

REVIEW

Advances in regional climate science in South America and Central America during the CORDEX Era

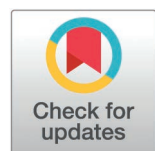
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Abstract

Latin America and the Caribbean have made major advances in regional climate modeling in the last 15 years, thanks to scientific initiatives in their different countries and their participation in the Coordinated Regional Downscaling EXperiment of the World Climate Research Program (CORDEX/WCRP). These efforts allowed North/South international cooperation from two CORDEX domains in the region: South America (SAM) and Central America, Mexico and the Caribbean (CAM). Many climate modeling activities and networking were developed in these two domains through capacity building workshops and project meetings on common topics of interest promoted by CORDEX. As a result, numerous studies have been published by scientists from these two domains focused on regional process understanding, climate impacts on different sectors, and assessments of the present state of the regional climate and their projected changes during the 21st century. This article reviews and discusses these topics and presents some challenges for the future advancement of regional climate modeling in CAM and SAM.



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Citation: Bettolli ML, Cavazos T, Reboita MS, Porfirio da Rocha R, da Silva ML, Hidalgo HG, et al. (2026) Advances in regional climate science in South America and Central America during the CORDEX Era. PLOS Clim 5(8): e0001015. <https://doi.org/10.1371/journal.pclm.0001015>

Editor: Valerio Lembo, CNR: Consiglio Nazionale delle Ricerche, ITALY

Published: August 6, 2026

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Funding: MLB was supported by the ANR-25-CE56-3663 project, by the University of Buenos Aires projects 20020220200028BA and 20020220200111BA, and the National Scientific and Technical Research Council project PIP 2021-2023 KE1 11220200100333CO. HH was supported by UCR grants VI-C6459 and VI-C5279. MO is funded by the AI4Science PN070500 fellowship within the "Generación

D" initiative, Red.es, Ministerio para la Transformación Digital y de la Función Pública, for talent attraction (C005/24-ED CV1). Funded by the European Union NextGenerationEU funds, through PRTR. RPR thanks to CNPq (Grants #305349/2022-8) and FAPESP (Grants #2025/05182-7 and 2024/00949-5) for financial support. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors declare that no competing interests exist.

1. Introduction

The current impacts of climate variability and climate change around the globe highlight the need for high resolution weather and climate information at regional and local scales, mainly in vulnerable areas. The observed changes of the circulation and thermal conditions of the atmosphere and ocean have been translated into unprecedented intensification of hurricanes, strong winds, exceptional droughts, destructive storms and long-duration heatwaves [1]. These events and their impacts call attention to a better understanding of the physical processes that modulate the regional climate simulations of South America (SAM) and Central America, Mexico and the Caribbean (CAM) regions (Fig 1) [3].

The spatial resolution of global climate models (GCMs) from the Climate Model Intercomparison Project (CMIP, e.g., [4,5]) used in the assessment reports of the Intergovernmental Panel on Climate Change have significantly evolved through the years, but they are still too coarse (approximately 1° to 1.5° spatial resolution) to adequately resolve the mesoscale circulations in regions of complex topography, with land-sea contrasts, different land cover etc., which are common features in CAM and SAM (Fig 1). Therefore, since 2009, the Coordinated Regional Downscaling EXperiment (CORDEX, [6]) of the World Climate Research Programme (WCRP) has promoted the use of regional climate models (RCM) and/or empirical statistical downscaling (ESD) in a coordinated framework to produce simulations of present and future regional climate scenarios to better understand regional processes and to foresee their possible changes and impacts associated with climate change. Both approaches have been used in CAM and SAM. Collaborative activities between the two domains have concentrated on using various RCMs or ESD methodologies through workshops, training, and academic mobility mainly focused on supporting the scientific advancement of graduate students and early career scientists.

Numerous studies have analyzed different aspects of the regional climates over CAM and SAM domains using RCMs and ESD, but only few reviews have accounted for their findings [e.g., 7–10]. In particular, [9,10] provide comprehensive reviews of the fundamentals of regional climate modeling, with a particular focus on applications related to climate prediction, variability, and projections for South America. However, it is important to note that, to date, no dedicated reviews exist for the CAM domain, and no studies have specifically reviewed CORDEX-related research in both the CAM and SAM domains. In this context, this article reviews the progress achieved over the past 15 years on regional climate modeling in CORDEX-CAM and CORDEX-SAM domains. We synthesize advances in dynamical downscaling, coordinated modeling activities, and the development of regional climate model ensembles across the two regions, with a specific focus on studies based on CORDEX simulations and CORDEX-related research. In particular, we highlight the evolution of the scientific community through collaborative initiatives, key research findings on shared and region-specific physical processes, and applications of regional climate information in impact-relevant sectors such as water resources, agriculture, and extreme event assessment. We also discuss current limitations and emerging challenges in regional climate modeling, and outline priorities for future research in these domains.

