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# Precipitation extremes over the tropical Americas under RCP4.5 and RCP8.5 climate change scenarios: Results from dynamical downscaling simulations

**Alexandre Araújo Costa**[1] | **Sullyandro Oliveira Guimarães**[1,2,3,4] | **Domingo Cassain Sales**[3] | **Francisco das Chagas Vasconcelos Junior**[3] | **Marcos Wender Santiago Marinho**[1] | **José Marcelo Rodrigues Pereira**[3] | **Eduardo Sávio Passos Rodrigues Martins**[3] | **Emerson Mariano da Silva**[1]

[1]State University of Ceará, Fortaleza
[2]Federal University of Ceará, Fortaleza
[3]Research Institute for Meteorology and Water Resources, Fortaleza
[4]Potsdam Institute for Climate Impact Research, Potsdam, Germany

**Correspondence**
Sullyandro Oliveira Guimarães, Potsdam Institute for Climate Impact Research (PIK), P.O. Box 60 12 03, 14412 Potsdam, Germany.
Email: sullyandro@gmail.com

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**Abstract**

The Regional Atmospheric Modelling System (RAMS) driven by data from the CMIP5 Earth System Model HadGEM2-ES was used to simulate daily precipitation over the tropical Americas for both current and future climate, including distinct scenarios (representative concentration pathways 4.5 and 8.5) and different time horizons (short-term, mid-term and long-term changes). The major objective was to evaluate possible future changes in extreme events, with emphasis on the intensity of precipitation events and the duration of wet and dry spells. According to RAMS, longer dry spells are expected over most regions of the tropical Americas in the future, with indications for Northeast Brazil, Caribbean, Northern Amazon, and shorter wet spells over Central America and Amazon. With the exception of the Caribbean, there is a general tendency towards the increased frequency of intense precipitation in the tropical Americas.

KEYWORDS

CMIP5, precipitation extremes, RAMS dynamical downscaling, RCP4.5, RCP8.5, tropical Americas

## 1 | INTRODUCTION

One of the biggest concerns regarding climatic changes is the potential increase in frequency and/or intensity of extreme meteorological/climatological events, such as heat waves, severe storms, extreme flood or drought. In addition to those changes in the number or severity of already known dangerous events, global warming may produce new, out of scale, unprecedented extremes (Trenberth, 2008; Seneviratne *et al.*, 2012; Mallakpour and Villarini, 2015). The most recent IPCC's assessment report also points to an increased chance of the occurrence of multiple simultaneous hazards (the so-called “compound extreme events”) that may amplify societal or environmental risk (IPCC, 2021).

A consistent increase in extreme precipitation has been addressed as one of the possible consequences of the enhancement of atmospheric water vapour mixing ratios in a warmer climate due to the nonlinearity of the Clausius–Clapeyron equation (Allen and Ingram, 2002;

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Pall *et al*., 2007; Kao and Ganguly, 2011; Romps, 2011). Observed trends analysed in IPCC AR5 show more areas with increases than decreases in heavy precipitation frequency/intensity/amount (Hartmann *et al*., 2013). There are also indications that those observed changes can be attributed to anthropogenic forcing, since Bindoff *et al*. (2013). A recent evaluation of the observations of precipitation by Dunn *et al*. (2020) shows an overall increase in extreme indices and points to a larger contribution to the total precipitation coming from extreme events in many regions of the world.

Over the tropical Americas, insufficient data coverage and limited evidence reduce confidence or impairs detection and attribution of extreme events and trends (as pointed out by Seneviratne *et al*., 2021). However, it is well known that the tropical Americas comprise some of the most vulnerable regions regarding severe droughts associated with precipitation decrease and/or evapotranspiration increase, such as Mexico, Central America and Northeast Brazil (IPCC, 2012). It also calls attention to the possible strong impacts of extreme conditions over the Amazon region that has been already plagued with both severe droughts, as in 2005 (Chen *et al*., 2009) and 2010 (Lewis *et al*., 2011) and floods as in 2009 (Marengo *et al*., 2011) and 2015/2016 (Yang *et al*., 2018).

In fact, Northeast Brazil (NEB) experienced in 2012–2016 the strongest and longest drought since the start of rainfall records (beginning of 20th century) (Marengo *et al*., 2018); its impacts on water availability are still observed so far (Azevedo *et al*., 2018; Cunha *et al*., 2019). Studies also indicate increasing trends in the number of consecutive dry days (CDD) and consecutive wet days (CWD) events during the onset of the wet season for the northernmost part of this region (Guerreiro *et al*., 2013; Oliveira *et al*., 2017), suggesting greater susceptibility both to extreme drought and aridization and erosion/loss of soil quality.

According to the PBMC (Brazilian Panel on Climate Change) a decrease of 10–20% in precipitation and an increase of 0.5–1°C in temperature are expected until 2040, with an additional increase in temperature from 1.5 to 2.5°C and an extra 25–35% decrease in rainfall patterns for 2041–2070. Such patterns tend to intensify at least until the end of the century, with significantly warmer conditions (increase of 3.5–4.5°C) and worsening of the regional water deficit, which can trigger a process of desertification of the caatinga (PBMC, 2012).

The IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels (SR15; IPCC, 2018) adds that such vulnerability in tropical and subtropical regions tends to increase significantly if we surpass the 1.5°C global temperature anomaly, especially regarding some specific variables, as the number of consecutive dry days (in Northeast Brazil, Southern Africa, portions of Northern and Eastern Africa) and annual 5-day maximum precipitation (in the Pacific Intertropical Convergence Zone region and most of the world's continental areas including some already plagued by extreme monsoonal floods as the Indian subcontinent), as shown by Hoegh-Guldberg *et al*. (2018). Specifically over the tropical Americas, recent research indicates a consistent projected increase in the intensity and frequency of heavy precipitation (Li *et al*., 2021), with different levels of confidence (Seneviratne *et al*., 2021).

Because of the lack of sufficient resolution, general circulation models (GCMs) tend to misrepresent the statistics of extremes; therefore, dynamical downscaling is often regarded as an alternative to better represent such statistics. Especially over land there is an understanding that refined orographic features allow regional climate models (RCMs) to add value to simulations from GCMs, as shown, for example, by Haensler *et al*. (2011), Di Luca *et al*. (2015) and Xu *et al*. (2018). As far as superimposed errors do not dominate their simulations, RCMs are also a physically based tool to increase the number of members in an ensemble, with lower computational cost than global model runs (although RCM members are not fully independent, as regional models must be forced by GCM data). Particularly regarding the tropical Americas, IPCC AR6 points out the limited number of RCM simulations available (Seneviratne *et al*., 2021) as a limitation in the analysis of projections of precipitation extremes.

In the present work, a regional climate model, forced by data from one of the Coupled Model Intercomparison Project, 5th Phase (CMIP5), was evaluated and used to simulate future changes in extreme precipitation events over the tropical Americas under RCPs 4.5 and 8.5. The paper evaluates projected changes on the intensity of daily precipitation events and the duration of wet and dry spells using several indices for hydroclimatic extremes, which is relevant for long-term planning and decision making in public policies in several areas such as water resources, agriculture, and civil defence.

## 2 | MATERIAL AND METHODS

### 2.1 | Model and simulations

In this work, the Regional Atmospheric Modelling System (RAMS, version 6.0; Pielke *et al*., 1992; Cotton *et al*., 2003) was driven by the Earth System version of the Hadley Centre Global Environmental Model (HadGEM2-ES; Collins *et al*., 2011) for both current climate ("historical run") and future scenarios (representative concentration pathways 4.5 and 8.5). The outcomes presented were obtained originally from simulations

