2014.35039.

Christensen JH, Kanikicharla KK, Aldrian E, An S Il, Albuquerque Cavalcanti IF, de Castro M, Dong W, Goswami P, Hall A, Kanyanga JK, Kitoh A, Kossin J, Lau NC, Renwick J, Stephenson DB, Xie SP, Zhou T, Abraham L, Ambrizzi T, Anderson B, Arakawa O, Arritt R, Baldwin M, Barlow M, Barriopedro D, Biasutti M, Biner S, Bromwich D, Brown J, Cai W, Carvalho L V., Chang P, Chen X, Choi J, Christensen OB, Deser C, Emanuel K, Endo H, Enfield DB, Evan A, Giannini A, Gillett N, Hariharasubramanian A, Huang P, Jones J, Karumuri A, Katzfey J, Kjellström E, Knight J, Knutson T, Kulkarni A, Kundeti KR, Lau WK, Lenderink G, Lennard C, Leung L yung R, Lin R, Losada T, Mackellar NC, Magaña V, Marshall G, Mearns L, Meehl G, Menéndez C, Murakami H, Nath MJ, Neelin JD, van Oldenborgh GJ, Olesen M, Polcher J, Qian Y, Ray S, Reich KD, de Fonseca BR, Ruti P, Screen J, Sedláček J, Solman S, Stendel M, Stevenson S, Takayabu I, Turner J, Ummenhofer C, Walsh K, Wang B, Wang C, Watterson I, Widlansky M, Wittenberg A, Woollings T, Yeh SW, Zhang C, Zhang L, Zheng X, Zou L. 2013. Climate phenomena and their relevance for future regional climate change. In: Intergovernmental Panel on Climate Change (ed) *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, 1217–1308.

Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, Friedlingstein P, Gao X, Gutowski WJ, T. Johns G, Krinner MS, Tebaldi C, Weaver AJ, Wehner M. 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. In: Stocker TF, D. Qin G-K, Plattner MT, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: United Kingdom, 1029–1136.

Coppola E, Sobolowski S, Pichelli E, Raffaele F, Ahrens B, Anders I, Ban N, Bastin S, Belda M, Belusic D, Caldas-Alvarez A, Cardoso RM, Davolio S, Dobler A, Fernandez J, Fita L, Fumiere Q, Giorgi F, Goergen K, Güttler I, Halenka T, Heinzeller D, Hodnebrog Ø, Jacob D, Kartsios S, Katragkou E, Kendon E, Khodayar S, Kunstmann H, Knist S, Lavín-Gullón A, Lind P, Lorenz T, Maraun D, Marelle L, van Meijgaard E, Milovac J, Myhre G, Panitz H-J, Piazza M, Raffa M, Raub T, Rockel B, Schär C, Sieck K, Soares PMM, Somot S, Srnec L, Stocchi P, Tölle MH, Truhetz H, Vautard R, de Vries H, Warrach-Sagi K. 2020. A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean. *Climate Dynamics*, 55(1–2): 3–34.

https://doi.org/10.1007/s00382-018-4521-8.

Cunha APMA, Tomasella J, Ribeiro-Neto GG, Brown M, Garcia SR, Brito SB, Carvalho MA. 2018. Changes in the spatial-temporal patterns of droughts in the Brazilian Northeast. *Atmospheric Science Letters*, 19(10): e855. https://doi.org/10.1002/asl.855.

Delworth TL, Rosati A, Anderson W, Adcroft AJ, Balaji V, Benson R, Dixon K, Griffies SM, Lee H-C, Pacanowski RC, Vecchi GA, Wittenberg AT, Zeng F, Zhang R. 2012. Simulated Climate and Climate Change in the GFDL CM2.5 High-Resolution Coupled Climate Model. *Journal of Climate*, 25(8): 2755–2781. https://doi.org/10.1175/JCLI-D-11-00316.1.

Díaz LB, Saurral RI, Vera CS. 2020. Assessment of South America summer rainfall climatology and trends in a set of global climate models large ensembles. *International Journal of Climatology*, joc.6643. https://doi.org/10.1002/joc.6643.

Espinoza JC, Ronchail J, Marengo JA, Segura H. 2019. Contrasting North–South changes in Amazon wet-day and dry-day frequency and related atmospheric features (1981–2017). *Climate Dynamics*, 52(9–10): 5413–5430. https://doi.org/10.1007/s00382-018-4462-2.