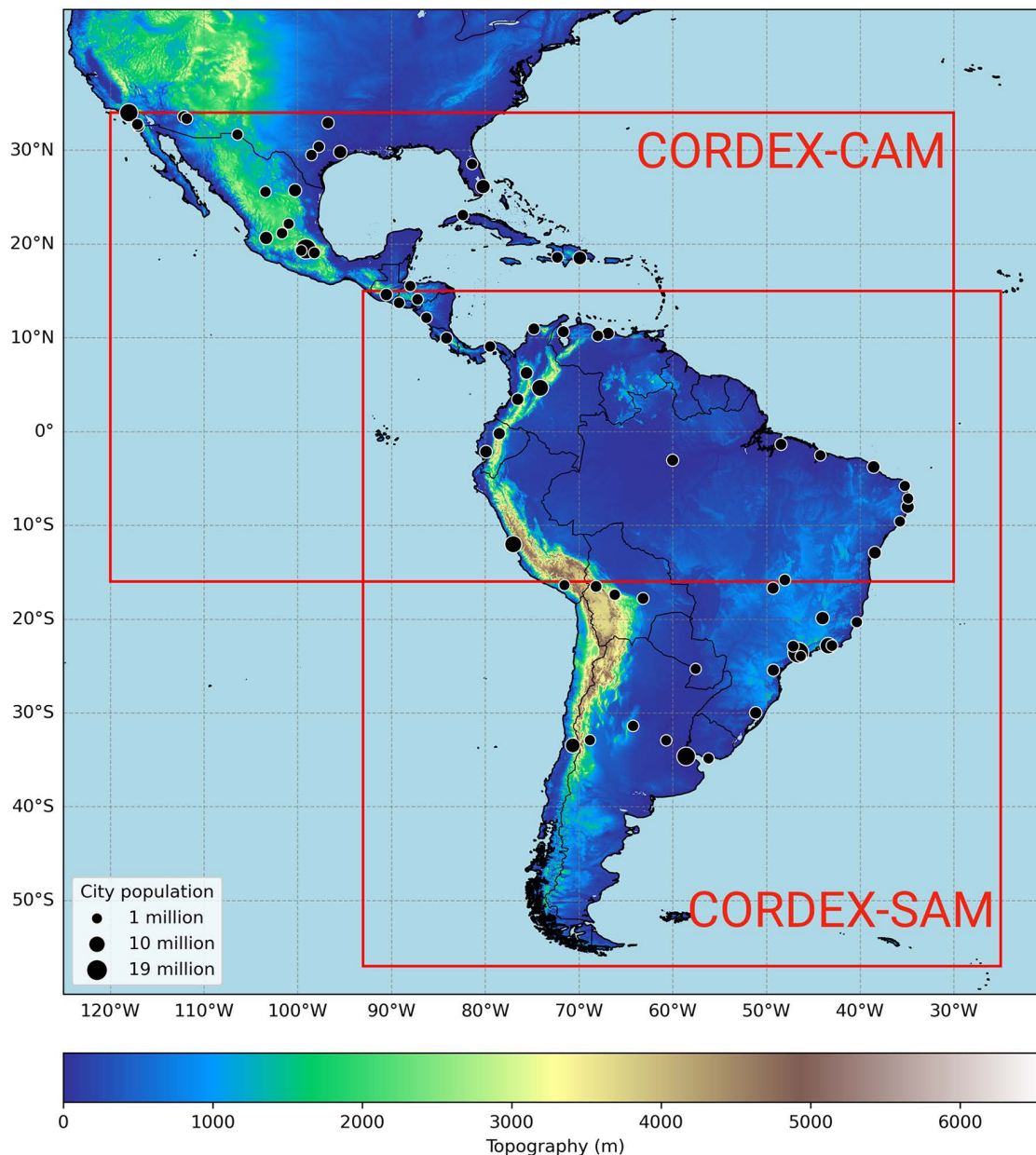


Fig 1. CORDEX CAM and SAM overlapping experimental domains. Cities with population over 1 million are displayed according to the Global Human Settlement - Urban Centre database R2024A [2]. Basemap coastlines and country boundaries used in this map are derived from the Natural Earth dataset (<https://www.naturalearthdata.com>), accessed via the Cartopy Python library. Topography is derived from the NOAA ETOP01 Global Relief Model (<https://www.ncei.noaa.gov/products/etopo-global-relief-model>). Both Natural Earth and topography datasets are not subject to copyright restrictions and are freely available for use and redistribution.

<https://doi.org/10.1371/journal.pclm.0001015.g001>

2. Overview of coordinated modelling activities within CAM and SAM

Over the past 15 years, the development of CORDEX modeling activities and research within the CAM and SAM domains has been complemented by other regional initiatives. Although not formally part of CORDEX, these efforts played a key

role in strengthening regional scientific communities through collaboration and networking, which consolidated the CORDEX foundations in the region. This is the case of the first regional climate modeling projects in SAM, such as CREAS [11] in the early 2000s and CLARIS-La Plata Basin (CLARIS-LPB, [12]) in 2008, as shown in the time line in Fig 2.

CORDEX was launched in 2009 as part of the WCRP with a primary objective of conducting coordinated RCM and ESD simulations over continental regions worldwide, such as in CAM and SAM domains (Fig 1). CLARIS-LPB, funded by the European Union, was established as a consortium of several institutions from South America and Europe and fitted very well within the CORDEX objectives. One of its aims was to develop a coordinated ensemble of RCM adhering to the CORDEX protocol to assess the impact of climate change on the hydroclimate of the La Plata Basin. In this context, the SAM region was able to build a comprehensive CORDEX RCM ensemble that was used to assess the impact of global warming on the mean climate of South America [12]. This first coordinated initiative allowed for an unprecedented advance on the production of RCM simulations in South American institutions, mainly in Argentina and Brazil. These efforts were the basis for further capacity building and networking in the region, and their outcomes were used for national communications [13], which provided valuable information for policy makers in the region.

Building on these initial endeavors over SAM, the CORDEX CAM and SAM community organized two major workshops in collaboration with the Variability of American Monsoons initiative (VAMOS/CLIVAR) and CORDEX, and co-financed by WCRP, the International Council of Scientific Unions, and the Interamerican Institute for Global Change Research. These workshops held in 2013 and 2014, in Lima, Peru, and Santo Domingo, Dominican Republic, respectively, brought together the international community of regional climate scientists to pursue the first assessment of the various CORDEX downscaling initiatives. These activities gathered more than 130 scientists and were the seed to coordinate regional climate science in CAM and SAM. At the same time, the development of ESD analyses within the CORDEX framework began to take shape through a series of workshops, such as in the University of Buenos Aires, Argentina, in 2014. Dynamical downscaling workshops were also carried out in Mexico (2014) and Costa Rica (2016; [14]). Since then, and supported by the CORDEX Points of Contacts, a series of workshops and special sessions in national and international conferences have been organized to foster collaborative interactions within the CORDEX CAM and SAM downscaling communities as well as with other CORDEX domains. S1 Table in the supplementary material summarizes these efforts.

