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Flood projections for selected Costa Rican main basins using CMIP6 climate models downscaled output in the HBV hydrological model for scenario SSP5-8.5

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Abstract:

Estimates from 3 statistically downscaled General Circulation Models (GCMs) from version 6 of the Coupled Model Intercomparison Project, namely the EC Earth3, GFDL ESM4 and MPI ESM1 2 HR are used in the HBV hydrological model to estimate design streamflow projections with 20, 50, and 100-year return periods for the selected main basins of Costa Rica. The changes in these streamflows were computed between the baseline period (1985–2015) and the mid-century projection (2035–2065) for the SSP5-8.5 scenario. The novelty resides in being the first study that explores the magnitude of climate changes in design flows of Costa Rica, a tropical country. Although, calibration and validation statistics are generally good for most of the basins, only around one quarter of the simulations reproduce the observed distribution of the 3-day annual maximum flows. Results show that the MPI model presents lower sensitivity with changes of different sign depending on the basin studied and the other two models suggest only significant increases in the design flow in most of the basins. Results of the model's ensemble suggests a great concern, as there is a general increase in the design flows, and the magnitudes of the changes are large, especially in the Pacific slope.

KEYWORDS streamflow; model; HBV; floods; general circulation model; climate change

INTRODUCTION

From 1988 to 2018 in Costa Rica, it was estimated that floods caused 3.1 billion (2015-constant) US dollars of damage; conversely, damage due to droughts was estimated at 0.2 billion US dollars and earthquakes resulted in 1.2 billion US dollars in damage (Ministerio de Planificación Nacional y Política Económica, 2019). Even if considering that Costa Rica is situated in a very active seismic zone, it is important to note that extreme floods represented the largest source of damage, contributing to 69% of the accumulated cost of these three types of impacts. This is the product of the high natural climate variability associated with the influence of climate processes in surrounding oceans (Durán-Quesada *et al.*, 2020; Maldonado *et al.*, 2018), the effect of anthropogenic climate change (Hidalgo *et al.*, 2019; 2021; Alfaro-Córdoba *et al.*, 2020; Pascale *et al.*, 2021), and the increasing vulnerability of the population (Quesada-Román *et al.*, 2020; Quesada-Román, 2022). Examples of natural climatic processes in the area are the teleconnections with El Niño-Southern Oscillation and the Pacific Decadal Oscillation in the Pacific Ocean plus the Atlantic Multidecadal Oscillation and the variations of the North Atlantic Subtropical High in the Caribbean/Atlantic (Durán-Quesada *et al.*, 2020; Maldonado *et al.*, 2018).

It is important to note that floods studies in tropical regions are generally scarce (some exceptions in Asia can be found in Das *et al.*, 2022; Pandey *et al.*, 2022; Mahato *et al.*, 2022), and in Central America the availability of regional/country studies is even rarer (for Costa Rica see Mendez *et al.*, 2022). In higher and mid latitudes, the main control on hydrology can be related to other physical processes, for example snow, which produces a very different streamflow seasonal cycle (and flood characteristics) compared to places without snow, as in the former case the precipitation is stored as snow during the winter and released in a smoother peak during the spring. Climate change in these regions can affect both processes: higher percentage of precipitation falling as rain, but also an earlier springtime peak (Huang *et al.*, 2020; Stewart, 2009). In Costa Rica where the hydrology is not controlled by snow, there is another, more general reason that can explain the increase in the rainfall intensity associated with global warming. It is thought that a warmer world linked to the effect of anthropogenic climate change would result in an increase in the water holding capacity of the atmosphere, a holding potential predicted by the Clausius-Clapeyron relationship (Clapeyron, 1834; Clausius, 1850). Likewise, in regions where there is a large prevalence of convective precipitation (P), the humidity from surrounding regions can add to the local water available and increase the intensity

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predicted by the Clausius-Clapeyron relationship (Adam, 2023). This is important as Costa Rica is characterized by the influence of convective storms and tropical cyclones. An example of how tropical cyclones can increase almost twice the intensity predicted by the Clausius-Clapeyron equation can be found in Reed *et al.* (2022).

There are many studies that have determined changes in floods with varied return periods at regional and global scales using different combinations of climate models, downscaling/bias-correcting methods and hydrological models (e.g. Bian *et al.*, 2021; Paudel *et al.*, 2023; Meresa *et al.*, 2022; Zhu *et al.*, 2017; Wang *et al.*, 2022; 2023; Sante *et al.*, 2021; Hirabayashi *et al.*, 2021; Gu *et al.*, 2022). These studies usually suggest that streamflows with return periods of 100 years (Q_{100}) for example, will shorten this return period in the future, implying higher frequency of floods in many regions (including Central America in the global studies); however, global scale studies have determined that there are places where models project reduced frequency of historical Q_{100} flows, for example in higher latitudes in North America, Eurasia and higher latitudes in South America (Hirabayashi *et al.*, 2021). Also, global scope studies have demonstrated increased future extreme flood fractions associated with hot-flood events in all climate regions of the world but the largest increase in the fractions occur in tropical regions (Gu *et al.*, 2022). These studies are very useful for producing a global perspective of flow frequencies, however higher-resolution studies are needed due to high spatial variability of Central America, associated with the presence of a complex topography and their interaction with prevailing winds.