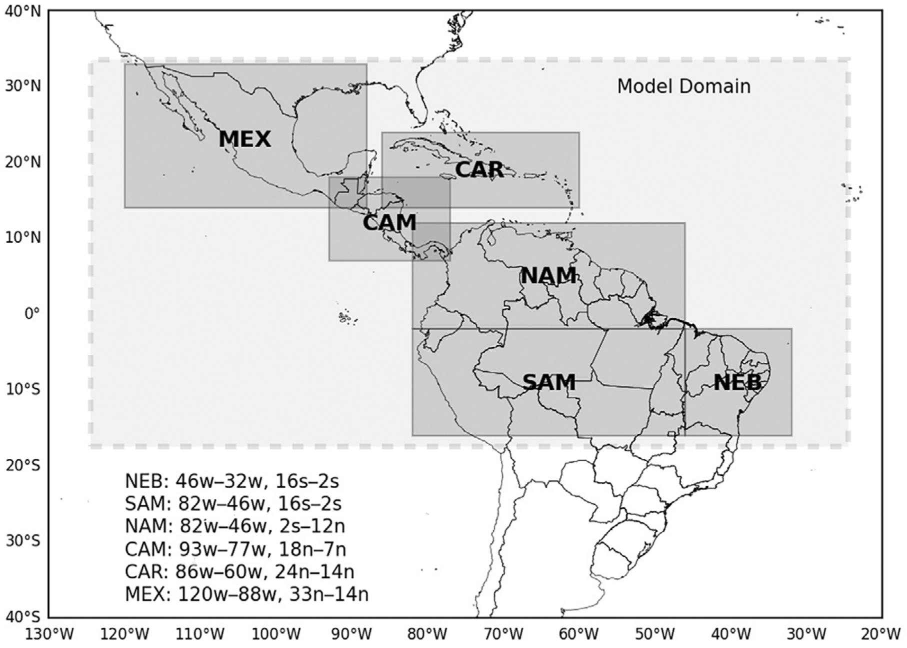

**FIGURE 1** Regional subdomains for data analysis: Northeast Brazil (NEB), southern Amazon (SAM), northern Amazon (NAM), Central America (CAM), Caribbean (CAR) and Mexico (MEX)

performed by the authors at the State University of Ceará (UECE), in collaboration with associated institutes.

As described in greater detail in Sales *et al.* (2015) and Guimarães *et al.* (2016), that regional climate model domain (Figure 1) corresponds approximately to the "Central America" of the Coordinated Regional Climate Downscaling Experiment (CORDEX) and comprises 252 × 136 horizontal grid points (50 km grid-spacing) and 29 vertical levels with variable resolution (model top at about 21 km). Sales *et al.* (2015) and Guimarães *et al.* (2016) also indicate the physical parameterizations used in the RAMS simulations. The atmospheric component of the forcing GCM comprises 192 × 145 horizontal grid points (~208 × 139 km) and 38 vertical levels (reaching 40 km in the top) (Collins *et al.*, 2011).

Downscaling runs were performed for a baseline period (1985–2005) and three timeslices under each RCP scenario, representing short-term (2015–2035), mid-term (2045–2065) and long-term (2079–2099) changes. Model validation was carried out against the TRMM (Tropical Rainfall Measuring Mission; Huffman *et al.*, 2007) observational dataset considering the 1998–2010 period. For the historical runs, the performance of both models was compared.

## 2.2 | Indices

Several indices were calculated to evaluate changes in the occurrence of hydroclimatic extreme events within the model domain, with special focus on the six subregions defined in Figure 1. The indices are defined according to Frich *et al.* (2002), Campbell *et al.* (2011) and Revadekar *et al.* (2012) and are listed in Table 1. The exceedance of precipitation thresholds used to calculate Rnn indices, the 5-day accumulated precipitation used to calculate Rx5, the CWD, and CDD are computed from simulated daily total accumulated rainfall in each model cell (same approach for TRMM dataset) for each year, and then averaged for the timeslices. In the calculation of the CWD and CDD indices, a "wet day" is assumed as the one in which the precipitation exceeds 1 mm, otherwise regarded as a "dry day." Projected changes in those indices are investigated for both scenarios and the three timeslices.

**TABLE 1** Extreme precipitation indices

| Index | Definition | Unit |
|---|---|---|
| Rnn | Average number of days in a year in which the precipitation exceeds the nn threshold (nn = 10, 20, 30, 40) | days |
| Rx5 | Maximum accumulated precipitation in five consecutive days in a year | mm |
| CWD | Average maximum period of consecutive wet days in a year | days |
| CDD | Average maximum period of consecutive dry days in a year | days |

## 3 | MODEL REPRESENTATION OF EXTREME PRECIPITATION INDICES IN CURRENT CLIMATE

Figure 2 represents the R10, R20, R30 and Rx5 indices for the 1985–2005 period as simulated by RAMS and HadGEM2-ES,

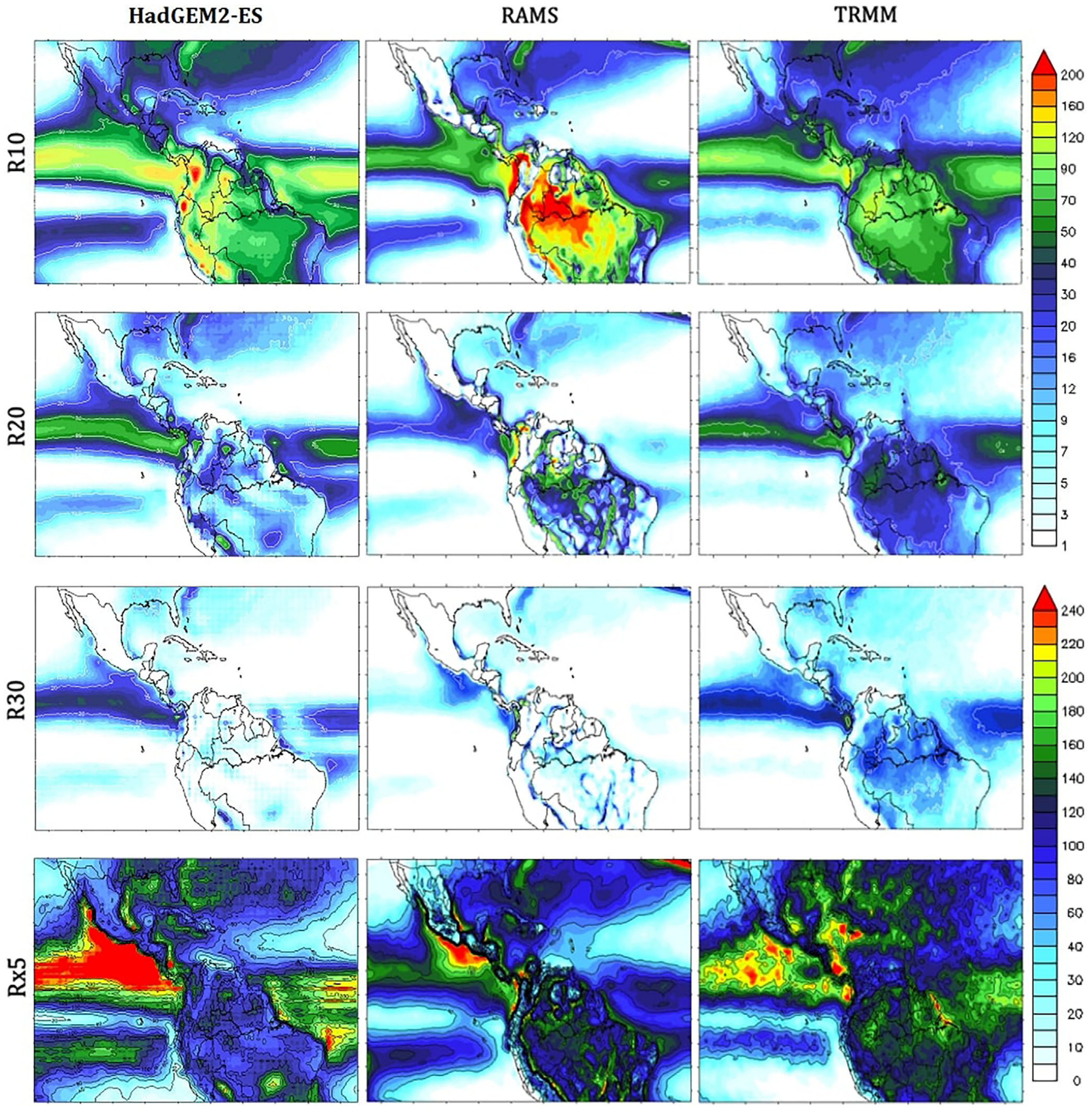

**FIGURE 2** R10 (days), R20 (days), R30 (days) and Rx5 (mm) indices according to HadGEM2-ES (historical run, 1985–2005), RAMS (historical run, 1985–2005) and TRMM (1998–2010). The upper scale to the right refers to the R10, R20 and R30 indices and the lower scale to the Rx5 index [Colour figure can be viewed at wileyonlinelibrary.com]

and the counterpart in TRMM data. A realistic representation of the Rnn indices, that is, the number of yearly rainfall events with accumulated precipitation in 1 day exceeding nn was achieved only below the 30 mm threshold in our regional climate simulations.