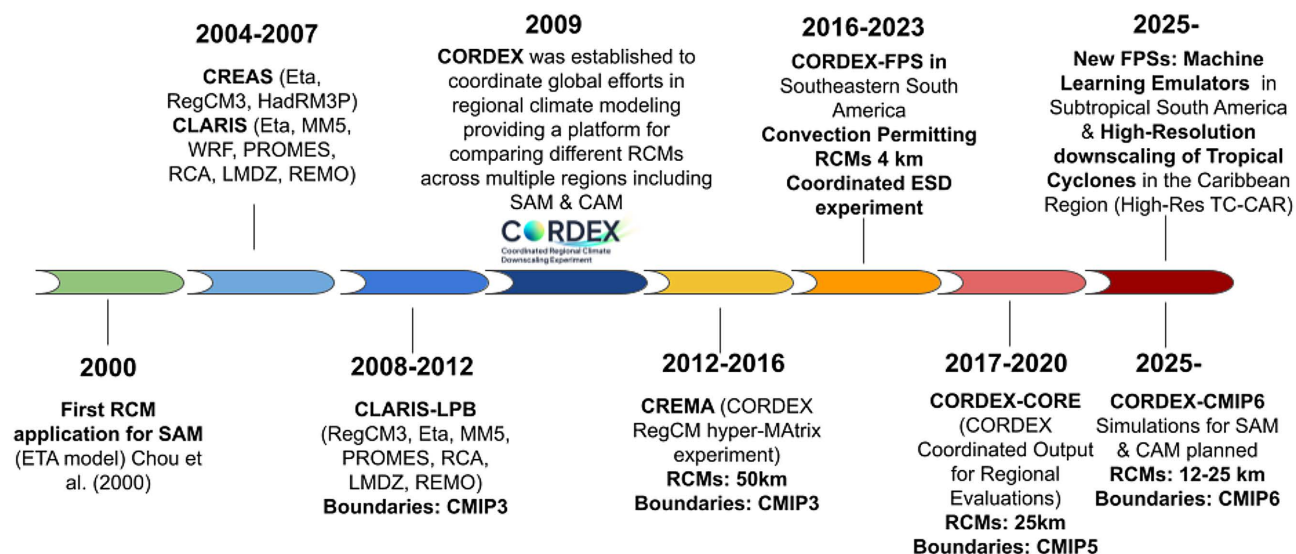


Fig 2. Timeline of the regional climate modeling activities in CAM and SAM.

<https://doi.org/10.1371/journal.pclm.0001015.g002>

The significant progress in regional climate modeling and related activities in the CAM and SAM domains have been largely driven by the contributions of early-career scientists, including PhD students and postdoctoral researchers, who partially developed their expertise and carried out many of the model simulations for the two domains during scientific visits to international research centres, such as the International Centre for Theoretical Physics (ICTP) in Trieste. Their work was complemented by the dedicated efforts of local researchers in obtaining funding from universities, research institutions, and projects supported by national science councils. In addition, financial support from WRCP, the ICTP, and the University of Cantabria (Spain) played a key role in enabling and sustaining this progress. When financial support has been available, activities have been conducted in person to promote scientific interaction and hands-on projects. Joint CAM and SAM online workshops started during the COVID pandemic (2020–2022) and have continued as a way to reduce our greenhouse gas footprint and to maintain collaborative engagements when financial resources are not available.

CORDEX has fostered capacity building and inspired new modeling activities at local and regional scales. In particular, the Flagship Pilot Studies (FPS), endorsed by CORDEX, are strategic activities focused on sub-continental scale targeting key scientific questions relevant for particular regions. A major strength of the FPSs is that they allow the integration of local modelling groups that do not have the computing and/or human resources to conduct simulations at the continental or domain scale required by the CORDEX standard protocols. In SAM, the FPS “Extreme precipitation events in South-eastern South America: a proposal for a better understanding and modeling” (2016–2024) investigated multi-scale processes and interactions that resulted in extreme precipitation events. It also developed actionable climate information from statistical and dynamical downscaling, including convection-permitting simulations, based on co-production of knowledge. The project was an inter-institutional collaborative initiative that brought together RCM and ESD scientists from different countries, as well as end users to support specific impact (agriculture and hydrological) studies. Different institutions from Argentina, Brazil, Uruguay, Spain, the Czech Republic, and Italy participated in this initiative producing a number of papers [15–20].

In addition, different modeling groups from SAM have contributed to the Urban FPS by conducting high-resolution simulations over São Paulo and Buenos Aires [21], as climate change in large cities is very relevant due to their impacts on society. Other FPS are under way in the two CORDEX domains to investigate climate extremes, emulation approaches and tropical cyclones at high spatial resolution.

3. Advances in the understanding of physical process: Present and future

This section presents an update of the advancements in understanding various physical processes that are common to CAM and SAM (Table 1), achieved through regional climate modeling in the CORDEX framework under present and climate change conditions. Table 1 also summarizes the main findings, limitations, and research gaps of CORDEX-related studies regarding the representation of regional processes and climate features by RCMs. For the analyses of the physical processes presented below various models were used (S2 Table), which were forced by reanalyses for the historical evaluations and with few GCMs from CMIP3 or CMIP5.

3.1. Mean and extreme climate

The mean climates of CAM and SAM are diverse as they span from mid-latitudes to subtropical, to tropical and equatorial climates in two hemispheres. Their climates and extremes are also modulated by the contrasting topography from coastal and island regions to cities, some with huge urbanization settlements, as well as by the high mountains and the influence of the Atlantic and Pacific oceans (Fig 1).

RCM simulations over CORDEX-SAM generally add value relative to their driving GCMs by improving the representation of precipitation spatial variability, particularly in regions with complex terrain [22–24], where higher spatial resolution allows for a more realistic representation of topography and associated processes. These improvements are especially

Table 1. Summary of the main findings, limitations, and research gaps identified in CORDEX-related studies over SAM and CAM discussed in the following subsections.

Feature	Main findings, limitations and gaps
Mean climate and extremes	Main findings: RCMs add value relative to their driving GCMs, particularly over regions with complex topography. Heatwave durations are generally well reproduced by the RCMs over CAM and SAM. In SESA, high-resolution and convection-permitting RCMs improve precipitation representation, including seasonal and diurnal cycles, and better capture precipitation extremes. RCMs reproduce the main circulation patterns in SAM. Convection-permitting RCMs capture the spatial distribution and diurnal cycle of extreme precipitation in SESA, and the urban - rural contrasts in temperature, relative humidity, wind speed and heatwaves in cities of SAM. High resolution and convection-permitting RCMs adequately reproduce the synoptic environment associated with extreme rainfall. Limitations and gaps: Warm bias over central SAM. Common cold bias at high elevations. Cold bias over continental CAM. Wet bias in the Amazon region and dry bias in Northeastern Brazil. Wet bias in mountains and tropical regions of CAM. Dry bias over southern Central America and the Caribbean. RCMs tend to simulate a reduced number of circulation patterns. Gap: Limited number of studies on climate extremes, particularly over CAM. Gap: Limited studies of associated circulations and mechanisms with climate extremes. Gap: CORDEX convection-permitting simulations remain limited over SAM and are not yet available over CAM.
Observed and projected changes in mean climate and extremes	Main findings: Robust warming projected across CAM and SAM. Robust signal towards a higher incidence of drought events in continental CAM, northeastern Brazil and the central Andes. RCMs provide more detailed regional information on future changes in precipitation, extremes and compound events than GCMs, especially over SAM. Limitations and gaps: Future precipitation changes remain uncertain in some regions and differ among RCMs and driving GCMs.
Cyclones and fronts.	Main findings: RCMs adequately reproduce the main cyclogenetic regions, frontal systems, and subtropical cyclone variability over SAM. The west coast of South America cyclogenetic region is well represented by convection-permitting RCMs. Over the South Atlantic Ocean extratropical cyclones and explosive extratropical cyclones are projected to decrease in frequency but increase in intensity. Subtropical cyclones are also projected to decrease in frequency by the end of the century, while no trends are found for tropical cyclones over this ocean basin. RCMs reproduce most features of the observed tropical cyclone climatology over CAM Limitations and gaps:: Remaining biases in precipitation associated with extratropical cyclones and fronts in SAM. RCM misrepresent the intensity of tropical cyclones over CAM
Low and Upper Level Jets	Main findings: Main jets over CAM and SAM are well represented by RCMs, Future projections show a consistent strengthening of low level jets and a shift in their location. RCMs project stronger intensities of mid-latitude upper-level jets, with a poleward shift under climate change scenarios consistent with the GCMs. Limitations and gaps:: RCMs show a weaker SALLJ and discrepancies in the timing of the CLLJ's maximum intensity. Gap: limited studies of low- and upper-level jets.
Monsoons	Main findings: Observed NAM and SAM rainfall seasonality and interannual variations are well captured by RCMs. Robust projection of delay in the onset and demise of monsoon rainfall, an increase in seasonality, and a reduction in the rainy season length under higher levels of radiative forcing over CAM and SAM. Limitations and gaps: Uncertainties remain in precipitation responses and land-atmosphere feedbacks over monsoon regions.