Flato G, Marotzke J, Abiodun B, Braconnot P, Chou SC, Collins W, Cox P, Driouech F, Emori S, Eyring V, Forest C, Gleckler P, Guilyardi E, Jakob C, Kattsov V, Reason C, Rummukainen M. 2013. Evaluation of Climate Models. In: Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia VB and PMM (ed) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: Cambridge, 741–866.

Fu R, Li W. 2004. The influence of the land surface on the transition from dry to wet season in Amazonia. *Theoretical and Applied Climatology*, 78(1–3). https://doi.org/10.1007/s00704-004-0046-7.

Funk C, Peterson P, Landsfeld M, Pedreros D, Verdin J, Shukla S, Husak G, Rowland J, Harrison L, Hoell A, Michaelsen J. 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific Data*, 2(1): 150066. https://doi.org/10.1038/sdata.2015.66.

Funk CC, Peterson PJ, Landsfeld MF, Pedreros DH, Verdin JP, Rowland JD, Romero BE, Husak GJ, Michaelsen JC, Verdin A. 2014. *A quasi-global precipitation time series for drought monitoring: U.S*. Sioux Falls.

Giorgi F, Coppola E, Solmon F, Mariotti L, Sylla M, Bi X, Elguindi N, Diro G, Nair V, Giuliani G, Turuncoglu U, Cozzini S, Güttler I, O'Brien T, Tawfik A, Shalaby A, Zakey A, Steiner A, Stordal F, Sloan L, Brankovic C. 2012. RegCM4: model description and preliminary tests over multiple CORDEX domains. *Climate Research*, 52: 7–29. https://doi.org/10.3354/cr01018.

Giorgi F, Im E-S, Coppola E, Diffenbaugh NS, Gao XJ, Mariotti L, Shi Y. 2011. Higher Hydroclimatic Intensity with Global Warming. *Journal of Climate*, 24(20): 5309–5324. https://doi.org/10.1175/2011JCLI3979.1.

Grimm AM. 2011. Interannual climate variability in South America: impacts on seasonal precipitation, extreme events, and possible effects of climate change. *Stochastic Environmental Research and Risk Assessment*, 25(4): 537–554. https://doi.org/10.1007/s00477-010-0420-1.

Grimm AM, Saboia JPJ. 2015. Interdecadal Variability of the South American Precipitation in the Monsoon Season. *Journal of Climate*, 28(2): 755–775. https://doi.org/10.1175/JCLI-D-14-00046.1.

Gulizia C, Camilloni I. 2015. Comparative analysis of the ability of a set of CMIP3 and CMIP5 global climate models to represent precipitation in South America. *International Journal of Climatology*, 35(4): 583–595. https://doi.org/10.1002/joc.4005.

Hastenrath S. 2012. Exploring the climate problems of Brazil's Nordeste: a review. *Climatic Change*, 112(2): 243–251. https://doi.org/10.1007/s10584-011-0227-1.

Hawkins E, Sutton R. 2009. The Potential to Narrow Uncertainty in Regional Climate Predictions. *Bulletin of the American Meteorological Society*, 90(8): 1095–1108. https://doi.org/10.1175/2009BAMS2607.1.

Hegerl GC, Black E, Allan RP, Ingram WJ, Polson D, Trenberth KE, Chadwick RS, Arkin PA, Sarojini BB, Becker A, Dai A, Durack PJ, Easterling D, Fowler HJ, Kendon EJ, Huffman GJ, Liu C, Marsh R, New M, Osborn TJ, Skliris N, Stott PA, Vidale P-L, Wijffels SE, Wilcox LJ, Willett KM, Zhang X. 2015. Challenges in Quantifying Changes in the Global Water Cycle. *Bulletin of the American Meteorological Society*, 96(7): 1097–1115. https://doi.org/10.1175/BAMS-D-13-00212.1.

Joetzjer E, Douville H, Delire C, Ciais P. 2013. Present-day and future Amazonian precipitation in global climate models: CMIP5 versus CMIP3. *Climate Dynamics*, 41(11–12): 2921–2936. https://doi.org/10.1007/s00382-012-1644-1.

Jones C, Carvalho LM V. 2013a. Climate Change in the South American Monsoon System: Present Climate and CMIP5 Projections. *Journal of Climate*, 26(17): 6660–6678. https://doi.org/10.1175/JCLI-D-12-00412.1.

