



Risk Assessment and Capacity Development in Costa Rica

Climate Hazard Models

August 2025

Prepared for:



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1 INTRODUCTION

The Global Risk Modelling Alliance (GRMA), supported by the InsuResilience Solutions Fund (ISF), is designed to enhance the capacity of countries and cities to conduct climate and disaster risk analysis with a financial perspective. The initiative addresses critical gaps in data and modelling, improving the quality of climate and disaster risk assessments at both national and subnational scales. To this end, GRMA works together with local partners to identify and define country-specific needs, while providing open-source risk management tools, data resources, and access to operational expertise in risk financing.

The starting point for risk modelling is the hazard component, which captures the various ways in which natural phenomena may manifest across a territory. Hazards are represented as a set of stochastically simulated events that are both collectively exhaustive and mutually exclusive, —that is, they cover all possible manifestations of the hazard while assuming independent events whose frequency of occurrence follows a natural power-law distribution (i.e., equivalent to a recurrence curve).

In the case of Costa Rica, the GRMA project considered four hydrometeorological hazards: riverine flooding, pluvial flooding, coastal flooding, and drought. All were evaluated at the national level. In addition, a high-resolution riverine flood model was developed specifically for the Heredia canton. Table 1 summarizes the hydrometeorological hazard models developed under this framework and their connection to the four GRMA – Costa Rica projects.

Table 1. Relationship between hydrometeorological hazard models and GRMA projects

Project	Riverine Flooding	Pluvial Flooding	Coastal Flooding	Drought
<i>Strategic project: Heredia</i>	■			
<i>Operational Project 1: National Route RN2</i>	■	■		
<i>Operational Project 2: Agriculture</i>	■	■		■
<i>Operational Project 3: Fu-Turismo</i>	■	■	■	

To evaluate these hazards, this study applies a methodology based on the modelling of meteorological forcing, from which hydrometeorological events are derived. Using historical records of precipitation and temperature, long synthetic time series (equivalent to thousands of years) are generated for these meteorological variables. This is achieved through a stochastic simulator that produces complete years of data, preserving both temporal and spatial correlations (i.e., based on first- and second-order statistics calculated from the historical series).

This approach constitutes a form of statistical downscaling, enabling the subsequent integration of climate change projections. Within the simulated series, it is possible to identify extreme conditions (e.g., rainfall excess, rainfall deficits, or extreme temperatures) that may occur at low frequencies (i.e., events not necessarily observed in the historical record). These extremes give rise to hazard events such as droughts, pluvial and riverine floods, or coastal flooding.

Through this probabilistic framework, the potential ways in which hazards may manifest across Costa Rica's territory can be characterized, providing inputs for subsequent catastrophic risk assessments.

This document corresponds to Deliverable 4 – Climate Hazard Models, which provides a detailed description of the hydrometeorological hazard models and their corresponding results. The report is structured into the following sections:

Section 1. Introduction

Section 2. Meteorological Forcing Modelling: details the simulation of meteorological time series and the incorporation of climate change into these simulations.

Section 3. Drought Hazard: focuses on the characterization of droughts derived from the simulated meteorological series.

Section 4. Flood Hazard: presents the national-scale hydrological response model for river basins and the national results of the simplified hydraulic model. This section also includes the more detailed two-dimensional model developed for Heredia.

Section 5. Coastal Flood Hazard: includes details of the tropical cyclone modelling and the specific consideration of climate change impacts on these events. A dedicated subsection on tsunamis is also provided.

Section 6. Training Program: provides a summary of the training program on climate hazard modelling, along with its current progress status.

2 METEOROLOGICAL FORCING MODELLING

This study draws on historical climate records from Costa Rica to analyze two key variables: daily accumulated precipitation and maximum, minimum, and mean temperatures. The primary data source is the national network of meteorological stations operated by the Instituto Meteorológico Nacional (IMN), whose direct observations provide accurate and reliable information on the country's atmospheric conditions. This primary source is prioritized because it ensures high-resolution local measurements, in contrast with indirect products such as radar or satellite datasets, which often present limitations in spatial resolution and accuracy in specific regions.

Nevertheless, due to the uneven distribution of stations and the presence of gaps in some historical series, remote sensing data were incorporated as a complement. Satellite records extend spatial coverage to regions with sparse instrumentation and help maintain the continuity of time series where in-situ data are incomplete. By integrating traditional meteorological observations with gridded products derived from remote sensing, a broader and more consistent representation of Costa Rica's climatic behavior is achieved.

For the validation and verification of the records, both the official IMN databases and international repositories providing standardized, globally available datasets were used. This combination of sources allows for cross-checking values and reducing the uncertainty associated with relying on a single input, thereby strengthening the quality of the datasets and providing a solid foundation for climate assessment and hydrological modelling in Costa Rica.

For this study, the period 1991–2020 was selected as the Base Climate period. This choice is grounded in the fact that it corresponds to the most recent climatological standard defined by the World Meteorological Organization (WMO, 2017), which establishes 30-year averages as the global reference for calculating climate normals. The *Base Climate* period used here thus represents the designated *reference* or *control period*, characterized by historical information, and reflecting current climatological conditions. The meteorological variables obtained for this base climate are subsequently perturbed to incorporate the influence of climate change, as presented in section 2.5.

2.1 National Catalogue of Meteorological Stations

The National Catalogue of Meteorological Stations of Costa Rica is a key tool for climate management and research in the country. This catalogue is managed by the Instituto Meteorológico Nacional (IMN), established in 1952 and responsible for observing, recording, and analyzing atmospheric and climatological conditions. Through this platform, information from the network of automatic stations operated by the IMN is organized and made available. These stations are strategically distributed across the national territory, covering regions such as the North Pacific, Central Pacific, South Pacific, Northern Zone, Central Valley, and both the Northern and Southern Caribbean sectors.

The automatic meteorological stations record, in real time, essential variables including air temperature, relative humidity, atmospheric pressure, wind speed and direction, as well as precipitation. These data are indispensable for producing forecasts, issuing early warnings, and analyzing climatic phenomena that may

impact populations and ecosystems. In addition, the station network supports historical monitoring and the study of climate variability in Costa Rica, providing a reliable, high-spatial resolution database.

The information collected is publicly available through the web portal of Instituto Meteorológico Nacional (<https://www.imn.ac.cr/web/imn/estaciones-automaticas>), which provides access to real-time data from automatic stations (IMN, Automatic Stations) and to an interactive map displaying monthly averages of variables such as precipitation, temperature, and wind (IMN, Interactive Map). In addition, the IMN has developed a viewer on the ArcGIS platform (National Station Catalogue) that visually integrates the location and characteristics of each station. Taken together, these resources constitute a modern and accessible information system, essential for scientific research, education, and decision-making in risk management and territorial planning in Costa Rica.

From the IMN, historical station data were received for precipitation (222 stations) and temperature and humidity (219 stations). Although the country has a significant number of ground-based stations, not all provide complete and concurrent coverage for the base climate period (1991–2020) defined for climatological normalization. Figure 1 and Figure 2 present histograms showing the distribution of missing data within the control period for IMN stations. As shown, there is a high density of missing data for the historical period characterized as the base climate, which makes it necessary to incorporate information from international databases. A complete station-by-station record of missing data is provided in Annex A.1.

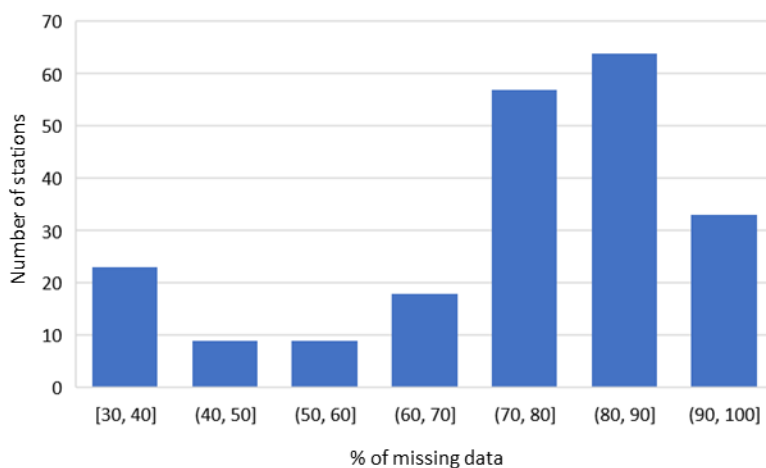


Figure 1. Distribution of missing precipitation data at IMN stations within the control period (1991–2020)

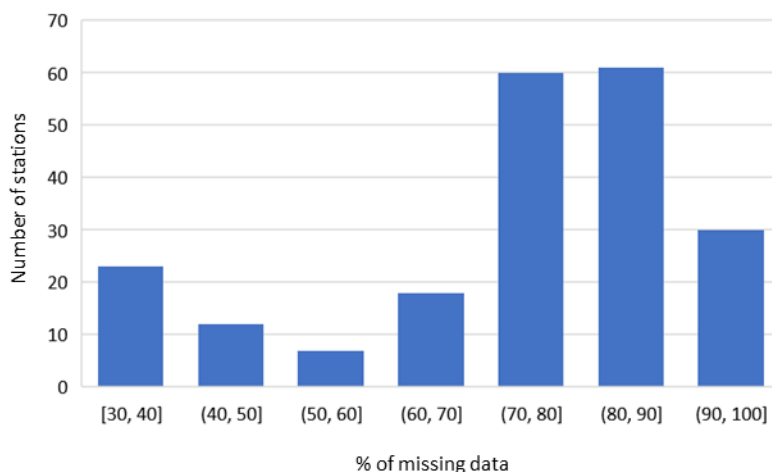


Figure 2. Distribution of missing temperature data at IMN stations within the control period (1991–2020)

2.2 International Climate Data Sources

Due to the irregular distribution of ground-based meteorological stations and the presence of data gaps within the reference period, this study incorporates climate datasets derived from satellite information and processed by international agencies. Among the most relevant are the CHIRPS dataset from the University of California, Santa Barbara and ERA5 from Copernicus.

The use of these sources offers several advantages: the datasets provide complete temporal and spatial coverage, are widely adopted by the international scientific community for climate analysis and hydroclimatic hazard assessment, and supply multiple climatic parameters required for the calculation of evapotranspiration. Furthermore, their spatial resolution is sufficient to support risk assessments at the national scale. Each dataset is described in detail below.

2.2.1 CHIRPS (Climate Hazards group InfraRed Precipitation with Stations)

CHIRPS is a highly regarded platform for precipitation analysis in tropical environments such as Costa Rica. It provides daily and monthly time series from 1981 to the present, with a high spatial resolution of approximately 0.05° (~ 5 km), covering latitudes from 50°S to 50°N (Climate Hazards Center, 2025). This dataset applies a hybrid methodology that integrates satellite-derived data (cold cloud duration, CCD), detailed climatology (CHPclim), and ground-based meteorological station observations. The result is a reliable set of products particularly useful for monitoring climate trends, seasonal droughts, and spatial patterns across large regions (Funk et al., 2015; Climate Hazards Center, 2025).

The most recent release, CHIRPS v3, incorporates improved algorithms for capturing extreme rainfall events and corrects biases such as underreporting in rain gauge stations. It provides near-real-time preliminary products with only a few days' latency, as well as finalized monthly products. Data are available in multiple formats (GeoTIFF, NetCDF, etc.) and temporal scales (daily, decadal, monthly, and annual) (Climate Hazards Center, 2025).

2.2.2 ERA5 – Copernicus Climate Change Service

ERA5, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and distributed through the Copernicus Climate Change Service (C3S) of the European Union, is one of the most comprehensive and widely used reanalysis datasets worldwide. It integrates satellite observations, meteorological station records, and numerical atmospheric modelling, producing climate information that is both consistent and physically robust (Hersbach et al., 2020, 2023).

ERA5 provides time series from 1940 to the present, with continuous updates and a delay of only about five days relative to the current date, making it suitable for both historical studies and near-real-time monitoring (Copernicus Climate Change Service, 2017). The dataset is available at hourly and daily resolutions, with a spatial resolution of approximately 0.25° (~ 31 km), enabling detailed analysis of climate variability across multiple scales.

One of the main advantages of ERA5s is the wide range of climate variables it provides: precipitation, temperature (mean, maximum, and minimum), solar radiation, specific humidity, surface air pressure, and wind speed, among others. In addition, these variables are adjusted to topography, which enhances their accuracy in regions with complex terrain such as Costa Rica (Hersbach et al., 2020). These characteristics make ERA5 a particularly valuable source for calculating evapotranspiration, a key parameter in agricultural drought modelling, water resource management, and assessing crop vulnerability to extreme conditions.

ERA5 data are freely available in widely used formats such as NetCDF and grid-based raster files, which can be easily integrated into Geographic Information Systems (GIS) and environmental modelling platforms. Its versatility, combined with temporal and spatial consistency, has led to its widespread use in international scientific research, particularly in studies of climate variability, long-term trends, and hydroclimatic risk assessments in tropical regions (Muñoz-Sabater et al., 2021).

2.3 Meteorological Information for the Base Climate

Meteorological information for the base climate must provide, at each data point within the territory, complete and concurrent daily records for the 1991–2020 period, covering at least four meteorological variables: daily accumulated precipitation, mean temperature, maximum temperature, and minimum temperature. In addition, the spatial distribution of the data points must be uniform and cover the entire territory of Costa Rica.

Although ground-based station data are always preferable, and Costa Rica has a substantial meteorological observation network, the available station dataset does not fully meet the criteria outlined above. For this reason, the source of meteorological time series for the control period in this study corresponds to records obtained from CHIRPS and ERA5. The data provided by IMN are used as control information for verification and adjustment of the CHIRPS and ERA5 series, as detailed in Section 2.3.1.

A total of 111 spatial locations were defined to uniformly cover Costa Rica's territory, as shown in Figure 3. These locations are referred to as virtual stations: while they do not correspond to actual meteorological stations, they provide daily-scale information for all variables of interest. Figure 4 and Figure 5 present

historical maps of multi-annual means for precipitation and temperature, calculated for the base period (1991–2020) using data from the virtual stations.

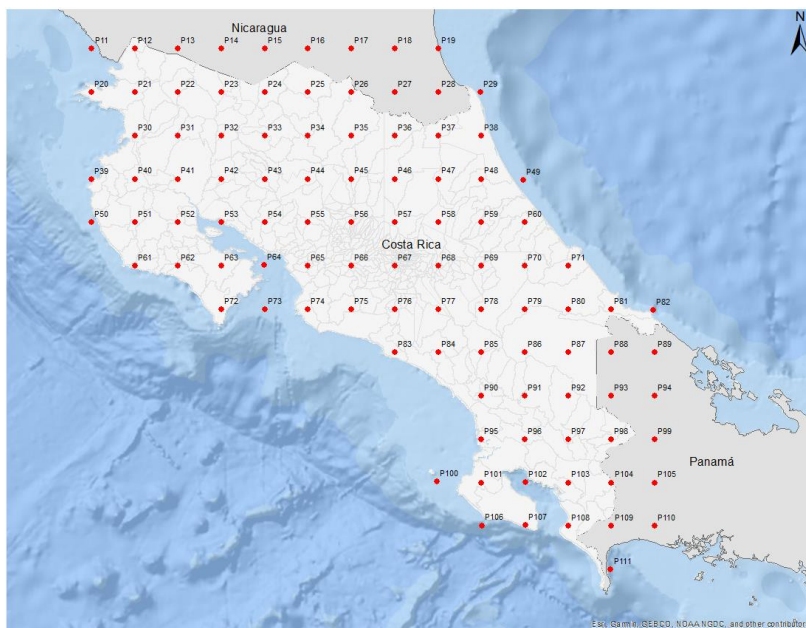


Figure 3. Selected virtual station points

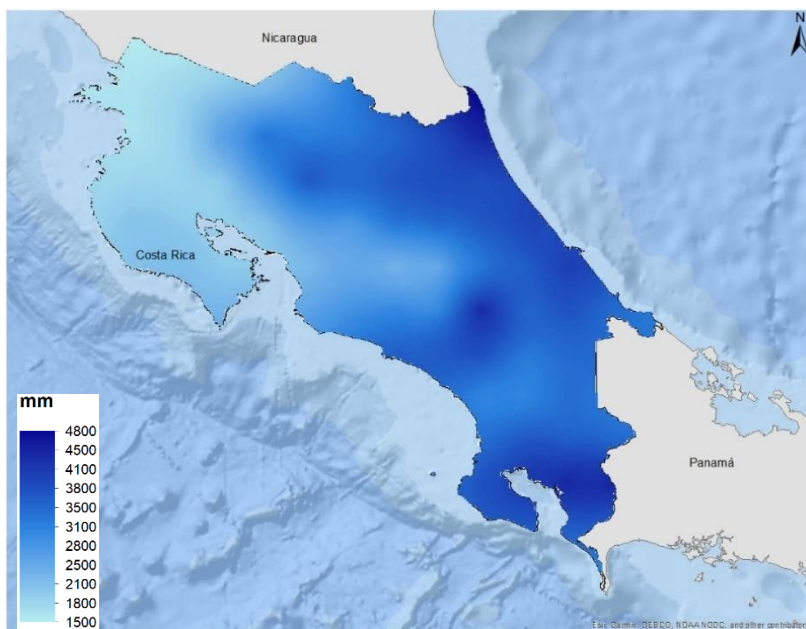


Figure 4. Multi-annual mean accumulated precipitation for the 1991–2020 period

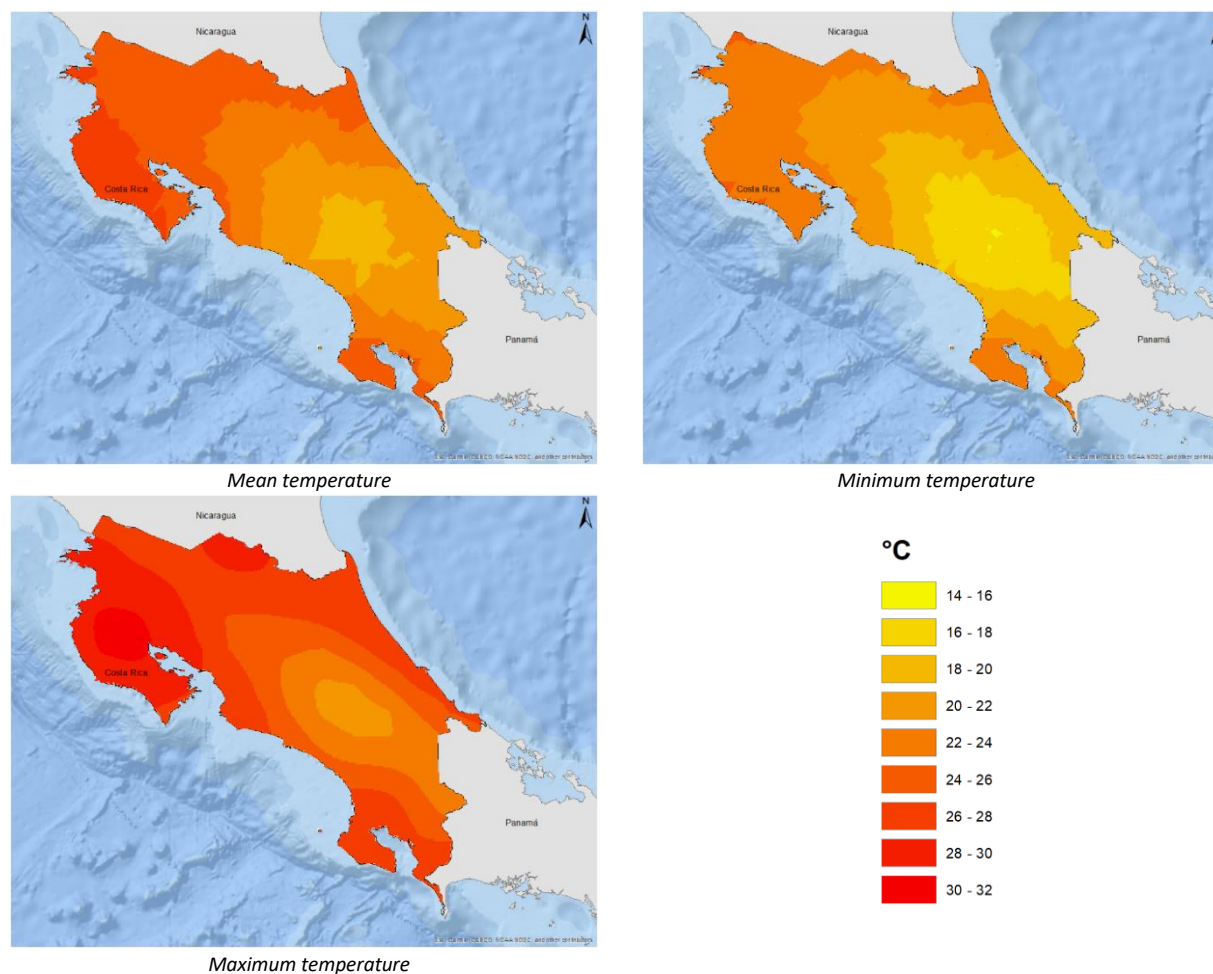
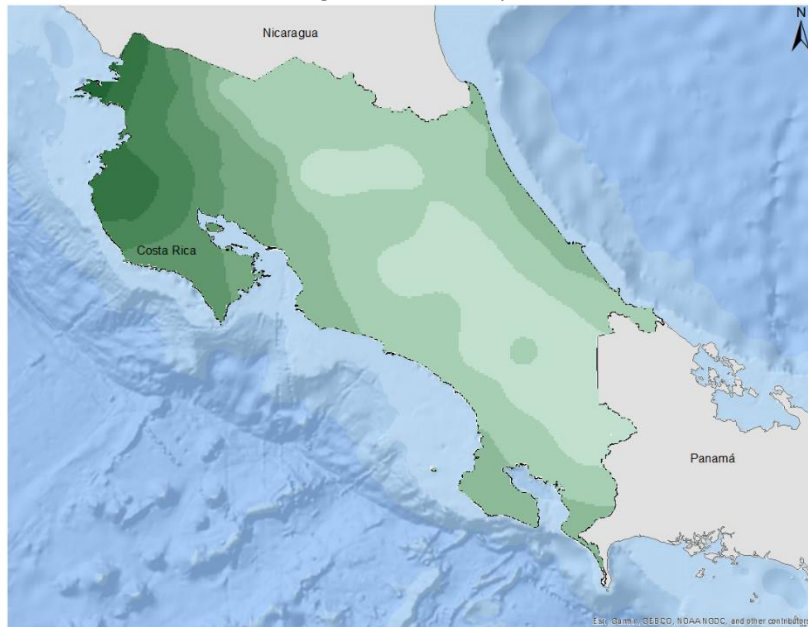


Figure 5. Multi-annual temperature for the 1991-2020 period

Reference evapotranspiration (ET_o) was calculated using the Penman–Monteith equation (see details in the *Inception Report* of this consultancy; INGENIAR-CIMNE 2025 for GRMA), which requires additional meteorological variables: relative humidity, atmospheric pressure, solar radiation, and wind speed. The values of these variables were also obtained from the ERA5 dataset. At each calculation point, complete daily-scale ET_o series were generated for the control period.

Figure 6 presents, as an example, the time series for the five variables—including ETo—for an arbitrarily selected location among the 111 virtual stations defined for Costa Rica. Figure 7 shows the spatial distribution of the historical daily mean ETo,



while

Figure 8 presents the historical annual mean ETo for Costa Rica during the 1991–2020 period.

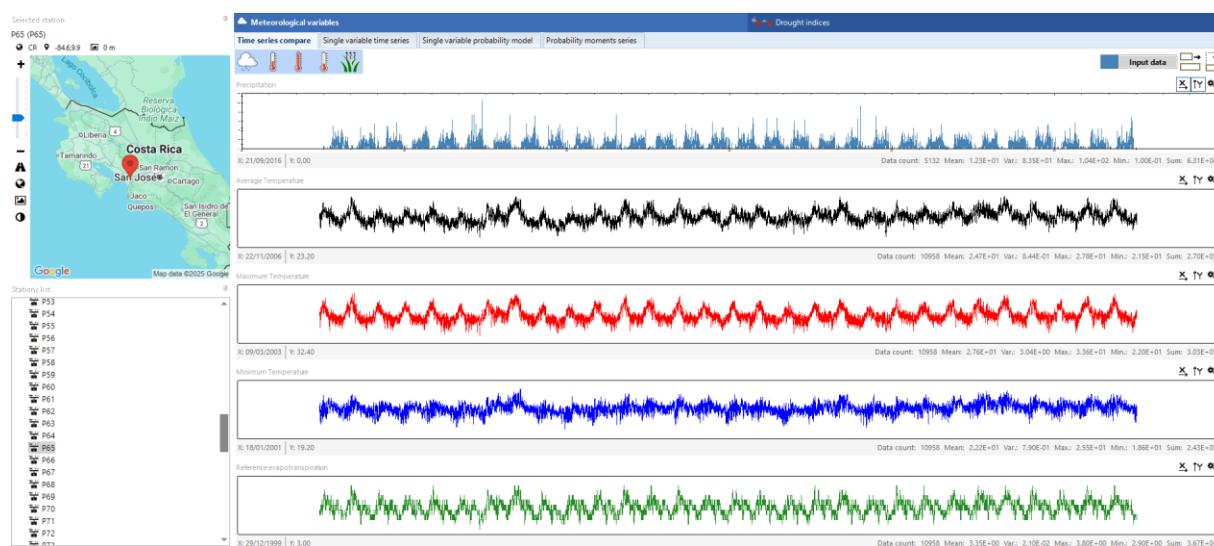


Figure 6. Historical climate summary at a grid station point. Extracted from DroughtPro software

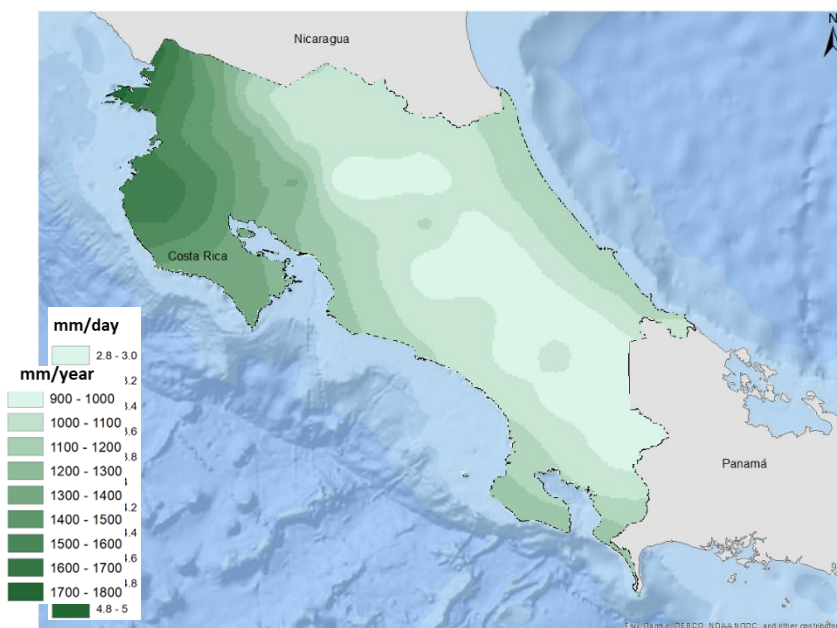


Figure 7. Mean daily evapotranspiration for the 1991–2020 period

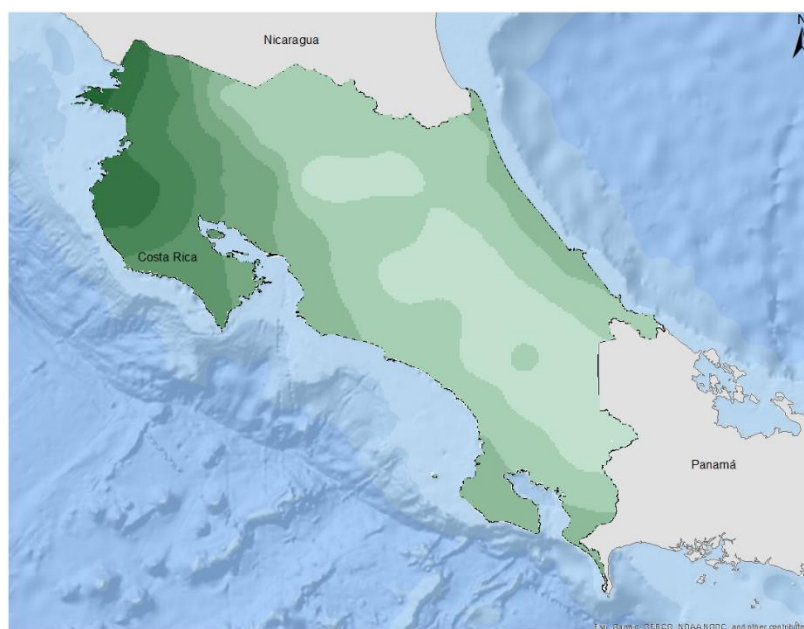


Figure 8. Mean annual evapotranspiration for the 1991–2020 period

2.3.1 Verification of the Adjustment of International Database Information

To ensure the reliability of the information derived from international datasets in relation to records obtained from ground-based meteorological stations, a validation of the degree of correspondence between both sources was conducted.

Historical records provided by the IMN were used, selecting 22 ground stations with complete series spanning more than 20 years (see Figure 9). The data from each ground station was compared with the nearest virtual station, in order to detect significant differences. As an example, results are presented below for only three stations. However, the complete analysis of the 22 selected stations is included in the project dataset.

Figure 10 shows the geographical location of the sample meteorological stations used for the comparison between ground-based records and satellite product data in Costa Rica. Three stations representative of climatically contrasting regions are included: Juan Santamaría International Airport, located in the Central Valley; Liberia Airport, situated in the northern Pacific region; and the Altamira station, located in the southern Pacific region of the country, in an area influenced by orography. These locations make it possible to evaluate the performance of the satellite dataset under diverse climatic contexts, ranging from higher-altitude areas with moderate thermal conditions to low-altitude regions characterized by higher temperatures and a marked seasonality of precipitation.

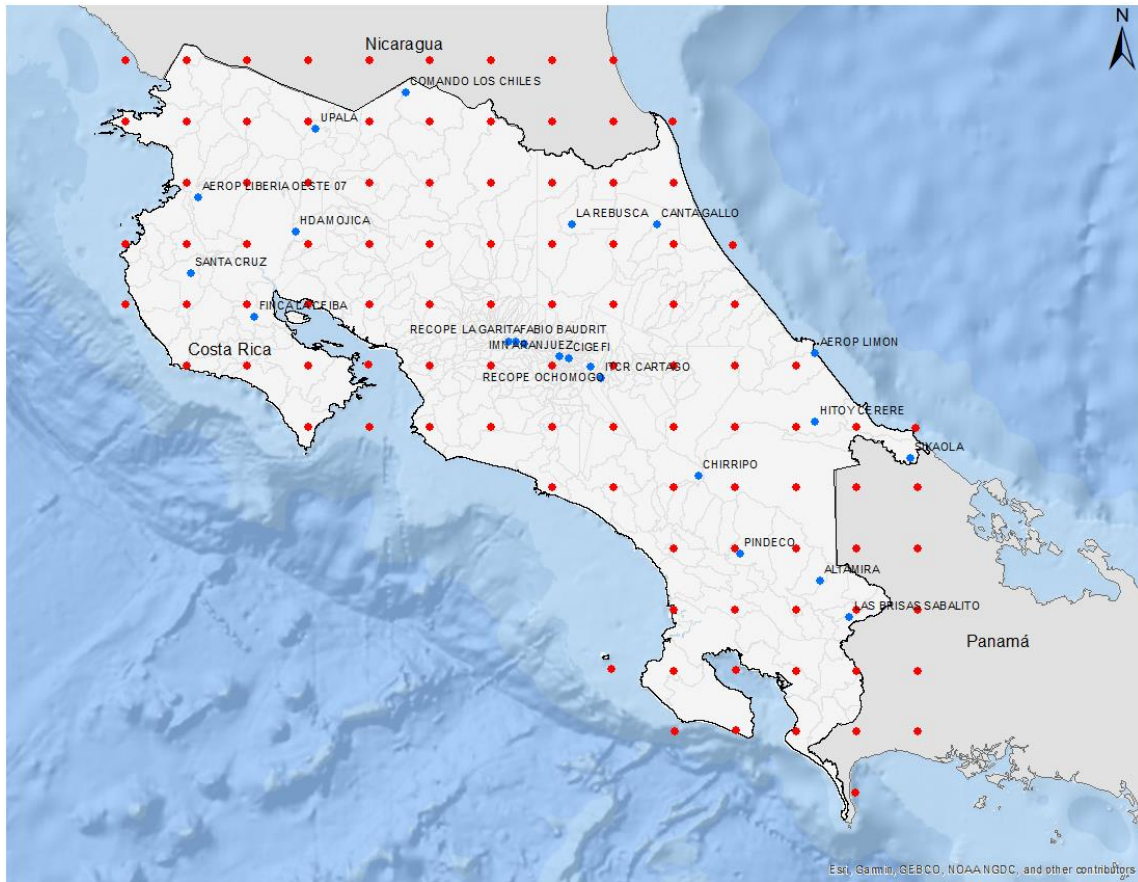


Figure 9. Satellite stations (red) and ground stations (blue)



Figure 10. Location of the compared station pairs (ground–satellite).

2.3.1.1 Precipitation

A comparison was carried out between precipitation data from the Juan Santamaría International Airport ground station and its nearest virtual station, P66, as well as from the Liberia West Airport station and point P30, and the Altamira station with point P97. These stations were selected based on their proximity to the corresponding CHIRPS–ERA5 virtual stations and the low proportion of missing data in their historical records¹.

Several statistical tests were performed on the daily values, as presented in Table 2 through Table 7. Significant agreement is observed for dry days in: Liberia West Airport station reports 64%, compared with 65% at station P30, while Juan Santamaría International Airport station records 36%, compared with 54% at station P66, and the Altamira station reports 15%, compared with 46% at station P97. . Regarding the data show a high degree of similarity: at Juan Santamaría, the average is 4.57 mm/day, compared with 5.09 mm/day at P66; and at Liberia West Airport it is 4.31 mm/day, compared with 4.33 mm/day at P30, and at Altamira it is 10.30mm/day, compared with 8.92 mm/day at P97.

Table 2. Daily precipitation statistical analysis – correlations between Juan Santamaría Airport station and P66

Metric		Value	Optimal value
Correlation coefficient	CC	0.23	1
Mean Squared Error	RMSE [mm/d]	8.39	0
Bias	BIAS	6.13	0
Mean error	ME [mm/d]	0.28	0

¹ The proportion of missing data refers to the number of days without observations at the station within the 1990–2020 control period.

Probability of Detection	POD	0.86	1
False Alarm Ratio	FAR	0.27	0
Success Index	CSI	0.65	1

Table 3. Daily precipitation statistical analysis – individual stations Juan Santamaría Airport and P66

Metric		JUAN SANTAMARIA Airp.	P66
Missing records	[-]	27.7%	0.0%
Maximum	[mm/day]	146	115
Mean	[mm/day]	4.57	5.09
90th percentile	[mm/day]	15.70	15.61
75th Percentile	[mm/day]	4.20	8.00
Zeros	[-]	36%	54%

Table 4. Daily precipitation statistical analysis – correlations between Liberia Airport station and P30

Metric		Value	Optimal value
Correlation coefficient	CC	0.31	1
Mean Squared Error	RMSE [mm/d]	9.67	0
Bias	BIAS	-1.92	0
Mean error	ME [mm/d]	-0.08	0
Probability of Detection	POD	0.91	1
False Alarm Ratio	FAR	0.19	0
Success Index	CSI	0.74	1

Table 5. Daily precipitation statistical analysis – individual stations Liberia West Airport and P30

Metric		LIBERIA Airp.	P30
Missing records	[-]	25.9%	0.0%
Maximum	[mm/day]	253	112
Mean	[mm/day]	4.31	4.33
90th percentile	[mm/day]	13.98	14.73
75th Percentile	[mm/day]	1.20	6.19
Zeros	[-]	64%	65%

Table 6. Daily precipitation statistical analysis – correlations between the Altamira and P97 stations

Metric		Value	Optimal Value
Correlation Coefficient	CC	0.22	1
Root Mean Square Error	RMSE [mm/day]	13.95	0
Bias	BIAS	-12.35	0
Mean Error	ME [mm/day]	-1.27	0
Probability of Detection	POD	0.77	1
False Alarm Ratio	FAR	0.26	0
Critical Success Index	CSI	0.61	1

Table 7. Daily precipitation statistical analysis – individual Altamira and P97 stations

Metric		Altamira	P97
Missing records	[-]	27.7%	0.0%
Maximum	[mm/day]	232	116

Mean	[mm/day]	10.30	8.92
90th percentile	[mm/day]	31.20	24.60
75th percentile	[mm/day]	13.90	13.97
Zeros	[-]	15%	46%

When examining the data at annual and monthly scales (Figure 11, Figure 12, Figure 13) show that both the IMN ground-based stations and the satellite products exhibit a consistent temporal evolution and seasonality throughout the study period. This indicates that the multiannual average precipitation adequately reproduces the characteristic climatic variability of the region.

In the case of the Juan Santamaría International Airport station, the values estimated by the P66 satellite product tend to be consistently higher than the ground-based station records, both in annual precipitation and in multiannual monthly means. This behavior could be associated, at least in part, with the presence of missing data in the observed series. Despite this positive bias, the satellite product is able to adequately capture the seasonal cycle, reproducing the minima during the dry season and the maxima associated with the wettest months.

A similar behavior is observed at the Liberia West Airport station, where the P30 product shows precipitation magnitudes very close to those recorded by the ground-based station, maintaining high consistency in both interannual variability and monthly seasonality.

For the Altamira station, the comparison with the P97 satellite product shows good overall agreement in both annual accumulated precipitation and multiannual mean monthly precipitation. Although in some years the ground-based station records higher maximum values than those estimated by the satellite, these differences are concentrated in specific years and do not alter the overall behavior of the time series. Such discrepancies are expected, given that satellite products may smooth extremes associated with intense and localized precipitation events that are captured at specific points by ground-based stations.

Despite differences in the relative magnitude of precipitation among stations—resulting in local underestimations or overestimations depending on the site analyzed—the multiannual mean monthly values are notably similar between the ground-based stations and the satellite products. This indicates that, beyond systematic biases in absolute values, both data sources consistently represent the mean climatic regime and the seasonal pattern of precipitation in the region.

Taken together, these results provide a preliminary validation of the use of satellite-based precipitation products, demonstrating their ability to reproduce the temporal and seasonal patterns observed at local stations, albeit with the presence of systematic biases that vary according to location and the product considered.

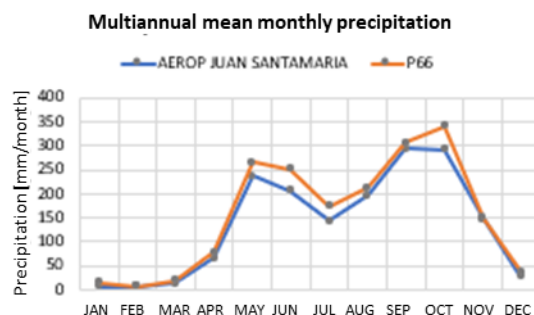
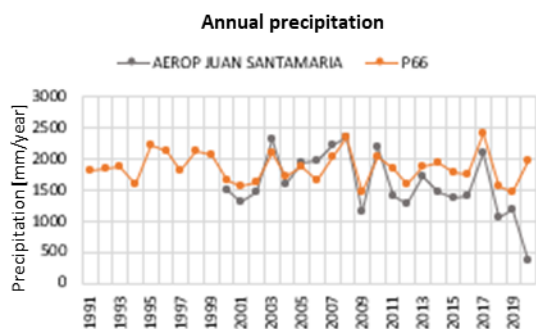


Figure 11. Comparison of annual values and monthly mean precipitation: Juan Santamaría Airport station and P66

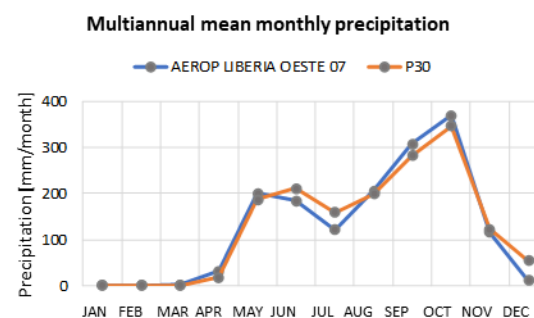
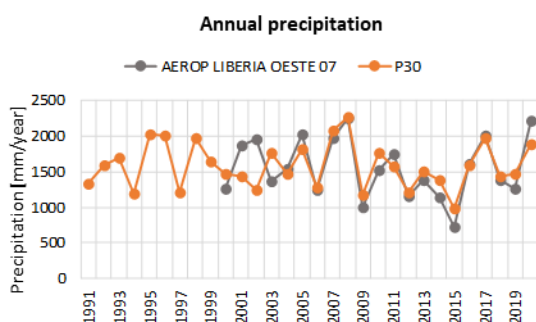


Figure 12. Comparison of annual values and monthly mean precipitation: Liberia West Airport station and P30

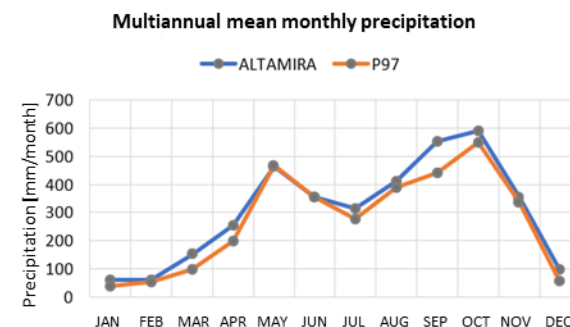
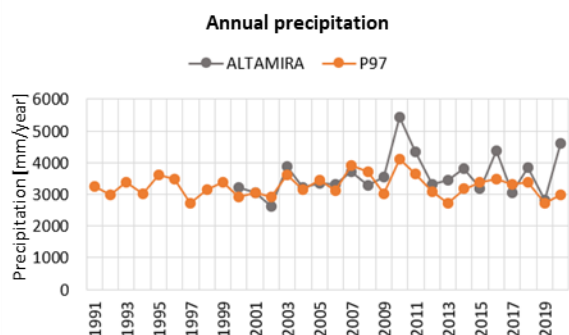


Figure 13. Comparison of annual values and monthly mean precipitation: Altamira station and P97

In addition to the overall agreement between ground-based and satellite datasets, the interannual variability of precipitation reflects the influence of large-scale climatic drivers such as the El Niño–Southern Oscillation (ENSO), as well as the contribution of local and regional extreme events. Periods of reduced precipitation, such as 1997–1998 and 2015–2016, are consistent with El Niño conditions, which are typically associated with drier-than-average conditions in the Pacific region of Costa Rica. Similarly, wetter conditions observed around 2008 and 2010–2011 coincide with La Niña events, which enhance rainfall across the region.

In addition to these ENSO-driven patterns, some pronounced precipitation peaks, such as those observed around 2003 and 2017, are not directly associated with strong ENSO phases, but rather with short-term

atmospheric processes, including intense convective activity and tropical cyclone influence (e.g., Hurricane Nate in 2017). Likewise, relatively dry conditions around 2001 may reflect transitional or neutral ENSO conditions combined with natural climate variability.

When comparing the histograms between stations (Figure 14, Figure 15, Figure 16), it is evident that the distribution of daily precipitation records shows a high frequency of dry days, along with a progressive decrease in the number of records as precipitation magnitude increases. However, some differences appear in the lower precipitation range (less than 5 mm/day), where the virtual station tends to register a larger number of events compared to the ground-based station. In contrast, for higher precipitation values, both sources display very similar behavior, indicating that the virtual station is able to accurately capture extreme rainfall events.

Taken together, these results suggest that, although there are limitations in representing light precipitation, the virtual station data provides consistent and reliable performance for the purposes of this study.

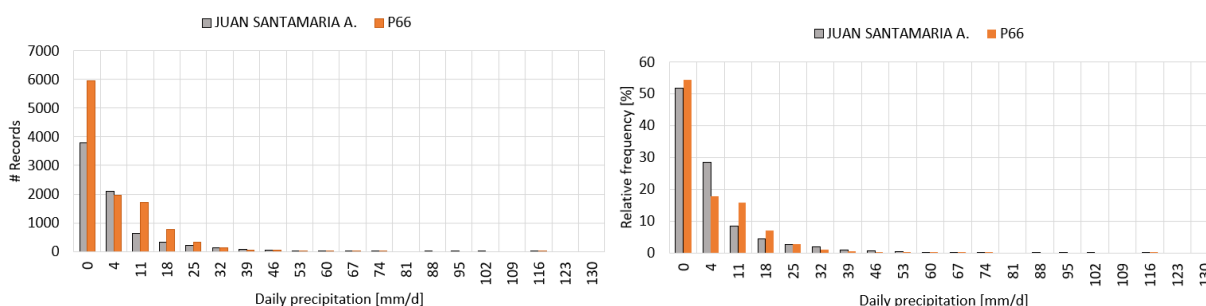


Figure 14. Comparison of daily precipitation histograms. Juan Santamaría airports P66 stations

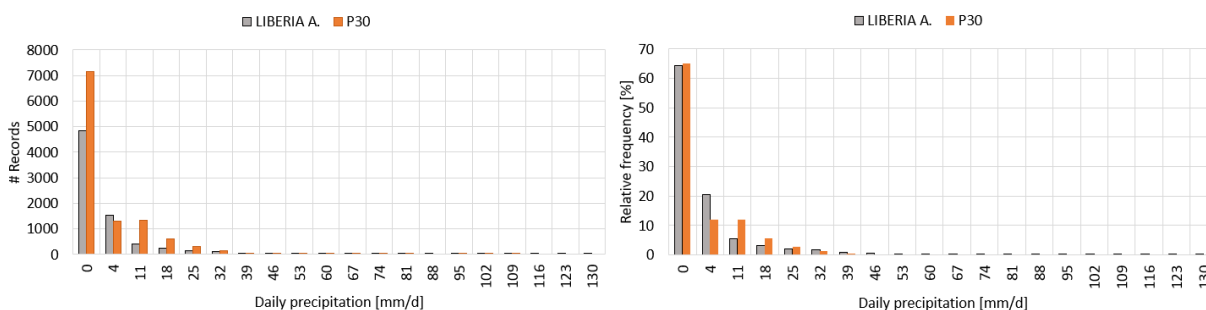


Figure 15. Comparison of daily precipitation histograms. Aeropuerto Liberia Oeste and P30 stations

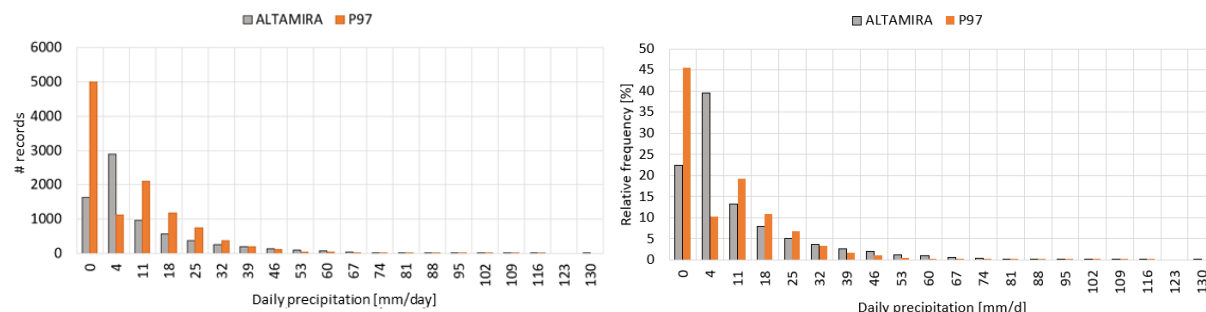


Figure 16. Comparison of daily precipitation histograms. Altamira and P97 stations

When analyzing precipitation at annual scales, a consistent behavior was identified across the evaluated stations. Although slight variations appear in extreme values throughout the period, the satellite station series remain within an acceptable range compared to the ground-based stations, adequately reproducing both wetter and drier periods. This overall correspondence can be observed in Figure 17, Figure 18, and Figure 19.

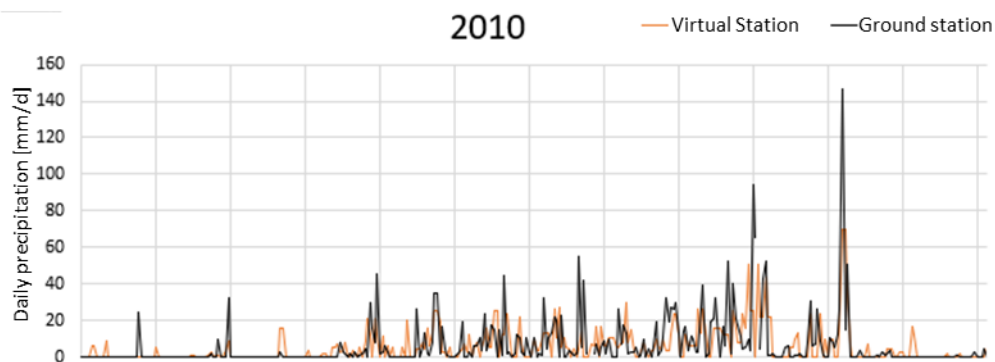


Figure 17. Comparison of daily values between Juan Santamaría and P66 stations for the year 2010.

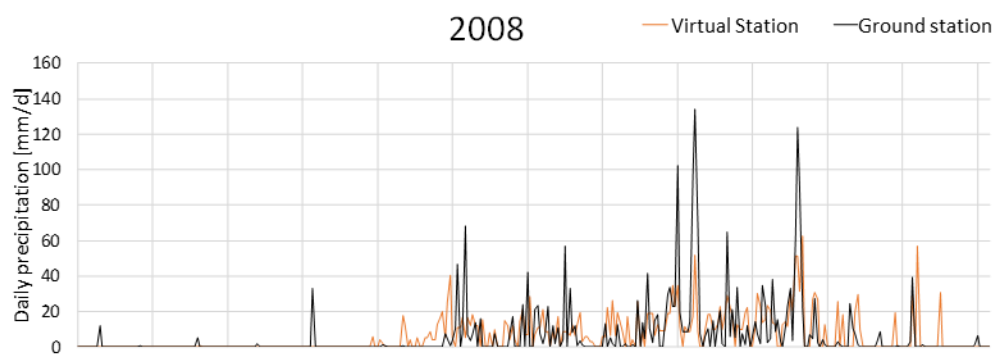


Figure 18. Comparison of daily values between Liberia Oeste airport and P30 stations for the year 2008.

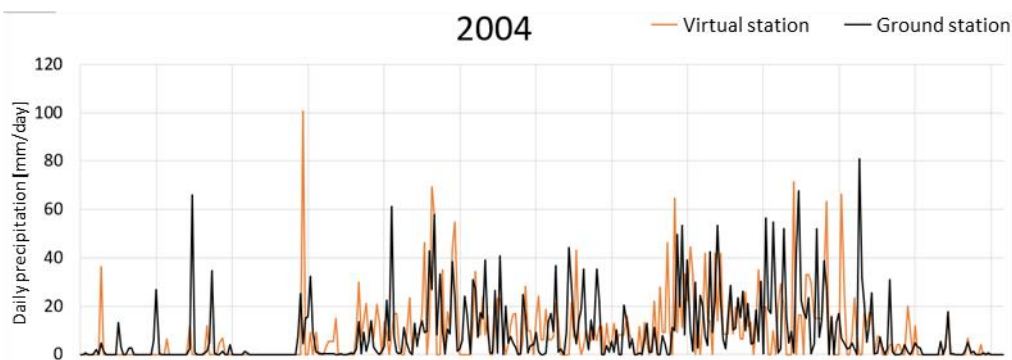


Figure 19. Comparison of daily values between Altamira and P97 stations for the year 2004.

The scatter plots in Figure 20, Figure 21, and Figure 22 show the relationship between precipitation records from ground-based stations and data from the CHIRPS dataset. Each color represents a different month of the year, allowing the correspondence to be examined across various climatic seasons. Overall, the points align around the trend line, indicating good agreement between the two sources of information.

For most months, the satellite-based estimates adequately reproduce the values recorded by the ground stations, particularly within intermediate precipitation ranges. However, the dispersion around the trend line is not homogeneous across the entire range of precipitation values. In particular, for values greater than 100 mm/month, greater variability is observed, suggesting higher uncertainty in the representation of moderate to intense precipitation events.

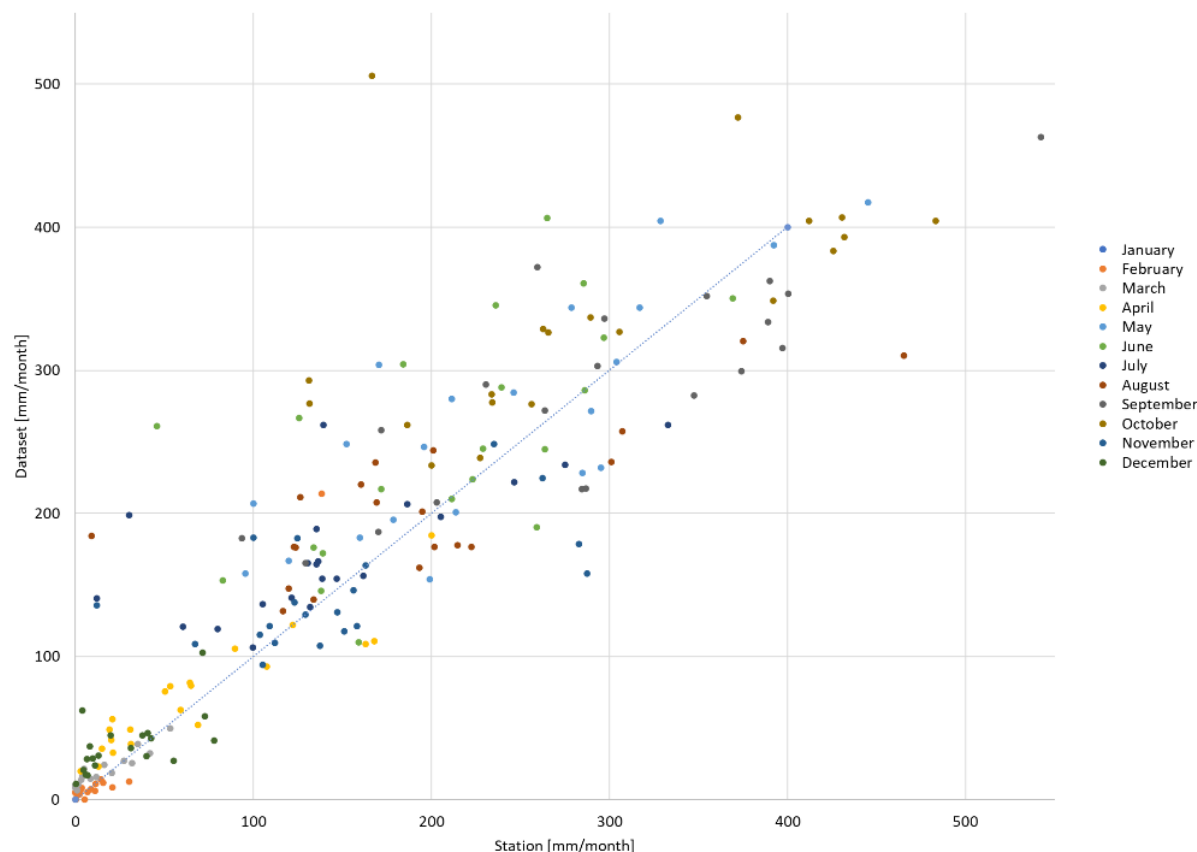


Figure 20. Scatter plot of monthly accumulated precipitation values: Juan Santamaría Airport and P66.

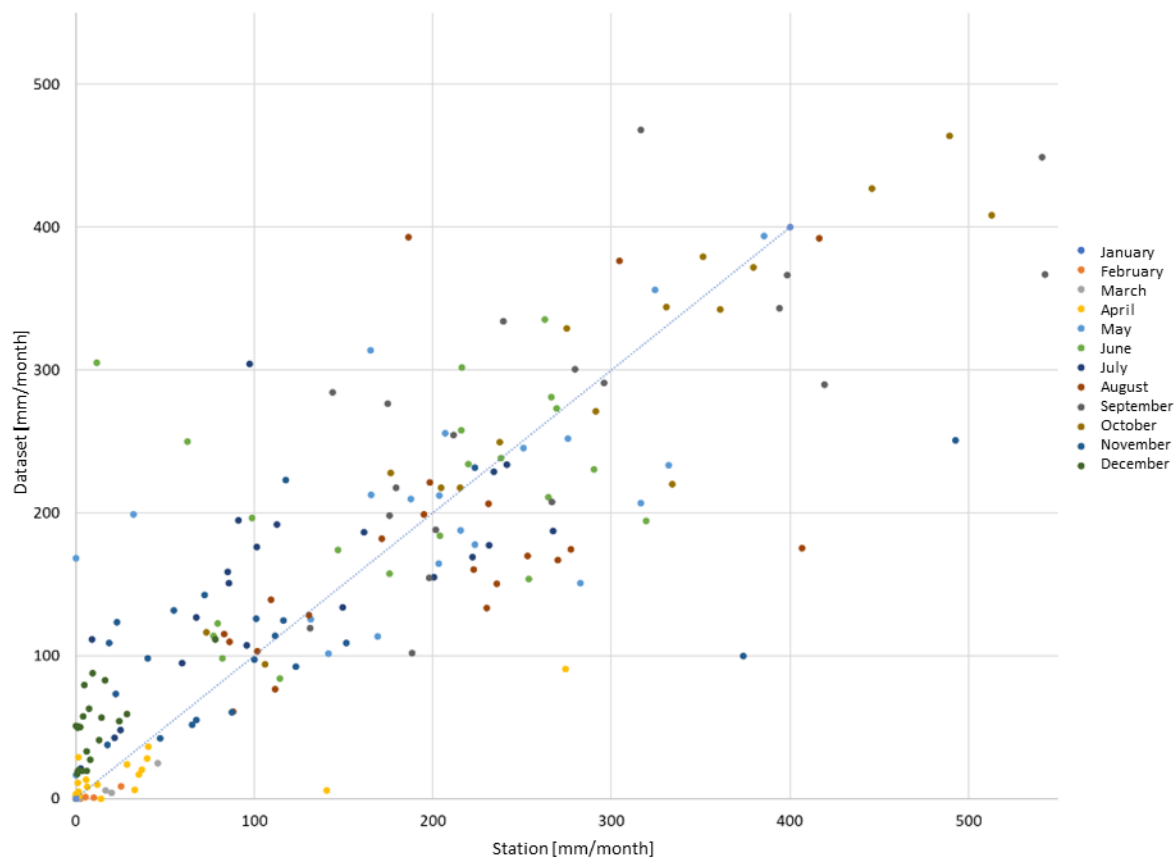


Figure 21. Scatter plot of monthly accumulated precipitation values: Liberia Oeste Airport and P30.

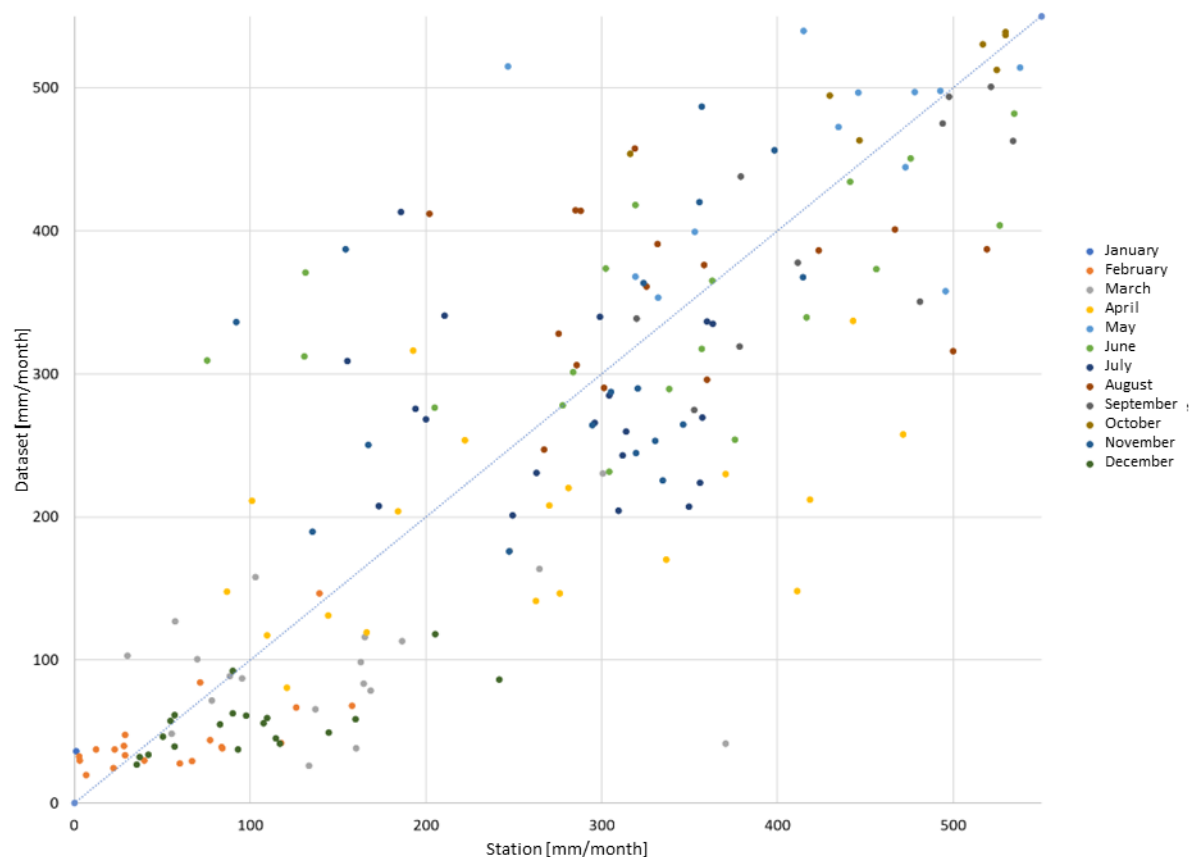


Figure 22. Scatter plot of monthly accumulated precipitation values Altamira and P97

From a seasonal perspective, the dry months (mainly January, February, and March) are clustered near the origin of the plot (0–100 mm/month), showing good agreement between both data sources under low-precipitation conditions. In contrast, the wettest months (such as September and October) concentrate the highest precipitation values, where greater scatter and deviations from the trend line are observed.

Although no clearly differentiated systematic seasonal bias by month is identified, the figures suggest that discrepancies between the satellite product and station observations increase during wet and transitional periods. This behavior may be associated with high spatial variability and the convective nature of precipitation during these periods. Overall, the results indicate an acceptable global agreement between both data sources, with more consistent performance under dry conditions and greater uncertainty at intermediate and high precipitation ranges.

2.3.1.2 Temperature

For temperature, the ground-based stations present missing data percentages of 27% (Juan Santamaría Airport) 26% (Liberia Airport), and 28% (Altamira). The monthly variations, including the warmest months, remained consistent across the analyzed stations, with only minimal differences in the range of values.

Table 8. Daily temperature statistical analysis – correlations between Juan Santamaría Airport station and P66

Metric		Value	Optimal value
Correlation coefficient	CC	2.35	1
Mean Squared Error	RMSE [°C]	0.58	0
Bias	BIAS	0.96	0
Mean error	ME [°C]	0.00	0

Table 9. Daily temperature statistical analysis – individual stations Juan Santamaría Airport and P66

Metric		JUAN SANTA MARIA Airp.	P66
Maximum	[°C]	26.3	25.3
Mean	[°C]	22.4	22.5
Median	[°C]	22.4	22.5
90th Percentile	[°C]	23.9	23.6
75th Percentil	[°C]	23.2	23.1
Missing records	[-]	27%	0%

Table 10. Daily temperature statistical analysis – correlations between Liberia Oeste Airport station and P30

Metric		Value	Optimal value
Correlation coefficient	CC	1.41	1
Mean Squared Error	RMSE [°C]	0.80	0
Bias	BIAS	-1.32	0
Mean error	ME [°C]	0.00	0

Table 11. Daily temperature statistical analysis – Individual stations Liberia Airport station and P30

Metric		LIBERIA Airp.	P66
Maximum	[°C]	31.4	30.1
Mean	[°C]	26.9	26.4
Median	[°C]	26.8	26.3
90th Percentile	[°C]	29.0	28.0
75th Percentil	[°C]	28.0	27.2
Missing records	[-]	26%	0%

Table 12. Daily temperature statistical analysis – correlations between Altamira and P97 stations

Metric		Value	Optimal value
Correlation coefficient	CC	2.16	1
Mean Squared Error	RMSE [°C]	0.56	0
Bias	BIAS	-0.18	0
Mean error	ME [°C]	0.00	0

Table 13. Daily temperature statistical analysis – Individual stations Altamira and P97

Metric		Altamira	P97
Maximum	[°C]	22.5	21.1
Mean	[°C]	18.4	18.3
Median	[°C]	18.3	18.2
90th Percentile	[°C]	19.6	19.3
75th Percentil	[°C]	19.0	18.8
Missing records	[-]	28%	0%

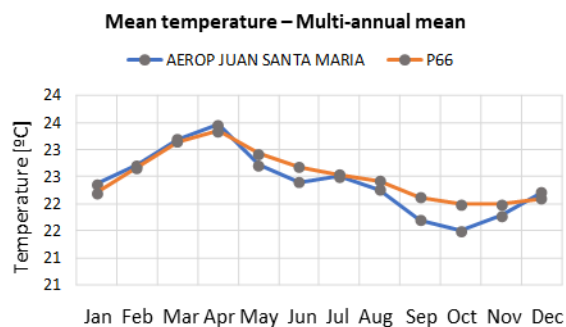
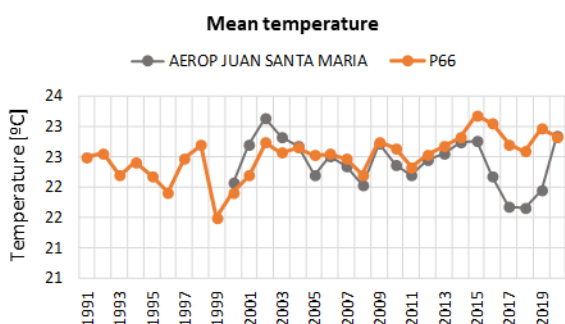


Figure 23. Comparison of annual and monthly temperature values. Juan Santamaría Airport and P66 stations

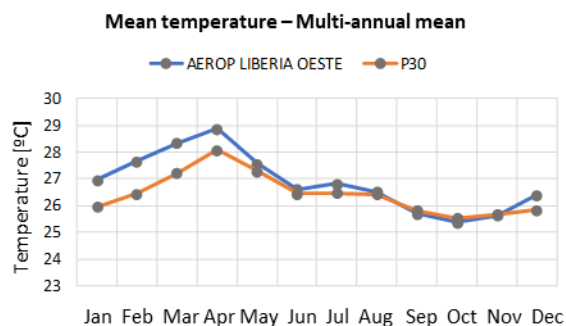
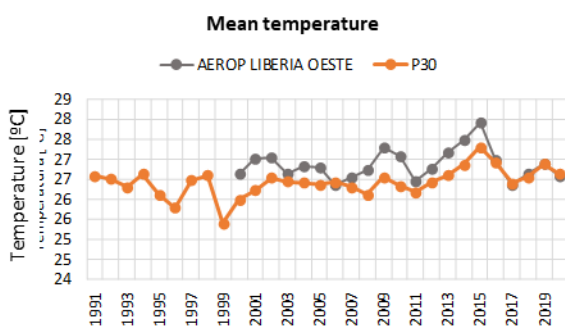


Figure 24. Comparison of annual and monthly temperature values. Aeropuerto Liberia Oeste and P30 stations

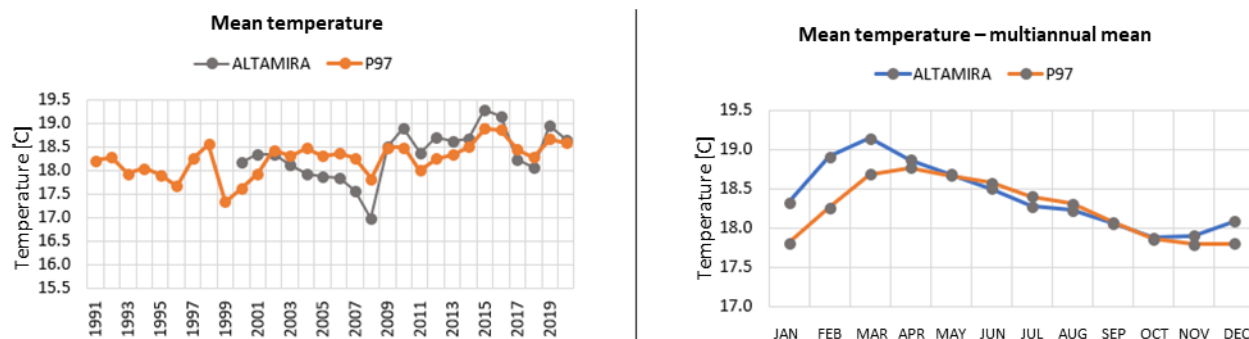


Figure 25. Comparison of annual and monthly temperature values. Altamira and P97 stations

The interannual variability of temperature (Figure 23 to Figure 25) exhibits a relatively stable behavior compared to precipitation, with only moderate fluctuations throughout the study period. Nevertheless, a secondary influence of large-scale climatic variability associated with the El Niño–Southern Oscillation (ENSO) can be identified. Slight increases in mean temperature are observed during El Niño periods, particularly around 1997–1998, 2009–2010, and 2015–2016, which is consistent with the warmer and drier conditions typically associated with these events in Costa Rica.

Conversely, slight decreases in temperature can be observed during La Niña periods, such as 1998–2000 and 2007–2008. In particular, the decrease observed around 2008 coincides with a well-defined La Niña event, during which increased cloud cover and precipitation likely contributed to reduced surface heating. Similar, although more prolonged, conditions can be associated with the 1998–2000 La Niña period, which also reflects slightly moderated temperature values.

The daily temperature histograms (Figure 26, Figure 27, and Figure 28) show the frequency distribution of the recorded values between the stations. Both series exhibit very similar behavior, with the largest concentration of records around 22 °C, 26 °C and 18 °C. The satellite station adequately reproduces the pattern observed at the ground station, although with slight differences in the frequency of certain intervals: for example, P66 tends to concentrate a larger number of records around 22 °C, while the ground station shows a somewhat more uniform distribution within that range. Overall, the coherence in the shape of the distribution indicates good agreement between the two sources of information.

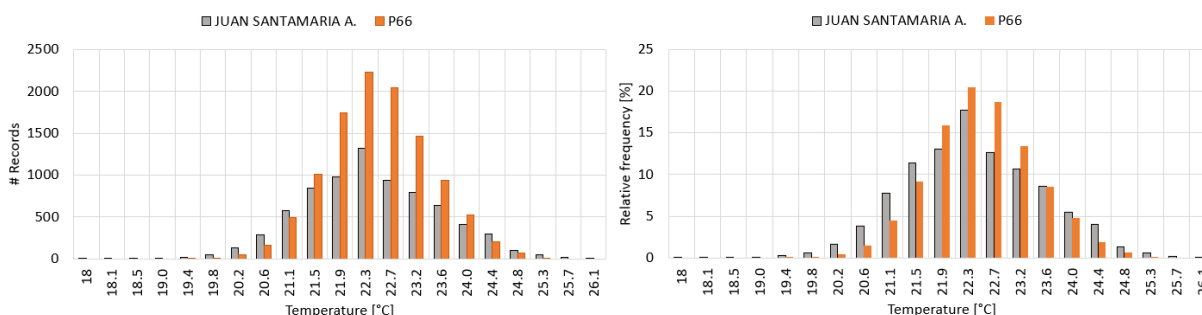


Figure 26. Comparison of daily temperature histograms. Juan Santamaría Airport and P66 stations

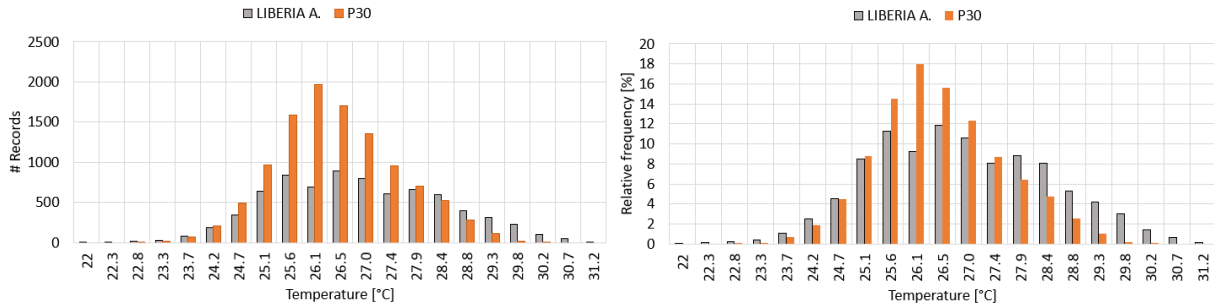


Figure 27. Comparison of daily temperature histograms. Liberia Oeste Airport and P30 stations

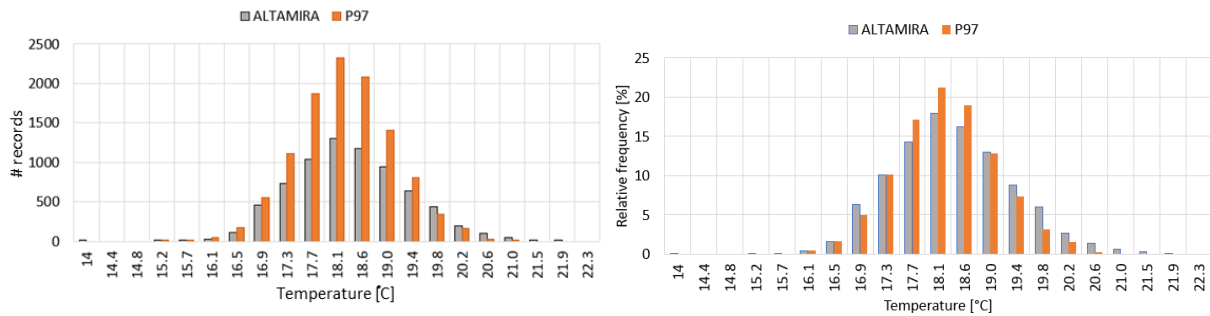


Figure 28. Comparison of daily temperature histograms. Altamira and P97 stations

In the annual graphs (Figure 29, Figure 30, and Figure 31), the trends of peaks and daily variations remain consistent between the ground-based and virtual stations, with coincident fluctuations during both warmer and cooler periods. The series tend to rise and fall synchronously over time.