(Continued)

Table 1. (Continued)

Feature	Main findings, limitations and gaps
Teleconnections	Main findings: RCMs adequately reproduce interannual precipitation and temperature variability linked to ENSO and other teleconnection patterns. Variability associated with the North American monsoon, midsummer drought, and subtropical jet is well represented
	Limitations and gaps: additional regional climate studies addressing teleconnection responses under climate change scenarios using CORDEX simulations are needed.

<https://doi.org/10.1371/journal.pclm.0001015.t001>

evident using high spatial resolutions (e.g., 0.22°). Despite their advantages over GCMs, simulations in CORDEX-SAM show a significant warm bias over central Argentina [25–27], possibly related to the overestimation of the incoming short-wave radiation, in agreement with an underestimation of the relative humidity at low levels of the atmosphere [27]. Errors in precipitation are regionally variable, particularly in tropical areas displaying dry (wet) biases over the Amazon basin (in northeast Brazil) [25–27], where the underestimation of both the moisture flux convergence and the relative humidity at lower levels of the atmosphere, are key factors influencing cloudiness [27]. Over the Andes, RCMs have a common cold bias at high elevations associated with an overestimation of precipitation and surface albedo, likely related to an overestimated snow cover [28–31]. Over the Atacama Desert, RCMs produce warm bias highlighting the complexity in representing land surface and radiative processes over the desert, including limitations in surface properties (e.g., albedo and emissivity), dust-related processes, and downwelling longwave radiation [22]. Convection-permitting simulations satisfactorily capture the urban-rural contrasts in temperature, relative humidity and wind speed representing the warmer, drier and weaker wind conditions over the cities [20].

In CORDEX-CAM, RCMs have shown large wet biases in mountain regions [7,8,32,33] and over northern Central America [30], while they depict a dry bias over southern Central America and the Caribbean. Temperature biases are mostly cold over the continental regions [34]. RCMs are able to adequately capture seasonal patterns, interannual variations, and maximum dry spell length in Mexico [7,32]. Central America and the Caribbean climates are challenging to simulate by GCMs and even by RCMs due to the narrowness of the region and size of the small islands, respectively. Nevertheless, RCMs add value by reducing the GCM temperature and precipitation biases [34,35], especially in subtropical regions [36].

Regarding climate extremes, most studies have focused on precipitation-related extremes, including both dry and wet events, while comparatively less attention has been given to temperature extremes and extremes in other climate variables. This imbalance is particularly evident in studies over CAM. In SAM, RCMs tend to overestimate warm temperature extremes, particularly over tropical South America, although some regional underestimations are also identified over the Andes, parts of Amazonia and Southern South America. Similar spatially heterogeneous biases were found in their driving GCMs [37,38]. Heatwave durations are generally well reproduced by the RCMs, although with some overestimation over northern South America and tropical regions, partly inherited from the driving GCMs [37,38]. Convection-permitting simulations well reproduce heatwaves over cities with more intense and more frequent heatwaves over the cities, compared with the rural environment [20].

RCMs generally reproduce the spatial distribution of extreme precipitation over South America, including the maximum values over the La Plata Basin, although important regional biases remain even in the higher resolution simulations from CORDEX-CORE [37,39,40]. Overestimation of precipitation extremes near the Andes is a well-known feature of RCM simulations, including both GCM- and reanalysis-driven experiments [37,39,41]. On the other hand, the dry spells over subtropical and northeastern SAM are overestimated by RCMs and their driving GCMs [37].

Over CAM, CORDEX-CORE RCMs show a good performance in simulating the extreme temperature indices (annual maximum temperature and heatwaves) as well as wet and dry indicators, as shown in a global assessment [38]. In

particular, RegCM tends to reproduce better the extreme indices of the CAM semiarid zones and flat-terrain regions, while in tropical regions with complex terrain it tends to overestimate the indices [36].

Regarding circulation characteristics in southern SAM, RCMs reproduce the main synoptic types and their daily frequencies, although they tend to simplify the predominant patterns into a reduced number of configurations [41].

When analyzing circulation associated with extreme precipitation over Southeastern South America (SESA) RCMs generally capture this relationship, exhibiting some limitations in the location and intensity of the resulting precipitation systems [41]. Consistent with these results and in contrast to parameterized convection, convection-permitting simulations (at 4 km resolution) not only intensified extreme precipitation events, but also modified the location of the maximum precipitation by modulating the low-level atmospheric circulation [16]. The vertically integrated moisture flux convergence was identified as a noticeable footprint of deep moist convection over the region, regardless of the model and timescale. In general, convection-permitting RCMs better capture the spatial distribution of extreme precipitation in SESA and add value in capturing the diversity of diurnal cycles observed over the region. They also corrected the shift in daily peak precipitation, obtaining a better agreement with local observations [17].