Overall, there is qualitative agreement between the regional model results and TRMM for R10, with spatial patterns associated, for instance to the ITCZ and the South America monsoon, although the number of precipitation events above the 10 mm threshold is overestimated by RAMS over the Amazon and underestimated over Mexico and some oceanic regions, especially in the tropical Atlantic. On the other hand, HadGEM2-ES overestimates precipitation events in the ITCZ region, showing agreement with TRMM in the northern region of South America (Amazon and Northeastern Brazil), Mexico and Central America.

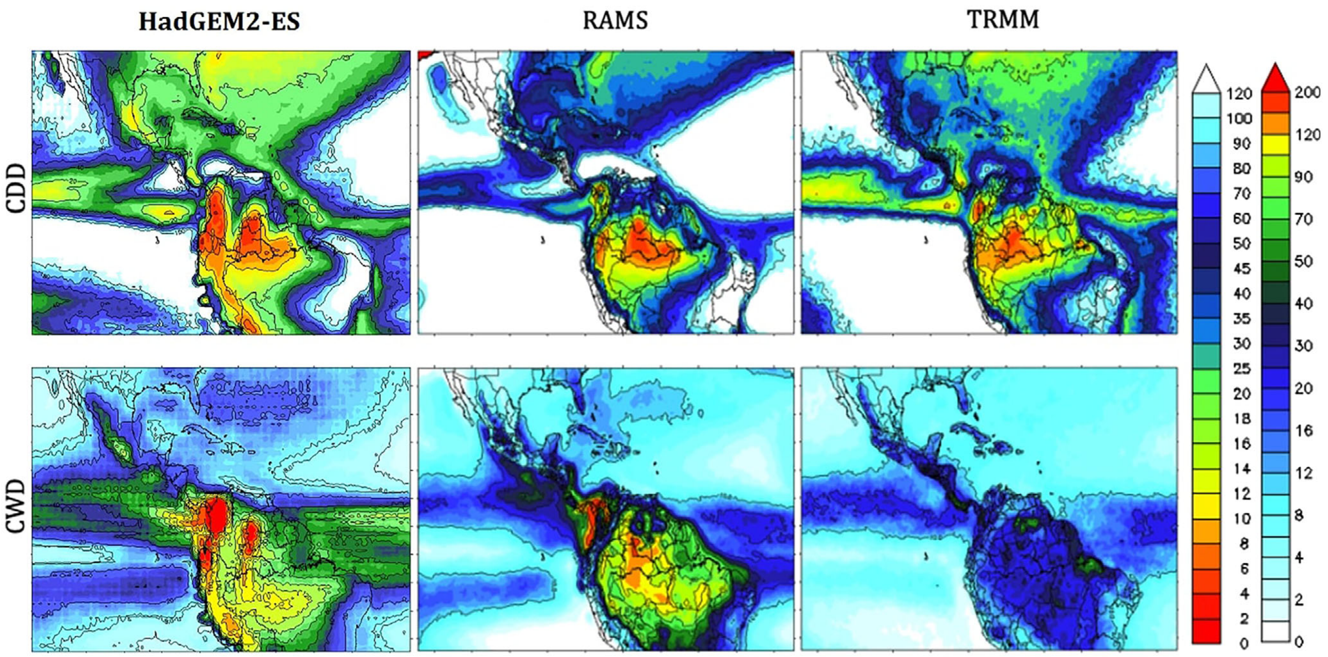

**FIGURE 3** CDD (days) and CWD (days) indices according to HadGEM2-ES (historical run, 1985–2005), RAMS (historical run, 1985–2005) and TRMM (1998–2010). The left scale refers to the CDD index and the scale to the right to the CWD index [Colour figure can be viewed at wileyonlinelibrary.com]

As far as R20 is concerned, again there is an overall agreement between the modelled fields and the observational dataset, especially over continental areas. However, regional model results for R20 in the Atlantic ITCZ region depart significantly from the observational counterpart, while the global model shows more remarkable agreement with the TRMM. Over again, RAMS produces a lower amount of events in the Mexico region compared to the HadGEM2-ES model. Regarding R30, the regional model tends to underestimate the number of events with respect to TRMM in most of the domain, although it better represents the continental area in relation to the GCM over South America, while the GCM better simulates the ocean part.

As shown in the lower panels of Figure 2, a good qualitative agreement exists among RAMS and TRMM spatial distribution of the maximum precipitation accumulated in five consecutive days (Rx5) over South America continental area. The largest discrepancies between RAMS and the observational database occur over the oceanic areas. The global model is also in good agreement with the TRMM in the continental region, but overestimates in the eastern Pacific adjacent to Mexico and Central America. The regional model reduces this bias. Both models also agree with the pattern over the Caribbean ocean region, but underestimate this index.

The ability of RAMS and HadGEM2-ES in representing dry and wet spells over the tropical Americas was also verified and again, models results for the historical run were compared against TRMM data. Figure 3 depicts the spatial distribution of the CDD and CWD indices for current climate. RAMS and HadGEM2-ES show overall qualitative agreement with TRMM. The representation of the CDD index by RAMS is particularly good over South America. The distance from HadGEM2-ES and TRMM in CWD values was in part improved via RAMS downscaling, mainly over ocean areas.

Regarding the average of those indices over the six regions defined in Figure 1 (considering only land), RAMS achieves a reasonable agreement with the observational estimation in South America regions as shown in Table 2. Modelled R10 is underestimated regarding TRMM over MEX and CAR, while HadGEM2-ES underestimates only in CAR. Over CAM, RAMS and HadGEM2-ES strongly agree with TRMM. Over both SAM and NEB, current climate R10 averages calculated by RAMS are larger than in the observational dataset. Over SAM, NAM and NEB, the GCM overestimates in ∼30% the observed R10, having the regional model greater error than the global. This positive bias characteristic in R10 (Figure 2) is common to the Rnn, being a pattern of sensitivity of the RAMS in the Amazon area.

Regarding R20, RAMS results tend to follow TRMM with very good agreement in most areas (except in MEX

**TABLE 2** Extreme indices in current climate according to TRMM (1998-2010), RAMS (1985-2005) and HadGEM2-ES (1985-2005) over the six regions (Figure 1).

| | | R10 | R20 | R30 | Rx5 | CDD | CWD |
|---|---|---|---|---|---|---|---|
| MEX | TRMM | 18.9 | 7.4 | 3.6 | 87.1 | 72.6 | 9.8 |
| | RAMS | 9.5 | 3.1 | 1.3 | 55.9 | 120.8 | 8.8 |
| | HadGEM | 22.6 | 7.0 | 2.9 | 96.3 | 51.6 | 21.9 |
| | Diff % RAMS | −49.7 | −58.1 | −63.9 | −35.8 | 66.4 | −10.2 |
| | Diff % HadGEM | 19.6 | −5.4 | −19.4 | 10.6 | −28.9 | 123.5 |
| CAR | TRMM | 25.6 | 11.2 | 6.1 | 148.7 | 30.0 | 10.6 |
| | RAMS | 17.4 | 5.5 | 2.1 | 91.1 | 50.3 | 12.1 |
| | HadGEM | 17.3 | 5.5 | 2.3 | 101.6 | 31.0 | 15.0 |
| | Diff % RAMS | −32.0 | −50.9 | −65.6 | −38.7 | 67.7 | 14.2 |
| | Diff % HadGEM | −32.4 | −50.9 | −62.3 | −31.7 | 3.3 | 41.5 |
| CAM | TRMM | 56.6 | 23.7 | 11.5 | 153.8 | 36.0 | 22.7 |
| | RAMS | 56.2 | 20.4 | 6.6 | 117.0 | 73.4 | 46.6 |
| | HadGEM | 57.6 | 19.7 | 7.1 | 146.8 | 55.7 | 66.8 |
| | Diff % RAMS | −0.7 | −13.9 | −42.6 | −23.9 | 103.9 | 105.3 |
| | Diff % HadGEM | 1.8 | −16.9 | −38.3 | −4.6 | 54.7 | 194.3 |
| NAM | TRMM | 64.8 | 25.8 | 11.6 | 130.7 | 25.3 | 22.4 |
| | RAMS | 95.5 | 27.1 | 6.1 | 108.6 | 39.7 | 70.9 |
| | HadGEM | 77.6 | 16.1 | 3.6 | 107.3 | 31.3 | 107.5 |
| | Diff % RAMS | 47.4 | 5.0 | −47.4 | −16.9 | 56.9 | 216.5 |
| | Diff % HadGEM | 19.8 | −37.6 | −69.0 | −17.9 | 23.7 | 379.9 |
| SAM | TRMM | 58.7 | 23.1 | 10.1 | 119.5 | 56.7 | 21.1 |
| | RAMS | 107.8 | 24.7 | 4.0 | 111.6 | 56.4 | 70.5 |
| | HadGEM | 77.3 | 12.9 | 3.0 | 103.4 | 30.4 | 109.7 |
| | Diff % RAMS | 83.6 | 6.9 | −60.4 | −6.6 | −0.5 | 234.1 |
| | Diff % HadGEM | 31.7 | −44.2 | −70.3 | −13.5 | −46.4 | 419.9 |
| NEB | TRMM | 30.7 | 12.8 | 5.8 | 126.9 | 74.1 | 14.4 |
| | RAMS | 52.6 | 15.8 | 2.9 | 111.8 | 118.3 | 37.6 |
| | HadGEM | 35.7 | 8.9 | 2.4 | 105.8 | 101.4 | 37.5 |
| | Diff % RAMS | 71.3 | 23.4 | −50.0 | −11.9 | 59.6 | 161.1 |
| | Diff % HadGEM | 16.3 | −30.5 | −58.6 | −16.6 | 36.8 | 160.4 |