In the Central America region in general, and in Costa Rica in particular, most of the studies of climate change impacts have been produced by analyzing projected changes in meteorological parameters such as precipitation and temperature (e.g. Karmalkar *et al.*, 2008; Stan *et al.*, 2020; Castillo and Amador, 2020), while fewer studies have used the climate model precipitation and temperature projections as input in hydrological models (e.g. Hidalgo *et al.*, 2013; Imbach *et al.*, 2012; Moreno *et al.*, 2019; Mendez *et al.*, 2022). These previous studies do not characterize daily variability from the models. In particular, the most recent study by Mendez *et al.* (2022) which analyzed climate change hydrological projections for 5 selected Costa Rican subbasins is different to our study, not only in the details of datasets used, but also in a very fundamental way as the authors used monthly instead of daily data and the delta downscaling method they applied consisted in shifting the observational dataset variability with a perturbation of the future monthly GCM-RCM anomalies with respect to the baseline period. This is different to the application of the daily downscaling method that we are presenting, which is based in conserving the daily variability of the bias-corrected GCMs. The daily variability is necessary for determining the changes in floods frequencies, as the type of floods that we observed are short lived of a few days. For example, in terms of floods it is not the same to observe a run of 7 days of 10 mm uniformly, as to observe a run of six dry days followed by one daily rainfall event of 70 mm. If in both cases, if the rest of the month is composed of dry days, the monthly accumulations would be the same, but the way it rains is not, which is important to flooding. In this way, monthly accumulations could not be used to identify changes in the frequency of floods using traditional flood frequency analysis. While changes in the monthly climatologies of streamflows are useful to determine water balance (volume) changes, they do not adequately express the changes in extreme events at shorter time scales. To our knowledge, our study is the first to estimate the magnitude of the changes in design flood under climate change for main basins in Costa Rica. It is also the first study to adapt the Navarro-Racines *et al.* (2020) method for downscaling daily GCM data.

It is important to determine future changes in streamflow that would allow better planning for extreme hydrometeorological events and for designing climate-resilient infrastructure for the future. Previous work in other regions of the world using General Circulation Models (GCMs) have determined future changes in the streamflow flood frequency curve, affecting streamflow with return periods used in the design of hydraulic structures (Das *et al.*, 2011; Yin *et al.*, 2018). This approach has been applied by Das *et al.* (2011) for California in the United States, but for snow-controlled basins. In this work, we will investigate changes in streamflow from the main 34 basins in Costa Rica using 3 GCMs and a hydrological model. The objective is to provide information for planners and infrastructure designers about future changes in design streamflow estimates, based on the SSP5-8.5 that represents the high end of the range of future pathways. We choose one single scenario to account for the more pessimistic outcome to validate our methodology. We wanted to present the flow correction factors for this case, considering that the design of structures would be performed using the most conservative case.

METHODS

Data from meteorological and hydrological stations were used for calibrating and validating a hydrological model. Data from GCMs were downscaled using a statistical method. The downscaled daily projections of precipitation (*P*) and temperature (*T*) for each of the 34 main basins of the country from the GCMs were used in the calibrated meteorological model to obtain future floods. The floods with return periods of 20, 50 and 100 years were estimated from a flood frequency analysis. Details of the procedure can be found in the supplementary information.

RESULTS AND DISCUSSION

Figure 1 shows the annual average distribution of *P* and *T* for Costa Rica. As can be seen, the more arid region is the north Pacific, and the wettest places are in the Caribbean slope and the south Pacific. Even in the most arid regions, and because Costa Rica is in a tropical region, the annual accumulations of around 1800 mm, are not insignificant, but their seasonal distribution in the Pacific slope is far from uniform, as during the dry season (November to April) there is hardly any rainfall at all (Maldonado *et al.*, 2018; Alfaro, 2002). *T* follows the influence of a complex topography characterized by lower tem-