Across Central America, the western Caribbean, and the eastern tropical Pacific, low-level circulation and precipitation are largely insensitive to expanding the regional model domain by 18–52% beyond its size [42]. In contrast, changes in the physical configuration of the RCM (RegCM) appear more consequential. Limitations in representing the low-level circulation linked to the Caribbean Low-Level Jet (CLLJ) hinder the representation of key precipitation features. RegCM simulations using the Grell cumulus scheme outperformed the mixed Grell–Emanuel option [42]. Higher-resolution and convection-permitting simulations could provide further insight into the representation of these circulation features and their associated precipitation processes.

3.2. Observed and projected changes in mean climate and extremes

Studies using CORDEX simulations have provided valuable insights into possible climatic changes across CAM and SAM. Both observations and CORDEX simulations of the present climate consistently show rising air mean temperatures across both CAM and SAM. In particular, over the coastal areas of the southern tip of South America, the observed negative temperature trend changes to positive in future scenarios [43]. Over the subtropical and southern Andes, temperature is projected to increase under all scenarios and time horizons, with the largest warming - up to 5°C - in the RCP8.5 scenario at the end of century (2071–2100), particularly in the subtropical Andes [29]. These projections also reveal a clear elevation-dependent warming signal, specifically north of 37°S where the Andes Mountains reach higher altitudes [29]. In contrast, mean precipitation changes exhibit a more spatially heterogeneous pattern. For instance, southern Amazonia presents a negative precipitation trend while the opposite occurs in parts of La Plata Basin, and this signal is projected to persist through the end of the century [9,26,39,44,45]. Across the Andes between Chile and Argentina (21°S–47°S), RCM projections indicate a decline in precipitation, ranging from -5% to -30%, depending on the scenario and time horizon [29]. Over the Peruvian Andes RCMs project a dipole in precipitation, with an increase in the north and a decrease in the south in the RCP8.5 scenario for 2070–2099 [46].

Over CORDEX-CAM, historical precipitation and temperature trends using three RCMs showed robust winter and summer warming signals and regional variations in rainfall patterns, particularly in monsoon-affected areas [33]. Future scenarios based on ESD of several GCMs [47,48] show continued warming across CORDEX-CAM through the 21st century and a significant drying, especially in southern Mexico and Central America. These results are consistent with other studies based on RCM simulations [32,49,50].

Moving to projections of extremes, temperature extremes in SAM show a significant agreement towards warmer conditions in extreme temperature indices (Fig 3), but precipitation signals differ between RCMs and their driving GCMs [39,51]. The RCM ensemble projects positive trends for extreme precipitation in the La Plata Basin, while over the tropics the projected changes in extreme events are more uncertain [40]. SESA is highlighted as a precipitation hotspot, with the

Long Term (2081-2100) RCP8.5 (rel. to 1986-2005)

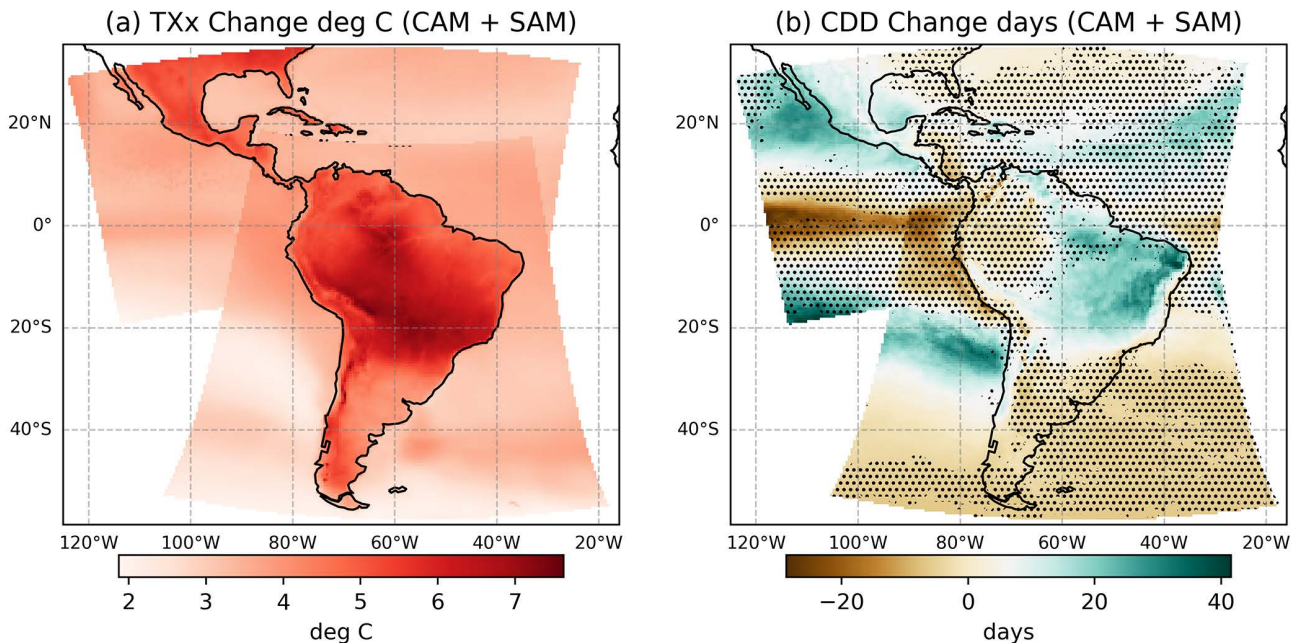


Fig 3. Change of the mean annual maximum temperature (TXx) (a) and the mean annual maximum in consecutive dry days (CDD) (b) between 2081-2100 under the RCP8.5 scenario and the historical period 1986-2005 as depicted by CORDEX simulations. Stippling indicates low model agreement, where fewer than 80% of models agree on the sign of change. This figure was plotted using the CORDEX simulations available in the IPCC interactive atlas. Source: <https://interactive-atlas.ipcc.ch/>.

<https://doi.org/10.1371/journal.pclm.0001015.g003>

main differences in signal intensity arising from the comparison between CORDEX-CORE RCMs and ESD simulations driven by the same GCMs [52]. In addition, future climate scenarios for Argentina show a consistent warming signal (both in mean temperatures and in the frequency of extremes) among GCMs, RCMs and ESD, which is strongest over the northern part of the country [53]. The uncertainty in future changes is considerably reduced by RCMs and ESD simulations when compared to their driving GCMs.

Over CAM, RCM projections of precipitation- and temperature-based extreme indices indicate a decline in consecutive wet days and an increase in consecutive dry days, alongside decreases in the frequency of cold days and nights and increases in warm days and nights [38]. Over the Greatest Antilles region, precipitation is projected to decrease, while the intensity of extreme events is expected to increase [35]. Drawing on ensembles of global and regional simulations including the CAM domain, simulations project widespread increases in heatwaves, maximum consecutive dry days, the fraction of precipitation exceeding the 95th percentile, and the hydroclimatic intensity index [54]. Collectively, these changes indicate a shift toward less frequent but more intense rainfall, alongside heightened risks of heatwaves, drought, and flooding under continued warming in CORDEX-CAM [54].