*Note*: The percent difference (Diff %) is model to TRMM.

and CAR). In the South American regions (NEB, SAM and NAM), the regional model reduces the error and reverses the bias of the global model. RAMS's and HadGEM2-ES R30 are often smaller than TRMM's, the models in all six regions are underestimating the index, but in South America (NEB, NAM and SAM) the regional model adds value in removing the GCM bias, while in the other three regions it reduces the amount of events compared to HadGEM2-ES.

The representation of the Rx5 index by the regional and global models is also adequate in most regions, although both models tend to somewhat underestimate it with respect to TRMM (except HadGEM2-ES over MEX). RAMS tends to simulate dry spells that are too long with respect to TRMM (for which HadGEM2-ES performs better), except over SAM for which the agreement is very good. The RCM also produces wet spells with durations close to TRMM's over MEX and CAR than the GCM, reducing large scale bias. Over the other regions, RAMS' CWD exceeds TRMM estimates by more than 100%.

The indexes with more improvements in the regional simulation were the CWD and R20 for most regions, with less confidence in the MEX and CAR. The model marginally added value via downscaling for the studied domain.

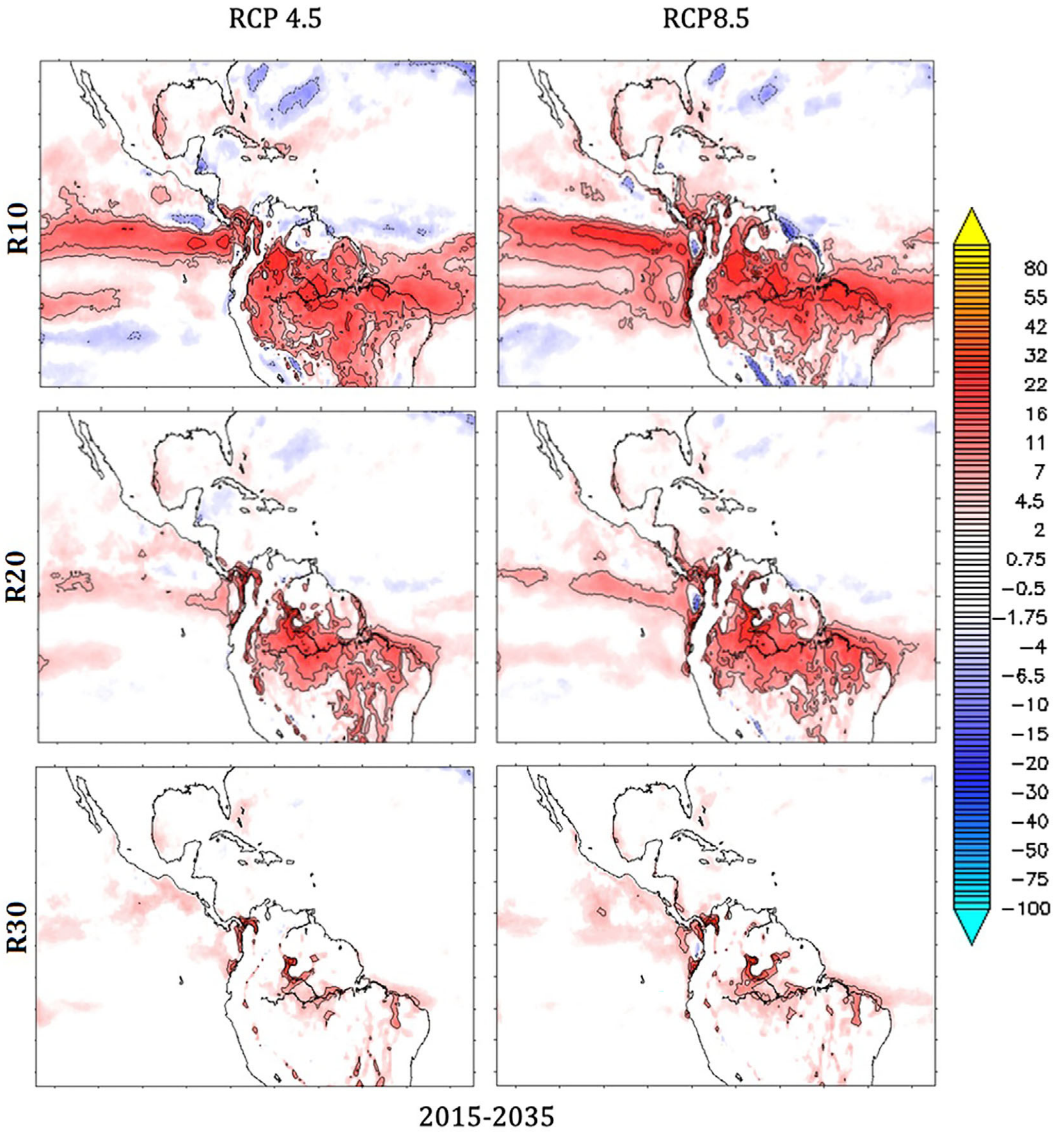

FIGURE 4 Projected R10 (days), R20 (days) and R30 (days) short (2015–2035) term changes according to RAMS, forced by HadGEM2-ES, under the RCP4.5 and RCP8.5 scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

## 4 | CHANGES IN EXTREME PRECIPITATION INDICES

Changes in the indices listed in Table 1, based on data from RCP4.5 and RCP8.5 simulations using the regional model are analysed in this section. Results concerning the spatial distribution of changes in the indices are shown in Figures 4–9, respectively, for projected R10, R20, R30, Rx5, CDD and CWD changes for both scenarios.

For short-term (2015–2035) period under both RCP4.5 and RCP8.5, R10 increases over the ITCZ, the Amazon and northern NEB by 10–20 events per year (Figure 4, upper panels). The largest R20 increase (on the order of 10 events per year) is projected over portions of northern South America, especially the Amazon River basin and northern NEB, with the area of enhanced R20 being slightly larger for the RCP8.5 (Figure 4, middle panels). Remarkable changes in R30 appear close to the Panama isthmus and over certain parts of the Amazon River basin and northern NEB (Figure 4, lower panels).