Jones C, Carvalho LM V. 2013b. Climate Change in the South American Monsoon System: Present Climate and CMIP5 Projections. *Journal of Climate*. American Meteorological Society, 26(17): 6660–6678. https://doi.org/10.1175/JCLI-D-12-00412.1.

Junquas C, Vera C, Li L, Le Treut H. 2012. Summer precipitation variability over Southeastern South America in a global warming scenario. *Climate Dynamics*, 38(9–10): 1867–1883. https://doi.org/10.1007/s00382-011-1141-y.

Khairoutdinov M, Randall D, DeMott C. 2005. Simulations of the Atmospheric General Circulation Using a Cloud-Resolving Model as a Superparameterization of Physical Processes. *Journal of the Atmospheric Sciences*, 62(7): 2136–2154. https://doi.org/10.1175/JAS3453.1.

Knutti R, Sedlacek J. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Clim. Change*. Nature Publishing Group, 3(4): 369–373.

Lau WK-M, Wu H-T, Kim K-M. 2013. A canonical response of precipitation characteristics to global warming from CMIP5 models. *Geophysical Research Letters*, 40(12): 3163–3169. https://doi.org/10.1002/grl.50420.

Lewis SL, Brando PM, Phillips OL, van der Heijden GMF, Nepstad D. 2011. The 2010 Amazon Drought. *Science*, 331(6017): 554.

Llopart M, Coppola E, Giorgi F, da Rocha RP, Cuadra S V. 2014. Climate change impact on precipitation for the Amazon and La Plata basins. *Climatic Change*, 125(1): 111–125. https://doi.org/10.1007/s10584-014-1140-1.

Magrin GO, Marengo JA, Boulanger J-P, Buckeridge MS, Castellanos E, Poveda G, Scarano FR, Vicuña S. 2014. Central and South America. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR and White LL (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, 1499–1566.

Maidment RI, Allan RP, Black E. 2015. Recent observed and simulated changes in precipitation over Africa. *Geophysical Research Letters*, 42(19): 8155–8164. https://doi.org/10.1002/2015GL065765.

Malhi Y, Aragao LEOC, Galbraith D, Huntingford C, Fisher R, Zelazowski P, Sitch S, McSweeney C, Meir P. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences*, 106(49): 20610–20615. https://doi.org/10.1073/pnas.0804619106.

Marengo JA, Ambrizzi T, da Rocha RP, Alves LM, Cuadra S V., Valverde MC, Torres RR, Santos DC, Ferraz SET. 2010a. Future change of climate in South America in the late twenty-first century: intercomparison of scenarios from three regional climate models. *Climate Dynamics*, 35(6): 1073–1097. https://doi.org/10.1007/s00382-009-0721-6.

Marengo JA, Cavalcanti IFA, Satyamurty P, Trosnikov I, Nobre CA, Bonatti JP, Camargo H, Sampaio G, Sanches MB, Manzi AO, Castro CAC, D'Almeida C, Pezzi LP, Candido L. 2003. Assessment of regional seasonal rainfall predictability using the CPTEC/COLA atmospheric GCM. *Climate Dynamics*, 21(5–6): 459–475. https://doi.org/10.1007/s00382-003-0346-0.

Marengo JA, Chou SC, Kay G, Alves LM, Pesquero JF, Soares WR, Santos DC, Lyra AA, Sueiro G, Betts R, Chagas DJ, Gomes JL, Bustamante JF, Tavares P. 2012. Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. *Climate Dynamics*, 38(9–10): 1829–1848. https://doi.org/10.1007/s00382-011-1155-5.

Marengo JA, Cunha APMA, Nobre CA, Ribeiro Neto GG, Magalhaes AR, Torres RR, Sampaio G, Alexandre F, Alves LM, Cuartas LA, Deusdará KRL, Álvala RCS. 2020. Assessing drought in the drylands of northeast Brazil under regional warming exceeding 4 °C. *Natural Hazards*. https://doi.org/10.1007/s11069-020-04097-3.

Marengo JA, Liebmann B, Kousky VE, Filizola NP, Wainer IC. 2001. Onset and End of the Rainy Season in the Brazilian Amazon Basin. *Journal of Climate*, 14(5): 833–852. https://doi.org/10.1175/1520-0442(2001)014<0833:OAEOTR>2.0.CO;2.

