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APPLICATION

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GCM compareR: A web application to assess differences and assist in the selection of general circulation models for climate change research

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Abstract

1. Climate change research often relies on downscaled general circulation models (GCM), projections of future scenarios that are used to build ecological and evolutionary models. With more than 35 different GCMs widely available at a resolution of 10 km and finer, standardized methods to understand the differences among GCM projections in a region of interest and to choose which GCM to use for analysis are essential to maximize relevance to policy and to assure a proper treatment of uncertainty.
2. To help researchers and policymakers understand and select form the range of available GCM scenarios, we have developed GCM compareR, an open-source web application written in R using SHINY. GCM compareR is freely accessible with an easy interactive user interface, has preloaded climate scenario data to increase the speed of analysis and is fully documented to ensure reproducibility. Users of the application need no prior experience in coding.
3. GCM compareR is designed to compare GCMs and different climate change scenarios to provide full, documented exploration of the possible alternative futures from within the range of projections in CMIP5 climate models. Designed with a wide group of users in mind, including ecologists, conservationists and policymakers, the application is designed to adapt analyses to any geographic area of interest. Results are provided as figures, tables and maps that clearly communicate the differences among model projections for the region. Additionally, the tool allows for the export of a report that records the parameter choices and results of a session, along with contextual information, to make the analysis fully transparent and replicable.

KEYWORDS

climate change, climate change scenarios, conservation, general circulation models, science communication, science policy, species distribution models, storylines

1 | INTRODUCTION

General circulation models (GCMs) are central to climate change research. These models provide insights about future climate, projecting regional climate change, assessing climate risks or planning adaptation policies (IPCC, 2014). GCMs, and particularly their higher resolution downscaled products, are often used in conservation science and ecology to project future biodiversity patterns (Araújo, Thuiller, & Pearson, 2006), evaluate protected area performance and adaptation in climate change scenarios (Hannah, 2008), perform assessments of future potential for species invasions (Roura-Pascual, Brotons, Peterson, & Thuiller, 2009) and evaluate the potential impacts of climate-related changes on vegetation, agriculture and resources such as water (Hannah et al., 2013; Taylor, Stouffer, & Meehl, 2012).

The GCMs are models of the dynamics of physical components of the atmosphere and ocean circulation (Flato et al., 2013), which may be projected to future greenhouse gas (GHG) emission scenarios linked to socio-economic scenarios, where the accumulation of climate forcing (e.g. greenhouse gas emissions) varies with aspects of climate policy such as amount of emissions, transition towards greener economies or the adoption of other mitigation policies (Moss et al., 2010). Problems with misinterpretation of the meaning of climate scenarios resulting from the applications of the storyline methods led to the adoption of an inverse approach (the representative concentration pathways or RCPs (van Vuuren et al., 2011). The RCPs were intended to remove any notion of prediction from the scenario by working back from the amount of future atmospheric warming to understand the GHG forcing pathway required to give the scenario outcome.

Currently, researchers and practitioners can choose from a large number of GCMs developed by meteorological research centres world-wide. As per the most recent evaluation, 22 global modelling centres have contributed >35 GCMs coordinated through the Coupled Model Intercomparison Project Phase 5 (CMIP5; Flato et al., 2013). Given a particular year in the future and an RCP, each GCM provides one projection to represent a plausible future climate. Nonetheless, although projections from these GCMs agree in the big picture, the spread among them is also significant (Rogelj, Meinshausen, & Knutti, 2012; Zappa & Shepherd, 2017), which is an indicator of the irreducible uncertainty concerning any unverifiable future projection. Variance among GCM projections results from differences in the model formulation, in the modelled climate response and its spatial structure, and from internal variability of climate systems (van den Hurk et al., 2014). Importantly, this variance poses serious implications that are policy relevant, because model choice may result in substantially different conclusions, influencing impact evaluation, and adaptation planning. For instance, the choice of GCM has been found one of the main sources of variability in projections resulting from species distribution models (Diniz-Filho et al., 2009; Thuiller, Guéguen, Renaud, Karger, & Zimmermann, 2019). For this reason, workflows to guide researchers approaching climate change scenarios and GCMs are needed to increase objectivity in research and assure a well-judged treatment of uncertainty (McSweeney, Jones, Lee, & Rowell, 2015; Shepherd et al., 2018).