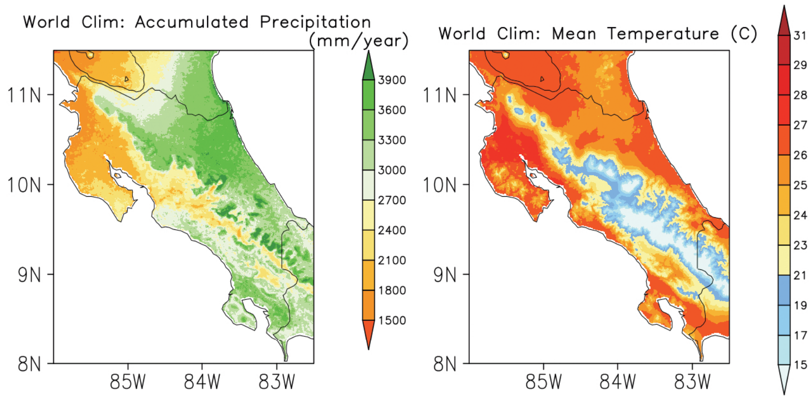
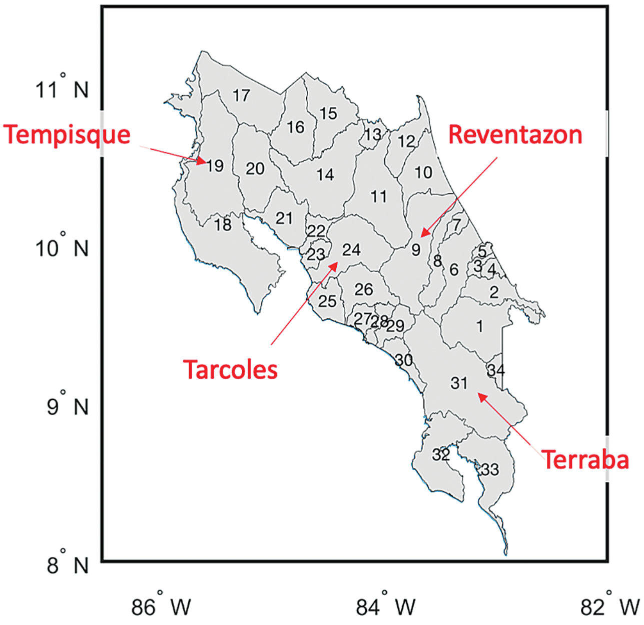


Figure 1. Annual average P accumulations and air temperature for Costa Rica from the WorldClim dataset. Period 1970–2020

peratures in the inland mountain ranges and warm coastal temperature averages (an elevation map is shown in Figure S1). Figure 2 shows the distribution and names of the main 34 basins in the country. Morphometrical characteristics of each of the basins can be found in Ministerio de Ambiente, Energía y Telecomunicaciones (2011). Although we performed the analysis for the 34 basins which are the official main divisions that cover the entire country of Costa Rica, some of the figures show examples of the analyses for four major basins in the Pacific (Tempisque, Tárcoles and Térraba) and the Caribbean (Reventazón) slope due to their economic importance for the country in terms of irrigation, hydropower, and/or their close location to large population centers.



1) SIXAOLA
2) LA ESTRELLA
3) BANANO
4) BANANITO
5) MOIN
6) MATINA
7) MADRE DE DIOS
8) PACUARE
9) REVENTAZON
10) TORTUGUERO
11) CHIRRIPO
12) SARAPIQUI
13) CUREÑA
14) SAN CARLOS
15) POCOSOL
16) RIO FRIO
17) ZAPOTE
18) PENINSULA DE NICOYA
19) TEMPISQUE
20) BEBEDERO
21) ABANGARES
22) BARRANCA
23) JESUS MARIA
24) TARCOLES
25) TUSUBRES
26) PARRITA
27) DAMAS
28) NARANJO
29) SAVEGRE
30) BARU
31) TERRABA
32) PENINSULA DE OSA
33) ESQUINAS
34) CHANGUINOLA

Figure 2. Main 34 basins in the country with their names. Four major basins of great economic importance in the Pacific and Caribbean slope are highlighted

Calibration and validation statistics of the hydrological model can be found in tables SII and SIII, respectively, and in Table SIV a Kolmogorov-Smirnov test (K-S; Wilks, 2019) was performed for each basin and GCMs to test the hypothesis that the 3-day maximums of the observed and modeled runoff series belong to the same distribution. As can be seen from tables SII, SIII and SIV, there are basins that perform better than others, and although the calibration and validation results are very good for most of the basins, the K-S test fails in many cases, supporting the idea that reproducing the distribution of streamflow extremes in some basins is a challenge for the suite of models used. As such, this suggest that, in general, the hydrological modelling is not the main source of uncertainty, but other uncertainties such as the GCM limitations and other sources of uncertainties that will be mentioned at the end of this paragraph can be affecting the results also. The results for those basins should be interpreted carefully. In the case of the KS test (Table SIV) it can be seen that, in general, basins tend to present similar results (whether the hypothesis is accepted or rejected) for the three GCMs, and the models gave good results in approximately one quarter of the basins. Other factors could be adding to the uncertainty of the results such as the complexity of each basin's topography, basin size (as this may affect for example the representativeness of the use of basin-wide time series of P, T, PET and runoff in a lumped hydrological model), morphometric characteristics of the basin, poor density of the precipitation and stream gauge networks in a particular location used for determining the observed data for calibration, hydrological and GCM model limitations and others such as the reduction of precipitation and peak flows due to spatial averaging of gridded precipitation (Bárdossy and Anwar, 2023).