For the intermediate time horizon (2045–2065), the projected changes under the RCP8.5 scenario are clearly more dramatic (Figure 5). R10 changes are largest over the Pacific ITCZ and in portions of western Amazon, with a notable area of an increase of more than 20 events per year under the RCP4.5 scenario whereas over the same regions changes are greater than 30 events per year under RCP8.5. Over the Atlantic ITCZ region, R10 is expected to increase in both scenarios however the variations are larger under RCP8.5 than in RCP4.5 over the ocean. Over NEB, an increase in R10 appears only in the RCP4.5 projection whereas little change is expected

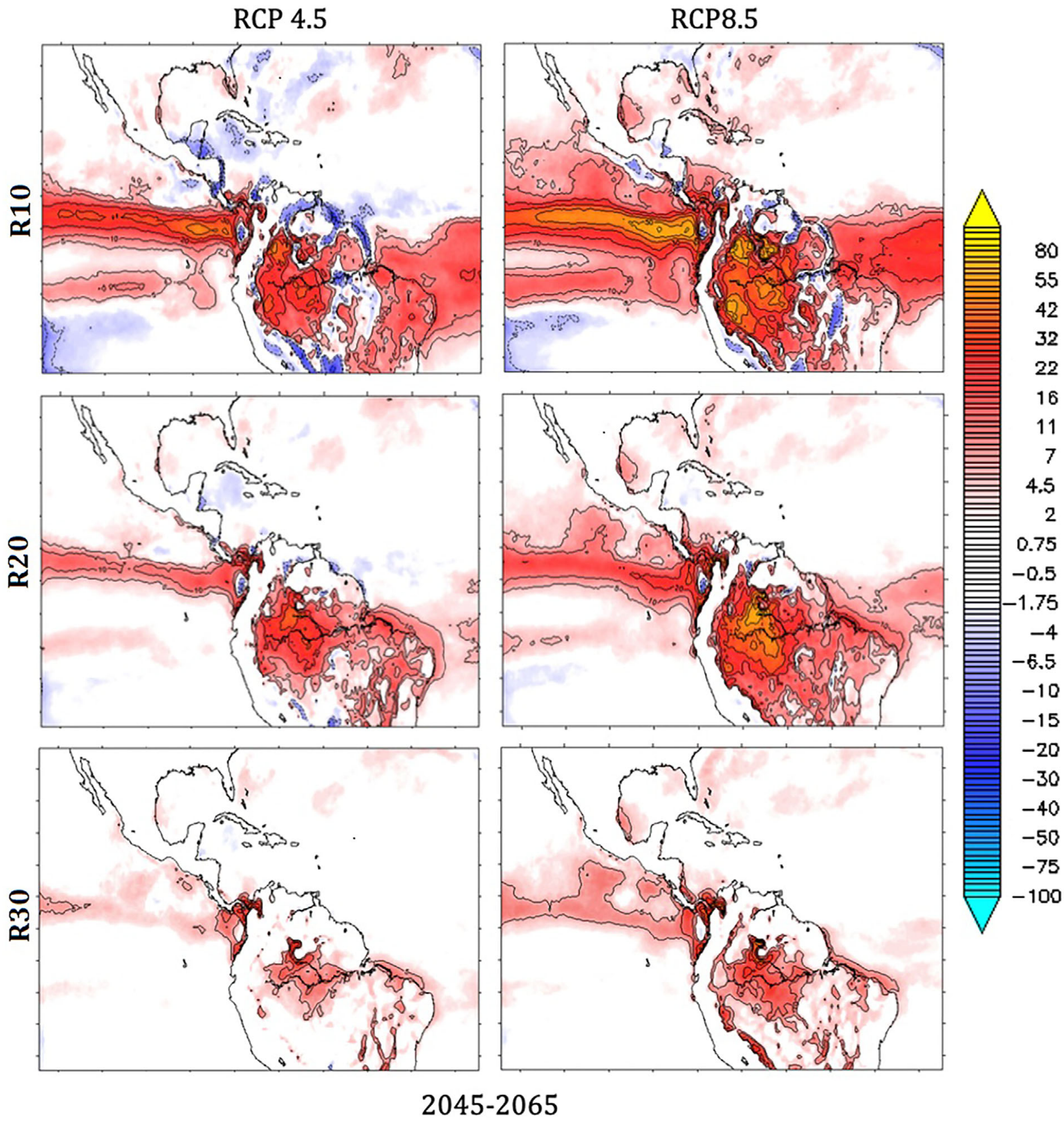

**FIGURE 5** Same as Figure 4, except for mid (2045–2065) term changes. R10 (days), R20 (days) and R30 (days) [Colour figure can be viewed at wileyonlinelibrary.com]

under RCP8.5, except over the northernmost portion of this region. Changes with opposite signs were projected over the Caribbean with an increase in R10 expected under the RCP8.5 scenario, especially over the islands, whereas under RCP4.5 a tendency of R10 reduction is shown, mainly over the ocean and the Yucatan peninsula. Both scenarios show a tendency towards a small decrease in R10 over eastern Amazon and certain regions of Venezuela and the Guianas (Figure 5, upper panels). The general feature of R20 changes is similar in both scenarios, but under RCP8.5 they are clearly exacerbated. The most important patterns of the projected changes in R20 are pronounced increases in the following regions: Pacific ITCZ, western Amazon and (to a lesser extent) northern and eastern coasts of NEB (Figure 5, middle panels). Large changes in R30 are already projected for 2045–2065, especially under the RCP8.5, over the Amazon, the Pacific ITCZ and NEB (Figure 5, lower panels).

Towards the end of the 21st century (2079–2099), the two projections (RCP4.5 and RCP8.5) tend to diverge in many aspects (Figure 6), in opposition to what was found for the previous cases. In both

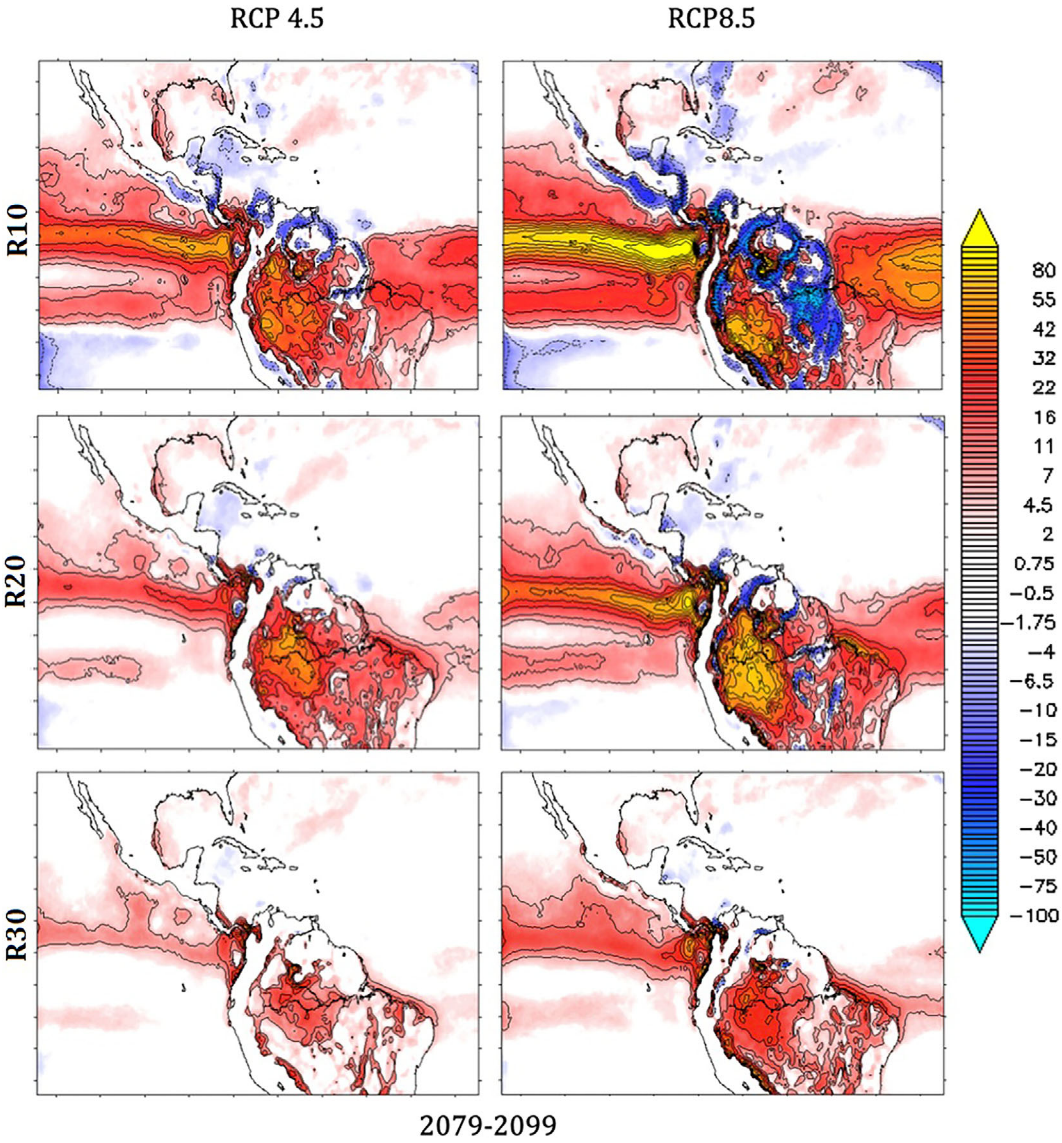

**FIGURE 6** Same as Figure 4, except for long (2079–2099) term changes. R10 (days), R20 (days) and R30 (days) [Colour figure can be viewed at wileyonlinelibrary.com]

scenarios, R10 is expected to increase over both Pacific and Atlantic ITCZ regions, but the expected changes under RCP8.5 are much larger (a factor of 2–3 compared to RCP4.5 changes). Over South America, distinct patterns emerge, as the RCP4.5 projection indicates a tendency of a moderate increase in R10 over most regions (except the extreme north of the continent and a small portion of the eastern Amazon River basin) whereas under RCP8.5 a sharp contrast appears with a strong increase in R10 over southwestern Amazon in opposition to a reduction over eastern Amazon (in both cases, the absolute value of the changes exceeds 50 events per year). Over northern NEB, an enhanced R10 is expected under both scenarios, with larger changes under RCP8.5.