Risk assessment and adaptation planning typically require considering all plausible scenarios, especially worst-case scenarios (Shepherd et al., 2018). To properly outline all plausible scenarios for future climate, a necessary step is to explore similarities and differences between the projections of different GCMs. In line with this, the 'storyline' approach was recently proposed (Zappa & Shepherd, 2017), where the full range of GCM projections for an RCP is disentangled into several, self-consistent narratives, each one made up by GCMs whose forecast is representative of that particular future climate. For instance, for a specific region, some GCMs may project a drier and warmer climate, while other climate models might project comparatively wetter and colder conditions. According to the storyline approach, these two narratives should be treated separately based on their distinct GCM, and the results should be communicated as different plausible and non-disposable alternatives of what we could expect from the future climate. By treating separately different groups of GCMs with similar characteristics, the storyline method promotes a transparent management of uncertainty where extreme or dissenting GCMs are not dismissed on the basis of being different. This contrasts with previous approaches, which focused on the average of the multi-model ensemble formed by CMIP5 GCMs, and where uncertainty appeared to vanish by being reduced to a confidence interval around the mean (Zappa & Shepherd, 2017).

However, evaluating potential storylines for a given study area is challenging, as it requires obtaining and working with all GCMs to understand their differences, which could be very human and computational resource-intensive. This limitation may lead modellers to select only one or a few GCMs on the basis of availability, familiarity with the provider climate centre and use in previous research (Barsugli et al., 2013), which does not guarantee the selection of models that represent the different ranges of responses in CMIP5 models (McSweeney & Jones, 2016; McSweeney et al., 2015). Thus, the context demands new tools that help researchers exploring future scenarios and assess differences between GCMs, for them to be able to identify relevant storylines within scenarios or to explore the different ranges of responses among candidate climate models. Ideally, these tools must circumvent the need for downloading all GCM layers, should provide the steps for a comprehensive yet simple comparative evaluation of their projections and allow for their application to varying temporal and spatial scales and geographic areas. In addition, these tools must be suited with rich descriptions of the workflows to endorse the well-judged use and choice of GCMs to facilitate a judicious and informed use by scientists and practitioners, especially in the case of those interested in climate change research that lack extensive climatological background.

1.1 | GCM compareR

We have developed the web application GCM compareR, an interactive open-source web application designed to assist researchers inspecting climate change scenarios and GCM projections, and to guide them towards informed choices, including the devise of different storylines that are policy relevant and manageable to develop, analyse and communicate. The application is written in R (R Core Team, 2017) using SHINY, a package for developing interactive web applications (Chang, Cheng, Allaire, Xie, & McPherson, 2018). The application was first developed as part of the *Spatial Planning for Protected Areas in Response to Climate Change* (SPARC) project, funded by the Global Environmental Facility (GEF), with a wide range of potential users in mind, including ecologists, conservation practitioners, educators and policymakers, and can be accessed online at https://ecoinformatica.net/GCMcompareR.html.

The GCM COMPARE
R offers quick access to preloaded CMIP5 downscaled GCMs for the four RCPs (van Vuuren et al., 2011) and allows users to compare their projections. It focuses on GCM projections for 19 bioclimatic variables (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005; Kriticos, Jarošik, & Ota, 2014), which are environmental variables derived from monthly temperature and precipitation broadly used in ecology and conservation science for their potential biological relevance (Austin, 2007). The outputs of the comparison are provided in the form of scatterplots and tables, and a diversity of maps, from which users can interpret the changes projected by climate models, determine their similarities and differences both quantitatively and qualitatively, and detach storylines within the ensemble. The application performs the comparison among GCMs in two ways (Figure 1), using as a reference either the current climate (baseline) or the average among the projections from all GCMs selected for analysis. In either of these methods, the difference between values for pixels in each downscaled GCM and the contrasting layer is computed to produce a map of differences. When contrasting with the mean ensemble, pixel differences may be scaled to produce unit-free outputs, so that differences for several bioclimatic variables can be combined. In the next step, differences across all pixels for a GCM difference map are averaged, resulting in an estimation of the GCM mean difference with respect to the reference. These averaged differences are then presented in a scatterplot where the user can assess the relationship among models for the selected scenario.