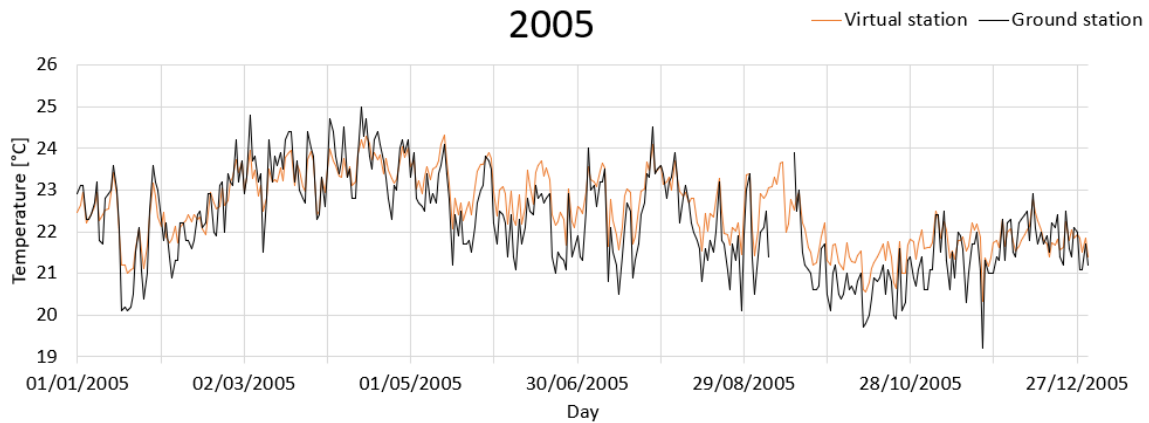


Figure 29. Comparison of daily values between Juan Santamaría Airport and P66 stations for the year 2005

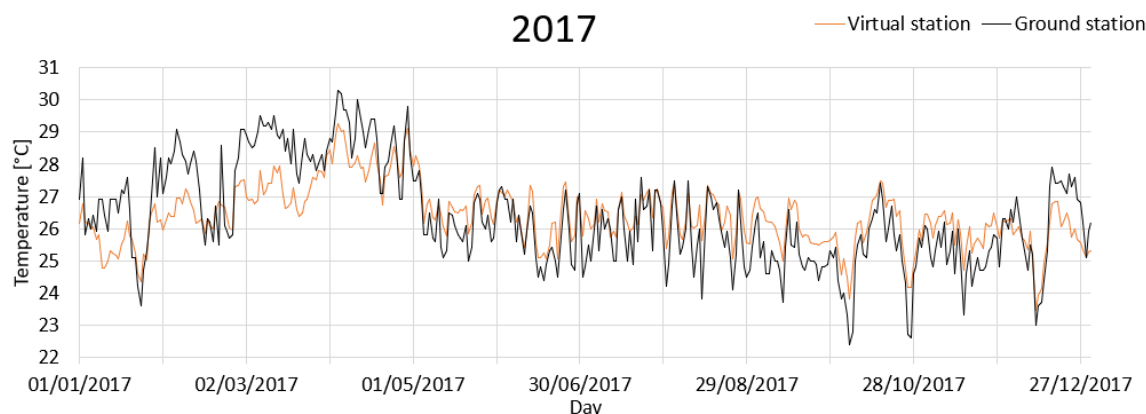


Figure 30. Comparison of daily values between Liberia Oeste Airport and P30 stations for the year 2017

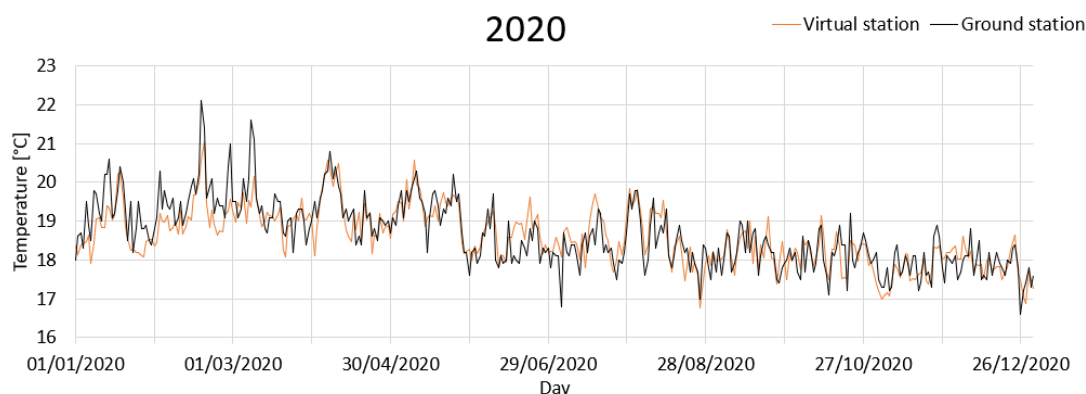


Figure 31. Comparison of daily values between Altamira and P97 stations for the year 2020

The scatter plots presented in Figure 32, Figure 33, and Figure 34 correspond to the comparison of mean monthly temperature between the meteorological stations and the corresponding satellite products. Overall, a clear linear relationship is observed between both data sources, with most points distributed around the 1:1 line, indicating an adequate ability of the satellite dataset to reproduce the mean monthly temperature observed at the ground-based stations.

In the case of Juan Santamaría International Airport (Figure 32), the main concentration of data lies within the approximate range of 21 to 24 °C, consistent with the thermal conditions characteristic of the Central Valley. For Liberia West Airport (Figure 33), a similarly well-defined linear relationship is observed, although with slightly greater scatter, particularly at higher temperature values. This behavior is expected in warmer climate regions and reflects the greater thermal variability typical of the lowland areas of the northern Pacific region.

At the Altamira station (Figure 34), mean monthly temperatures occur within a lower range, consistent with its higher elevation and cooler climatic conditions. In this case, although a consistent relationship between station records and the satellite product is maintained, greater data scatter is observed,

suggesting higher variability in the representation of monthly temperature compared to lower-altitude stations.

Across the three stations analyzed, the lowest mean monthly temperature values are mainly concentrated during the months with the strongest influence of the rainy season, whereas from March and April onward a progressive increase in temperature is evident. This increase is associated with drier conditions and enhanced solar radiation.

These scatter plots demonstrate that the satellite products adequately reproduce the seasonal pattern and climatic variability of mean monthly temperature at ground-based stations located in climatically contrasting regions, although with differences in the degree of scatter depending on local conditions and site elevation.

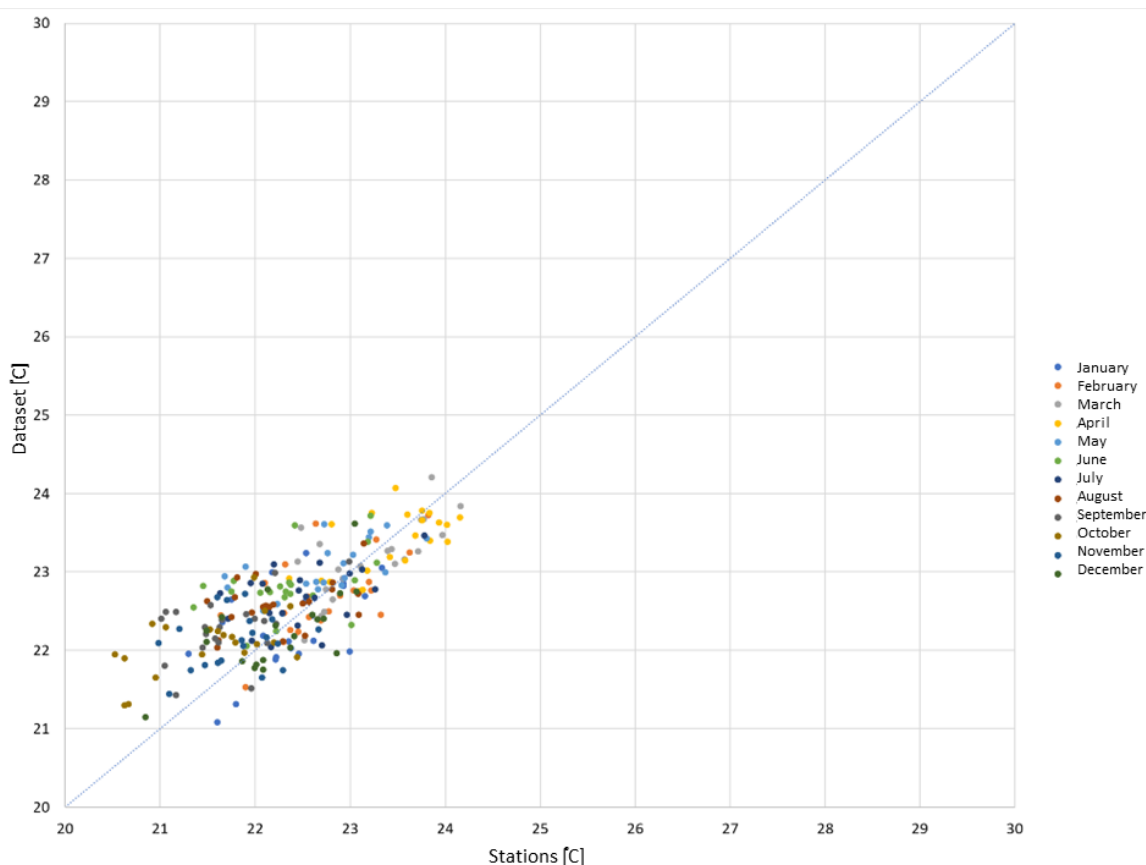


Figure 32. Scatter Plot of Monthly Mean Temperature Values: Juan Santamaría Airport and P66.

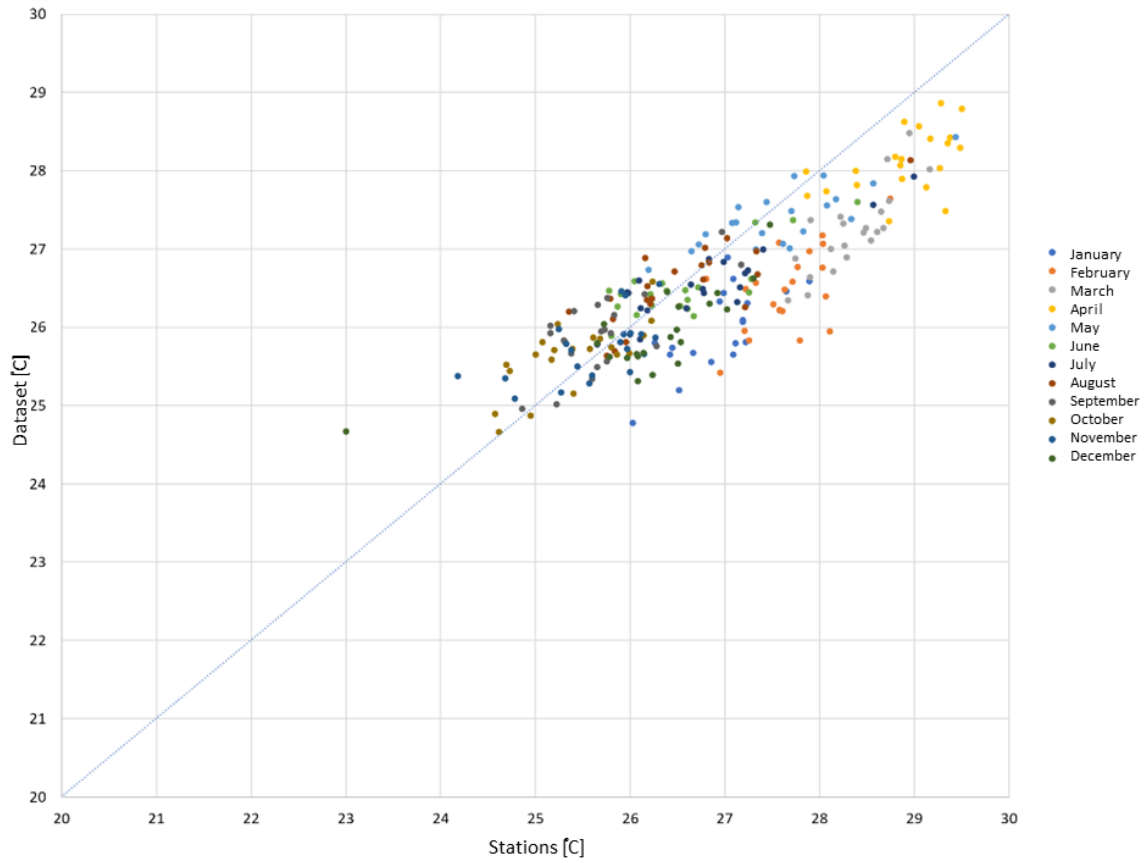


Figure 33. Scatter Plot of Monthly Mean Temperature Values: Liberia Oeste Airport and P30

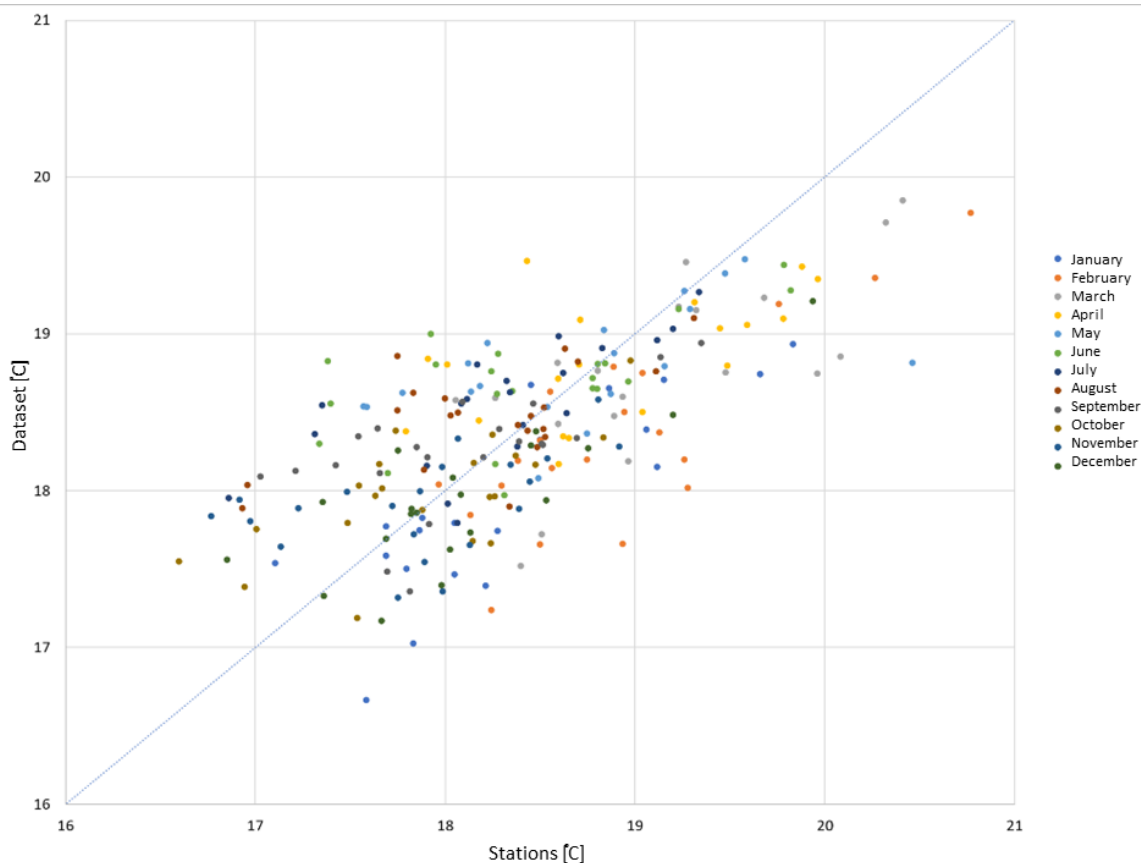


Figure 34. Scatter Plot of Monthly Mean Temperature Values: Altamira and P97

From the analyses presented, it can be concluded that the information from the CHIRPS and ERA5 datasets adequately reproduces the records from the ground-based stations. The observed differences fall within reasonable bounds and are therefore not considered critical for the hazard and risk assessments conducted in this consultancy. Consequently, there is no need to apply correction factors to the information from the virtual stations.

Although this section presents the analysis for only three locations in the territory, the project dataset includes the complete analysis for 22 ground stations.

2.4 Simulations for the Base Climate

For the 111 virtual stations defined in Costa Rica, the procedure described in the Inception Report of this consultancy was applied to generate simulated series representing possible variations of precipitation and temperature over time, under climatic conditions corresponding to the control period, or base climate. A total of 1,000 simulations were carried out, each corresponding to a complete calendar year, thus producing daily series of precipitation as well as minimum, mean, and maximum temperature.

These simulations were developed with two main objectives: (i) to capture variations inherent to the Costa Rican base climate that may not have been recorded in the historical meteorological data, in order to incorporate them into hazard event simulations; and (ii) to establish a solid basis for the downscaling of projected changes from Global Circulation Models (GCMs), considering different greenhouse gas emission scenarios.

The simulations were generated using the Drought Pro software (Bernal et al., 2018), which implements the methodology described below documented in the Inception Report (Section 6.1.1) (Cardona et al., 2025). This methodology has been tested in various countries and climatic contexts, showing suitable and reliable results for risk assessment (see, for example, Bernal et al., 2017; Maskrey et al., 2019; Cardona et al., 2020).

The proposed methodology uses a synthetic climate generator based on parametric probability distributions to define historical climate datasets and to estimate the probability of occurrence of a given precipitation or temperature value, even beyond the range of historical observations. The methodology treats each day of the year as a separate analysis and identifies the probability distribution that best fits the historical records. Subsequently, random values of daily precipitation and temperature are generated for a given number of simulation years using the parameters of the selected distributions.

To evaluate the goodness of fit of the probability distributions, the Kolmogorov–Smirnov goodness-of-fit test was applied. A significance level of 0.05 was established to determine whether the sample follows a given distribution, implying that the probability of concluding that the data do not follow a specified probability distribution when they actually do, is only 5%. When p-values above the significance level are obtained, the null hypothesis cannot be rejected, and therefore it cannot be concluded that the data do not fit the distribution under consideration.

In the specific case of precipitation, since it is necessary to distinguish between rainy and non-rainy days, the probability density function is defined as a discrete distribution representing the probability of rainfall, coupled with a continuous distribution that determines rainfall intensity when rain occurs (see Figure 35). The probability of occurrence of a dry day (P_0) is defined as the ratio of dry days to the total number of days in the sample.

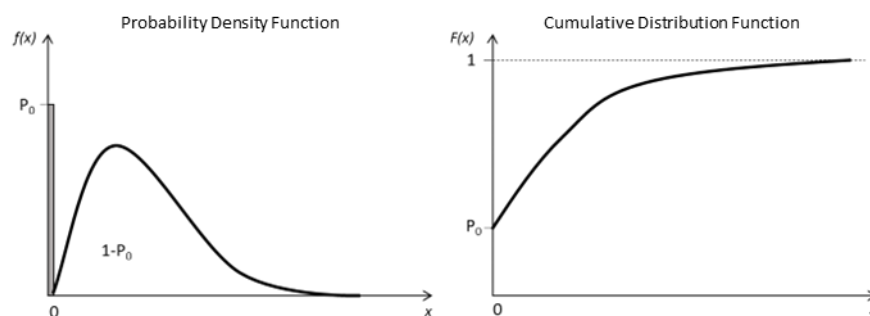


Figure 35. Illustration of coupled probability density and cumulative distribution functions for precipitation

After defining the most appropriate probability distribution for precipitation and temperature (mean, maximum, and minimum) for each of the 365 days of the year, random numbers are generated for a given number of simulation years (on the order of 1,000 years). In this way, random time series of climatic data

are produced for each station within Costa Rican territory. Subsequently, in order to incorporate the correlation between precipitation and temperature values over successive time periods, the autocorrelation matrix is computed for each of the generated random series. Temporal autocorrelation indicates the correlation of a variable with its past and future values (Wilks, 2006).

In addition, the effects of spatial correlation are included, representing the occurrence of simultaneous values at multiple stations within the study area, by using the spatial autocorrelation matrix among values from the different recording stations. In this way, unrealistic abrupt changes in precipitation, temperature, and other variables are avoided.

One of the advantages of the stochastic climate time series generation methodology is the ability to obtain extreme outlier values, which refer to precipitation amounts exceeding the historical maximum records and temperature values falling outside the mean range observed at the stations. This implies that the modeled series include precipitation and temperature values that have not been observed historically, but that may nonetheless occur in the future, even if with low probability.

Consequently, climatic variability is implicitly incorporated into the generation of these synthetic series, as they are correlated with their past and future values (temporal correlation) and with other stations within the study area (spatial correlation). Figure 36 presents a flowchart of the stochastic generation process for meteorological time series, specifically for precipitation and temperature.

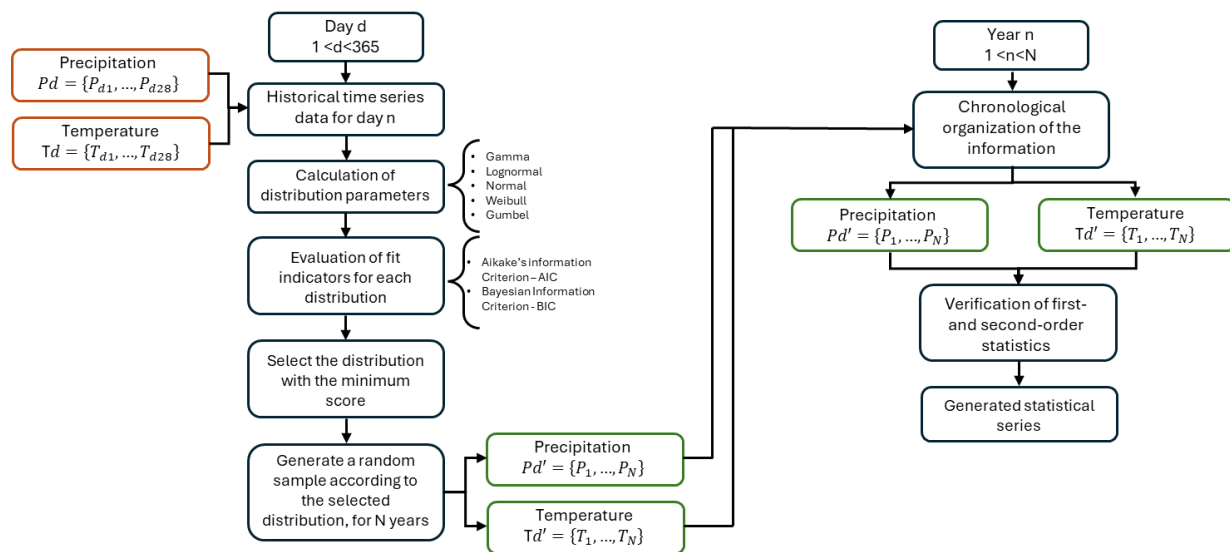


Figure 36. Flowchart of the synthetic time series generation process.

The base climate simulations constitute an extensive dataset that cannot be fully illustrated in this report. The complete set of simulations is available in the project dataset. Nevertheless, to illustrate the results, simulations obtained at four arbitrarily selected locations are presented below. For each location, the daily series of precipitation and mean temperature are shown. In addition, maps of precipitation and temperature are included for an arbitrarily selected day within the same simulation. This illustrates the results in their full dimension, since the simulations provide both temporal and spatial distributions of the meteorological variables. Figure 37 through Figure 40 present these illustrations.

Figure 41 through Figure 44 show the comparison between the multi-annual mean values of accumulated annual precipitation and mean air temperature, for both historical data and simulations. This comparison serves to illustrate the agreement between historical values and the generated simulations. On this basis, it can be stated that the simulations are indeed representative of the base climate and can be used as meteorological forcing for hazard modeling.

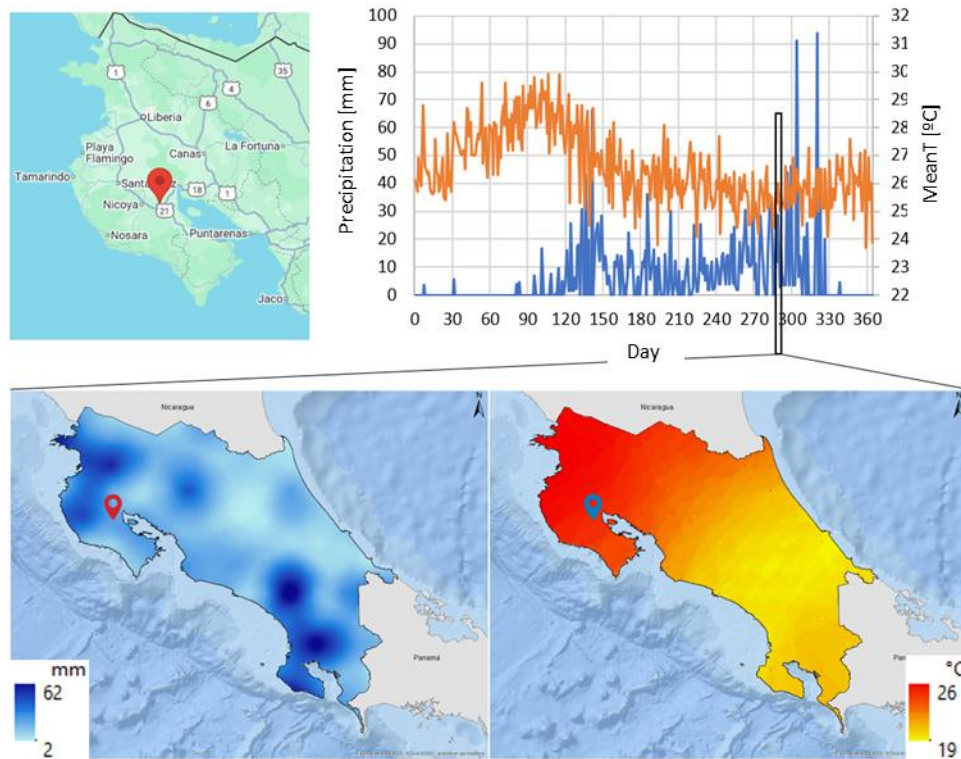


Figure 37. Simulation 737 at point P52. Annual (top), day 288 (bottom)

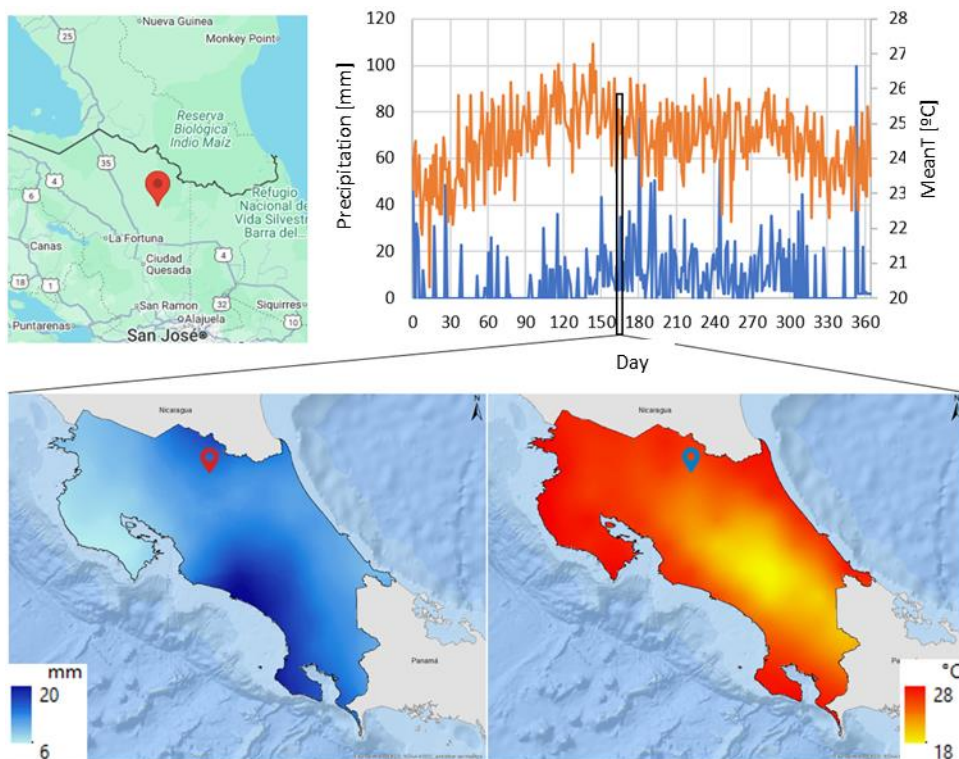


Figure 38. Simulation 222 at point P35. Annual (top), day 163(bottom)

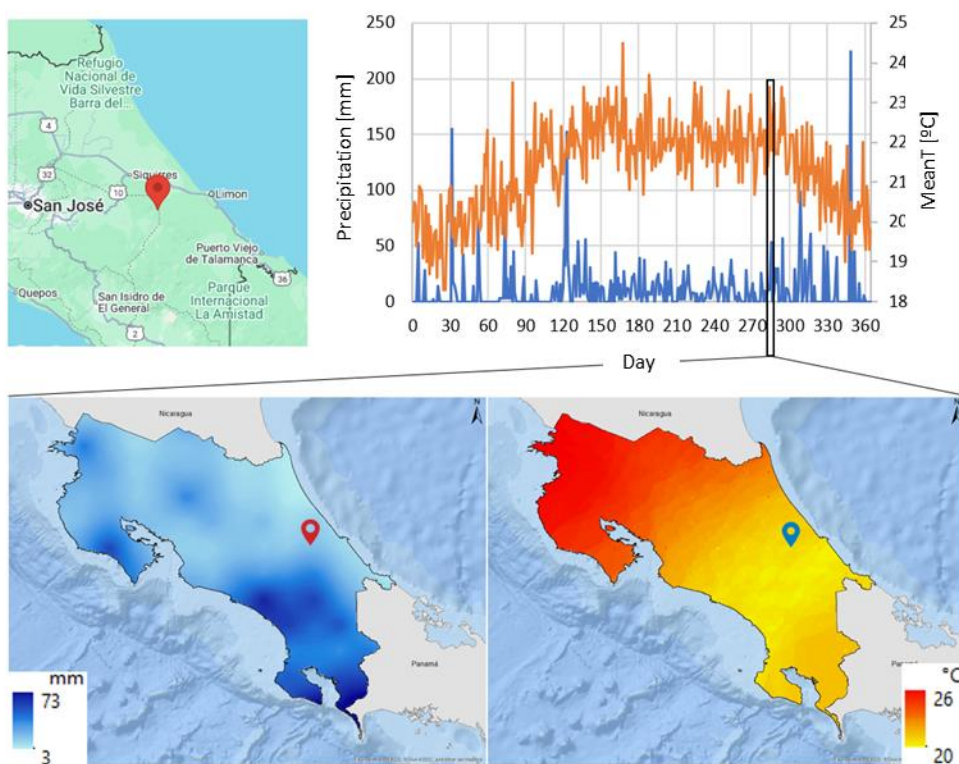


Figure 39. Simulation 286 at point P70. Annual (top), day 285 (bottom)

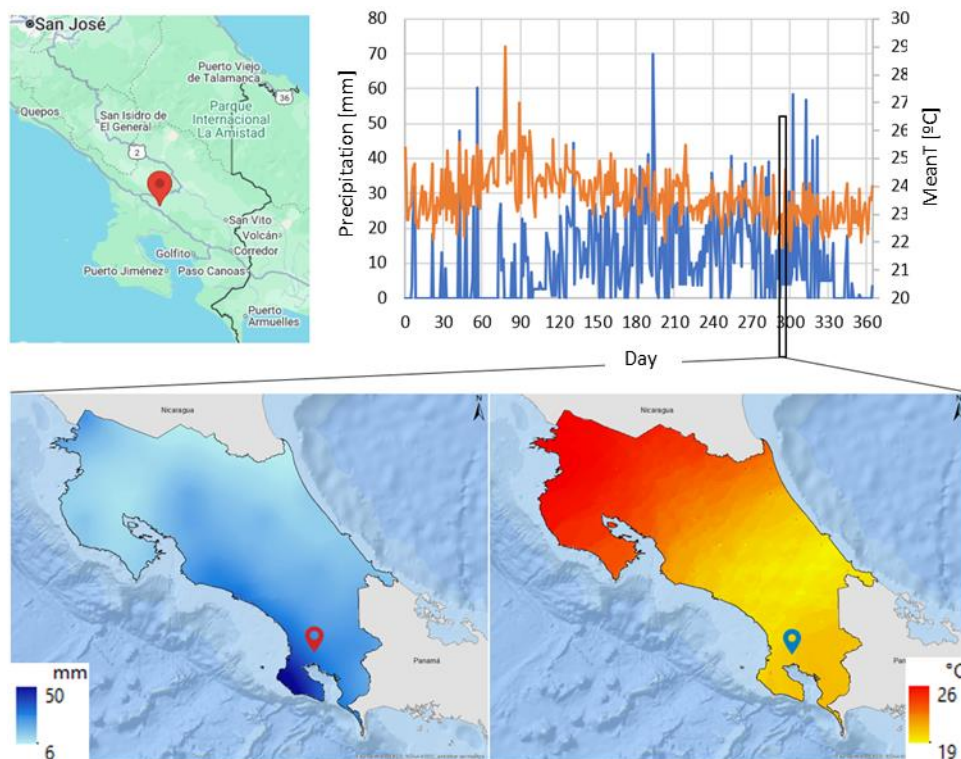
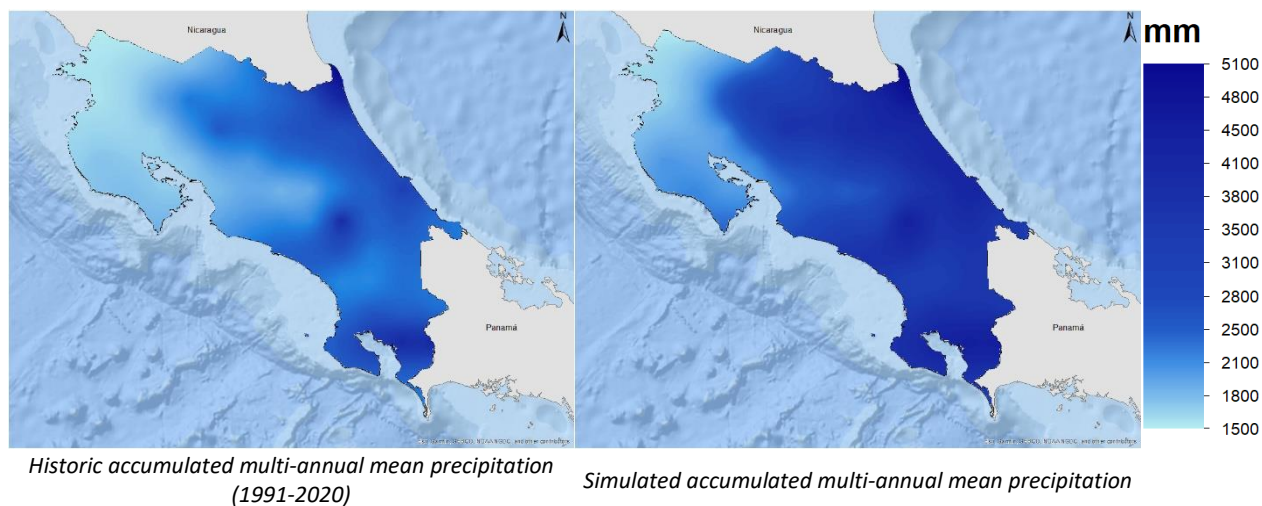
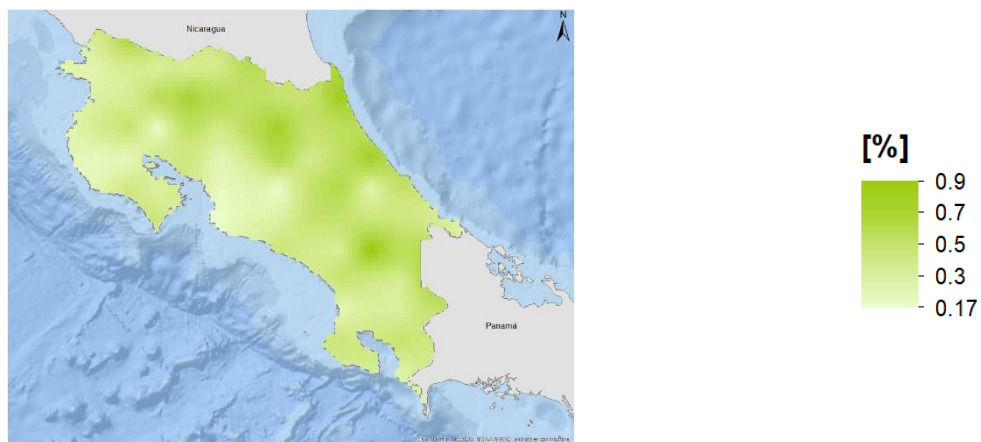


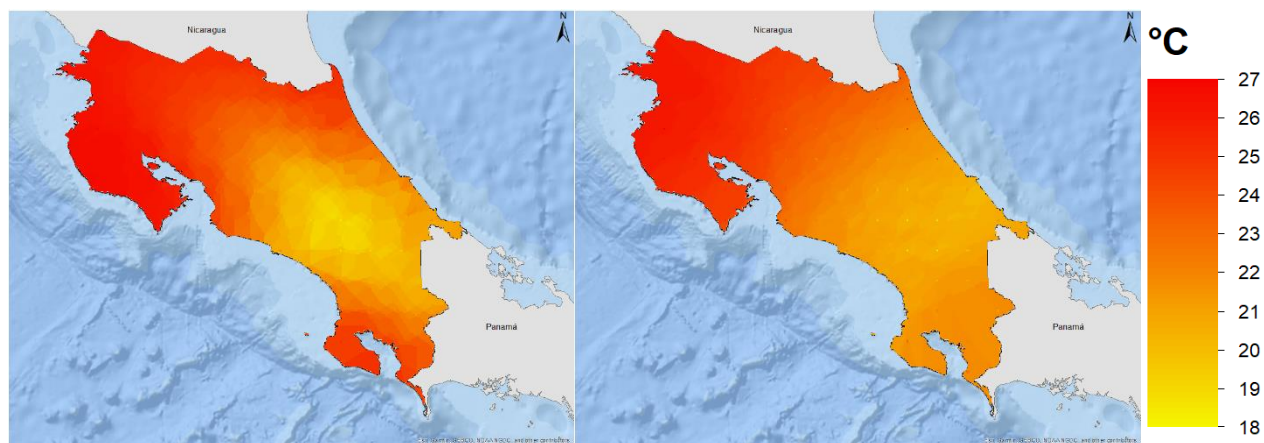
Figure 40. Simulation 15 at point P96. Annual (top), day 291 (bottom)





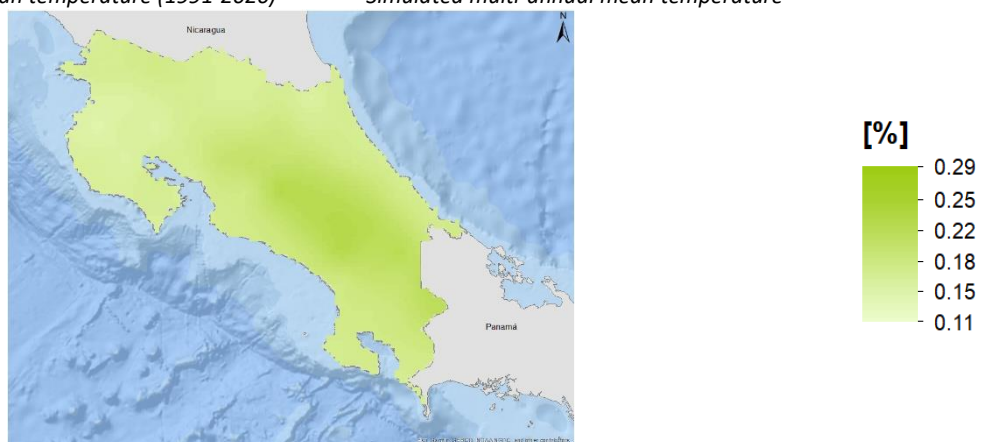
Percentage difference between simulated and historical data

Figure 41. Comparison of multi-annual means of mean precipitation between historical data and simulations



Historical multi-annual mean temperature (1991-2020)

Simulated multi-annual mean temperature



Percentage difference between simulated and historical data

Figure 42. Comparison of multi-annual means of mean temperature between historical data and simulations.

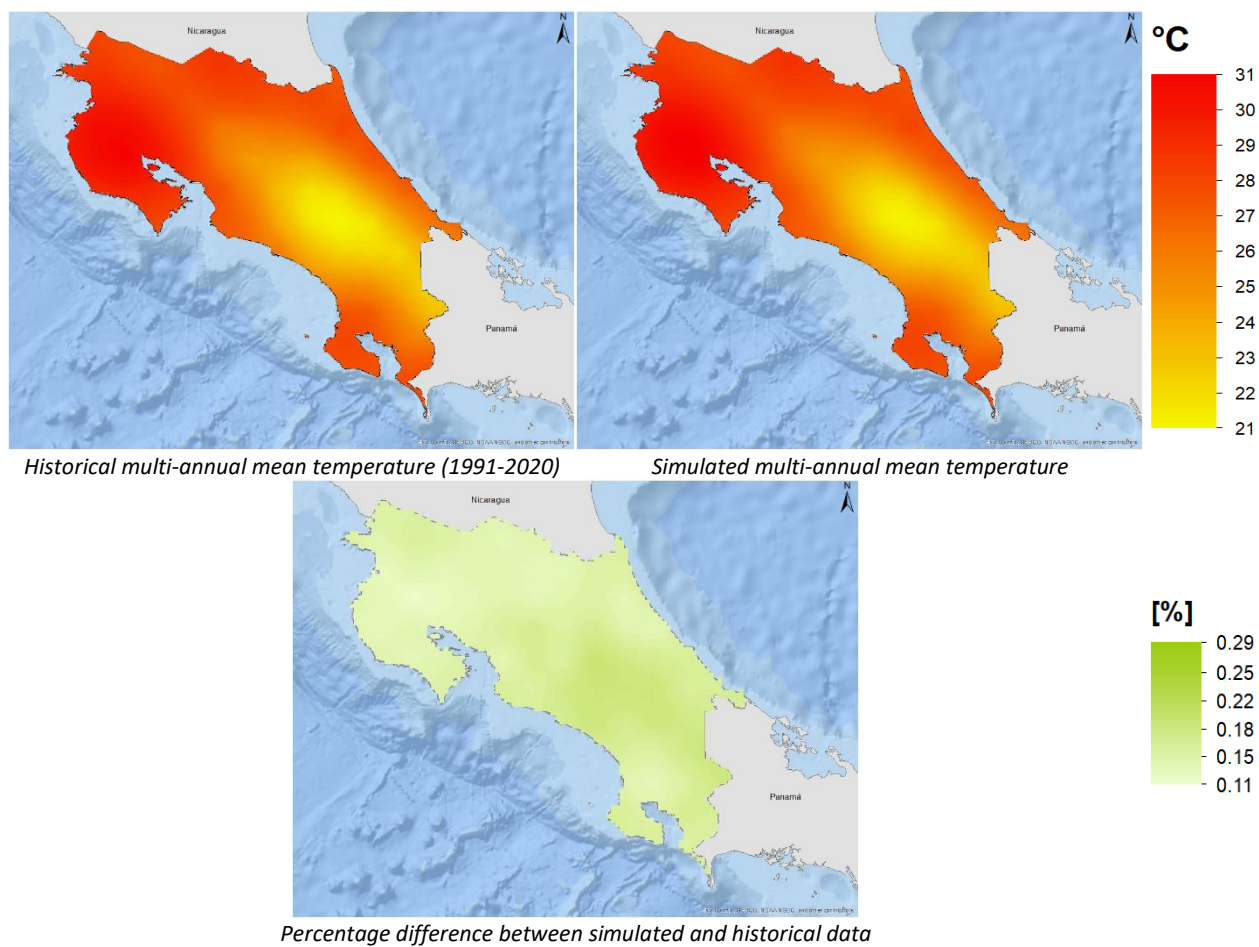
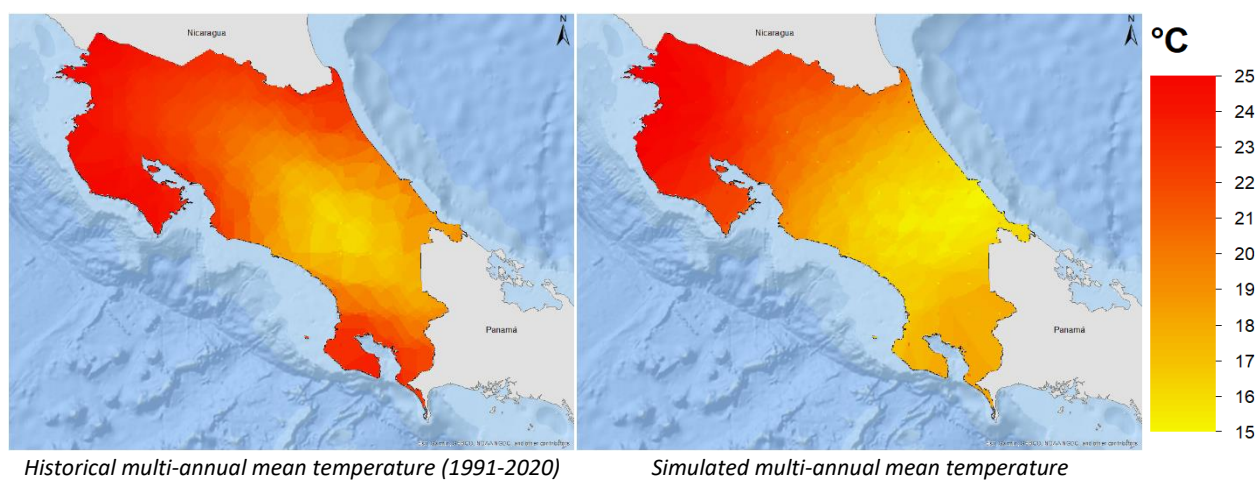
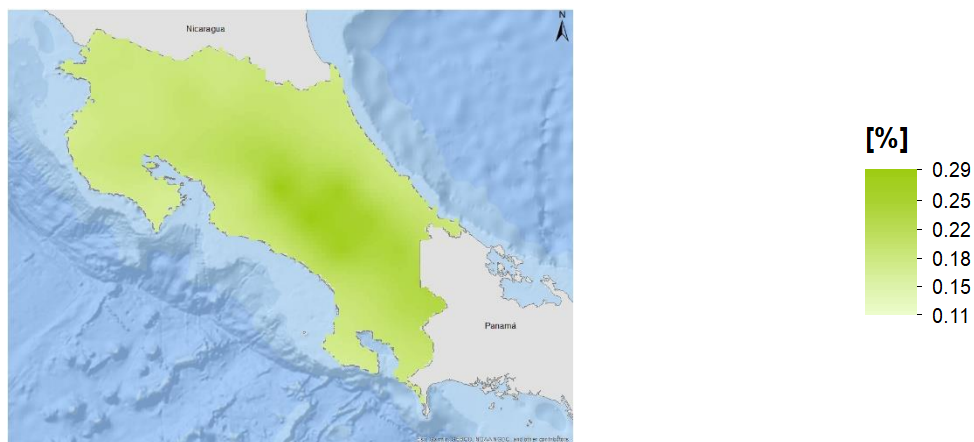


Figure 43. Comparison of multi-annual means of maximum temperature between historical data and simulations.





Percentage difference between simulated and historical data

Figure 44. Comparison of multi-annual means of minimum temperature between historical data and simulations.

2.5 Incorporation of Climate Change

Climate change is incorporated using the delta method, by applying the projected variations from Global Circulation Models (GCMs) directly to the base climate simulations. This constitutes a statistical downscaling method that enables the simulation of projected future climatological changes at the meteorological scale, while preserving the variability inherent to the historical control period.

The incorporation of climate change into the simulated time series constitutes a statistical downscaling procedure, based on the stochastic generation of meteorological series described above. In this approach, the temporal variability and variance inherent to the meteorological variables are assumed to be sufficiently well defined by the historical climate, and therefore only the mean values of the simulated series are modified in order to incorporate the changes projected by atmospheric Global Circulation Models (GCMs).

To incorporate climate change into the generation of climatic series, projections from selected GCMs available in CMIP6 (Coupled Model Intercomparison Project Phase 6) are analyzed under four emission scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

For this study, three GCMs included in CMIP6 are employed: EC-Earth3, GFDL-ESM4, and MPI-ESM1-2-LR. These models were selected based on recommendations from previous studies for Costa Rica (Rojas-Soto et al., 2022; Rojas-Soto et al., 2024), where the authors identified them as the most representative for the country according to criteria of performance, regional climate representativeness, and diversity of responses under high-emission forcing scenarios (SSP5-8.5).

In terms of performance, the ensemble reasonably reproduces the annual cycle and the distribution of temperature and precipitation across Central America, with moderate biases and a coherent projected signal among models. According to comparative CMIP6 performance analyses (Almazroui et al., 2021), after evaluating each GCM's ability to simulate mean, maximum, and minimum temperatures, as well as spatial and temporal precipitation patterns, it can be concluded that these three models produce results consistent with historical observations, with low deviation.

The three models have been previously used for hydroclimatic hazard modeling in Costa Rica (see Rojas-Soto et al., 2022; Rojas-Soto et al., 2024). As explained earlier, the downscaling procedure applied in this consultancy consists of modifying the climatic time series according to the changes projected by the selected GCM circulation models. This approach allows the generation of meteorological-scale time series that are consistent with the projected climate for the future periods of interest.

The result of the downscaling process is therefore a set of time series at a daily temporal resolution, spatially located at the points corresponding to the meteorological model data (see Figure 9), that is, with a spatial resolution of 0.25 degrees (approximately 30 km). Since the simulated series are adjusted based on projected changes, it is not necessary—within the framework proposed here—to apply bias correction to the selected GCMs.

GFDL-ESM4, developed by the NOAA Geophysical Fluid Dynamics Laboratory, is a state-of-the-art coupled atmosphere–ocean–biosphere system with improvements in cloud physics, ocean dynamics, and biogeochemistry. Its CMIP6 configuration has demonstrated strong capability in representing tropical variability and hydrological extremes, making it particularly useful for exploring high-impact scenarios (Dunne et al., 2020).

EC-Earth3, developed by a European consortium, incorporates improvements in atmosphere–ocean coupling and in the representation of aerosols and clouds. It typically provides intermediate and consistent responses for hydrometeorological variables, making it a useful “pivot” within the ensemble (Döscher et al., 2022).

MPI-ESM1-2-LR, from the Max Planck Institute for Meteorology, is characterized by stable atmosphere–ocean coupling and recent developments in cloud microphysics and ocean mixing. Its projections tend to be more moderate, providing the “low” end of the plausible range and helping to balance the ensemble (Mauritsen et al., 2019).

This combination of models—one typically high-impact (GFDL-ESM4), one intermediate (EC-Earth3), and one more conservative (MPI-ESM1-2-LR)—provides both physical and statistical diversity, thereby reducing the bias of relying on a single cloud or circulation scheme and enhancing the robustness of the results (Dunne et al., 2020; Döscher et al., 2022; Mauritsen et al., 2019).

As mentioned, the forcing trajectories considered correspond to the illustrative scenarios of CMIP6 based on the Shared Socioeconomic Pathways (SSPs): SSP1-2.6 (rapid mitigation with low forcing), SSP2-4.5 (intermediate), SSP3-7.0 (high, with major obstacles to sustainable development), and SSP5-8.5 (very high, fossil-fuel dependent). These scenarios combine socioeconomic narratives with consistent concentration and radiative forcing pathways and constitute the standard framework for comparing the sensitivity of future climate to different emission trajectories (Riahi et al., 2017; Meinshausen et al., 2020; O’Neill et al., 2016). Using the same set of SSPs across all models facilitates direct comparison of responses.

For the time horizons, three reference years were adopted: 2035, 2050, and 2100, representing near-term, mid-century, and end-of-century periods, respectively. This selection follows the practice of the IPCC AR6, which evaluates changes in the windows 2021–2040 (near term), 2041–2060 (mid-term), and 2081–2100 (end of century). Working with these milestones allows the articulation of results with decision-making scales relevant to Costa Rica: infrastructure planning and water management by 2035, sectoral

investments and land-use planning by 2050, and long-term policies and ecosystem resilience by 2100 (IPCC, 2021, Ch. 4; SPM).

In summary, the combined use of GFDL-ESM4, EC-Earth3, and MPI-ESM1-2-LR under the trajectories SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, and evaluated for 2035, 2050, and 2100, provides a balanced framework for estimating climate impacts in Costa Rica. This configuration integrates well-documented and validated models, sufficient physical diversity to encompass a range of hydroclimatic responses, and IPCC-standardized scenarios that allow linking results to public policy and risk management decisions.

The combination of the three models, emission trajectories, and target years, in addition to the base climate, results in 37 distinct climate scenarios. These scenarios are fundamental for estimating the hazards and risks associated with climate change within the context of this consultancy. Table 14 summarizes the scenarios considered, providing a comprehensive overview of the potential climatic variations for Costa Rica.

The climates presented in Table 14 are applicable to the modeling of floods and droughts, but not to the modeling of tropical cyclones. This is because the GCMs that allow the simulation of tropical cyclone tracks are not necessarily the same as those selected here. Therefore, different definitions of future climate are employed for tropical cyclone modeling, as described in greater detail in Section 5.1.2.

Table 14. Future climates considered in this consultancy

GCM	Pathway	Target year	GCM	Pathway	Target year
EC-Earth3	SSP1-2.6	2035	GFDL-ESM4	SSP3-7.0	2050
EC-Earth3	SSP2-4.5	2035	GFDL-ESM4	SSP5-8.5	2050
EC-Earth3	SSP3-7.0	2035	GFDL-ESM4	SSP1-2.6	2100
EC-Earth3	SSP5-8.5	2035	GFDL-ESM4	SSP2-4.5	2100
EC-Earth3	SSP1-2.6	2050	GFDL-ESM4	SSP3-7.0	2100
EC-Earth3	SSP2-4.5	2050	GFDL-ESM4	SSP5-8.5	2100
EC-Earth3	SSP3-7.0	2050	MPI-ESM1-2-LR	SSP1-2.6	2035
EC-Earth3	SSP5-8.5	2050	MPI-ESM1-2-LR	SSP2-4.5	2035
EC-Earth3	SSP1-2.6	2100	MPI-ESM1-2-LR	SSP3-7.0	2035
EC-Earth3	SSP2-4.5	2100	MPI-ESM1-2-LR	SSP5-8.5	2035
EC-Earth3	SSP3-7.0	2100	MPI-ESM1-2-LR	SSP1-2.6	2050
EC-Earth3	SSP5-8.5	2100	MPI-ESM1-2-LR	SSP2-4.5	2050
GFDL-ESM4	SSP1-2.6	2035	MPI-ESM1-2-LR	SSP3-7.0	2050
GFDL-ESM4	SSP2-4.5	2035	MPI-ESM1-2-LR	SSP5-8.5	2050
GFDL-ESM4	SSP3-7.0	2035	MPI-ESM1-2-LR	SSP1-2.6	2100
GFDL-ESM4	SSP5-8.5	2035	MPI-ESM1-2-LR	SSP2-4.5	2100
GFDL-ESM4	SSP1-2.6	2050	MPI-ESM1-2-LR	SSP3-7.0	2100
GFDL-ESM4	SSP2-4.5	2050	MPI-ESM1-2-LR	SSP5-8.5	2100

An example of the projected changes for the target year 2035 is presented below, corresponding to the SSP1 emission pathway and one of the selected GCM models, for both precipitation and temperature. Projected change maps for all other climates are presented in Annex A.2.

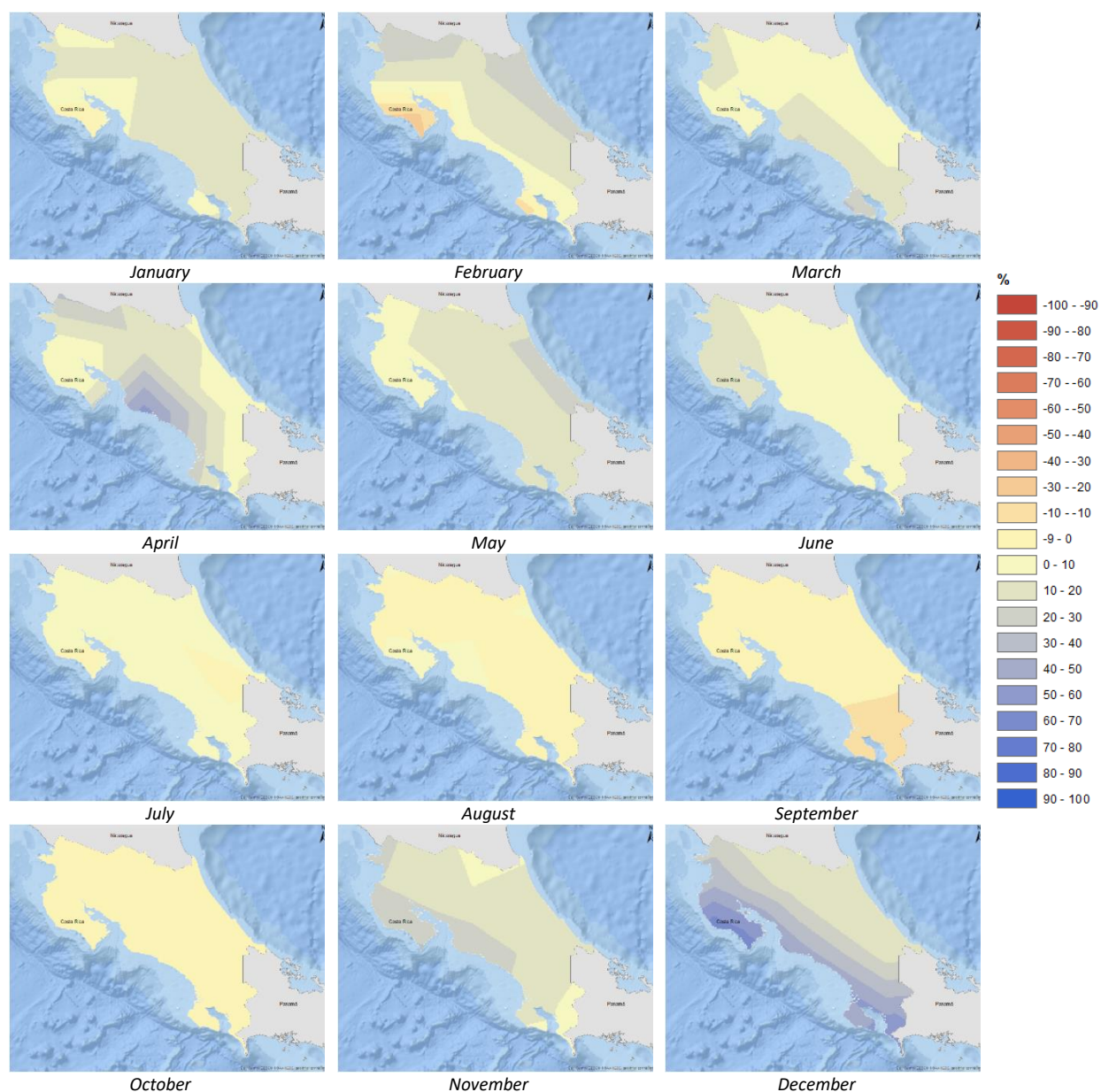


Figure 45. Percentage change in precipitation – Model: GFDL-ESM4, SSP1-2.6, Future year 2035

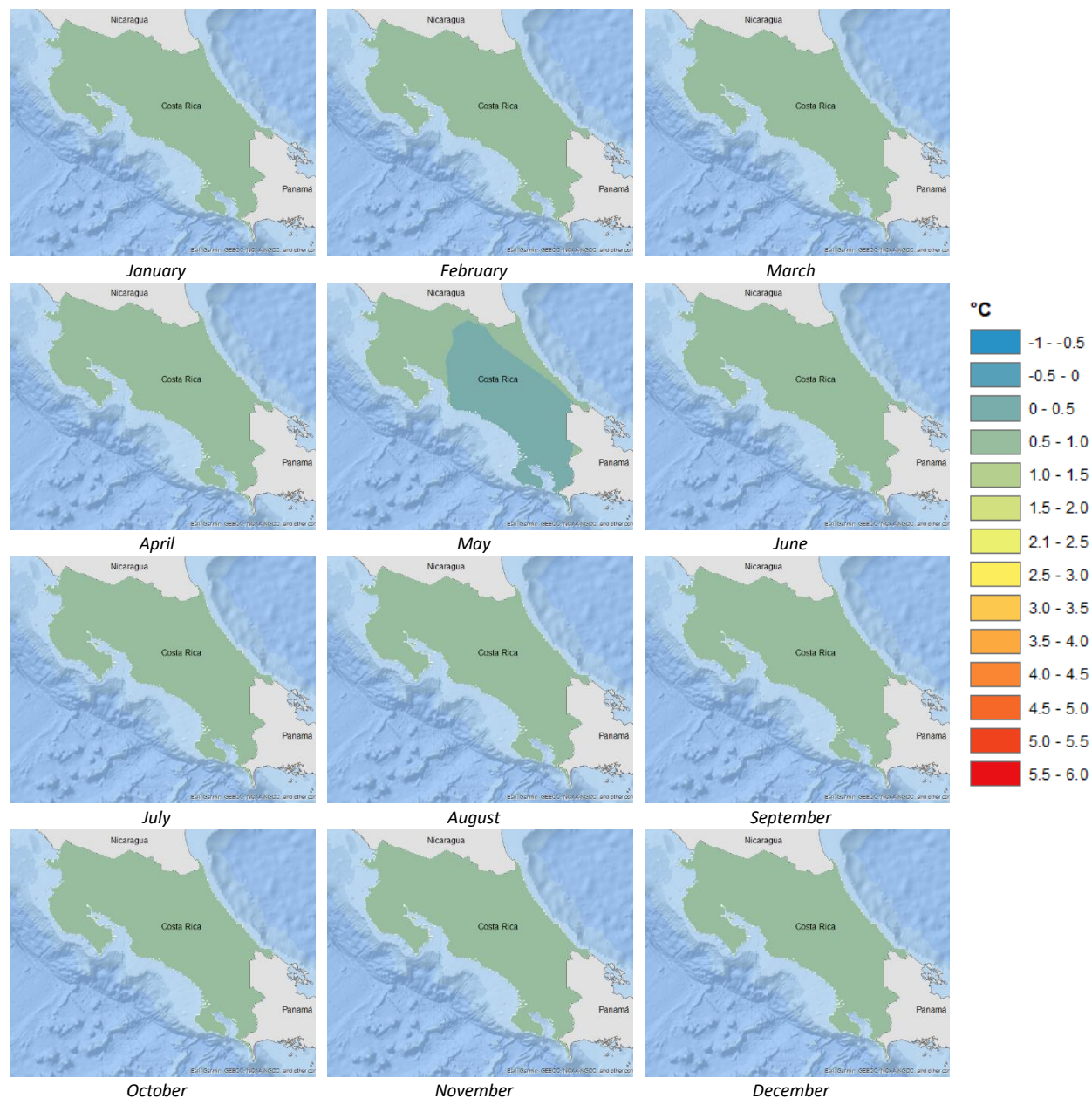


Figure 46. Temperature change (°C) – Model: GFDL-ESM4, SSP1-2.6, Future year 2035

2.6 Climate Behavior at a Specific Location under Future Scenarios

In addition to the spatially presented projected changes, it is useful to illustrate how climate projections manifest at a specific point in the territory. For this purpose, a reference station was selected (P57), where changes in precipitation and temperature simulated by the ensemble of selected GCMs were evaluated, under the emission pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) and for the target years (2035, 2050, and 2100).

This point-based exercise allows for a clearer view of the dispersion among models, as well as the magnitude of variations compared to the base climate. Figure 48 and Figure 49 summarize the results for the selected station, serving as a representative example of how future conditions may vary locally depending on the model and the emission scenario considered.

The graphs display precipitation and temperature values for an arbitrarily selected day, from one of the simulations, at an arbitrarily chosen location.



Figure 47. P57 station location.

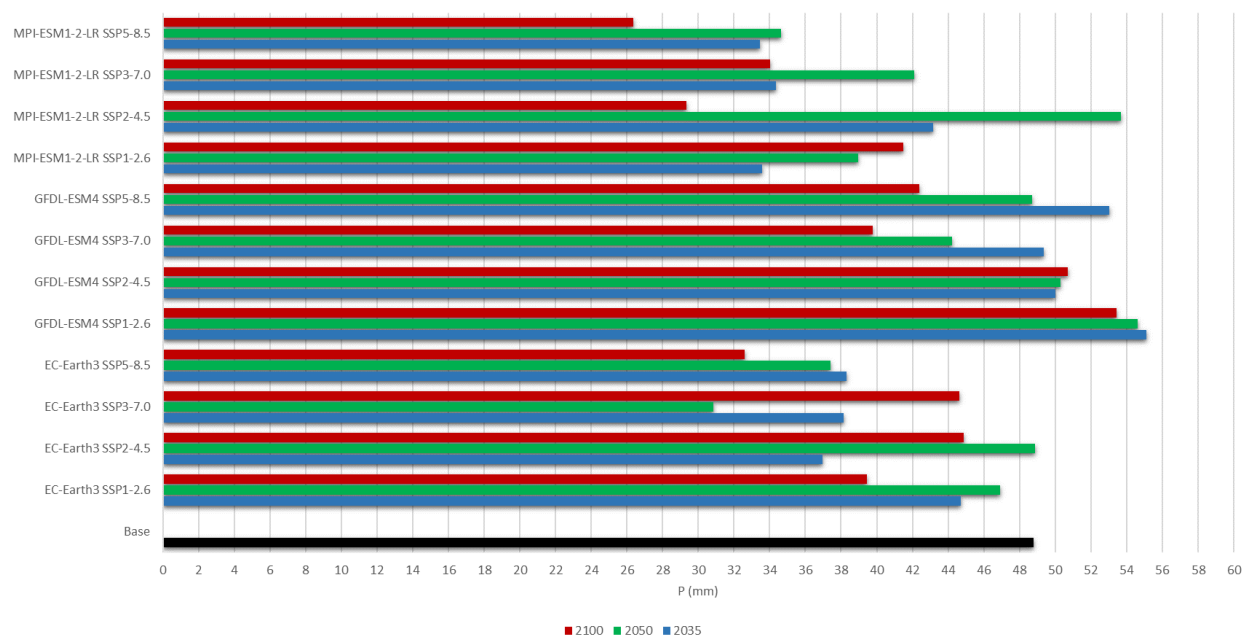


Figure 48. Precipitation at Point P57 of the virtual station grid for day 5 of simulation 1, Modified under each future climate considered

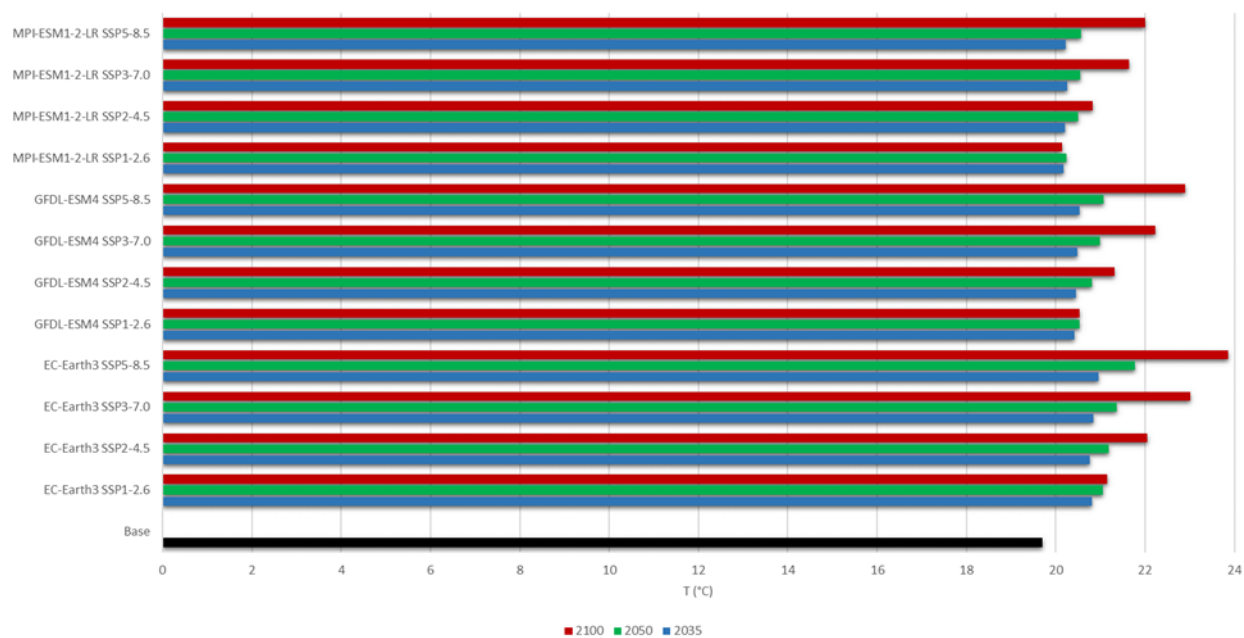


Figure 49. Temperature at point P57 of the virtual station grid for day 1 of simulation 1, modified under each future climate considered.

3 DROUGHT HAZARD

Drought is one of the most complex and recurrent climate phenomena, characterized by the temporary reduction in water availability within a given territory, whether due to precipitation deficits, excessive evapotranspiration, or a combination of both factors. Unlike other hydrometeorological events such as floods or storms, drought does not manifest abruptly or immediately; instead, it develops progressively, with impacts accumulating over time. These impacts affect agriculture, potable water supply, hydroelectric generation, and ecosystems.

3.1 Drought Indices Considered

Given the difficulty of defining and quantifying drought with a single parameter, several drought indices have been developed. These are statistical tools designed to synthesize climatic information and transform it into comparable values that make it possible to identify, monitor, and evaluate the intensity, duration, and spatial extent of such events. These indices are primarily based on variables such as precipitation and evapotranspiration, and they mainly allow the characterization of meteorological droughts, although some indices also provide limited insights into agricultural or hydrological droughts.

In this study, meteorological drought indices are employed, since the impact on productive systems, — that is, whether or not an agricultural drought occurs— requires an additional modeling step involving risk assessment.

The use of drought indices is fundamental for climate risk management and decision-making across multiple sectors. Due to their standardized nature, they enable comparisons across different temporal and geographic scales, as well as the evaluation of potential impacts under conditions of climate variability and climate change. Among the most widely used internationally are the Standardized Precipitation Index (SPI), which is based exclusively on precipitation anomalies, and the Standardized Precipitation-Evapotranspiration Index (SPEI), which also incorporates the effect of temperature on atmospheric water demand.

3.1.1 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) is one of the most widely used indicators worldwide for the evaluation and monitoring of meteorological drought. It was proposed by McKee et al. (1993) with the objective of providing a quantitative and comparable measure of precipitation deficits or surpluses across different temporal scales and climatic regions.

The SPI measures precipitation anomalies relative to the historical distribution at a given location. For its calculation, the accumulated precipitation series (monthly, quarterly, annual, etc.) is fitted to a probability distribution —generally the Gamma distribution— and subsequently transformed into a standard normal distribution. The result is an index with a mean of zero and a standard deviation of one, which makes it possible to determine whether a given period is wetter or drier than normal relative to the site's typical climatic conditions (JSCEDO, 2020).

Its main advantage lies in its temporal flexibility: it can be calculated at different timescales (e.g., 1, 3, 6, 12, or 24 months), which allows for the characterization of different types of droughts (McKee et al., 1993):

- Short timescales (1–3 months): the SPI reflects conditions affecting rainfed agriculture and the immediate availability of water for vegetation.
- Medium timescales (6–12 months): it represents the impact on water availability for rivers, reservoirs, and aquifers.
- Long timescales (24 months or more): it is associated with large-scale hydrological droughts.

In the SPI, positive values indicate wetter-than-normal conditions, while negative values indicate drier-than-normal conditions. In general, an SPI below -1 indicates moderate drought, below -1.5 severe drought, and below -2 extreme drought. Due to its standardization, the SPI is comparable across different regions and climates, which has led the World Meteorological Organization (WMO) to recommend it as a standard for drought monitoring.

3.1.2 Standardized Precipitation and Evapotranspiration Index (SPEI)

The Standardized Precipitation Evapotranspiration Index (SPEI) is an indicator designed to complement and expand upon the information provided by the SPI, by incorporating not only precipitation anomalies but also the effect of temperature and, consequently, atmospheric water demand. It was developed by Vicente-Serrano et al. (2010) in response to the need for an index sensitive to climate change conditions, in which rising global temperatures intensify evapotranspiration processes and thereby alter the hydrological balance.

The SPEI is based on the series of accumulated precipitation minus potential evapotranspiration (ET_o). This difference ($P - ET_o$) represents the climatic balance between water supply and demand. Subsequently, as in the SPI, the resulting series is fitted to a probability distribution (log-logistic) and standardized to produce an index that is comparable over time and across regions (Vicente-Serrano et al., 2010).

The main strength of the SPEI is that it makes it possible to evaluate not only meteorological droughts (precipitation deficits) but also agricultural and hydrological droughts associated with increased evapotranspiration due to higher temperatures. This makes it particularly useful in the context of global warming, where soil moisture reduction and crop water stress can occur even under near-normal precipitation conditions, as a result of higher evaporation (Vicente-Serrano et al., 2010).

As with the SPI, the SPEI can be calculated at multiple temporal scales, making it a versatile tool for different sectors. Its values are interpreted in a similar way: negative values indicate water deficit and drought, while positive values reflect wet conditions. For example, an SPEI below -1 indicates moderate drought, below -1.5 severe drought, and below -2 extreme drought.

3.2 Time Series of Drought Indicators

Drought indicator time series must be evaluated using moving temporal windows that span the entire length of the simulated series. These windows are typically defined in months. It is common to use 3-, 6-, or 12-month windows to characterize the variables whose statistics yield a given value of the selected drought indicator. Figure 50 presents the time series of SPI-12 (top) and SPEI-12 (bottom), both calculated

from baseline climate data at a point within the grid of virtual stations, using 12-month moving temporal windows. Both indices exhibit a similar evolution, oscillating between wet conditions (positive values) and dry conditions (negative values). However, the SPEI shows a greater amplitude in extreme events, reaching values close to ± 4 , while the SPI rarely exceeds ± 3 . This reflects the influence of potential evapotranspiration in the SPEI calculation, which amplifies the drought signal under conditions of higher atmospheric water demand.

In general terms, the most intense droughts were concentrated in specific episodes within the series, while other periods were dominated by wet conditions, highlighting the pronounced climatic variability of the region.

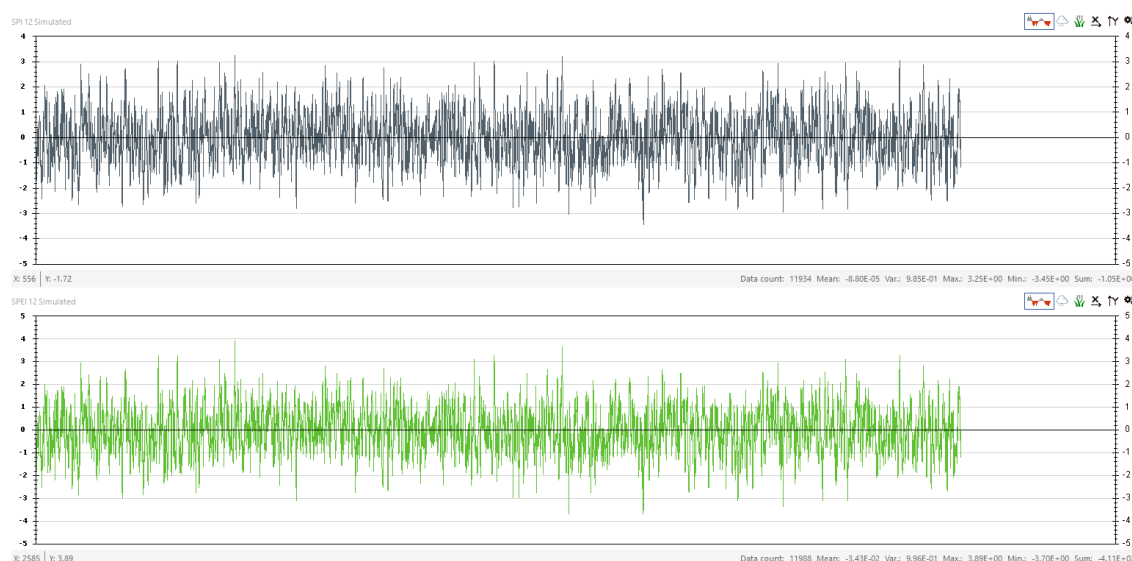


Figure 50. Standardized Precipitation Index (SPI) calculated at a 12-month scale (top), and Standardized Precipitation Evapotranspiration Index (SPEI) calculated at a 12-month scale (bottom) for an arbitrary location. Baseline climate. Extracted from the DroughtPro software.

Figure 51 shows the cumulative drought severity curves for the same indices: SPI-12 (top) and SPEI-12 (bottom). These curves represent the integration of the indicator time series, allowing visualization of the cumulative effect over time of the persistence (or absence) of wet or dry conditions. It is observed that, although both indices display similar patterns, the SPEI tends to reflect more pronounced and prolonged declines, highlighting greater drought severity when the effect of potential evapotranspiration is incorporated. This underscores the utility of SPEI compared to SPI for identifying drought conditions under climate change scenarios, where higher temperatures intensify the deficit of available soil moisture.