The mean daily streamflow of the selected four basins is

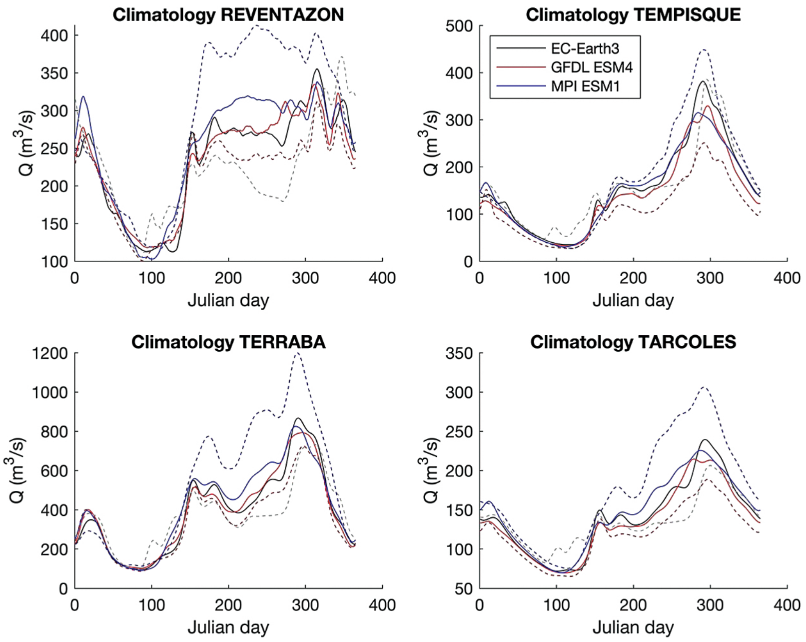


Figure 3. 11-day moving average of mean daily average of streamflow (m^3/s) for selected basins, models and epochs. Solid lines correspond to the historical (1985–2015) scenario for the three models; dashed lines correspond to the mid-century SSP5-8.5 projection for the three models. Black and grey lines: EC Earth, dark and bright red: GFDL ESM4 and dark and bright blue: MPI ESM1 2 MR

presented in Figure 3. As can be seen, the basins in the Pacific slope have generally lower streamflow values during the dry season (November to April), than the basin in the Caribbean slope (Reventazón). This is characteristic of the difference in the climate regimes of both slopes in the country (Herrera, 1985; Solano and Villalobos, 1999; Alfaro, 2002). It is interesting to note that in terms of their climatology, their historical (baseline) scenario is similar for the three models, but their future scenario is very different from model to model. In terms of their streamflow seasonal cycle, the EC Earth3 and the GFDL ESM4 tend to suggest future drier conditions during the wet season, while MPI ESM1 2 HR depicts a wetter future. As mentioned before, however, this observation cannot be verified to be reasonable or not, since the model selection was based on past (baseline scenario) data and accuracy of future climate sensitivities cannot be assessed with current information.

In Figure 4, examples of the flood frequency analyses for selected basins and for the EC Earth3 model are shown. The black lines are the analyses for the historical period and the red lines for the mid-century SSP5-8.5 scenarios. For this model, one can see that the streamflow with return periods of 20, 50 and 100 years (Q_{20}, Q_{50}, Q_{100}, respectively) tend to be higher in the future for the selected basins. The Supplementary Information includes the Q_{20}, Q_{50} and Q_{100} estimations for all models individually and for the ensemble (see tables SV to SXVI), computed for the two scenarios (historical and mid-century).

Inspection of the Q_{20} estimation for the selected major basins (Figure 5) shows that the difference between the historical and mid-century scenario for the MPI ESM1 model is much lower than the difference in other models and varies in sign for each of the basins. The other models, especially GFDL ESM4, suggest consistently wetter Q_{20} for the future. It is important to note these model-to-model differences that are affecting the results. In all figures the ensemble results calculated as the mean of individual models will be added.

In Figure 6, maps of the difference (%) between the mid-century and the historical Q_{20}, Q_{50} and Q_{100} estimations are included. The individual models are shown, as well as the ensemble. As can be seen, the mentioned lower sensitivity of the MPI ESM1 model results in a lighter map. Overall, the increase in the design floods in the ensemble maps, especially for the Pacific coast is of great concern, as it suggests larger flood volumes. The Pacific slope, has an increasing exposure to positive extreme hydroclimatic events, associated with tropical cyclone influence (Hidalgo *et al.*, 2020; 2023; Quesada-Román, 2021; 2022; Quesada-Román *et al.*, 2020). The magnitude of the changes is another issue that warns us of large possible impacts for the future, as in some of the cases the future floods are more than double the historical estimates. These results deserve more studies, and, monitoring of the streamflow in the country should be a high priority.