We caution that the application does not replace formal model evaluations based on their skill at reproducing historic data (e.g. Bellenger, Guilyardi, Leloup, Lengaigne, & Vialard, 2014), whose results may be incorporated to GCM COMPARER analyses (i.e. by excluding extreme 'outliers' or poor performing GCMs at reproducing a particular climate phenomenon fundamental for a given region, such as ENSO or monsoons). Moreover, we emphasize that good practice requires using the application in combination with knowledge of those aspects of climate that are more relevant for a given system of study.

The next section includes a summary of the application modules and a description of its results. We subsequently present a case study where we show the use of GCM COMPARER to explore a specific climate change scenario, revealing information that is used to guide

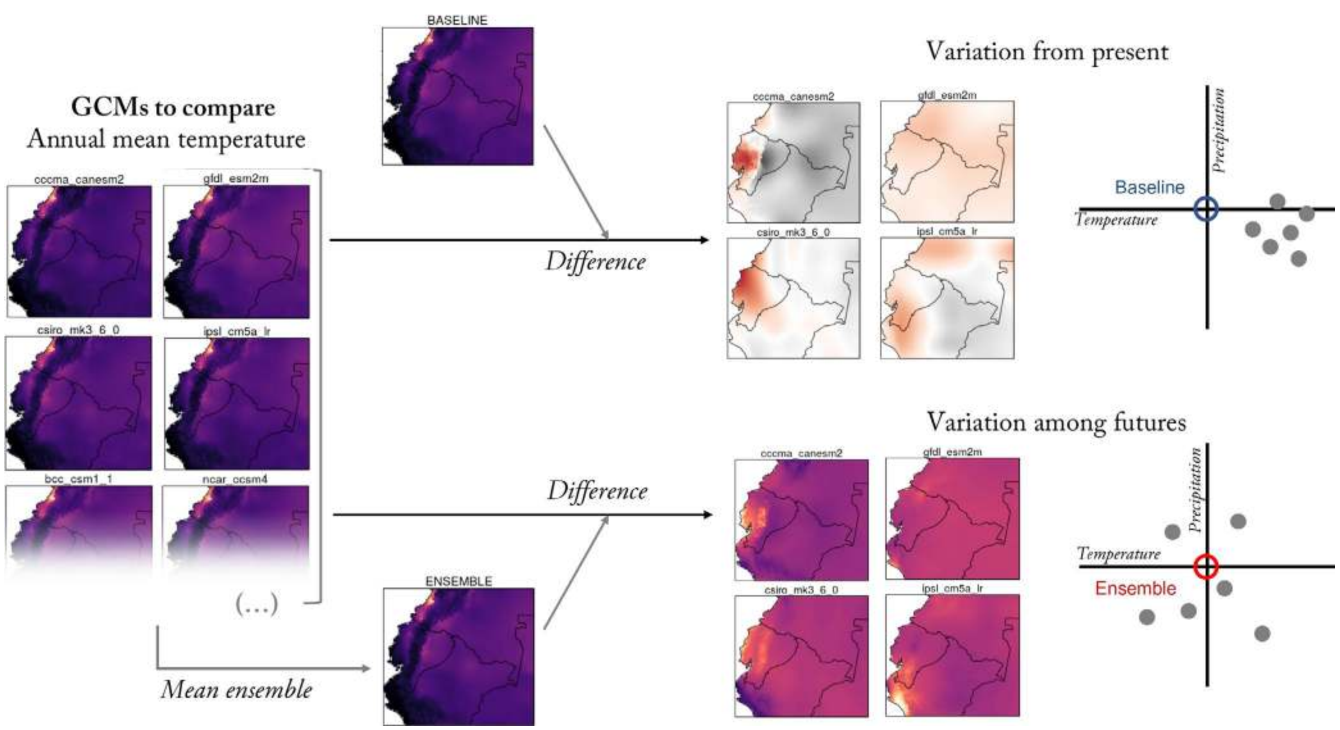

FIGURE 1 Schema of the two methodologies used to evaluate differences between general circulation models (GCMs). In Variation from present, values in the baseline are subtracted for each downscaled GCM to use the current climate as a reference. In Variation among futures, the ensemble multi-model mean is first calculated as a raster by averaging values in all GCMs. Later, values in the ensemble mean are subtracted for each downscaled GCM to use the multi-model average as a reference

the selection of a group of GCMs to assess the climate risk of a group of mountain amphibian species.