According to the present simulations, the long term relative changes in the R20 and R30 indices can be very large over certain regions. Especially under the RCP8.5 scenario, large increases in R20 and R30 are expected over western Amazon (Figure 6). One striking feature in Figures 4–6 is the similarity between the mid-term projection under RCP8.5 and the long-term projection under RCP4.5 for R10, R20 and R30.

Projected changes in Rx5 (Figure 7) tend to be larger over the oceans under both scenarios and for the three analysed periods. Over the continents, important changes are initially projected over NEB and following the Amazon River. As time progressed (mid-term interval), the area of enhanced Rx5 (changes above 10 mm) spread out, reaching the entire western Amazon under RCP8.5 whereas RCP4.5

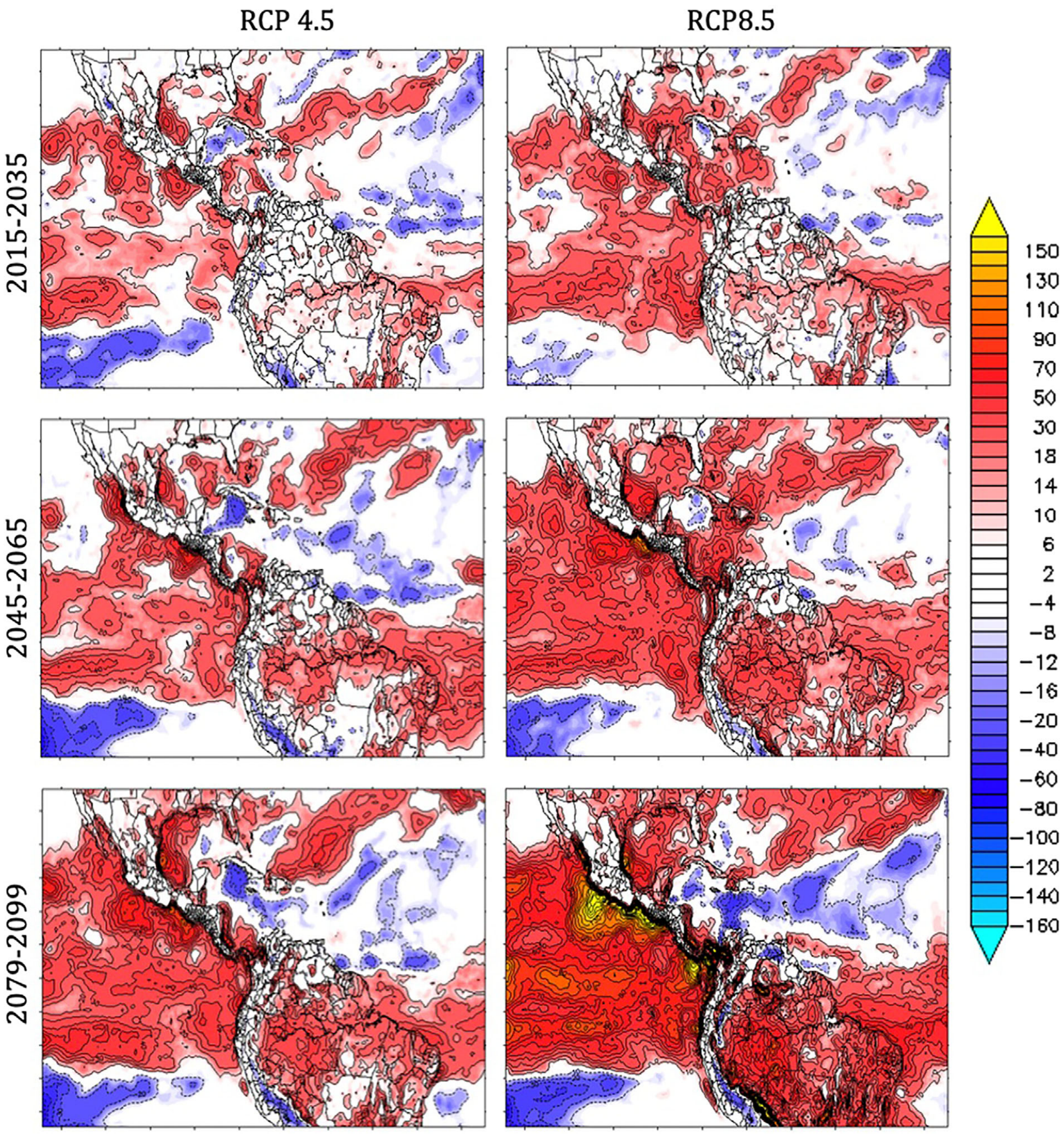

**FIGURE 7** Projected Rx5 (mm) short (2015–2035), mid (2045–2065) and long (2079–2099) term changes according to RAMS, forced by HadGEM2-ES, under the RCP4.5 and RCP8.5 scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

changes are not so large and still tend to be confined to areas around the river. The most outstanding increase in 5-day maximum precipitation occurs under the RCP8.5 scenario for the 2079–2099 period. In this case, Rx5 increases by more than 30 mm over almost the entire NEB and western Amazon, with changes exceeding 50 mm in some areas.

Figures 8 and 9 show projected changes in CDD and CWD respectively. Short-term and mid-term changes in the maximum number of consecutive dry days are larger over the oceans, with a general pattern of reduced CDD over the ITCZ (especially the Pacific ITCZ) and increased CDD over the subtropical oceans. Towards the end of the century, the overall patterns over the oceans (decreased CDD over the Pacific ITCZ and enhanced CDD over the subtropical areas) are further intensified, especially under the RCP8.5 scenario. Over the continents, the RCP8.5 scenario produces much greater changes, especially over most of Mexico, Northeast Brazil and over the Guianas and eastern Amazon (Figure 8, lower right panel). It is important to remark that RAMS does not show improvements (regarding HadGEM2-ES) in CDD for most of the