CONCLUSIONS

Changes in design flows due to climate change have been computed for the main 34 basins of Costa Rica. It is evident, that simulating the correct distribution of 3-day annual maximum floods is a challenge for different reasons, from limitations of the climate and hydrological models to the lack of meteorological and hydrological data, as well as other different systematic errors. Nevertheless, the

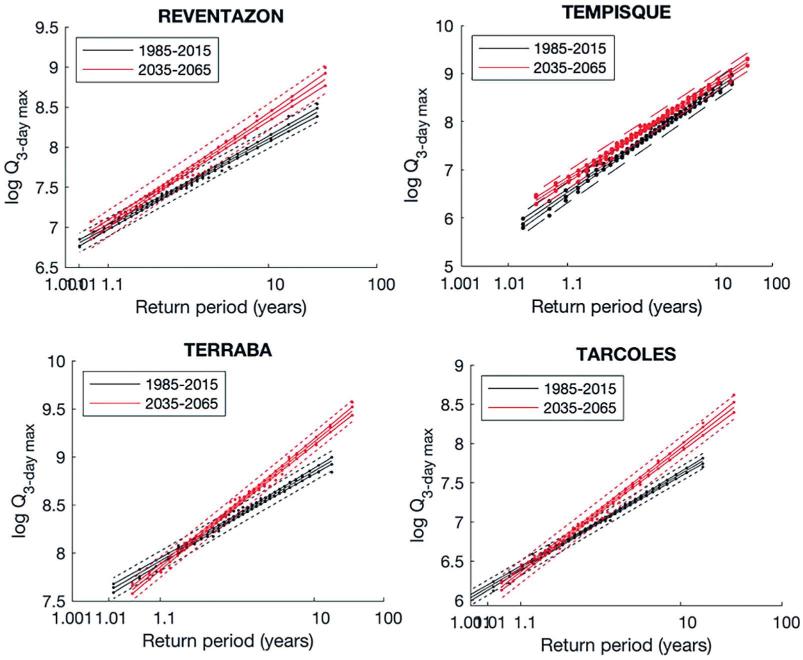


Figure 4. Flood frequency analysis for selected basins and epochs fitted using a Log-Pearson type III distribution. Analysis for model EC Earth3. The solid lines represent the fit and the confidence intervals (p = 0.05) for calibration and the dashed lines are the intervals for prediction. Black lines: historical scenario (1985–2015); red lines: mid-century scenario SSP5-8.5 projection (2035–2065)

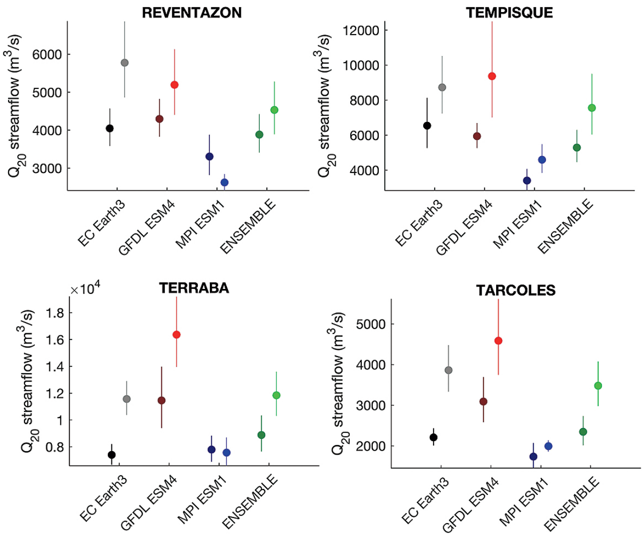


Figure 5. Flood with 20 years return period for different basins, scenarios, and models. For each model two scenarios are shown: the historical (1985–2015) in darker colors and the SSP5-8.5 mid-century scenario (2035–2065) in lighter corresponding color. The bars represent the confidence intervals (p = 0.05) of prediction using Log-Pearson fits of both epochs separately. Black and grey lines: EC Earth, dark and bright red: GFDL ESM4 and dark and bright blue: MPI ESM1 2 MR

model seems to calibrate and validate well for most of the basins and for others the information provided can still be useful. This suggests that the hydrological model may not