1.2 | Walkthrough

The application is divided into tabs that are read from left to right (Figure 2). These tabs are used to select the GCMs to be compared, the climate change scenario and a study area, as well as to retrieve results and generate a reproducible report. Documentation for the use of the application and the methods available guides the user throughout the application.

1. **Introduction.** This first tab contains general information on the application, developers and instructions for its use.
2. **Definition of a scenario.** The second tab is used to define the comparison. **Results.** The next three tabs report the results as maps, plots and tables.
3. *Explore selected GCMs*. This tab presents the maps of the selected variables and all GCMs for the study area using a common colour scale, useful for the direct comparison of climate models.
4. *Variation from present*. These results use the current climate as a reference to explore the future scenario and present the spread among GCMs' projections as scatter plots (*spread of GCMs*). The projected change from the baseline for each GCM is also shown as a map, where information from the spatial patterning in the forecasted climate variation may be drawn (*Maps of variation*).
5. *Variation among futures*. These results use the ensemble multi-model mean as a reference to explore future scenarios. The spread among GCMs is assessed as scatter plots (*spread of GCMs*), where the distance of GCMs to the mean may be scaled, and a set of maps (*Maps of variation*) that show how different from the multi-model mean is each GCM on a pixel-by-pixel basis.
6. A number of GCMs are selected within an RCP and year (note that GCMs from different RCPs or years cannot be mixed).
7. More options can be used to define a regional study area using the interactive map and menus for country, biome or ecoregion selection. A menu is used to select at least a pair of bioclimatic variables on which the comparison is based. Data for the downscaled variables for each GCMs (delta method) were obtained in raster format from the Research Program on Climate Change, Agriculture and Food Security (CCAFS by CGIAR, http://ccafs-climate.org/data_spatial_downscaling/).
8. The action button 'COMPARE' triggers the start of analyses and unblocks result tabs.
9. **Report.** The last tab generates a downloadable report that summarizes all initial conditions and presents all results. The report, which provides contextual information to help the interpretation of results, is intended at making the analyses reproducible and to be used in their communication.