Marengo JA, Nobre CA, Tomasella J, Oyama MD, Sampaio de Oliveira G, de Oliveira R, Camargo H, Alves LM, Brown IF. 2008. The Drought of Amazonia in 2005. *Journal of Climate*, 21(3): 495–516. https://doi.org/10.1175/2007JCLI1600.1.

Marengo JA, Oliveira GS, Alves LM. 2015. Climate Change Scenarios in the Pantanal. , 227–238.

Marengo JA, Ronchail J, Alves LA. 2013. Tropical South America east of the Andes. *State of the Climate in 2013*. Bulletin of the American Meteorological Society, 94: S159–S160.

Marengo JA, Rusticucci M, Penalba O, Renom M. 2010b. An intercomparison of observed and simulated extreme rainfall and temperature events during the last half of the twentieth century: part 2: historical trends. *Climatic Change*, 98(3–4): 509–529. https://doi.org/10.1007/s10584-009-9743-7.

Marengo JA, Souza CM, Thonicke K, Burton C, Halladay K, Betts RA, Alves LM, Soares WR. 2018. Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. *Frontiers in Earth Science*, 6. https://doi.org/10.3389/feart.2018.00228.

Marengo JA, Williams ER, Alves LM, Soares WR, Rodriguez DA. 2016. Extreme Seasonal Climate Variations in the Amazon Basin: Droughts and Floods. , 55–76.

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao Z-C. 2007. Global Climate Projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press Cambridge: United Kingdom, 747–845.

Neale RB, Richter JH, Jochum M. 2008. The Impact of Convection on ENSO: From a Delayed Oscillator to a Series of Events. *Journal of Climate*, 21(22): 5904–5924. https://doi.org/10.1175/2008JCLI2244.1.

Nobre CA, Marengo JA, Seluchi ME, Cuartas LA, Alves LM. 2016. Some Characteristics and Impacts of the Drought and Water Crisis in Southeastern Brazil during 2014 and 2015. *Journal of Water Resource and Protection*, 08(02): 252–262. https://doi.org/10.4236/jwarp.2016.82022.

O'Gorman PA. 2015. Precipitation Extremes Under Climate Change. *Current Climate Change Reports*, 1(2): 49–59. https://doi.org/10.1007/s40641-015-0009-3.

Pendergrass AG, Hartmann DL. 2014. Two Modes of Change of the Distribution of Rain. *Journal of Climate*, 27(22): 8357–8371. https://doi.org/10.1175/JCLI-D-14-00182.1.

Pendergrass AG, Knutti R, Lehner F, Deser C, Sanderson BM. 2017. Precipitation variability increases in a warmer climate. *Scientific Reports*, 7(1): 17966. https://doi.org/10.1038/s41598-017-17966-y.

Pfahl S, O'Gorman PA, Fischer EM. 2017. Understanding the regional pattern of projected future changes in extreme precipitation. *Nature Climate Change*, 7(6): 423–427. https://doi.org/10.1038/nclimate3287.

Phillips OL, Aragao LEOC, Lewis SL, Fisher JB, Lloyd J, Lopez-Gonzalez G, Malhi Y, Monteagudo A, Peacock J, Quesada CA, van der Heijden G, Almeida S, Amaral I, Arroyo L, Aymard G, Baker TR, Banki O, Blanc L, Bonal D, Brando P, Chave J, de Oliveira ACA, Cardozo ND, Czimczik CI, Feldpausch TR, Freitas MA, Gloor E, Higuchi N, Jimenez E, Lloyd G, Meir P, Mendoza C, Morel A, Neill DA, Nepstad D, Patino S, Penuela MC, Prieto A, Ramirez F, Schwarz M, Silva J, Silveira M, Thomas AS, Steege H t., Stropp J, Vasquez R, Zelazowski P, Davila EA, Andelman S, Andrade A, Chao K-J, Erwin T, Di Fiore A, C. EH, Keeling H, Killeen TJ, Laurance WF, Cruz AP, Pitman NCA, Vargas PN, Ramirez-Angulo H, Rudas A, Salamao R, Silva N, Terborgh J, Torres-Lezama A. 2009. Drought Sensitivity of the Amazon Rainforest. *Science*, 323(5919): 1344–1347. https://doi.org/10.1126/science.1164033.

