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RESEARCH ARTICLE

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Assessment of rainfall variability and future change in Brazil across multiple timescales

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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-pass filter to isolate variability on daily, weekly, monthly, intra-seasonal, and El Nino Southern Oscillation (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 that is, 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

Brazil, climate change, climate extremes, rainfall, variability

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 semi-arid 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 world's largest wetlands, located in a large floodplain in the centre 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, 2015–2016 (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 2014–2015 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 (dos Santos, 2007). The frequency and severity of other natural disasters include flash floods and landslides have increased, affecting millions in the last decade (CEPED, 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 1,000 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*., 2010a, 2010b; 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 (RCM) (Alves and Marengo, 2010; Marengo *et al*., 2010a; Blázquez *et al*., 2012; Joetzjer *et al*., 2013; Chou *et al*., 2014a; Gulizia and Camilloni, 2015; Sánchez *et al*., 2015; Vera and Díaz, 2015; Cavalcanti and Silveira, 2016; Yoon, 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 8.5 (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 analysed.

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 2015–2016 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 analysed 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 programme (Taylor *et al*., 2012) under a high-emission scenario, 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

2.1 | 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) analysed 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 were 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).

2.2 | 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, RCP8.5 for CMIP5 (Table 1; Taylor *et al*., 2012). All data (models and observation) were regridded to 2.5° horizontal resolution, in order to perform a fair comparison across different products. All models results are from the experiment using the r1i1p1 ensemble member.

2.3 | 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.

TABLE 1 List of CMIP5 models used in this study

Model name	Modelling centre (or group)
ACCESS1.0	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia
ACCESS1-3	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia
Bcc.csm1.1.m	Beijing Climate Centre, China Meteorological Administration
BNU.ESM	Beijing Normal University, China
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada
CCSM4	National Centre For Atmospheric Research (NCAR), USA
CESM1.BGC	National Science Foundation–Department of Energy–National Center for Atmosphere Research/United States
CMCC.CESM	Centro Euro-Mediterraneo per I Cambia-menti, Italy
CMCC.CM	Centro Euro-Mediterraneo per I Cambia-menti, Italy
CMCC.CMS	Centro Euro-Mediterraneo per I Cambia-menti, Italy
CNRM.CM5	Centre National de Recherches Meteorologiques, Meteo-France, France
CSIRO.Mk3.6.0	Australian Commonwealth Scientific and Industrial Research Organization, Australia
EC.Earth	Royal Netherlands Meteorological Institute, Netherlands
FGOALS.g2	Institute of Atmospheric Physics, Chinese Academy of Sciences, China
FGOALS.s2	Institute of Atmospheric Physics, Chinese Academy of Sciences, China
GFDL.CM3	Geophysical Fluid Dynamics Laboratory, USA
GFDL.ESM2G	Geophysical Fluid Dynamics Laboratory, USA
GFDL.ESM2M	Geophysical Fluid Dynamics Laboratory, USA
GISS.E2.R	Goddard Institute for Space Studies, USA
inmcm4	Institute of Numerical Mathematics Russia
IPSL.CM5A.LR	Institut Pierre-Simon Laplace, France
IPSL.CM5A.MR	Institut Pierre-Simon Laplace, France
IPSL.CM5B.LR	Institut Pierre-Simon Laplace, France
MIROC5	AORI, NIES, JAMSTEC, Japan
MIROC.ESM.CHEM	AORI, NIES, JAMSTEC, Japan
MIROC.ESM	AORI, NIES, JAMSTEC, Japan
MPI.ESM.LR	Max Planck Institute for Meteorology, Germany
MPI.ESM.MR	Max Planck Institute for Meteorology, Germany
MRI.CGCM3	Meteorological Research Institute, Japan
NorESM1.M	Norwegian Climate Centre, Norway

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°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°–34°W), (SAM) South America Monsoon (NDJFM, 20°–10°S, 55°–45°W), (LPB) La Plata Basin (NDJFM, 35°–20°S, 65°–45°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