Figure 51. Cumulative severity curve for SPI-12 (top) and SPEI-12 (bottom) at an arbitrary location. Baseline climate. Source: DroughtPro software.

3.3 Identification of Drought Events

Meteorological drought indicators are widely used to identify drought events by detecting moisture conditions below the long-term average. These indicators can define both the duration and the severity of drought events. The start and end dates determine the period during which a drought indicator remains continuously below a predefined critical threshold (the lower the indicator value, the more intense the drought). The severity of a drought denotes the cumulative deficiency of a drought parameter below this threshold between the start and end dates. The relationship between severity and duration defines the drought intensity (Mishra & Singh, 2010). These concepts are schematically illustrated in Figure 52.

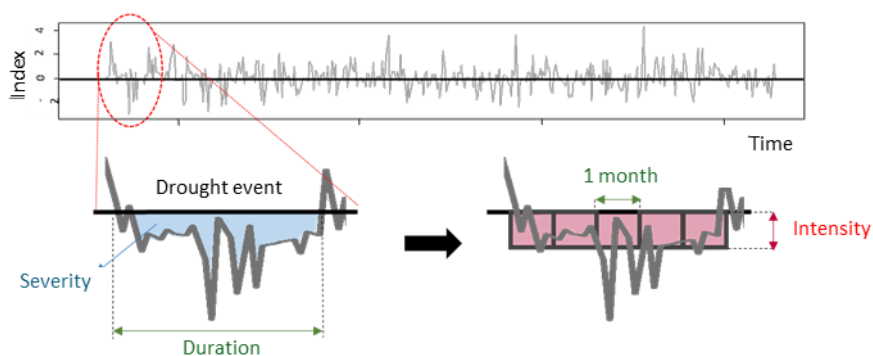


Figure 52. Schematic representation of drought indicators and the concepts of severity, duration, and intensity of events in the time series.

The detection of drought events within an indicator time series is a relatively straightforward process, consisting of identifying the points in time along the series where the index falls below a predefined threshold value. Standardized drought indicators, such as SPI and SPEI, can be compared with one another.

The drought events are characterized using these indicators can be classified according to the categories presented in Table 15.

Table 15. Drought classification according to the standardized indicators value

Drought type	Value of indicator
No drought	Greater than 0
Light	Between -1 and 0
Moderate	Between -1.5 and -1
Severe	Lower than -1.5
Extreme	Lower than -2

Figure 53 to Figure 56 show listings of drought events identified at arbitrarily selected points within the model for Costa Rica. Each event is characterized by a start and end date (corresponding to months in the series, since the indicator is always evaluated at a monthly scale), duration, and severity. Each image also includes a Severity–Duration diagram, which relates these two measures for all events identified in the series at each site. In all cases, the events were selected using a threshold of -2.

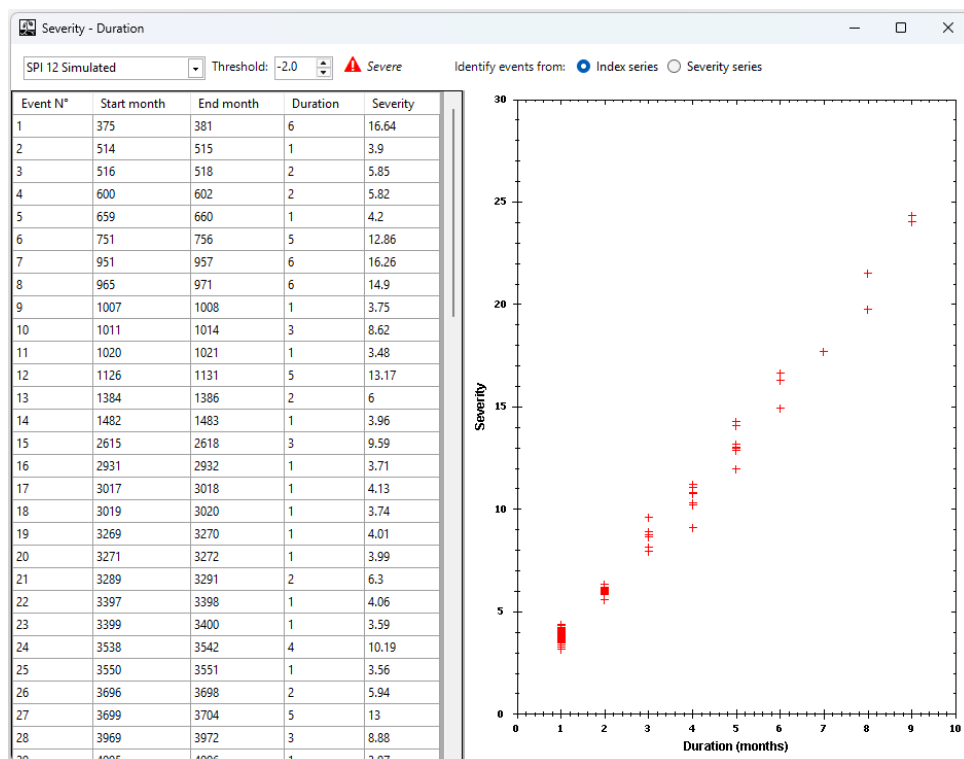


Figure 53. List of events and diagram Severity-Duration for droughts in point P70, for SPEI 12. Taken from DroughtPro software

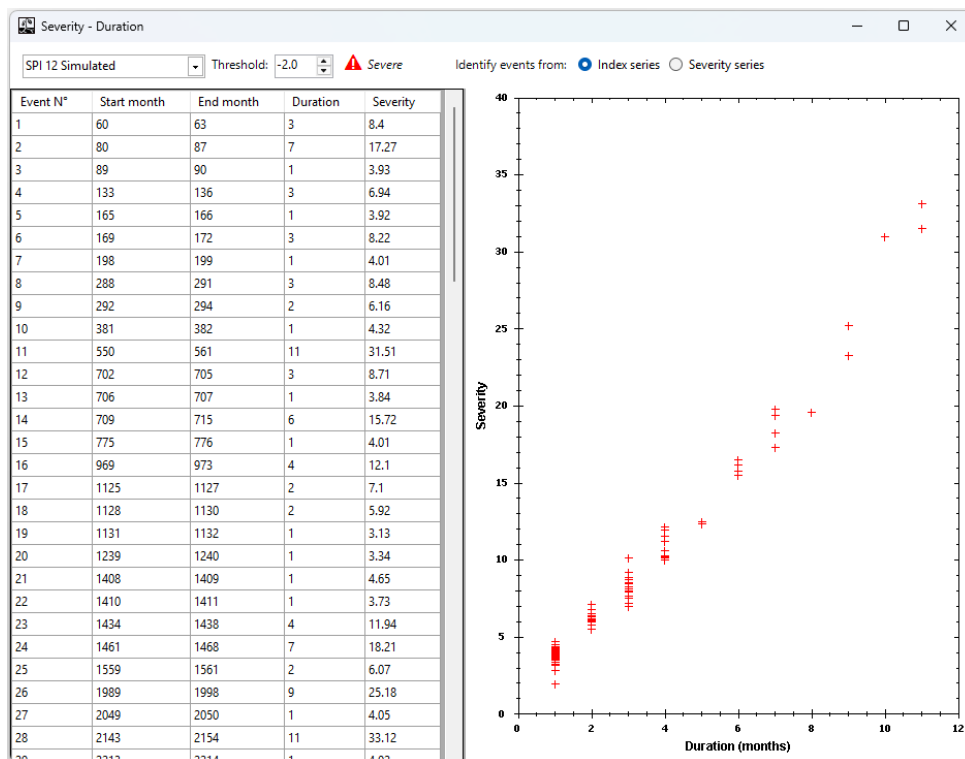


Figure 54. List of events and diagram Severity-Duration for droughts in point P96, for SPEI 12. Taken from DroughtPro software.

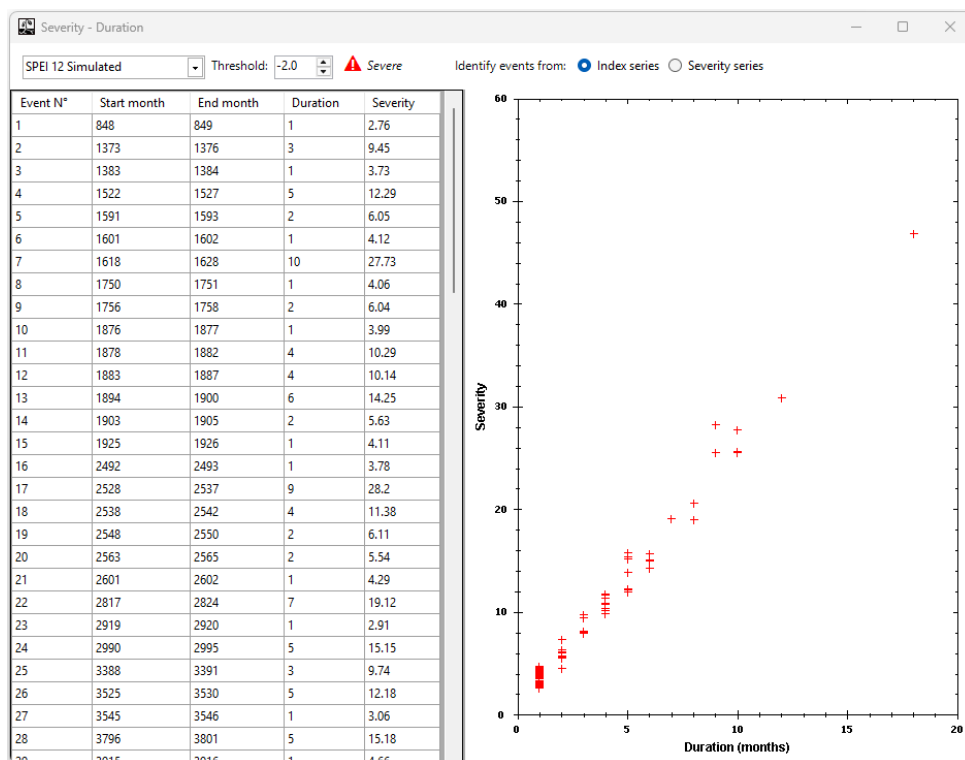


Figure 55. List of events and diagram Severity-Duration for droughts in point P52, for SPEI 12. Taken from DroughtPro software

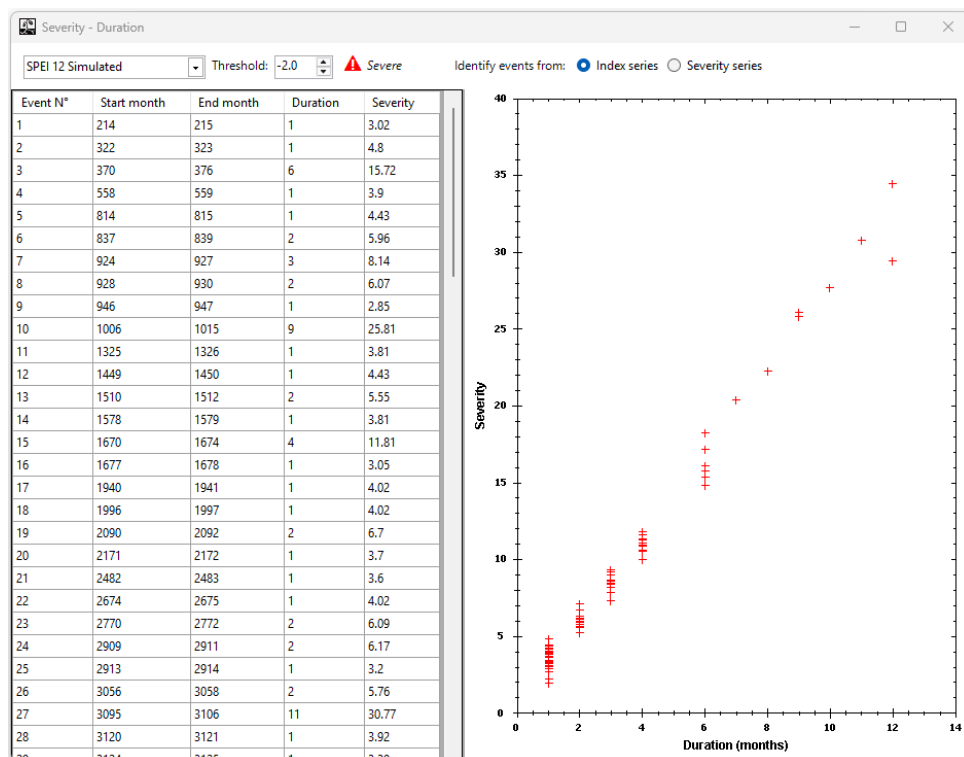


Figure 56. List of events and diagram Severity-Duration for droughts in point P35, for SPEI 12. Taken from DroughtPro software

The severity–duration series and diagrams presented correspond to a single location within the model. Evidently, the same information is available for all modeled locations, making it possible to visualize indicator values at specific points in time across the entire country.

The simulated series can be summarized into hazard curves and uniform hazard maps, which describe the exceedance rate of drought indicator values, under the assumption that the occurrence of these events over time follows a stochastic renewal process. The exceedance rate of an indicator’s value can be evaluated directly from the corresponding series, as shown below:

$$v(I) = \frac{N - 1}{t} \quad \text{Equation 1}$$

where $v(I)$ is the annual exceedance rate of an indicator with value I , N is the number of times the indicator value is exceeded, and t is the total length of the simulated series. The exceedance rate is the multiplicative inverse of the return period (i.e., $v(I) = 1/T_R$). Since indicator values are negative under drought conditions and positive under excess moisture, it is necessary to multiply the entire indicator series by -1 before applying Equation 1.

As an example, Figure 57 to Figure 60 present hazard curves, expressed as *return period versus indicator*, for four arbitrarily selected locations in Costa Rica. Likewise, Figure 61 and Figure 62 show uniform hazard maps for return periods of 2, 5, 10, 25, 50, 100, 250, 500, and 1,000 years, for SPI-12 and SPEI-12, respectively.

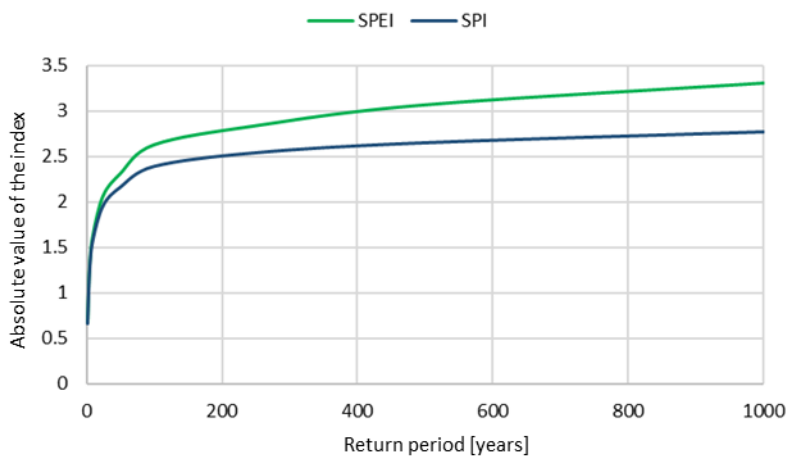


Figure 57. Hazard curves in point P70

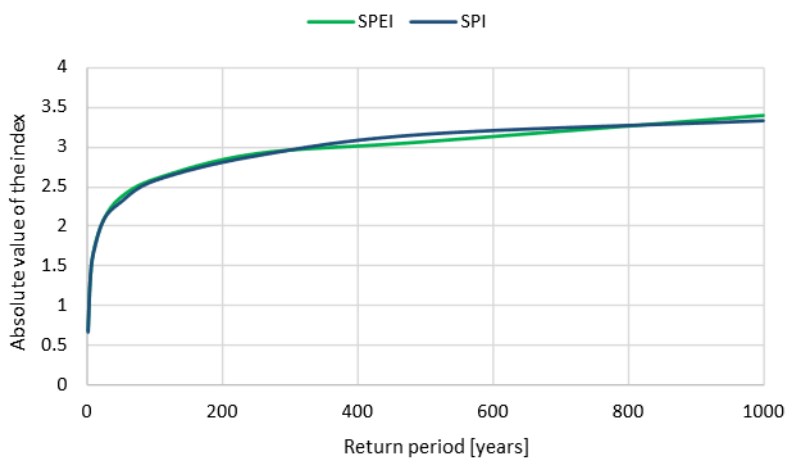


Figure 58. Hazard curves in point P96

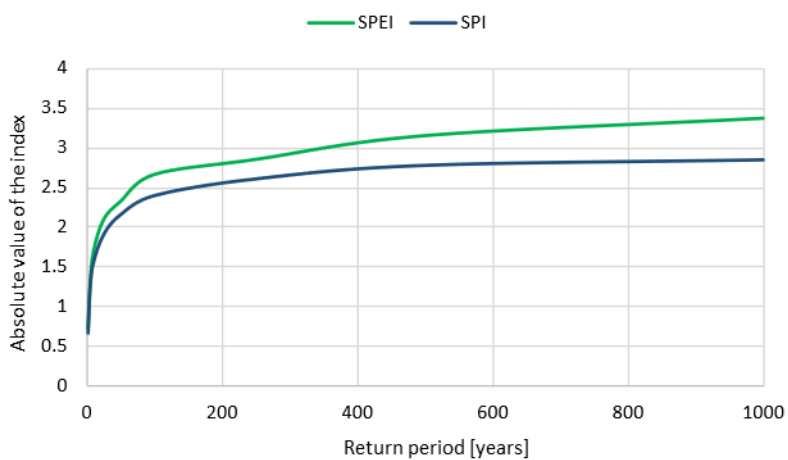


Figure 59. Hazard curves in point P52

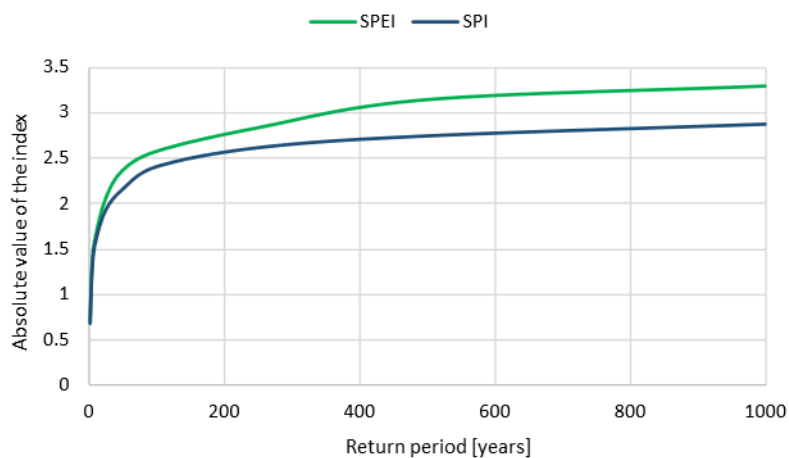


Figure 60. Hazard curves in point P35

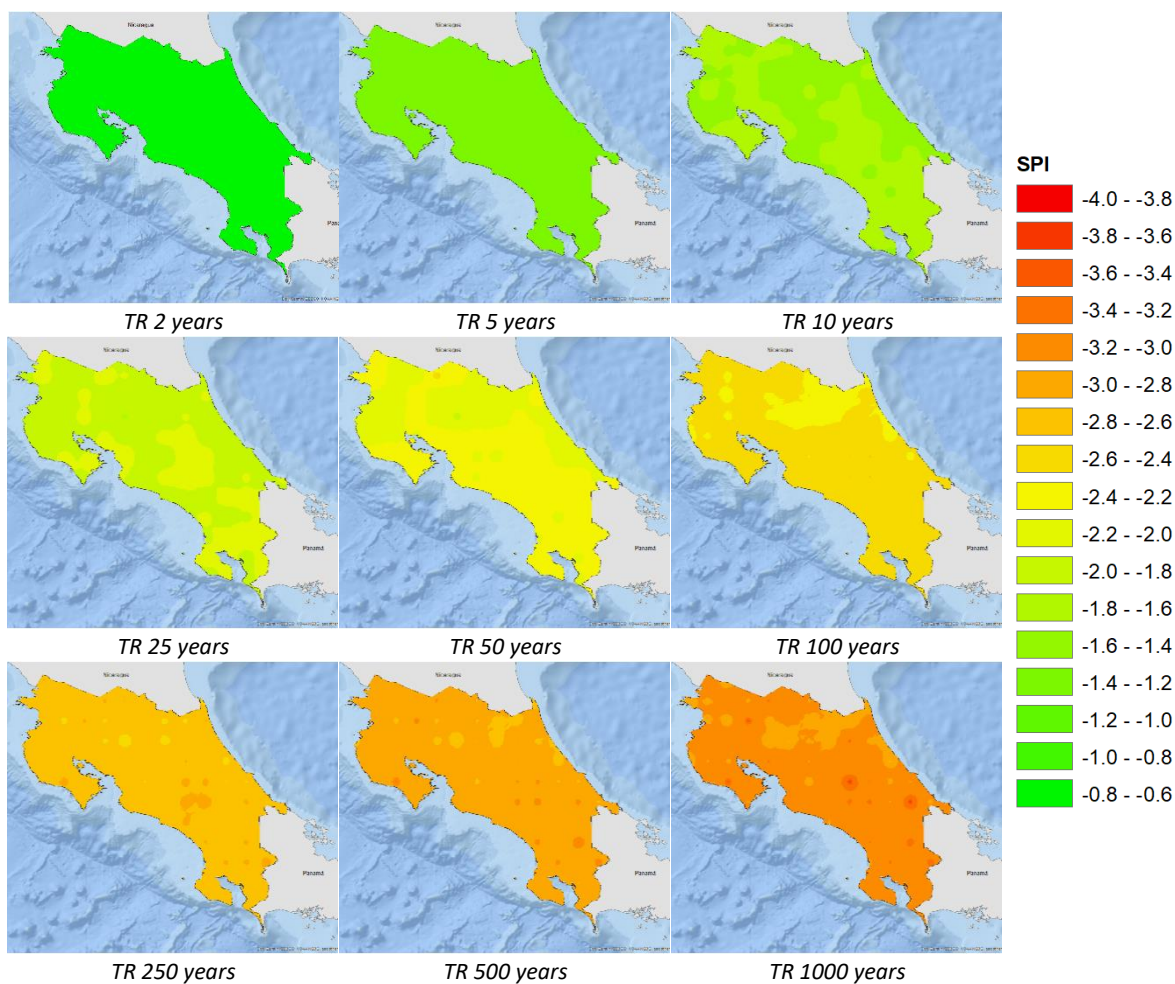


Figure 61. Uniform hazard maps for SPI-12. Baseline climate

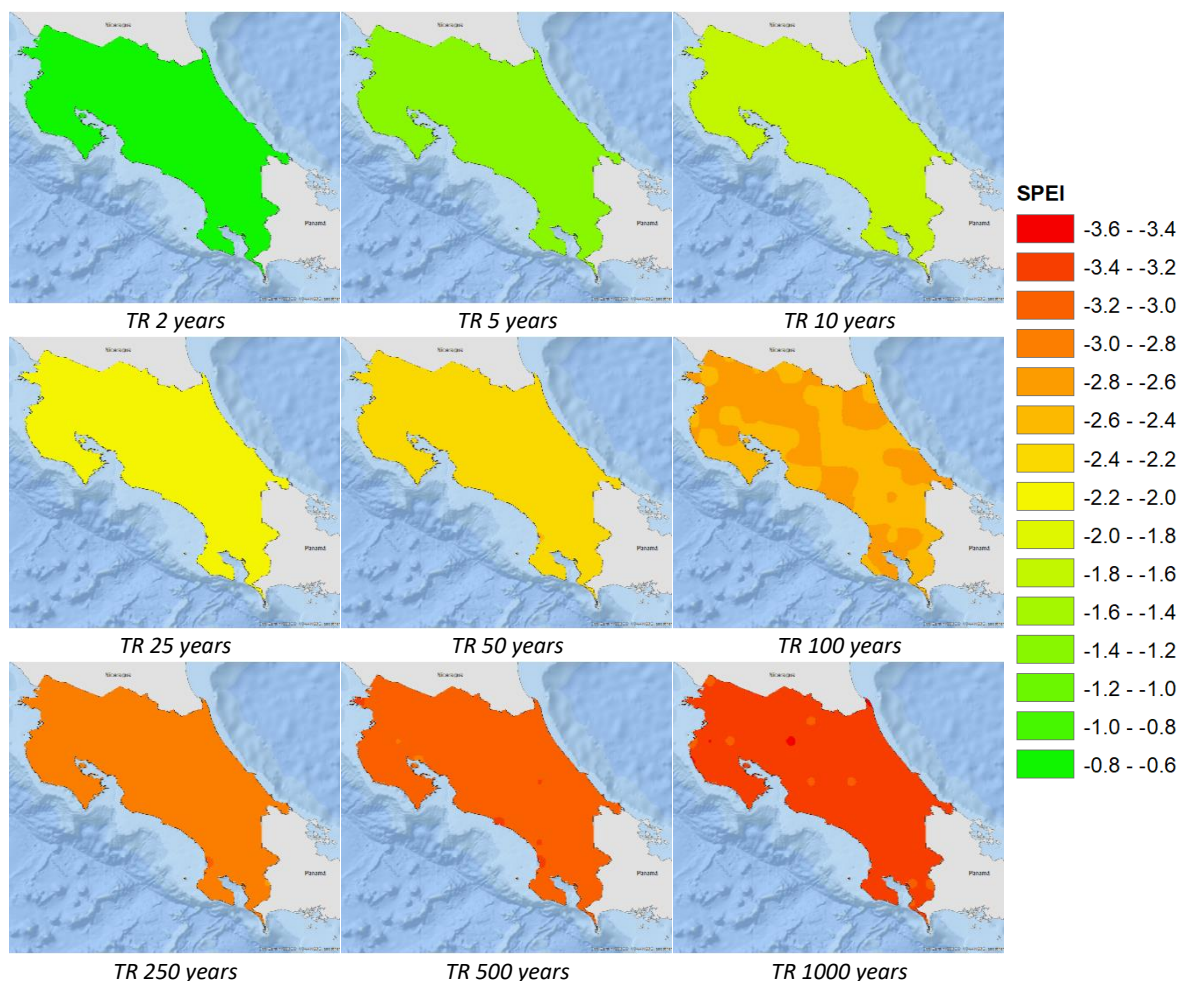


Figure 62. Uniform hazard maps for SPEI-12. Baseline climate.

The maps shown in Figure 61 and Figure 62 were calculated under baseline climate conditions. This means that equivalent results can also be obtained under future climate conditions. As part of this study, 36 different versions of future climate were defined, as summarized in Table 14, considering different GCMs, emission pathways, and future target years. The complete set of drought hazard results for all these climates is included in the project dataset. They are not presented in this report to avoid excessive length. However, for illustrative purposes, Figure 63 presents the uniform hazard maps for SPEI-12 in Costa Rica, considering the climate defined as: *EC-Earth3 model, SSP5-8.5 pathway, year 2050*.

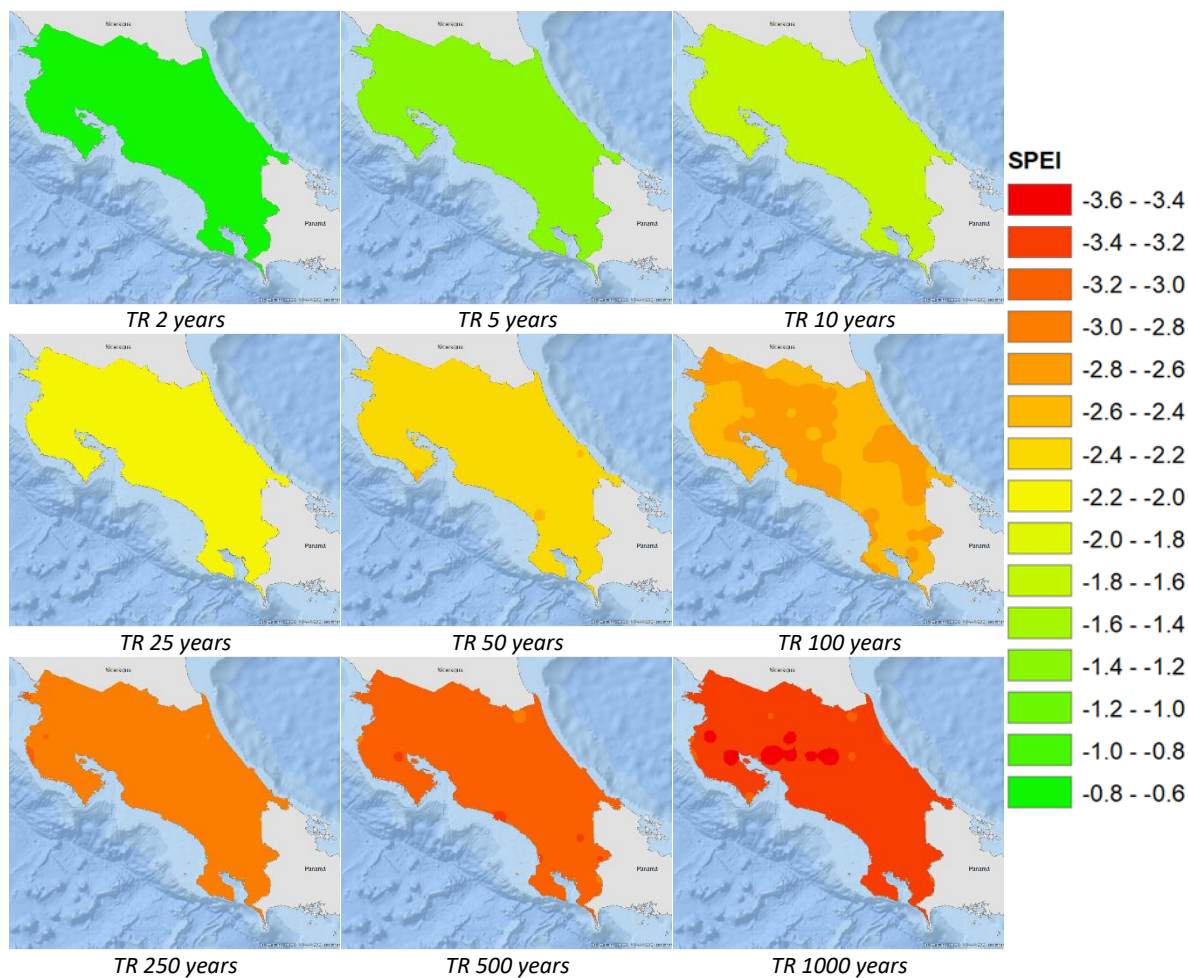


Figure 63. Uniform hazard maps for SPEI-12. EC-Earth3 model, SSP5-8.5 scenario, year 2050.

4 FLOOD HAZARD

Flood hazard develops as a result of excess precipitation, which may lead, on the one hand, to soil oversaturation that generates waterlogging conditions (pluvial flooding), and on the other, to excessive runoff forcing rivers and streams beyond their capacity, resulting in overflow (fluvial flooding). Other related phenomena, such as flash floods or riverbank scouring, are not included within the scope of this study. Coastal flooding is addressed separately, as it requires a different modeling approach, and is presented in Section 5. Methodological details of the flood hazard assessment are provided in Annex A.3.

This chapter also includes a specific hydraulic model for the Pirro River, located in the canton of Heredia, which is presented in Section 4.5.4. This is due to the fact that, given the characteristics and resolution of the Strategic Project, a higher-resolution flood model is required. The Pirro River, whose channel runs through the canton of Heredia, was selected jointly with the Technical Working Group, who expressed their interest in understanding flood modeling for this particular river and its importance for the municipality. The co-development of the model, from its initial definition, made it possible to modify the scope originally proposed by the consultant for the Virilla River, shifting it instead to the Pirro River, which is of greater relevance to Heredia.

4.1 Scope of the Flood Model

As mentioned in the Inception Report of this consultancy, the scope of flood modeling covers both pluvial flooding and fluvial flooding, at the national level in order to serve as input for risk assessments in Operational Projects 1, 2, and 3, as well as at the level of the canton of Heredia for the Strategic Project. While the flood phenomena considered allow for a broad characterization of flood risk, there are certain limitations that should be clearly stated.

In the specific case of fluvial flooding, the scope of the GRMA Costa Rica project includes only slow-onset flooding caused by river overbank flow. That is, other phenomena—particularly torrential flows—are not included within the scope of this work. Modeling torrential flows requires additional modeling components that are not included in the methodological approach presented in the Inception Report and Annex A.3. These components involve aspects such as mixed flow discharge generated by torrential rainfall in catchments, the rheology of this mixed flow and its hydraulics, as well as its impacts on critical structures such as bridges, where, for example, local scour of piers can significantly contribute to the overall impact. Addressing a phenomenon of this nature requires a specialized methodological approach that is substantially different from the one adopted in this study.

Furthermore, as also indicated in the Inception Report of this consultancy, the methodological approach to fluvial flooding caused by river overbank flow differs between the national model (applicable to Operational Projects 1, 2, and 3) and the Heredia model (applicable to the Strategic Project). The reason for this difference is essentially the modeling scale. In the case of the national model, the objective is to cover the entire territory of Costa Rica, which requires modeling 34 river basins and their main drainage networks. Achieving this within the time frame established for the execution of these works necessarily involves trade-offs and simplifications, without which the task would not be feasible.

Therefore, national-scale modeling is carried out using one-dimensional models of the selected river reaches. These models represent river geometry through cross-sections and solve energy balance equations in an approximate manner to estimate water levels within the channels. Although this represents a simplified hydraulic approach, its high computational efficiency makes it suitable for achieving the expected modeling results.

In contrast, the flood model for the canton of Heredia, given its reduced geographical scale, allows for a qualitative local improvement through the application of a two-dimensional model, which provides a better representation of overbank hydraulics. This model is significantly more computationally demanding; however, due to the limited geographic extent of the canton, it enables an adequate description of flooding within a reasonable computation time.

4.2 Inputs for Modeling

The primary input for flood hazard modeling consists of the simulated meteorological series presented in the section 2. These provide the meteorological forcing both under baseline climate conditions and under potential future climates, considering the modifying effects of climate change. Flood hazard assessment also requires additional layers of information to support the construction of evaluation models, in accordance with the methodologies described in Section 6.3 of the Inception Report.

The Digital Elevation Model (DEM) is used to define runoff pathways and low-lying areas prone to flooding. Land cover is directly linked to runoff generation, infiltration, and evapotranspiration; this relationship is quantified through the Curve Number (CN) method (*Soil Conservation Service*), which defines the potential hydrological response of the surface to intense rainfall events.

Watersheds, along with the river network, constitute the natural channels through which water flows toward discharge points, and their delineation is essential for modeling flow concentration and accumulation potential in low-lying areas. Geomorphometric data provides key information on slopes, curvatures, and stream orders, enabling the estimation of flow velocity, concentration time, and the potential for erosion or flooding.

4.2.1 Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) used in this study was derived from the high-resolution ALOS PALSAR Radiometrically Terrain Corrected (RTC) product, with a pixel size of 12.5 meters (Alaska Satellite Facility, 2014; Gis & Beers, 2018). This DEM is part of the dataset processed by the Alaska Satellite Facility (ASF) through the application of Radiometric Terrain Correction (RTC) to Synthetic Aperture Radar (SAR) scenes from the ALOS satellite, operated by the Japan Aerospace Exploration Agency (JAXA), collected between 2006 and 2011.

Figure 64 presents the DEM for the entire territory of Costa Rica. Its relatively high resolution enables the analysis of slopes, drainage networks, and other geomorphological features that are essential for modeling.

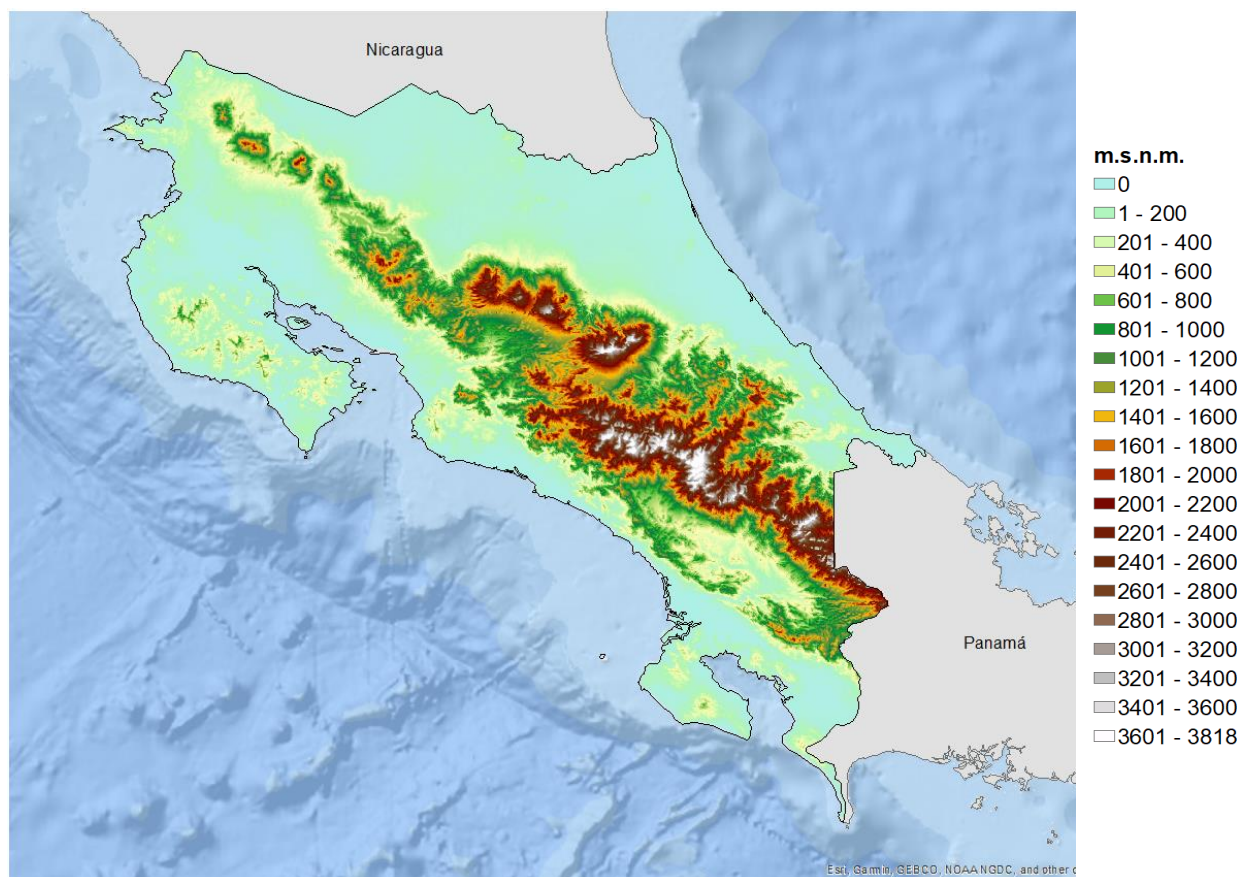


Figure 64. Digital Elevation Model (DEM). The scale shows elevation in meters above sea level.

The DEM is a key input for the delineation of watersheds, river networks, and geomorphometric parameters. In other words, it defines the drainage conditions required for fluvial flood modeling. It also enables the identification of areas prone to waterlogging, according to the land type classification included in Annex A.3.

Figure 65 shows the classification of the Topographic Accumulation Potential (TAP) obtained at the national level.

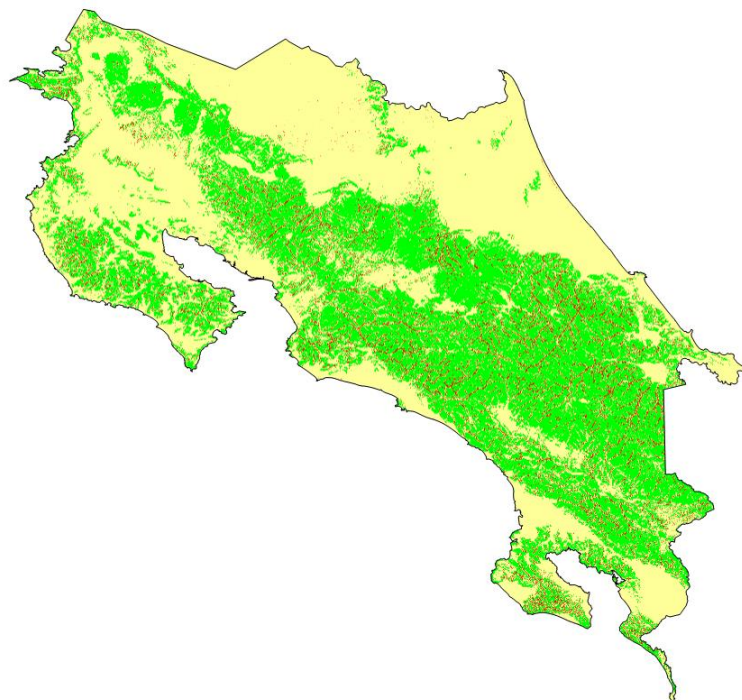


Figure 65. Topographic Accumulation Potential (TAP). Red = High. Yellow = Medium. Green = Low.

4.2.2 Land Cover

An updated land-use map of Costa Rica was used, developed by Vargas (2020) and published on GitHub as a baseline raster layer for the year 2020. The product was generated from the combination of multiple data sources—including forest cover, agricultural areas, and conservation boundaries—through a reproducible workflow in R (resampling, rasterization, merging, reclassification, and statistical analysis). This map provides a high-resolution representation of land cover (see Figure 66).

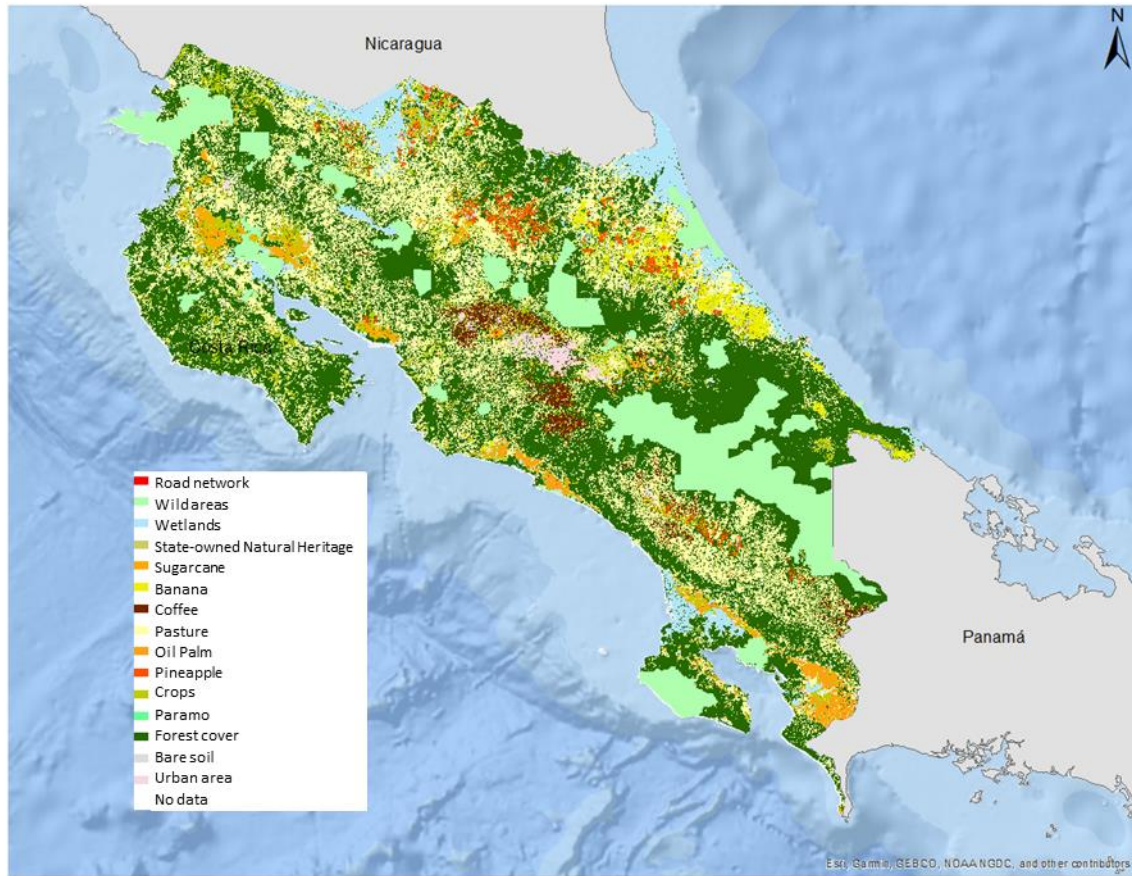


Figure 66. Land cover (Vargas, 2020)

4.2.3 Curve Number

The Curve Number (CN) is a hydrological parameter used to estimate surface runoff generated by precipitation events in watersheds. This index was developed by the U.S. *Soil Conservation Service* (SCS), now part of the *Natural Resources Conservation Service* (NRCS), and is presented in the technical report TR-55 (USDA, 1986).

The CN is based on an empirical equation that relates total precipitation (P), direct runoff (Q), and the maximum potential retention (S) of a watershed. The fundamental equation is:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{Equation 2}$$

where Q is direct runoff (mm), P is total precipitation (mm), and S is the maximum potential retention (mm), defined as:

$$S = \frac{25400}{CN} - 254 \quad \text{Equation 3}$$

The CN varies between 30 and 100, where:

- CN = 30 corresponds to high-infiltration conditions (e.g., sandy soils with dense vegetation).
- CN = 100 indicates total runoff conditions (e.g., impervious surfaces such as pavements or rooftops).

The determination of CN is based on four main factors:

- Hydrologic Soil Group (HSG): Classification of soils according to their infiltration capacity.
- Land Use and Treatment: Type of land cover (forest, pasture, urban areas, etc.).
- Hydrologic Condition of the Land: Vegetation condition and soil management (good, fair, poor).
- Antecedent Moisture Condition (AMC): Soil moisture level prior to the rainfall event (dry, average, wet).

The combination of these factors allows for the assignment of a specific CN to each area, facilitating the estimation of surface runoff and the planning of stormwater management measures. Table 16 presents the CN values assigned to each land-cover class. These values were determined following the methodology established in NRCS TR-55 (USDA, 1986), which considers the factors mentioned above. The assignment of CN is essential for modeling surface runoff and assessing flood risk, as it reflects the infiltration capacity and runoff potential of each land-cover type.

Table 16. Curve number assigned

Land cover	Estimated CN	Description	Source
Paved roads	98	Paved roads are considered fully impervious surfaces; high CN reflects near-total runoff.	TR-55, urban impervious areas table
Protected natural areas (forest)	55	Forest in good condition has high infiltration capacity; moderate-to-low CN.	TR-55, <i>Woods good condition</i> ; Minnesota Stormwater Manual
Wetlands	98	Typically saturated or impermeable, generating immediate runoff; comparable to open water.	TR-55 land use open water CN = 100; WA DOT (approx.)
State natural heritage lands	55	Similar to well-conserved forests — high infiltration, intact vegetation.	Same as forest (protected areas)
Sugarcane	78	Row crops in good condition typically have CN ~78.	TR-55, <i>Row crops, good</i> ; NRCS guidelines
Banana	78	Similar to row crops in good condition; assigned analogous CN value.	Analogous to <i>Row crops, good</i> (TR-55)
Coffee (shrub crop)	72	Similar to shrub crops; CN value aligned with <i>woods/grass combination, poor-fair</i> (~72–79).	TR-55 <i>woods/grass combo poor-fair</i> ; Minnesota Stormwater Manual
Pasture	74	Pasture in good condition typically has CN ~74.	TR-55 <i>Pasture, good</i> (74); NRCS guidelines
Oil palm (African palm)	74	Similar to shrub crops or pasture; assigned by analogy to <i>Pasture, good</i> .	Based on <i>Pasture, good</i> (TR-55)
Pineapple	78	Row crop, similar to sugarcane; assigned analogous CN value of 78.	Based on <i>Row crops, good</i> (TR-55)
Generic crops	78	Typical CN value for well-managed row crops.	TR-55 <i>Row crops, good</i> ; NRCS guidelines
Páramo (high-altitude grassland)	55	Dense vegetation, high infiltration; similar to forests or protected areas.	Equivalent to <i>Woods good</i> / protected areas
Forest cover	55	Forest in good condition with high infiltration capacity.	TR-55 <i>Woods, good</i> ; Minnesota Stormwater Manual
Bare soil	77	Exposed soil without vegetation; CN value for <i>newly graded pervious</i> surfaces.	TR-55 <i>Newly graded pervious</i> (77); Minnesota Stormwater Manual
Dense urban areas (residential)	85	Area with ~65% impervious surface; typical CN value for small-lot residential developments.	TR-55 <i>Residential, 65% impervious</i> = 85; Minnesota Stormwater Manual

Paved roads – CN: 98

Paved roads are considered completely impervious surfaces, which generate almost total runoff of rainfall. According to TR-55 (USDA, 1986), this type of surface has a CN value of 98, regardless of the hydrologic soil group, since infiltration capacity is practically null.

Protected Wilderness Areas (forest) – CN: 55

Forests in good condition have a high infiltration capacity due to dense vegetation cover, organic matter accumulation, and soil protection against erosion. TR-55 assigns a CN value of 55 to this type of land cover, reflecting moderate runoff and a favorable hydrological response (USDA, 1986).

Wetlands – CN: 98

Wetlands, being permanently saturated, generate immediate runoff during rainfall events. According to TR-55, they are classified analogously to open water bodies, with a CN value of 98, which reflects the absence of significant additional storage capacity or infiltration (USDA, 1986).

State Natural Heritage Areas – CN: 55

State-protected areas, similar to well-preserved forests, maintain a high infiltration capacity thanks to the good condition of their vegetation cover. Therefore, they are assigned a CN value of 55, in accordance with the TR-55 classification for forests in good condition, which represents a low potential for surface runoff (USDA, 1986).

Sugarcane – CN: 78

Row crops such as sugarcane, when cultivated under good management practices, provide moderate soil cover that allows partial infiltration of rainfall. According to TR-55, row crops in good condition are assigned a CN value of 78, which reflects an intermediate runoff capacity (USDA, 1986).

Banana – CN: 78

Banana plantations, similar to other well-managed row crops, present soil coverage that facilitates moderate water infiltration. By analogy with sugarcane, a CN value of 78 is assigned following NRCS guidelines, reflecting a comparable hydrological response (USDA, 1986).

Coffee (shrub) – CN: 72

Shrub crops such as coffee, under moderate vegetation conditions, display an intermediate infiltration capacity. TR-55 assigns a CN value of 72 to land uses that combine forest and grassland in poor-to-fair condition, which indicates a moderate level of surface runoff (USDA, 1986).

Pasture – CN: 74

Well-managed pasture provides soil cover that allows efficient water infiltration. TR-55 assigns a CN value of 74 for pastures in good condition, indicating a moderate runoff capacity (USDA, 1986).

Oil Palm (African palm) – CN: 74

African oil palm plantations, similar to well-maintained pasture, provide ground cover that facilitates water infiltration. By analogy with the CN assigned to pasture, a value of 74 is used according to NRCS guidelines (USDA, 1986).

Pineapple – CN: 78

Pineapple, like other row crops under good management, provides soil cover that allows moderate water infiltration. By analogy with the CN assigned to sugarcane, a CN value of 78 is applied following NRCS guidelines (USDA, 1986).

Generic Crops – CN: 78

Well-maintained agricultural crops, under favorable conditions, provide soil cover that supports moderate infiltration. TR-55 assigns a CN value of 78 for row crops in good condition, which reflects an intermediate runoff capacity (USDA, 1986).

Páramo – CN: 55

The páramo ecosystem, with its dense vegetation and high infiltration capacity, exhibits characteristics similar to well-preserved forests. Therefore, it is assigned a CN value of 55, consistent with the TR-55 classification for forests in good condition (USDA, 1986).

Forest Cover – CN: 55

Forest cover in good condition has a high infiltration capacity due to dense vegetation and the presence of litter. TR-55 assigns a CN value of 55 for forests in good condition, which indicates a moderate runoff potential (USDA, 1986).

Bare Soil – CN: 77

Bare soil, lacking vegetation, has reduced infiltration capacity, which generates greater runoff. TR-55 assigns a CN value of 77 for newly graded pervious soils, indicating a relatively high runoff potential (USDA, 1986).

Dense Urban Areas (Residential) – CN: 85

Dense residential urban areas, with approximately 65% impervious surface, exhibit characteristics that significantly influence surface runoff. According to TR-55, for residential areas with a lot size of 1/8 acre or less (approximately 500 m² per lot) and 65% impervious cover, the assigned CN value is 85. This value reflects high runoff potential due to the considerable proportion of impervious surfaces, such as pavements, roofs, and streets, which limit water infiltration (USDA, 1986).

Figure 67 presents the Curve Number (CN) map for Costa Rica. It should be noted that the CN values presented were obtained from the processing of the land cover layer (see Figure 66), applying the definitions described above.

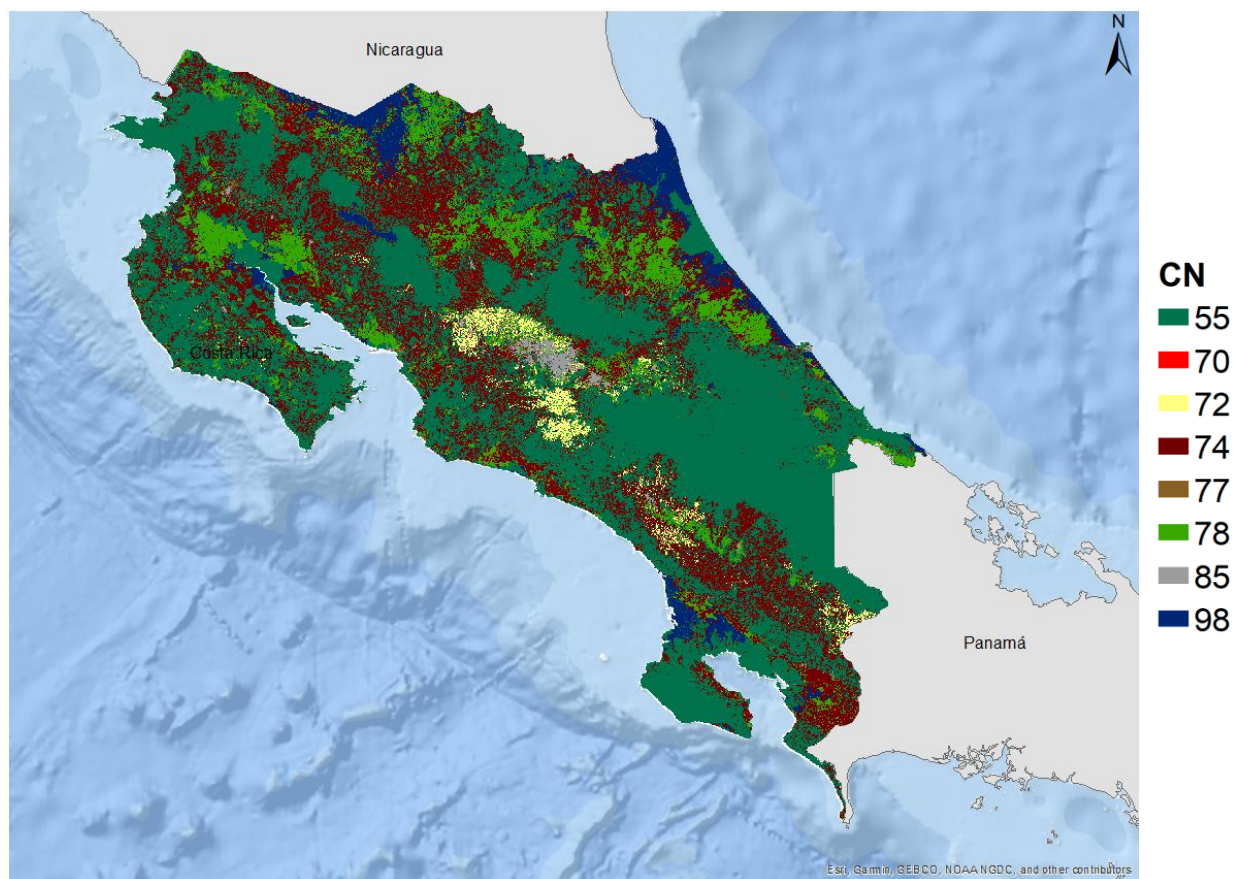


Figure 67. Curve number

4.2.4 Watershed and River Network

In Costa Rica, the watersheds are mainly distributed across three slopes: the Pacific Ocean, the Caribbean Sea, and the San Juan River. Each of these slopes contains multiple watersheds that vary in size, location, and hydrological characteristics. For example, the Tempisque River watershed, located on the Pacific slope, is one of the largest and most important for agriculture in the region (ANRCCR, 2021; INA, n.d.).

A map illustrating the 34 main watersheds of Costa Rica is presented below. Figure 69 shows the river network of Costa Rica.



Figure 68. Hydrographic basins

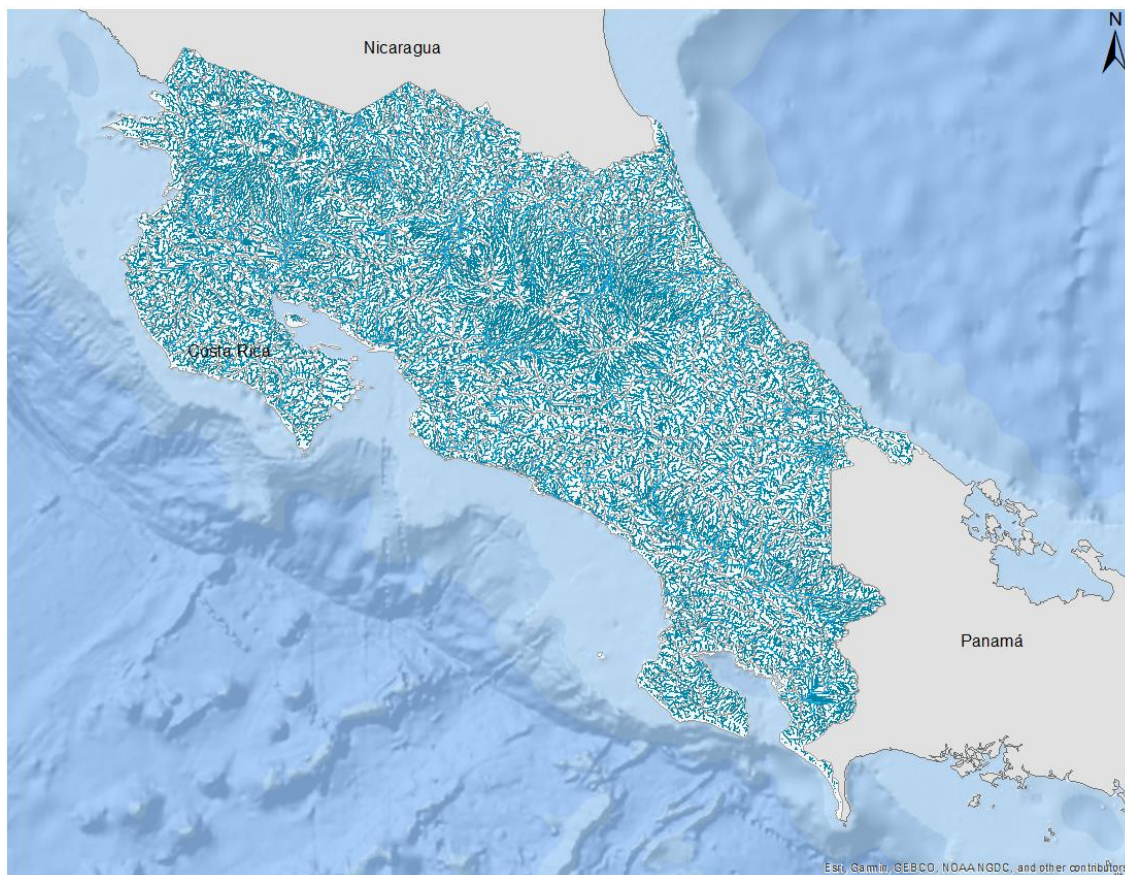


Figure 69. Drainage network

In Costa Rica, the document *Study of the Watersheds of Costa Rica*, prepared by the National Meteorological Institute (IMN), presents a comprehensive analysis of the country's 34 main watersheds. From a biophysical, climatological, geological, and socioeconomic perspective, the study characterizes each watershed using variables such as geography, geology, hydrogeology, landslide susceptibility, soil analysis, life zones, protected areas, as well as demographic aspects, and water supply and demand.

This work, intended to support integrated water management planning, is particularly aimed at students, professionals, and researchers interested in the planning, utilization, conservation, and rehabilitation of natural resources within Costa Rican watersheds (IMN, 2011). Annex A.4 presents a brief description of each basin, together with a summary of the morphometric parameters of interest.

4.3 Hydrological Response of the Basins

As part of the flood hazard modeling, the hydrological response of the river basins in Costa Rica was evaluated both at their outlet points and at multiple upstream locations, in order to establish variations in streamflow across different positions along the channels.

As an example, this report presents the hydrographs obtained for 100 high-precipitation events selected from the 1,000-year simulated meteorological series, for four basins in Costa Rica. The hydrographs

presented here consider complete basins, i.e., they are calculated at their outlet points. Similar results are available for all basins listed in the project dataset.

4.3.1 Tempisque River Basin

According to the study conducted by Trabado (2023) in the upper Tempisque River basin, observed streamflows were analyzed at the Guardia hydrological station, operated by the Costa Rican Institute of Electricity (ICE). This station contains daily records of mean discharge for the period 1981–2010. During this interval, an average discharge of 26 m³/s and a maximum discharge of 903 m³/s were reported.

On the other hand, Espinoza-Rivera (2018) documented that during the passage of Tropical Storm Nate, in October 2017, estimated discharges ranged between 1,400 and 1,550 m³/s in the Tempisque River, specifically in the Las Palmas sub-basin. The rainfall generated by this event corresponds to an approximate return period of 50 years according to Espinoza-Rivera (2018). Additionally, Barquero (2019) carried out a hydrological modeling study using precipitation induced by Hurricane Nate on October 4, 2017, when the system was developing off the Caribbean coast of Costa Rica (on that date, Nate was classified as a Tropical Storm). Barquero (2019) used the HEC-HMS software and estimated a peak discharge of 2,057.2 m³/s in the Las Palmas sub-basin.

Based on the simulated climate data and hydrological modeling, synthetic hydrographs were generated for each of the basins considered. These hydrographs allow an estimated representation of peak discharges associated with different return periods, thus facilitating hydrological assessment and hydraulic flood modeling in each region.

The following figure presents the synthetic discharges obtained for the Tempisque River Basin. Each curve represents an individual synthetic event, randomly selected from the set of stochastic meteorological simulations generated for the basin. These realizations are presented to illustrate the variability in the shape and magnitude of the hydrographs, and not as design events or probabilistic thresholds.

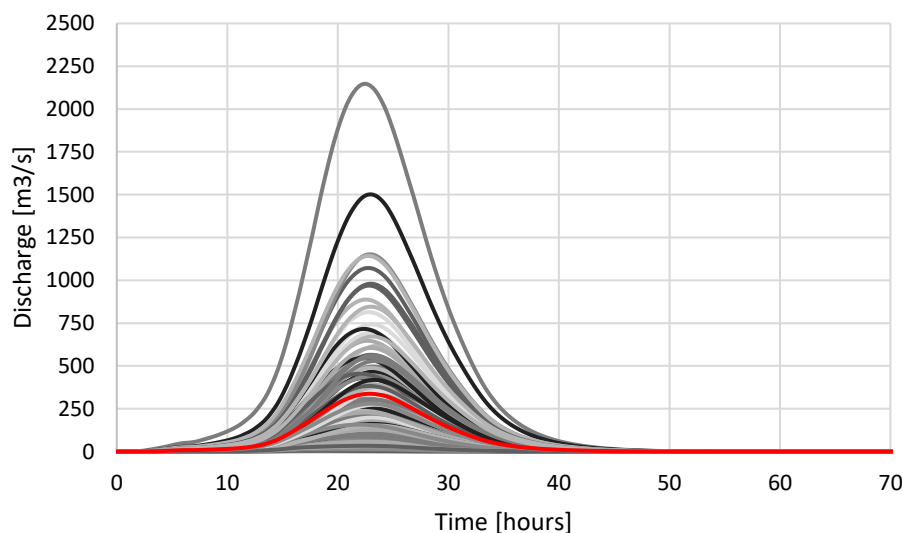


Figure 70. 100 synthetic hydrographs generated for the Tempisque river basin. The red curve represents the mean.

4.3.2 Matina River Basin

Watson et al. (2022) reported historical peak discharges of up to 2,500 m³/s during the period 1981–1995. Based on the analysis of annual maximum discharges and using the Weibull statistical distribution, discharge values were estimated for different return periods. For a 5-year return period, the projected discharge was approximately 1,200 m³/s; for 25 years, values reached up to 3,000 m³/s; and for a 100-year return period, the discharge was estimated at 4,000 m³/s.

Figure 71 presents the synthetic discharges obtained for the Matina River Basin.

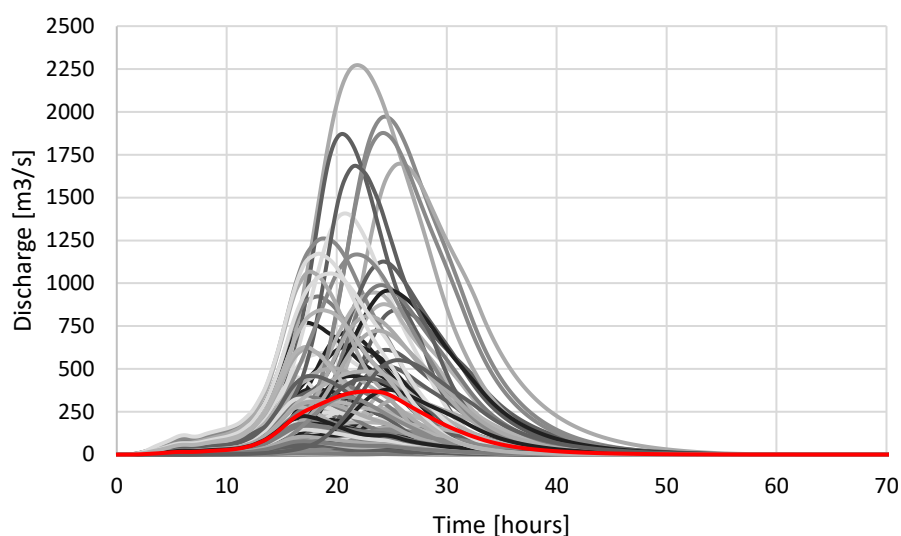


Figure 71. 100 synthetic hydrographs generated for the Matina river basin. The red curve represents the mean.

Although the peak discharges shown differ from the values reported by Watson et al. (2022), these differences can be attributed to discrepancies in methodology and scale of analysis. The estimates presented by Watson et al. are derived from an extreme value statistical analysis applied to annual maximum discharges, which involves extrapolation to long return periods and therefore entails considerable uncertainty. In contrast, the synthetic hydrographs presented in this study correspond to individual stochastic realizations randomly selected from a large ensemble of hydrological simulations, rather than design events associated with specific return periods.

In addition, the simulated discharges reflect catchment-scale hydrological processes and spatially distributed precipitation inputs, which tend to attenuate peak flows when compared to statistically extrapolated extremes. Consequently, differences in peak magnitudes are expected and reflect the distinct objectives and underlying assumptions of the two approaches.

4.3.3 Pacuare River Basin

Rodríguez Rojas (2019) carried out a hydraulic modeling study considering the influence of the Pacuare River channels, which would be affected by an estimated peak discharge of 2,776.9 m³/s. This work was developed within the framework of SENARA's investment plan, based on the 2015 Emergency Declaration and supported by General Emergency Plan No. 39056.

A hydrological analysis was conducted based on events with a 25-year return period, supported by a hydrometeorological database derived from available information, which enabled the generation of the required hydrographs. In addition, a rainfall–runoff model was developed from the analysis of rainfall data associated with extreme events that had detailed precipitation and runoff records. This information, provided by the Costa Rican Institute of Electricity (ICE) and the National Banana Corporation (CORBANA), was key for generating the hydrographs used in the hydraulic modeling.

The synthetic discharges obtained for the Pacuare River Basin are presented in Figure 72.

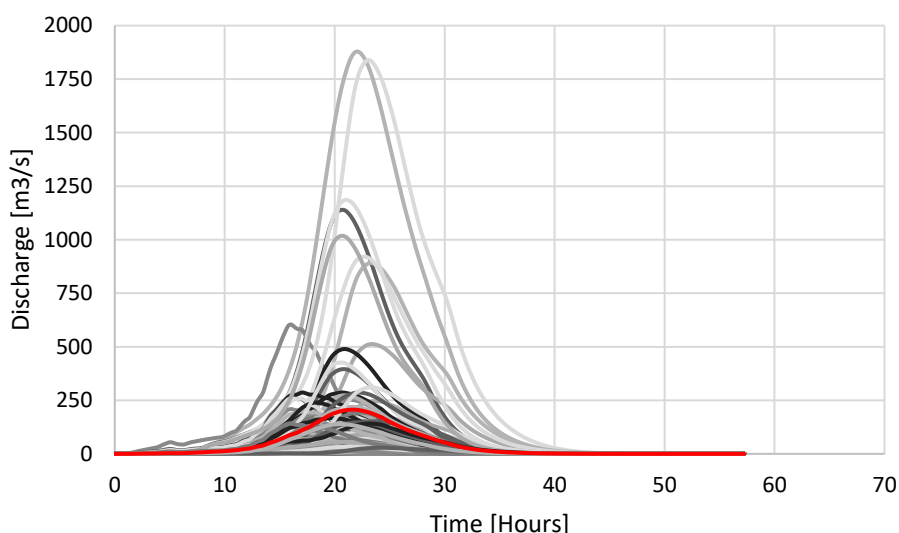


Figure 72. 100 synthetic hydrographs generated for the Pacuare river basin. The red curve represents the mean.

The figure shows peak discharges that, in some cases, exceed the value reported by Rodríguez-Rojas (2019). These higher peaks may be associated with events having return periods greater than the 25-year design event considered in that hydraulic study. The synthetic hydrographs represent a range of possible hydrological responses, including more extreme but less frequent events, which explains the presence of higher peak discharges in the simulations.

4.3.4 Reventazón River Basin

Mojica (1967) reported maximum recorded discharges of up to 1,600 m³/s in the upper Reventazón River Basin during the period between 1954 and 1966. These values correspond to measurements taken at the

location known as Angostura, which defines a sub-basin of the Reventazón River with an area of 1,367 km².

The synthetic discharges obtained for the Reventazón River Basin are presented in Figure 73.

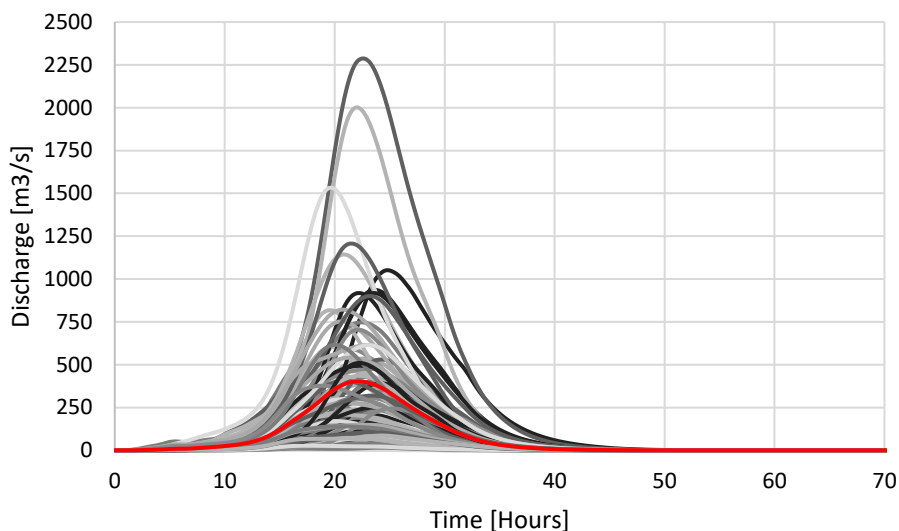


Figure 73. 100 synthetic hydrographs generated for the Reventazon river basin. The red curve represents the mean.

These values exceed those reported by Mojica (1967), which is expected given the difference in spatial coverage. The historical records correspond to the Angostura station, which represents only an upper sub-basin of the Reventazón River. In contrast, the synthetic hydrographs presented here reflect the hydrological response of the entire Reventazón River basin, resulting in higher peak discharges due to the larger contributing drainage area.

4.4 National-Level Flood Hazard Assessment

Following the methodology presented in Annex A.3, the flood hazard was assessed through two complementary approaches:

- Pluvial flooding, focused on waterlogging of the terrain due to soil oversaturation.
- Fluvial flooding, referring to the overflow of rivers and streams.

In both cases, the meteorological forcing corresponds to the simulation series previously defined.

From Figure 74 to Figure 79, uniform hazard maps are presented for 25, 50, 100, 200, 500, and 1000-year return periods for pluvial flooding in Costa Rica, considering the baseline climate. In turn, from Figure 80 to Figure 85, uniform hazard maps are shown for the same return periods, but for fluvial flooding.

As expected, the phenomenon of pluvial flooding —i.e., surface waterlogging or ponding— is considerably less severe than fluvial flooding. Therefore, the contribution of pluvial flooding to the overall flood risk is expected to be marginal. This can be observed in the maps presented. Note the color scale, which

corresponds to flood depth, and clearly shows that pluvial flood depths are at least one order of magnitude lower than those associated with fluvial flooding.

It is also important to note that pluvial flooding, as it refers to surface water accumulation due to terrain waterlogging, tends to produce hazard maps with a larger spatial extent. In contrast, fluvial flooding is mainly concentrated along rivers and streams, as well as in outlet areas such as deltas, estuaries, or bays, which limits its spatial extent. In other words, river basins and channels act as accumulators of incident precipitation, conveying large volumes of water into relatively small areas. This behavior is not manifested in the same way for pluvial flooding, where the spatial distribution of the phenomenon is strongly controlled by topography (the DEM), and therefore may cover larger territorial extents.

The maps presented correspond to the hazard under baseline climate conditions. It should be noted that the maps presented correspond to integrated hazard maps, that is, they integrate the contribution of all individual flood events. This means that the floods shown in the maps for different return periods cannot occur during a single event. As previously mentioned, and as summarized in Table 14, a total of 36 possible future climates are being considered according to the combinations of GCM, emission pathway, and target year. The complete set of corresponding hazard maps is included in the project dataset.

However, for illustration purposes, Figure 86 presents the fluvial flood hazard maps for a 1000-year return period under the climates EC-Earth3 SSP5-8.5 2100, GFDL-ESM4 SSP5-8.5 2100, and MPI-ESM1-2-LR SSP5-8.5 2100, compared against the baseline climate. This is intended to highlight the variations induced by climate change.

It should be emphasized, however, that these maps are only illustrative examples of the complete set of results, which are not included in this report to avoid excessive length.

The final resolution of the flood hazard assessment results is the same as that of the topographic information used as input, namely 30-meter pixel resolution for the national model and 5-meter pixel resolution for the local model of the canton of Heredia. This resolution adequately describes flood behavior, allowing the capture of the minimum hydraulic features required according to the scale of the models. Likewise, it provides sufficient detail for risk assessment across the different projects included in this consultancy.