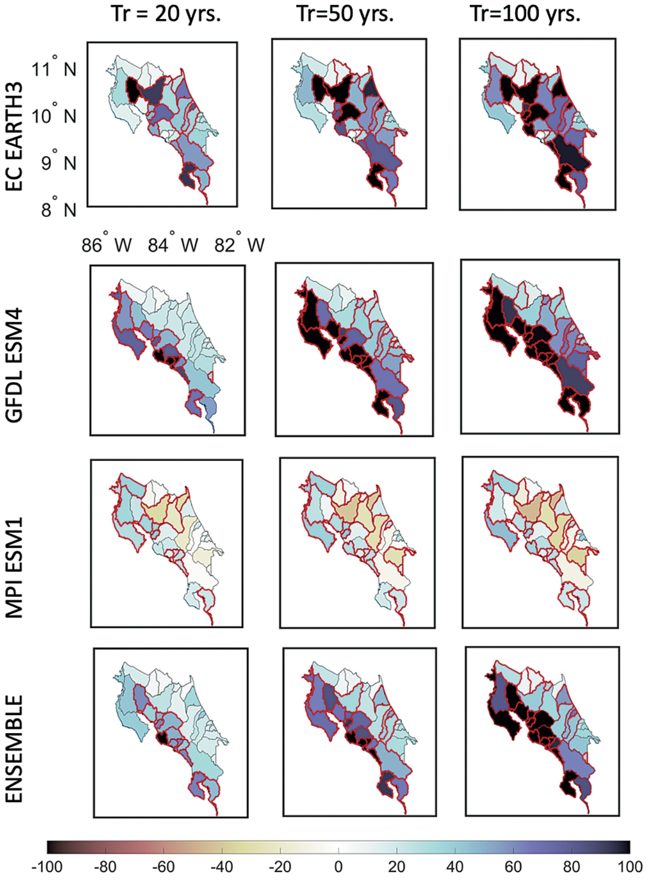


Figure 6. Difference (%) of streamflow with different return periods (Tr) for the individual models and for the ensemble of GCMs used in this study. Basins showing significant changes (p = 0.05) are depicted with red borders

be the main source of uncertainty, and other limitations can have a greater influence. In general, there is a projected increase of design floods in the country, that should be taken into consideration, especially due to the large magnitude of the changes. This information can be useful to planners and for future adaptation studies.

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SUPPLEMENTS

Text S1. Detailed description of methods
Figure S1. Large domain used for bias-correction of the GCM data using ERA5
Table SI. Models and gridded datasets used in this study
Table SII. Calibration statistics for the main 34 basins of Costa Rica at daily and monthly time-scales
Table SIII. Validation statistics for the main 34 basins of Costa Rica at daily and monthly time-scales
Table SIV. Results of the Kolmogorov-Smirnov test to test if the timeseries of 3-days annual maximum flows from observations and models, are drawn from the same underlying continuous population
Table SV. Streamflow with a 20-year return period (Q_{20}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the EC Earth3 model
Table SVI. Streamflow with a 20-year return period (Q_{20}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the GFDL ESM4 model
Table SVII. Streamflow with a 20-year return period (Q_{20}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the MPI ESM1 2 HR model
Table SVIII. Streamflow with a 20-year return period (Q_{20}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the three models
Table SIX. Streamflow with a 50-year return period (Q_{50}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the EC Earth3 model
Table SX. Streamflow with a 50-year return period (Q_{50}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the GFDL ESM4 model
Table SXI. Streamflow with a 50-year return period (Q_{50}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the MPI ESM1 2 model
Table SXII. Streamflow with a 50-year return period (Q50) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the three models used
Table SXIII. Streamflow with a 100-year return period (Q_{100}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the EC Earth3 model
Table SXIV. Streamflow with a 100-year return period (Q_{100}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the GFDL ESM4 model
Table SXV. Streamflow with a 100-year return period (Q_{100}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the MPI ESM1 2 HR model
Table SXVI. Streamflow with a 100-year return period (Q_{100}) in m^3/s for two scenario slices: the historical (1985–2015) and mid-century (2035–2065). Results shown are for the three models

REFERENCES

Adam D. 2023. What a 190-year-old equation says about rainstorms in a changing climate. *Proceedings of the National Academy of Sciences of the United States of America* **120**: e2304077120. DOI: 10.1073/pnas.2304077120.

Alfaro EJ. 2002. Some characteristics of the annual precipitation cycle in Central America and their relationships with its surrounding tropical oceans. *Tópicos Meteorológicos Y Oceanográficos* **9**: 88–103.

Alfaro-Córdoba M, Hidalgo HG, Alfaro EJ. 2020. Aridity trends in Central America: a spatial correlation analysis. *Atmosphere* **11**: 427. DOI: 10.3390/atmos11040427.

Bárdossy A, Anwar F. 2023. Why do our rainfall–runoff models keep underestimating the peak flows? *Hydrology and Earth System Sciences* **27**: 1987–2023. DOI: 10.5194/hess-27-1987-2023.

Bian G, Zhang J, Chen J, Song M, He R, Liu C, Liu Y, Bao Z, Lin Q, Wang G. 2021. Projecting hydrological responses to climate change using CMIP6 climate scenarios for the upper Huai river basin, China. *Frontiers in Environmental Science* **9**: 759547. DOI: 10.3389/fenvs.2021.759547.

Castillo R, Amador JA. 2020. Precipitation and temperature in Costa Rica at the end of the century based on NEX-GDDP projected scenarios. *Atmosphere* **11**: 1323. DOI: 10.3390/atmos11121323.

Clapeyron É. 1834. Memoire sur la puissance motrice de la chaleur. *Journal de l´École Polytechnique* **14**: 153–190 (In French).

Clausius R. 1850. On the moving force of heat and the laws of heat which may be deduced therefrom. *Poggendorf's Annalen* **79**: 368–369.

Das S, Kamruzzaman M, Islam ARMT. 2022. Assessment of characteristic changes of regional estimation of extreme rainfall under climate change: a case study in a tropical monsoon region with the climate projections from CMIP6 model. *Journal of Hydrology* **610**: 128002. DOI: 10.1016/j.jhydrol.2022.128002.

Das T, Dettinger MD, Cayan DR, Hidalgo HG. 2011. Potential increase in floods in California's Sierra Nevada under future climate projections. *Climatic Change* **109**: 71–94. DOI: 10.1007/s10584-011-0298-z.