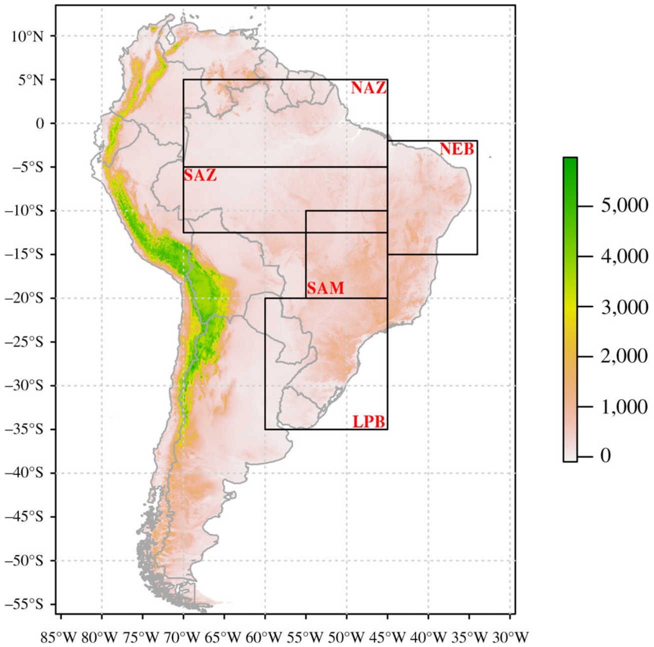


FIGURE 1 Topography (m) and selected land areas for the computation of change in precipitation variability during the peak rainfall season: (NAZ) northern Amazon (JFMAM, 5°S–5°N, 70°–45°W), (SAZ) southern Amazon (NDJFM, 12.5°–5°S, 70°–45°W), (NEB) Northeast Brazil (FMAM, 15°–2°S/45°S–34°W), (SAM) South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

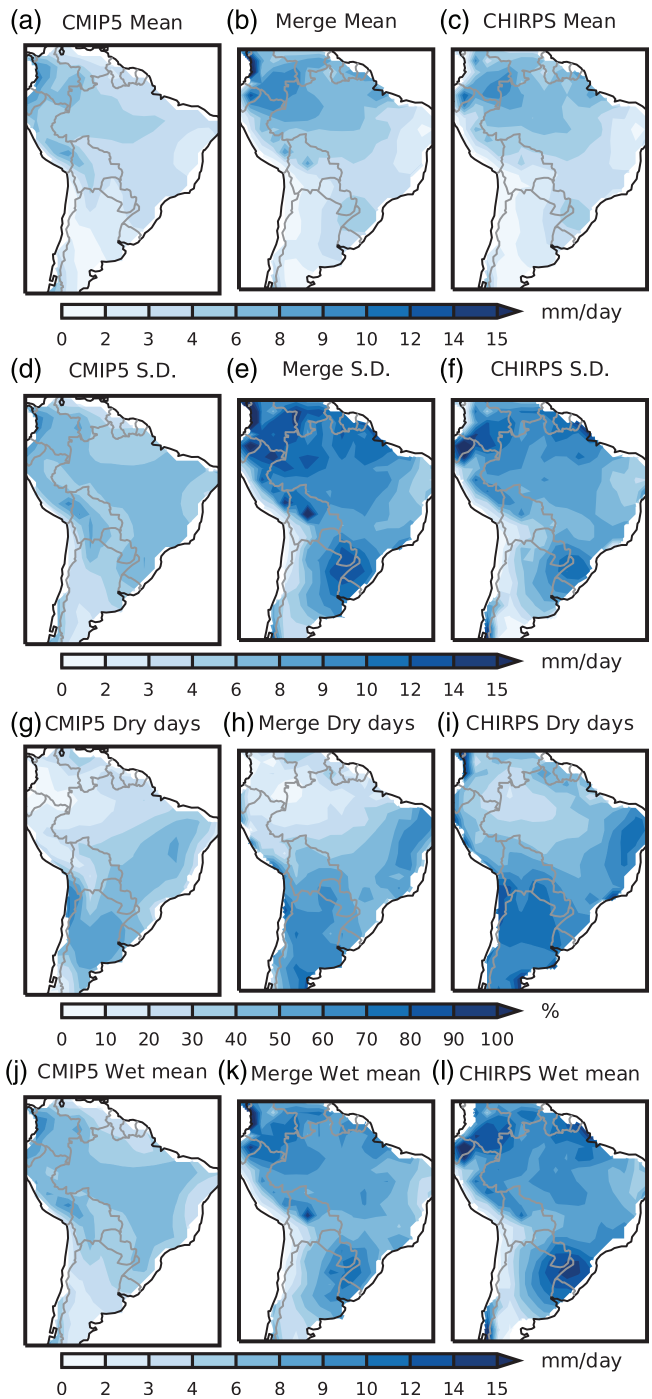


FIGURE 2 CMIP5 ensemble mean versus observed for South America for the 20th-century climate: (a, b, c) mean annual precipitation (mm·day^{-1}), (d, e, f) standard deviation (mm·day^{-1}), (g, h, i) dry-day fraction (%), and (j, k, l) conditional wet-day mean rainfall (mm·day^{-1}). First column: CMIP5 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 [Colour figure can be viewed at wileyonlinelibrary.com]

Carvalho, 2013; 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, 2013; 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 >1·mm·day^{-1}), 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 1·mm·day^{-1}. 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, although 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^{-1}, 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.