CORDEX-based studies also investigated changes in meteorological drought characteristics, [55,56]. In SAM, areas including the northeastern part of Brazil and the central Andes may also see increased drought exposure, with variations depending on the specific warming levels and scenarios [29,39] (Fig 3). Moreover, CORDEX-CORE simulations show robust future increases of coincident compound events of heatwaves and droughts over northern South America and southern Brazil [37,57], while an increase in the sequential dry spells followed by extreme precipitation events is also expected in SESA [37].

In CAM, the observed drought trends in the North American monsoon and the mid-summer drought regions are well captured by RegCM [58]. Future changes towards a higher incidence of drought events are expected to persist, especially under scenarios with higher warming levels (Fig 3). Key drivers of drought conditions are reductions in precipitation, increases in atmospheric evaporative demand associated with higher temperatures, or the combined effect of both factors. Nevertheless, a more comprehensive understanding of drought processes requires assessing how these meteorological anomalies propagate into soil moisture deficits and hydrological drought conditions [55].

3.3. Cyclones and fronts

The three primary cyclogenetic regions along the eastern coast of South America (the southeastern and southern coasts of Brazil, the extreme south of Brazil and Uruguay, and the southeast coast of Argentina) and their seasonal variations have been well reproduced by RCMs [59,60]. On the west coast of South America, a semi-stationary type of cyclones with genesis around 30°S is also well represented by RCMs and convection-permitting RCMs [61,62]. Many extratropical cyclones that develop near southern Argentina and Uruguay have an associated cold front that affects La Plata basin. RCMs generally capture the annual frequency of cold fronts in this region, but with some seasonal biases in precipitation [63].

Following the uncommon occurrences of hurricane Catarina (03/2004) and the subtropical cyclone Anita (03/2010) near the Brazilian coast, research on these types of systems gained attention [59]. Considering the climatology of subtropical cyclones using CORDEX-RCMs, it was demonstrated that the RCMs outperformed the GCMs in representing the mean and interannual variability of subtropical cyclones [63]. Future RCM projections of different types of synoptic-scale cyclones over the South Atlantic Ocean suggest that extratropical cyclones will decrease in frequency but increase in intensity [64], a trend also observed for explosive extratropical cyclones [65]. Subtropical cyclones are projected to decrease in frequency by the end of the century [66], while no trends are found for tropical cyclones over this ocean basin [67].

While tropical cyclones are rare in the South Atlantic, they are common in the tropical seas surrounding north of South America and the Caribbean and Pacific coasts of CORDEX-CAM [68,69]. RCMs reproduce most features of the observed tropical cyclone climatology in this region, except for their intensity [68,69]. Sensitivity to horizontal resolution was assessed in the CORDEX-CAM domain, and found that higher resolution (25 km in contrast to 50 km), increased the cyclogenesis in the Northeastern Tropical Pacific [70]. More studies on present and future changes of tropical cyclones and hurricanes in CORDEX-CAM using RCMs are presented in a companion paper of this CORDEX special collection [71].

3.4. Low and Upper Level Jets

Over the CAM and SAM domains, there are three main low-level jets: Great Plains low-level jet (GPLLJ), CLLJ, and South American low-level jet (SALLJ). These jets have been well represented by RCMs, although with some differences in intensity, such as a weaker SALLJ and discrepancies in the timing of the CLLJ's maximum intensity [72]. Projections under the RCP2.6 and RCP8.5 scenarios indicate a consistent strengthening of these jets and a shift in their location. The CLLJ and SALLJ are projected to expand westward, while the GPLLJ is expected to migrate eastward [72]. However, simulations of the CORDEX North America domain revealed a westward expansion of the GPLLJ, although with little shift in the jet core [73]. Future scenarios suggest a strengthening of the CLLJ during summer [32] and a weakening during winter [74]. The CLLJ may also expand eastward and northward of the core region during summer, and it may contract during winter.

Regarding the upper-level jets, GCMs have projected stronger intensities with a poleward shift in both hemispheres under climate change scenarios (e.g., [75]). RCMs show similar results for the mid-latitudes of the Southern Hemisphere [66,76].

The relatively limited number of studies highlights the need for further investigation of low-level jets over CAM and SAM, particularly secondary regional low level jets and their interactions with regional precipitation and moisture transport. Additional studies are also needed to better understand the representation, variability, and projected changes of upper-level jets in both regions.

3.5. Monsoons

According to the modern definition proposed by [77], a monsoon region is characterized by strong precipitation seasonality, with approximately six months of dry conditions and six months of wet conditions. In the literature, the term monsoon is commonly used to refer to the wet period. RCM simulations successfully reproduce the main seasonal characteristics of the SAM and North American (NAM) monsoon systems, including their spatial precipitation patterns, seasonality, and annual cycle. Some regional biases remain with a delayed monsoon onset over parts of the Amazon and an earlier monsoon demise in some regions of SAM and CAM, and over mountain regions [78]. Monsoon rainfall in CAM and SAM is projected to experience a spatially robust delay in the onset and demise, an increase in seasonality, and a reduction in the rainy season length under higher levels of radiative forcing [78]. This is in agreement with CMIP6-GCMs for the SAM monsoon [79]. In addition, during the wet austral season (November–March), a decrease in precipitation over the Amazon Basin, and an increase across the La Plata Basin are expected, however, these changes are not projected to cause retreat or expansion of the monsoon area over the continent relative to the present climate (1995–2014) [80]. The wet conditions projected for La Plata basin at the end of the century are associated with moisture convergence from the South Atlantic Ocean, while the negative signal projected in Amazonian precipitation is associated with a reduction in evapotranspiration [26]. In other subregions of the SAM monsoon the RCMs disagree in the projection of the surface-atmosphere coupling highlighting the uncertainties in future climate [80].

3.6. Teleconnections

They refer to large-scale interactions within the coupled atmosphere–ocean system through which heat sources or anomalies in one region influence atmospheric circulation and climate variability in distant regions via atmospheric wave propagation and oceanic circulation processes. There are many teleconnection patterns, and one of the most widely discussed in the literature is the El Niño–Southern Oscillation (ENSO) [81]. The ENSO phenomenon is one of the most important sources of interannual variability that creates extreme weather and climate anomalies over CAM and SAM. RCM simulations show that the mean ensemble and individual RCM realizations generally preserve the broad regional scale of the ENSO signal from the GCMs, but adding regional detail in line with the observations over different regions around the world, including CAM and SAM [82,83].