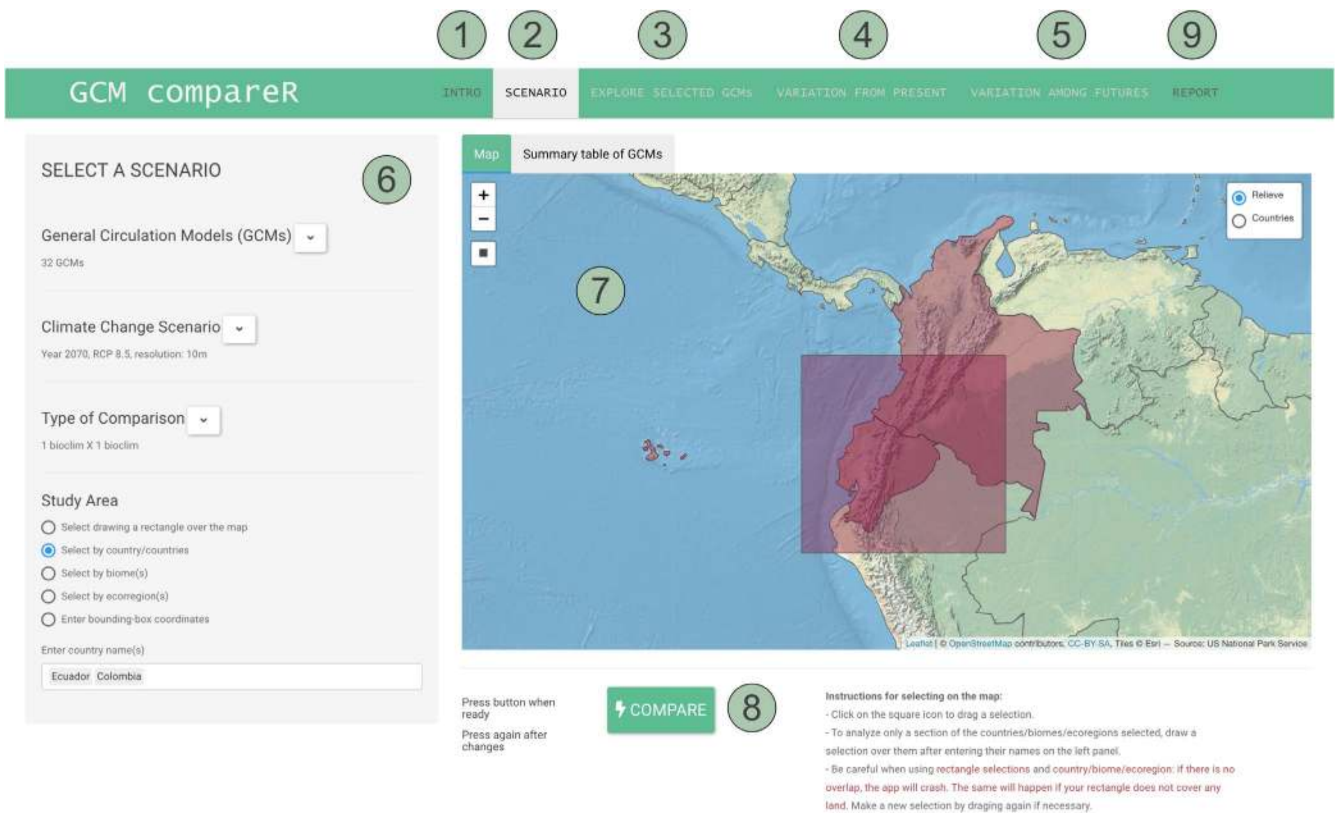

FIGURE 2 Overview of GCM compareR with its key features highlighted: (1) introduction, (2) scenario selection, and result tabs: (3) explore selected GCMs, (4) variation from present, (5) variation among futures, (6) sidebar for scenario definition, (7) interactive map for delimiting the area of interest, (8) button to start the analyses and (9) tab to download a report of the analyses conducted

2 | USE EXAMPLE: A PRELIMINARY EXPLORATION OF CLIMATE CHANGE, AND GCM SELECTION, FOR AN ASSESSMENT OF THE CLIMATE RISK OF ENDANGERED ANDEAN TOADS

2.1 | Introduction

Atelopus is a genus of frogs inhabiting the high Andean mountains in Ecuador and Colombia in South America (Coloma et al., 2010). In the last few years, several *Atelopus* species have been reported as extinct in many locations that were part of its historic range (La Marca et al., 2005; Ron, Duellman, Coloma, & Bustamante, 2003). These local extinctions might be the consequence of changing climatic conditions, as amphibian species are sensitive to warming and drying conditions (La Marca et al., 2005), which are likely to increase regionally according to climate change reports (IPCC, 2014). Moreover, *Atelopus* frogs are affected by the fungal disease caused by *Batrachochytrium dendrobatidis*, whose prevalence is expected to increase in these climatic conditions (La Marca et al., 2005). In this context, exploring the potential evolution of climatic conditions within species ranges could provide critical insights to assess the conservation and extinction risk of species. The use of niche modelling to project changes in a species climatic niche under a climate change scenario can inform about the conservation of suitable potential distribution area (Guisan, Thuiller, & Zimmermann, 2017), which may be used to plan conservation policy with the objective to assure the persistence of the species (Araújo et al., 2006). An important step preceding the niche modelling is to explore the potential climatic change that the region will experience, and obtaining information about GCM projections for the selection of a representative subset of climate models that matches the computing capabilities of the research group. The next sections focus on this preliminary step.