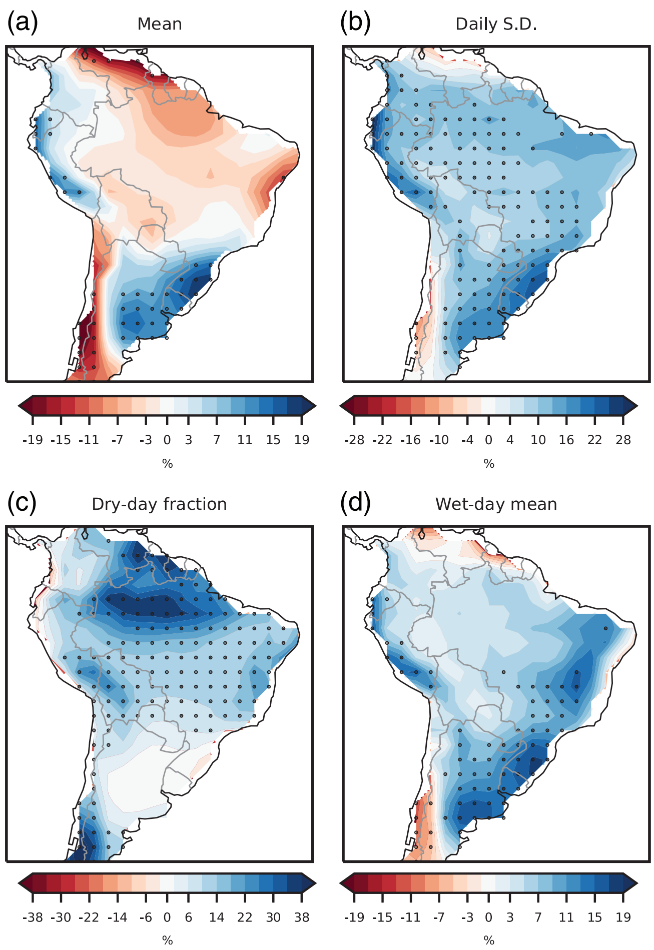


FIGURE 3 Projected multi-model mean annual precipitation change (%) (a), change in daily standard deviation (%) (b), change in dry-day fraction (threshold of 1 mm·day^{-1} for designating dry days) (%) (c) and change in conditional wet-day mean rainfall (%) (d). Units are in percentage (%) and change 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 [Colour figure can be viewed at wileyonlinelibrary.com]