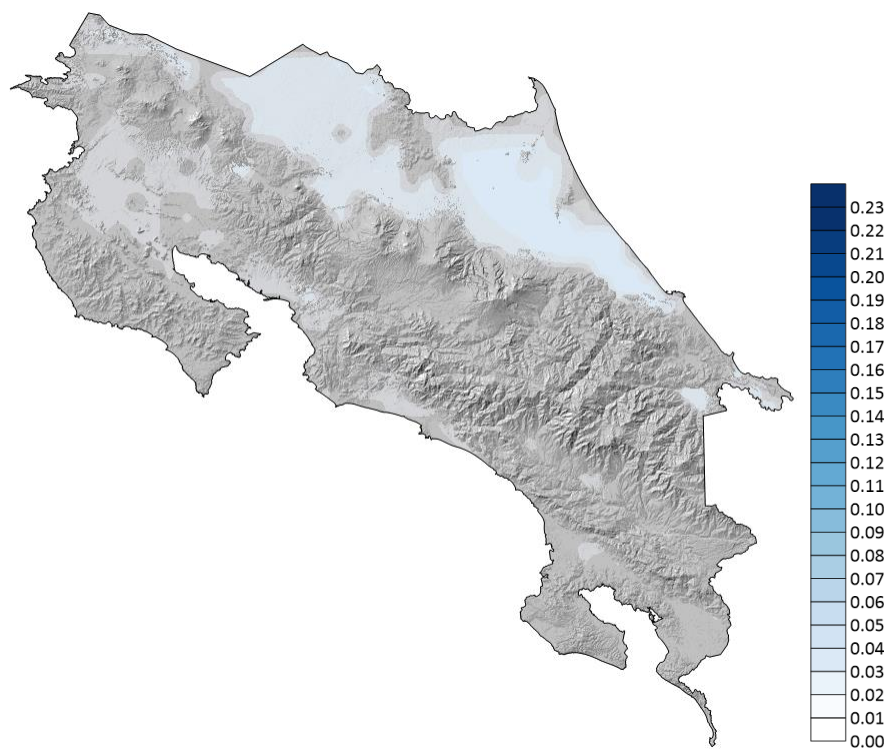


Figure 74. Pluvial flood Hazard map for base climate. TR = 25 years. Flood depth in meters.

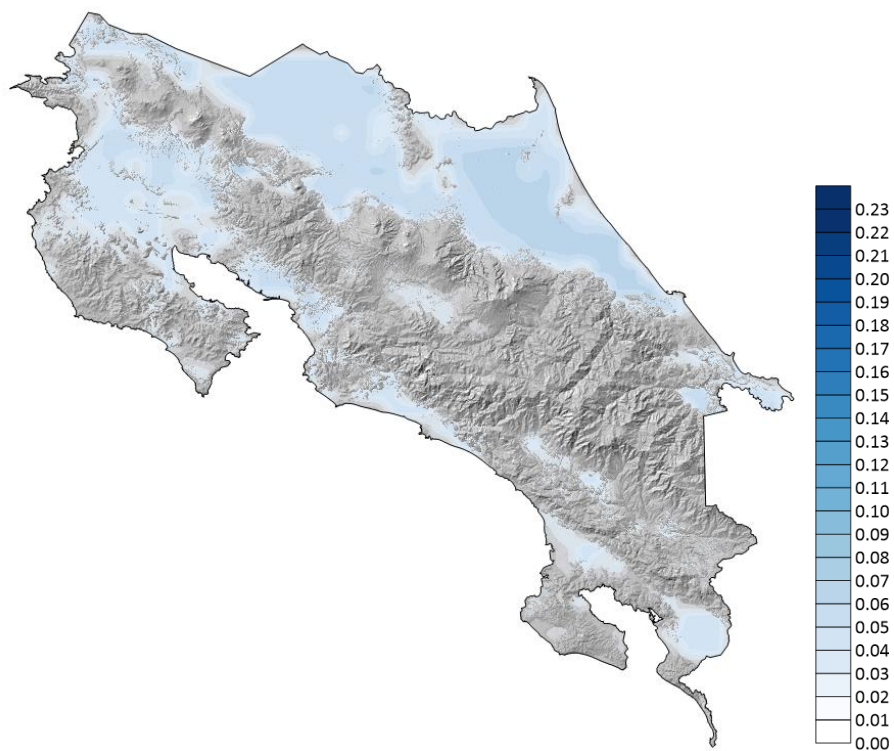


Figure 75. Pluvial flood Hazard map for base climate. TR = 50 years. Flood depth in meters.

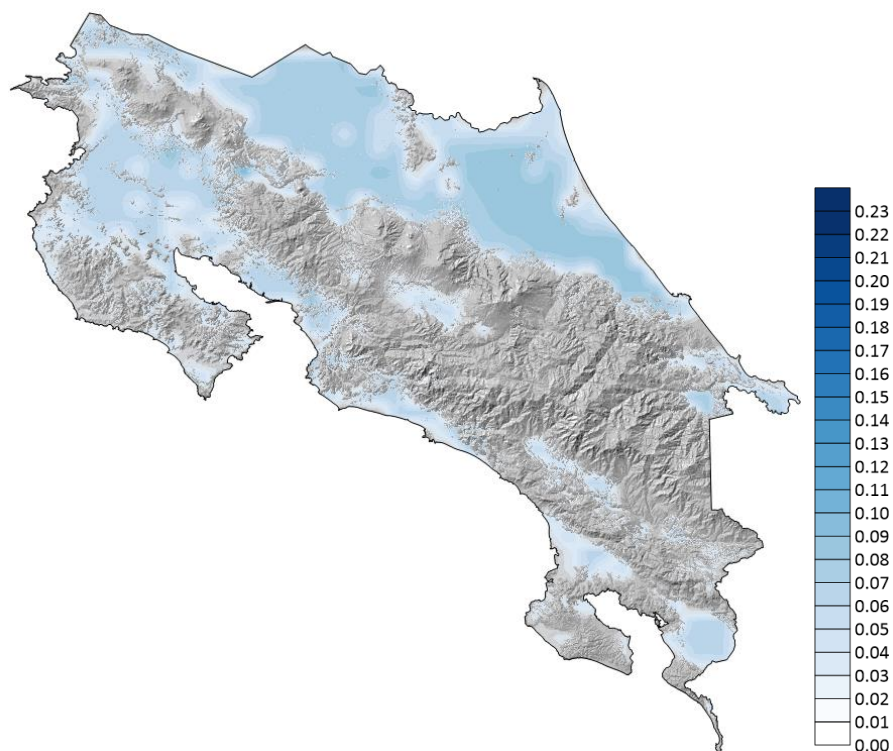


Figure 76. Pluvial flood Hazard map for base climate. TR = 200 years. Flood depth in meters.

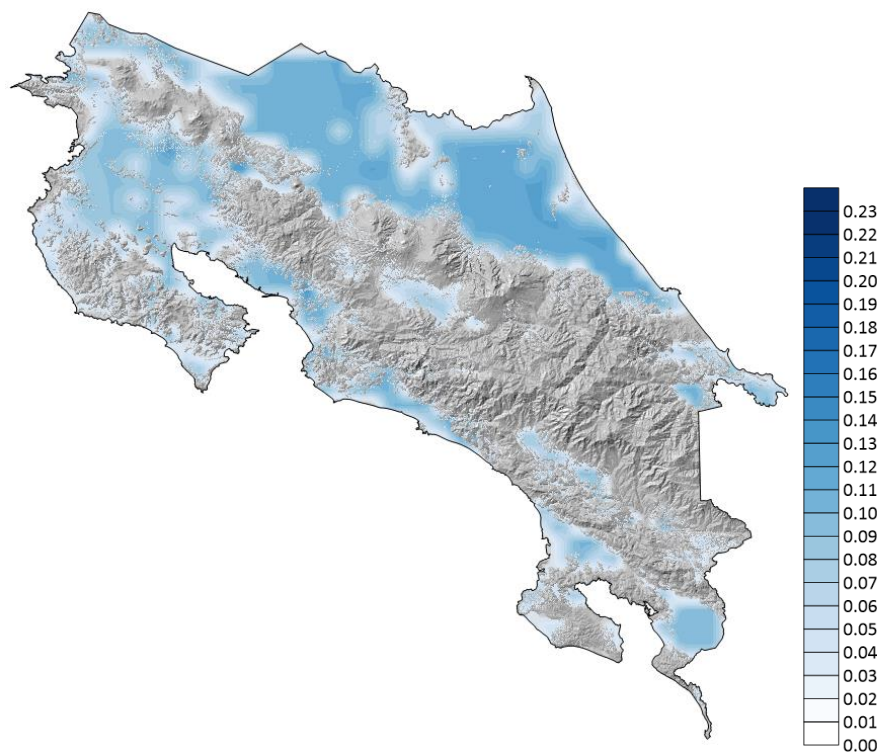


Figure 77. Pluvial flood Hazard map for base climate. TR = 100 years. Flood depth in meters.

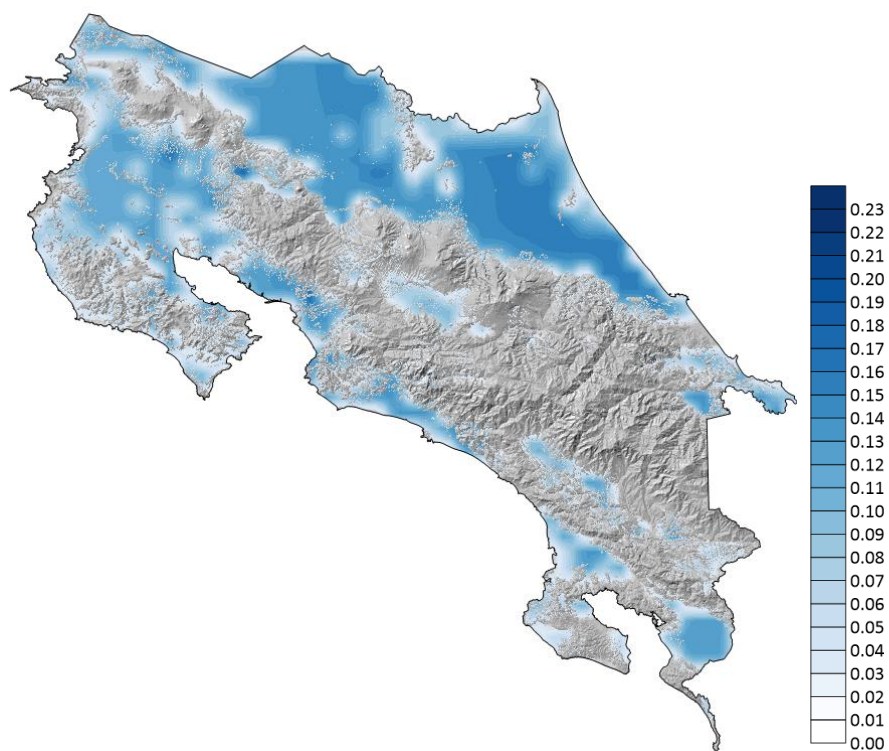


Figure 78. Pluvial flood Hazard map for base climate. TR = 500 years. Flood depth in meters.

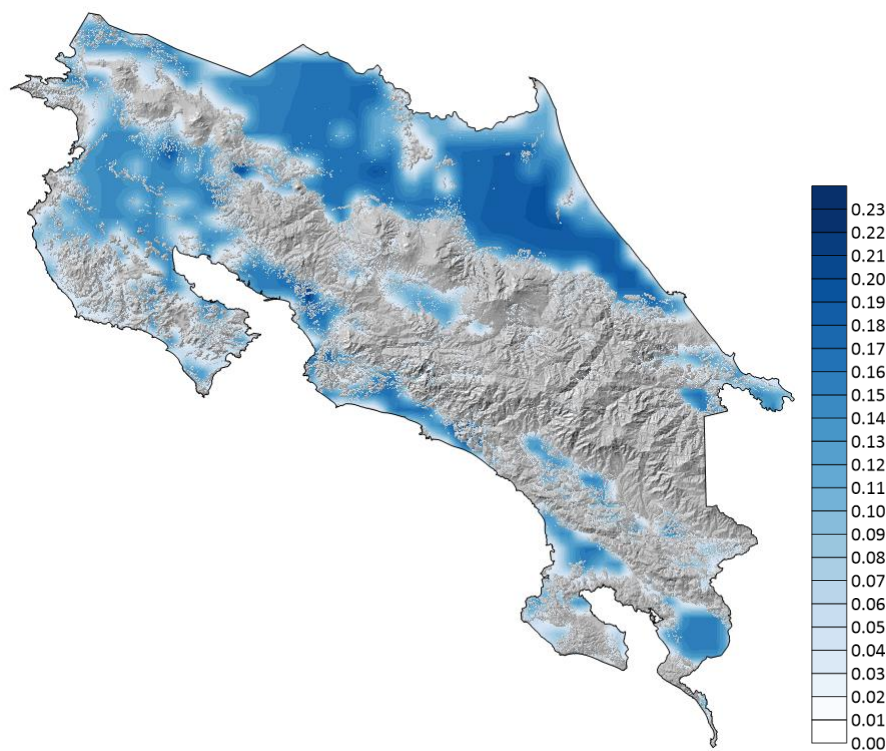


Figure 79. Pluvial flood Hazard map for base climate. TR = 1000 years. Flood depth in meters.



Figure 80. Riverine flood hazard map for base climate. TR = 25 years. Flood depth in meters.

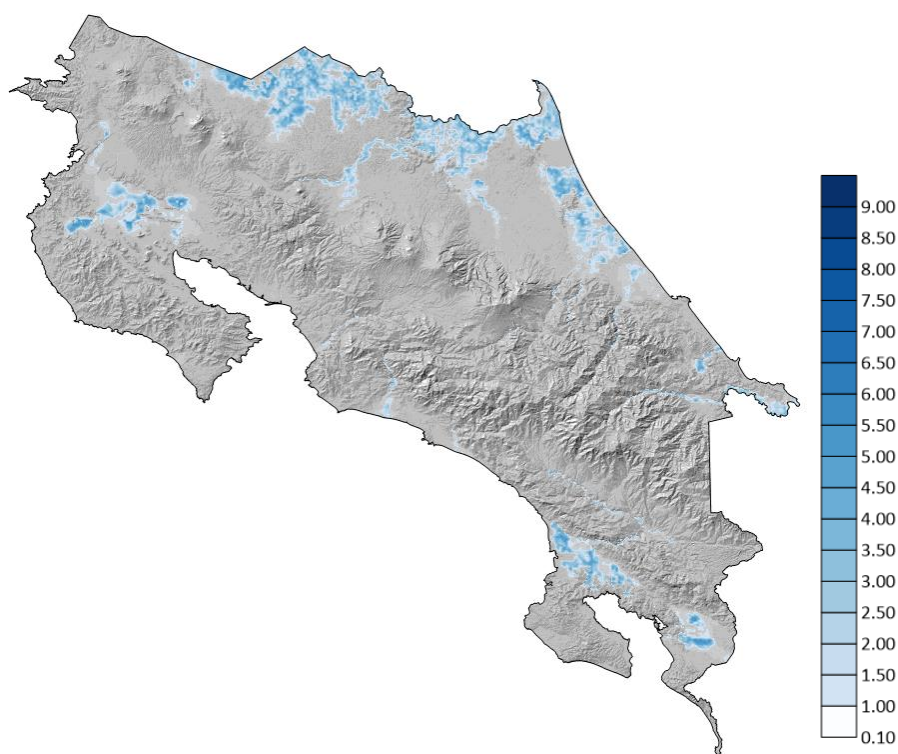


Figure 81. Riverine flood hazard map for base climate. TR = 50 years. Flood depth in meters.



Figure 82. Riverine flood Hazard map for base climate. TR = 100 years. Flood depth in meters.

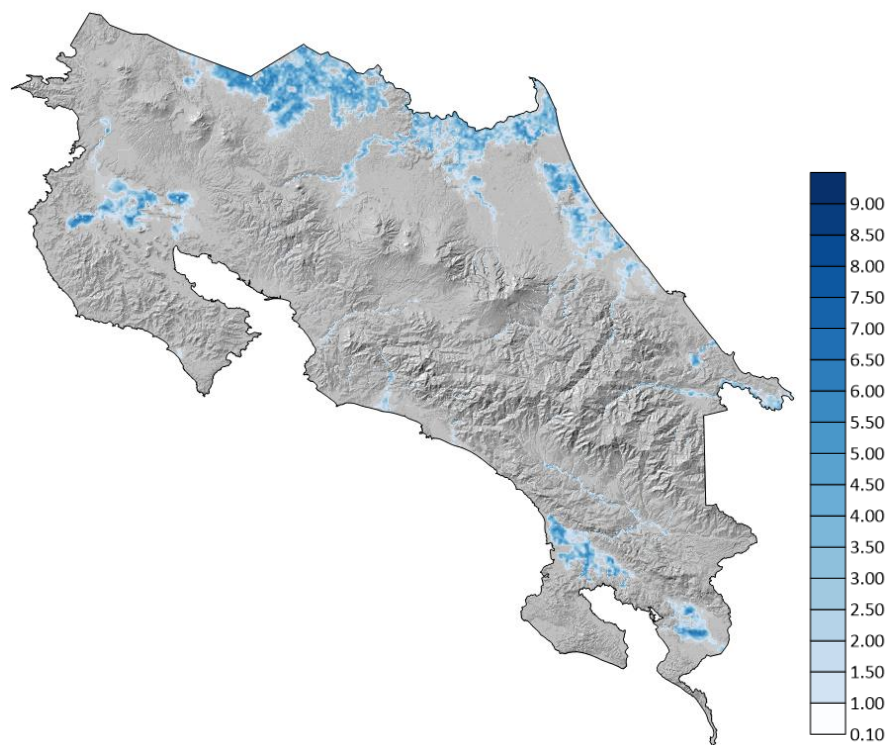


Figure 83. Riverine flood Hazard map for base climate. TR = 200 years. Flood depth in meters.

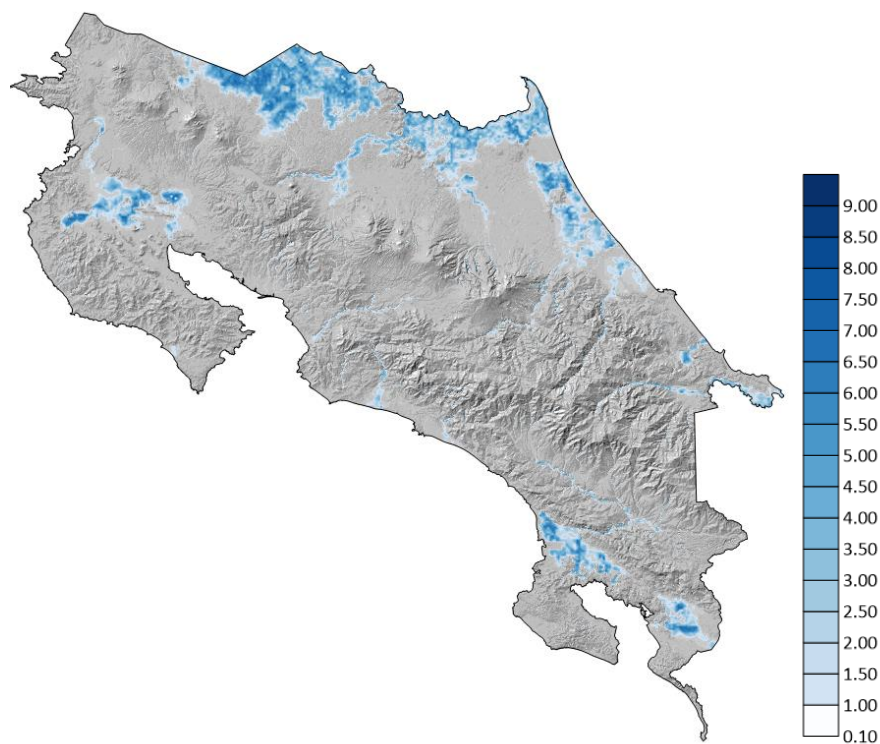


Figure 84. Riverine flood hazard map for base climate. TR = 500 years. Flood depth in meters.

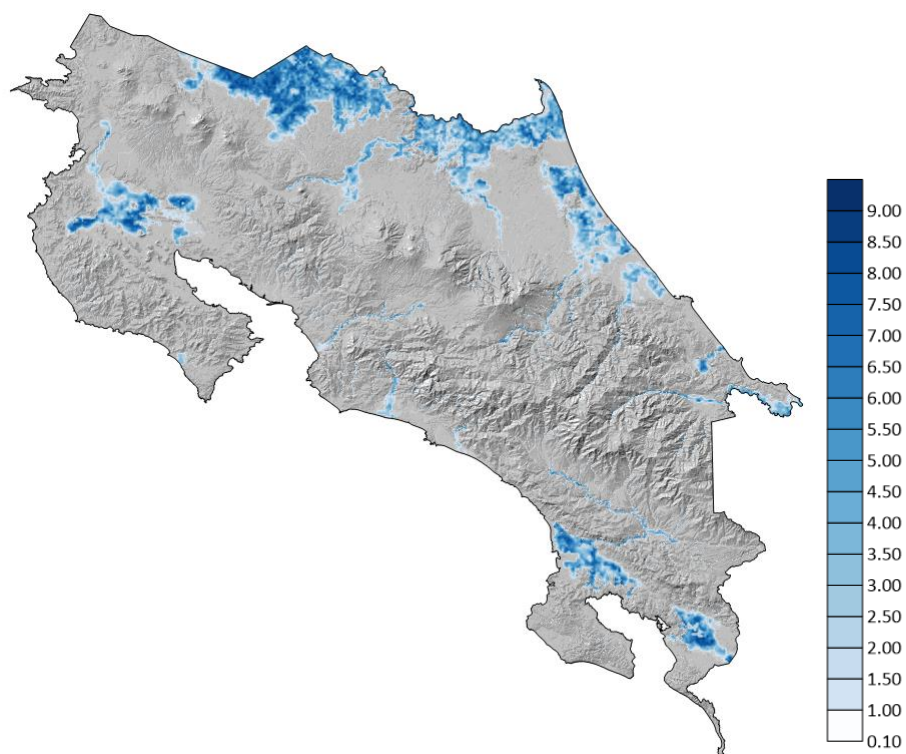


Figure 85. Riverine flood Hazard map for base climate. TR = 1000 years. Flood Depth in meters

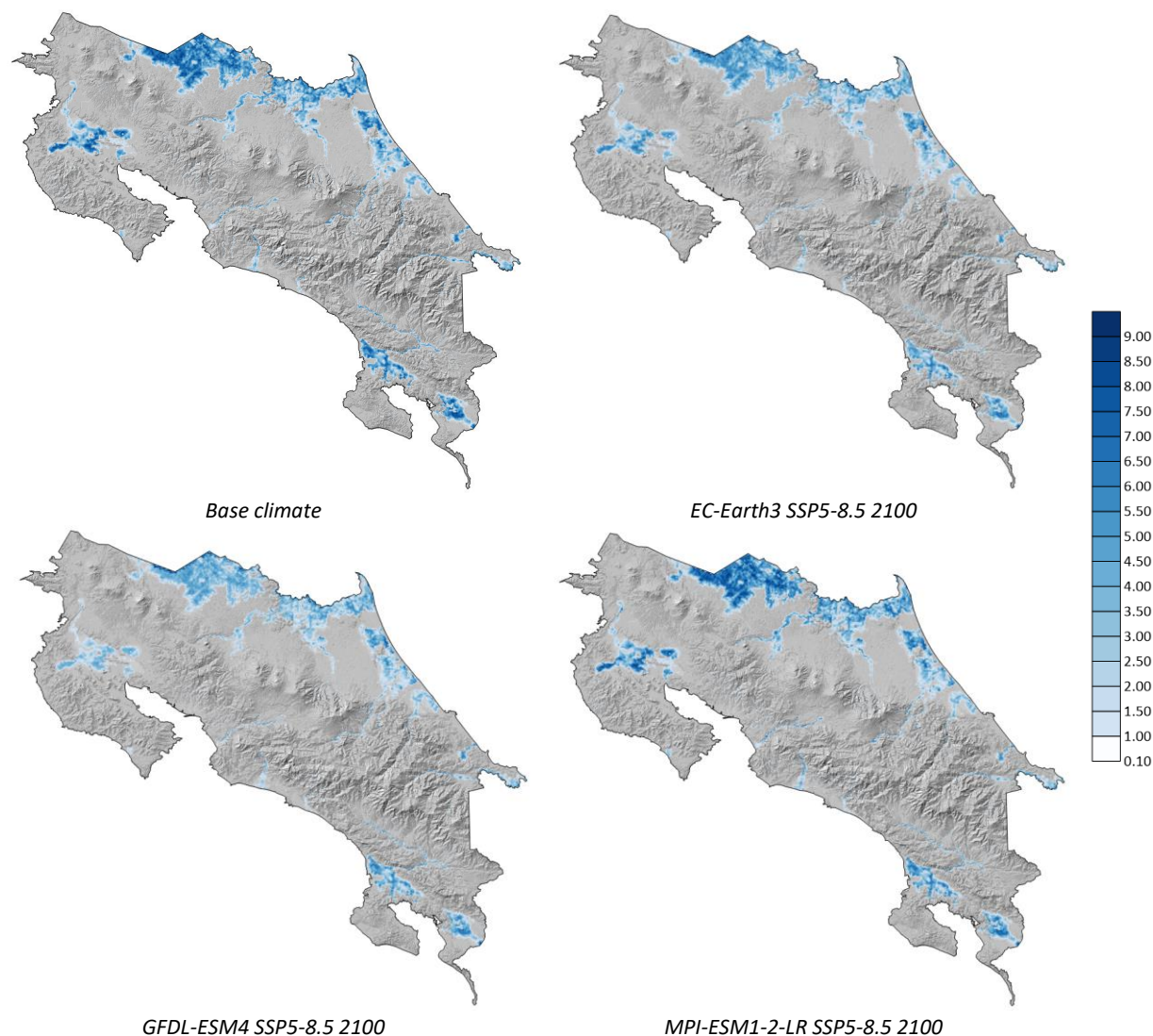


Figure 86. Comparison of hazard maps TR = 1000 years, for 3 future climates. Flood depth in meters

4.4.1 Comparison of Flood Hazard with the GRAF Project

The GRAF Project (Global Risk Assessment Framework) of UNDRR was implemented in Costa Rica in 2024, delivering risk results for floods and earthquakes in selected sectors. Regarding flood hazard information, the project relies on the flood hazard dataset developed by CIMA for the UNDRR GAR 2015 report. Since INGENIAR-CIMNE was responsible for risk modeling in the GAR 2015, this dataset is available for comparative purposes.

Figure 87 presents the flood hazard map for a 1000-year return period, both from the GRAF Project (same as GAR 2015) and from the current study (same as Figure 85). At the image scale shown, the differences appear minimal and are practically imperceptible. This is largely because the calculation methods are

similar, and therefore, when parameterized with baseline climate meteorological information, they are expected to yield consistent results.

Further details of the flood hazard evaluation method developed by CIMA for the GAR 2015 model can be found in Rudari et al. (2015).

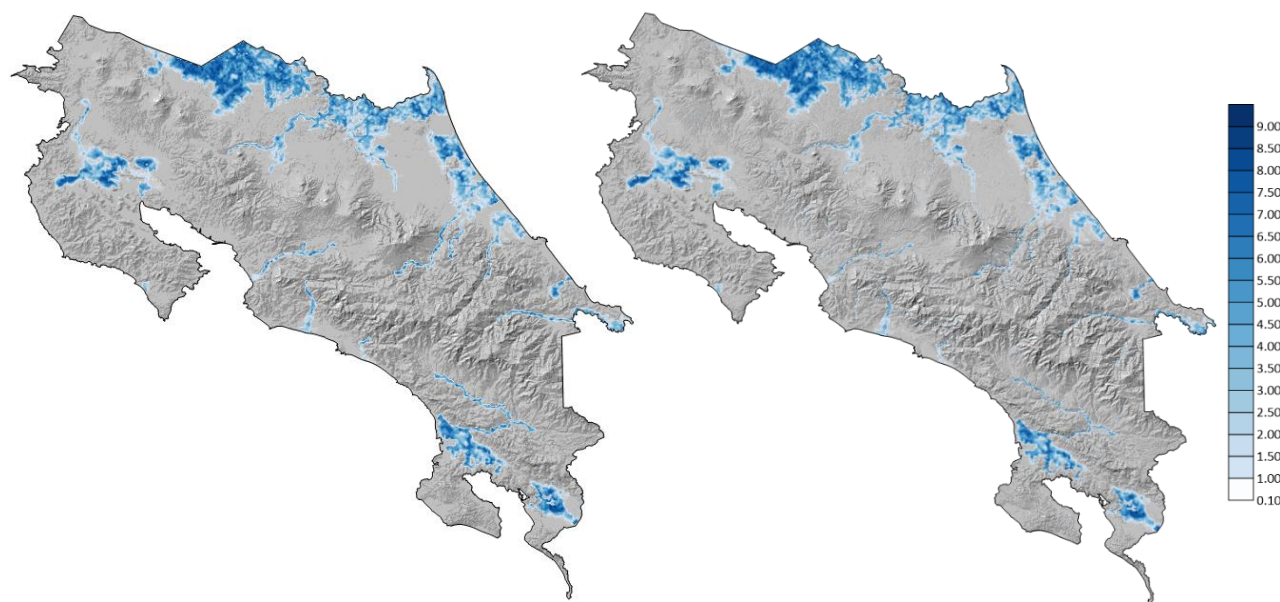


Figure 87. Comparison of 1000 years riverine flood hazard maps. Left.: GRAF. Right.: This work.

However, the results are not identical. From a methodological standpoint, there are differences in the approach, primarily in the hydrological models. In the GRAF model, streamflows are estimated, approximately, using triangular hydrographs, whereas in this study a distributed hydrological model (ModClark) is employed, which provides a more accurate representation of infiltration conditions in the terrain.

In addition, there are differences in the calculation resolution. The GRAF model uses a spatial resolution of 0.009 degrees (approximately 1 km per pixel). While this resolution is acceptable for a global-scale model, it is too coarse for a country such as Costa Rica. By contrast, the flood model developed in this study uses a spatial resolution of 0.00018 degrees (approximately 30 meters per pixel).

The resulting differences can be observed in Figure 88 to Figure 90, where three arbitrarily selected regions within Costa Rica are illustrated.

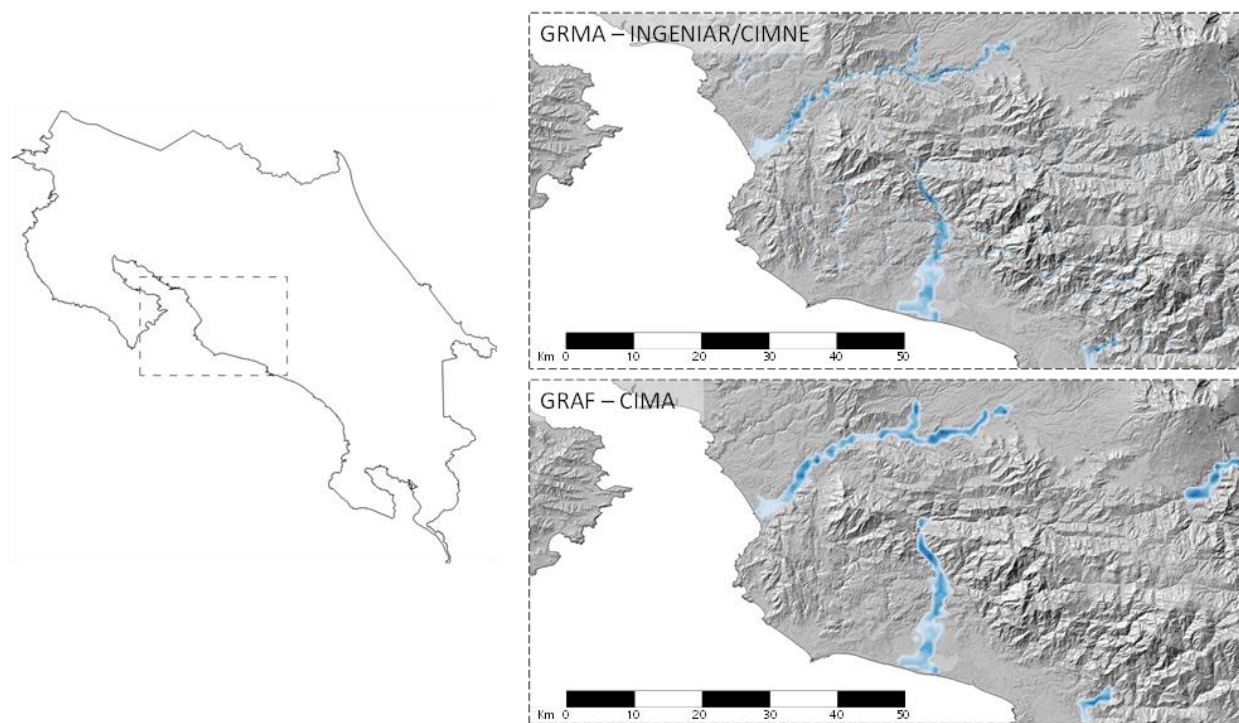


Figure 88. Comparison of 1000 years riverine flood hazard maps in the region enclosed by the box.

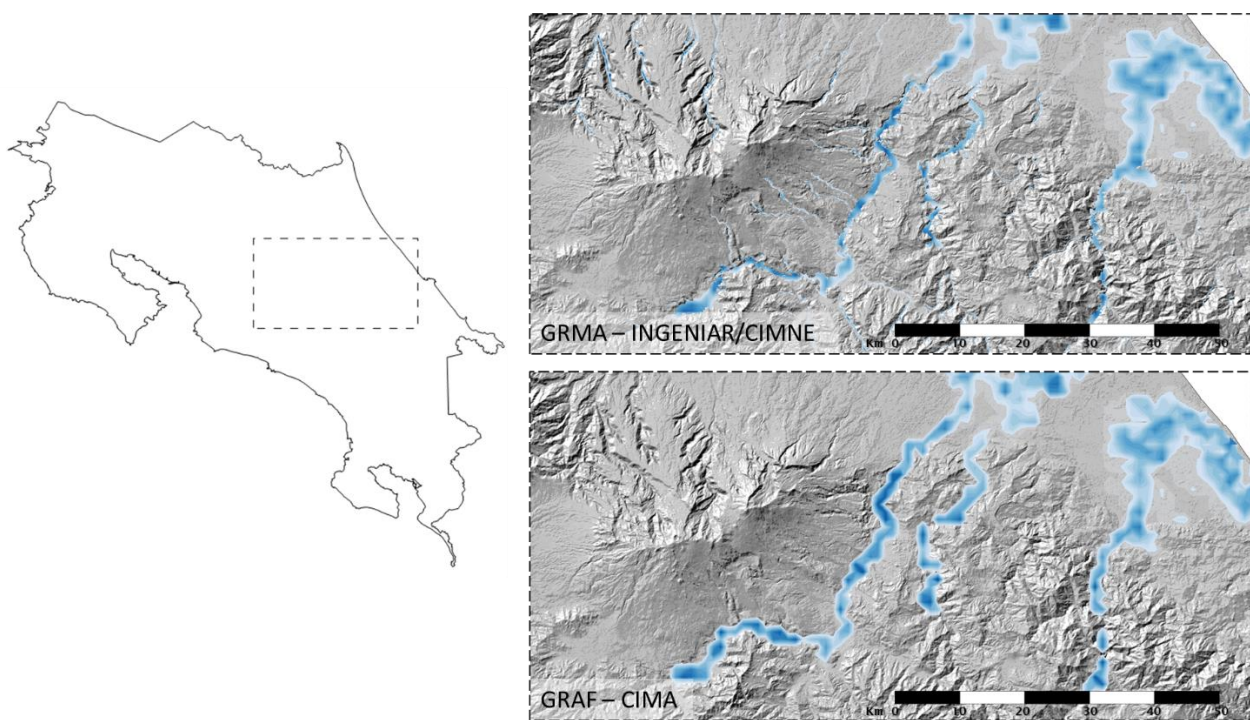


Figure 89. Comparison of 1000 years riverine flood hazard maps in the region enclosed by the box.

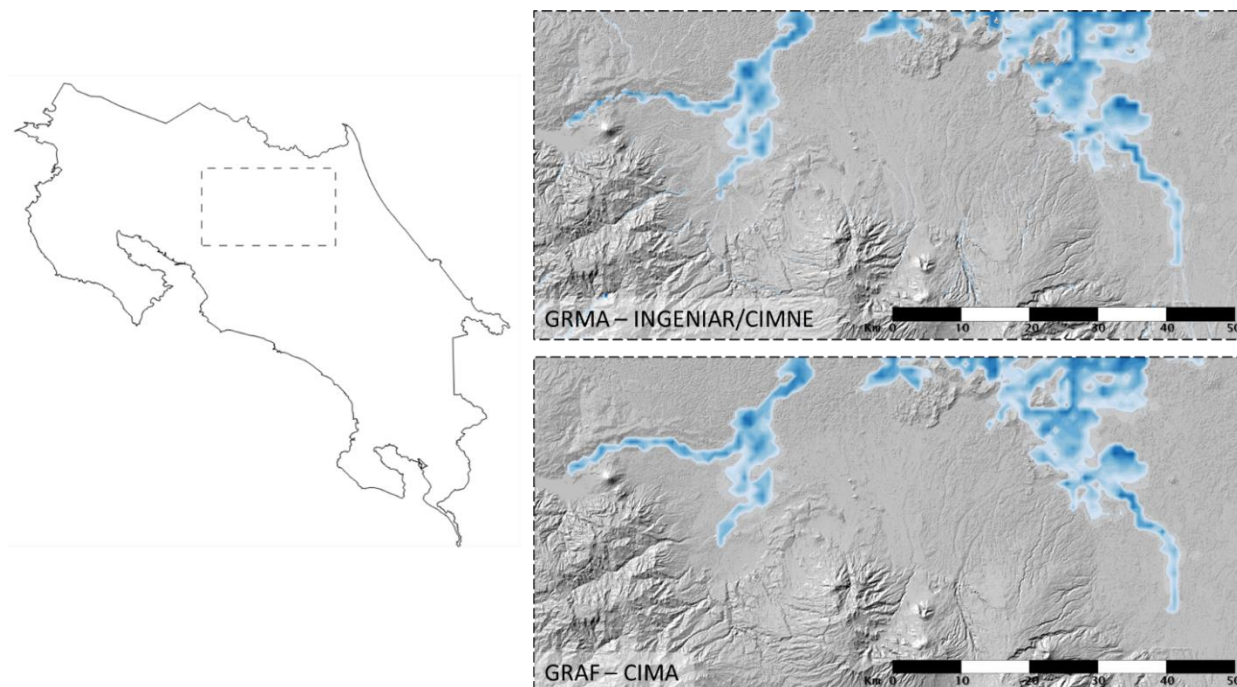


Figure 90. Comparison of 1000-year fluvial flood hazard maps in the area enclosed by the box.

Finally, the point-by-point difference across the country was calculated between the 1000-year return period flood map for Costa Rica used in the GRAF project and the flood map computed in this project. The difference was calculated as follows:

$$\text{Difference} = h_{GRMA} - h_{GRAF} \quad \text{Equation 4}$$

The result is shown in Figure 91. Red areas indicate that the GRMA model provides a higher value than GRAF, while blue areas show the opposite. As can be seen, many of Costa Rica's rivers and streams appear outlined in red, which indicates that the GRMA model is able to incorporate them due to its higher resolution. In other words, the GRAF model is blind to these streams because of its low spatial resolution. Likewise, some blue patches can be observed around river channels. This occurs because those rivers are indeed included in the GRAF model but, again, at low resolution, which artificially enlarges the floodable areas around the channels. This situation has been corrected in the GRMA model, allowing for a better definition of riverbanks. Finally, in broadly floodable zones, the results match quite well, with slight differences in blue —meaning that GRAF slightly overestimates flooding compared to GRMA.

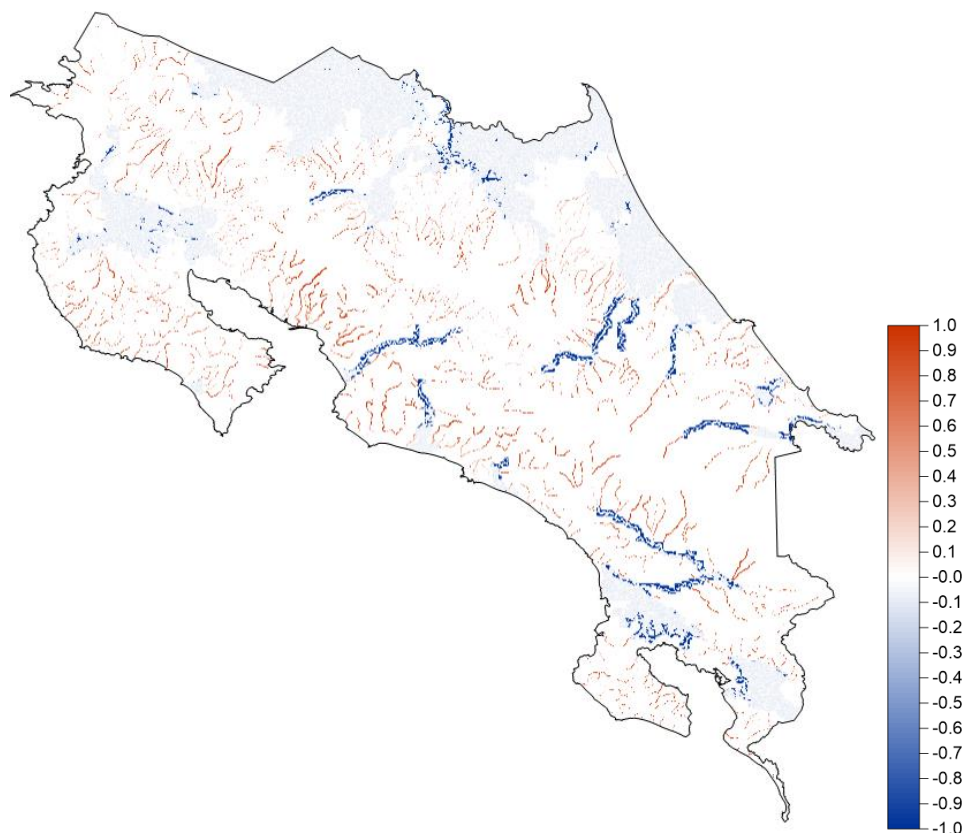


Figure 91. Difference between GRMA and GRAF flood models. Scale in meters.

It is worth noting that, although the differences mentioned exist, they are to be expected when modifying the spatial resolution and calculation models. While the GRMA model is a higher-resolution model developed to operate at a national scale, the GRAF model —originally designed at a global scale— remains an acceptable model whose results are reasonable despite its coarser resolution.

4.5 Flood Hazard for canton of Heredia

As at the national level, flood hazard was evaluated for the canton of Heredia considering both pluvial flooding (surface water ponding) and fluvial flooding (river overbank flow).

4.5.1 Pluvial Flooding in the Canton of Heredia

The assessment of pluvial flood hazard in Heredia follows the same principles applied at the national level. That is, based on a digital elevation model, areas exposed to surface water ponding and areas not exposed are identified as a function of topographic form. Figure 92 shows the digital elevation model used for the canton of Heredia, which has a spatial resolution of 5 meters per pixel. The assessment methodology is described in Annex A.3.

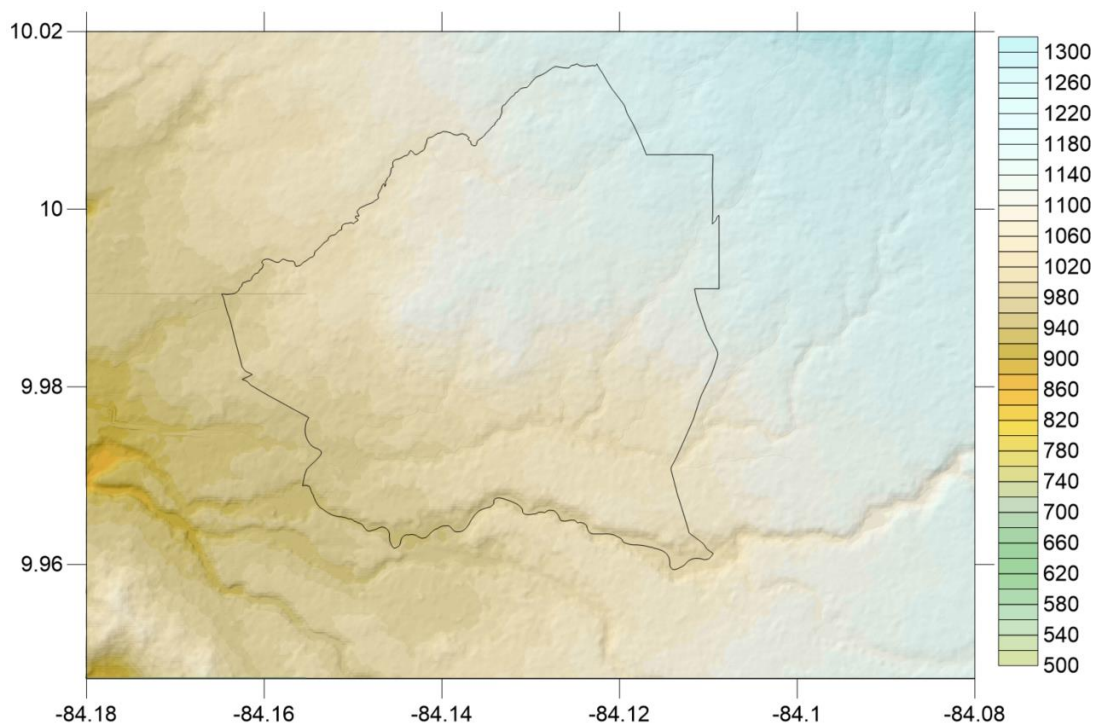


Figure 92. Digital elevation model for the canton of Heredia. The scale represents meters above sea level.

By applying the methodology described in Annex A.3, the results summarized in the maps shown in Figure 93 to Figure 97 are obtained. The map scale represents flood depth, expressed in meters. Elevated areas or zones with positive terrain curvature, where pluvial flooding is not expected to occur, are highlighted; these correspond to areas with very low or null accumulation of precipitation volume. Otherwise, most of the canton area exhibits pluvial flooding intensities. It should be noted that these intensities are very low, with maximum values below 13 cm for a 1,000-year return period.

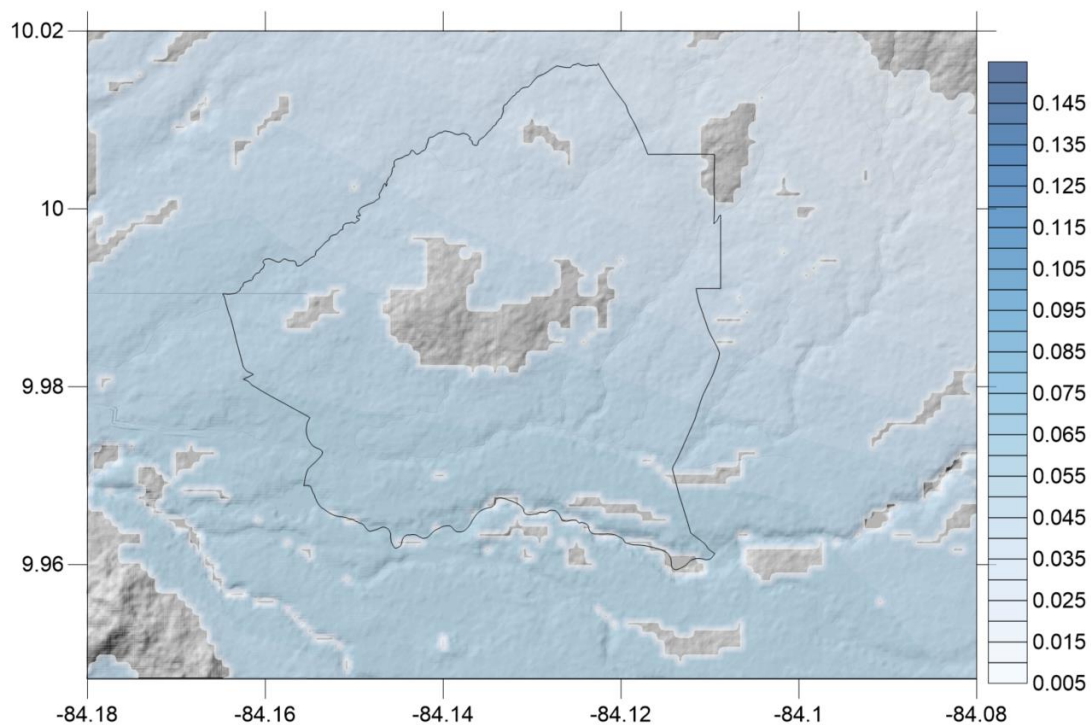


Figure 93. Pluvial flood hazard map for the canton of Heredia for a 100-year return period. The scale represents flood depth in meters.

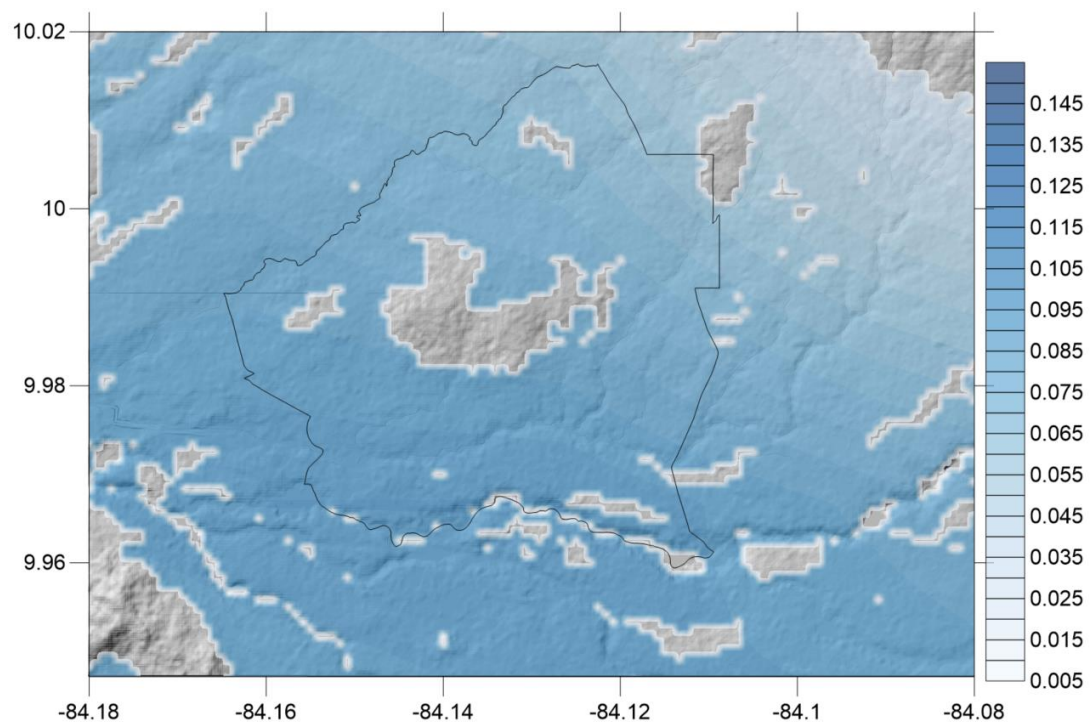


Figure 94. Pluvial flood hazard map for the canton of Heredia for a 500-year return period. The scale represents flood depth in meters.

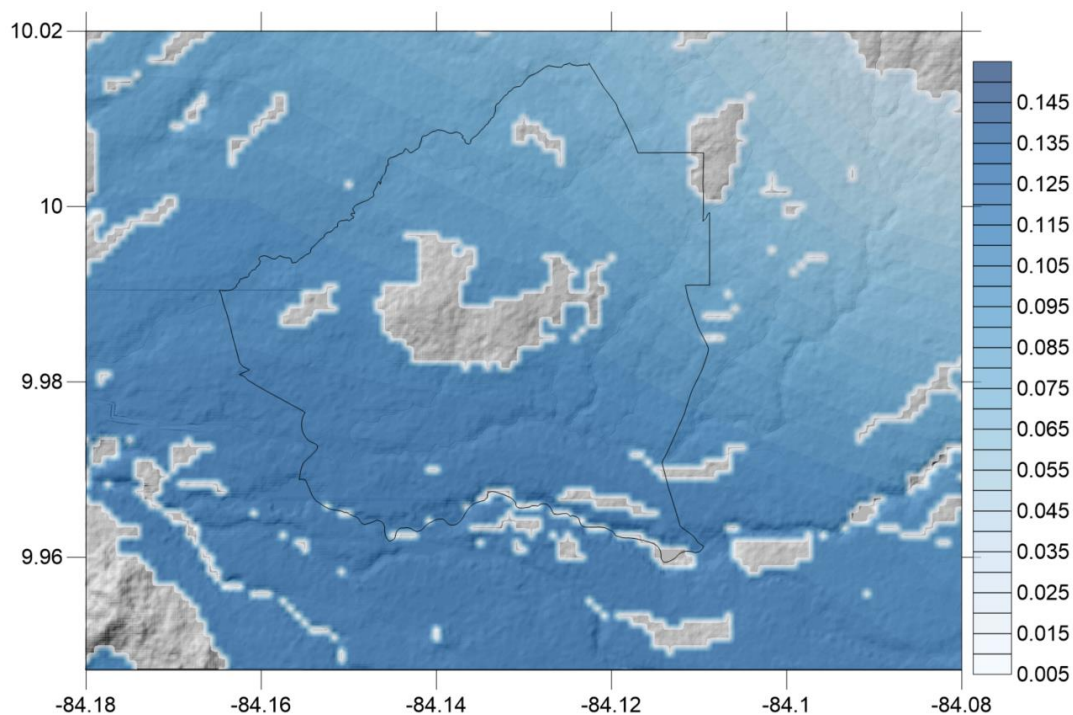


Figure 95. Pluvial flood hazard map for the canton of Heredia for a 1,000-year return period. The scale represents flood depth in meters.

4.5.2 Fluvial Flooding in the Canton of Heredia

The Pirro River basin extends across three cantons. In its upper section, to the north, it belongs to the canton of San Rafael; towards the east, it covers part of the canton of San Pablo; and in its middle and lower sections, it flows through the central canton of Heredia. The basin has a total area of 10,678 km², most of which is located within the urban area of Heredia.

The Pirro River originates near Cerro Piedra (also known as Peineta) and is part of the Bermúdez River basin, which in turn is a tributary of the Virilla River.

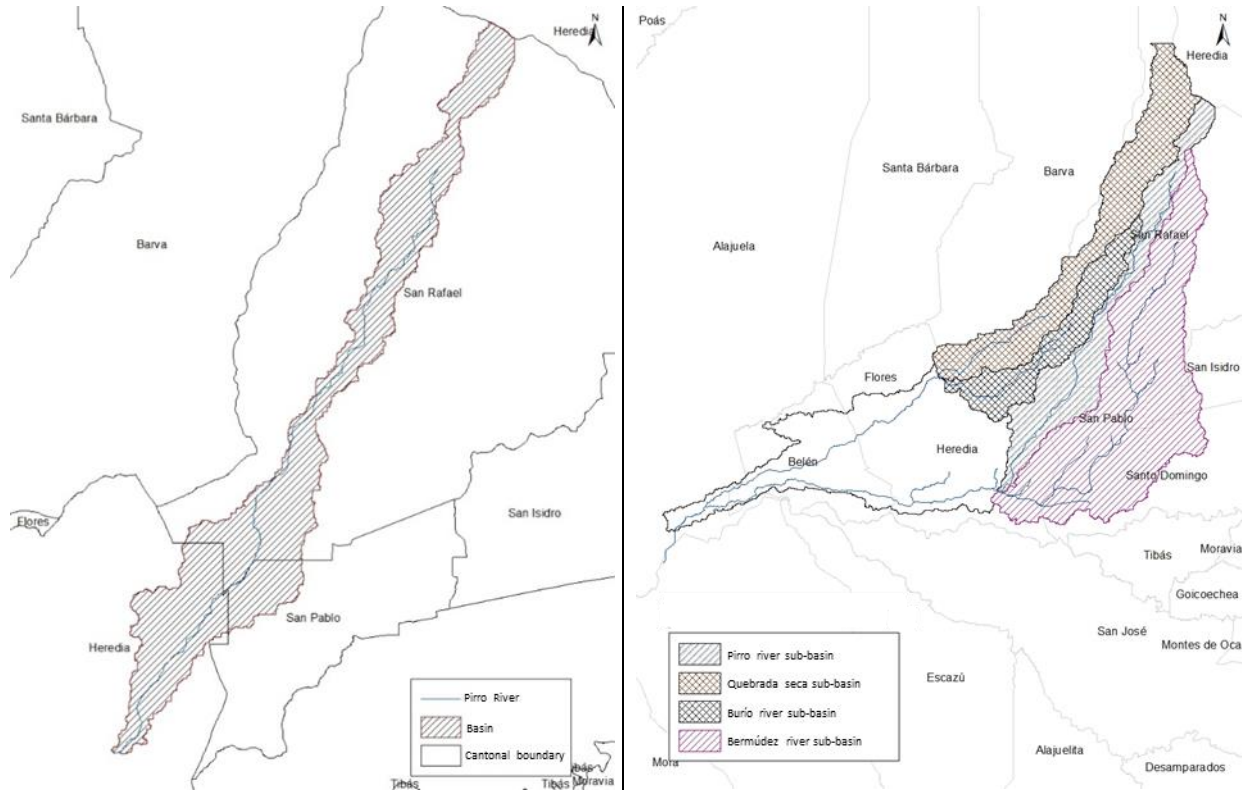


Figure 96. Left.: Pirro river basin. Right.: Pirro, Bermudez and Burio river basins

For this reason, in addition to the analysis of the Pirro River basin, the study also considered the Bermúdez River (mentioned earlier), the Burío River, and the Quebrada Seca stream. The analysis area was expanded to include most of the canton of Heredia, the entire canton of San Pablo, and portions of the cantons of Santo Domingo and San Rafael, covering a total area of 82.38 km². Figure 96 shows the location of the mentioned basins.

The topographic data used was obtained from EOS DATA ANALYTICS, specifically a DEM with a spatial resolution of 4.7 meters, with a maximum elevation of 2298.13 m.a.s.l. within the basin. Figure 97 presents the DEM for this study area.

The land cover classification was derived from the updated land use map of Costa Rica developed by Vargas (2020). Based on this land cover, the Curve Number (CN) was determined, following the same procedure previously described in Section 4.2.3.

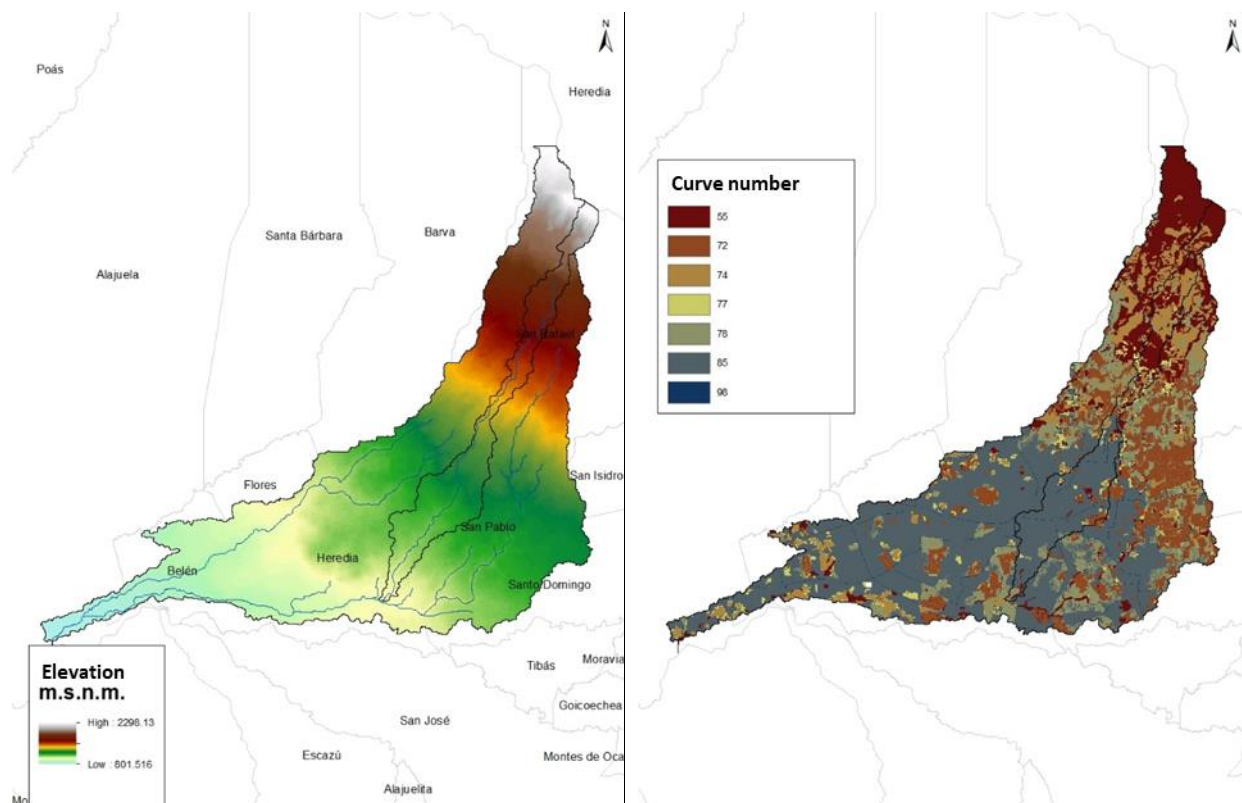


Figure 97. Left.: Digital Elevation Model. Right.: Curve number. Burlo, Pirro, and Bermudez river basins.

The hydraulic modeling in this case is carried out using a two-dimensional model, in which the hydrodynamic behavior is approximated by averaging velocities over depth and solving the flow in the two horizontal directions. This approach makes it possible to model the flow within the river channels and their overflow, with a level of detail appropriate for the purposes of the project. In this study, the HEC-RAS v6.0 software is used as the two-dimensional hydraulic modeling engine.

Given the strong dependence of the model on topography, the DEM is subjected to preprocessing to correct potential gaps in the file, fill artificial sinks, or remove spurious peaks that may exist due to resolution errors in the data or the rounding of elevations to the nearest integer. The DEM was processed using the HydroTools, with the objective of accurately representing the river channels.

Figure 98 shows the DEM before and after preprocessing, in the lower region of the study basin. Although the differences may appear subtle, they are highly significant for the quality of hydrodynamic modeling.

Additionally, a procedure for indexing the known channels was applied to ensure that surface flow accurately followed the river network. For this purpose, the DEM was compared with official river maps of Costa Rica and satellite imagery in order to identify the actual channel locations and adjust the river lines when deviations were observed in the DEM. The channel width and depth were estimated from these sources, as no bathymetric data were available. This step ensures that the hydrodynamic modeling adequately captures flow within the channels and potential overflows.

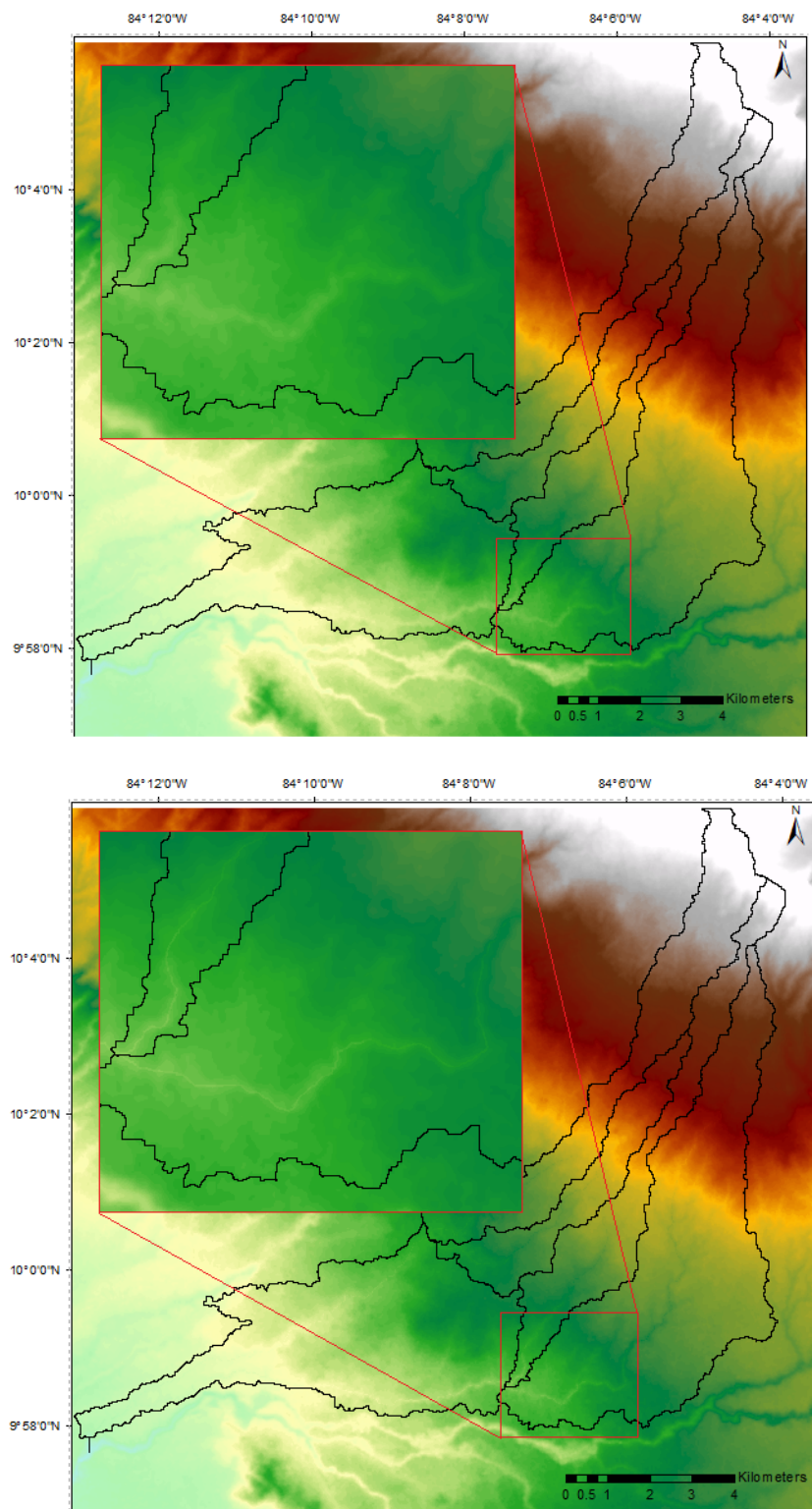


Figure 98. Digital Elevation Model before (top) and after (bottom) preprocessing.

The area for 2D modeling was defined by setting an upper boundary in high, non-floodable zones, and a lower boundary at the river's outlet point, located approximately 5 km west of the boundary of the Heredia canton. Within this domain, a grid with a resolution of 10 m x 10 m per pixel was defined. Figure 99 shows the extent of the two-dimensional model.

In order to improve the accuracy of the modeling in areas of highest hydraulic interest, a local mesh refinement was applied along the main channels within the 2D domain. This consisted of a denser mesh (4 m x 4 m) aligned with the axes of rivers and streams, while the rest of the domain maintained a resolution of 10 m x 10 m. The mesh refinement allows for a more detailed capture of surface variations and velocity gradients associated with flow in natural channels, improving the representativeness of the model.

To represent flow resistance within the 2D domain, Manning's roughness coefficients (n) were assigned according to the type of surface and the characteristics observed in the field. For the main channels with rocky beds, presence of stones, debris, and margins with sparse vegetation, $n = 0.05$ was used, consistent with Chow (1959) and Arcement & Schneider (1989), who report ranges of 0.035–0.060 for natural channels with gravel beds and 0.045–0.055 for sections with irregularities and heterogeneous obstructions. For paved streets and urban plazas, $n = 0.014$ was assigned, while green areas with grass and scattered vegetation were modeled with $n = 0.03$. In residential areas, which combine impervious surfaces (streets, patios), small gardens, and obstacles such as fences and buildings, $n = 0.035$ was assigned, realistically representing surface flow resistance in densely urbanized areas. The selection of these values allows for hydraulic modeling consistent with the heterogeneity of surfaces within the domain, incorporating both channel roughness and the characteristics of urban and residential areas

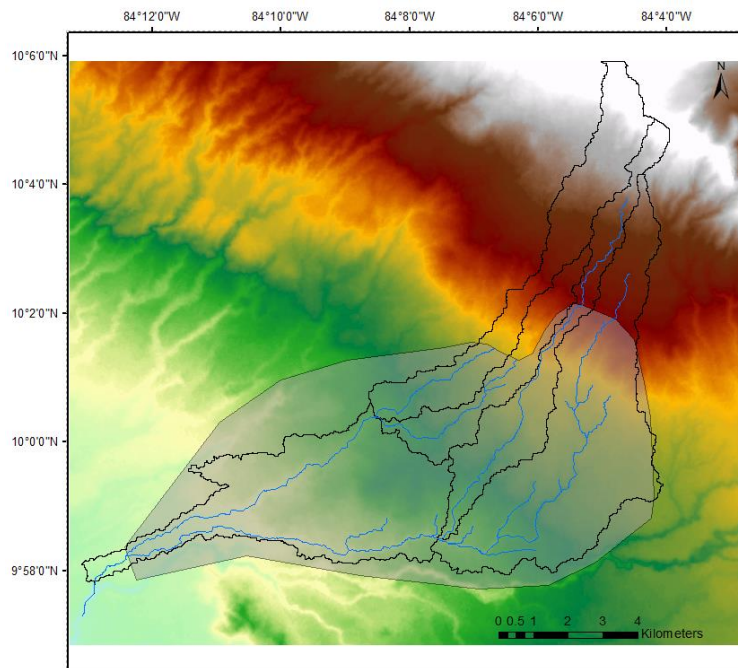


Figure 99. Extent of the two-dimensional hydraulic model.

The hydrological response of the considered catchments was modeled under the simulated meteorological forcing, resulting in hydrographs of rising flow that are used as inputs to the two-dimensional hydraulic model. The resulting flows from the subcatchments were calculated using the modified Clark method, presented in the Initial Report, and applied to the main channels as inflow points within the 2D domain. These inflows do not occur simultaneously but are staggered according to the concentration times of the tributary catchments, as indicated in Figure 100. Simultaneously, HEC-RAS 2D accounts for the rainfall directly over the mesh, converting it into surface runoff and progressively routing it into the channels. In this way, the model integrates both the contributions from upstream subcatchments and the rainfall over the domain, ensuring that flows are not underestimated and that flood levels adequately reflect the different storm events and the complete flow dynamics within the study area.

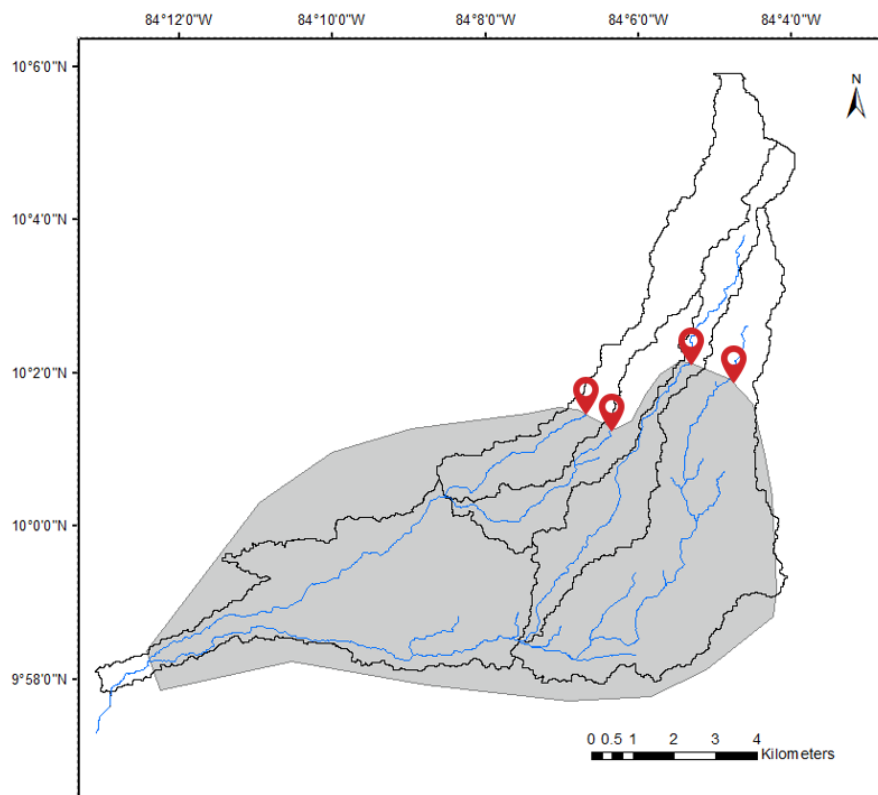


Figure 100. Hydrodynamic model load points.

Figure 101 shows four precipitation scenarios obtained from the meteorological simulations over the study area, presented as examples to illustrate the results of the modeling. These scenarios were arbitrarily selected to visualize different responses of the watersheds and the hydraulic model.

Each sub-basin generates the corresponding flood hydrographs, which are presented in Figure 102, under the associated precipitation scenario. These hydrographs are routed through the two-dimensional model,

entering at the previously defined inflow points, and result in the hydraulic response shown in Figure 103 to Figure 106.