2.2 | Methods

GCM compareR can be used to quickly and simply assess the future climate scenario in Ecuador–Colombia according to GCM projections. In the 'Scenario' tab of the application, 28 of the 32 available GCMs were selected for comparison. *MIROC_ESM*, *MIROC_ESM_CHEM*, *MIROC5* and *CSIRO_MK3_6_0* were excluded because these models are inferior in their skill at reproducing ENSO, a major determinant of precipitation patterns in the region (Bellenger et al., 2014). The year 2070 and RCP 8.5 were selected to complete the definition of the climate change scenario. The bioclimatic variables 'mean annual temperature' and

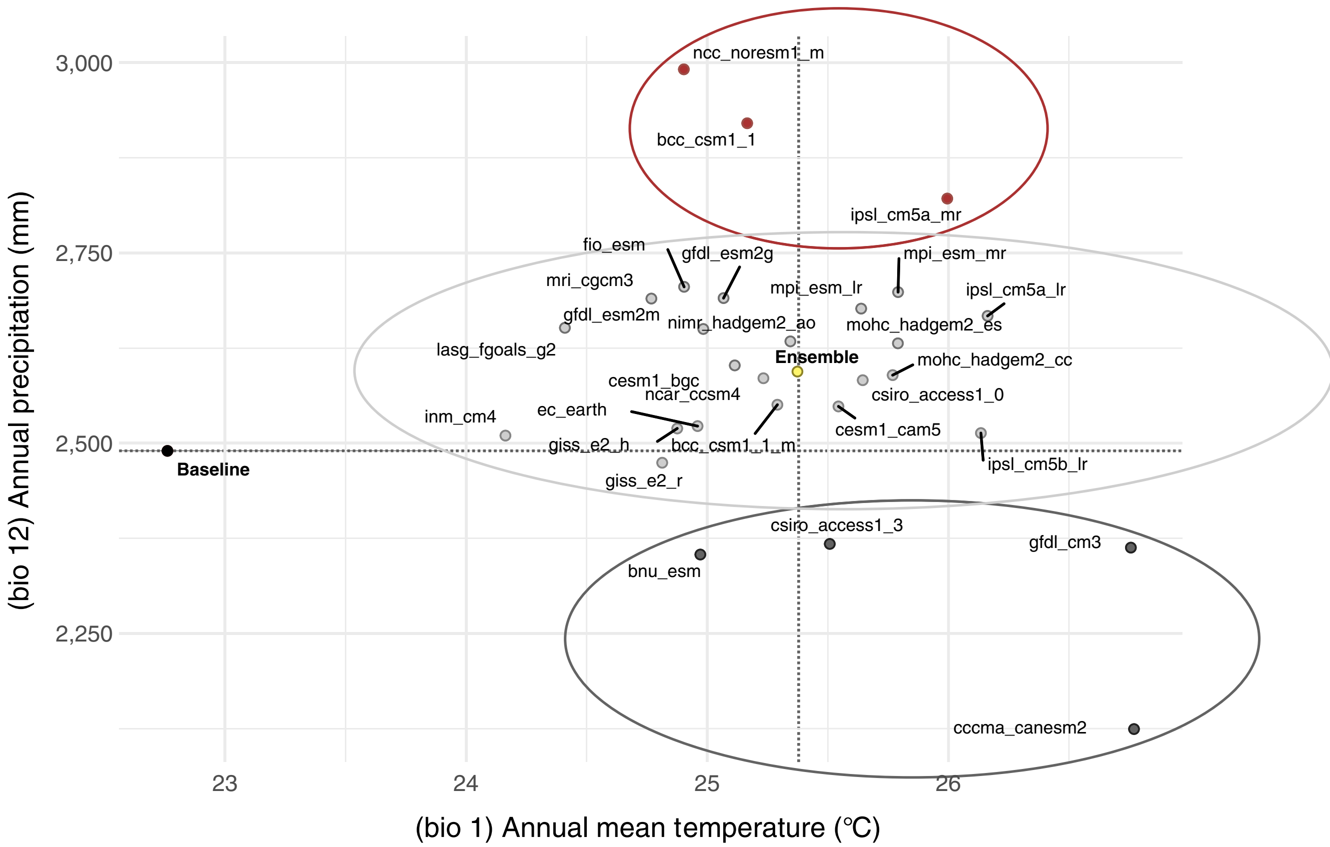

FIGURE 3 Spread of general circulation model (GCM) projections for annual mean temperature (*x*-axis) and annual precipitation (*y*-axis). Current climate (baseline) and the ensemble multi-model mean (ensemble) are shown among each GCM. GCMs projecting a larger increase in precipitations than the multi-model mean are shown in red, and those projecting a decrease in dark grey. Circles have been drawn over GCM compareR plot output

'annual precipitation' were selected for the *x* and *y* axis of the comparison because the *Atelopus* species are sensitive to these variables. The study area was first selected by restricting the analysis to Ecuador and Colombia and then delimiting a square that removed North Colombia and all islands, where the species are absent.