The boreal winter climate in CORDEX-CAM is strongly modulated by the position of the subtropical westerly jet and its tropical-midlatitude teleconnections, such as ENSO, the Pacific North America, the North Atlantic Oscillation, and the Arctic Oscillation. RegCM4 historical simulations are able to adequately simulate different variations of the position and intensity of the jet stream linked to the various teleconnection patterns and their climatic impacts in CORDEX-CAM and the United States [84]. Thus, much of the interannual variability of temperature and precipitation is linked to ENSO. Over southern Mexico and Central America interannual variations are also linked to ENSO and sea surface temperature anomalies between the eastern Pacific and the Atlantic oceans, which have been found more realistic in RegCM4 than in GCMs [32]. In addition, the interannual variation of rainfall and droughts in the North American monsoon and the midsummer drought region are well simulated by RCMs and linked to ENSO and the Atlantic Multidecadal Oscillation [33,58].

There is a clear need for additional regional climate studies addressing teleconnection responses under climate change scenarios using CORDEX simulations.

4. Impact studies

The enhanced detail of RCM simulations is essential for assessing region-specific impacts of climate variability and change. In this sense, CORDEX-CAM and SAM CORDEX simulations were used on several applications to investigate the impact of climate change on agriculture, wind energy, streamflow, and ecology, among other sectors. The main findings of these studies are summarized in [Table 2](#).

4.1. Residential buildings and thermal comfort

Studies consistently project increasing thermal discomfort and heat stress under future warming scenarios, particularly in urban areas of SAM [94]. Bias adjustment methods influence the magnitude of projected heat stress changes, although uncertainties remain smaller than the spread among raw RCM simulations [85–87].

4.2. Heatwaves and fire risk

Over the Pantanal, future projections indicate substantial increases in heatwave frequency and fire risk, where burned areas are expected to intensify under stronger warming scenarios [88].

4.3. Energy

Climate change is projected to modify renewable energy resources across CAM and SAM, including changes in wind power density, photovoltaic potential, and solar radiation [49,89–92]. Future warming is also expected to increase cooling energy demand [88]. Some technological adaptations, such as phase-change material (PCM)-based cooling systems, could reduce efficiency losses and improve photovoltaic energy production under warmer climates [93].

4.4. Agriculture and winegrape production

Climate change may significantly affect crop yields and agricultural suitability. Bias correction strongly influences crop yield projections, while crop simulations driven by CPRCMs inherit uncertainties from climate inputs, particularly precipitation [19,95,96]. Viticulture areas and production in Mexico may decrease under warming scenarios, whereas bias-corrected RCMs show potential for future viticultural zoning applications in Argentina [97–99].

4.5. Hydrology

Future projections indicate reduced streamflow and aquifer recharge in Cuba's Cauto River Basin due to warming and precipitation decreases. Hydrological simulations driven by CPRCMs generally agree with observation-driven simulations, although they remain highly sensitive to precipitation intensity and spatial distribution [18,100].

5. Future challenges and perspectives

In addition to the weaknesses outlined in Table 1, several overarching challenges persist in the region, including the availability of large coordinated RCM/ESD ensembles, availability and integration of observations at high temporal and spatial resolution from different sources, the computational cost of high-resolution simulations, and the development of robust approaches to separate forced signals from internal variability at regional scales. A further cross-cutting challenge is to ensure that advances in regional climate modelling effectively translate into actionable information for decision-making, through systematic evaluation of model added value, robust communication of uncertainty, and sustained regional capacity and infrastructure.

The coordinated implementation of ESD techniques over CAM and SAM remains a significant challenge for regional communities. Although several studies have evaluated different ESD approaches across the regions [48,52,53,101–104], only a limited number have been carried out in a coordinated manner within the CORDEX framework [15,18]. The rapid expansion of machine learning applications in climate modelling provides an opportunity to explore their potential for downscaling and regional climate emulation, enabling a more computationally efficient representation of physical processes and changes in the climate system. This offers an opportunity for regional communities to address shared scientific challenges in a coordinated way. However, to fully leverage this potential, parallel efforts in capacity building in machine learning techniques and in the management of large volumes of data are essential.

Table 2. Summary of modeling studies applied to climate impacts in different sectors and regions using RCMs and/or ESD simulations in CORDEX CAM and SAM domains.

Impact Sector	Domain RCM/ESD	Key results/findings	Region	Reference
Residential buildings	CORDEX-SAM RCM	RCM-driven energy simulations, thermal performance and comfort under future climate change context: heat discomfort condition increases as the scenarios evolve.	São Paulo, Brazil	[85]
Thermal comfort	CORDEX-SAM RCM	Present and future projections of thermal comfort index IPET (Indoor Perceived Equivalent Temperature): All simulation members show a warming pattern for IPET, which rises from 19.1–21.3°C, for the present, to 23.5–25.1°C, for the future climate. IPET in the future climate becomes higher than temperature due to the relative humidity increase.	São Paulo metropolitan area, Brazil	[86]
Thermal comfort	CORDEX-SAM RCM	Sensitivity of results to bias adjustment methods applied to CORDEX-CORE simulations for heat stress indices: heat stress based on fixed thresholds showed larger discrepancies among bias adjustment methods in the magnitude of changes by the end of the century, but still below the spread in raw RCM outputs.	Southern South America	[87]
Fire risk and heatwaves	CORDEX-SAM RCM	Historical and future fire risk and heatwave trends: The percentage of Pantanal under heatwave will most likely increase in the future reaching 35% near 2100 under RCP2.6 and up to 80% in RCP8.5. Burned area could increase accordingly, making the historic 2020 fire season merely average in the future.	Pantanal region	[88]
Energy	CORDEX-CAM RCM	Projections of wind energy resources in the Caribbean for the 21st century. Wind is expected to increase in: most of the Caribbean in the wet season associated with the extension of the North Atlantic Subtropical high; and only in the southeastern coast during the dry season due to an increase in land-ocean temperature gradient.	Caribbean	[89]
Energy	CORDEX-CAM RCM	Historical and future scenarios of cooling and heating degree days. Increased population and energy-intensity could lead in the long term to higher energy demand and GHG emissions.	México	[49]
Energy	CORDEX-CAM RCM	Historical and future scenarios of photovoltaic potential (PVP). PVP might decrease in the future.	México	[90]
Energy	CORDEX-SAM RCM	Historical and future scenarios of wind power density (WPD). WPD might increase in the north of South America, center-east Brazil and latitudes higher than 50°S.	South America	[91]
Energy	CORDEX-SAM RCM	Solar radiation is projected to increase in some regions and energy generation can rise with gains of up to 4.17%	Chile	[92]
Energy	CORDEX-SAM RCM	Integrated thermal–electrical–economic assessment of photovoltaic modules incorporating PCM under present and projected Mediterranean and arid climatic conditions. Although future warming would increase photovoltaic module temperatures, PCM integration substantially reduces them, mitigating efficiency losses. Simulations also indicate increased energy production and economic benefits with only a minimal increase in electricity generation costs.	Chile	[93]
Building energy	CORDEX-SAM RCM	Framework to manage uncertainties in energy simulations: the cooling (heating) energy demand exhibits substantial variations, ranging from 27–37 (303–330) MJ/m ² in a moderate emissions context to 51–70 (266–326) MJ/m ² in a high emissions scenario. Improvements in building efficiency correlate with reduced uncertainty and, in the context of higher emissions, the projected energy demand can range between 24–37 (201–243) MJ/m ²	South America	[94]
Agriculture	Bias-corrected CORDEX-SAM RCM	Impact of bias correction on future crop yield projections: soybean production simulated by the CROPGRO-Soybean model. Yield projections obtained using the raw RegCM4 data differed from the bias-corrected results by as much as 40%.	Brazil	[95]
Agriculture	CORDEX-CAM & SAM Observational + RCM model indices	Bioclimatic indices linked to soy and maize yields through linear regression models. Regression models using bias-corrected RCM data exhibited remarkable concordance with observed yield data in Mexico and Brazil, explaining more than 70% of maize yield variance, and indicated improved soy yield performance in Argentina.	Latin America	[96]