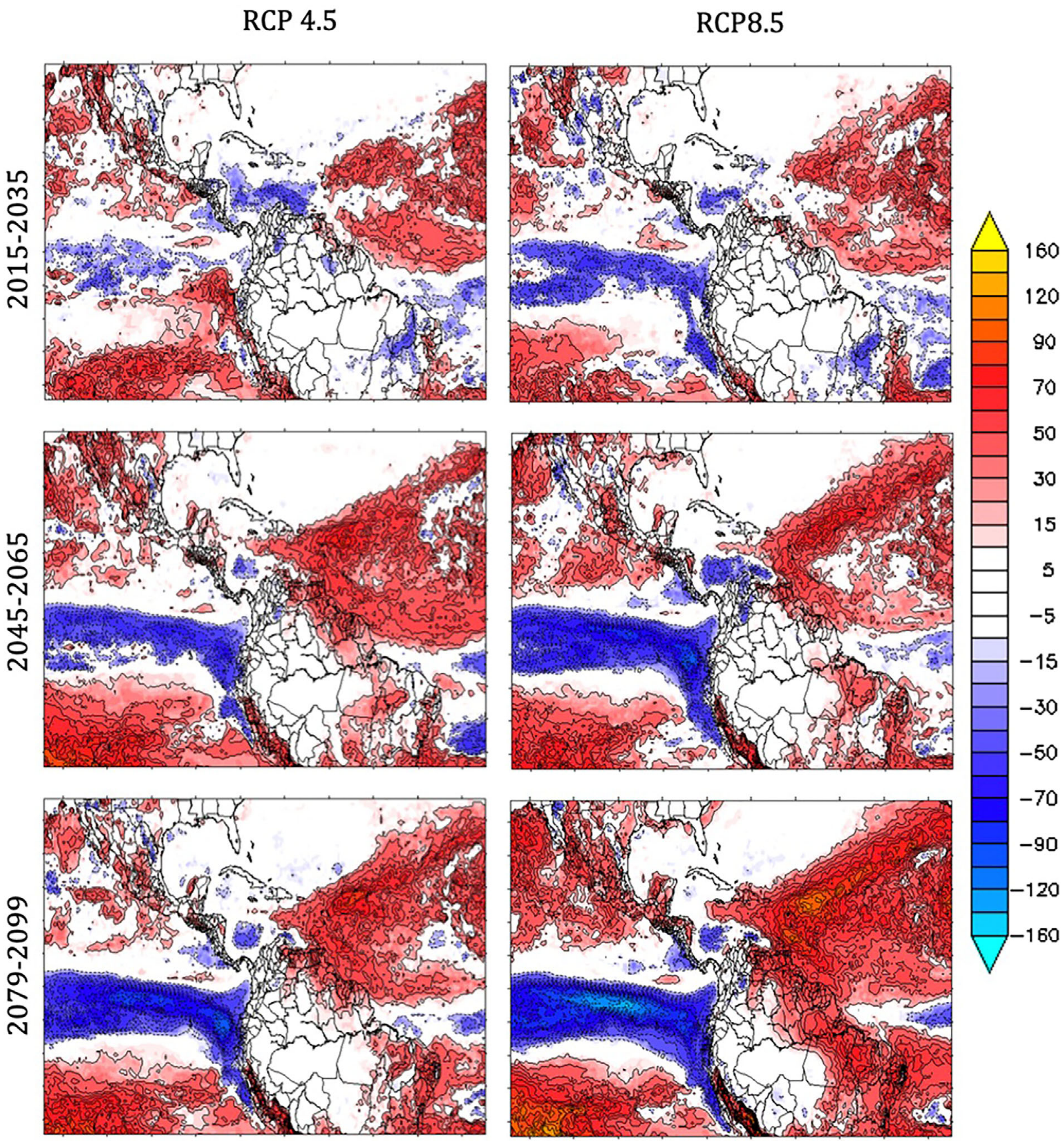

**FIGURE 8** Same as Figure 7, except for CDD (days) [Colour figure can be viewed at wileyonlinelibrary.com]

areas (except in SAM), providing less confidence to them (Table 2).

According to projections results, changes in CWD are generally towards longer wet spells over the tropical oceans (except off boast Atlantic and Pacific coasts of Central America) and shorter wet spells over most continental areas, especially in the RCP8.5 scenario. A noteworthy reduction is expected over Amazon, as well as over southern Central America (particularly over Panama and Costa Rica). In contrast, Brazil Northeast and Central areas are the most remarkable in increase of CWD (Figure 9).

Table 3 summarizes the changes in the average values of those indices over the six analysed regions. Statistically significant changes are indicated by grey shading in the table cells (confidence levels of 95%, 99% and 99.9% denoted by light, medium and dark grey tones, respectively). In general, the most remarkable projected changes are expected by the end of the century under RCP8.5. Over MEX, this includes increased R20, R30 and Rx5 indices under both climate change scenarios, with distinction to a projected 61.2% increase in R30 (less confidence). Over CAR, most projected changes are relatively small, except for the expected CDD increase (31.8%, less

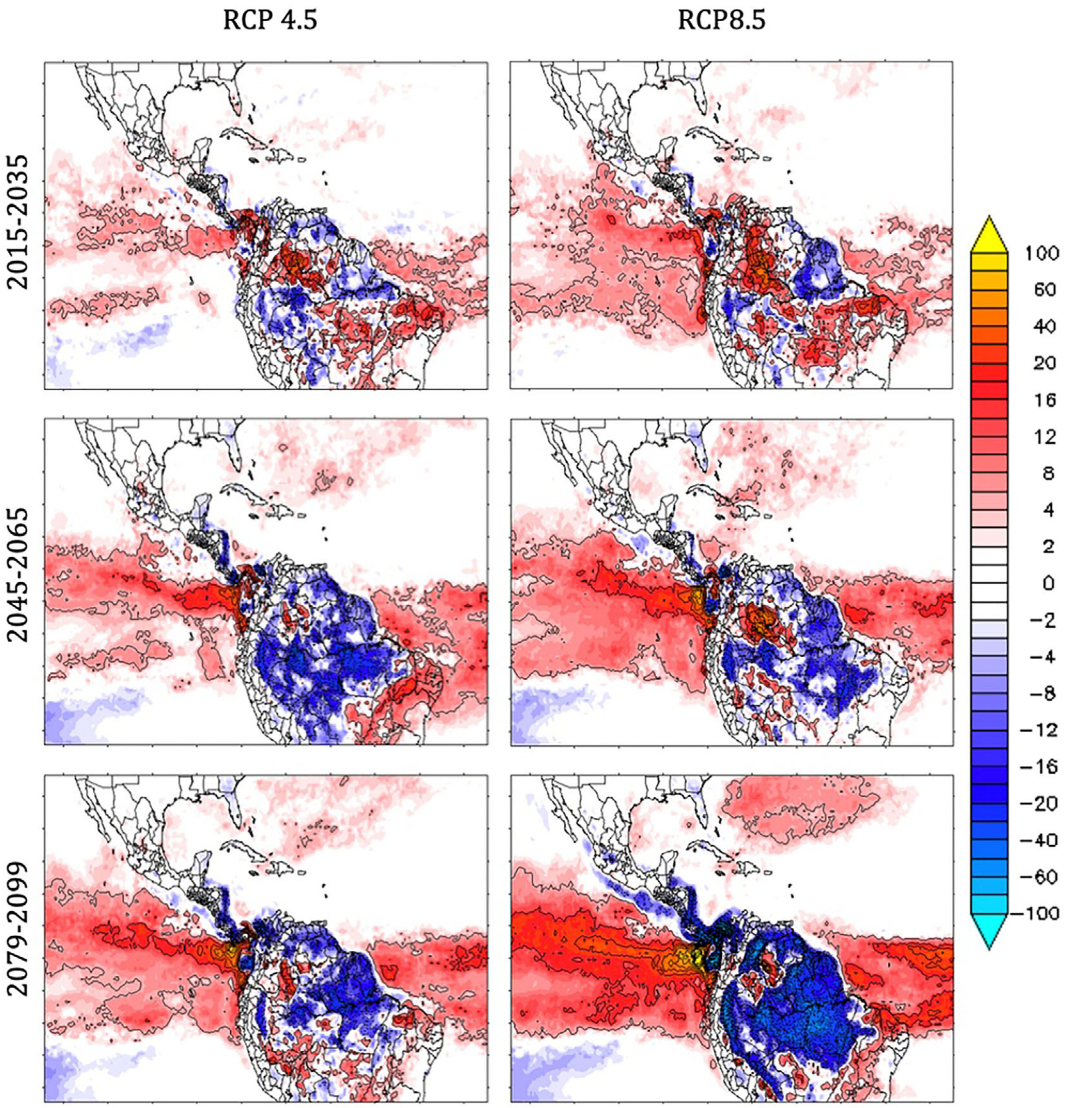

**FIGURE 9** Same as Figure 7, except for CWD (days) [Colour figure can be viewed at wileyonlinelibrary.com]

confidence). That CAR projection agrees with Jones *et al.* (2016) and Stennett-Brown *et al.* (2017). The larger changes in the indices over CAM are increases in R20 (26.0%), R30 (75.5%) and Rx5 (31.2%). CWD reductions in CAM (−26.7%) are the largest among all regions, although with more confidence than the GCM. NAM is expected to undergo significant changes including a doubling of the R30 index, a 20% reduction in CWD and the largest increase in the CDD index among all regions (42%). Large changes are expected in SAM, with increased R20 (88.5%), R30 (248.3%) and Rx5 (32.4%), along with significantly increased CDD (14.0%) and reduced CWD (−19.4%). Finally, NEB also exhibits large projected changes in most indices, including large increases in R20 (85.4%), R30 (237.4%) and Rx5 (38.0%), as well as a significant increase in the CDD (29.3%).