Ploshay JJ, Lau N-C. 2010. Simulation of the Diurnal Cycle in Tropical Rainfall and Circulation during Boreal Summer with a High-Resolution GCM. *Monthly Weather Review*, 138(9): 3434–3453. https://doi.org/10.1175/2010MWR3291.1.

Polade SD, Pierce DW, Cayan DR, Gershunov A, Dettinger MD. 2015. The key role of dry days in changing regional climate and precipitation regimes. *Scientific Reports*, 4(1): 4364. https://doi.org/10.1038/srep04364.

Power SB, Delage FPD. 2018. El Niño–Southern Oscillation and Associated Climatic Conditions around the World during the Latter Half of the Twenty-First Century. *Journal of Climate*, 31(15): 6189–6207. https://doi.org/10.1175/JCLI-D-18-0138.1.

Raia A, Cavalcanti IFA. 2008. The Life Cycle of the South American Monsoon System. *Journal of Climate*, 21(23): 6227–6246. https://doi.org/10.1175/2008JCLI2249.1.

Rivera JA, Hinrichs S, Marianetti G. 2019. Using CHIRPS Dataset to Assess Wet and Dry Conditions along the Semiarid Central-Western Argentina. *Advances in Meteorology*, 2019: 1–18. https://doi.org/10.1155/2019/8413964.

Rozante JR, Moreira DS, de Goncalves LGG, Vila DA. 2010. Combining TRMM and Surface Observations of Precipitation: Technique and Validation over South America. *Weather and Forecasting*, 25(3): 885–894. https://doi.org/10.1175/2010WAF2222325.1.

Sánchez E, Solman S, Remedio ARC, Berbery H, Samuelsson P, Da Rocha RP, Mourão C, Li L, Marengo J, de Castro M, Jacob D. 2015. Regional climate modelling in CLARIS-LPB: a concerted approach towards twentyfirst century projections of regional temperature and precipitation over South America. *Climate Dynamics*, 45(7–8): 2193–2212. https://doi.org/10.1007/s00382-014-2466-0.

Santos RF dos. 2007. *Vulnerabilidade Ambiental*. MMA: Brasília.

Sillmann J, Kharin V V., Zhang X, Zwiers FW, Bronaugh D. 2013. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. *Journal of Geophysical Research: Atmospheres*, 118(4): 1716–1733. https://doi.org/10.1002/jgrd.50203.

Silva VBS, Berbery EH. 2006. Intense Rainfall Events Affecting the La Plata Basin. *Journal of Hydrometeorology*, 7(4): 769–787. https://doi.org/10.1175/JHM520.1.

Skinner CB, Poulsen CJ, Chadwick R, Diffenbaugh NS, Fiorella RP. 2017. The Role of Plant CO 2 Physiological Forcing in Shaping Future Daily-Scale Precipitation. *Journal of Climate*, 30(7): 2319–2340. https://doi.org/10.1175/JCLI-D-16-0603.1.

Solman SA, Blázquez J. 2019. Multiscale precipitation variability over South America: Analysis of the added value of CORDEX RCM simulations. *Climate Dynamics*, 53(3–4): 1547–1565. https://doi.org/10.1007/s00382-019-04689-1.

Sperber KR, Annamalai H, Kang I-S, Kitoh A, Moise A, Turner A, Wang B, Zhou T. 2013. The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. *Climate Dynamics*, 41(9–10): 2711–2744. https://doi.org/10.1007/s00382-012-1607-6.

Spracklen DV, Baker JCA, Garcia-Carreras L, Marsham JH. 2018. The Effects of Tropical Vegetation on Rainfall. *Annual Review of Environment and Resources*, 43(1): 193–218. https://doi.org/10.1146/annurev-environ-102017-030136.

Taylor KE, Stouffer RJ, Meehl GA. 2012. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, 93(4): 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.

Torres RR, Lapola DM, Marengo JA, Lombardo MA. 2012. Socio-climatic hotspots in Brazil. *Climatic Change*, 115(3–4): 597–609. https://doi.org/10.1007/s10584-012-0461-1.

Torres RR, Marengo JA. 2013. Uncertainty assessments of climate change projections over South

America. *Theoretical and Applied Climatology*, 112(1–2): 253–272. https://doi.org/10.1007/s00704-012-0718-7.

van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK. 2011. The representative concentration pathways: an overview. *Climatic Change*, 109(1–2): 5–31. https://doi.org/10.1007/s10584-011-0148-z.