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, that is, we note that the

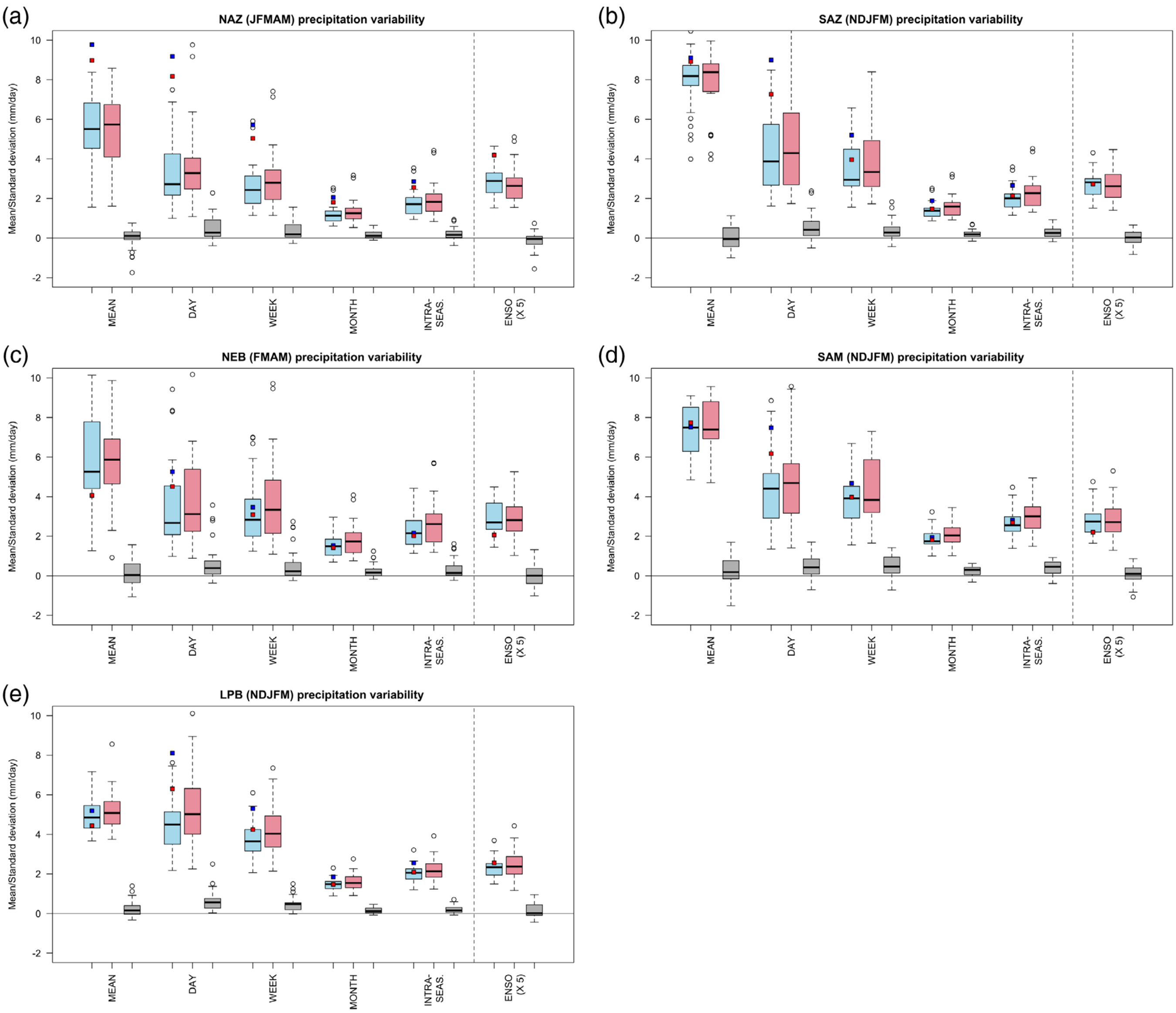


FIGURE 4 Mean and standard deviation (mm·day^{-1}) of rainy season for HIST (blue), RCP8.5 (pink), and difference (grey) for (a) northern Amazonia—NAZ, (b) southern Amazonia—SAZ, (c) Northeast Brazil—NEB, (d) South America Monsoon—SAM, and (e) La Plata Basin—LPB regions (values are ×5 for annual, and 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 [Colour figure can be viewed at wileyonlinelibrary.com]

observation values fell within the inter-quartile range of GCMs.

This result may be because CMIP5 ensemble has 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 do not 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 recently, 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.

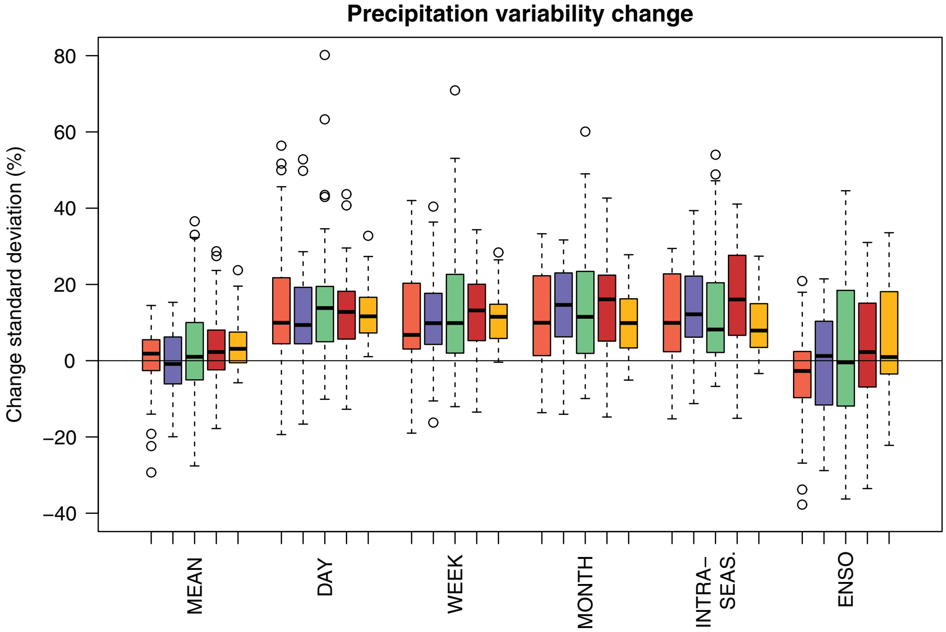
Strong interannual rainfall variability is a major climatological feature in northeast Brazil (NEB). It is influenced by the SST in the tropical Pacific and Atlantic oceans (Marengo *et al*., 2020). Furthermore, the mean precipitation during the wet season (FMAM) is primarily influenced by north–south 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 (grey 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.

In addition, 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, 2013) 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 (grey 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.

Although 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 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 subregions. Overall, all projected changes are fairly similar across different regions, that is, 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 21st 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

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 [Colour figure can be viewed at wileyonlinelibrary.com]



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

In summary, the results vary 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 that is, 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 intraseasonal 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 RCMs and CPMs, 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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