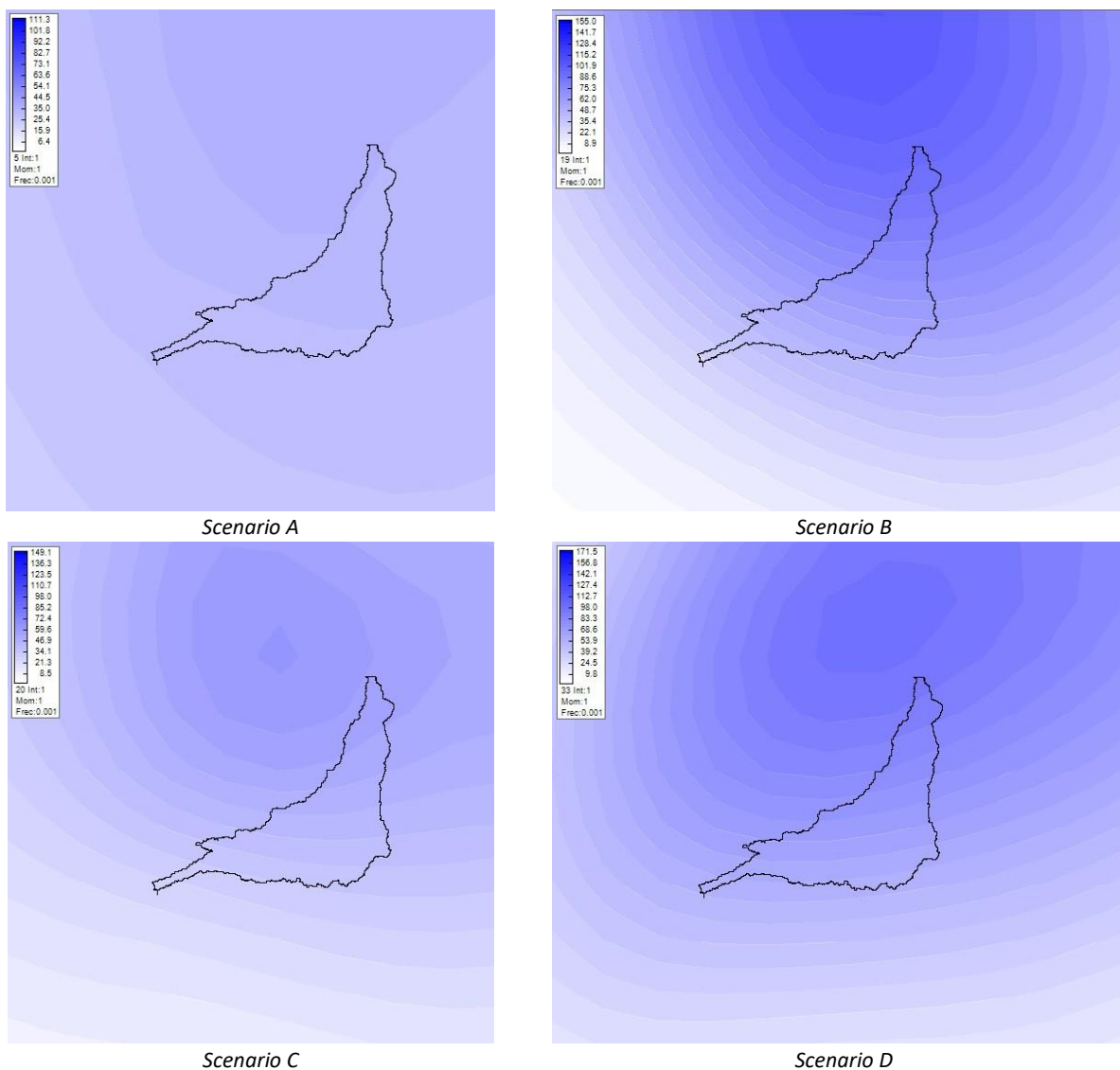


Figure 101. Precipitation distribution in selected scenarios

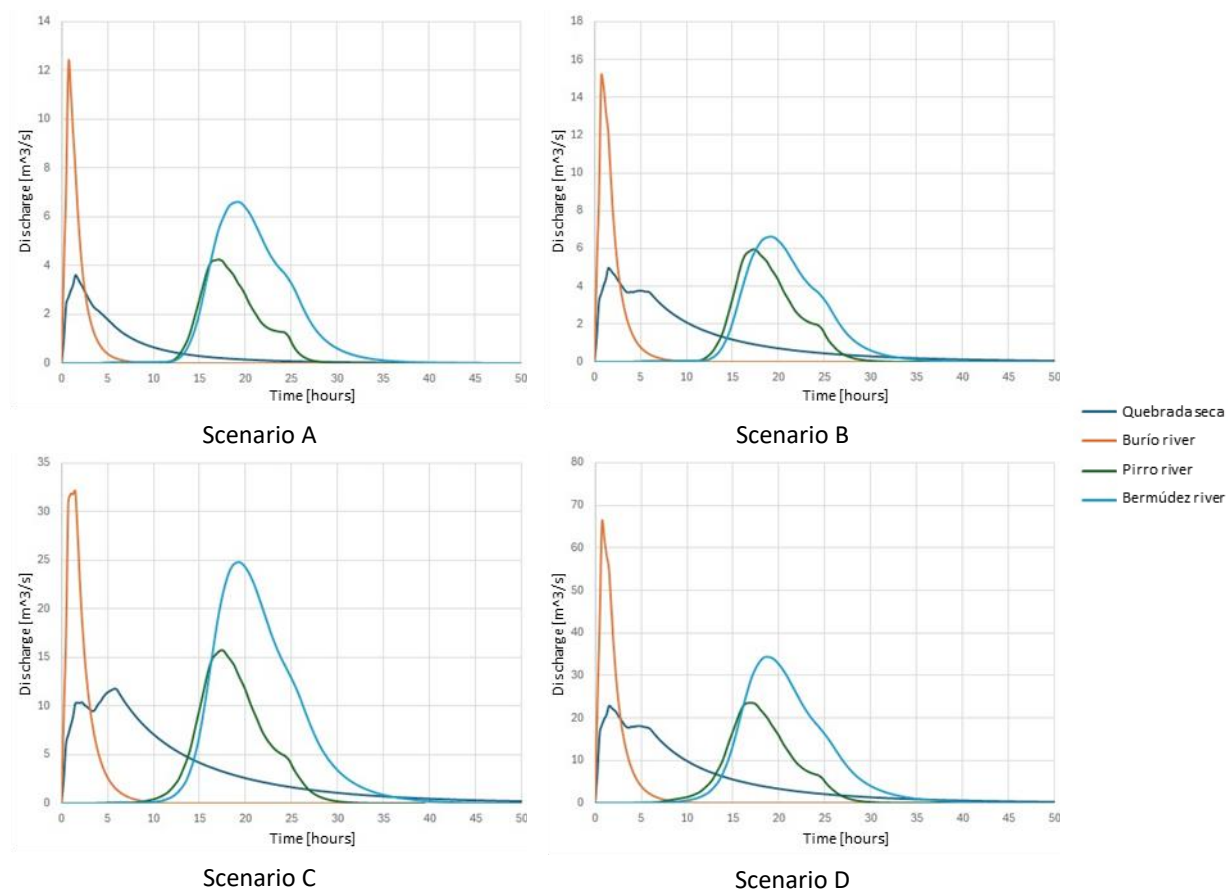


Figure 102. Hydrographs of basin response to selected precipitation events.

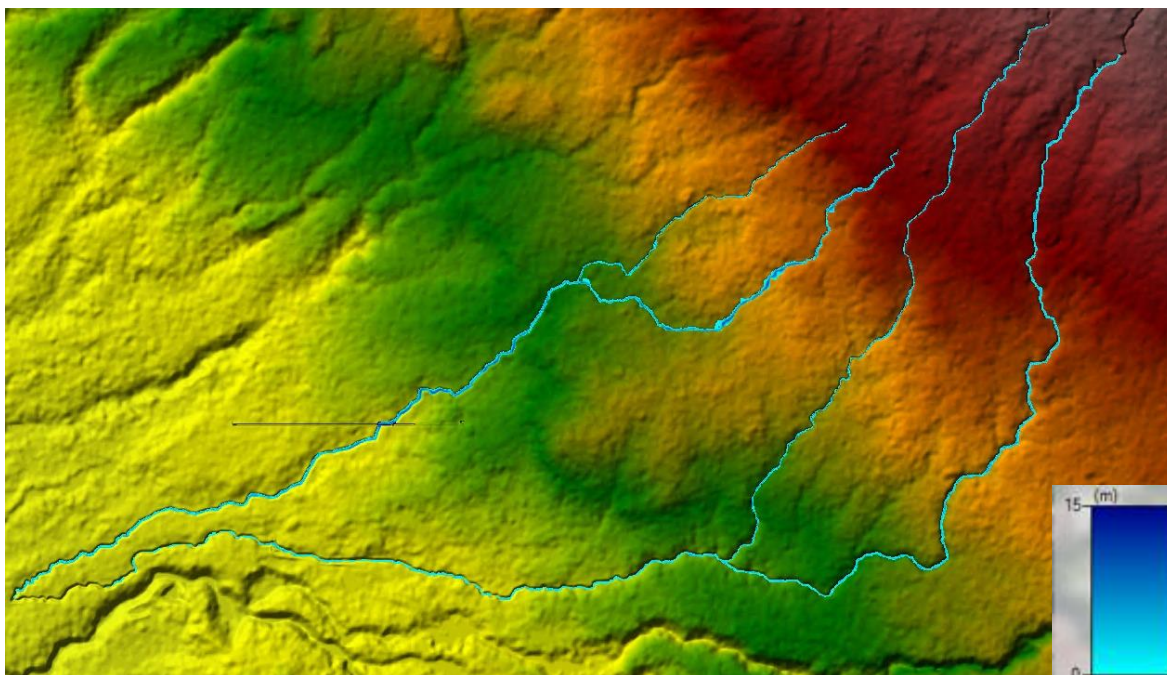


Figure 103. Hydraulic model response for selected scenarios. Scenario A

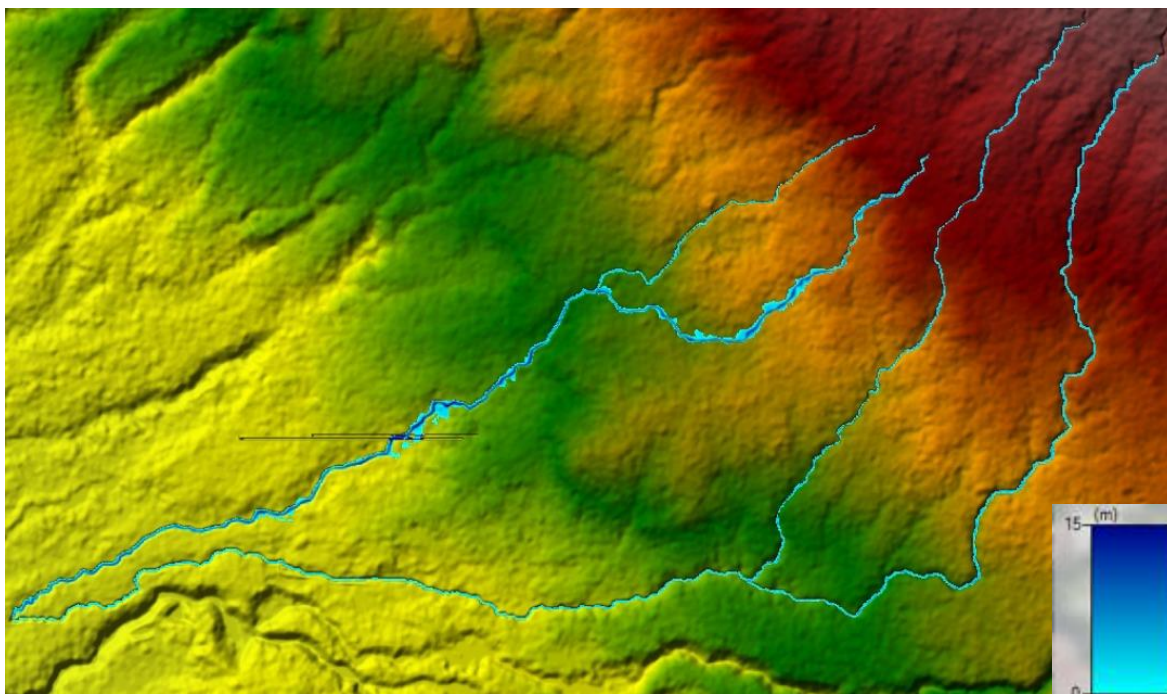


Figure 104. Hydraulic model response for selected scenarios. Scenario B

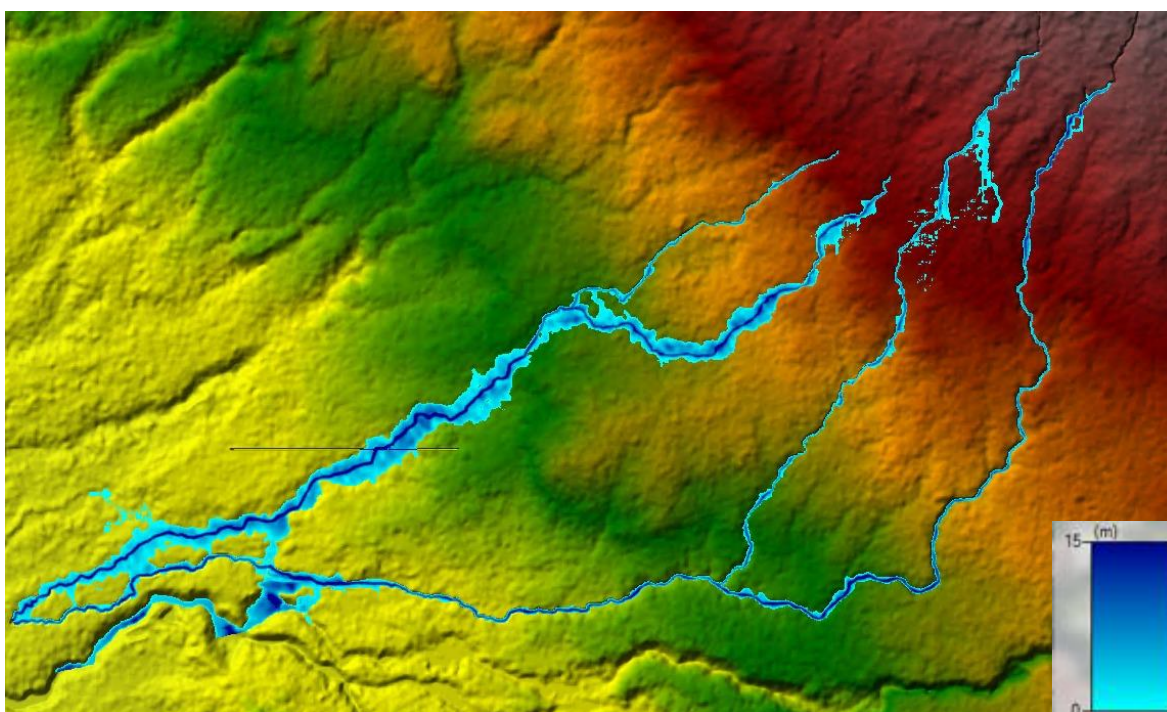


Figure 105. Hydraulic model response for selected scenarios. Scenario C

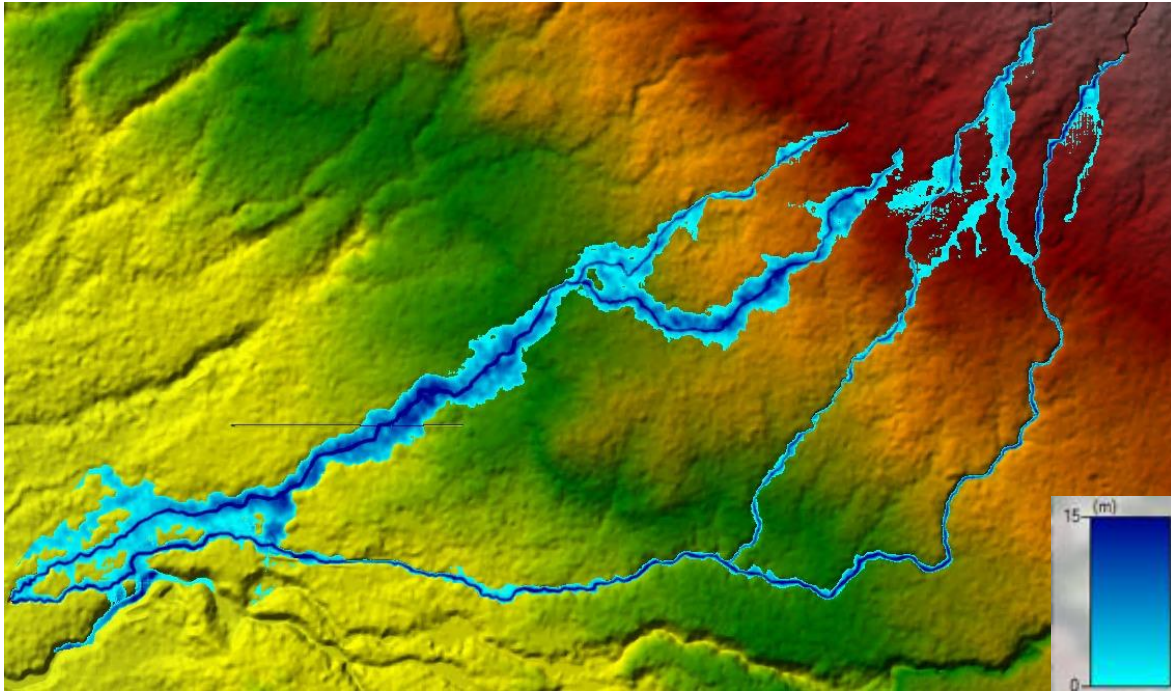


Figure 106. Hydraulic model response for selected scenarios. Scenario D

5 COASTAL FLOOD HAZARD

In this study, coastal flooding is triggered by extreme meteorological phenomena, particularly hurricanes, due to their ability to produce sea level surges along the coast. Although hurricanes do not typically make direct landfall on Costa Rican shores, they generate storm surge elevations that can result in potential coastal flooding. Tsunamis are also taken into account in the assessment of coastal flooding, as presented in Section 5.3.

5.1 Inputs for the Modeling

5.1.1 Historical tracks

The tracks of historical hurricanes, along with their associated intensity parameters and their variation along the trajectory, were obtained from the IBTrACS database (International Best Track Archive for Climate Stewardship) of the National Oceanic and Atmospheric Administration (NOAA). This database is the most comprehensive and widely recognized global archive of tropical cyclone tracks and characteristics (Knapp et al., 2010).

The IBTrACS dataset includes the following information:

- Date (hour, day, month, and year) of each observation
- Central pressure of the cyclone (in millibars)
- Geographic position (latitude, longitude)
- Maximum sustained wind speed averaged over 1 minute

For the Atlantic Ocean, the database contains 1,589 tropical cyclones from 1851 to 2025. For the Pacific Ocean, it includes 965 tropical cyclones from 1950 to 2025.

Figure 107 and Figure 108 show the tracks of tropical cyclones for the Atlantic and Pacific Oceans, respectively, as recorded in the IBTrACS database up to the year 2025.

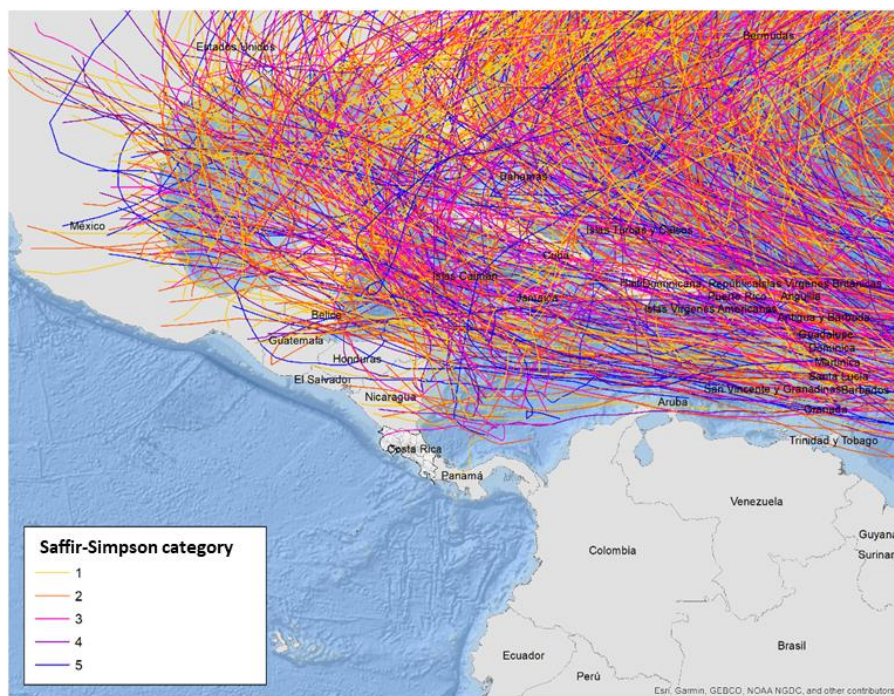


Figure 107. Historical tracks in the Atlantic Ocean basin

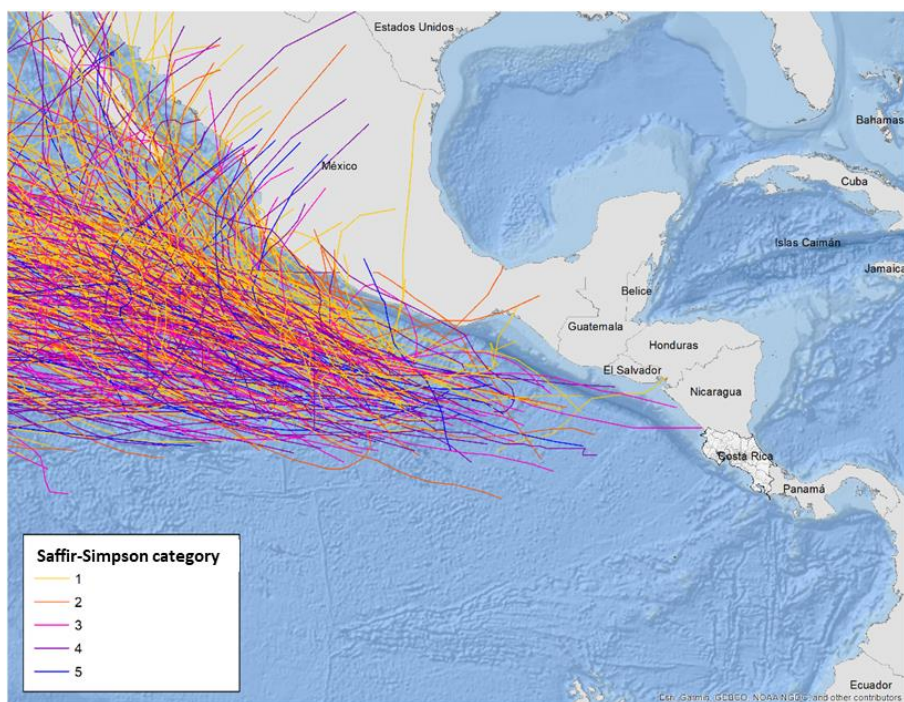


Figure 108. Historical tracks in the Pacific Ocean basin

5.1.2 Simulated Track for Future Climate

In order to incorporate the perturbations caused by climate change in both cyclogenesis and the lifecycle of storms, it is necessary to include projections derived from global circulation models (GCMs) of the variables that influence the formation and movement of tropical cyclones.

For this purpose, the hurricane catalog is composed of historical records obtained from IBTrACS, complemented with a representative sample from the STORM dataset developed by Bloemendaal et al. (2020).

This dataset provides the equivalent of 10,000 years of simulated tracks, generated using a stochastic model of the main characteristics that determine tropical cyclone tracks, such as: Central pressure, forward speed and direction, location of cyclogenesis, sea surface temperature, mean sea level pressure, among other variables.

Bloemendaal et al. (2020) included in their STORM model the projections of five global circulation models (GCMs), which are currently the only ones with the spatial and temporal resolution necessary to approximate mesoscale meteorological processes. These models are: CMCC-CM2-VHRA, CNRM-CM6-1-HR, EC-Earth3P-HR, and HadGEM3-GC31-HM, all obtained from the PRIMAVERA High Resolution Model Intercomparison Project (HighResMIP), a subproject of CMIP6.

The future tracks have been determined using STORM, based on the projections of the GCMs mentioned above, in all cases considering an RCP8.5 emissions pathway, as this is the only pathway included in this assessment. At present, no projections are available with the same level of resolution for other greenhouse gas emission pathways.

On top of the selected STORM tracks, additional stochastic simulations were performed to generate new tracks covering the full spectrum of possible events across a wide range of frequencies and intensities.

As a consequence, it is not possible to model coastal flood hazard for the same set of future climates presented in Table 14 (those applicable to drought and pluvial/fluviat flood hazards). Instead, it is only possible to model one emissions pathway (SSP5-8.5), with a combined result of the four GCMs, but not with projections obtained separately for each individual model.

In other words, the future cyclone tracks are derived from an ensemble of HighResMIP models, rather than from each model individually. This implies that, for coastal flooding, results are available only under two future climate scenarios, as summarized in Table 17.

Table 17. Future climates considered for coastal flood

GCM	Pathway	Target year
HighResMIP	SSP5-8.5	2035
HighResMIP	SSP5-8.5	2050

Figure 109 and Figure 110 show the simulated cyclone tracks under climate change conditions for the Atlantic and Pacific Oceans, respectively.

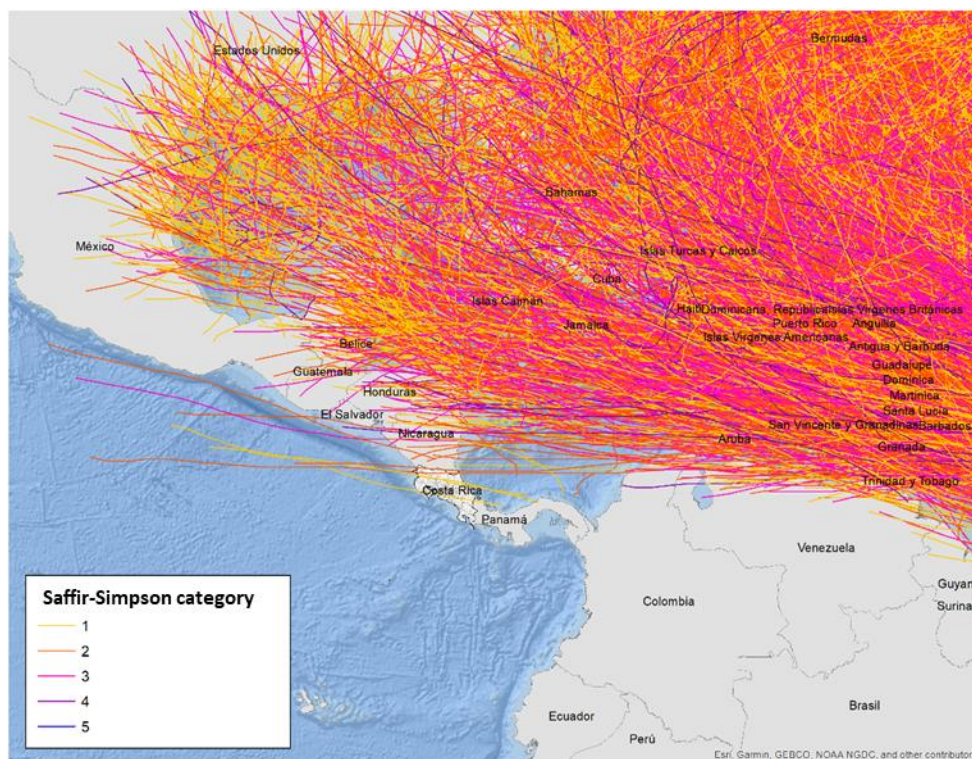


Figure 109. Simulated pathways with climate change in the Atlantic Ocean basin

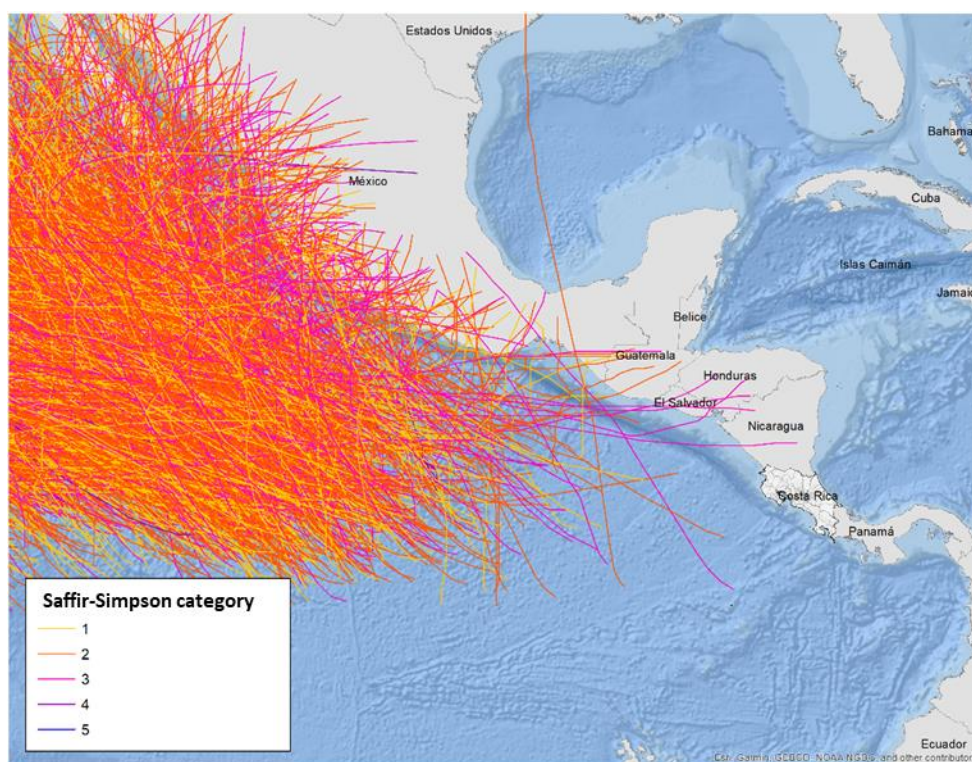


Figure 110. Simulated pathways with climate change in the Pacific Ocean basin

5.1.3 Sea Level Rise

In order to incorporate sea level rise under future climate conditions, data from the *Global Sea Level Change Time Series (1950–2050)*, developed under the Copernicus Climate Change Service (C3S), was used. This dataset was generated from the *Global Tide and Surge Model (GTSM) version 3.0*, a hydrodynamic model that simulates water levels at 10-minute intervals, incorporating climate forcings from both reanalysis and global circulation models (Deltares, 2021).

For the historical period (1950–2014), climate forcings come from ERA5 and CMIP6 historical simulations, while for the future (2015–2050) projections derived from five GCMs of the HighResMIP-CMIP6 project were used, under the SSP5-8.5 emissions scenario. This approach is fully consistent with what was described for the definition of future cyclone tracks, ensuring coherence in the definition of future climates to be considered.

Regarding its spatial resolution, the dataset provides a global latitude-longitude grid with variable spacing depending on proximity to the coast: 0.1° at coastal points, 0.25° up to 100 km offshore, and up to 1° beyond 500 km from the shoreline. In the temporal domain, the series include data from 1950 to 2050, with resolutions of 10 minutes, hourly values, and annual averages (Hermans et al., 2023).

The main variable used in this study corresponds to the annual mean sea level relative to the baseline period, expressed in meters. This metric integrates multiple contributions to sea level rise, including thermal expansion of the oceans, changes in ocean circulation, contributions from the Greenland and Antarctic ice sheets, as well as glacio-isostatic adjustment. However, it does not consider local processes such as tectonic or sedimentary subsidence, which in certain regions may amplify or counteract the observed changes (IPCC, 2021).

Annual sea level rise values were obtained for the years 2035 (Figure 111) and 2050 (Figure 112), specifically along Costa Rica's coastal strip.

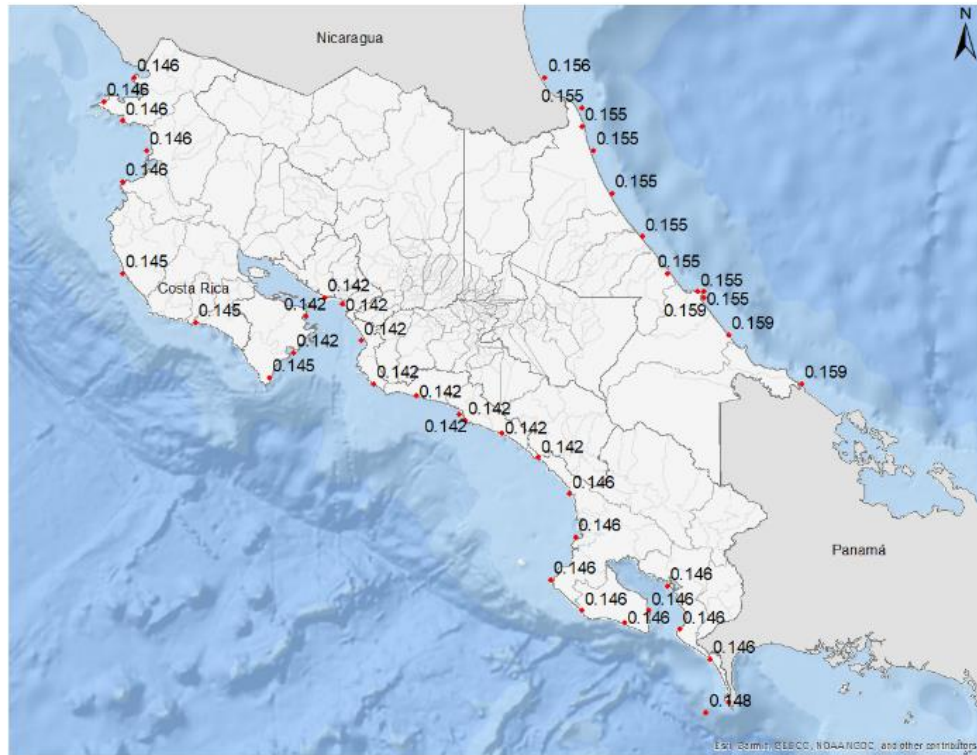


Figure 111. Sea level rise by 2035

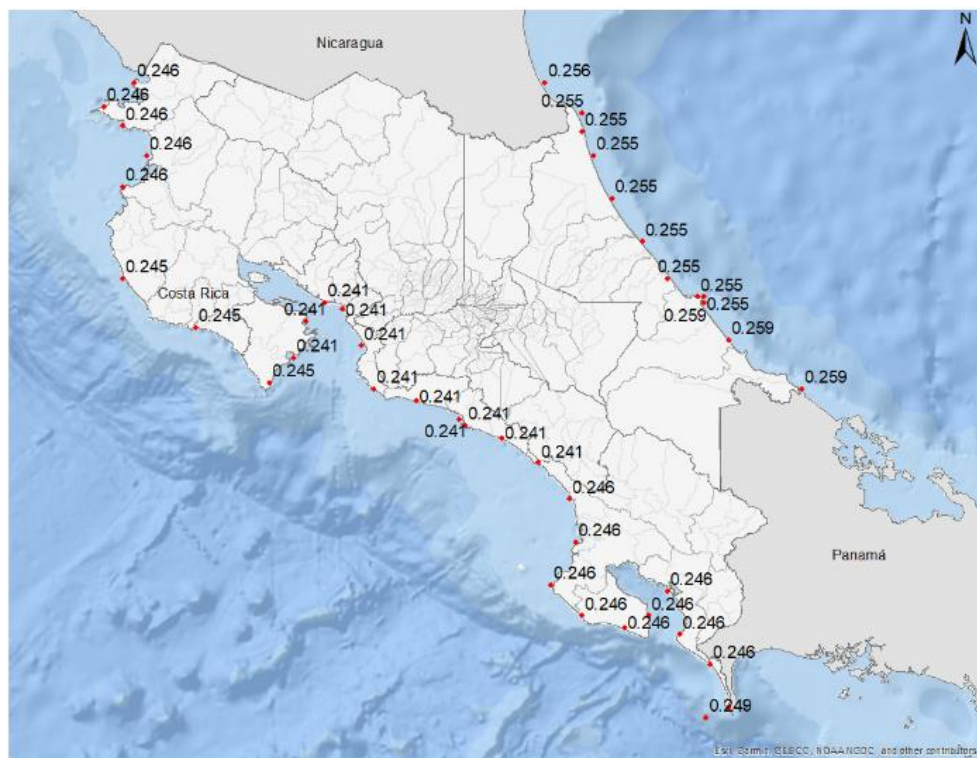


Figure 112. Sea level rise by 2050

5.1.4 Bathymetry and Topography

Bathymetry is necessary for calculating sea level rise and the resulting storm surge generated during the passage of a hurricane over a coastal area. The bathymetric data used corresponds to the 2024 version of the GEBCO² (General Bathymetric Chart of the Oceans), whose continuous global bathymetric model has a spatial resolution of 15 arc seconds, equivalent to approximately 500 meters at the equator. This makes it one of the highest-resolution global bathymetric models currently available.

The topographic information is the same as that presented in Figure 113, which corresponds to a raster with a spatial resolution of 12.5 m.

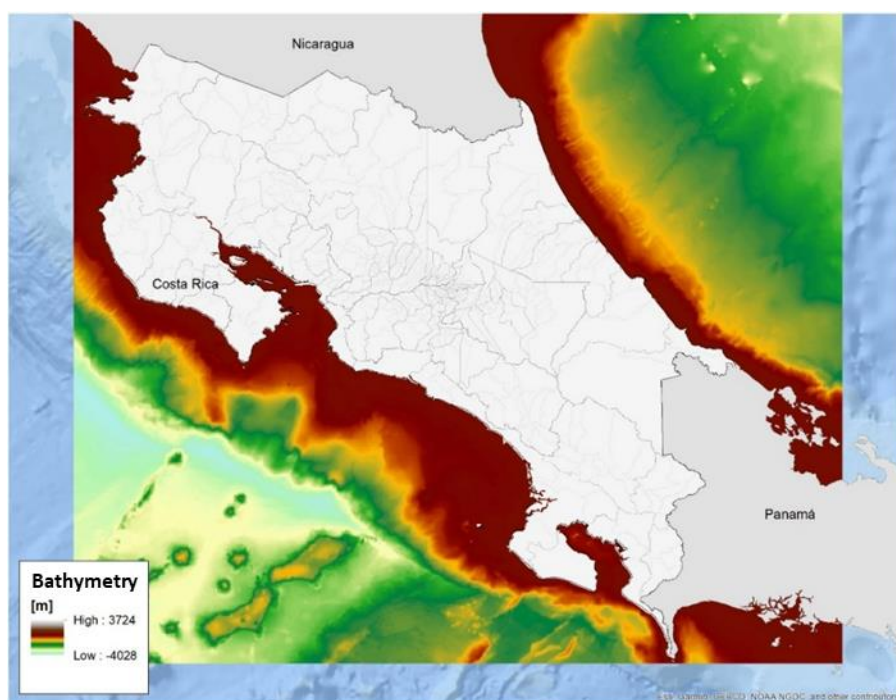


Figure 113. Bathymetry. Source: GEBCO.

5.2 Coastal Flood Hazard Assessment

Uniform hazard maps for storm surge were calculated along the Atlantic and Pacific coasts of Costa Rica, using flood depth as the intensity measure. The calculations were carried out using the Tropical Cyclone Hazard Modeler (TCHM)³.

Figure 114 presents the uniform hazard maps of run-up height generated by storm surge along the Costa Rican coastline for return periods of 50, 100, 250, 500, and 1000 years, under the baseline climate scenario. These maps are shown in terms of run-up height, since at the map scale, any detail related to coastal

² Dataset is available for visualization and download in the link: <https://download.gebco.net/>.

³ TCHM is the tropical cyclone hazard assessment module of CAPRA ROBOT.

flooding would be imperceptible. This format allows for a clear visualization of the hazard across the entire extent of Costa Rica's coastlines.

Similarly, Figure 115 shows the uniform hazard maps of run-up height considering the climate scenario with emissions pathway SSP5-8.5 for the year 2050.

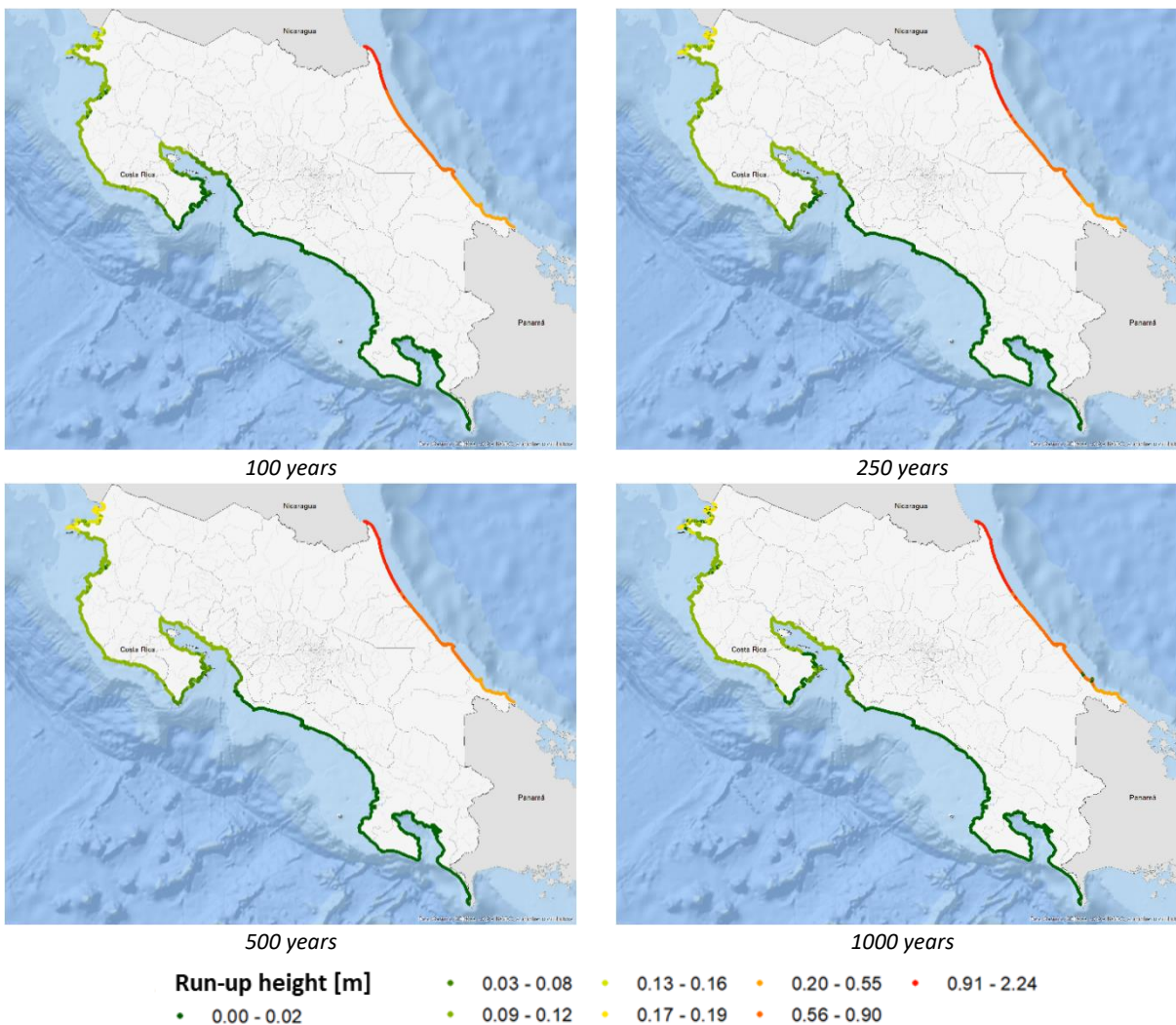


Figure 114. Uniform hazard maps for coastal flooding (run-up height) under the baseline climate scenario

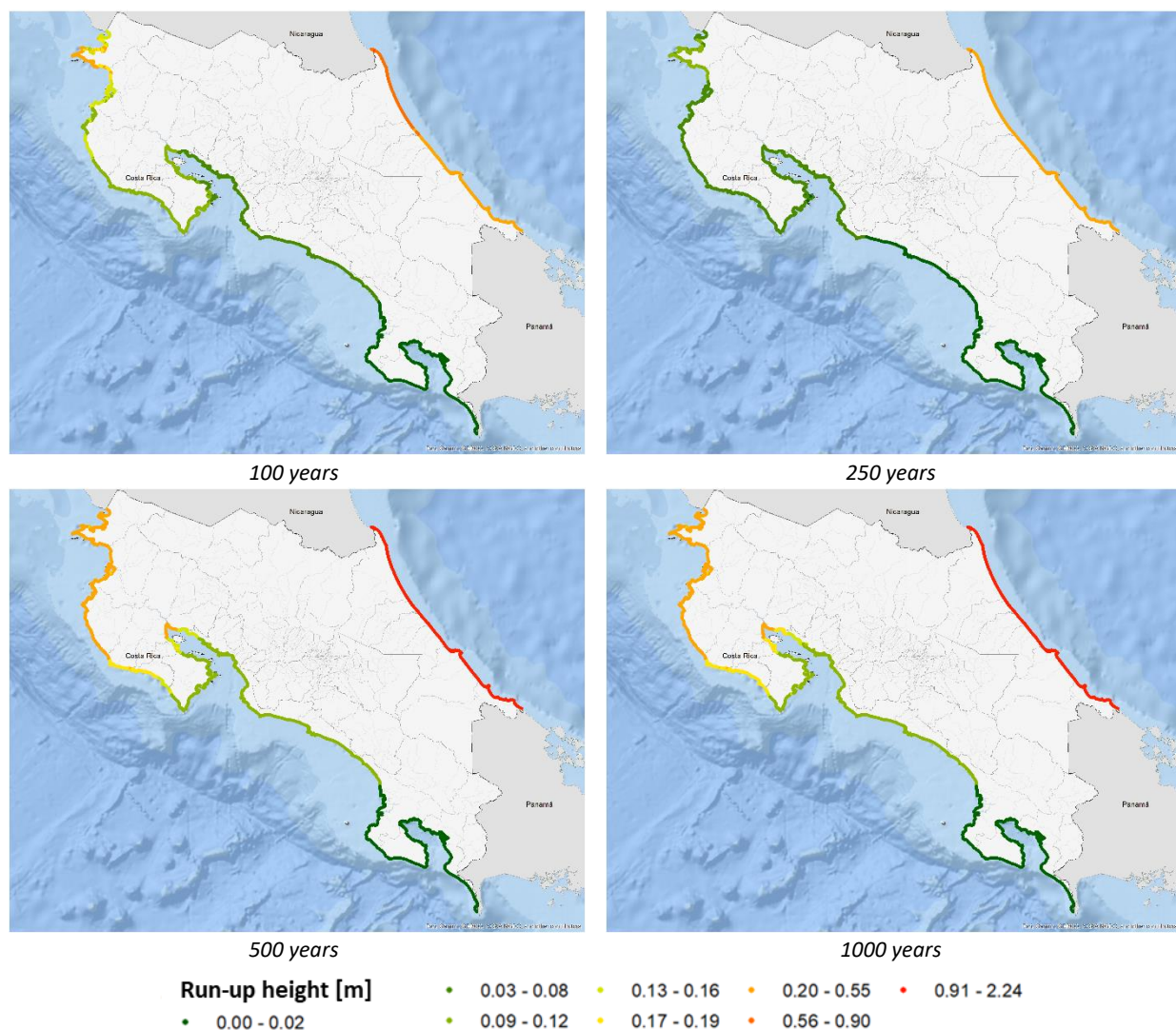


Figure 115. Uniform hazard maps for coastal flooding (run-up height) under the SSP5-8.5 climate scenario by 2050

The inland extent of coastal flooding is only perceptible when viewing portions of the coastline. For this reason, the model results are illustrated below for selected sectors of the Caribbean and Pacific coasts of Costa Rica, considering a 1,000-year return period under baseline climate conditions. Likewise, Figure 117Figure 119 shows a zoomed-in view of the city of Limón, in order to illustrate the 1,000-year return period coastal flood hazard at a finer spatial scale. It is emphasized that this is only a selection of coastal sectors, intended to illustrate the reader. Nevertheless, the complete set of results can be consulted in the project dataset.

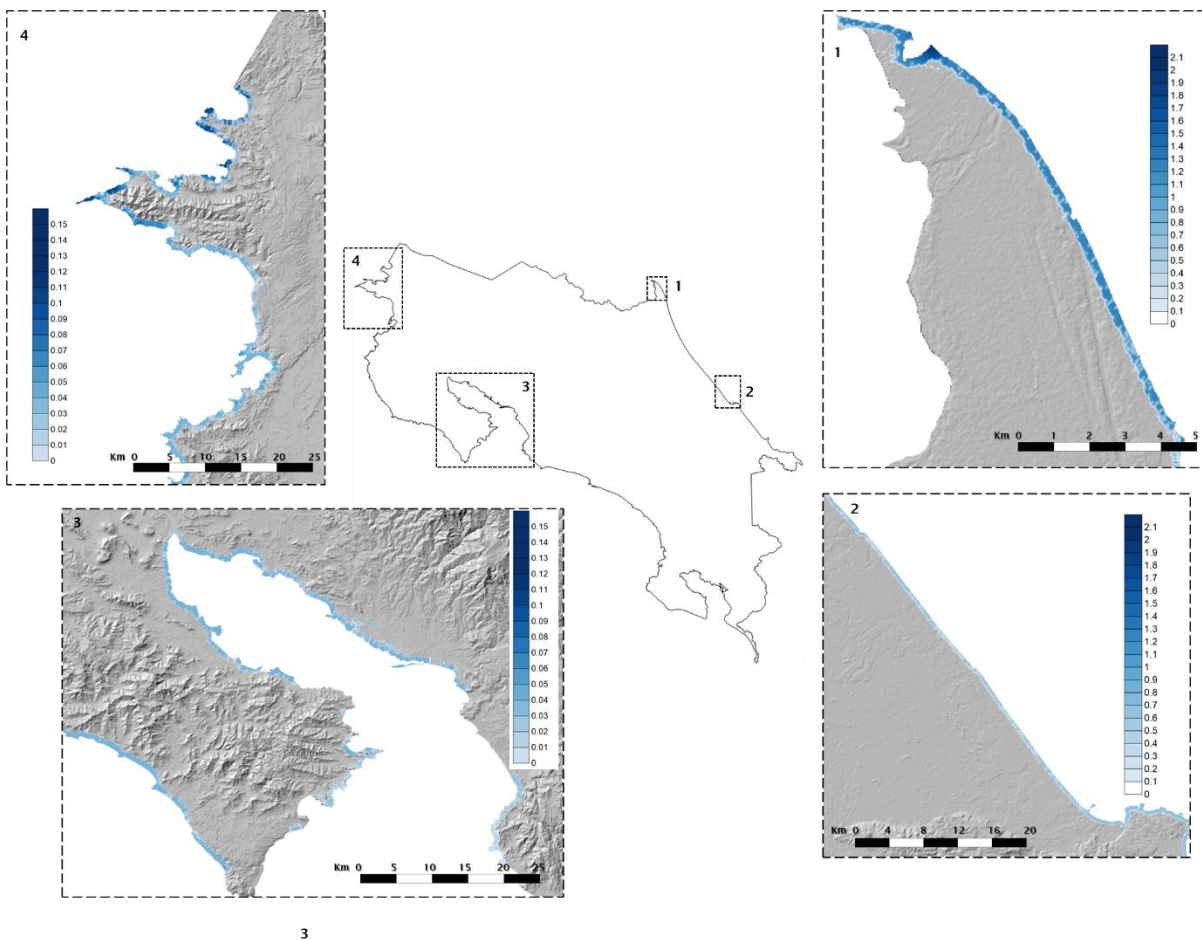


Figure 116. Close-ups of selected sectors of the Costa Rican coast. Coastal flooding with a 1,000-year return period under baseline climate conditions. Flood depth in meters.

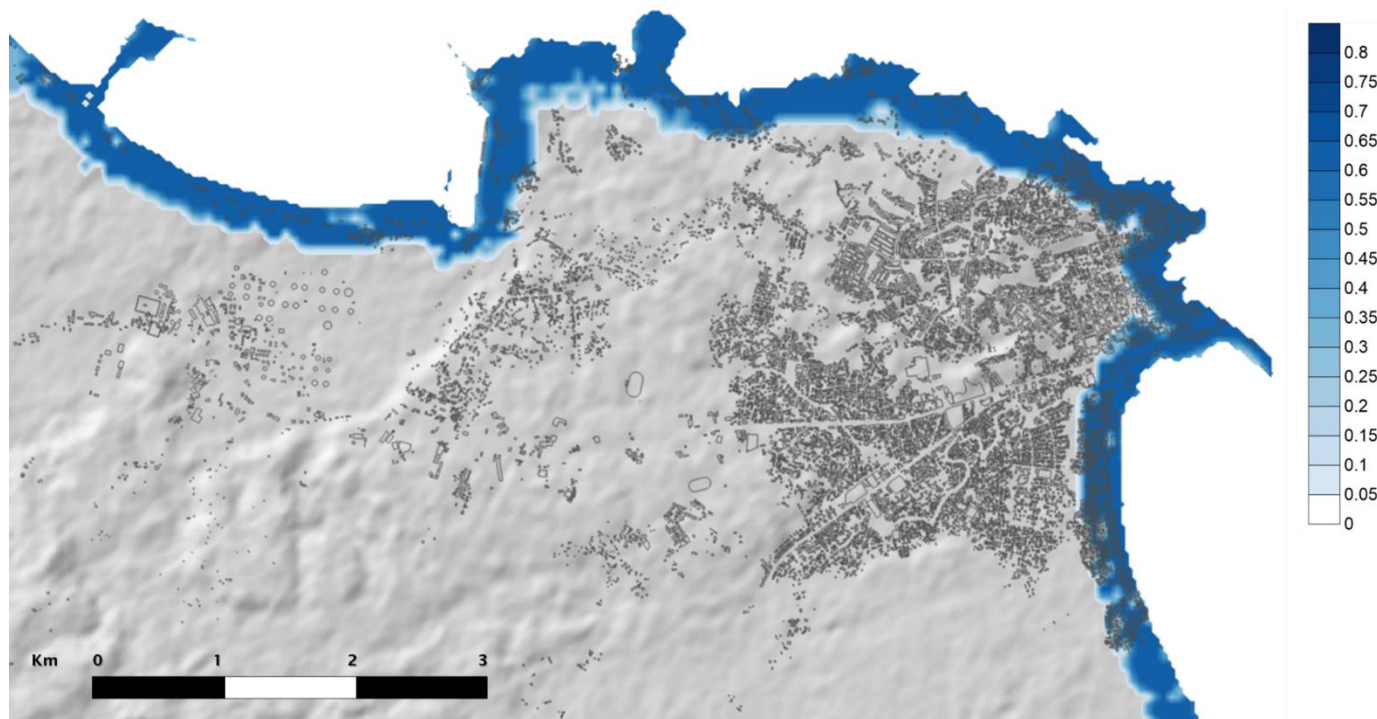


Figure 117. Zoomed-in view of the city of Limón. Coastal flooding for a 1,000-year return period under baseline climate conditions. Flood height in meters.

5.3 Coastal Flooding from Tsunami

As an added value, coastal flooding from tsunamis was evaluated along Costa Rica's Pacific coast, using the seismic hazard model presented in the Geohazards report of this consultancy⁴ (ASLAC model) for the definition of seismic events used in the calculations (generation model), and the propagation and arrival model described in the Inception Report.

A set of earthquakes capable of triggering tsunamis along the Pacific coast of Costa Rica was defined. These events correspond to high-magnitude, relatively shallow earthquakes generated in the subduction zone. Based on the consultant's experience, the selection thresholds for seismic events were established as a moment magnitude M_w greater than or equal to 7 and a focal depth of less than 20 km.

Figure 119 shows the selected seismic events. The upper panel presents the catalog of events with $M_w \geq 7$ generated in the Costa Rican Pacific subduction zone, obtained from a 10,000-year equivalent stochastic catalog generated using the ASLAC model. The lower panel of Figure 119 shows only the subset of earthquakes with hypocentral depths shallower than 20 km. This subset corresponds to the group of events used in the tsunami hazard assessment, consisting of 240 earthquakes.

⁴Document entitled: "Review of Geological Hazard Data and Recommendations for Application in Risk Assessment." INGENIAR-CIMNE 2025 for GRMA.

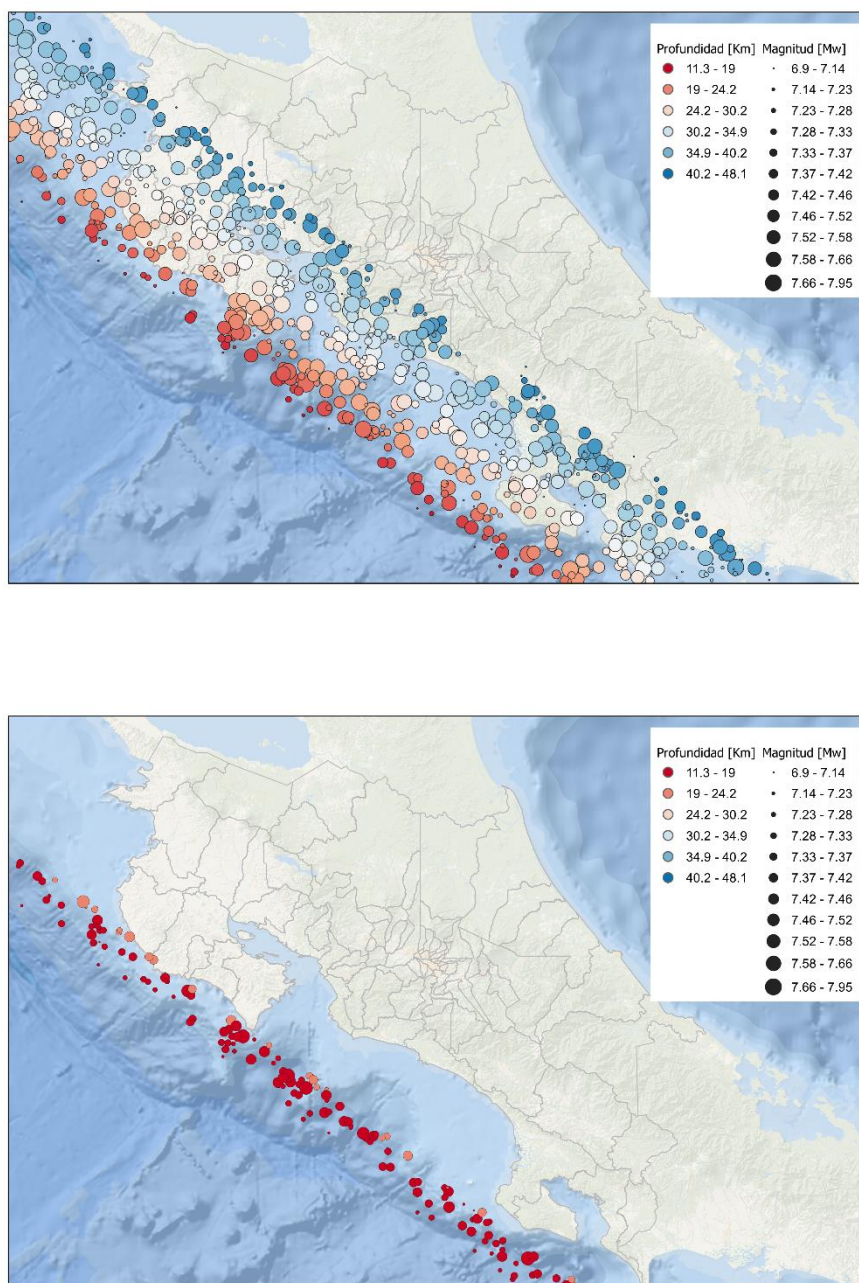


Figure 118. Seismic events used for tsunami modeling. Top: subduction-zone earthquakes with $M_w \geq 7$. Bottom: subset of earthquakes with hypocentral depths less than 20 km.

For each earthquake, the calculation method described in Annex A.6 is applied and coastal inundation is evaluated using the same topographic and bathymetric information presented previously (see Section 5.1.4). The integration of these results makes it possible to obtain tsunami coastal inundation heights for different return periods. The corresponding tsunami inundation height maps for other return periods are included in the project dataset.

As a result, run-up height values were obtained, as shown in Figure 119, for different return periods. Similar to the coastal flooding analysis from tropical cyclones, Figure 120 presents several close-ups of sectors along the Pacific coast for a 1,000-year return period.

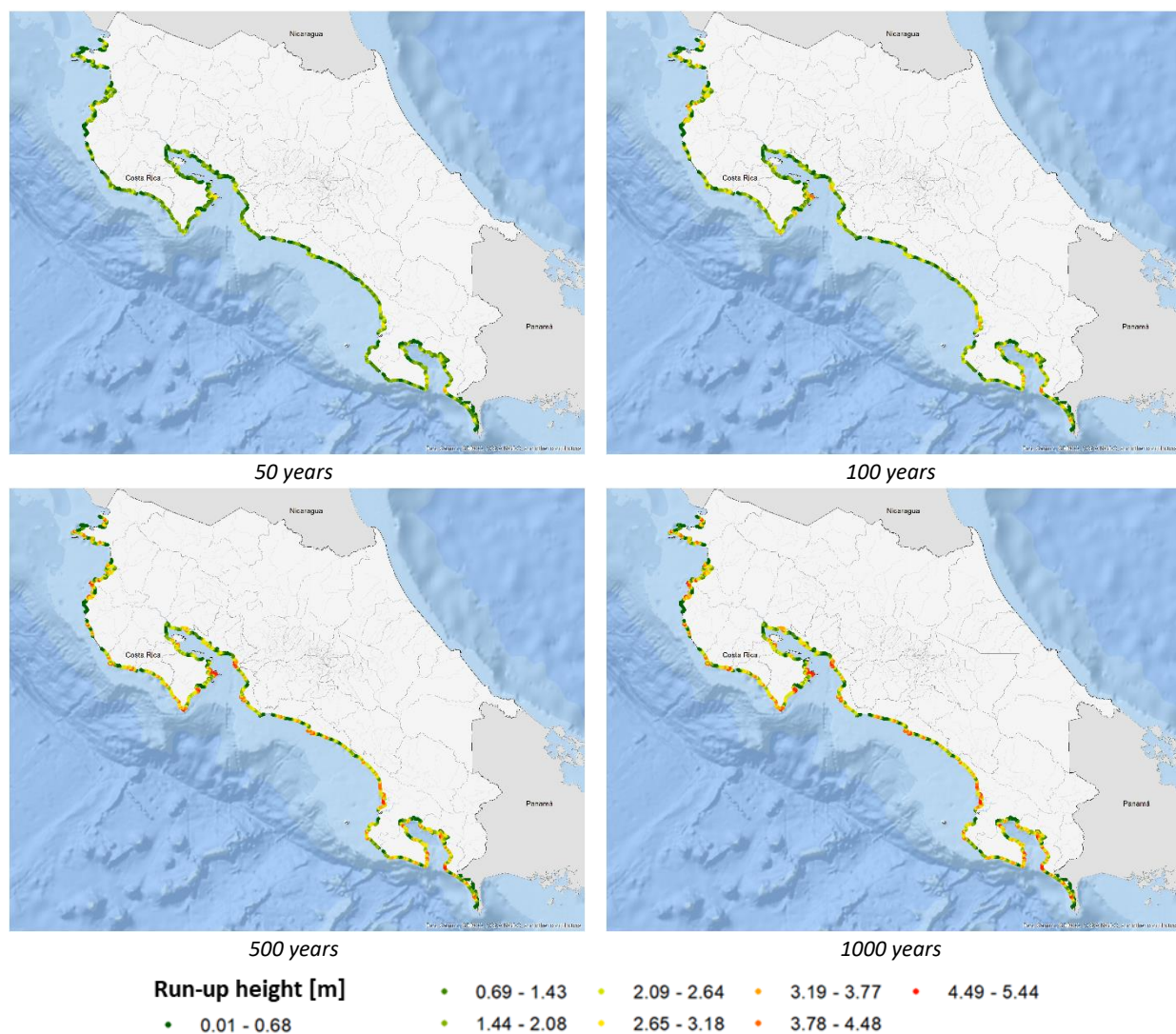


Figure 119. Uniform hazard maps of coastal flooding by tsunami (run-up height)

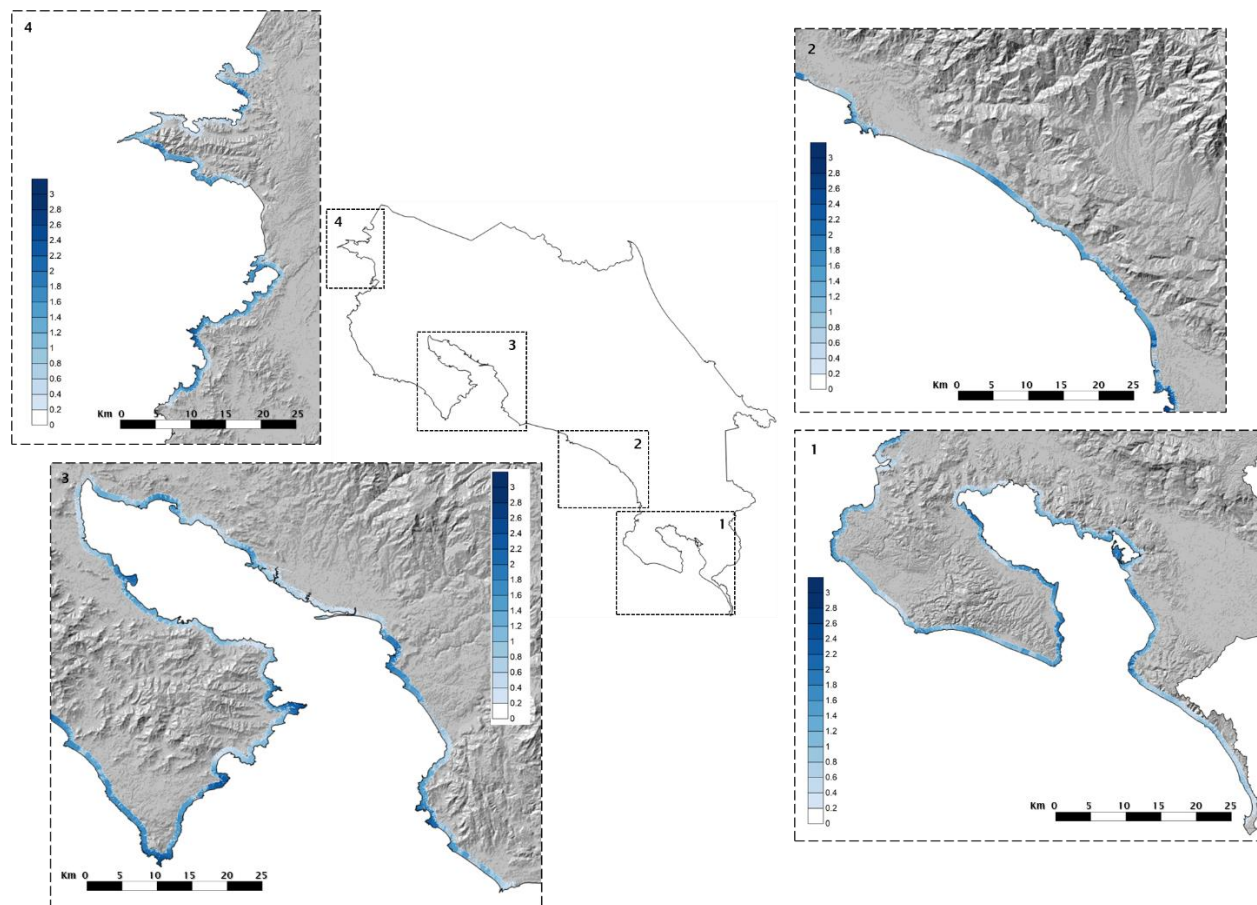


Figure 120. Close-ups of selected sectors of the Costa Rican coast. Coastal flooding by tsunami with a 1000-year return period. Flood height in meters.

6 CAPACITY DEVELOPMENT PROGRAM

As part of the capacity-building process in risk modeling, the Course on Probabilistic Disaster Risk Modeling was developed. This course is aimed at professionals, specialists, and researchers linked to the Technical Working Group of the GRMA – Costa Rica program, as well as officials from other local entities with an interest in the subject, with backgrounds in Earth sciences, engineering, mathematics, physics, econometrics, or financial/actuarial analysis.

The main objective of the course is to provide participants with the scientific foundations necessary to understand and perform risk modeling, as well as to interpret its results. By the end of the training process, participants will be capable of carrying out risk assessments for natural hazards using advanced tools from the CAPRA-ROBOT system.

The asynchronous training course officially began on March 18, 2025. It has an approximate duration of 24 weeks, with an estimated weekly dedication of 2 hours. However, the actual duration will depend on the individual's personal commitment to the course.

This course covers all the modeling topics included in the GRMA – Costa Rica project, as detailed in the Inception Report of this consultancy. This includes, of course, training activities on seismic, volcanic, and landslide hazard and risk.

6.1 Módulo 1 - Fundamentals

The asynchronous course officially began on March 18, 2025 with Module 1, which covered the general foundations of probabilistic risk assessment. Upon completion of this module, participants continued with Module 2, focused on natural hazard modeling and the assessment of the vulnerability of exposed elements.

6.2 Módulo 2 – Components of Risk Modeling

Module 2, which started on May 13, 2025, allows each participant to select the hazard of interest among those considered in the GRMA project. In other words, the module provides theoretical and practical materials on hazard modeling and the vulnerability assessment of exposed elements for all hazards covered by the project, thus enabling specialized training tailored to the needs of the participants.

This report presents a summarized description of the scope and contents of the modules related exclusively to tropical cyclones, flooding, and drought.

6.2.1 Tropical Cyclones

This module begins by covering the methods required to incorporate climate change into the assessment of hydrometeorological risks, given that phenomena such as intense rainfall—key triggers in the occurrence of landslides—are significantly affected by it.

Subsequently, it addresses key meteorological concepts related to the formation of tropical depressions, storms, and cyclones, their life cycle, wind field and storm surge models, as well as modeling approaches.

From an engineering perspective, it also includes topographic effects, gust duration transformations, housing response, and building damage models.

In addition, the mathematical models necessary for the correct application and understanding of probabilistic risk assessment theory, its results, and associated metrics are presented. Table 18 provides a detailed breakdown of the topics covered in each unit.

Table 18. Syllabus of Module 2: Tropical Cyclones

Unit	Title	Topics
1	Basic Concepts of Climate Change	•Earth's climate system •Energy balance •General circulation of the atmosphere •Radiative forcing •Greenhouse gas emissions •Global circulation models • Global projections
2	Structure and Formation of Tropical Cyclones	•Structure •Conditions for formation •Generation of tropical cyclones •Saffir–Simpson scale •Tracks and warnings
3	Effects of Tropical Cyclones	•Gradient wind •Boundary layer •Gust wind speed •Storm surge hydrographs •Ekman spiral •Low-pressure surge
4	Probabilistic Assessment of Tropical Cyclone Hazard	•Track completeness •Track perturbation •Cyclone catalog and hazard integration •Influence of climate change on tropical cyclone formation •Sea level rise trends
5	Damage Models: Fragility and Vulnerability Functions	•Fragility curves •Vulnerability curves
6	Vulnerability to Wind and Flooding	•Wind effects on structures •Pressure loads on buildings •Cyclic wind loads on tall buildings •Vulnerability to wind field •Vulnerability to debris impact •Vulnerability to storm surge flooding

The theoretical sessions are complemented with hands-on practical sessions, where participants will learn to use specialized software for modeling tropical cyclone hazards, including:

Tropical Cyclones Hazard Modeler (TCHM): TCHM is the module of the CAPRA Robot platform dedicated to tropical cyclone hazards. It implements calculation methodologies for strong winds, storm surge, and accumulated precipitation. TCHM adequately simulates the strengthening and weakening of tropical cyclones as they advance along random tracks, as well as their surface effects in terms of hazard intensity.

Vulnerability Studio: This tool allows modeling the vulnerability of exposed elements through mathematical functions that relate hazard intensity to direct physical impact. It implements several methods for creating vulnerability functions adapted to different types of hazards, enabling the estimation of probability loss functions for different intensity levels.

CAPRA ROBOT: This is the risk calculation engine. It allows for the computation of the Loss Exceedance Curve (LEC) for any exposure database, using the probabilistic risk assessment framework (CAT-type). This module enables the aggregation of losses from different hazards, generating multi-hazard risk results. CAPRA ROBOT calculates financial metrics such as the Average Annual Loss (AAL), the Probable Maximum Loss (PML), among others.

By using these tools, participants will be able to carry out probabilistic modeling of tropical cyclone hazards and risk estimations, fully aligned with the CAPRA methodology applied in the GRMA project. These capacities are consistent with the objectives of Operational Project 3, strengthening the integration of technical tools into disaster risk management in the tourism sector.

6.2.2 Flood

This module begins by covering the methods required to incorporate climate change into the assessment of hydrometeorological risks, given that phenomena such as rainfall are significantly affected by this factor.

Subsequently, it addresses key aspects of riverine flooding, which occurs when excessive rainfall over a prolonged period causes a river to exceed its capacity, overflow its banks, and flood nearby areas, depending on the local topography.

A climate generator is used to obtain precipitation series that follow the same regime as historical records in the study area.

From an engineering perspective, the module analyzes the stochastic series of intense rainfall, as well as the identification of the set of extreme rainfall events that may trigger floods.

It also addresses full hydrological and hydraulic analyses of the watershed and the river channel.

In addition, the necessary mathematical models are presented for the correct application and understanding of probabilistic risk assessment theory, as well as its results and associated metrics.

Table 19 presents in detail the topics to be covered in each unit.

Table 19. Syllabus of Module 2: Floods

Unit	Title	Topics
1	Basic Concepts of Climate Change	•The Earth's climate system •Energy balance •General circulation of the atmosphere •Radiative forcing •Greenhouse gas emissions •Global circulation models •Global projections

2	Incorporating Climate Change into Hazard and Risk Modeling	•Downscaling •Stochastic simulation •Scaling rule •All-variations model
3	Hydrological Modeling	•Hydrological cycle •Reynolds transport theorem •Hydrological system: precipitation, evapotranspiration, infiltration, and runoff •Hydrograph of watershed outflow
4	Hydraulic Modeling	•One-dimensional modeling •Two-dimensional modeling •HEC-RAS
5	Damage Models: Fragility and Vulnerability Functions	•Fragility curves •Vulnerability curves •Binary vulnerability
6	Flood Vulnerability	•Rainfall-landslide thresholds •Rainfall-induced landslides •Earthquake-induced landslides

The theoretical sessions are accompanied by hands-on sessions where students will learn to operate specialized software for flood hazard modeling, including:

Drought Pro: An advanced simulation tool that enables the stochastic modeling of meteorological forcing, particularly rainfall, as a triggering phenomenon for landslides. The system was initially designed for drought modeling (hence its name) but has evolved into a general climate simulation system. Through a stochastic climate generator, it produces multiple simulations of meteorological variables (such as precipitation and temperature), based on the available historical daily series in the territory. Thanks to these capabilities, it is applied to the modeling of various phenomena such as droughts, floods, landslides, or wildfires, allowing the construction of probabilistic models of meteorological forcing.

Flood Analyst: A software tool focused on flood hazard assessment. It calculates hazard intensities for heavy rainfall events and river floods at multiple locations within the area of interest. Flood Analyst generates stochastic events of heavy rainfall and is coupled with the HEC-RAS software (Brunner & Bonner, 1994), which performs the hydrological and hydraulic analysis for each event and provides the associated flood footprint.

Vulnerability Studio: A tool that models the vulnerability of exposed elements through mathematical functions that relate hazard intensity to direct physical impact. It implements several methods for creating vulnerability functions tailored to different types of hazards, enabling the estimation of loss probability functions for various intensity levels.

CAPRA ROBOT: As mentioned previously, it is the risk calculation engine. It allows the calculation of the Loss Exceedance Curve (LEC) for any exposure database, using the probabilistic CAT-type risk assessment framework. This module enables the aggregation of losses from different hazards, producing multi-hazard risk results. CAPRA ROBOT also calculates financial metrics such as the Average Annual Loss (AAL), the Probable Maximum Loss (PML), among others.

Participants will be able to conduct probabilistic flood hazard modeling and risk estimation using these tools, which are aligned with the CAPRA methodology applied in the GRMA project. These capacities are consistent with the objectives of the Strategic Project and Operational Projects 1, 2, and 3, aimed at strengthening technical capacities for disaster risk assessment in the road infrastructure, tourism, and agricultural sectors, as well as for buildings and infrastructure in the canton of Heredia.

6.2.3 Drought

This module begins by covering the methods required to incorporate climate change into the assessment of hydrometeorological risks, given that phenomena such as intense rainfall are significantly affected by it.

Subsequently, it addresses the generation of future climate conditions that combine precipitation deficits with above-average temperatures over a defined period, within a specific geographical area. Using information from future stochastic events, it is possible to conduct a prospective drought assessment for the agricultural sector, in order to evaluate crop damage and quantify losses. The total reduction in yield can be calculated due to water stress in cultivated lands across a region or the entire country, considering the different growth stages of crops. Similarly, the reduction in livestock production can be quantified based on the decrease in available pasture for animals during drought events.

Table 20 presents in detail the topics that will be covered in each unit.

Table 20. Syllabus of Module 2: Drought

Unit	Title	Topics
1	Basic Concepts of Climate Change	•Earth's climate system •Energy balance •General circulation of the atmosphere •Radiative forcing • Greenhouse gas emissions •Global circulation models •Global projections
2	Incorporating Climate Change into Hazard and Risk Modeling	•Downscaling •Stochastic simulation •Scaling rule • All variations model
3	Hydrological Modeling	•Hydrological cycle •Reynolds transport theorem •Hydrological system: precipitation, evapotranspiration, infiltration, and runoff •Outflow hydrograph of the watershed
4	Types of Drought and Indicators	•Meteorological drought •Agricultural drought •Hydrological drought •Drought indicators •Standardized indicators
5	Crop Response to Water	•Exposed elements of the agricultural sector and characteristics •Soil characteristics required for vulnerability modeling •Crop water response model •Water balance •Crop development •Biomass production •Yield
6	Livestock Carrying Capacity	•

The theoretical sessions will be complemented with hands-on practical sessions where participants will learn to use specialized software for drought hazard modeling, such as:

Drought Pro: An advanced simulation tool that allows stochastic modeling of meteorological forcing. The system was initially conceived for drought modeling (hence its name) but has evolved into a general climate simulation system. Through a stochastic climate generator, it creates multiple simulations of meteorological variables (such as precipitation and temperature), based on the historical daily series available in the territory. Given these capabilities, it is used for modeling multiple different phenomena, such as droughts, floods, landslides, or wildfires, allowing the construction of probabilistic models of meteorological forcing.
Vulnerability Studio: A tool that allows modeling the vulnerability of exposed elements through mathematical functions that relate hazard intensity to direct physical impact. It implements various methods for creating vulnerability functions adapted to different types of hazards, enabling the estimation of loss probability functions for different intensity levels.

At the end, participants will be able to carry out probabilistic drought hazard modeling and risk assessments, using these tools aligned with the CAPRA methodology employed in the GRMA project. These capacities are in line with the objectives of Operational Project 2, aimed at strengthening technical capabilities for disaster risk assessment in the agricultural sector.