(Continued)

Table 2. (Continued)

Impact Sector	Domain RCM/ESD	Key results/findings	Region	Reference
Agriculture	CORDEX-FPS-SESA	Use of CPRCM outputs for maize and soybean yield simulation: simulated crop yields showed substantial spatial and temporal differences among CPRCM-driven simulations and relative to observation-driven simulations, inheriting a large part of the uncertainty from the CPRCM climate inputs, particularly from precipitation.	Brazil	[19]
Winegrape Production	CORDEX-CAM RCM	Global warming threatens to reduce the viticulture areas of Mexico at the end of the 21st century, forcing adaptation: the number of cool nights ($T_{min} < 12^{\circ}\text{C}$) could be reduced during the current harvest season (September) affecting winegrape acidity and flavour. Suitable areas for viticulture might be reduced.	Mexico	[97]
Winegrape Production	CORDEX-CAM RCM	Global warming threatens to reduce the viticulture areas of Mexico at the end of the 21st century, forcing adaptation: temperature increases could reduce the yield between 18% and 35%	Baja California, Mexico	[98]
Winegrape Production	CORDEX-SAM RCM	Bias-corrected CORDEX-CORE simulations represent the current viticultural zoning of Malbec grape production in Argentina and motivates their use for future grape production zoning studies in Argentina.	Argentina	[99]
Hydrology	CORDEX-CAM RCM	Projected warming, decreased precipitation, reduced streamflow and aquifer recharge in Cuba's Cauto River Basin under RCP8.5.	Cuba	[100]
Hydrology	CORDEX-FPS-SESA	Use of CPRCM and deep learning ESD outputs for streamflow simulation: CPRCM-driven streamflow simulations show good agreement with observation-driven simulations, although streamflow responses remain highly sensitive to the intensity and spatial distribution of simulated precipitation.	Southeastern South America	[18]

<https://doi.org/10.1371/journal.pclm.0001015.t002>

In recent years, the regional climate modeling community has progressed in the implementation of the non-hydrostatic option in some RCMs, to explicitly solve the vertical pressure gradient and convection. This option is fundamental for an improved understanding of the physical processes that occur at finer scales (km-scale resolutions), such as convective storms and extreme weather and climate events that occur at local scales. Since 2021, the use of km-scale simulations in RCMs has increased in CORDEX-SAM [17]. However, a more realistic local climate representation and the construction of ensembles of simulations to address uncertainty studies need large computational power and storage capacity, which are not always available in these regions. Further major challenges in regional climate modeling in SAM and CAM are to accurately represent atmospheric processes over complex terrains such as the Andes, the Sierra Madres in Mexico, and the mountains of Central America.

Key aspects of these two major challenges will be addressed through two FPS initiatives started in 2025 (Fig 2). The rapid intensification of tropical storms and hurricanes and their projections will be tackled using high spatial and temporal convection-permitting modeling within the initiative “High-Resolution downscaling of tropical cyclones in the Caribbean Region” (FPS-High-Res TC-CAR). In parallel, the FPS “Enhancing climate downscaling at km-scale in sub-tropical South America using machine learning CPRCM-CMIP6 emulators” focuses on assessing machine learning-based ESD models and convection-permitting RCM emulators to obtain high resolution climate projections. Apart from these initiatives that involve regional modelling communities and international institutions, it is essential to strengthen collaborative efforts that integrate coordinated CORDEX modelling activities with other ongoing WCRP initiatives, to identify common scientific priorities and leverage synergies.

The coupling of atmospheric regional climate models with other climate system components (ocean, hydrology, biogeochemistry, land surface and vegetation) is essential for improving the understanding of key regional climate processes. The implementation of Regional Earth System Models in CAM and SAM is still at an early stage [105], however their potential and relevance are increasingly recognized by the regional scientific community.

Detection and attribution of extremes and their changes also remain among the top research priorities using CORDEX simulations in CAM and SAM. Unprecedented heatwaves (e.g., [106,107]), droughts [108], future changes of tropical cyclones [109,110], rapid intensification of hurricanes such as Otis and Beryl, and heavy floods affecting urban centers and coastal areas (e.g., [111]) are only few examples of possible attribution studies at regional scale. While RCMs provide added value for representing local processes and extremes, their systematic use in detection and attribution studies is still lacking in CAM and SAM [108]. Advancing attribution studies within the CORDEX framework would strengthen the link between regional climate information and climate risk assessments, supporting more robust interpretation of observed changes and projected impacts.

Supporting information

S1 Table. Workshops and capacity building activities carried out in the CAM and SAM domains.

(PDF)

S2 Table. RCMs and GCMs used in CAM and SAM (except MIROC5 GCM that was used only in SAM) in the CORDEX framework [112–117].

(PDF)

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