Duran-Quesada AM, Sorí R, Ordoñez P, Gimeno L. 2020. Climate perspectives in the intra–americas seas. *Atmosphere* **11**: 959. DOI: 10.3390/atmos11090959.

Gu L, Chen J, Yin J, Slater LJ, Wang HM, Guo Q, Feng M, Qin H, Zhao T. 2022. Global increases in compound flood-hot extreme hazards under climate warming. *Geophysical Research Letters* **49**: e2022GL097726. DOI: 10.1029/2022GL097726.

Herrera W. 1985. Vegetación y clima en Costa Rica. Vol. 2, Universidad Estatal a Distancia, San José, Costa Rica; 118 (in Spanish).

Hidalgo HG, Amador JA, Alfaro EJ, Quesada B. 2013. Hydrological climate change projections for Central America. *Journal of Hydrology* **495**: 94–112. DOI: 10.1016/j.jhydrol.2013.05.004.

Hidalgo HG, Alfaro EJ, Amador JA, Bastidas A. 2019. Precursors of quasi-decadal dry-spells in the Central America dry corridor. *Climate Dynamics* **53**: 1307–1322. DOI: 10.1007/s00382-019-04638-y.

Hidalgo HG, Alfaro EJ, Hernández-Castro F, Pérez-Briceño PM. 2020. Identification of tropical cyclones' critical positions associated with extreme precipitation events in Central America. *Atmosphere* **11**: 1123. DOI: 10.3390/atmos11101123.

Hidalgo HG, Alfaro EJ, Pérez-Briceño PM. 2021. Projected Climate Changes of CMIP5 models in La Cruz, Guanacaste, Costa Rica. *Revista de Biología Tropical* **69**: 60–73. DOI: 10.15517/rbt.v69iSuppl.2.48307 (in Spanish with English summary).

Hidalgo HG, Alfaro EJ, Valverde KT, Bazo J. 2023. Probability of induced extreme precipitation events in Central America due to tropical cyclone positions in the surrounding oceans. *Natural Hazards* **116**: 2917–2933. DOI: 10.1007/s11069-022-05790-1.

Hirabayashi Y, Tanoue M, Sasaki O, Zhou X, Yamazaki D. 2021. Global exposure to flooding from the new CMIP6 climate model projections. *Scientific Reports* **11**: 3740. DOI: 10.1038/s41598-021-83279-w.

Huang X, Stevenson S, Hall AD. 2020. Future warming and intensification of precipitation extremes: a "double whammy" leading to increasing flood risk in California. *Geophysical Research Letters* **47**: e2020GL088679. DOI: 10.1029/2020GL088679.

Imbach P, Molina L, Locatelli B, Roupsard O, Mahe G, Neilson R, Corrales L, Scholze M, Cialis P. 2012. Modeling potential equilibrium states of vegetation and terrestrial water cycle of Mesoamerica under climate change scenarios. *Journal of Hydrometeorology* **13**: 665–680. DOI: 10.1175/JHM-D-11-023.1.

Karmalkar AV, Bradley RS, Diaz HF. 2008. Climate change scenario for Costa Rican montane forests. *Geophysical Research Letters* **35**: L11702. DOI: 10.1029/2008GL033940.

Mahato PK, Singh D, Bharati B, Gagnon AS, Singh BB, Brema J. 2022. Assessing the impacts of human interventions and climate change on fluvial flooding using CMIP6 data and GIS-based hydrologic and hydraulic models. *Geocarto International* **37**: 11483–11508. DOI: 10.1080/10106049.2022.2060311.

Maldonado T, Alfaro EJ, Hidalgo HG. 2018. A review of the main drivers and variability of Central America Climate and seasonal forecast systems. *Revista de Biología Tropical* **66**: S153–S175. DOI: 10.15517/rbt.v66i1.33294.

Mendez M, Calvo-Valverde LA, Imbach P, Maathuis B, Hein-Grigg D, Hidalgo-Madriz JA, Alvarado-Gamboa LF. 2022. Hydrological response of tropical catchments to climate change as modeled by the GR2M model: a case study in Costa Rica. *Sustainability* **14**: 16938. DOI: 10.3390/su142416938.

Meresa H, Tischbein B, Makonnen T. 2022. Climate change impact on extreme precipitation and peak flood magnitude and frequency: observations from CMIP6 and hydrological models. *Natural Hazards* **111**: 2649–2679. DOI: 10.1007/s11069-021-05152-3.

Ministerio de Ambiente, Energía y Telecomunicaciones. 2011. *Estudio de las Cuencas Hidrográficas de Costa Rica, análisis biofísico, climatológico y socioeconómico*. Ministerio de Ambiente, Energía y Telecomunicaciones, Instituto Meteorológico Nacional; 728 (in Spanish). http://cglobal.imn.ac.cr/index.php/publications/estudio-de-las-cuencas-hidrograficas-de-costa-rica/. Last access: June 16, 2023.