Vera CS, Díaz L. 2015. Anthropogenic influence on summer precipitation trends over South America in CMIP5 models. *International Journal of Climatology*, 35(10): 3172–3177. https://doi.org/10.1002/joc.4153.

Wang B, Luo X, Yang Y-M, Sun W, Cane MA, Cai W, Yeh S-W, Liu J. 2019. Historical change of El Niño properties sheds light on future changes of extreme El Niño. *Proceedings of the National Academy of Sciences*, 116(45): 22512–22517. https://doi.org/10.1073/pnas.1911130116.

Watson PAG, Berner J, Corti S, Davini P, Hardenberg J, Sanchez C, Weisheimer A, Palmer TN. 2017. The impact of stochastic physics on tropical rainfall variability in global climate models on daily to weekly time scales. *Journal of Geophysical Research: Atmospheres*, 122(11): 5738–5762. https://doi.org/10.1002/2016JD026386.

Westra S, Fowler HJ, Evans JP, Alexander L V., Berg P, Johnson F, Kendon EJ, Lenderink G, Roberts NM. 2014. Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics*, 52(3): 522–555. https://doi.org/10.1002/2014RG000464.

Xavier DR, Barcellos C, Freitas CM de. 2014. Eventos climáticos extremos e consequências sobre a saúde: o desastre de 2008 em Santa Catarina segundo diferentes fontes de informação. *Ambiente & Sociedade*, 17(4): 273–294. https://doi.org/10.1590/1809-4422ASOC1119V1742014.

Yin L, Fu R, Shevliakova E, Dickinson RE. 2012. How well can CMIP5 simulate precipitation and its controlling processes over tropical South America? *Climate Dynamics*, 41(11): 3127–3143. https://doi.org/10.1007/s00382-012-1582-y.

Yoon J-H. 2016. Multi-model analysis of the Atlantic influence on Southern Amazon rainfall. *Atmospheric Science Letters*, 17(2): 122–127. https://doi.org/10.1002/asl.600.

Zambrano F, Wardlow B, Tadesse T, Lillo-Saavedra M, Lagos O. 2017. Evaluating satellite-derived long-term historical precipitation datasets for drought monitoring in Chile. *Atmospheric Research*, 186: 26–42. https://doi.org/10.1016/j.atmosres.2016.11.006.

Zhang W, Zhou T. 2019. Significant Increases in Extreme Precipitation and the Associations with Global Warming over the Global Land Monsoon Regions. *Journal of Climate*, 32(24): 8465–8488. https://doi.org/10.1175/JCLI-D-18-0662.1.

Zhang X, Wan H, Zwiers FW, Hegerl GC, Min S. 2013. Attributing intensification of precipitation extremes to human influence. *Geophysical Research Letters*, 40(19): 5252–5257. https://doi.org/10.1002/grl.51010.

Zittis G. 2018. Observed rainfall trends and precipitation uncertainty in the vicinity of the Mediterranean, Middle East and North Africa. *Theoretical and Applied Climatology*, 134(3–4): 1207–1230. https://doi.org/10.1007/s00704-017-2333-0.

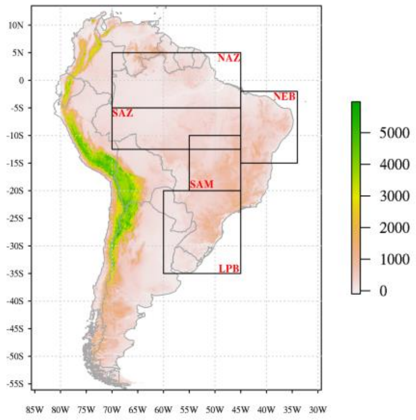

Figure 1. Topography (m) and selected land areas for the computation of change in precipitation variability during the peak rainfall season: (NAZ) northern Amazon (JFMAM, 5−S–5−N, 70−– 45−W), (SAZ) southern Amazon (NDJFM, 12.5−–5−S, 70−–45−W), (NEB) Northeast Brazil (FMAM, 15−–2−S/45−S–34−W), (SAM) South America Monsoon (NDJFM, 20−–10−S/55−–45−W), (LPB) La Plata Basin (NDJFM, 35−–20−S/65−–45−W)