## 5 | DISCUSSION AND SUMMARY

In this paper, daily precipitation from dynamical downscaling simulations of current and future climate using RAMS, forced by HadGEM2-ES for historical, RCP4.5 and RCP8.5 were analysed. The simulations design follows the Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi *et al.*, 2009; Ambrizzi *et al.*, 2019) framework. Primarily, the historical runs are validated by comparison with the observational dataset, as similarly addressed in other works such as de Brito *et al.* (2018). As shown in the comparison between model results for a baseline period (1985–2005) and present climate data from TRMM, RAMS is capable of representing several characteristics of extreme events over the tropical Americas, including its spatial distribution, the duration of wet and dry spells for different regions, and so forth.

**TABLE 3** Projected percent changes in the extreme indices over the six regions (Figure 1) for three time slices under RCP4.5 and RCP8.5 scenarios

| | | | R10 | R20 | R30 | Rx5 | CDD | CWD |
|---|---|---|---|---|---|---|---|---|
| MEX | RCP4.5 | 2015–2035 | +7.9 | +12.9 | +16.0 | −2.5 | +6.8 | +2.0 |
| | | 2045–2065 | +2.7 | +12.4 | +21.0 | +10.8 | +8.0 | −0.1 |
| | | 2079–2099 | +16.1 | +32.9 | +50.2 | +24.9 | +4.7 | +6.1 |
| | RCP8.5 | 2015–2035 | +11.5 | +20.6 | +26.9 | +9.0 | +2.1 | +5.8 |
| | | 2045–2065 | +9.8 | +25.2 | +41.7 | +21.5 | +6.3 | +3.3 |
| | | 2079–2099 | +7.2 | +32.2 | +61.2 | +36.1 | +11.7 | −1.2 |
| CAR | RCP4.5 | 2015–2035 | +9.3 | +12.4 | +18.2 | −9.5 | +3.6 | −5.4 |
| | | 2045–2065 | −7.0 | −5.4 | −0.6 | +0.8 | +16.5 | +1.9 |
| | | 2079–2099 | −7.5 | −8.2 | −4.7 | +1.3 | +5.8 | −2.3 |
| | RCP8.5 | 2015–2035 | +8.9 | +15.3 | +26.3 | +10.3 | −4.3 | +7.8 |
| | | 2045–2065 | +14.2 | +22.1 | +31.6 | +20.4 | +9.5 | +13.8 |
| | | 2079–2099 | −11.8 | −13.1 | −10.2 | +2.6 | +31.8 | −1.9 |
| CAM | RCP4.5 | 2015–2035 | +3.5 | +9.2 | +14.1 | −2.7 | +1.1 | −6.8 |
| | | 2045–2065 | +1.1 | +13.5 | +31.3 | +9.1 | +6.6 | −4.6 |
| | | 2079–2099 | +3.5 | +22.0 | +52.0 | +15.7 | +1.1 | −6.9 |
| | RCP8.5 | 2015–2035 | +6.5 | +16.2 | +29.1 | +10.5 | +0.3 | +2.8 |
| | | 2045–2065 | +9.7 | +29.1 | +61.0 | +19.0 | +1.6 | −1.1 |
| | | 2079–2099 | −4.3 | +26.0 | +75.5 | +31.2 | +4.7 | −26.7 |
| NAM | RCP4.5 | 2015–2035 | +7.6 | +17.3 | +22.5 | +3.5 | −6.5 | +1.8 |
| | | 2045–2065 | +5.6 | +23.6 | +44.7 | +7.9 | +22.0 | −6.1 |
| | | 2079–2099 | +7.6 | +35.5 | +71.1 | +12.1 | +18.6 | −8.3 |
| | RCP8.5 | 2015–2035 | +9.1 | +21.8 | +33.8 | +6.2 | +2.5 | +4.0 |
| | | 2045–2065 | +12.6 | +40.9 | +77.7 | +13.7 | +6.8 | −0.1 |
| | | 2079–2099 | −1.3 | +45.0 | +109.8 | +21.3 | +42.1 | −20.0 |
| SAM | RCP4.5 | 2015–2035 | +8.2 | +20.1 | +25.4 | +4.0 | +1.3 | +3.1 |
| | | 2045–2065 | +6.9 | +29.3 | +52.2 | +14.0 | +10.8 | −10.7 |
| | | 2079–2099 | +14.3 | +58.9 | +109.0 | +32.4 | +5.8 | −2.6 |
| | RCP8.5 | 2015–2035 | +7.5 | +23.5 | +32.5 | +6.2 | −2.1 | −2.9 |
| | | 2045–2065 | +13.4 | +56.5 | +114.8 | +16.6 | +9.1 | −6.1 |
| | | 2079–2099 | +6.9 | +88.5 | +248.3 | +32.4 | +14.0 | −19.4 |
| NEB | RCP4.5 | 2015–2035 | +12.1 | +31.1 | +60.8 | +11.4 | −3.2 | +11.3 |
| | | 2045–2065 | +22.3 | +46.5 | +92.3 | +16.2 | +7.1 | +17.2 |
| | | 2079–2099 | +17.1 | +53.8 | +123.3 | +17.4 | +16.3 | +7.0 |
| | RCP8.5 | 2015–2035 | +14.7 | +33.4 | +60.9 | +11.4 | −3.2 | +12.6 |
| | | 2045–2065 | +9.3 | +37.3 | +92.9 | +16.7 | +11.0 | −2.6 |
| | | 2079–2099 | +23.0 | +85.4 | +237.4 | +38.0 | +29.3 | +13.3 |

*Note*: Changes with confidence above 95%, 99% and 99.9% are highlighted with light, medium and dark grey shading, respectively.

Therefore, RAMS downscaling over the domain of the tropical Americas might be a valid tool to assess possible changes in the occurrence of hydroclimatic extreme events over that region, mainly for the Amazon region, where results better fit patterns across the studied extremes indices.

As in many other modelling studies, projections indicate a general tendency towards increased frequency of intense precipitation in tropical Americas (Marengo *et al.*, 2009; Campbell *et al.*, 2011; Karmalkar *et al.*, 2011; McLean *et al.*, 2015; IPCC, 2021). Except for some future timeslice over Caribbean region, such tendency is clearly for all regions accompanied by a projected reduction in the wet season duration (as it is clearly the case over eastern Amazon, under the RCP8.5 scenario for the 2079–2099). In addition, longer dry spells are also expected over most regions of the tropical Americas, with indicatives for Northeast Brazil (medium confidence). Regions that are expected to be affected by more pronounced changes in the statistics of extreme precipitation events include the ITCZ, especially over the Pacific Ocean, southern Central America and large portions of the Amazon and Northeast Brazil (high confidence). Those tendencies are particularly strong under the heavy-emission scenario (RCP8.5), in agreement with IPCC (2021) trends for heavy precipitation over land, projected to increase the frequency and intensity, regarding future global warming of 1.5, 2 and 4°C.

Particularly remarkable features in the projections are the very large increase in the R20 and R30 indices over the South America under RCP8.5 scenario (high confidence), the enhanced Rx5 (above 30%) over Mexico, Central America, Northeast Brazil (again under RCP8.5) and Southern Amazon (both scenarios), the marked CDD increase over the Caribbean, Northern Amazon and Northeast Brazil and the decrease in CWD (less confidence) over Central America and both Amazonian subdomains. Moreover, there is a strong coherence between projected mid-term changes under RCP8.5 and long-term changes under RCP4.5 regarding precipitation extremes index (R10, R20 and R30) over the tropical Americas.

RAMS Rx5 and CDD future projections for most of the studied areas (except for Central America Rx5) follows the IPCC (Arias *et al.*, 2021; Seneviratne *et al.*, 2021, p. 1566, fig. 11.16) results based on simulations from the CMIP6 multimodel ensemble (32 global climate models) using the SSP5-8.5 scenario.

It is worth mentioning that, for studies of applications and mitigation policies, the results presented in this work should not be considered as a unique possibility. Similar to the work presented by Llopart *et al.* (2019), they must be combined with other results (derived both from GCM and RCM) for a more comprehensive understanding of the impacts on various environmental and socio-economic sectors.

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## CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

## ORCID

*Sullyandro Oliveira Guimarães* https://orcid.org/0000-0002-0574-6616

*Domingo Cassain Sales* https://orcid.org/0000-0001-7564-8969

*Francisco das Chagas Vasconcelos Junior* https://orcid.org/0000-0002-1558-8383

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