2.3 | Results

In general, GCMs project a warmer future climate where precipitations could remain stable, increase or decrease (Figure 3). GCM projections are within a range of 25.5 ± 1°C of future averaged annual temperature, ~2.5°C warmer than the current climate. Importantly, some climate models (*GFDL_CM3*, *CCCMA_CANESM2*) project an increase of 2.5°C higher than others (*INM_CM4*). Regarding precipitation, most models project a small increase to values of 2,600 ± 100 mm compared to the current 2,500 mm of annual rain. Four GCMs project a decrease in rains (*BNU_ESM*, *CSIRO_ACCESS1_3*, *GFDL_CM3*, *CCCMA_CANESM2*; Figure 3, dark grey) and three GCMs project a larger increase (*IPSL_CM5A_MR*, *BCC_CSM1_1* and *NCC_NORESM1_M*; Figure 3, red).

The spatial variability of the projected changes shows that temperature could be expected to increase mostly uniformly across the countries according to all models. The projected change in precipitation is more spatially heterogeneous and variable. Models projecting an overall decrease in precipitation show a pattern where the

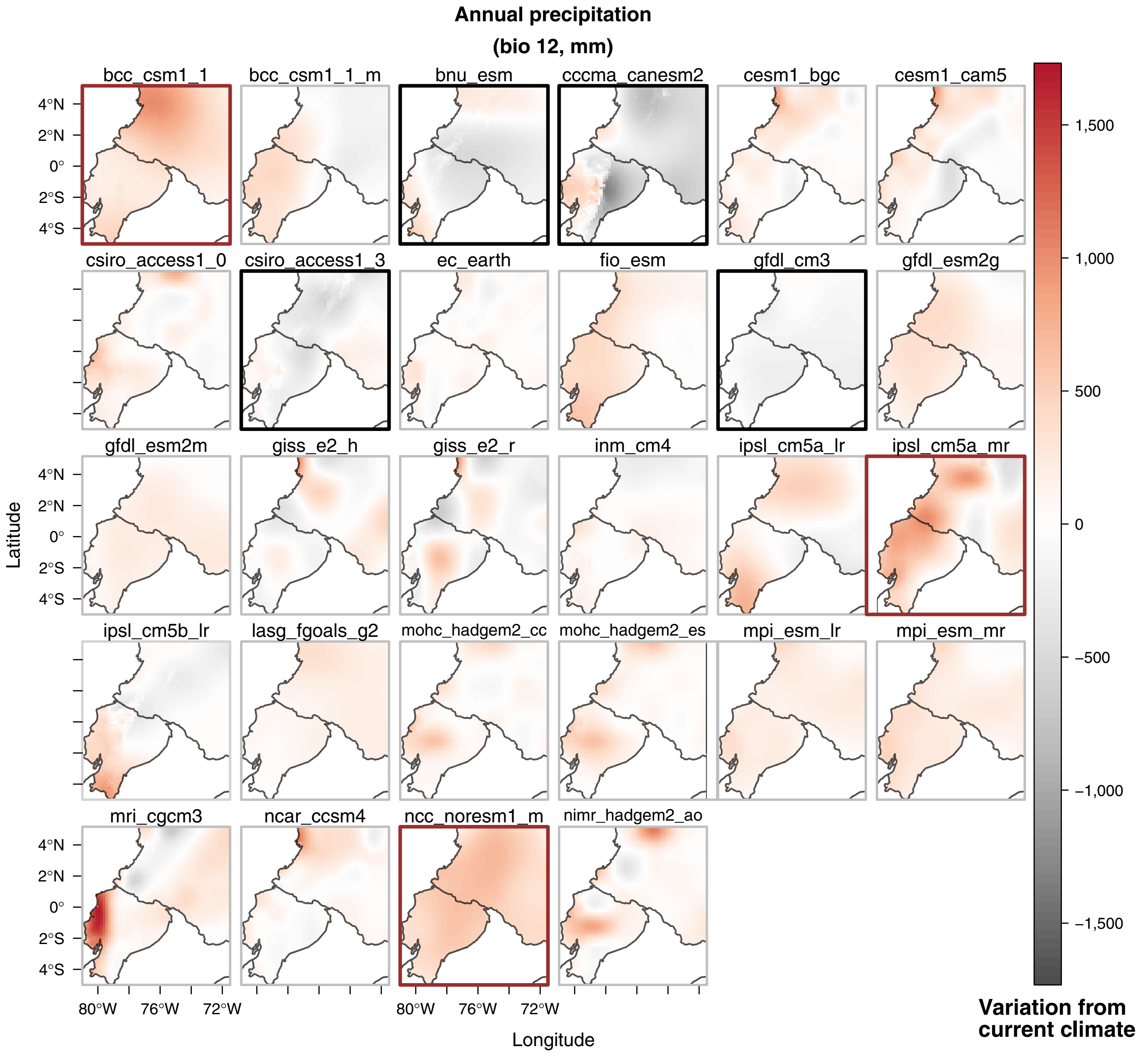

FIGURE 4 Maps of the spatial variability of projected change in annual precipitations for the year 2070 and RCP 8.5. General circulation models (GCMs) projecting a decrease in precipitation (see Figure 3) are indicated with a red border, and GCMs projecting a large increase in precipitation have a dark grey border. Colour in maps' borders has been added after GCM compareR analysis

reduction of rain occurs mostly in sectors to the East of the study area, corresponding to the Amazon west slopes and other humid broadleaf forests, while other parts are projected to maintain rainfall totals or experience small increases (Figure 4, dark grey box). In the case of the three GCMs showing a larger increase in rains, *BCC_CSM1_1* and *NCC_NORESM1_M* project the increase to occur across the study area, while *IPSL_CM5A_MR* restricts the increase to the southwestern sector (Figure 4, red box). Most GCMs that are similar to the multi-model mean are characterized by smooth variations in precipitation (Figure 4, light grey box), with a contrasting exception, *MRI_CGCM3*, showing the largest increase in rains among GCMs to the west of the study area.