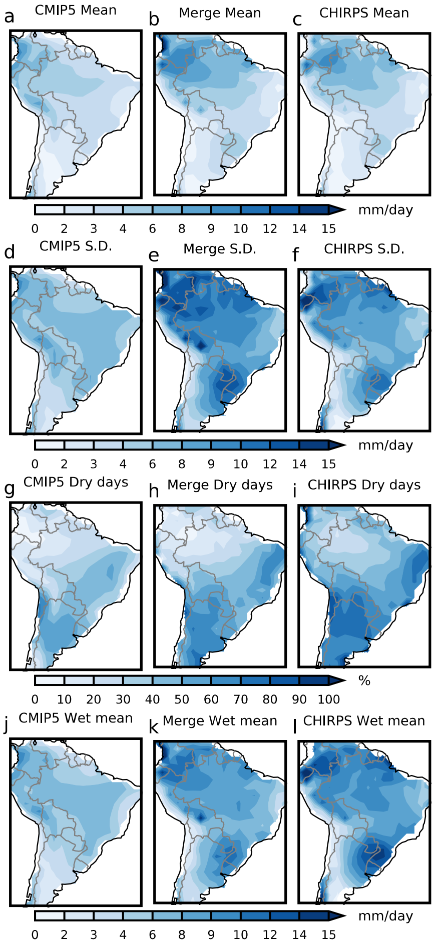

Figure 2. CMIP5 ensemble mean versus observed for South America for the 20th-century climate: (a, b, c) mean annual precipitation (mm_day^{-1}), (d, e, f) standard deviation (mm_day^{-1}), (g, h, i) dry-day fraction (%), and (j, k, l) conditional wet-day mean rainfall (mm_day^{-1}). First column: CMIP5 ensemble mean; second and third columns: Observations (MERGE and CHIRPS datasets, respectively). Historical period 1950–2000 is used for CMIP5, 1998–2019 for MERGE, and 1981–2018 for CHIRPS. Highlighted are regions that correspond to northern Amazon (NAZ), southern Amazon (SAZ), Northeast Brazil (NEB), South America Monsoon (SAM), La Plata Basin (LPB) and are considered for detailed analysis

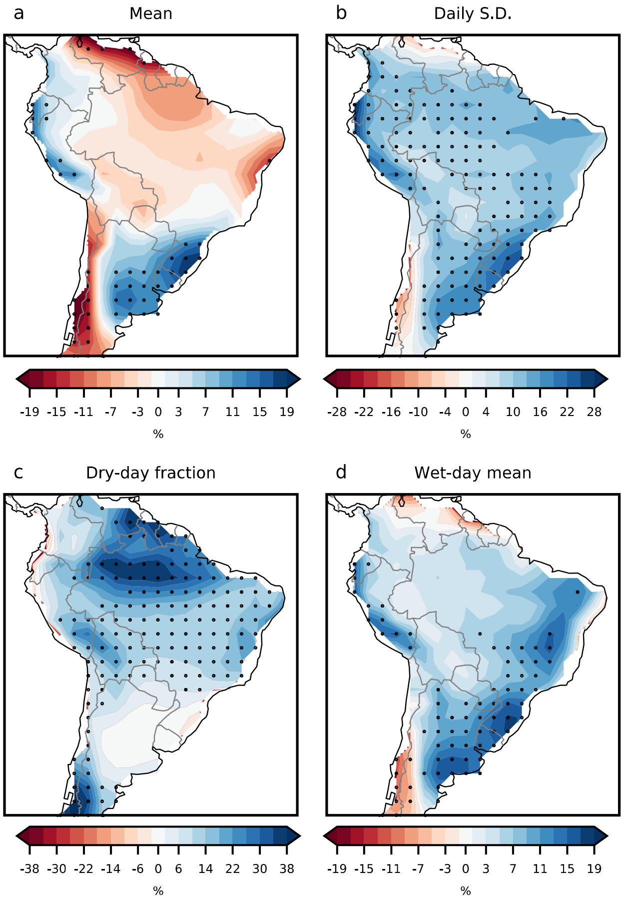

Figure 3. Projected multi-model mean annual precipitation change (%) (a), change in daily standard deviation (%) (b), change in dry-day fraction (threshold of 1 mm_day^{-1} for designating dry days) (%) (c) and change in conditional wet-day mean rainfall (%) (d). Units are in percentage (%) and change is for the period 2050–2100, relative to 1950–2000. Stippling indicates areas where the sign of change is consistent among at least 80% of the models used in this analysis