6.3 Módulo 3 – Advanced Applications

Once Module 2 has been successfully completed, participants may continue with Module 3, which focuses on advanced applications in risk management and climate change adaptation. This module represents the final stage of the course and is essential for gaining a comprehensive understanding of the entire process. While it is recommended to take all three modules for complete training, those interested only in understanding the general structure of the risk management process and its strategic relevance may choose to move directly from Module 1 to Module 3.

This module will address key topics for decision-making in contexts of high uncertainty and complex systems, such as resilience modeling in dynamic systems, holistic risk assessment, robust decision-making, risk control engineering, and an introduction to financial protection against disasters. Table 21 provides a detailed overview of the topics covered in each unit.

This module is particularly valuable as it provides advanced tools to integrate the technical analysis of risk with planning, investment, and public policy processes.

Table 21. Syllabus of Module 2: Advanced applications

Unit	Title	Topics
1	Resilience Modeling of Infrastructure Systems	•System concept •Interdependence of elements •Supply/demand imbalance •Performance curves •Performance simulation
2	Holistic Risk Assessment	•Definition of context conditions •Social fragility and lack of resilience •Aggravation coefficient

		• System of indicators and membership functions • Disaggregation of holistic indicators
3	Robust Decision-Making	• Deep uncertainty • Uncertain future states • Random set theory • Imprecise risk metrics • Decision-making under deep uncertainty
4	Risk Control Engineering	• Risk control process • Formulation of intervention actions • Stochastic optimization • Investment curves • Optimal management and adaptation plans
5	Introduction to Financial Protection	• Types of financial instruments • Justification and costs of instruments • Risk retention and transfer structures • Insurance claim modalities • Introduction to CAT Bonds

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A.1 LIST OF MISSING DATA FROM METEOROLOGICAL STATIONS

The following lists the meteorological stations of the IMN, identified with a unique code, and indicates the initial and final dates of variable recording, as well as the amount of available and missing data within the control period 1991–2020.

Precipitation Data

Station code	Start date	End date	Data available in the control period	Missing data in the control period
1003	01/01/2000	23/12/2014	5192	5766
100615	12/10/2001	14/03/2006	1560	9398
100631	01/01/2000	11/02/2009	2976	7982
100633	12/02/2004	14/02/2025	5928	5030
100641	09/03/2007	05/03/2025	4738	6220
100643	11/12/2009	24/03/2025	4039	6919
100645	31/07/2012	19/09/2017	1775	9183
100649	16/01/2013	10/02/2025	2668	8290
100651	16/05/2013	05/03/2025	2712	8246
100653	04/09/2013	12/09/2024	2658	8300
100655	23/10/2014	21/03/2025	2253	8705
100659	16/06/2015	24/10/2018	1227	9731
2002	01/01/2000	11/07/2017	3221	7737
2004	01/01/2000	28/06/2000	180	10778
2007	24/05/2008	15/08/2019	2604	8354
2009	23/11/2013	08/03/2018	1547	9411
69597	01/01/2000	15/01/2003	1111	9847
69633	01/01/2000	28/03/2025	6991	3967
69647	07/11/2002	25/12/2024	6348	4610
69649	01/01/2000	11/07/2002	923	10035
69651	01/01/2000	23/07/2004	1664	9294
69655	01/01/2000	14/02/2005	1872	9086
69659	01/01/2000	29/08/2002	964	9994
69661	01/01/2000	23/03/2017	5608	5350
69677	01/04/2001	13/10/2021	7007	3951
69679	01/01/2000	10/02/2025	7335	3623
69681	01/01/2000	17/12/2024	7039	3919
69695	24/09/2008	25/10/2024	3797	7161
69697	22/10/2009	17/09/2021	3987	6971
69699	15/03/2011	19/02/2025	3114	7844
69701	21/09/2011	20/01/2025	3390	7568
69707	23/07/2013	17/09/2014	422	10536
69709	20/08/2012	01/12/2024	3056	7902
69711	10/04/2013	13/11/2024	2773	8185
69713	12/04/2013	19/02/2025	2821	8137
69715	22/04/2013	10/12/2024	2738	8220
69717	17/09/2013	10/10/2024	2398	8560
69719	28/10/2015	30/08/2022	1413	9545
69721	08/10/2013	17/06/2024	2642	8316

Station code	Start date	End date	Data available in the control period	Missing data in the control period
69723	10/10/2013	04/02/2025	2593	8365
69725	15/10/2014	01/11/2024	2121	8837
69727	26/03/2014	29/11/2024	2452	8506
69729	22/09/2014	10/10/2024	2177	8781
69731	05/11/2014	07/10/2024	2059	8899
69735	20/02/2015	13/11/2024	2012	8946
69737	13/05/2015	10/03/2025	1864	9094
69739	14/05/2015	19/02/2025	2059	8899
69743	24/03/2017	07/01/2025	1376	9582
69745	07/09/2017	14/02/2018	161	10797
69747	21/04/2017	20/01/2025	1147	9811
69749	10/05/2017	24/01/2025	1332	9626
69751	31/05/2018	21/01/2025	946	10012
7115	01/01/2000	01/01/2025	6897	4061
7121	01/01/2000	05/12/2005	2109	8849
7123	16/01/2014	17/11/2021	1673	9285
72141	01/01/2000	01/06/2004	1611	9347
72145	01/01/2000	18/11/2004	1744	9214
72149	23/03/2004	05/03/2025	5214	5744
72153	10/11/2004	14/11/2024	5549	5409
72157	01/01/2000	21/02/2025	7363	3595
72159	27/10/2002	10/01/2025	5950	5008
72161	10/11/2004	04/03/2014	3190	7768
72163	31/03/2012	22/08/2024	3166	7792
72165	21/09/2012	28/08/2024	2794	8164
72167	11/04/2013	12/02/2025	2739	8219
72169	24/11/2020	15/10/2024	38	10920
72171	25/11/2020	29/09/2022	37	10921
72173	27/11/2020	16/09/2024	35	10923
72177	24/11/2015	22/08/2024	1333	9625
72179	12/12/2014	19/02/2020	1766	9192
72181	20/05/2015	26/03/2025	1981	8977
72183	27/04/2016	05/12/2024	1710	9248
72185	17/08/2017	26/08/2024	1127	9831
72187	04/08/2017	21/02/2022	987	9971
72189	07/08/2017	04/10/2024	1230	9728
72191	31/08/2017	14/03/2025	1129	9829
72193	19/01/2018	26/08/2024	1062	9896
72195	09/02/2018	07/02/2025	1057	9901
72197	06/09/2018	23/10/2019	413	10545
73123	01/01/2000	14/02/2025	7353	3605
73129	01/01/2000	22/02/2025	7448	3510
73137	03/11/2004	19/02/2025	5470	5488
73141	18/07/2007	06/01/2025	2804	8154
73143	26/01/2010	10/01/2025	3560	7398
73145	31/10/2011	09/10/2024	3185	7773
73147	19/12/2011	01/01/2025	3178	7780

Station code	Start date	End date	Data available in the control period	Missing data in the control period
73149	16/02/2012	23/06/2024	3176	7782
73151	20/10/2007	20/03/2025	2053	8905
73153	05/07/2013	05/08/2024	2737	8221
73155	27/09/2013	07/01/2025	2555	8403
73157	01/11/2013	12/09/2024	2597	8361
73159	13/02/2014	04/03/2025	2124	8834
73161	26/02/2015	07/08/2024	2081	8877
73163	10/09/2018	08/07/2024	282	10676
73167	07/05/2015	21/12/2024	2056	8902
73169	17/07/2017	05/02/2025	1214	9744
73171	06/09/2018	14/02/2025	848	10110
73173	26/09/2019	05/02/2025	454	10504
7449	25/06/2003	12/11/2003	141	10817
7451	01/01/2000	20/02/2025	7555	3403
7453	01/01/2000	04/03/2025	7039	3919
7459	02/11/2013	28/11/2024	2529	8429
7461	29/02/2012	15/10/2024	2839	8119
7463	07/03/2012	04/03/2025	3032	7926
7465	23/09/2015	31/08/2016	219	10739
7467	04/04/2013	05/03/2025	2684	8274
7469	21/09/2015	15/10/2024	868	10090
7471	13/06/2016	22/08/2024	1573	9385
7473	18/05/2017	19/02/2025	1253	9705
7475	24/07/2017	22/08/2024	1254	9704
7477	18/05/2017	04/02/2025	1324	9634
7481	21/04/2017	05/03/2025	1351	9607
7483	27/09/2017	21/08/2024	1192	9766
7651	01/01/2000	18/10/2005	2104	8854
7655	01/01/2000	07/03/2025	7351	3607
7657	21/10/2009	01/10/2021	4078	6880
7659	06/05/2011	24/01/2025	3510	7448
7661	29/10/2014	12/11/2024	2243	8715
7663	14/09/2016	11/11/2024	1300	9658
7665	24/07/2017	15/03/2020	876	10082
7667	23/11/2017	11/11/2024	1116	9842
7823	01/01/2000	21/05/2007	2661	8297
7827	07/01/2001	12/12/2024	6744	4214
7829	01/01/2000	08/11/2000	312	10646
7831	19/07/2013	07/04/2022	2406	8552
7833	08/07/2016	25/11/2024	1638	9320
7835	04/07/2017	19/08/2024	998	9960
7919	22/12/2020	18/10/2024	10	10948
8013	19/08/2014	11/07/2023	2186	8772
8113	03/12/2014	17/02/2025	1830	9128
815	01/01/2000	17/02/2025	7389	3569
8211	22/11/2012	22/01/2025	2888	8070
8213	31/10/2013	09/11/2022	2513	8445

Station code	Start date	End date	Data available in the control period	Missing data in the control period
8215	07/11/2014	21/01/2025	1983	8975
8217	03/03/2017	08/03/2024	1400	9558
8219	05/06/2017	11/09/2024	1274	9684
837	11/09/2013	08/10/2024	2408	8550
840	01/01/2000	05/11/2002	1022	9936
84124	01/11/2001	07/08/2002	256	10702
84139	13/01/2000	18/03/2025	7488	3470
84141	01/01/2000	07/01/2025	7544	3414
84143	01/01/2000	10/06/2005	1988	8970
84145	01/01/2000	07/03/2012	4197	6761
84167	01/01/2000	02/09/2002	976	9982
84169	01/01/2000	17/02/2025	7317	3641
84179	06/03/2002	05/08/2002	153	10805
84181	20/02/2003	27/11/2024	5471	5487
84185	23/09/2008	17/02/2025	4037	6921
84187	01/01/2000	21/01/2025	7623	3335
84189	07/04/2003	04/02/2025	6384	4574
84191	01/01/2000	25/03/2025	6963	3995
84193	01/08/2008	19/02/2025	4255	6703
84195	01/01/2000	05/03/2015	5497	5461
84197	05/11/2001	22/01/2025	6730	4228
84199	31/03/2005	22/01/2025	5391	5567
84203	14/11/2007	22/08/2022	3527	7431
84205	04/06/2009	10/06/2015	2022	8936
84207	13/09/2010	14/02/2025	3111	7847
84209	30/09/2011	10/02/2025	2899	8059
84213	24/06/2011	14/02/2025	3306	7652
84215	14/11/2012	14/01/2025	2852	8106
84217	28/06/2012	25/02/2025	2537	8421
84219	01/03/2011	25/02/2025	3457	7501
84221	05/09/2011	22/01/2025	3001	7957
84225	20/09/2012	06/01/2025	2887	8071
84227	05/07/2012	12/02/2014	436	10522
84231	29/08/2012	22/01/2025	2926	8032
84233	14/01/2013	17/02/2025	2518	8440
84235	27/08/2013	02/11/2016	1122	9836
84237	27/08/2013	23/09/2024	2659	8299
84239	24/10/2013	25/03/2025	2397	8561
84241	30/10/2013	06/08/2024	2572	8386
84243	19/11/2013	21/11/2024	2529	8429
84245	19/11/2020	11/07/2024	43	10915
84247	23/02/2016	10/06/2020	1451	9507
84249	13/05/2015	20/09/2024	1934	9024
84251	09/10/2014	25/11/2024	1887	9071
84283	04/05/2018	10/02/2025	703	10255
84285	05/03/2015	14/01/2025	1958	9000
84293	18/09/2015	26/09/2024	1825	9133

Station code	Start date	End date	Data available in the control period	Missing data in the control period
84295	10/11/2015	25/04/2023	1615	9343
8521	01/01/2000	13/02/2025	6337	4621
8523	27/01/2005	14/02/2025	5109	5849
8525	06/11/2013	24/02/2025	2217	8741
8527	16/01/2016	03/11/2020	1692	9266
8613	06/05/2015	25/02/2025	2066	8892
8713	01/01/2000	07/02/2025	6384	4574
8835	01/01/2000	06/08/2010	3689	7269
8841	01/01/2000	10/06/2009	3446	7512
8847	28/02/2009	14/01/2025	4110	6848
8849	16/07/2013	06/01/2025	2723	8235
8851	17/02/2015	14/01/2025	2145	8813
8855	31/05/2017	24/01/2025	1311	9647
9011	01/01/2000	01/06/2005	1814	9144
9013	08/10/2008	25/02/2025	4397	6561
9015	12/03/2014	25/02/2025	2361	8597
9413	31/01/2012	01/01/2025	3002	7956
9415	27/03/2014	27/02/2025	2406	8552
9417	13/08/2020	28/09/2024	139	10819
9419	16/12/2016	01/01/2025	981	9977
963	14/05/2013	06/12/2024	2776	8182
98101	01/01/2000	07/12/2009	592	10366
98103	30/09/2009	01/08/2021	4056	6902
98105	26/11/2013	25/09/2024	2495	8463
98107	15/12/2016	05/03/2025	1468	9490
98109	22/06/2017	16/09/2024	1289	9669
9875	01/01/2000	25/02/2025	7453	3505
9879	01/01/2000	17/06/2008	2878	8080
9887	01/01/2000	12/03/2025	7002	3956
9891	01/01/2000	24/02/2025	7671	3287
9895	01/01/2000	26/03/2025	7316	3642
9897	17/06/2008	10/02/2025	4489	6469
9899	18/06/2008	23/10/2018	3401	7557

Temperature data

Station code	Start date	End date	Data available in hte control period	Missing data in the control period
1003	01/01/2000	23/12/2014	5361	5597
100615	12/10/2001	14/03/2006	1560	9398
100631	01/01/2000	11/02/2009	2976	7982
100633	16/10/2003	14/02/2025	6017	4941
100641	09/03/2007	05/03/2025	4783	6175
100643	11/12/2009	24/03/2025	4039	6919
100645	31/07/2012	19/09/2017	1855	9103
100649	16/01/2013	10/02/2025	2874	8084

Station code	Start date	End date	Data available in hte control period	Missing data in the control period
100651	16/05/2013	05/03/2025	2688	8270
100653	04/09/2013	12/09/2024	2295	8663
100655	23/10/2014	21/03/2025	2245	8713
100659	16/06/2015	24/10/2018	1227	9731
2002	01/01/2000	11/07/2017	3221	7737
2004	01/01/2000	28/06/2000	180	10778
2007	24/05/2008	15/08/2019	3110	7848
2009	23/11/2013	08/03/2018	1547	9411
69597	01/01/2000	15/01/2003	1111	9847
69633	01/01/2000	28/03/2025	7236	3722
69647	07/11/2002	25/12/2024	6375	4583
69649	01/01/2000	11/07/2002	923	10035
69651	01/01/2000	23/07/2004	1663	9295
69655	01/01/2000	14/02/2005	1872	9086
69659	01/01/2000	29/08/2002	972	9986
69661	01/01/2000	23/03/2017	5721	5237
69677	29/03/2001	13/10/2021	6984	3974
69679	01/01/2000	10/02/2025	7439	3519
69681	01/01/2000	17/12/2024	7157	3801
69695	06/01/2008	25/10/2024	4495	6463
69697	22/10/2009	17/09/2021	3987	6971
69699	15/03/2011	19/02/2025	3156	7802
69701	21/09/2011	20/01/2025	3390	7568
69707	23/07/2013	17/09/2014	422	10536
69709	20/08/2012	01/12/2024	3056	7902
69711	10/04/2013	13/11/2024	2763	8195
69713	12/04/2013	19/02/2025	2736	8222
69715	22/04/2013	10/12/2024	2784	8174
69717	17/09/2013	10/10/2024	2663	8295
69719	28/10/2015	05/10/2022	1633	9325
69721	08/10/2013	07/10/2024	2642	8316
69723	10/10/2013	04/02/2025	2593	8365
69725	15/10/2014	01/11/2024	2145	8813
69727	26/03/2014	29/11/2024	2452	8506
69729	22/09/2014	10/10/2024	2177	8781
69731	05/11/2014	07/10/2024	2232	8726
69735	20/02/2015	13/11/2024	2078	8880
69737	13/05/2015	10/03/2025	2041	8917
69739	14/05/2015	19/02/2025	2059	8899
69743	24/03/2017	07/01/2025	1379	9579
69745	07/09/2017	14/02/2018	161	10797
69747	21/04/2017	20/01/2025	1147	9811
69749	10/05/2017	24/01/2025	1332	9626
69751	31/05/2018	21/01/2025	866	10092
7115	01/01/2000	01/01/2025	6715	4243
7121	01/01/2000	05/12/2005	2152	8806
7123	16/01/2014	08/07/2022	2134	8824

Station code	Start date	End date	Data available in hte control period	Missing data in the control period
72141	01/01/2000	01/06/2004	1611	9347
72145	01/01/2000	18/11/2004	1744	9214
72149	23/03/2004	04/02/2025	5179	5779
72153	10/11/2004	14/11/2024	5660	5298
72157	01/01/2000	21/02/2025	7391	3567
72159	27/10/2002	10/01/2025	5864	5094
72161	10/11/2004	04/03/2014	3167	7791
72163	31/03/2012	22/08/2024	3166	7792
72165	21/09/2012	28/08/2024	2980	7978
72167	11/04/2013	12/02/2025	2784	8174
72169	24/11/2020	15/10/2024	38	10920
72173	27/11/2020	16/09/2024	35	10923
72177	24/11/2015	22/08/2024	1450	9508
72179	12/12/2014	19/02/2020	1766	9192
72181	20/05/2015	26/03/2025	2052	8906
72183	27/04/2016	05/12/2024	1710	9248
72185	17/08/2017	26/08/2024	1127	9831
72187	04/08/2017	21/02/2022	1152	9806
72189	07/08/2017	04/10/2024	1230	9728
72191	31/08/2017	14/03/2025	1219	9739
72193	19/01/2018	26/08/2024	1059	9899
72195	09/02/2018	07/02/2025	1057	9901
73123	01/01/2000	14/02/2025	7469	3489
73129	01/01/2000	22/02/2025	7566	3392
73137	03/11/2004	19/02/2025	5507	5451
73141	18/07/2007	06/01/2025	3049	7909
73143	26/01/2010	10/01/2025	3844	7114
73145	31/10/2011	09/10/2024	3221	7737
73147	19/12/2011	01/01/2025	3215	7743
73149	16/02/2012	23/06/2024	3176	7782
73151	20/10/2007	20/03/2025	2053	8905
73153	05/07/2013	05/08/2024	2737	8221
73155	27/09/2013	07/01/2025	2547	8411
73157	01/11/2013	12/09/2024	2617	8341
73159	13/02/2014	04/03/2025	2409	8549
73161	26/02/2015	07/08/2024	2081	8877
73163	10/09/2018	08/07/2024	282	10676
73167	07/05/2015	21/12/2024	2056	8902
73169	17/07/2017	05/02/2025	1264	9694
73171	06/09/2018	14/02/2025	616	10342
73173	26/09/2019	05/02/2025	454	10504
7449	25/06/2003	12/11/2003	141	10817
7451	01/01/2000	20/02/2025	7494	3464
7453	01/01/2000	04/03/2025	7024	3934
7459	02/11/2013	28/11/2024	2585	8373
7461	29/02/2012	15/10/2024	3049	7909
7463	07/03/2012	04/03/2025	3102	7856

Station code	Start date	End date	Data available in hte control period	Missing data in the control period
7465	23/09/2015	20/02/2017	517	10441
7467	04/04/2013	05/03/2025	2731	8227
7469	21/09/2015	15/10/2024	887	10071
7471	13/06/2016	22/08/2024	1663	9295
7473	18/05/2017	19/02/2025	1243	9715
7475	24/07/2017	22/08/2024	1254	9704
7477	18/05/2017	04/02/2025	1324	9634
7481	21/04/2017	05/03/2025	1351	9607
7483	27/09/2017	21/08/2024	1192	9766
7651	01/01/2000	18/10/2005	2029	8929
7655	01/01/2000	07/03/2025	7228	3730
7657	21/10/2009	01/10/2021	4025	6933
7659	06/05/2011	24/01/2025	3510	7448
7661	29/10/2014	12/11/2024	2191	8767
7663	14/09/2016	11/11/2024	1570	9388
7665	24/07/2017	15/03/2020	876	10082
7667	23/11/2017	11/11/2024	1116	9842
7823	01/01/2000	21/05/2007	2599	8359
7827	07/01/2001	12/12/2024	6766	4192
7829	01/01/2000	08/11/2000	312	10646
7831	16/09/2013	04/01/2022	2664	8294
7833	08/07/2016	25/11/2024	1517	9441
7835	04/07/2017	19/08/2024	998	9960
7919	22/12/2020	18/10/2024	10	10948
8013	19/08/2014	11/07/2023	2216	8742
8113	03/12/2014	17/02/2025	2073	8885
815	01/01/2000	17/02/2025	7342	3616
8211	22/11/2012	22/01/2025	2888	8070
8213	31/10/2013	09/11/2022	2513	8445
8215	07/11/2014	21/01/2025	2247	8711
8217	03/03/2017	08/03/2024	1400	9558
8219	05/06/2017	11/09/2024	1274	9684
837	11/09/2013	08/10/2024	2495	8463
840	01/01/2000	05/11/2002	1022	9936
84124	01/01/2000	05/09/2002	979	9979
84139	13/01/2000	18/03/2025	7488	3470
84141	01/01/2000	07/01/2025	7605	3353
84143	01/01/2000	10/06/2005	1988	8970
84145	01/01/2000	07/03/2012	4196	6762
84167	01/01/2000	02/09/2002	976	9982
84169	01/01/2000	17/02/2025	7445	3513
84179	06/03/2002	05/08/2002	153	10805
84181	20/02/2003	27/11/2024	5943	5015
84185	17/04/2008	17/02/2025	4148	6810
84187	01/01/2000	21/01/2025	7629	3329
84189	07/04/2003	04/02/2025	6373	4585
84191	01/01/2000	25/03/2025	7501	3457

Station code	Start date	End date	Data available in hte control period	Missing data in the control period
84193	01/08/2008	19/02/2025	4270	6688
84195	01/01/2000	05/03/2015	5504	5454
84197	05/11/2001	22/01/2025	6715	4243
84199	02/11/2004	22/01/2025	5562	5396
84203	14/11/2007	22/08/2022	3526	7432
84205	04/06/2009	10/06/2015	2022	8936
84207	13/09/2010	14/02/2025	3762	7196
84209	30/09/2011	10/02/2025	3067	7891
84213	30/06/2011	14/02/2025	3355	7603
84215	14/11/2012	14/01/2025	2970	7988
84217	17/11/2013	25/02/2025	2572	8386
84219	01/03/2011	25/02/2025	3457	7501
84221	05/09/2011	22/01/2025	2202	8756
84225	20/09/2012	06/01/2025	2887	8071
84227	05/07/2012	12/02/2014	471	10487
84231	29/08/2012	22/01/2025	2707	8251
84233	14/01/2013	17/02/2025	2689	8269
84235	27/08/2013	02/11/2016	1158	9800
84237	27/08/2013	23/09/2024	2659	8299
84239	24/10/2013	25/03/2025	2565	8393
84241	30/10/2013	06/08/2024	2615	8343
84243	19/11/2013	22/01/2025	2565	8393
84245	19/11/2020	14/10/2024	43	10915
84247	23/02/2016	10/06/2020	1424	9534
84249	13/05/2015	20/09/2024	2059	8899
84251	09/10/2014	25/11/2024	1931	9027
84283	04/05/2018	17/05/2024	781	10177
84285	05/03/2015	14/01/2025	2127	8831
84293	18/09/2015	26/09/2024	1854	9104
84295	10/11/2015	25/04/2023	1632	9326
8521	01/01/2000	13/02/2025	6079	4879
8523	27/01/2005	14/02/2025	5150	5808
8525	06/11/2013	24/02/2025	2217	8741
8527	16/01/2016	03/11/2020	1692	9266
8613	06/05/2015	25/02/2025	2066	8892
8713	01/01/2000	07/02/2025	6450	4508
8835	01/01/2000	06/08/2010	3618	7340
8841	01/01/2000	10/06/2009	3446	7512
8847	28/02/2009	14/01/2025	4234	6724
8849	16/07/2013	06/01/2025	2723	8235
8851	17/02/2015	14/01/2025	2145	8813
8855	31/05/2017	24/01/2025	1311	9647
9011	01/01/2000	01/06/2005	1794	9164
9013	08/10/2008	25/02/2025	4397	6561
9015	12/03/2014	15/11/2024	2343	8615
9413	31/01/2012	01/01/2025	3013	7945
9415	27/03/2014	27/02/2025	2406	8552

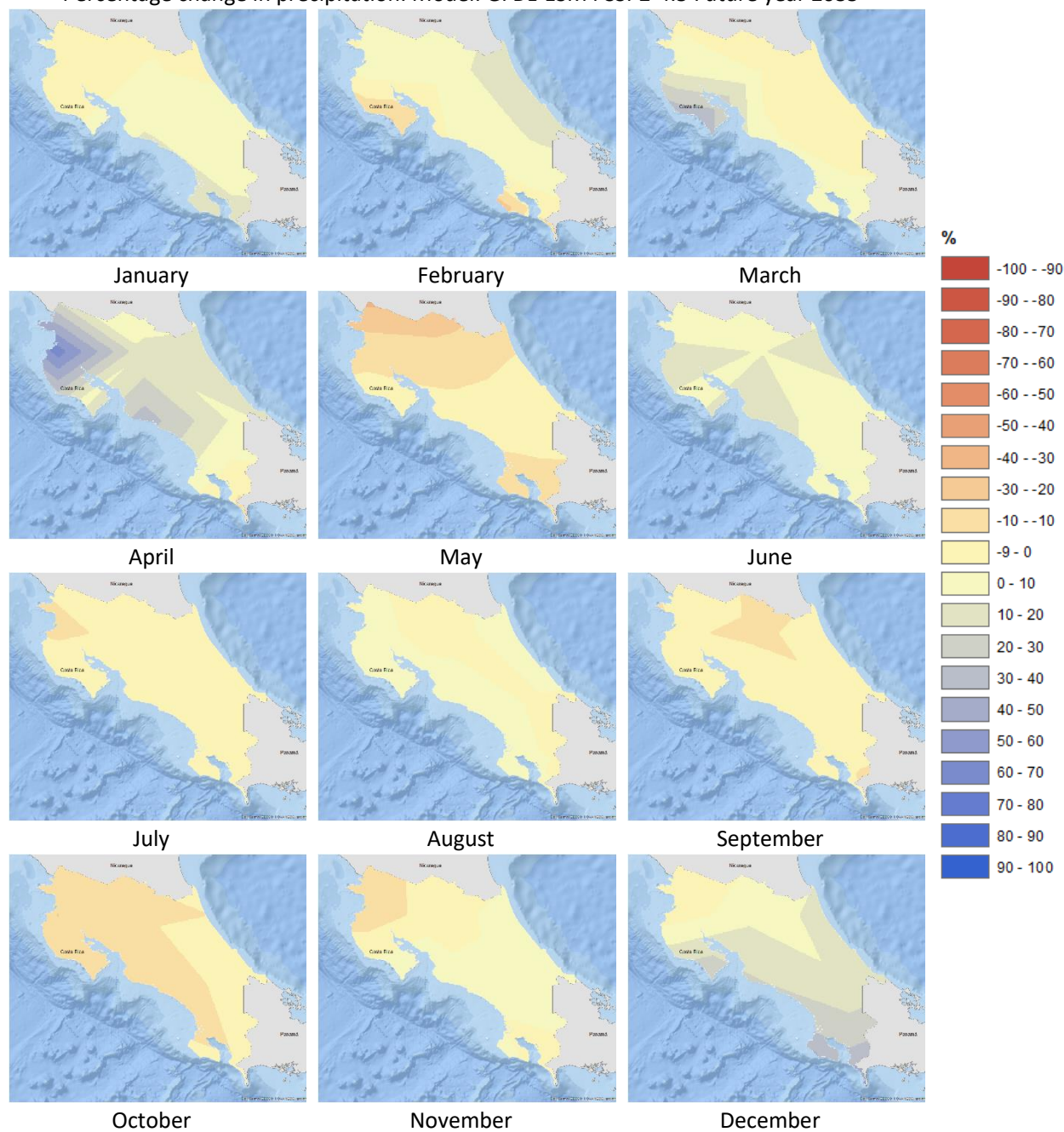
Station code	Start date	End date	Data available in hte control period	Missing data in the control period
9417	13/08/2020	28/09/2024	139	10819
9419	16/12/2016	01/01/2025	981	9977
963	14/05/2013	06/12/2024	2676	8282
98101	01/01/2000	07/12/2009	592	10366
98103	30/09/2009	01/08/2021	4103	6855
98105	26/11/2013	25/09/2024	2495	8463
98107	15/12/2016	05/03/2025	1473	9485
98109	07/12/2017	16/09/2024	1121	9837
9875	01/01/2000	25/02/2025	7470	3488
9879	01/01/2000	17/06/2008	2878	8080
9887	01/01/2000	12/03/2025	7002	3956
9891	01/01/2000	24/02/2025	7444	3514
9895	01/01/2000	26/03/2025	7260	3698
9897	17/06/2008	10/02/2025	4524	6434
9899	18/06/2008	23/10/2018	3401	7557

A.2 CLIMATE CHANGE SCENARIOS

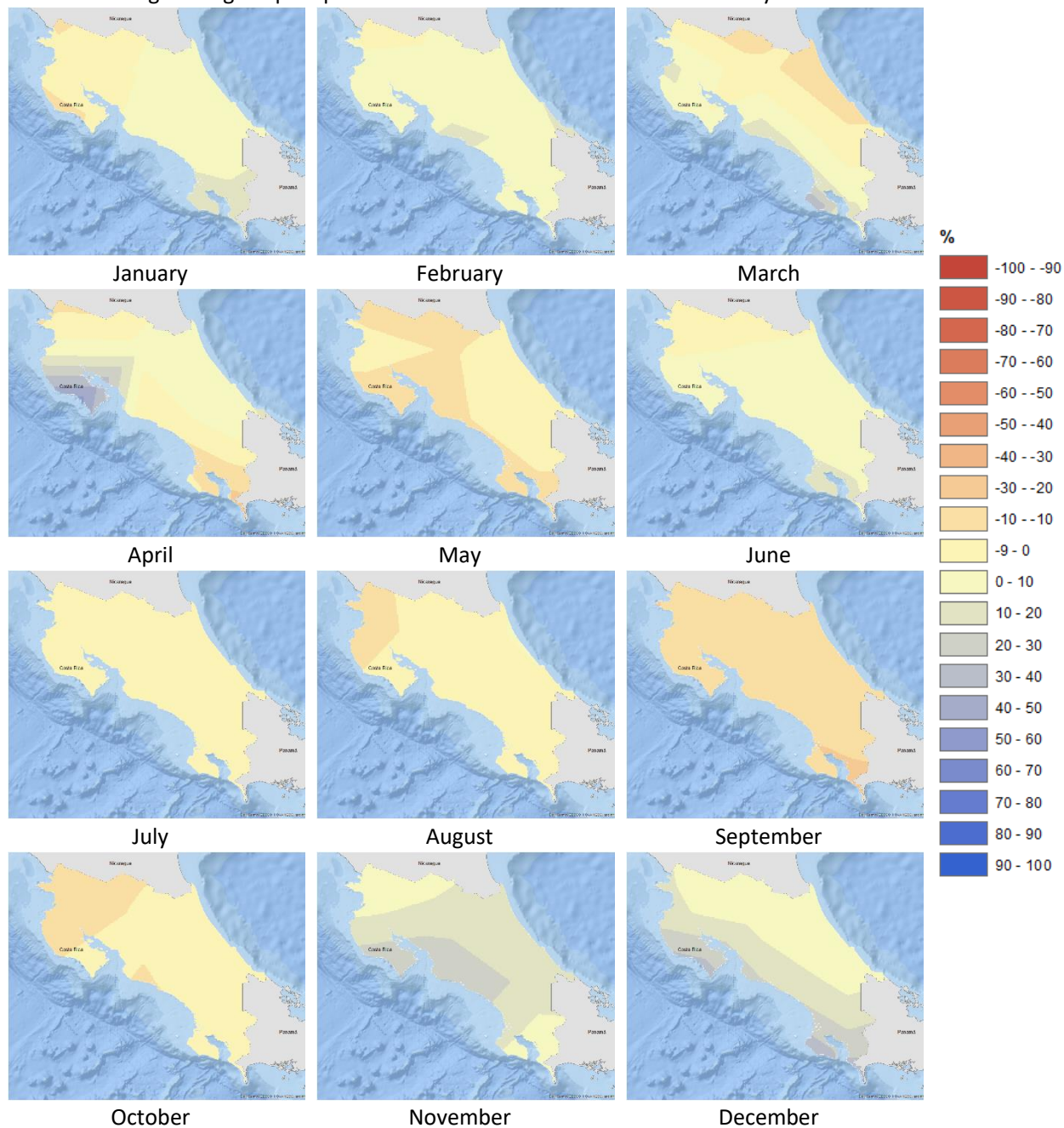
In this annex, the variations in percentage (%) for precipitation and in °C for temperature are presented, corresponding to the GFDL-ESM4, EC-Earth3, and MPI-ESM1-2-LR models under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 pathways, and evaluated for the years 2035, 2050, and 2100.

Precipitation SSP2-4.5

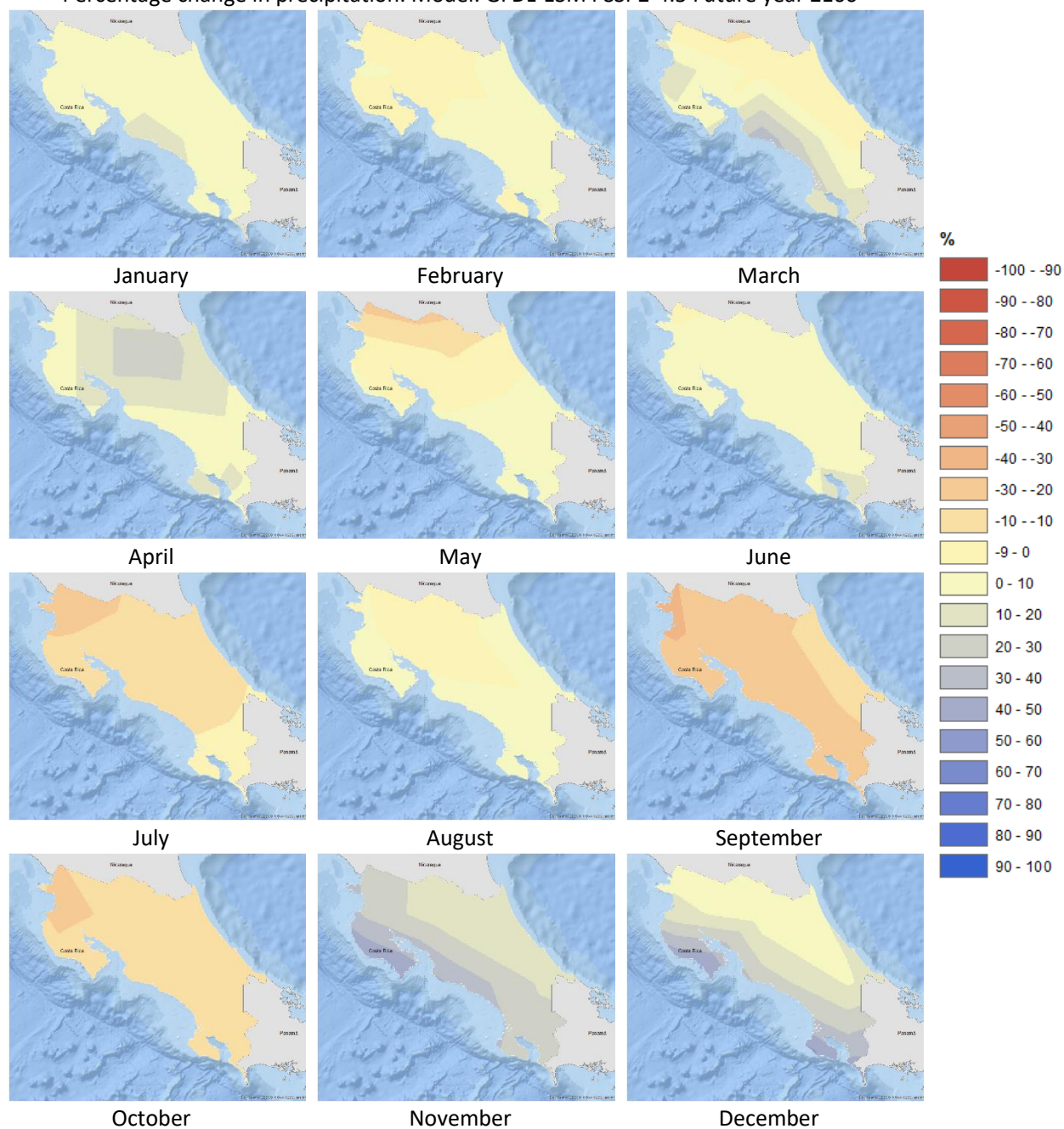
Percentage change in precipitation. Model: GFDL-ESM4 SSP2-4.5 Future year 2035



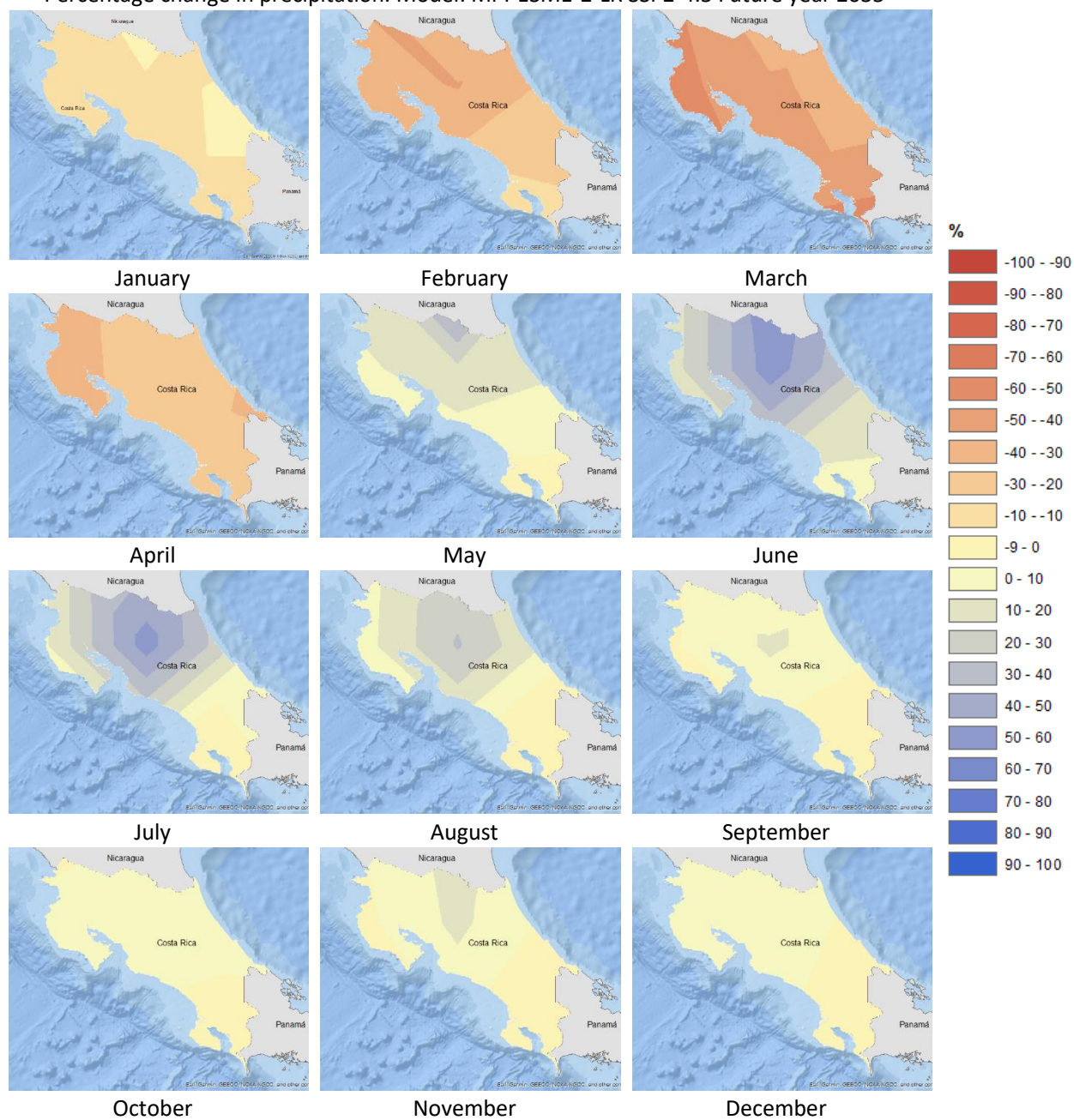
Percentage change in precipitation. Model: GFDL-ESM4 SSP2-4.5 Future year 2050



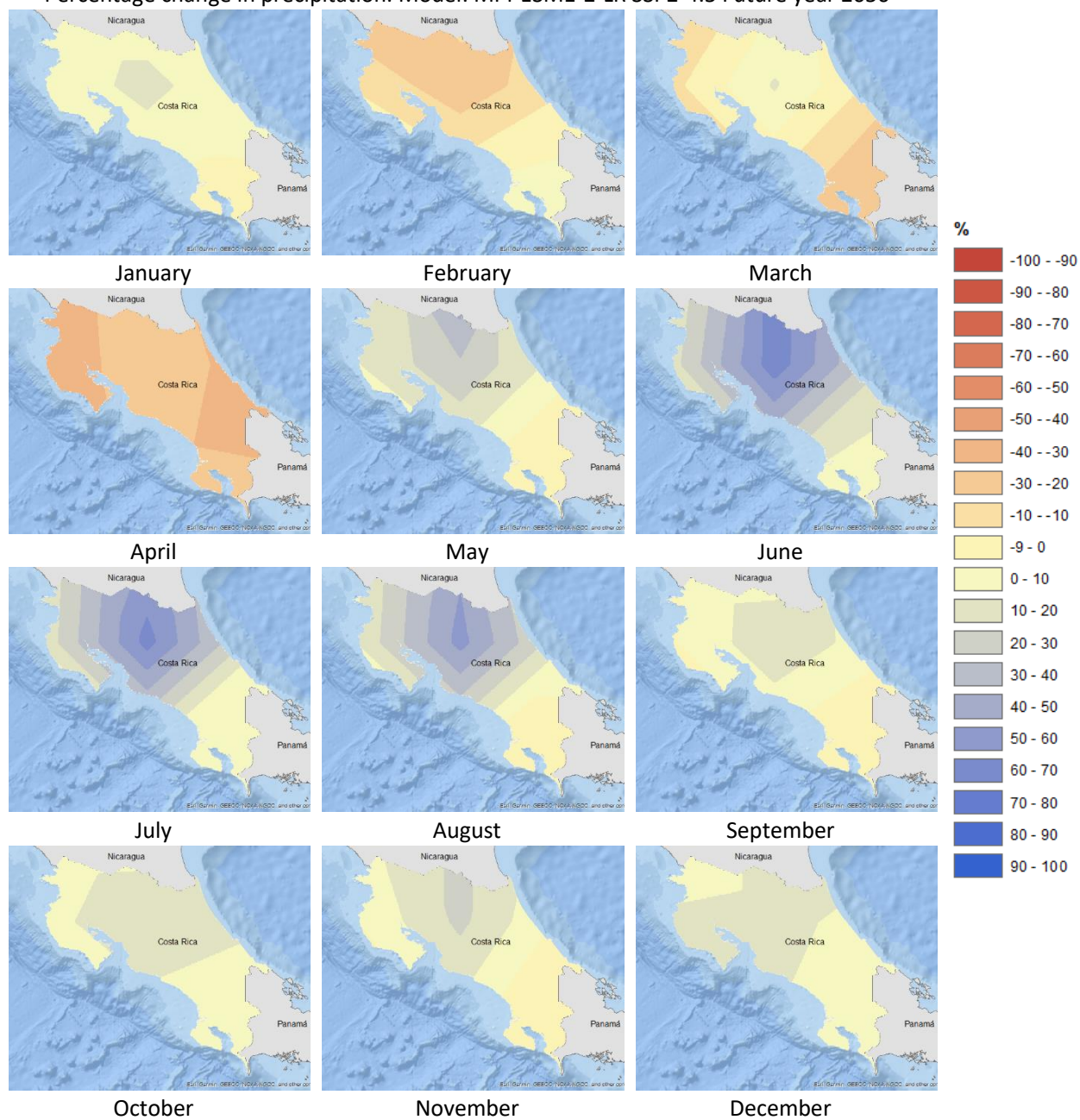
Percentage change in precipitation. Model: GFDL-ESM4 SSP2-4.5 Future year 2100



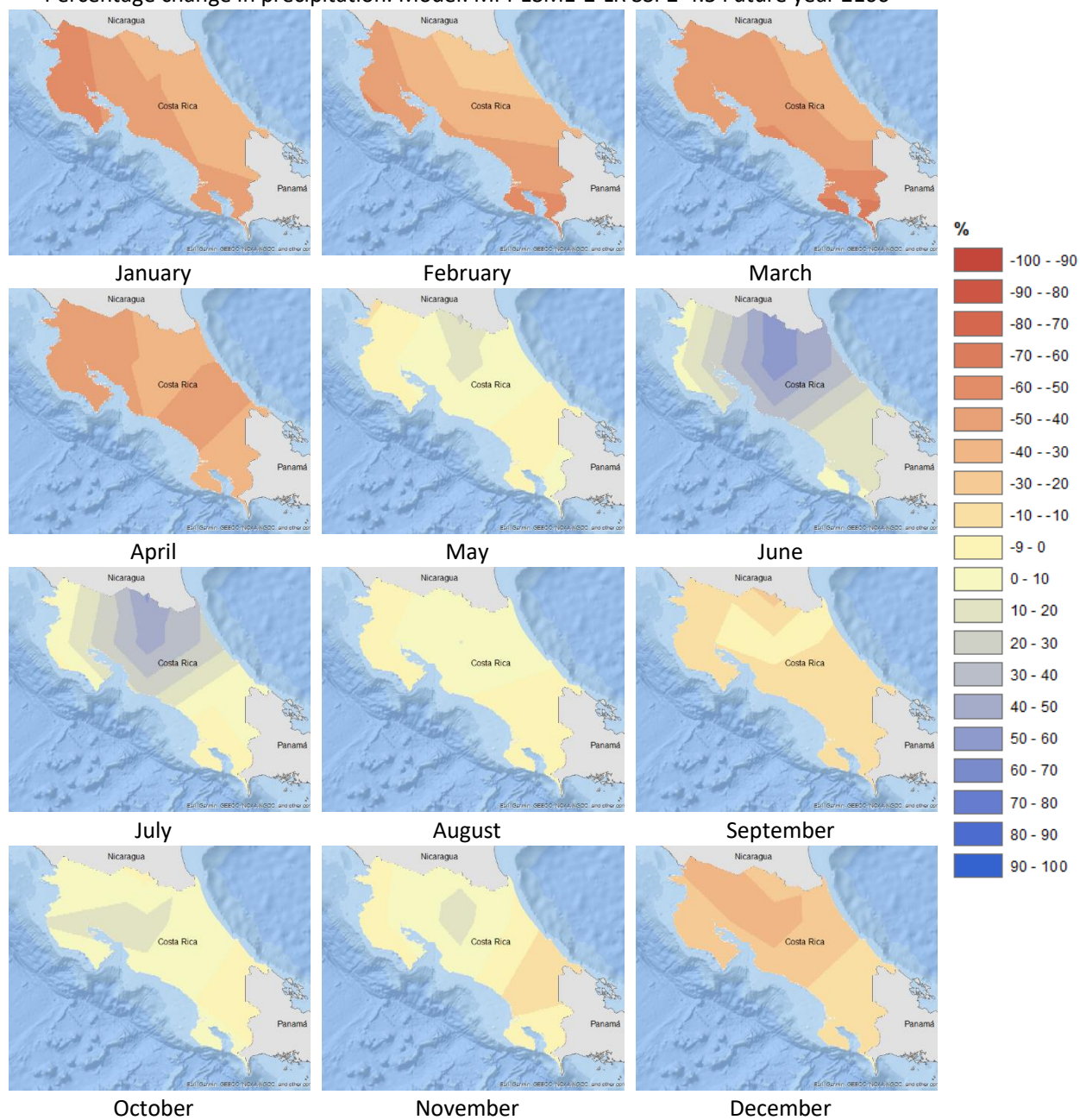
Percentage change in precipitation. Model: MPI-ESM1-2-LR SSP2-4.5 Future year 2035



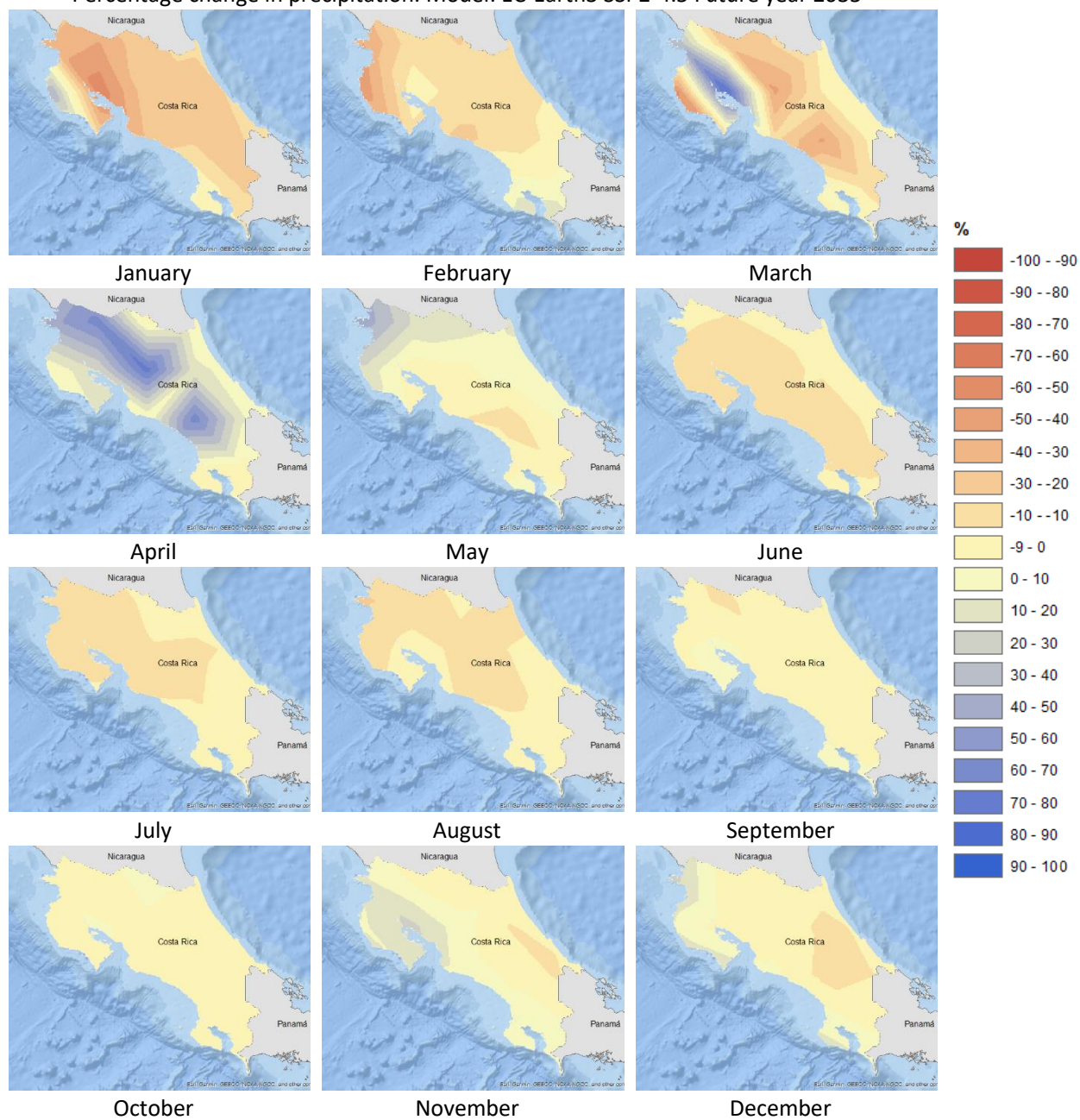
Percentage change in precipitation. Model: MPI-ESM1-2-LR SSP2-4.5 Future year 2050



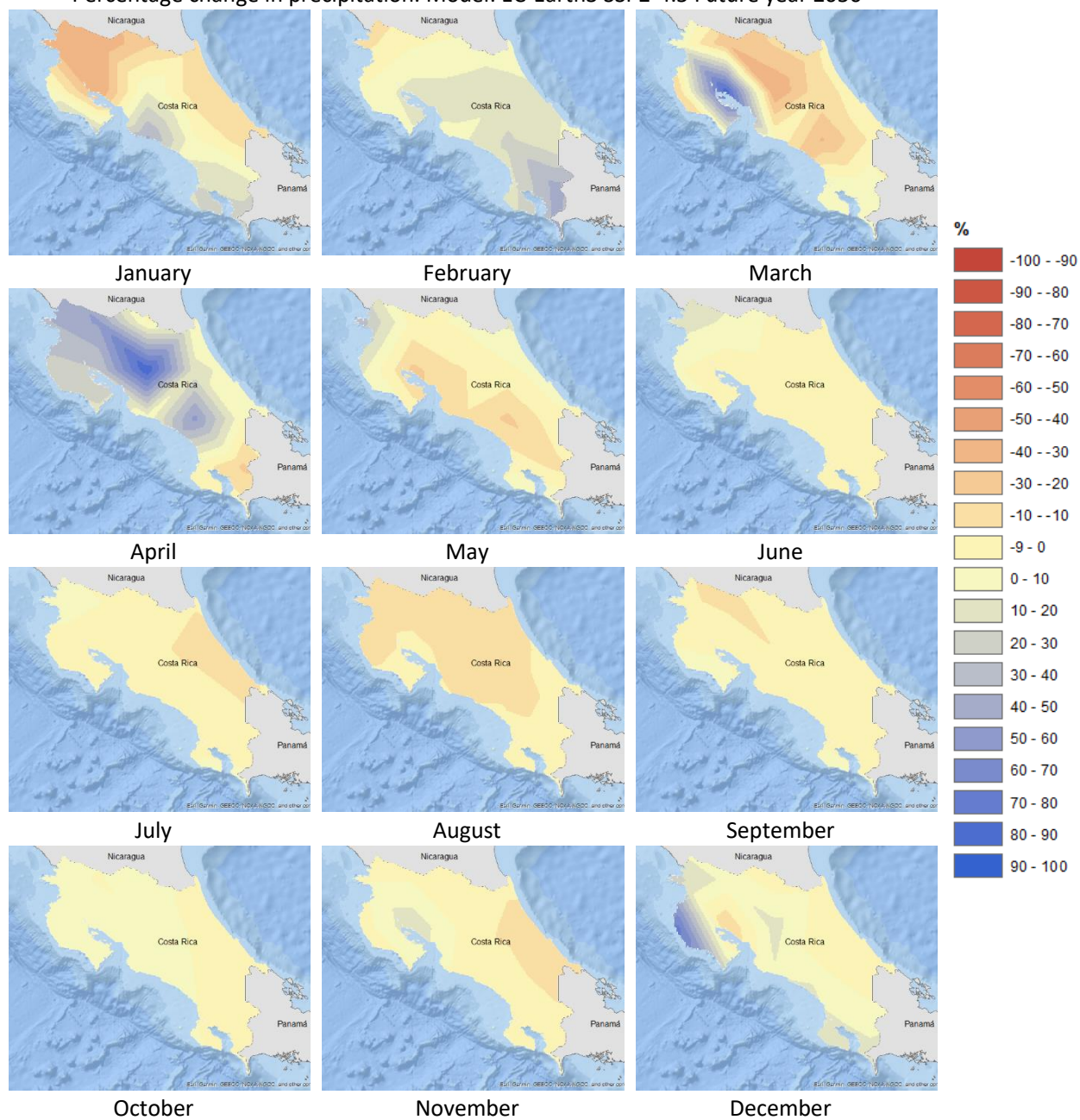
Percentage change in precipitation. Model: MPI-ESM1-2-LR SSP2-4.5 Future year 2100



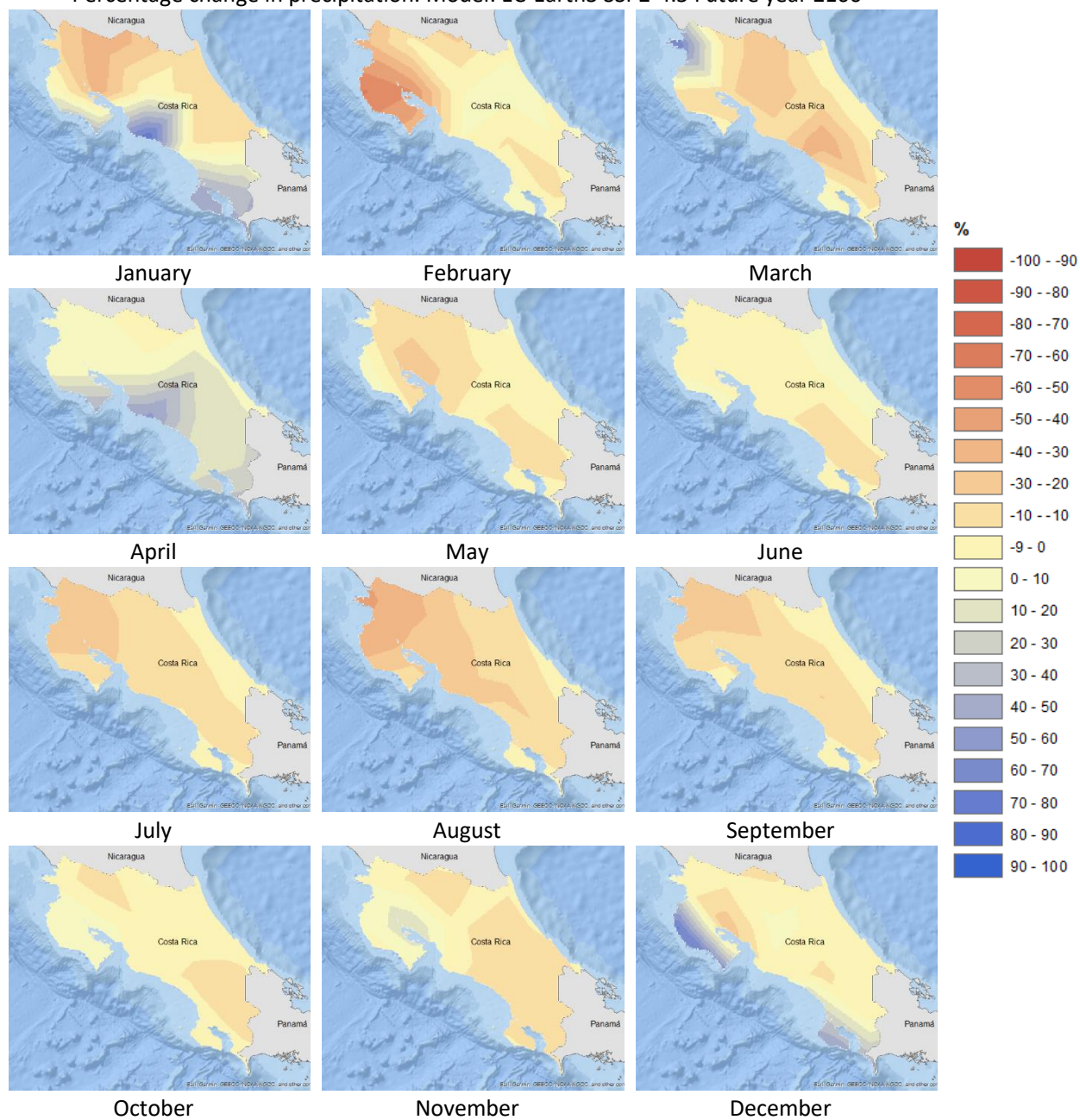
Percentage change in precipitation. Model: EC-Earth3 SSP2-4.5 Future year 2035



Percentage change in precipitation. Model: EC-Earth3 SSP2-4.5 Future year 2050

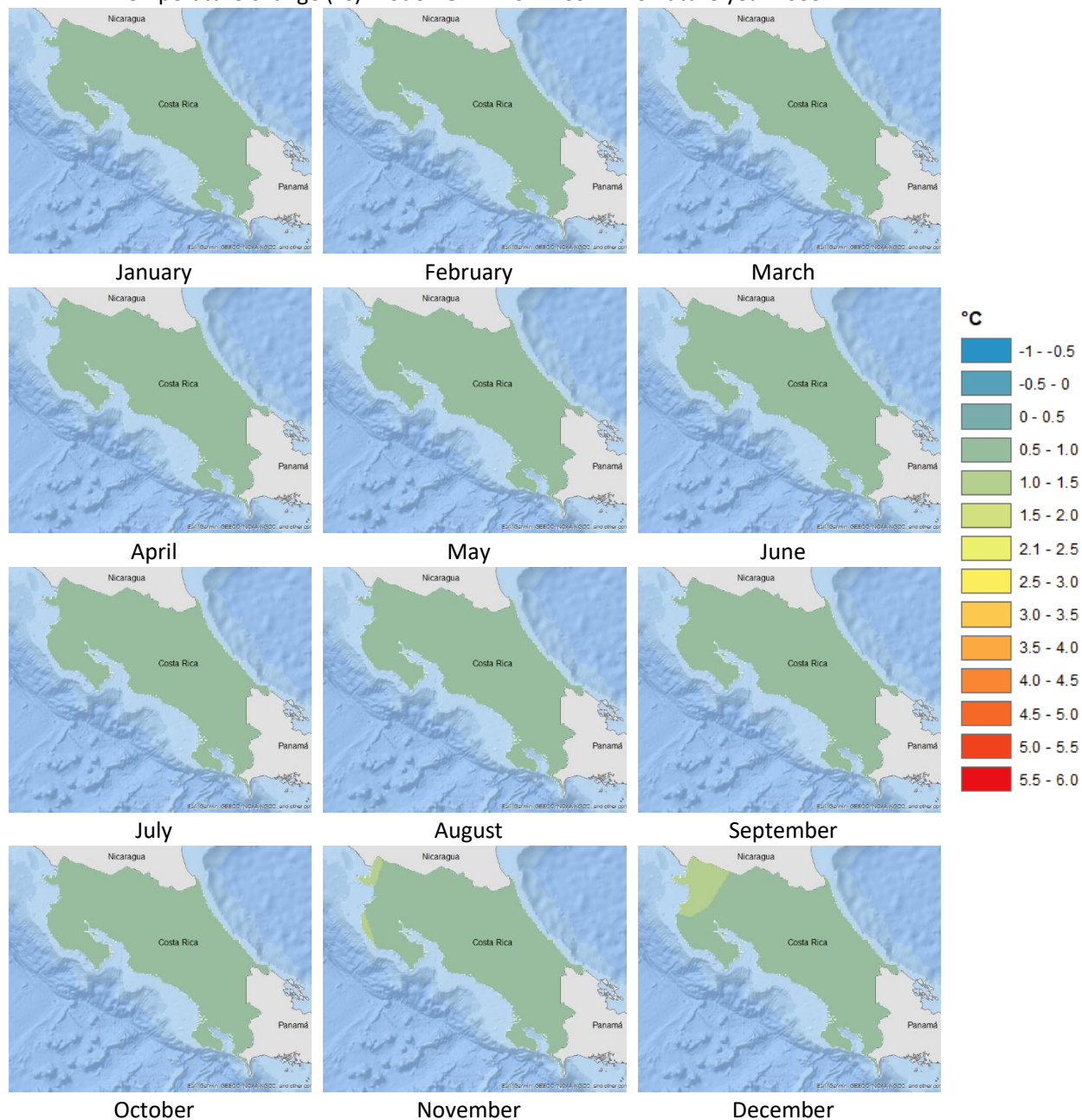


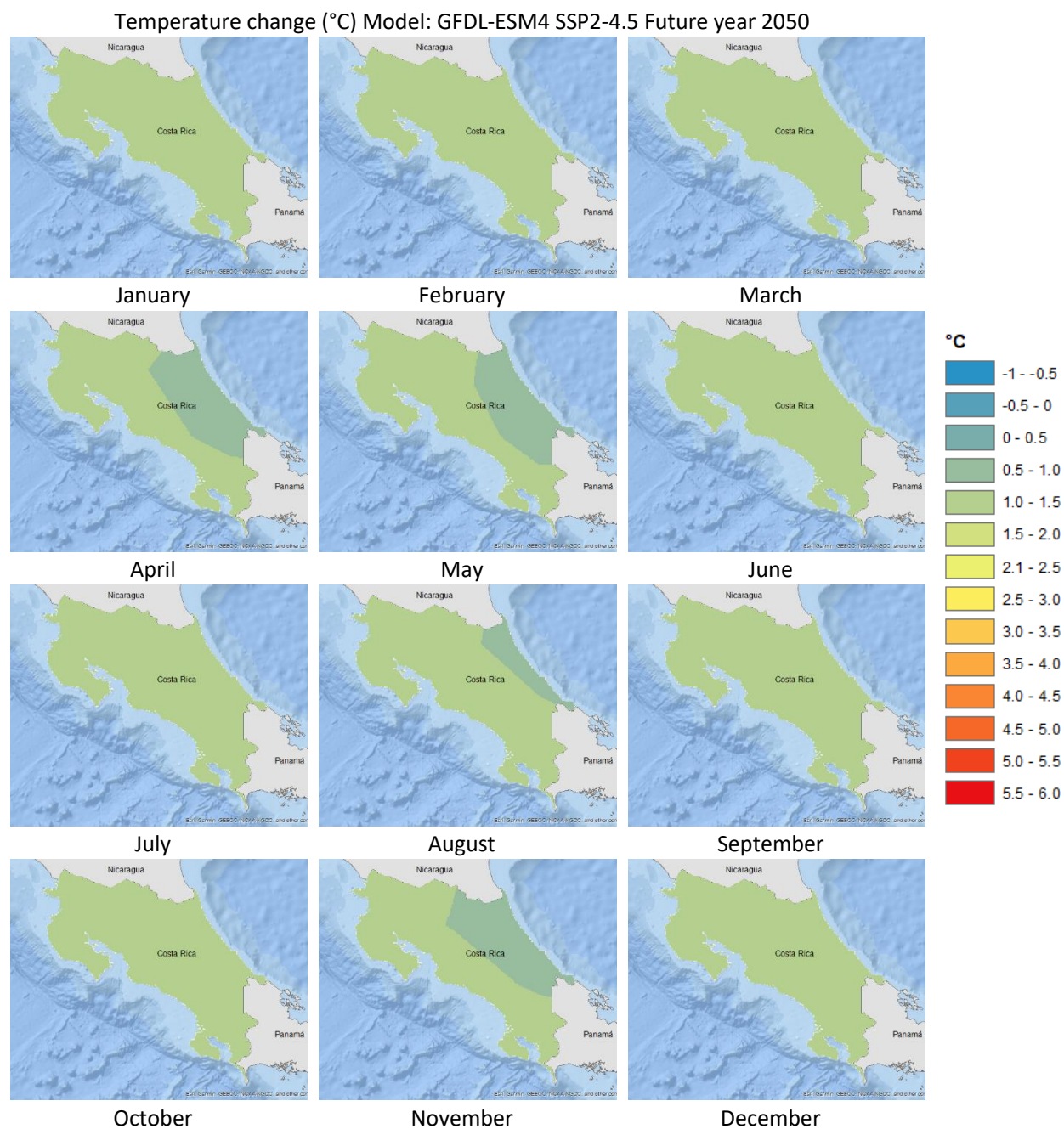
Percentage change in precipitation. Model: EC-Earth3 SSP2-4.5 Future year 2100



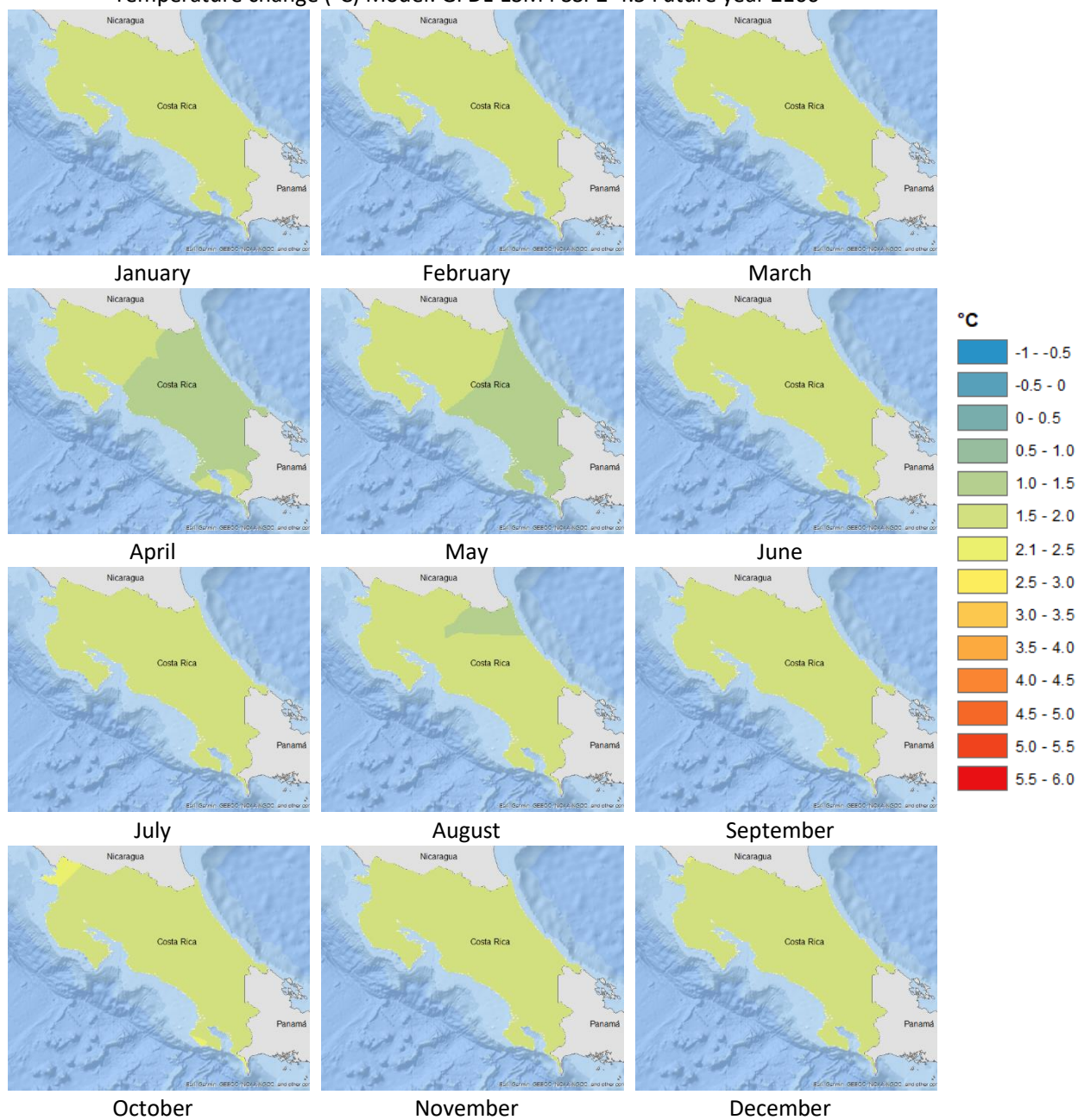
Temperature SSP2-4.5

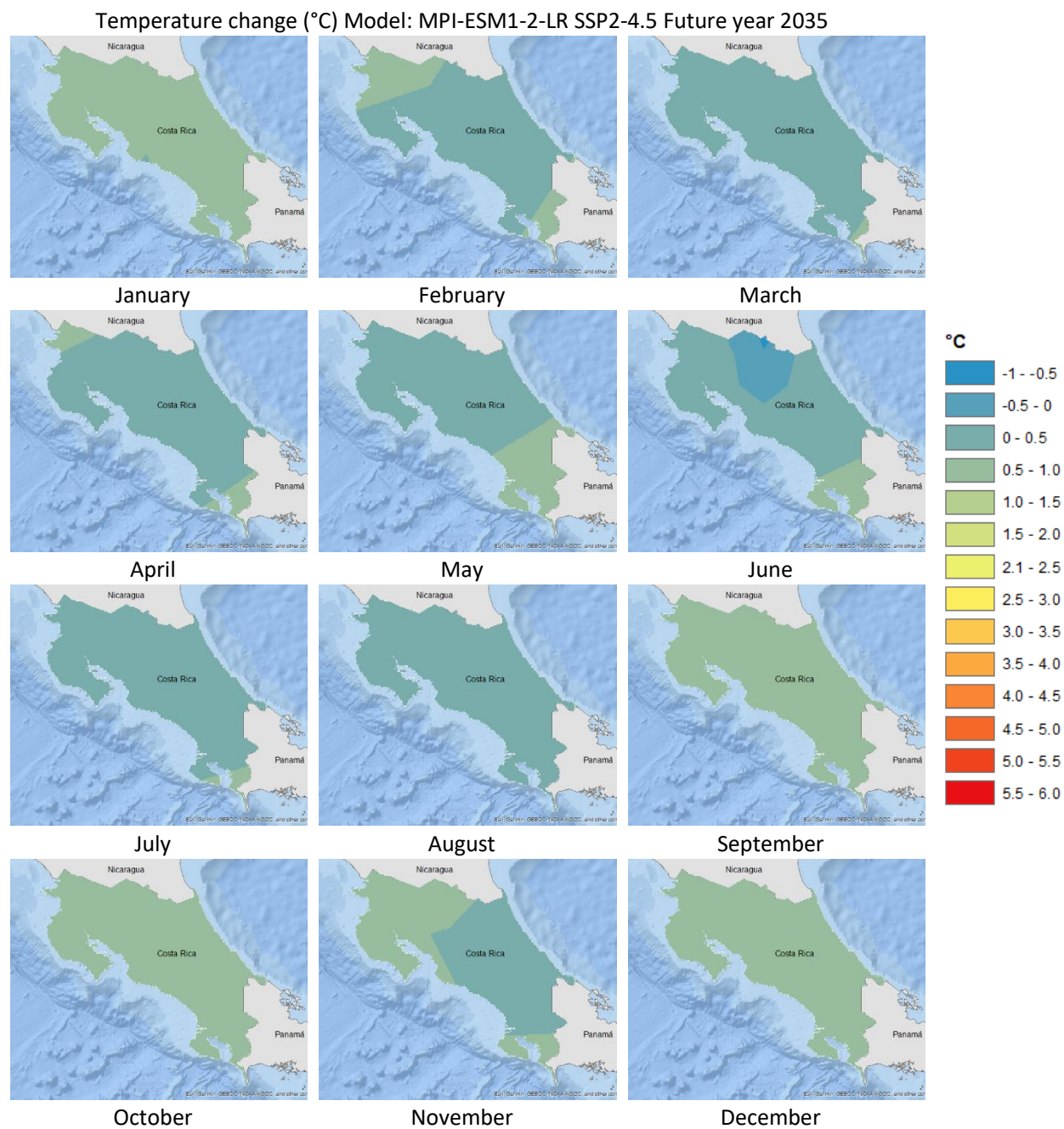
Temperature change (°C) Model: GFDL-ESM4 SSP2-4.5 Future year 2035