Based on these results, projections of species distributions models to study the potential impact of climate change on *Atelopus* species may focus on three different storylines, where, in addition to the temperature increase, the region experiences: (a) a reduction of rains in humid ecoregions (Figures 3 and 4, red); (b) small changes in precipitations (Figures 3 and 4, light grey); or (c) an increase of rains above-average (Figures 3 and 4, dark grey). The three storylines may use, respectively, the following GCMs: *CSIRO_ACCESS1_0*, *NCAR_CCSM4* and *BCC_CSM1_1*. Additional GCMs (e.g. *GFDL_CM3*, *MPI_ESM_MR*, *IPSL_CM5A_MR*) may be added if computationally possible to enrich storyline explorations. Lastly, a more detailed exploration could examine GCMs projecting smaller and greater temperature change within storylines to investigate the potential effect of more accentuated warming.

2.4 | Final remarks and future directions

GCM compareR is an innovative application designed to make climate change research richer, interactive, geographically adaptable and more reproducible, as well as to help with the communication of scenarios and storylines focusing on a proper management of uncertainty. Some future plans for the application include expanding the set of preloaded environmental dataset (e.g. to include monthly averages of temperature and precipitation, other bioclimatic variables; Karger et al., 2017; Kriticos et al., 2014) and their projection years, as well as adapting to CMIP6 when the variables become available.

With the goal of contributing to clarity and replicability in climate change research in mind, we emphasize that projections and scenarios do not constitute statistical distributions of the future climate. Given the irreducible nature of uncertainties associated with future projections, the results of GCM compareR are suitable for illustrating potential biophysical scenarios, but are not intended to be used for making predictions of future states.

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AUTHORS' CONTRIBUTIONS

J.F., D.C. and P.A.M. conceived the idea for the application and led the writing of the manuscript; J.F., D.C., P.R.R., L.H. and P.A.M. designed the application, discussed its development and participated in the writing; J.F., D.C. and P.R.R. wrote the code as back-end and front-end developers.

DATA AVAILABILITY STATEMENT

GCM compareR can be accessed at https://ecoinformatica.net/GCMcompareR.html. The app code is available on Github (https://github.com/marquetlab/GCM_compareR; https://doi.org/10.5281/zenodo.3625191 (marquetlab & Fajardo, 2020).

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