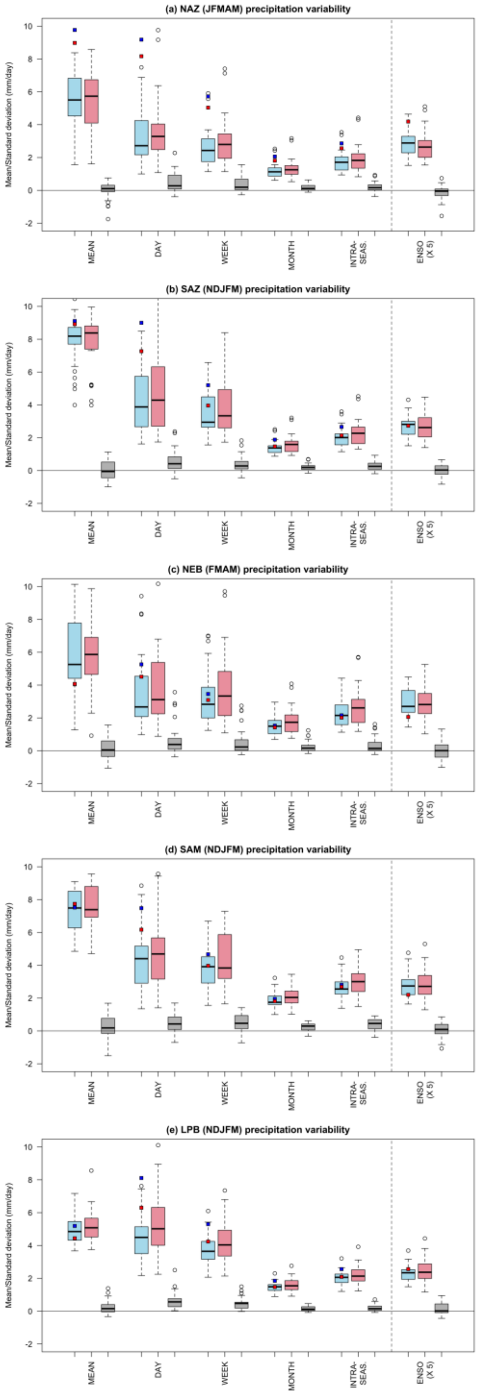

Figure 4. Mean and standard deviation (mm_day^{-1}) of rainy season for HIST (blue), RCP8.5 (pink), and difference (grey) for (a) northern Amazonia—NAZ, (b) southern Amazonia—SAZ, (c) Northeast Brazil—NEB, (d) South America Monsoon—SAM, and (e) La Plata Basin—LPB regions (values are ×5 for annual, and interannual bands). Observations from MERGE (blue squares) and CHIRPS (red squares) data sets are shown as dark blue squares. The boxes show median and upper and lower quartiles, the whiskers indicate values within 1.5 interquartile ranges of the lower and upper quartiles, and the circles indicate outliers beyond this range

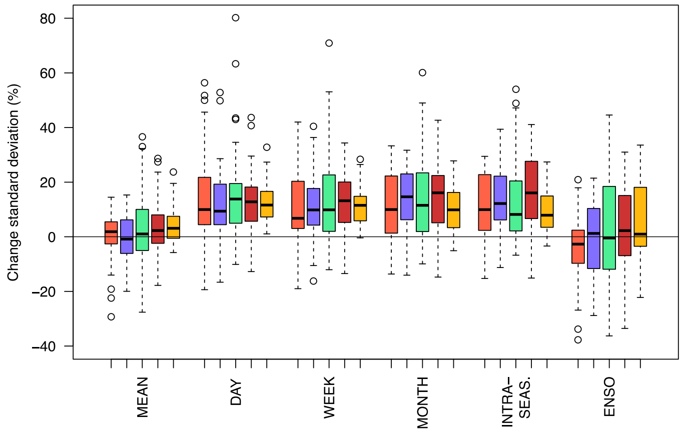

Figure 5. Precipitation variability change by timescales among Brazilian sub-regions: Northern Amazonia (orange), southern Amazonia (purple), Northeast Brazil (green), South America Monsoon (red), and La Plata basin (yellow). The boxes show median and upper and lower quartiles, the whiskers indicate values within 1.5 interquartile ranges of the lower and upper quartiles, and the circles indicate outliers beyond this range