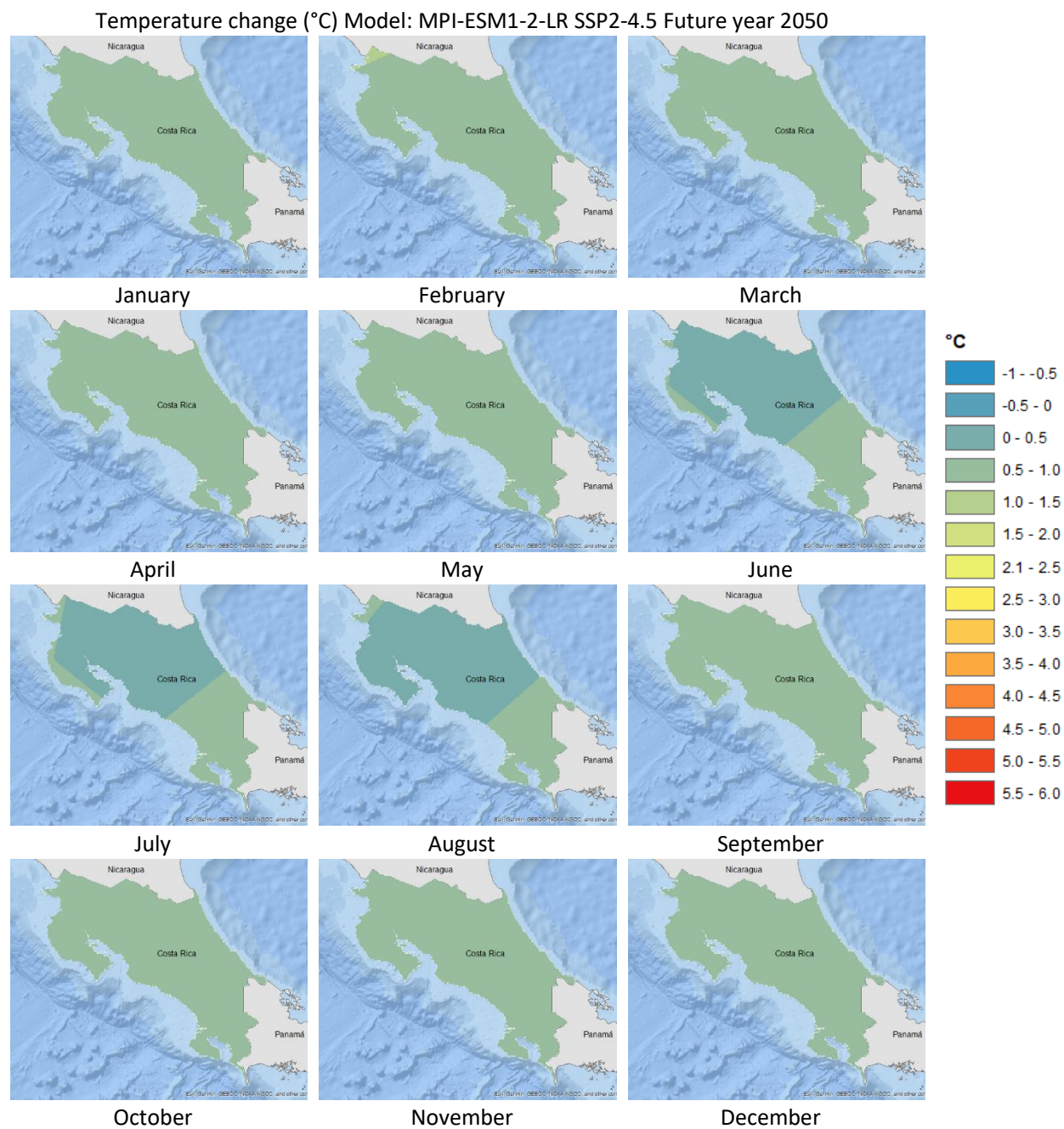


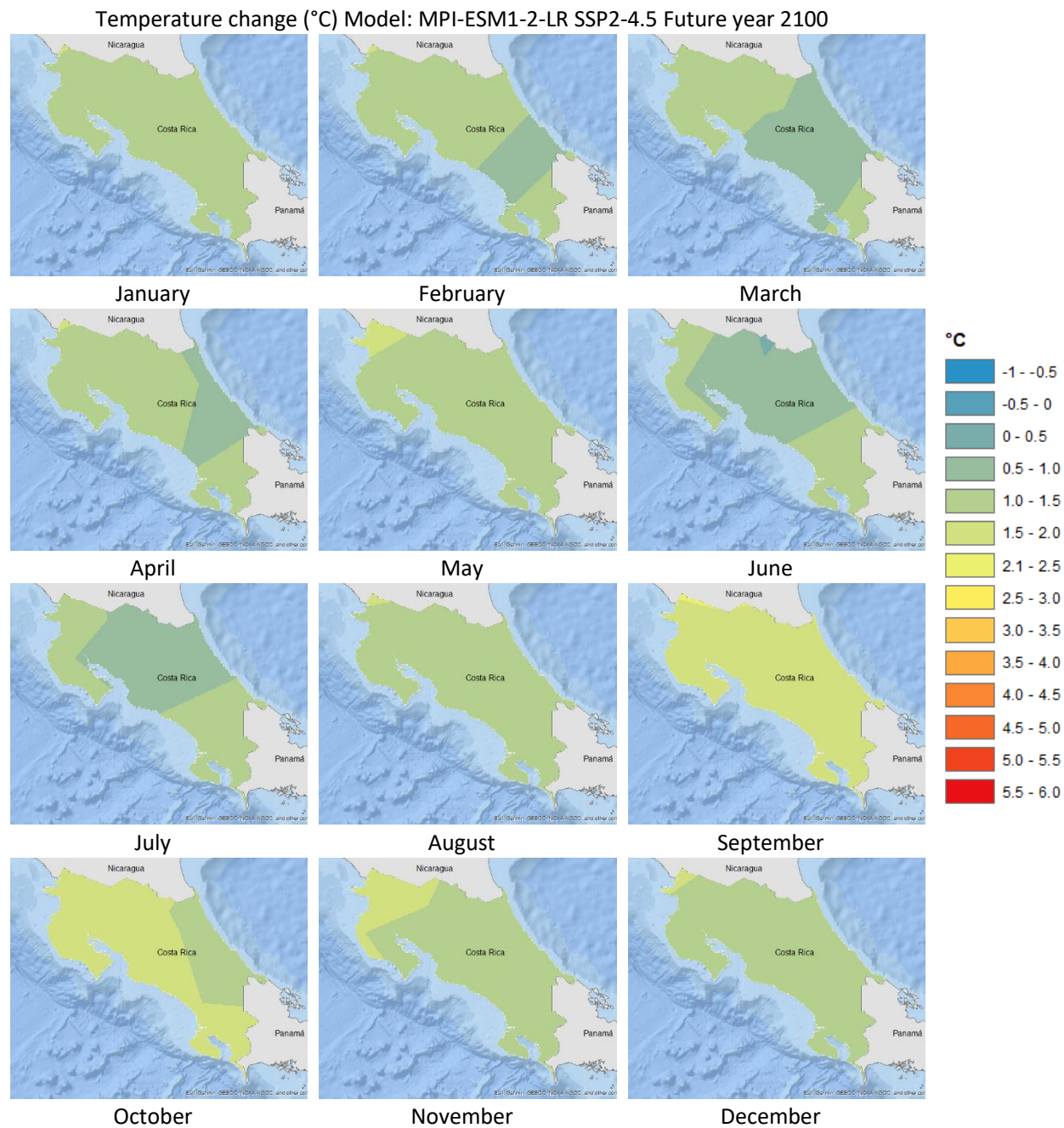


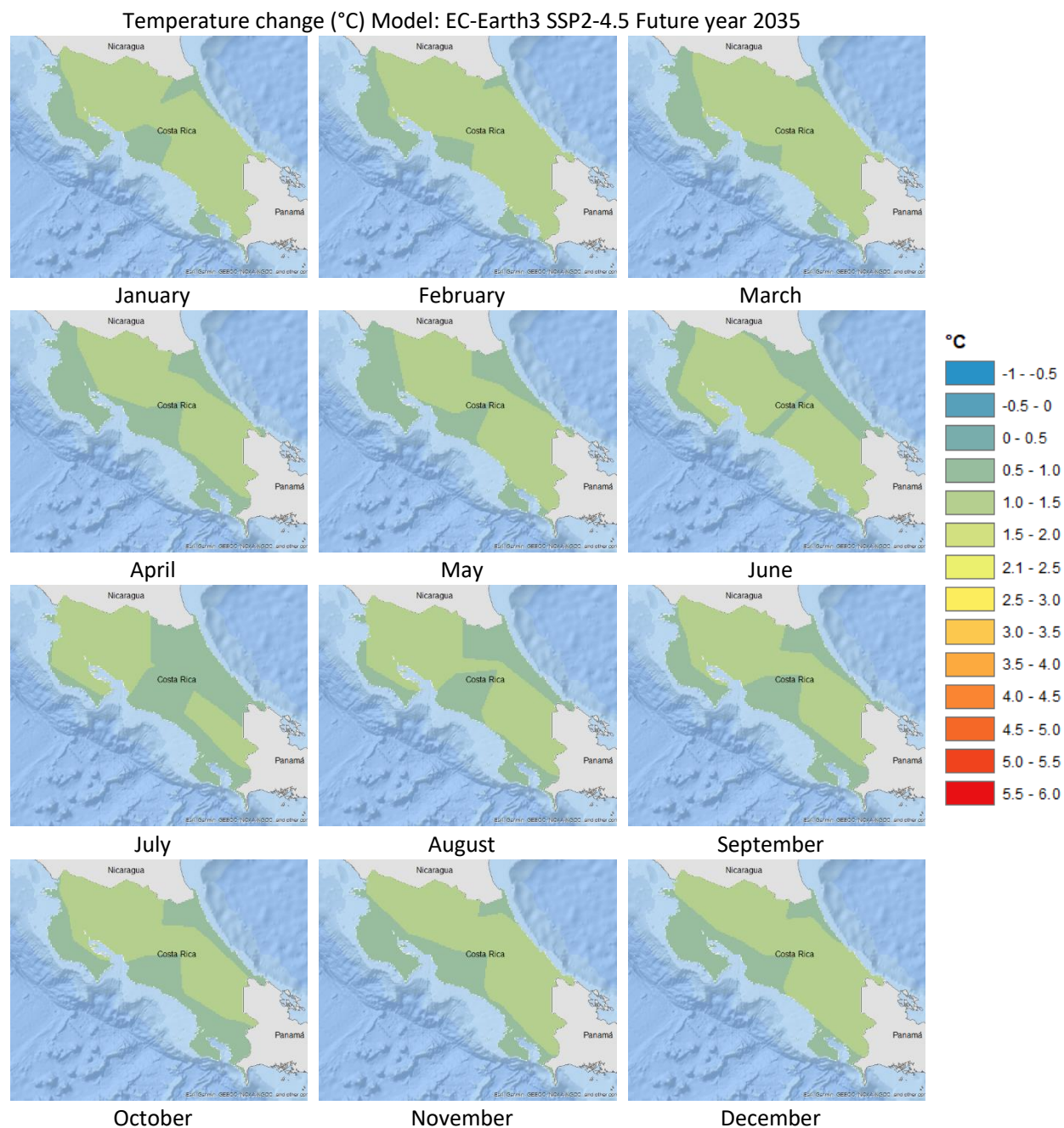
Temperature change (°C) Model: GFDL-ESM4 SSP2-4.5 Future year 2100

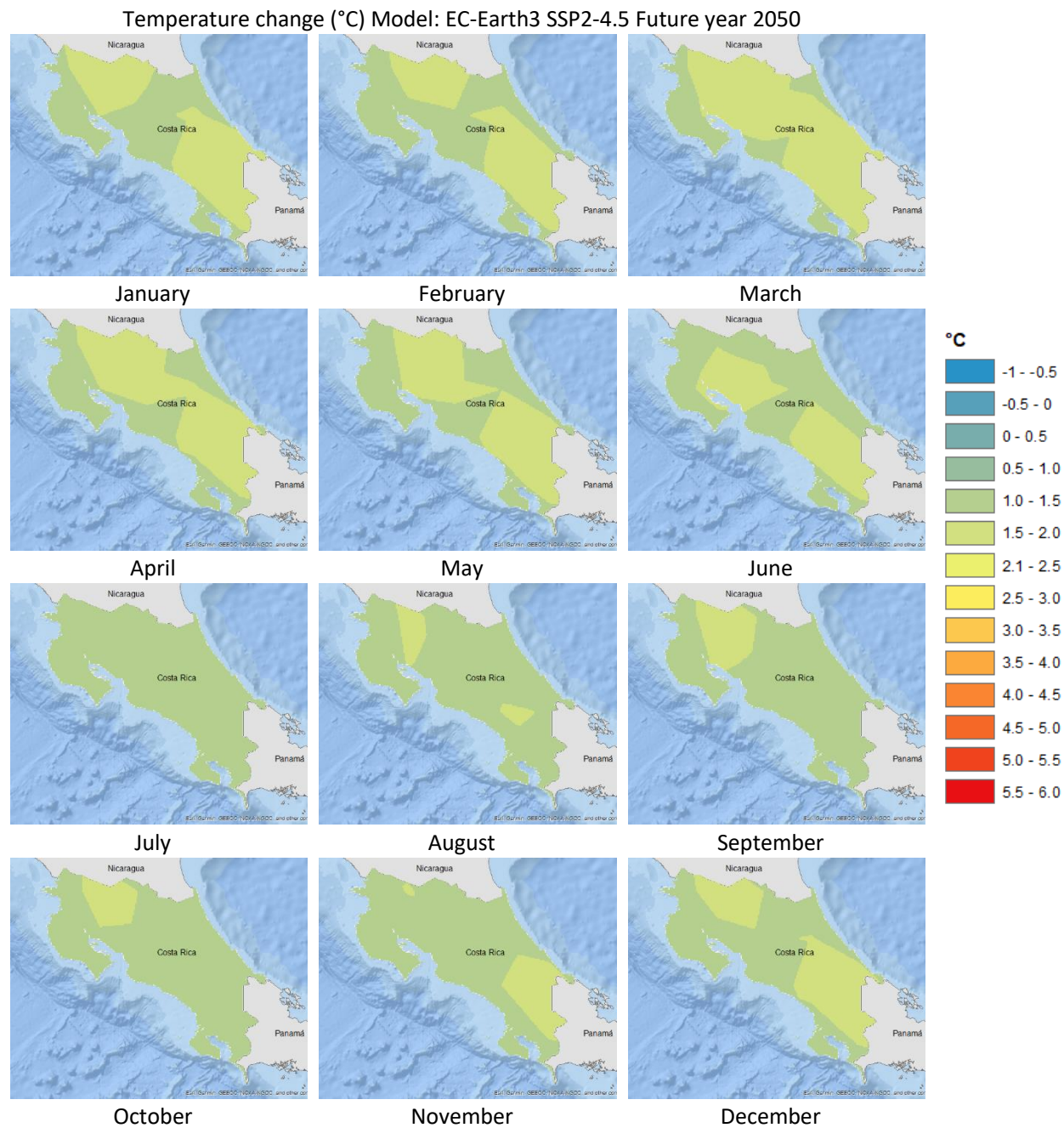


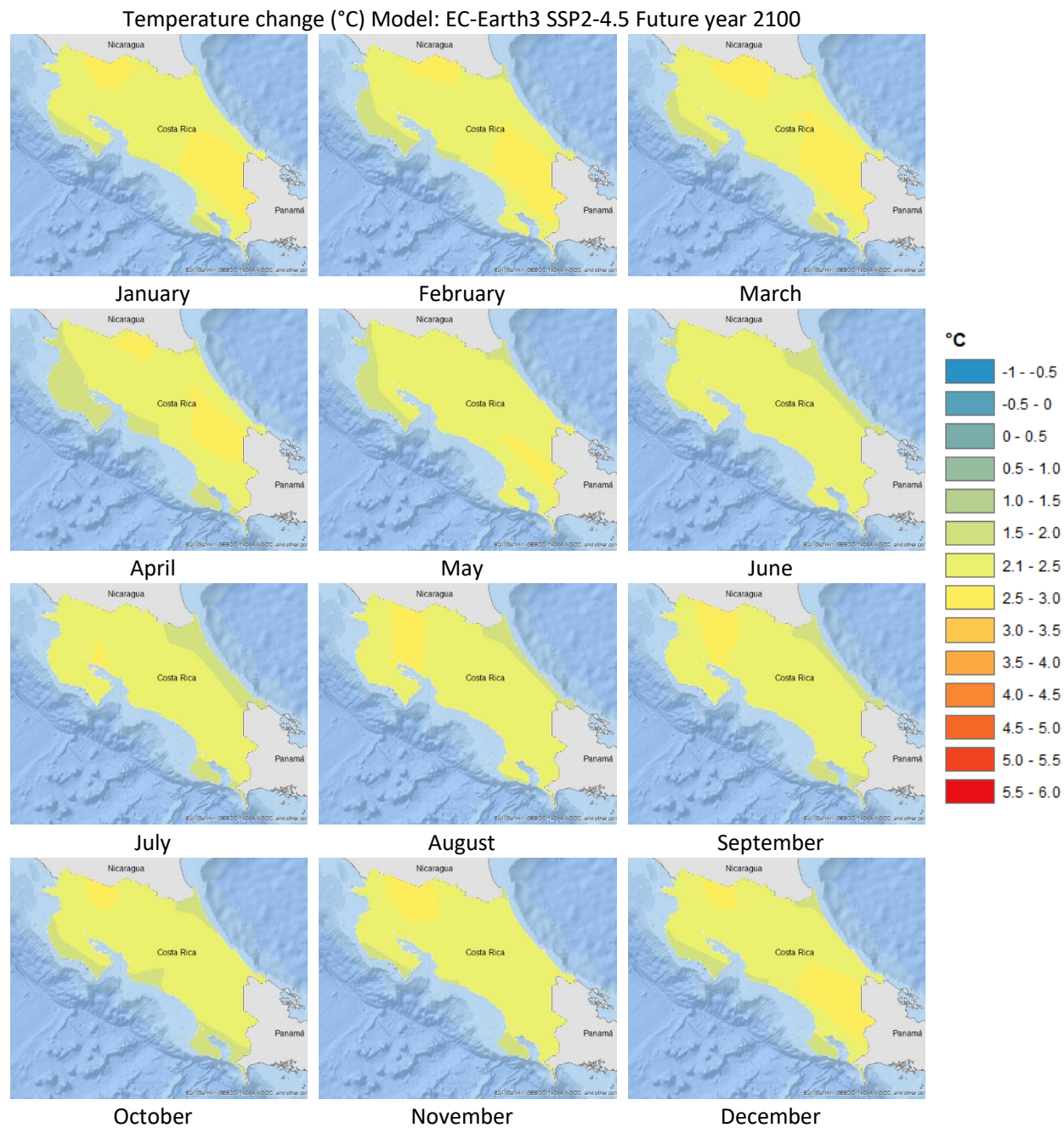






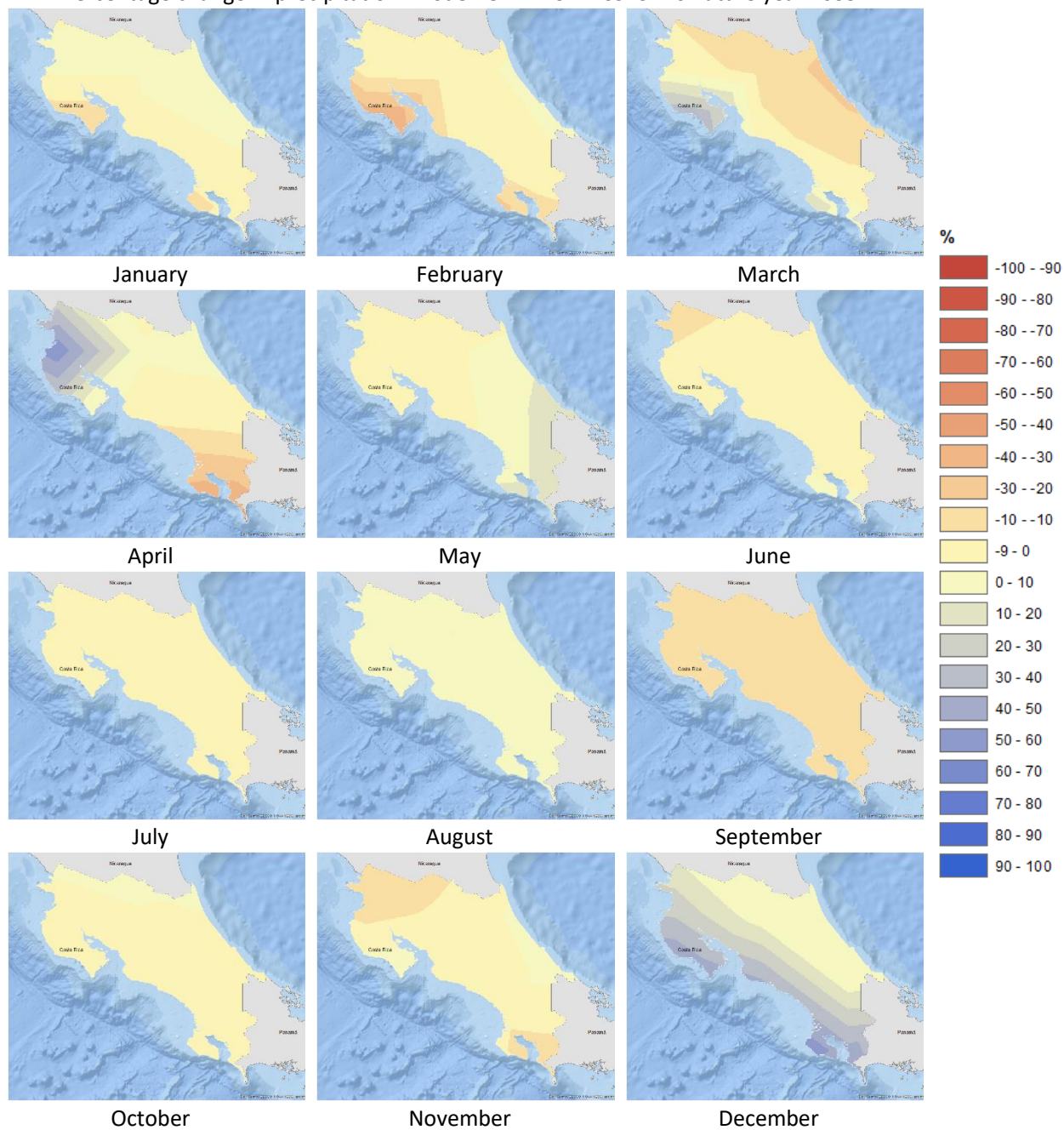




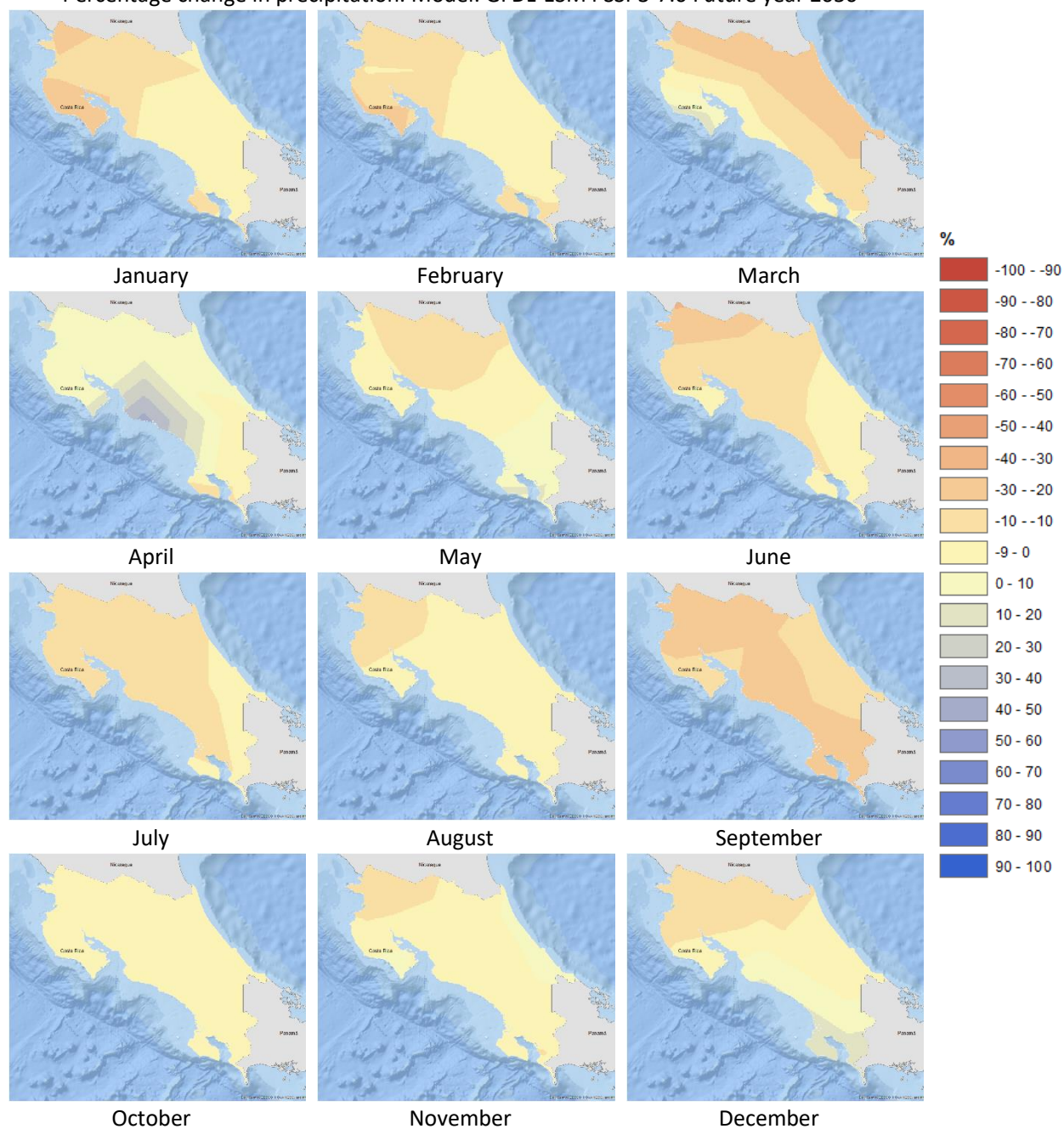


Precipitation SSP3-7.0

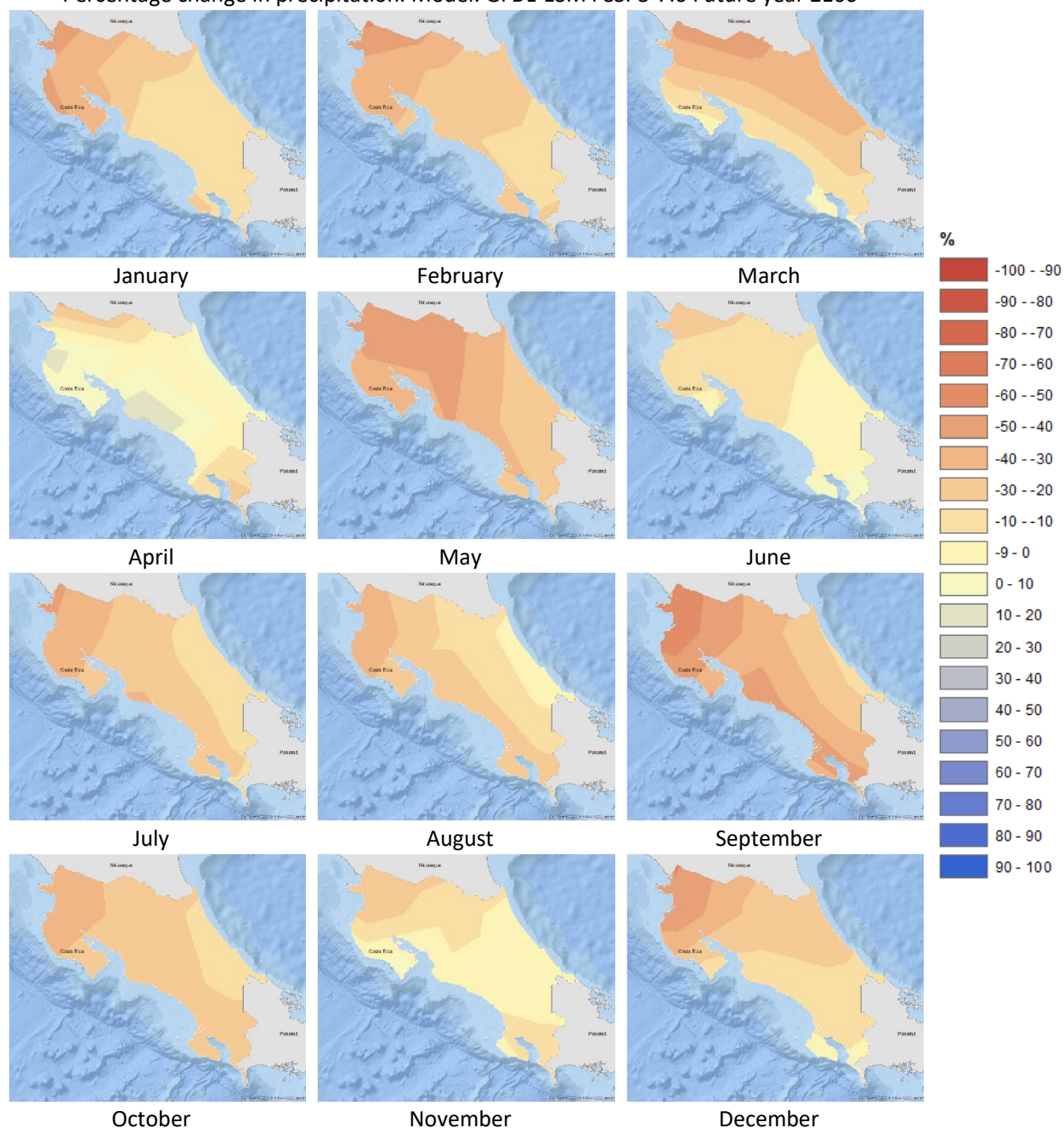
Percentage change in precipitation. Model: GFDL-ESM4 SSP3-7.0 Future year 2035



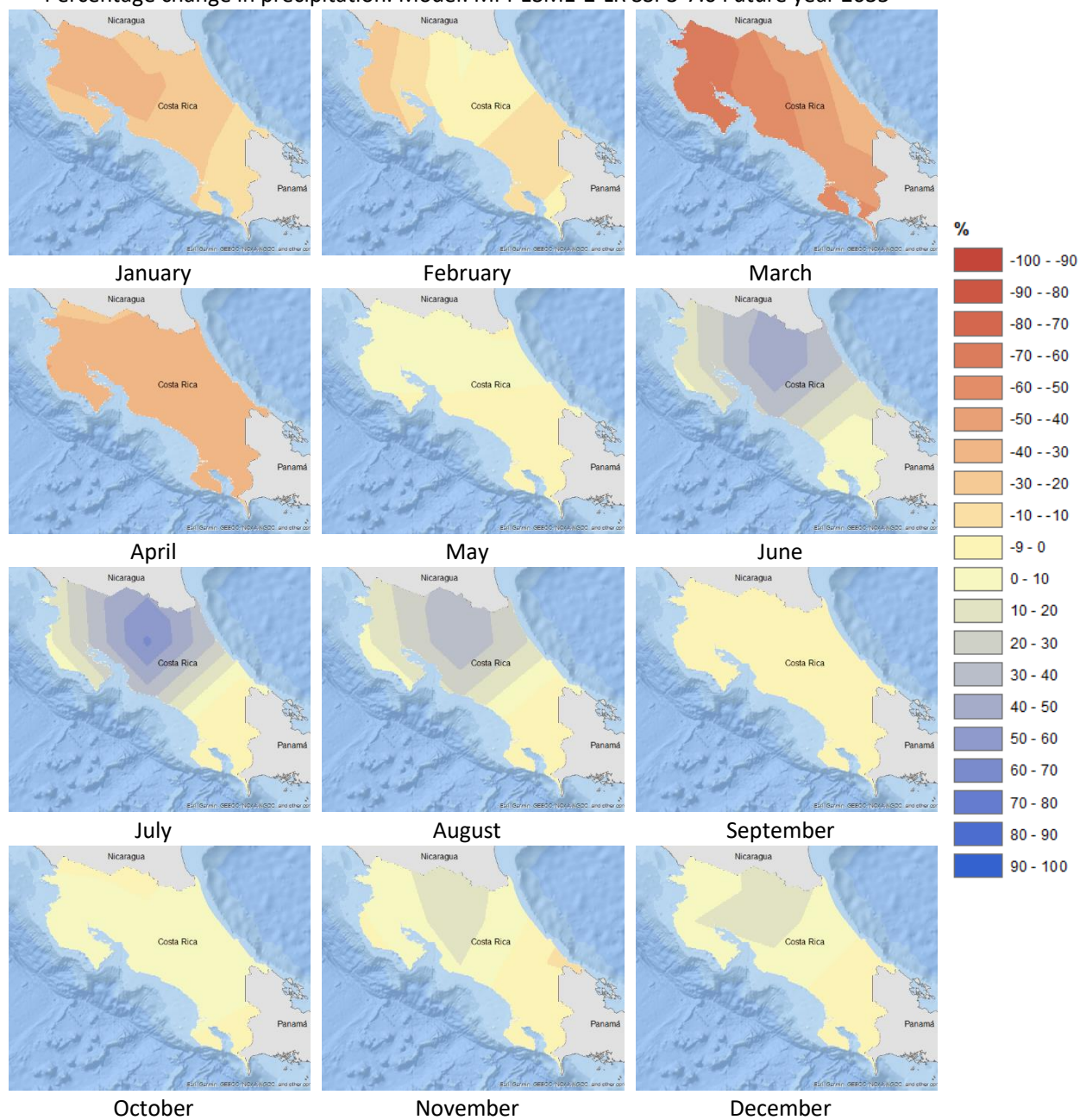
Percentage change in precipitation. Model: GFDL-ESM4 SSP3-7.0 Future year 2050



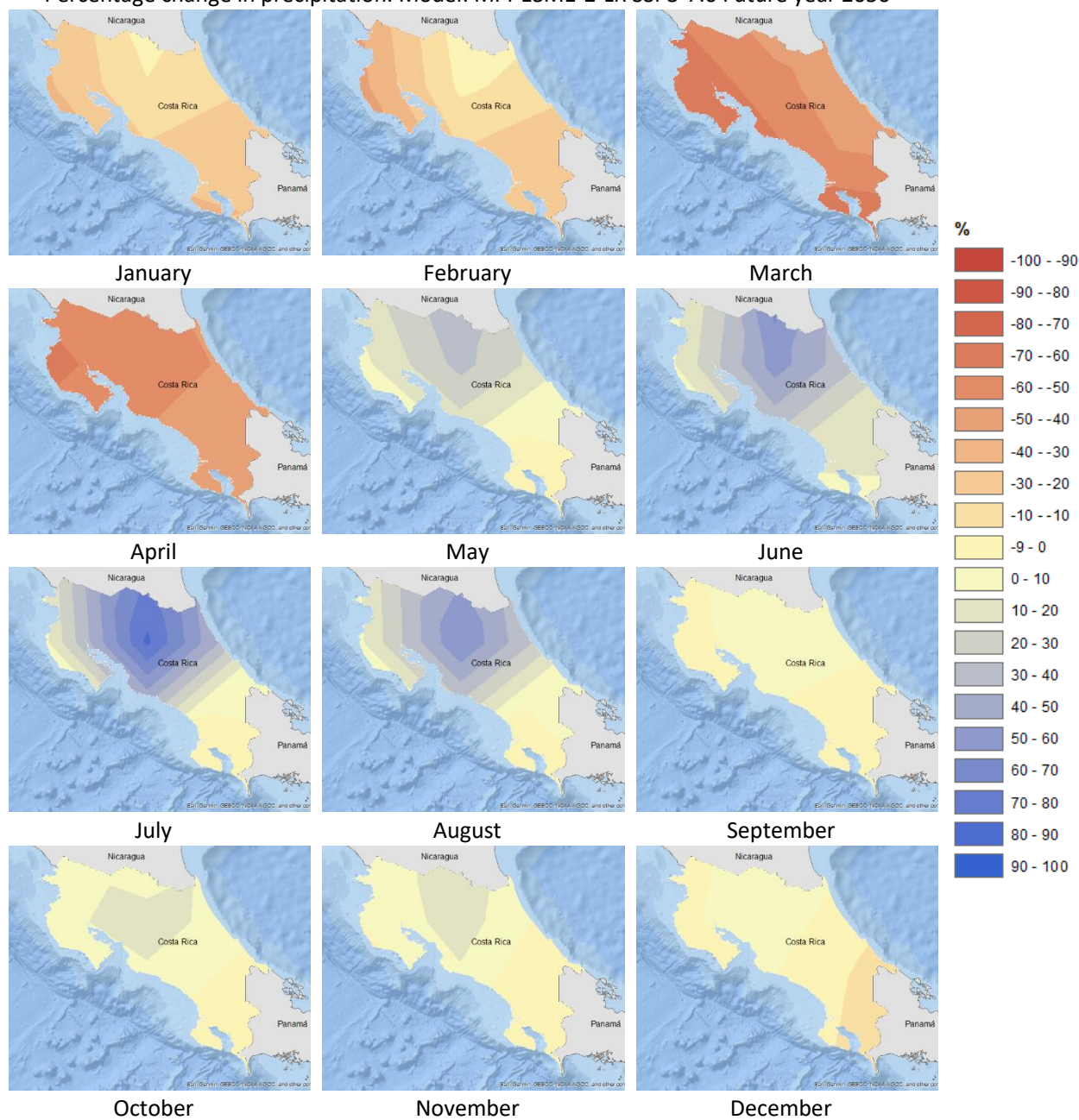
Percentage change in precipitation. Model: GFDL-ESM4 SSP3-7.0 Future year 2100



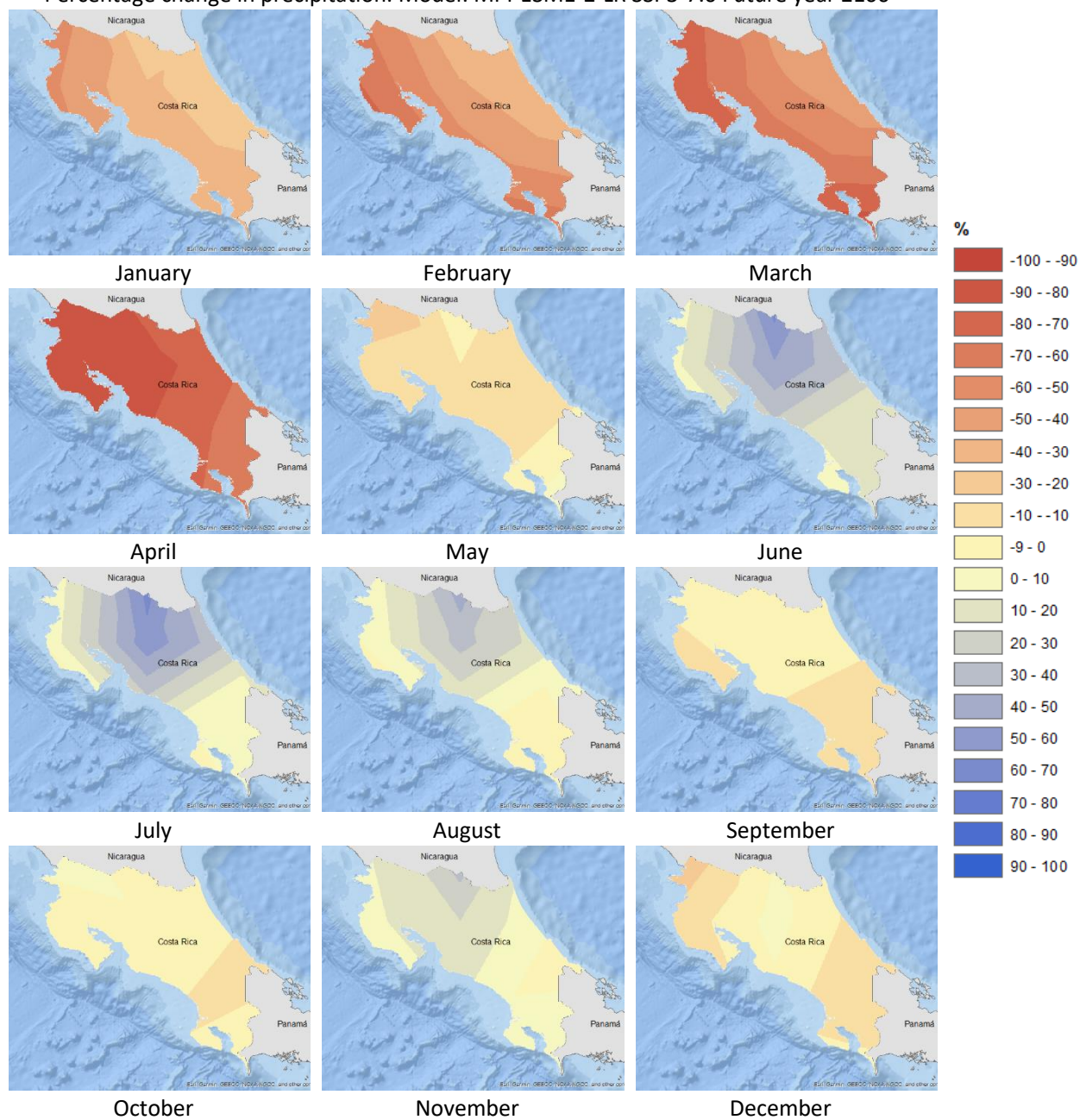
Percentage change in precipitation. Model: MPI-ESM1-2-LR SSP3-7.0 Future year 2035



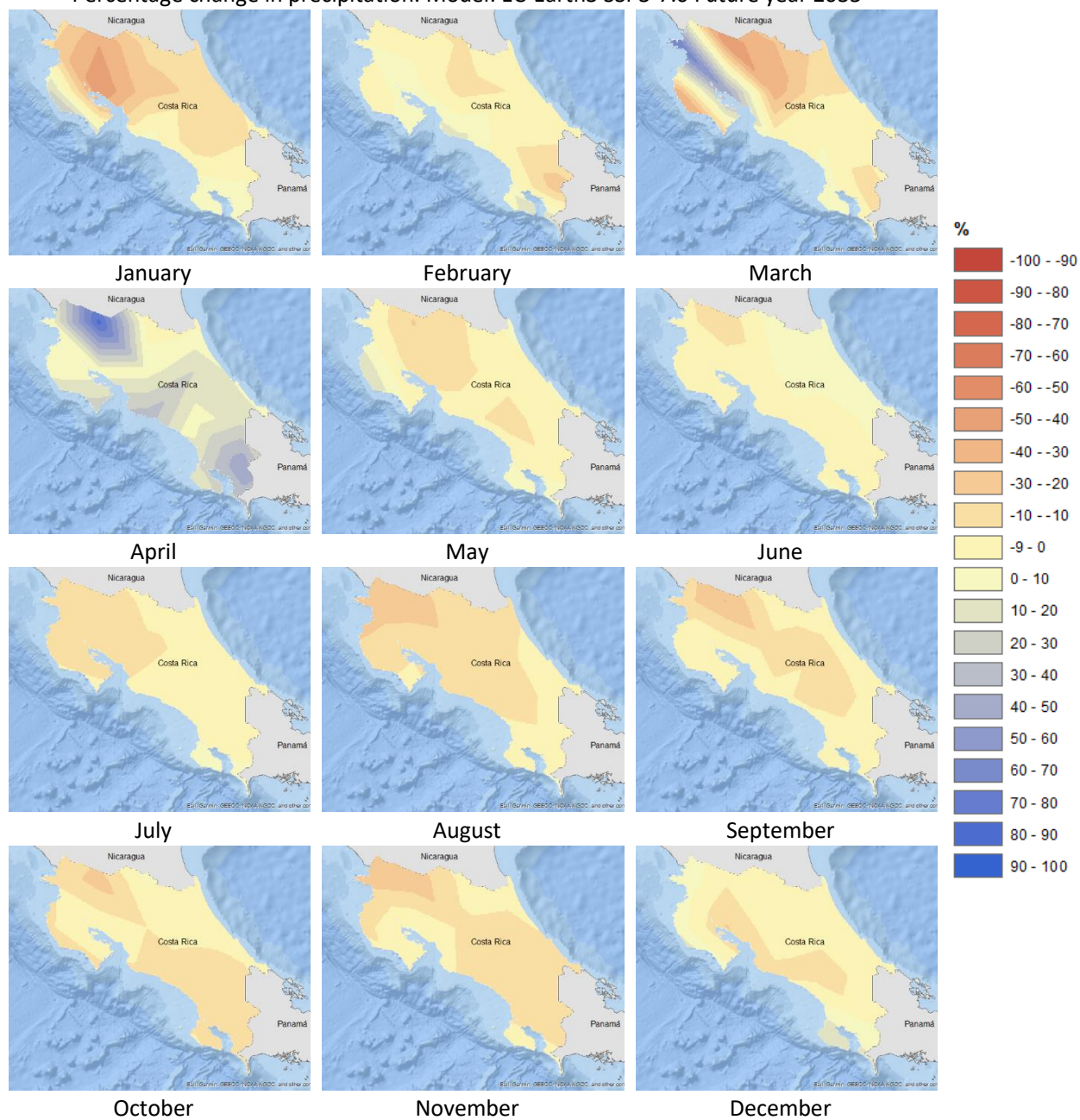
Percentage change in precipitation. Model: MPI-ESM1-2-LR SSP3-7.0 Future year 2050



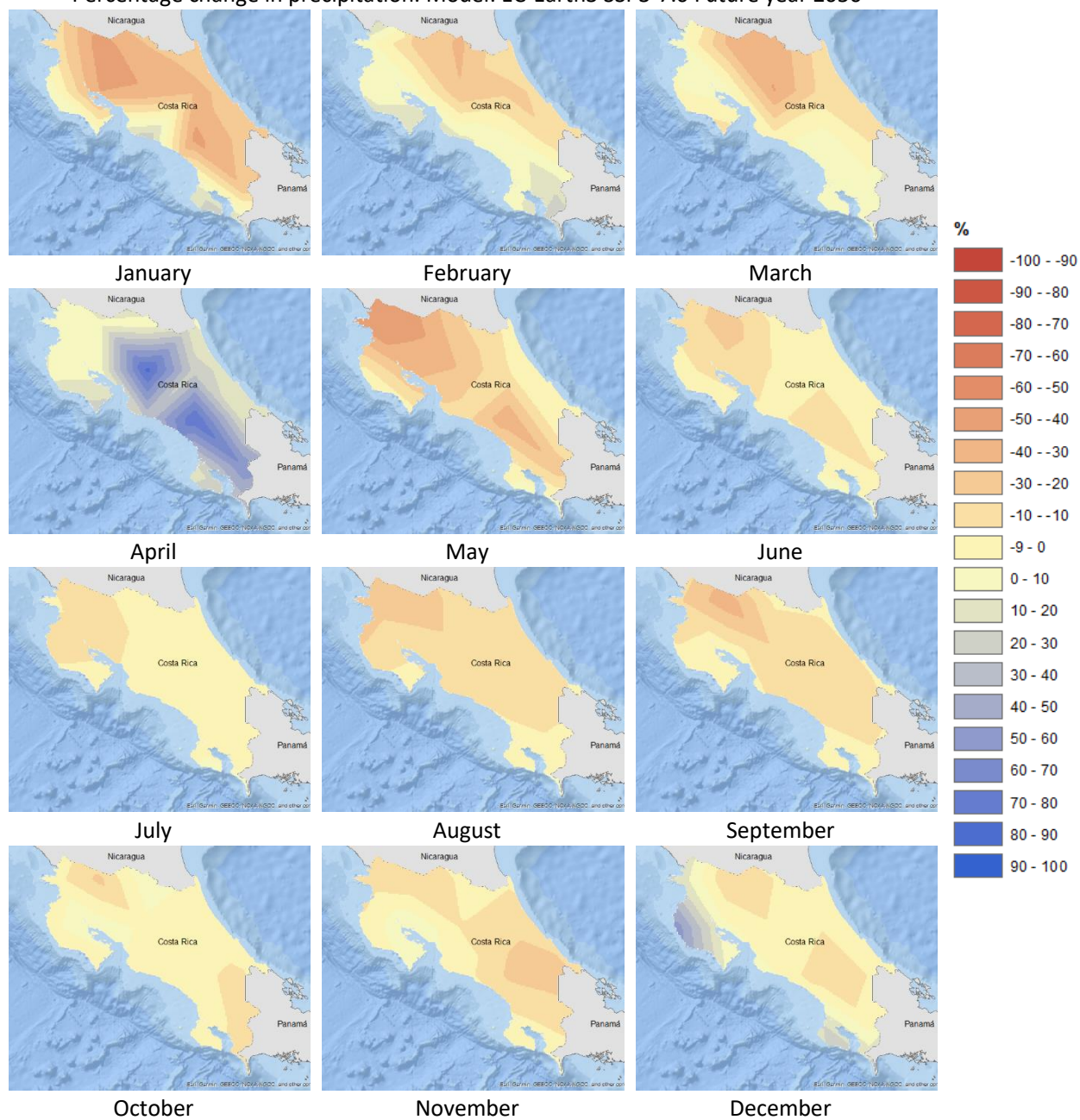
Percentage change in precipitation. Model: MPI-ESM1-2-LR SSP3-7.0 Future year 2100



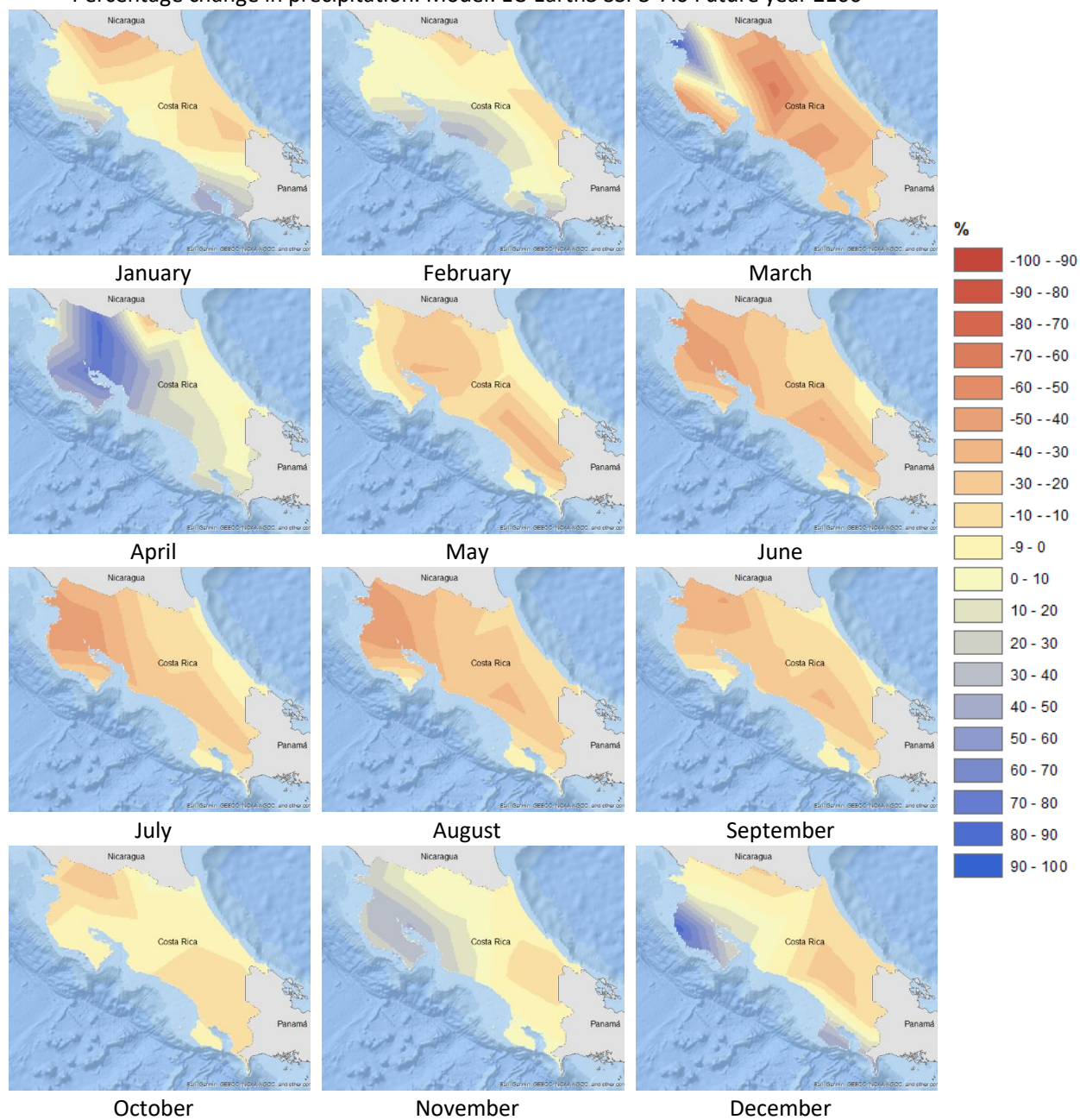
Percentage change in precipitation. Model: EC-Earth3 SSP3-7.0 Future year 2035



Percentage change in precipitation. Model: EC-Earth3 SSP3-7.0 Future year 2050

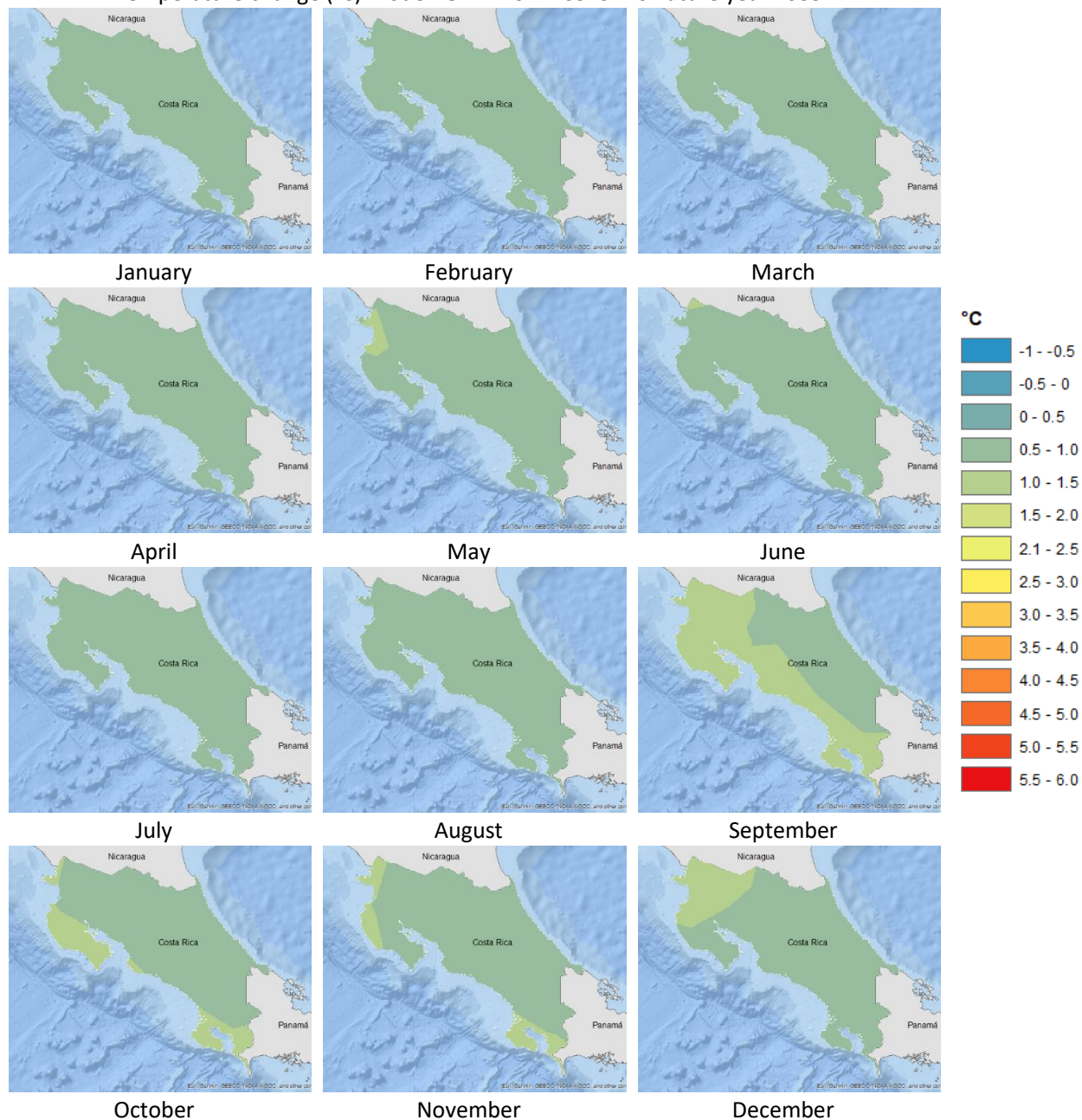


Percentage change in precipitation. Model: EC-Earth3 SSP3-7.0 Future year 2100

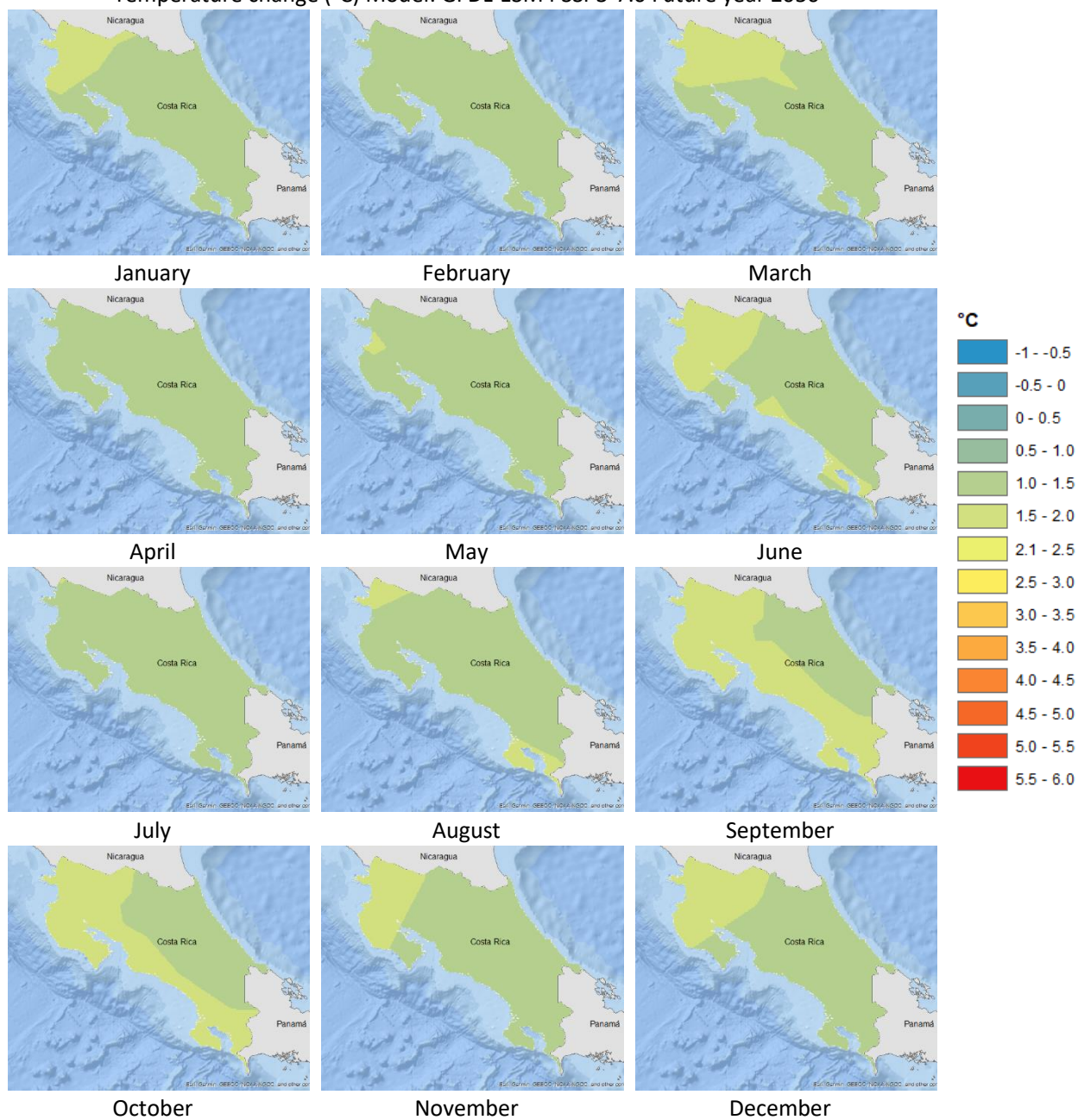


Temperature SSP3-7.0

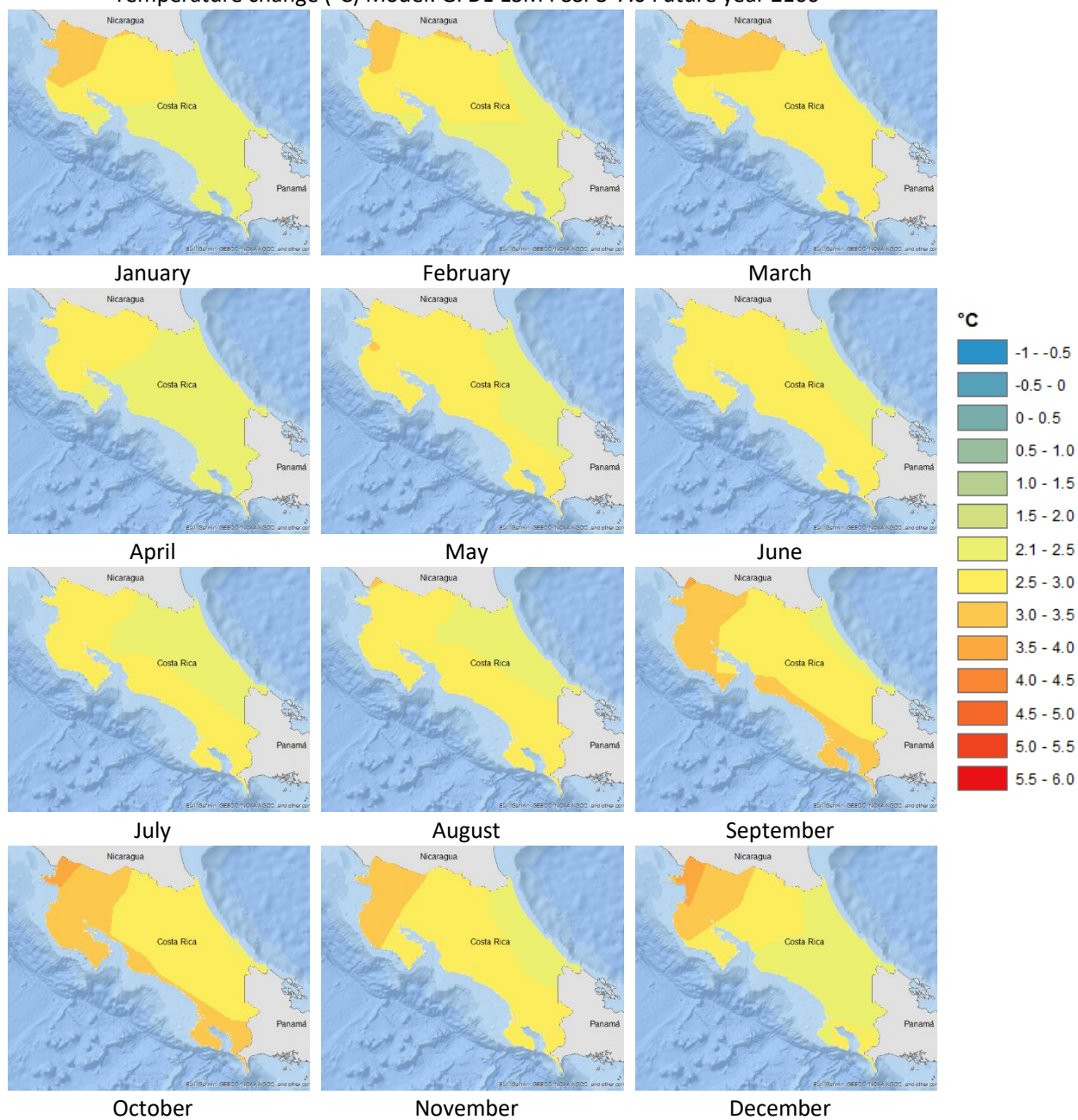
Temperature change (°C) Model: GFDL-ESM4 SSP3-7.0 Future year 2035

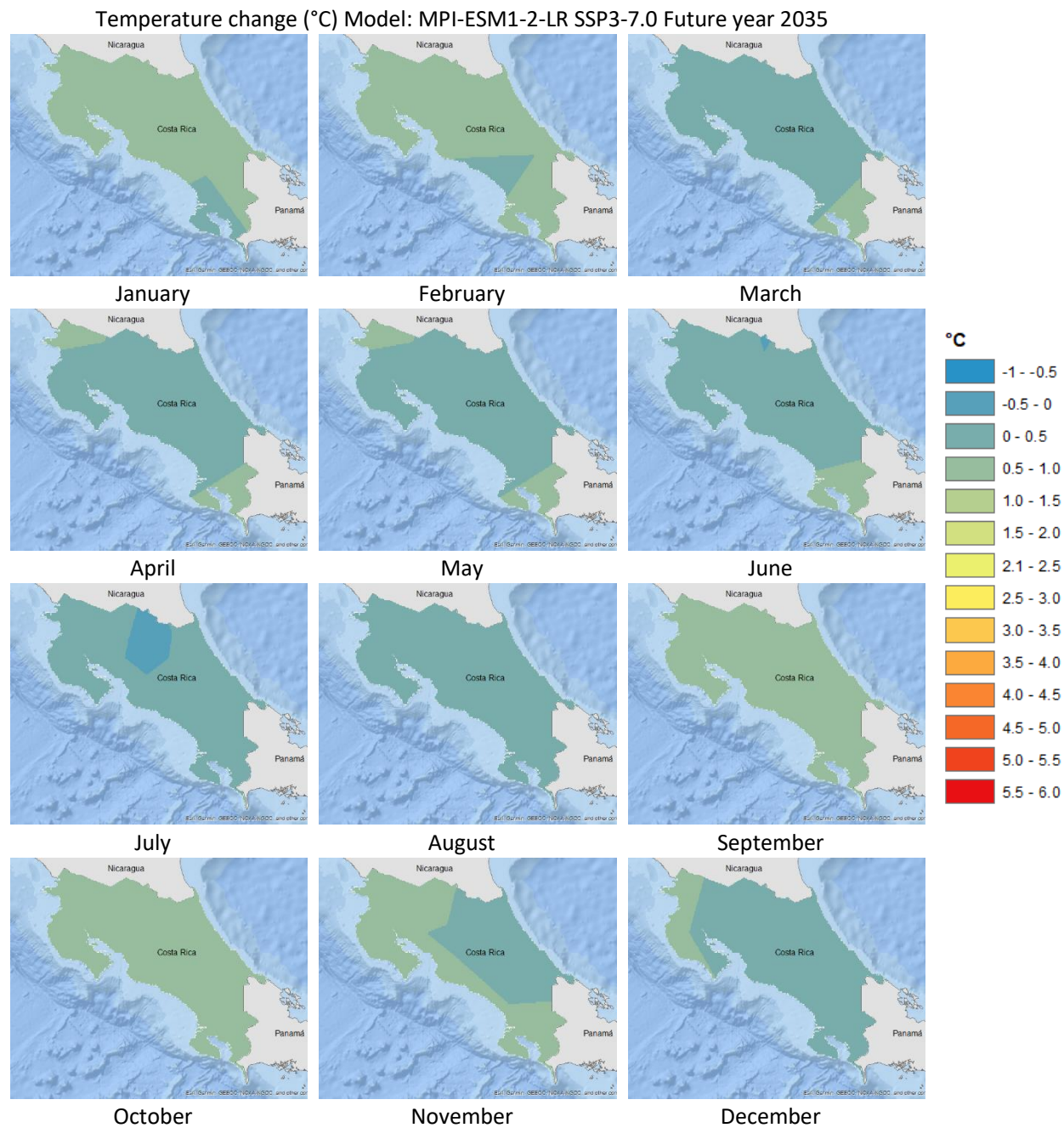


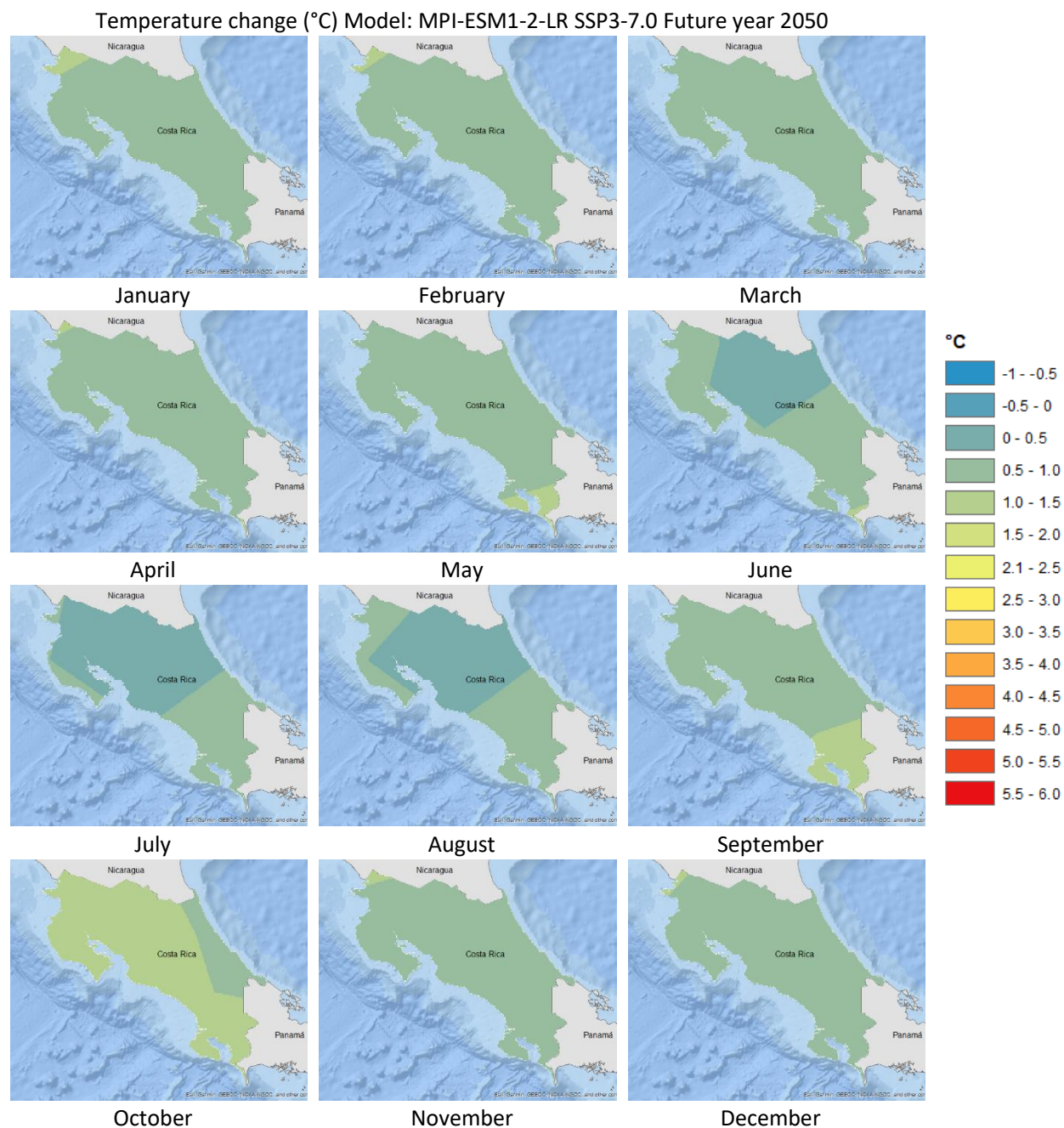
Temperature change (°C) Model: GFDL-ESM4 SSP3-7.0 Future year 2050

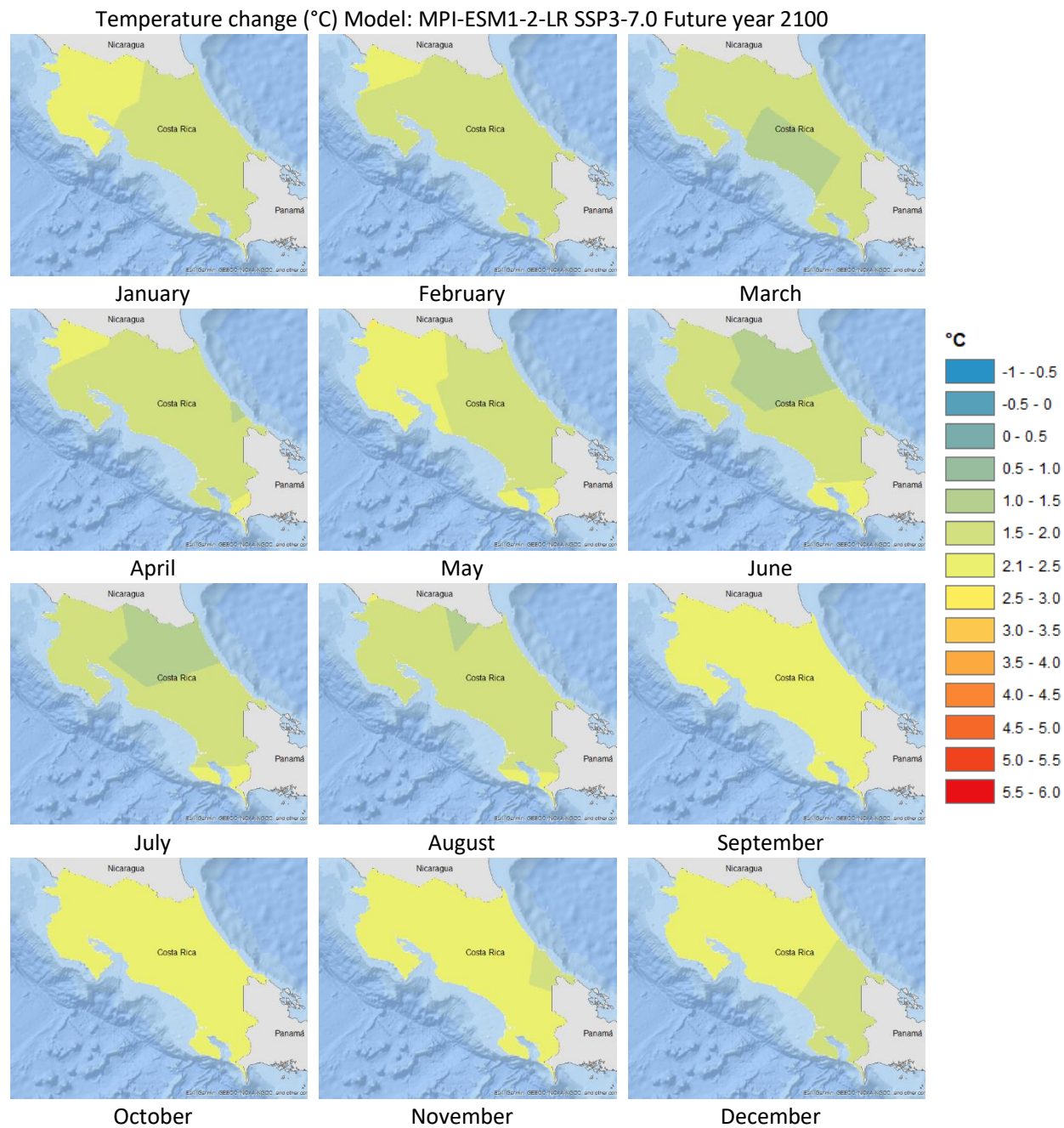


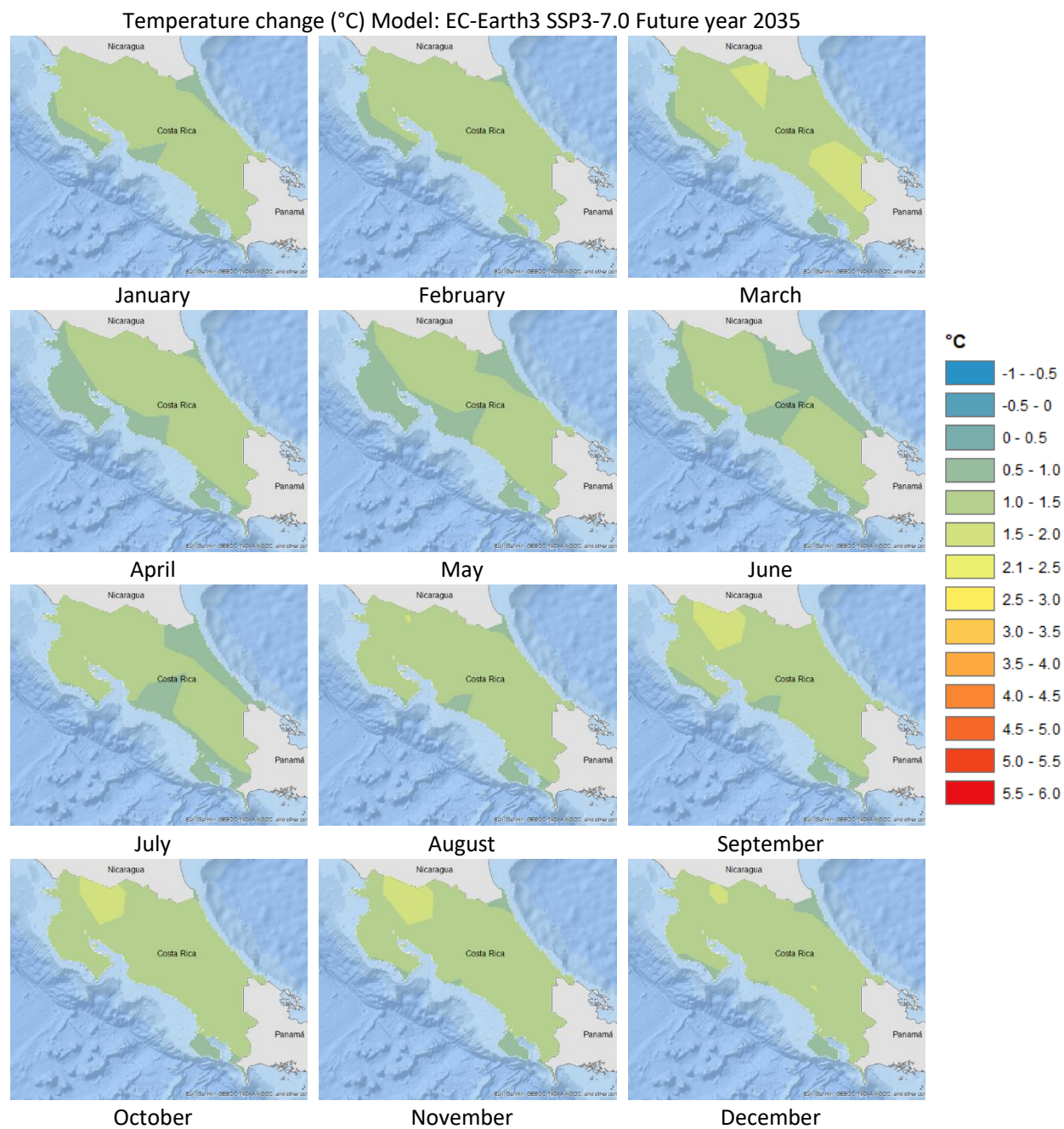
Temperature change (°C) Model: GFDL-ESM4 SSP3-7.0 Future year 2100