Ministerio de Planificación Nacional y Política Económica. 2019. *Costa Rica impacto de los fenómenos naturales para el período 1988–2018, por sectores, provincias, cantones y distritos: compendio*. Ministerio de Planificación Nacional y Política Económica, Unidad de Inversiones Públicas, Ministerio de Agricultura y Ganadería. Secretaría Ejecutiva de Planificación Sectorial Agropecuaria, San José, Costa Rica; 340 (in Spanish).

Moreno ML, Hidalgo HG, Alfaro EJ. 2019. Cambio climático y su efecto sobre los servicios ecosistémicos en dos parques nacionales de Costa Rica, América Central. *Revista Iberoamericana de Economía Ecológica* **30**: 16–38 (in Spanish with English summary).

Navarro-Racines C, Tarapues J, Thornton P, Jarvis A, Ramirez-Villegas J. 2020. High-resolution and bias-corrected CMIP5 projections for climate change impact assessments. *Scientific Data* **7**: 7. DOI: 10.1038/s41597-019-0343-8.

Pandey D, Tiwari AD, Mishra V. 2022. On the occurrence of the observed worst flood in Mahanadi River basin under the warming climate. *Weather and Climate Extremes* **38**: 100520. DOI: 10.1016/j.wace.2022.100520.

Pascale S, Kapnick SB, Delworth TL, Hidalgo HG, Cooke WF. 2021. Natural variability vs forced signal in the 2015–2019 Central American drought. *Climatic Change* **168**: 16. DOI: 10.1007/s10584-021-03228-4.

Paudel S, Joshi N, Kalra A. 2023. Projected future flooding pattern of Wabash river in Indiana and Fountain Creek in Colorado: an assessment utilizing bias-corrected CMIP6 climate data. *Forecasting* **5**: 405–423. DOI: 10.3390/forecast5020022.

Quesada-Román A. 2021. Landslide risk index map at the municipal scale for Costa Rica. *International Journal of Disaster Risk Reduction* **56**: 102144. DOI: 10.1016/j.ijdrr.2021.102144.

Quesada-Román A. 2022. Flood risk index development at the municipal level in Costa Rica: a methodological framework. *Environmental Science & Policy* **133**: 98–106. DOI: 10.1016/j.envsci.2022.03.012.

Quesada-Román A, Villalobos-Portilla E, Campos-Durán D. 2020. Hydrometeorological disasters in urban areas of Costa Rica, Central America. *Environmental Hazards* **20**: 264–278. DOI: 10.1080/17477891.2020.1791034.

Reed KA, Wehner MF, Zarzycki CM. 2022. Attribution of 2020 hurricane season extreme rainfall to human-induced climate change. *Nature Communications* **13**: 1905. DOI: 10.1038/

s41467-022-29379-1.

Sante FD, Coppola E, Giorgi F. 2021. Projections of river floods in Europe using EURO-CORDEX, CMIP5 and CMIP6 simulations. *International Journal of Climatology* 41: 3203–3221. DOI: 10.1002/joc.7014.

Solano J, Villalobos R. 1999. *Regiones y subregiones climáticas de Costa Rica*. Documento Técnico de Gestión de Desarrollo, Instituto Meteorológico Nacional, San José, Costa Rica; 32 (in Spanish).

Stan K, Sanchez-Azofeifa A, Calvo-Rodriguez S, Castro-Magnani M, Chen J, Ludwig R, Zou L. 2020. Climate change scenarios and projected impacts for forest productivity in Guanacaste Province (Costa Rica): lessons for tropical forest regions. *Regional Environmental Change* **20**: 14. DOI: 10.1007/s10113-020-01602-z.

Stewart IT. 2009. Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes* **23**: 78–94. DOI: 10.1002/hyp.7128.

Wang L, Wang J, He F, Wang Q, Zhao Y, Lu P, Huang Y, Cui H, Deng H, Jia X. 2023. Spatial-temporal variation of extreme precipitation in the Yellow-Huai-Hai-Yangtze Basin of China. *Scientific Reports* **16**: 9312. DOI: 10.1038/s41598-023-36470-0.

Wang Y, Xu HM, Li YH, Liu LL, Hu ZH, Xiao C, Yang TT. 2022. Climate change impacts on runoff in the Fujiang River basin based on CMIP6 and SWAT model. *Water* **14**: 3614. DOI: 10.3390/w14223614.

Wilks D. 2019. Statistical Methods in the Atmospheric Sciences. 4th Edition. Elsevier, Amsterdam, Netherlands; 818.

Yin J, Guo S, He S, Guo J, Hong X, Liu Z. 2018. A copula-based analysis of projected climate changes to bivariate flood quantiles. *Journal of Hydrology* **566**: 23–42. DOI: 10.1016/j.jhydrol.2018.08.053.

Zhu D, Das S, Ren Q. 2017. Hydrological appraisal of climate change impacts on the water resources of the Xijiang basin, South China. *Water* **9**: 793. DOI: 10.3390/w9100793.