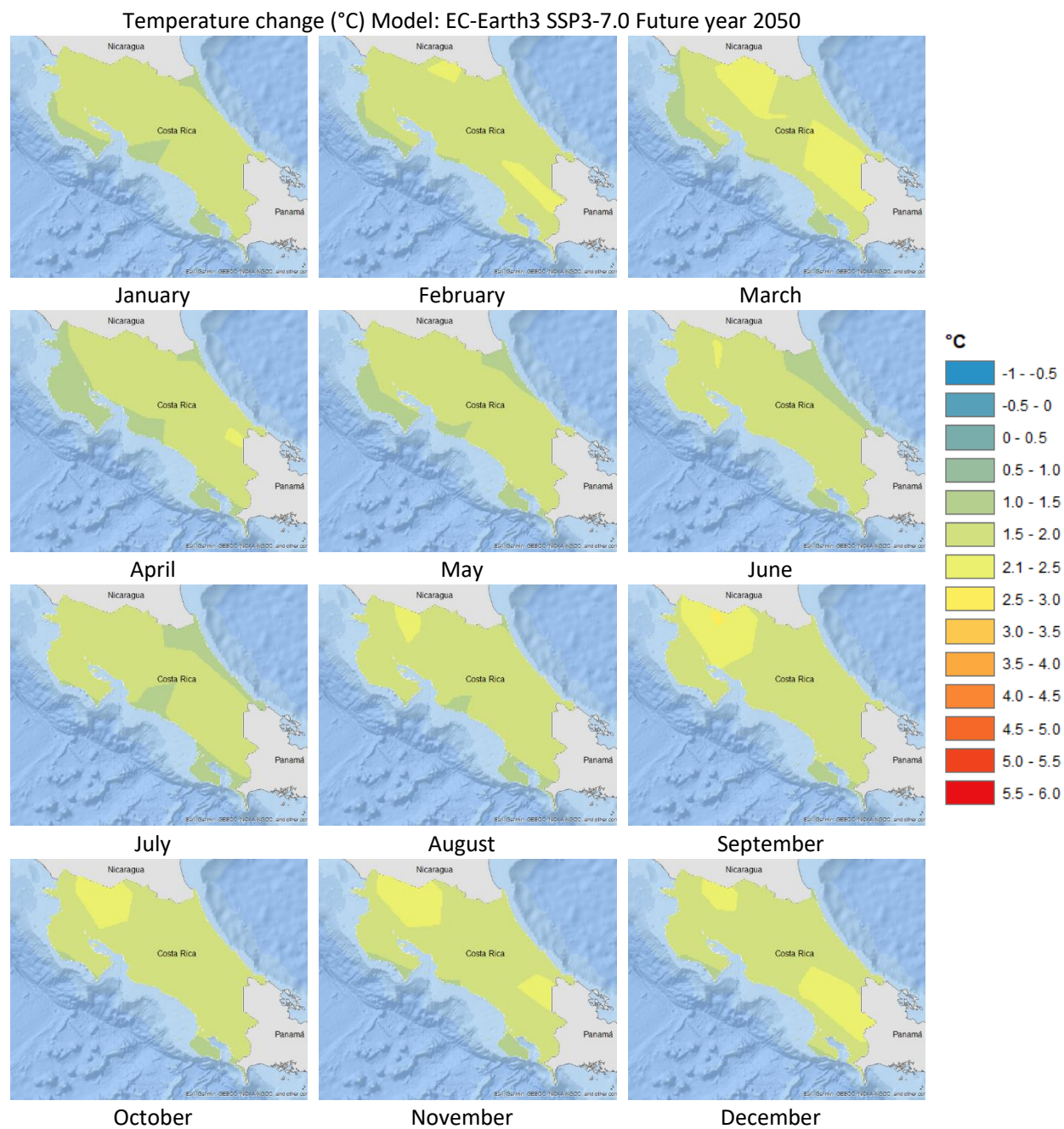


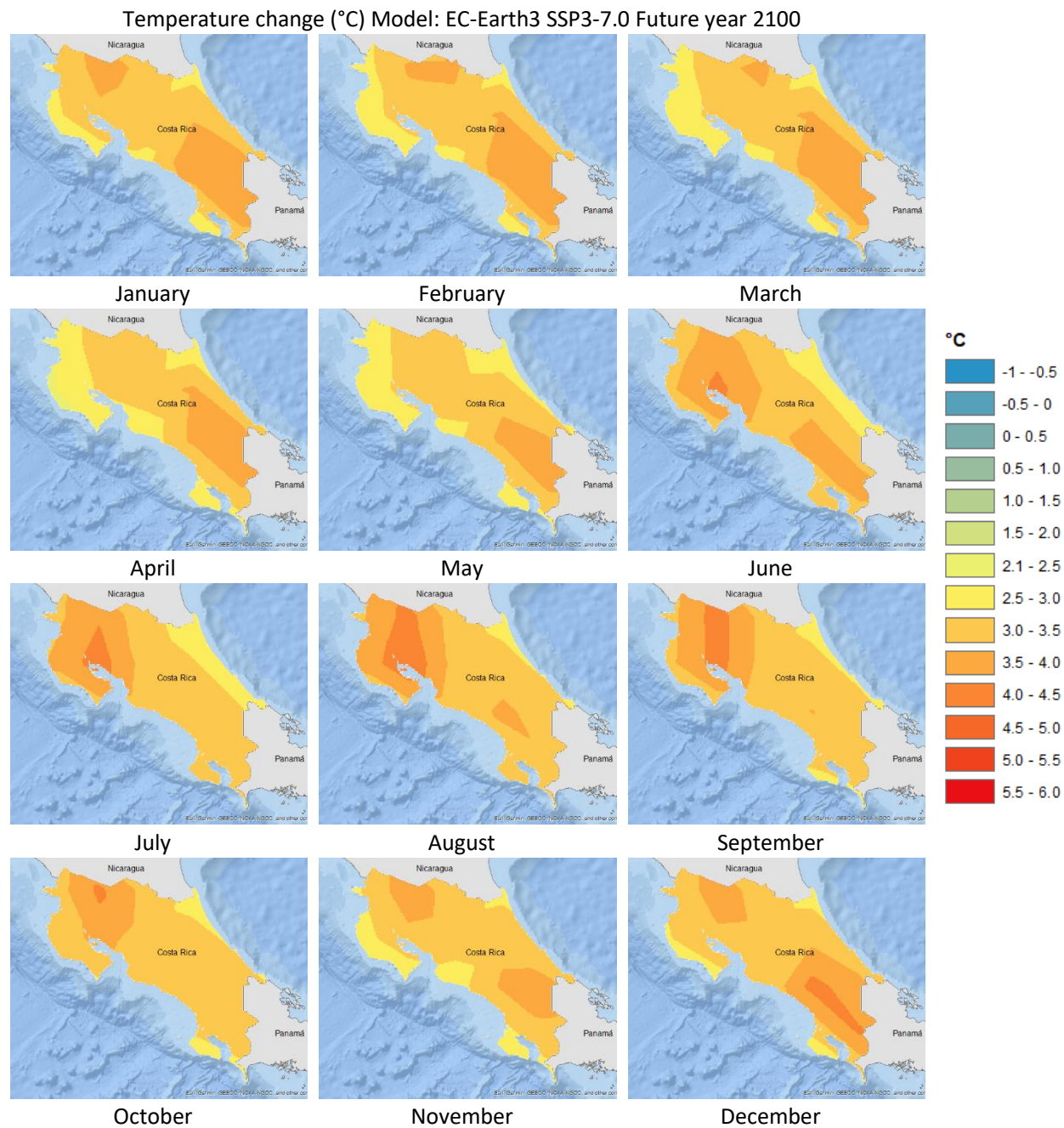






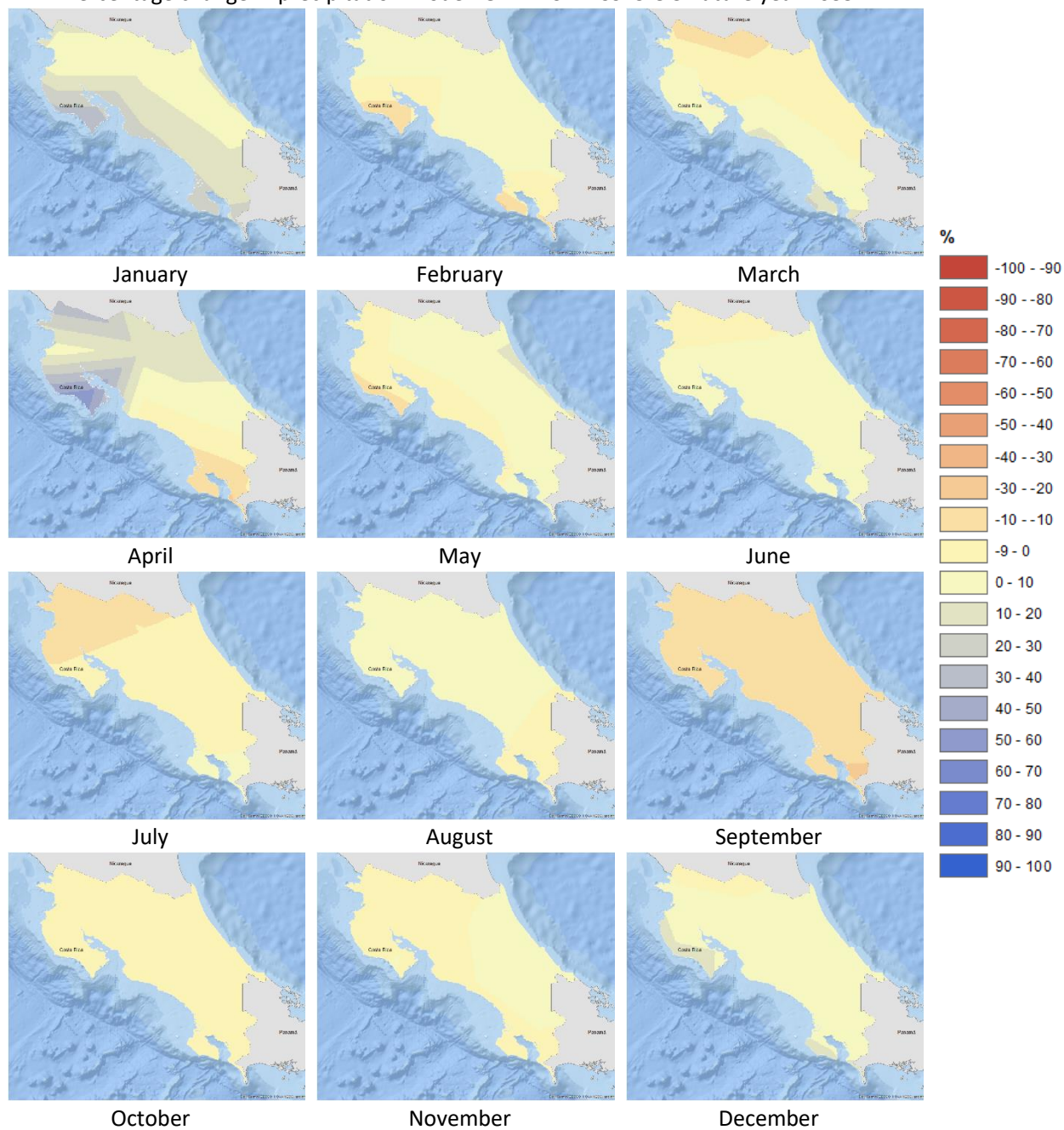




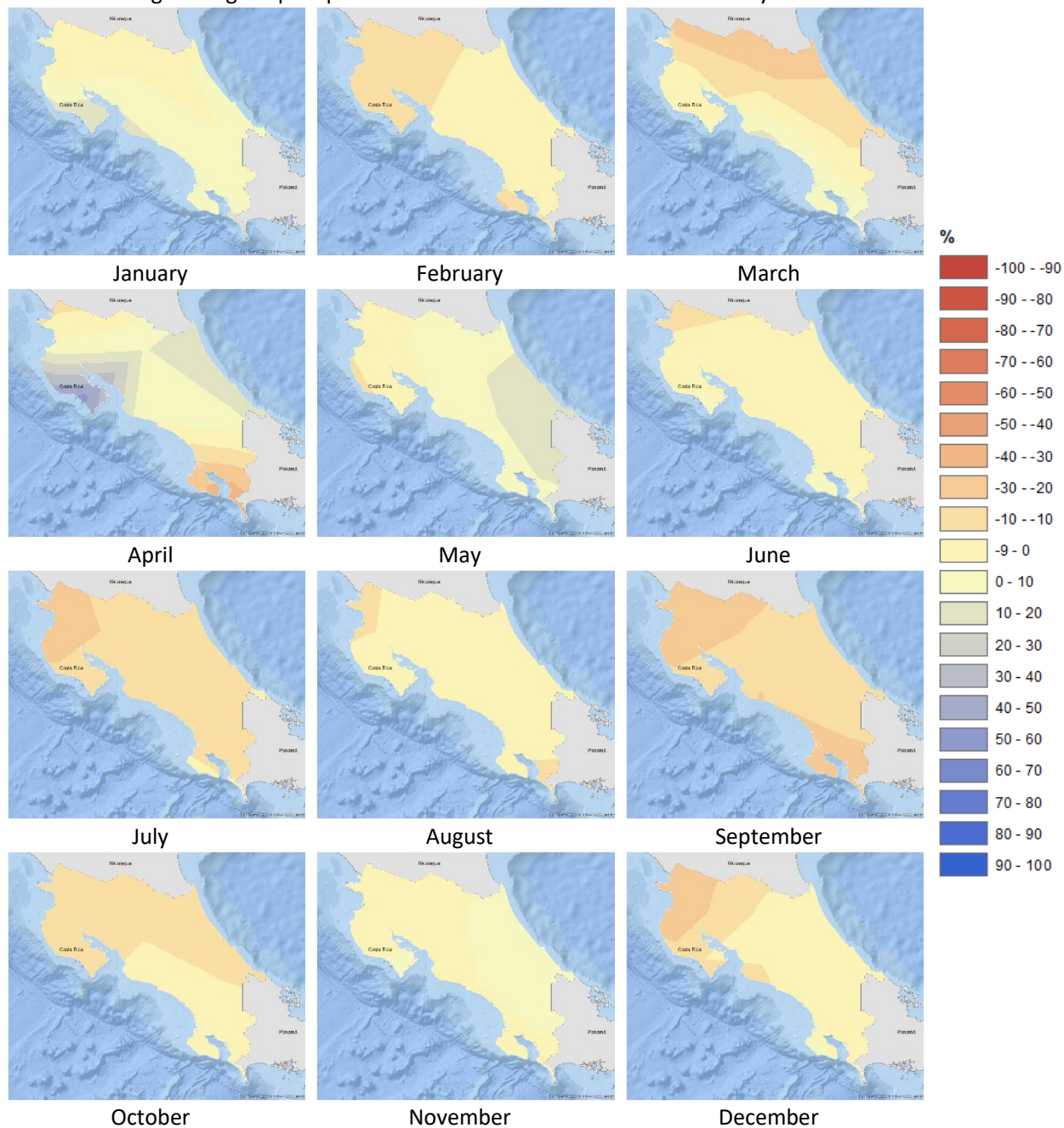


Precipitation SSP5-8.5

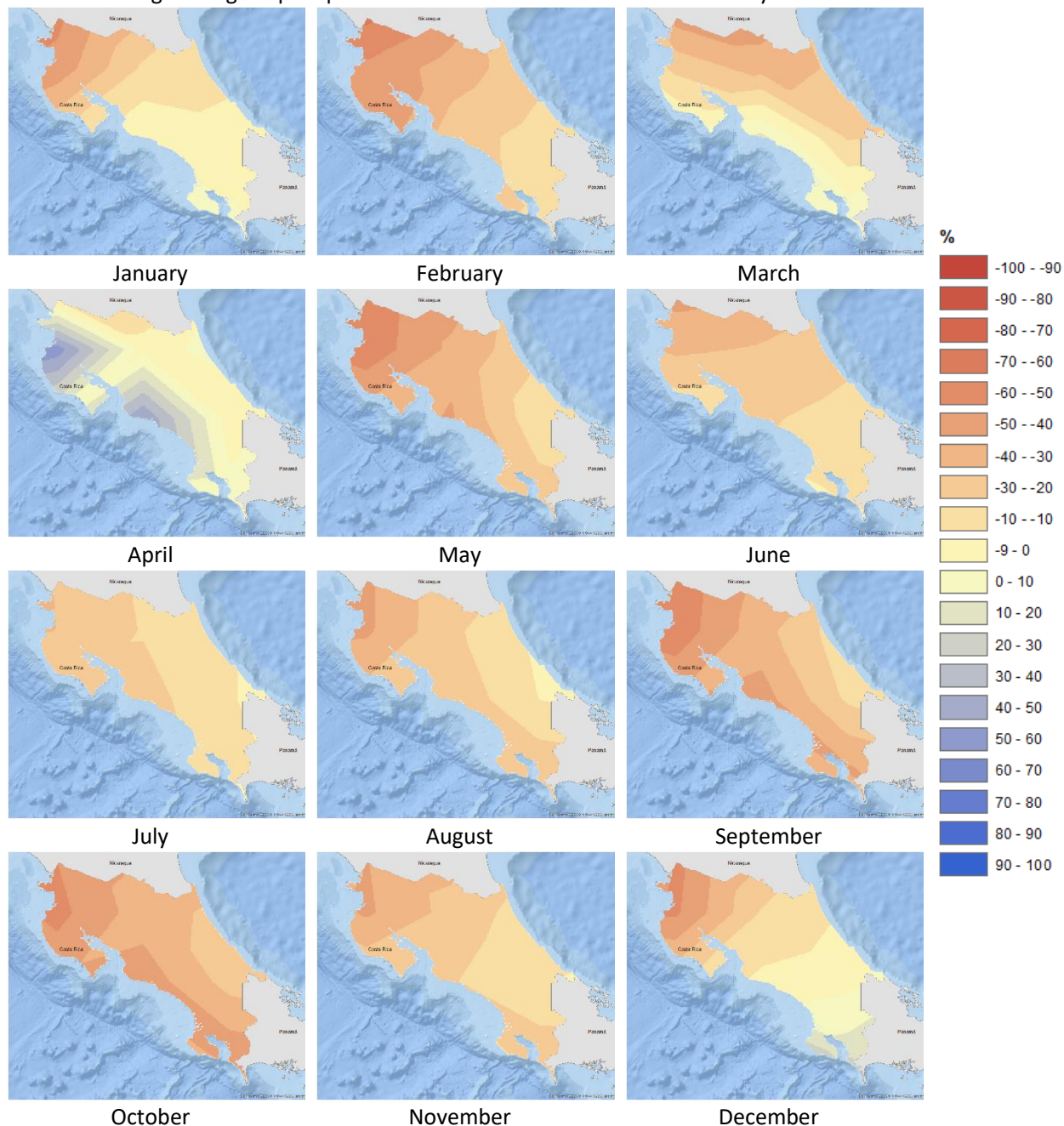
Percentage change in precipitation Model: GFDL-ESM4 SSP5-8.5 Future year 2035



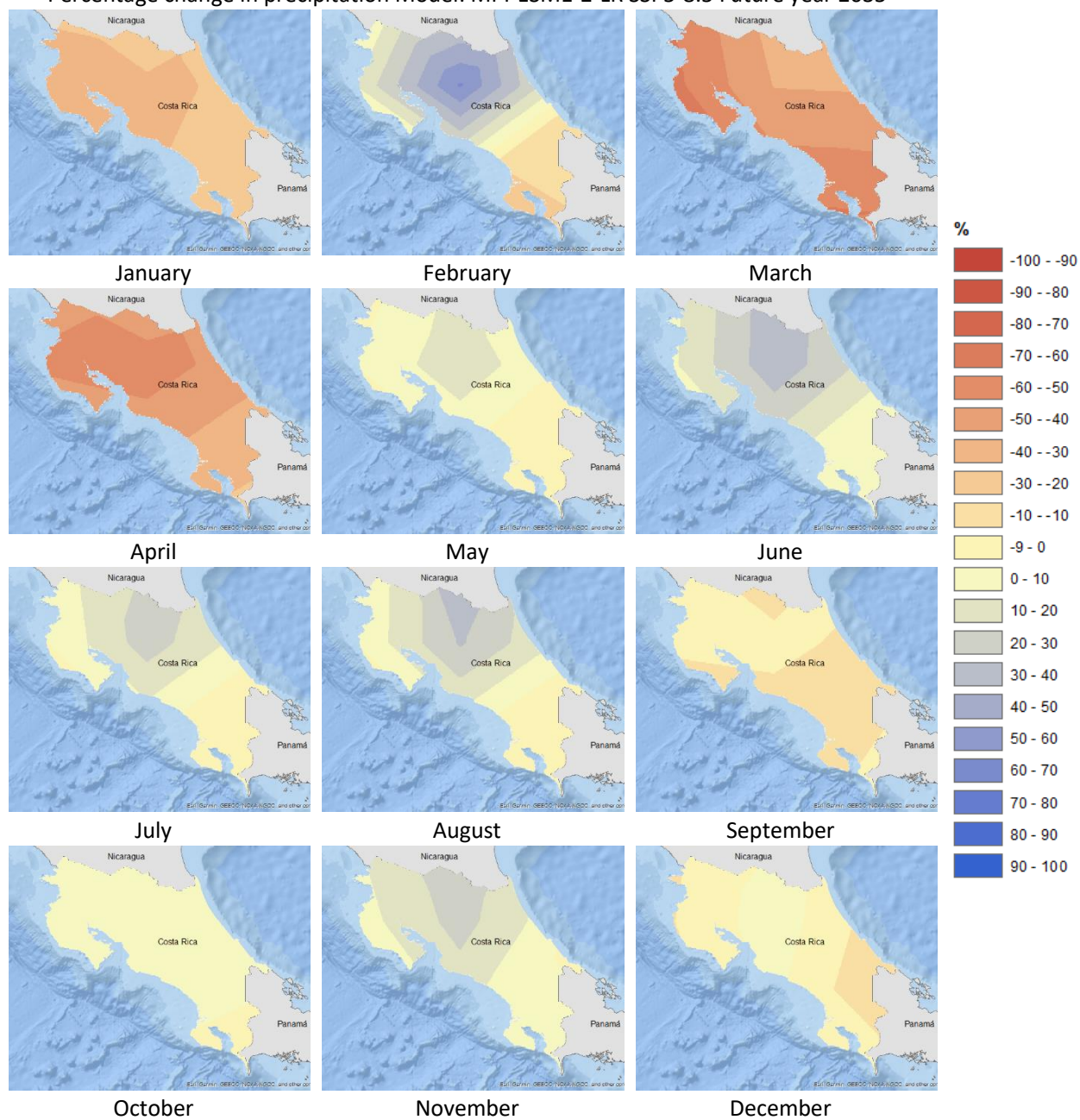
Percentage change in precipitation Model: GFDL-ESM4 SSP5-8.5 Future year 2050



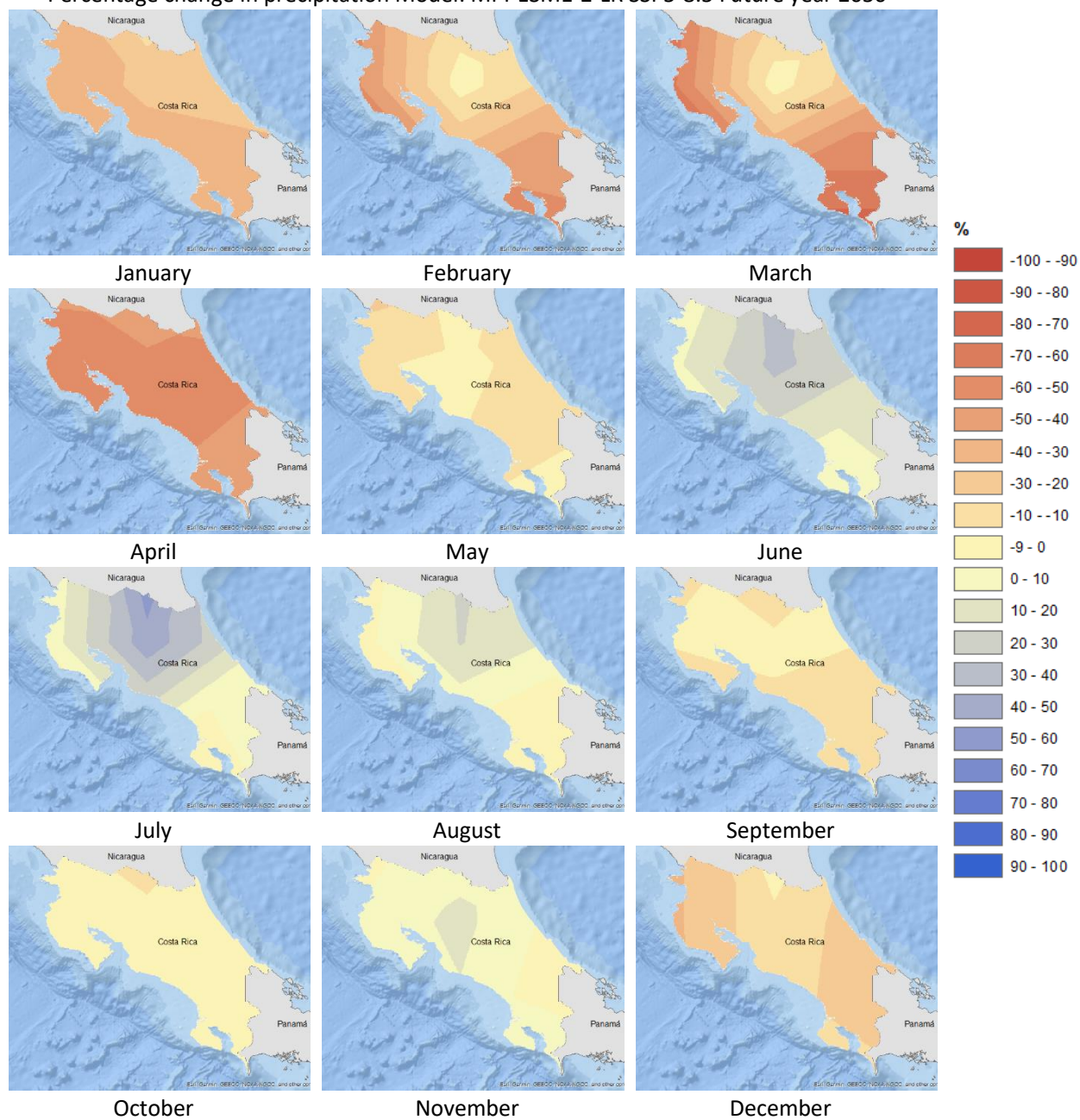
Percentage change in precipitation Model: GFDL-ESM4 SSP5-8.5 Future year 2100



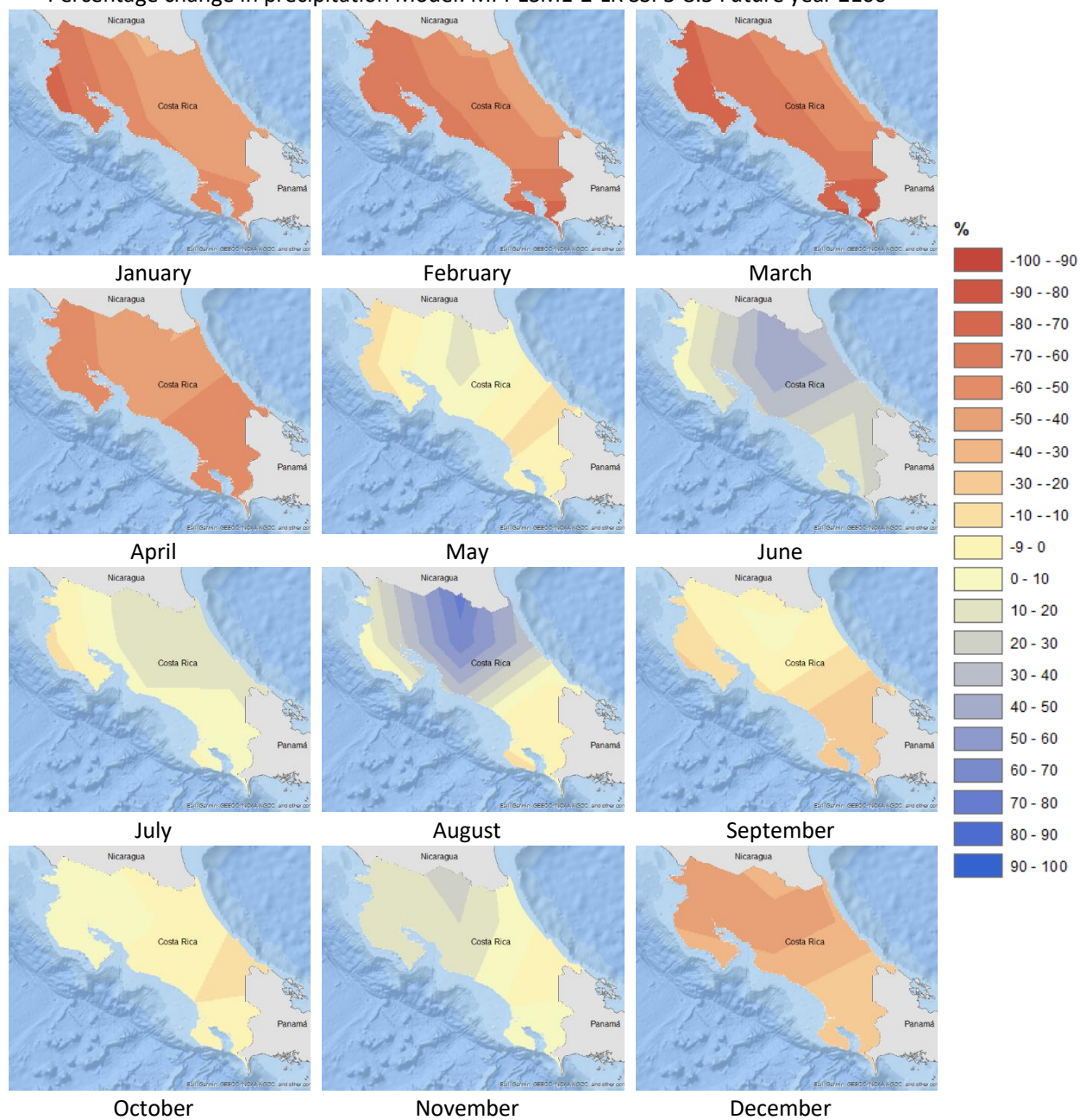
Percentage change in precipitation Model: MPI-ESM1-2-LR SSP5-8.5 Future year 2035



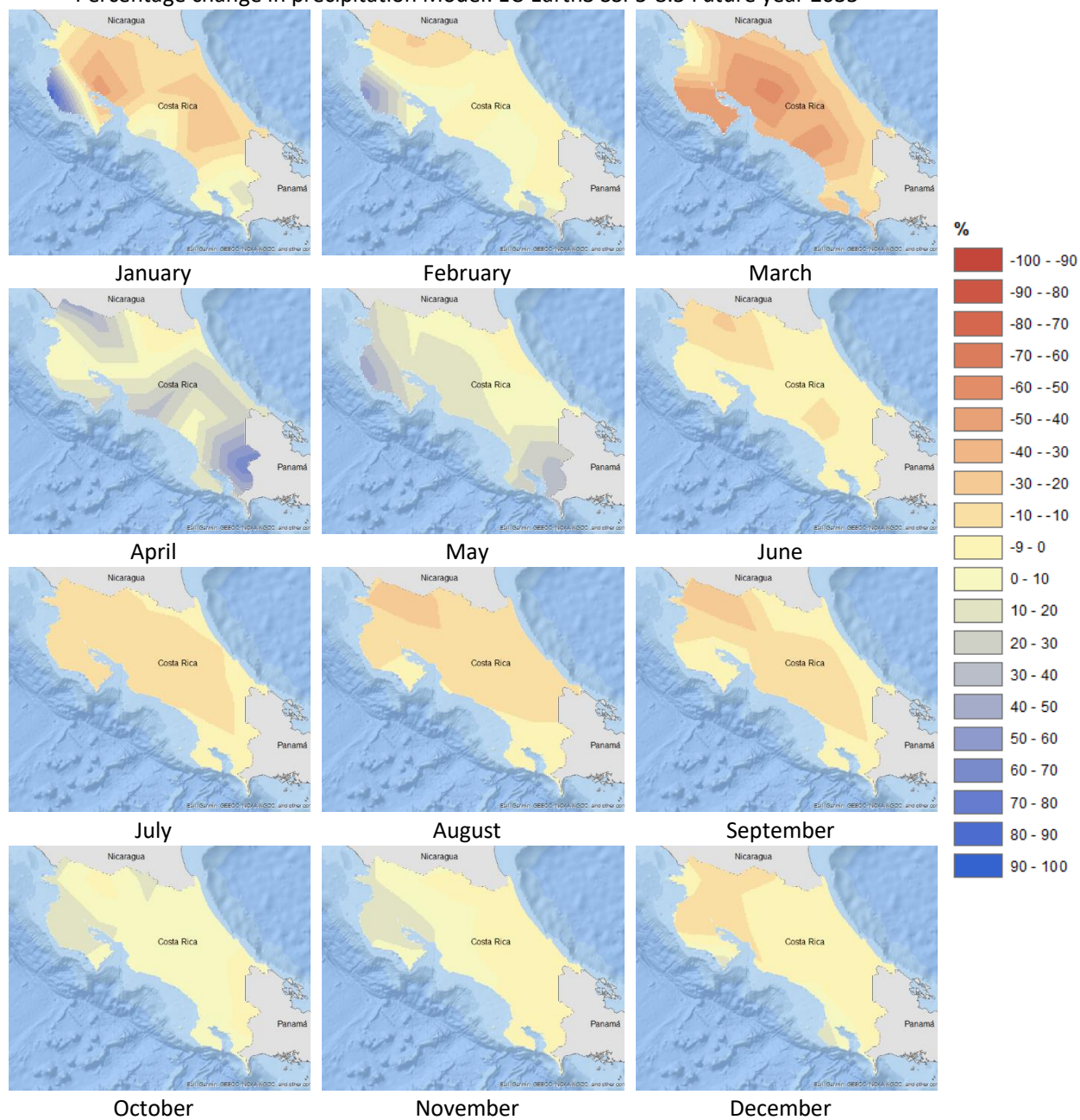
Percentage change in precipitation Model: MPI-ESM1-2-LR SSP5-8.5 Future year 2050



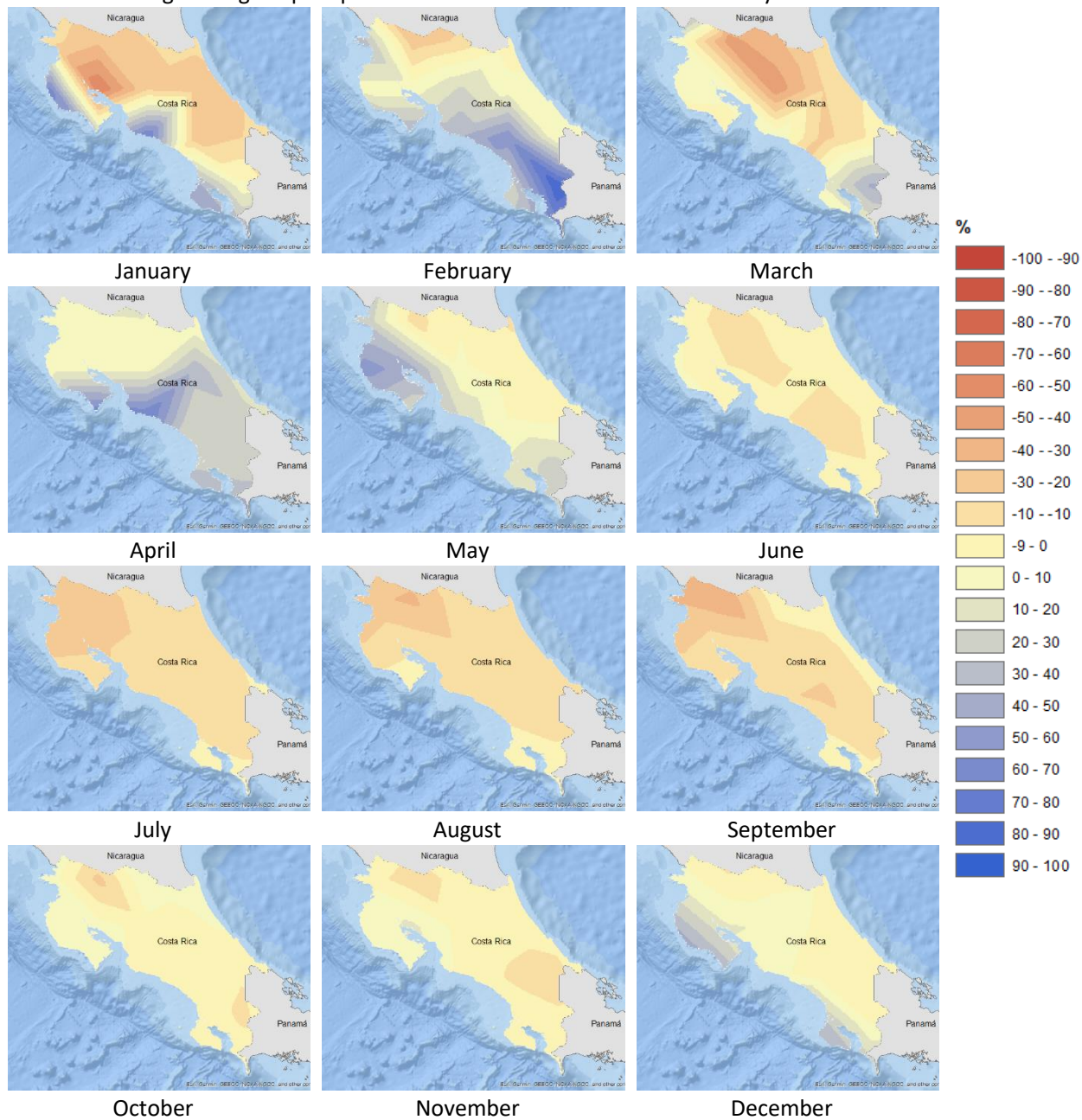
Percentage change in precipitation Model: MPI-ESM1-2-LR SSP5-8.5 Future year 2100



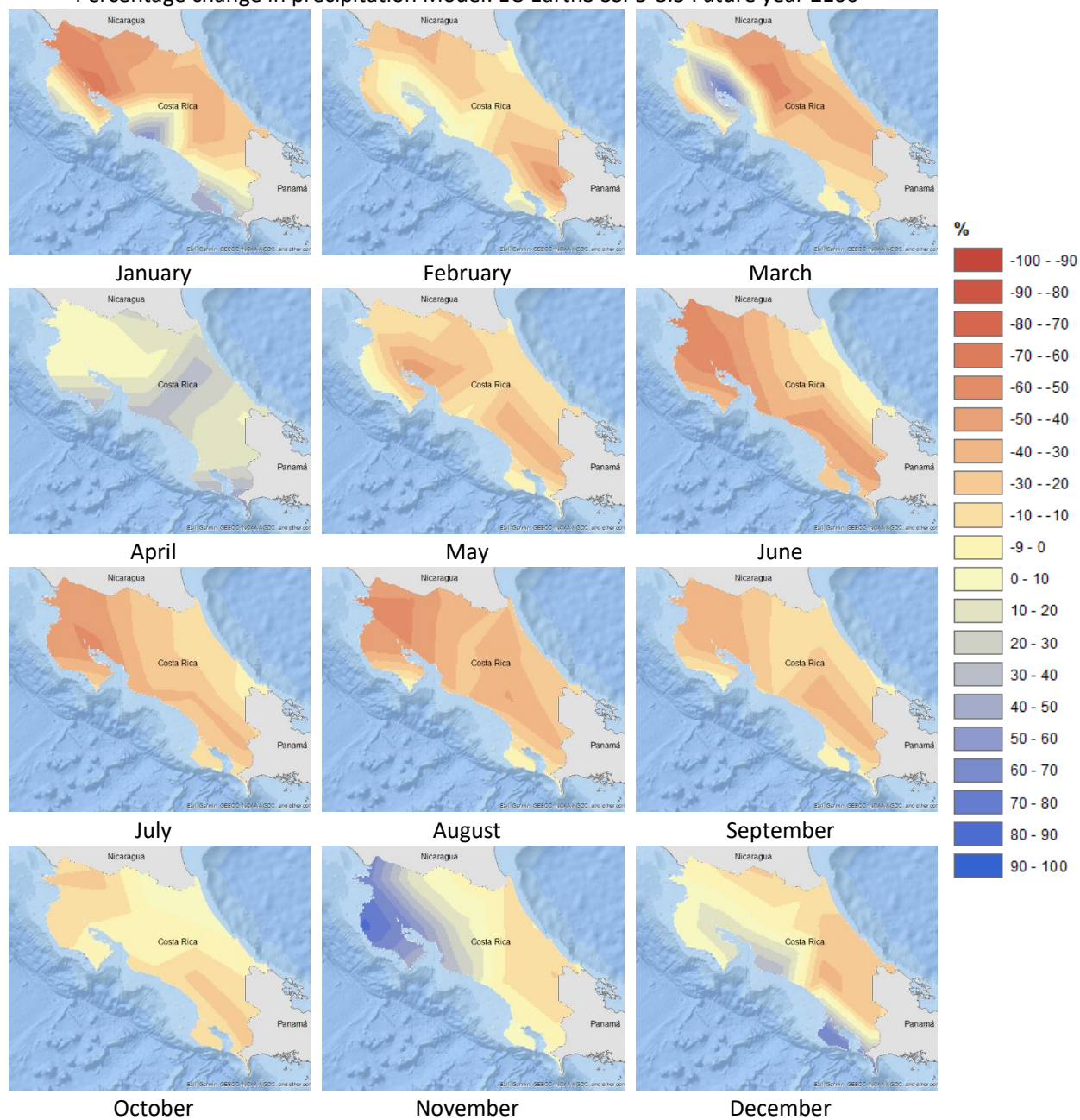
Percentage change in precipitation Model: EC-Earth3 SSP5-8.5 Future year 2035



Percentage change in precipitation Model: EC-Earth3 SSP5-8.5 Future year 2050

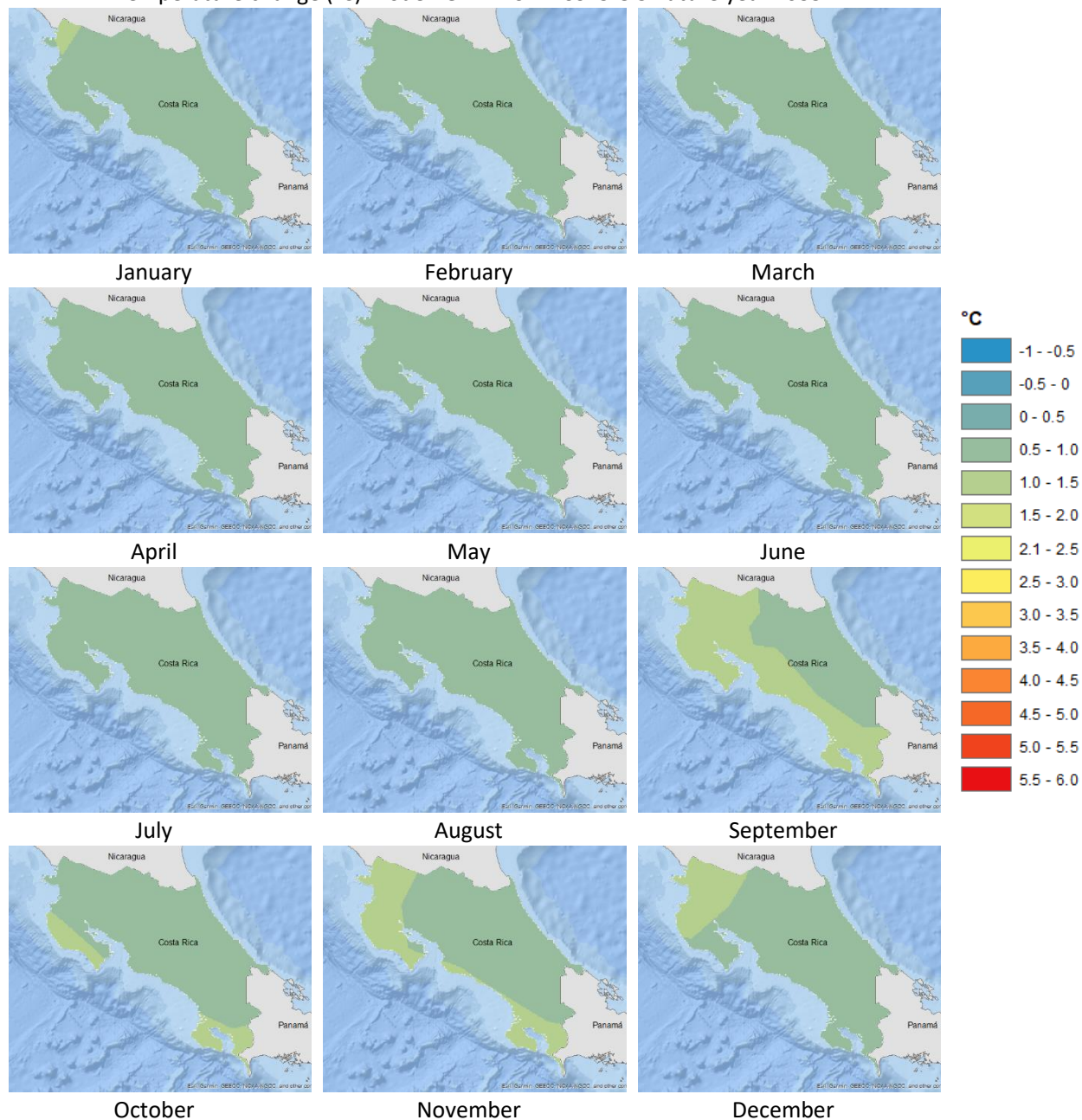


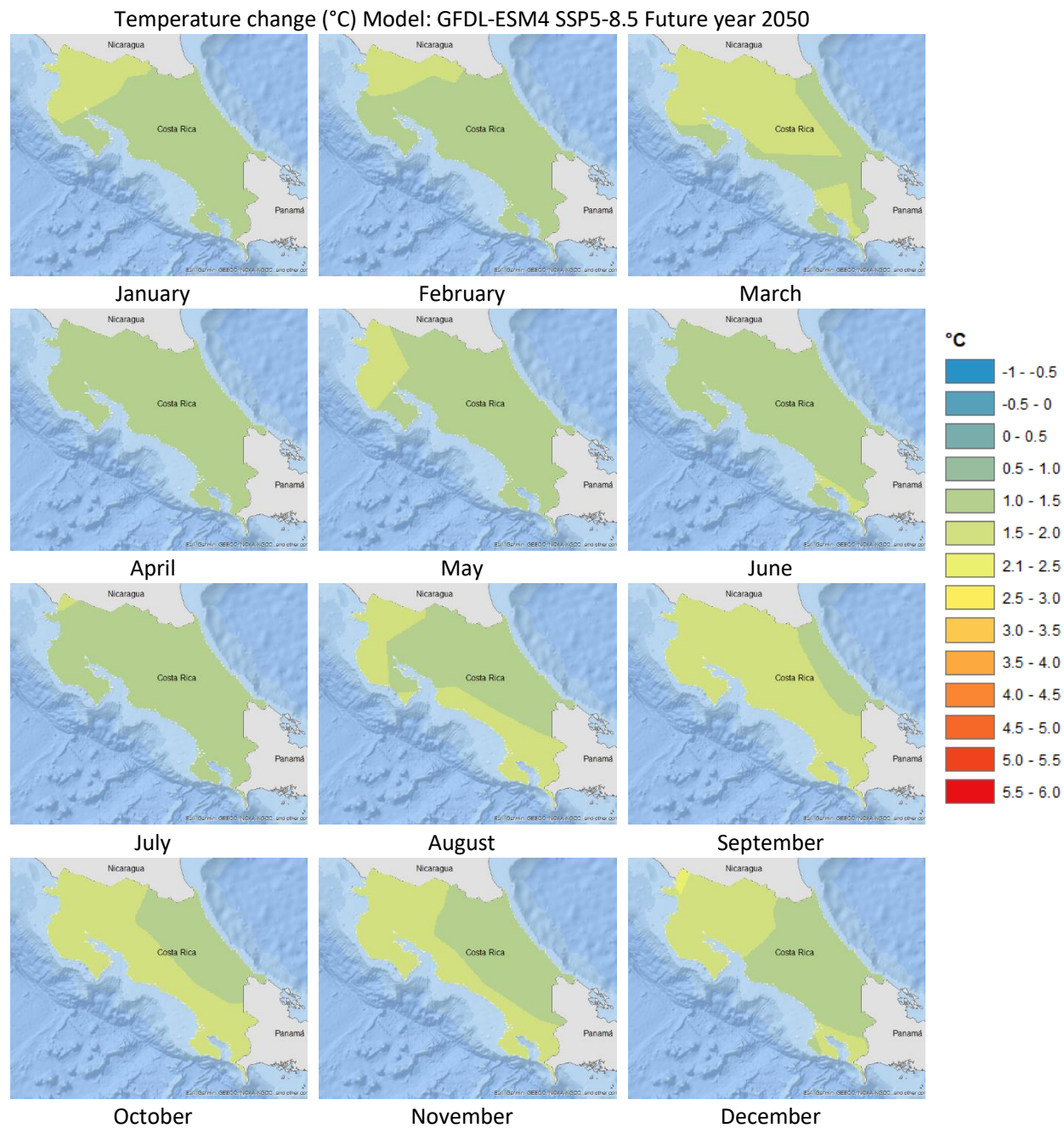
Percentage change in precipitation Model: EC-Earth3 SSP5-8.5 Future year 2100



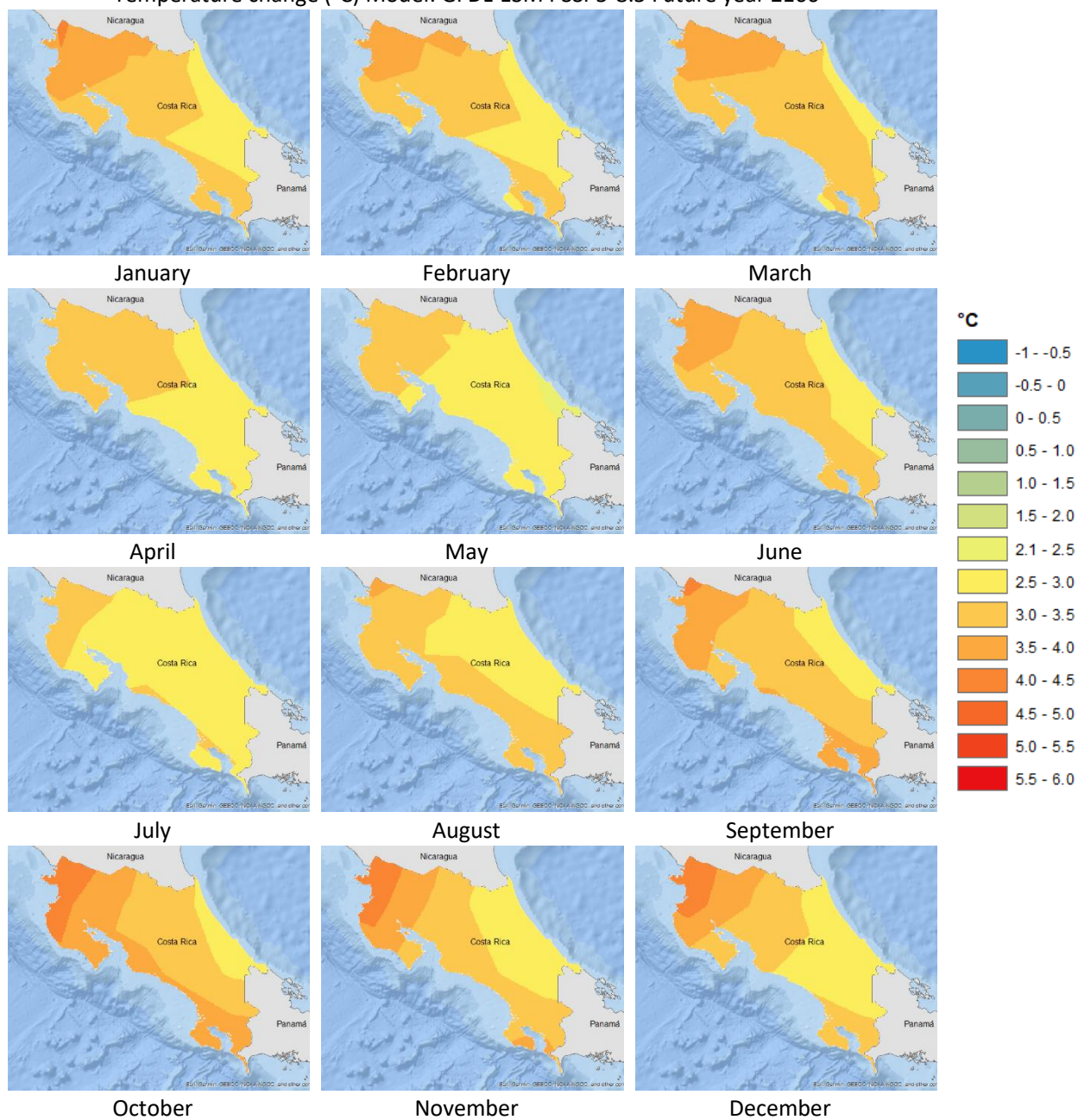
Temperature SSP5-8.5

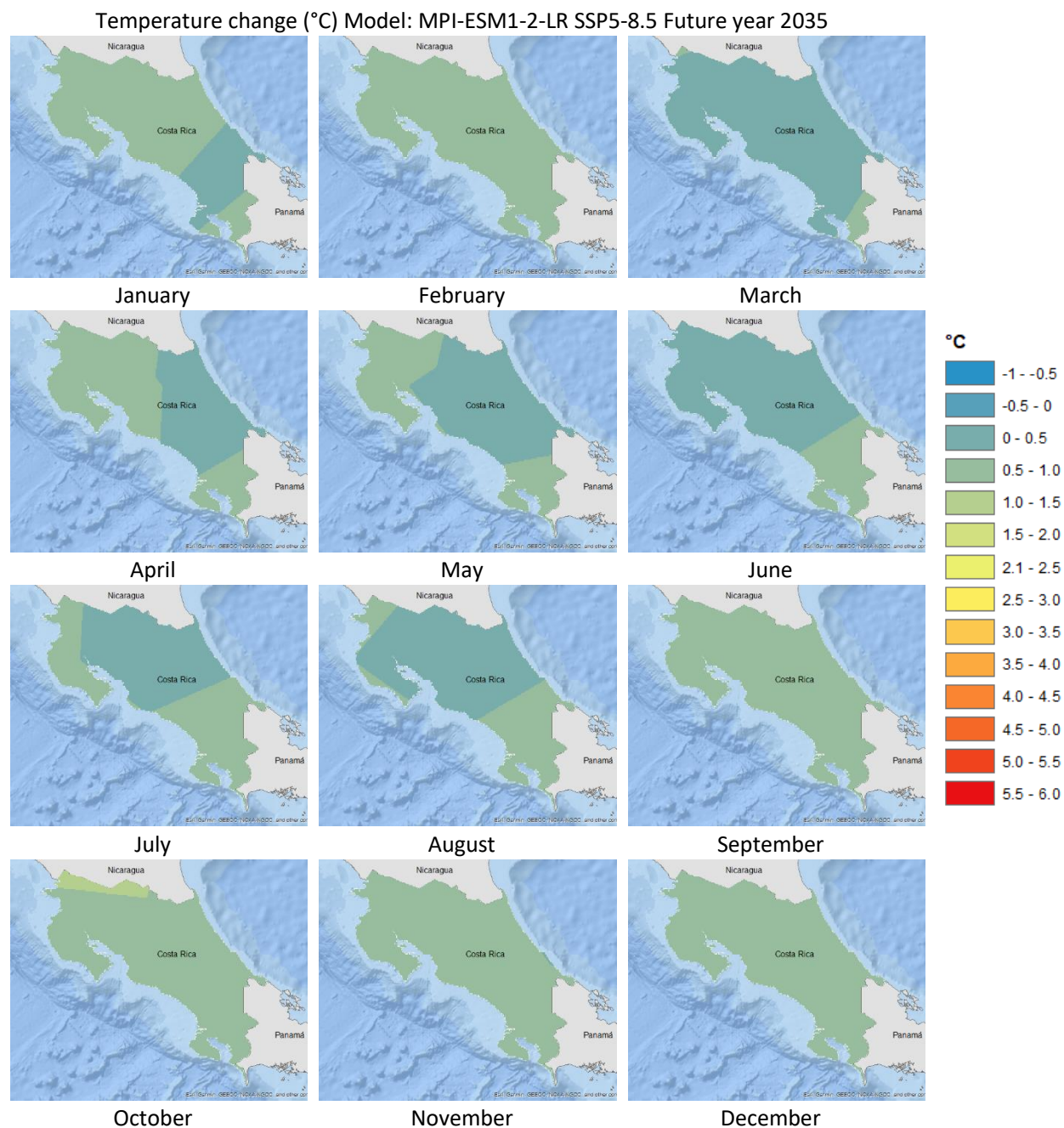
Temperature change (°C) Model: GFDL-ESM4 SSP5-8.5 Future year 2035

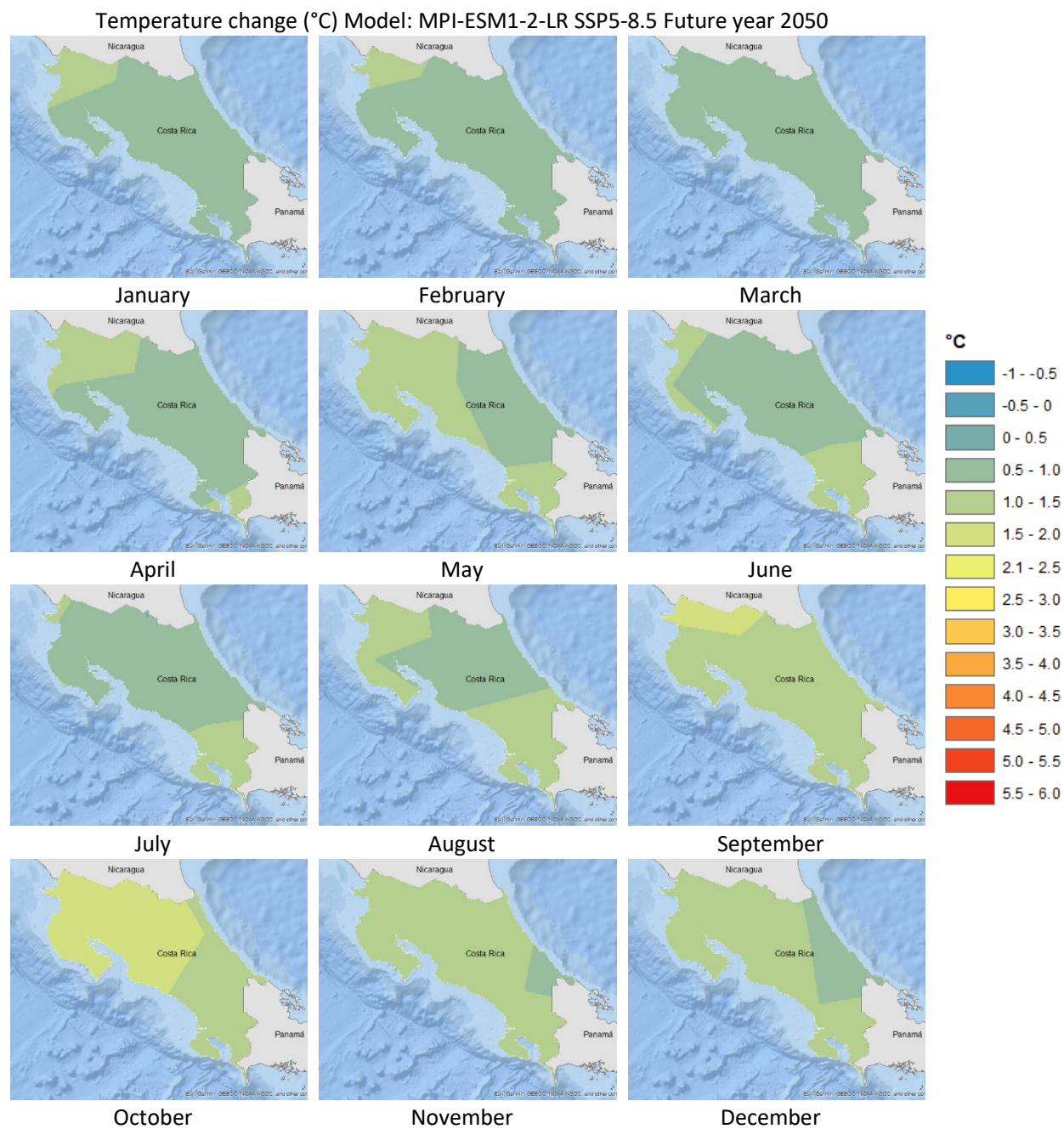


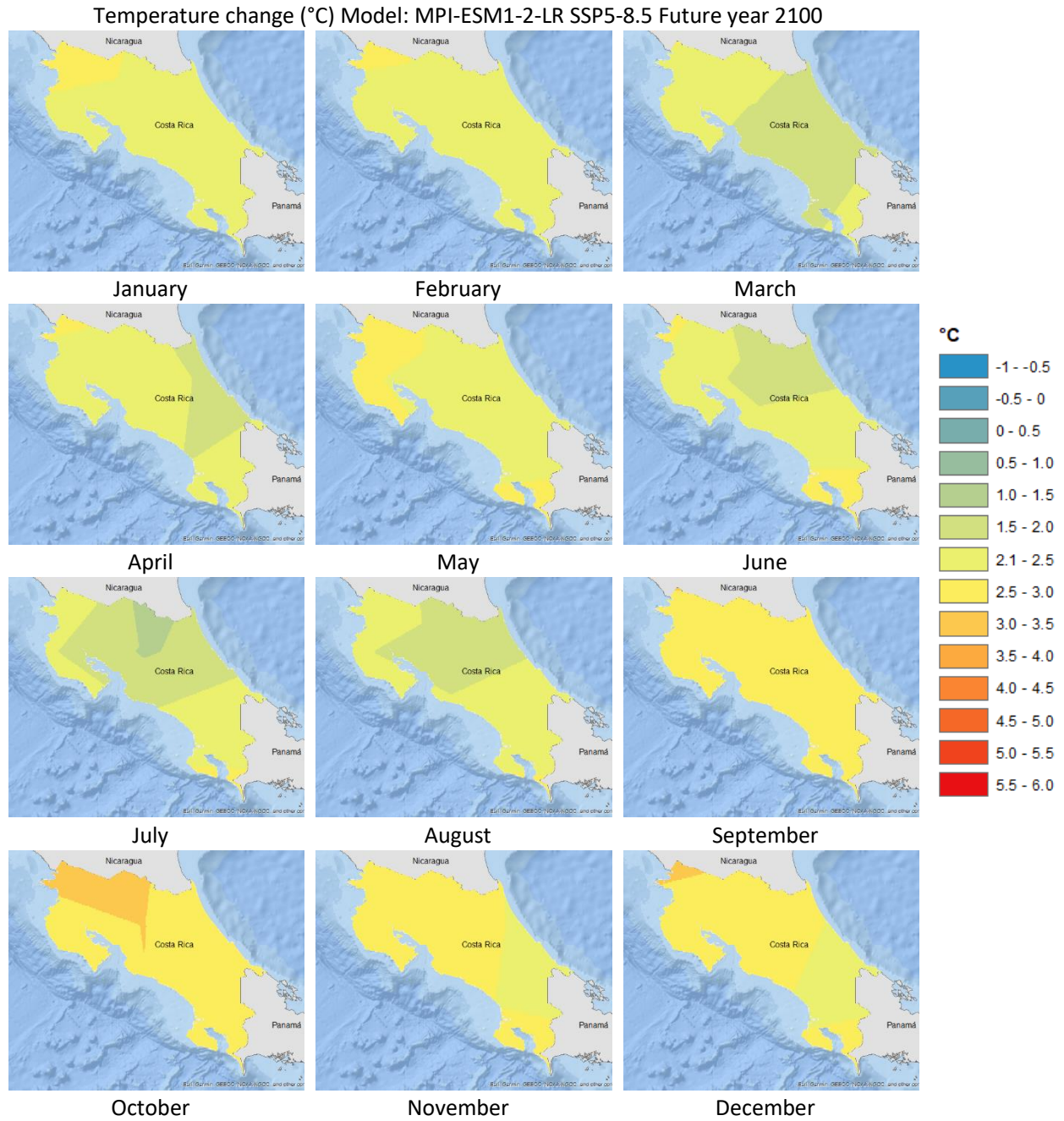


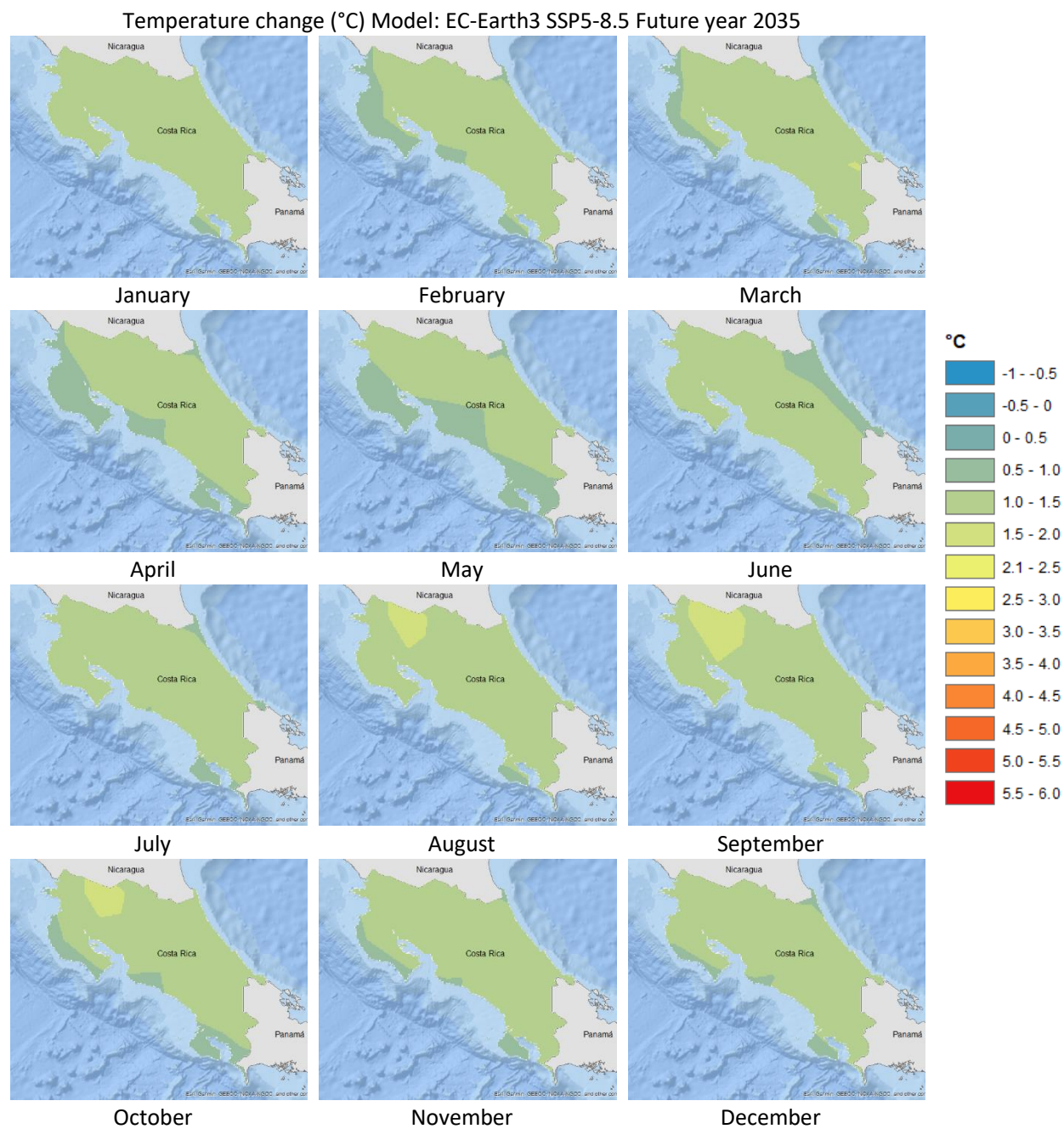
Temperature change (°C) Model: GFDL-ESM4 SSP5-8.5 Future year 2100

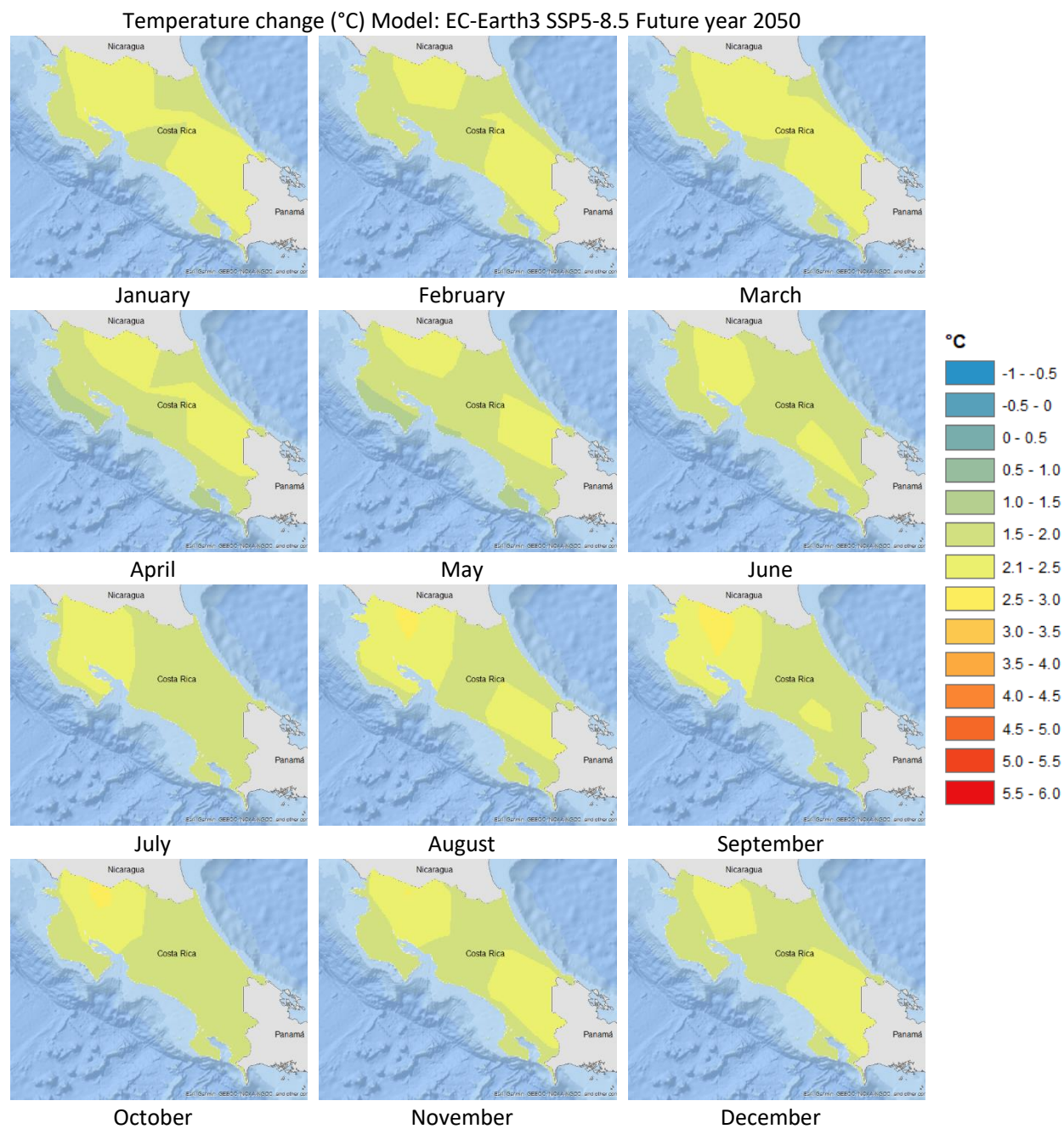


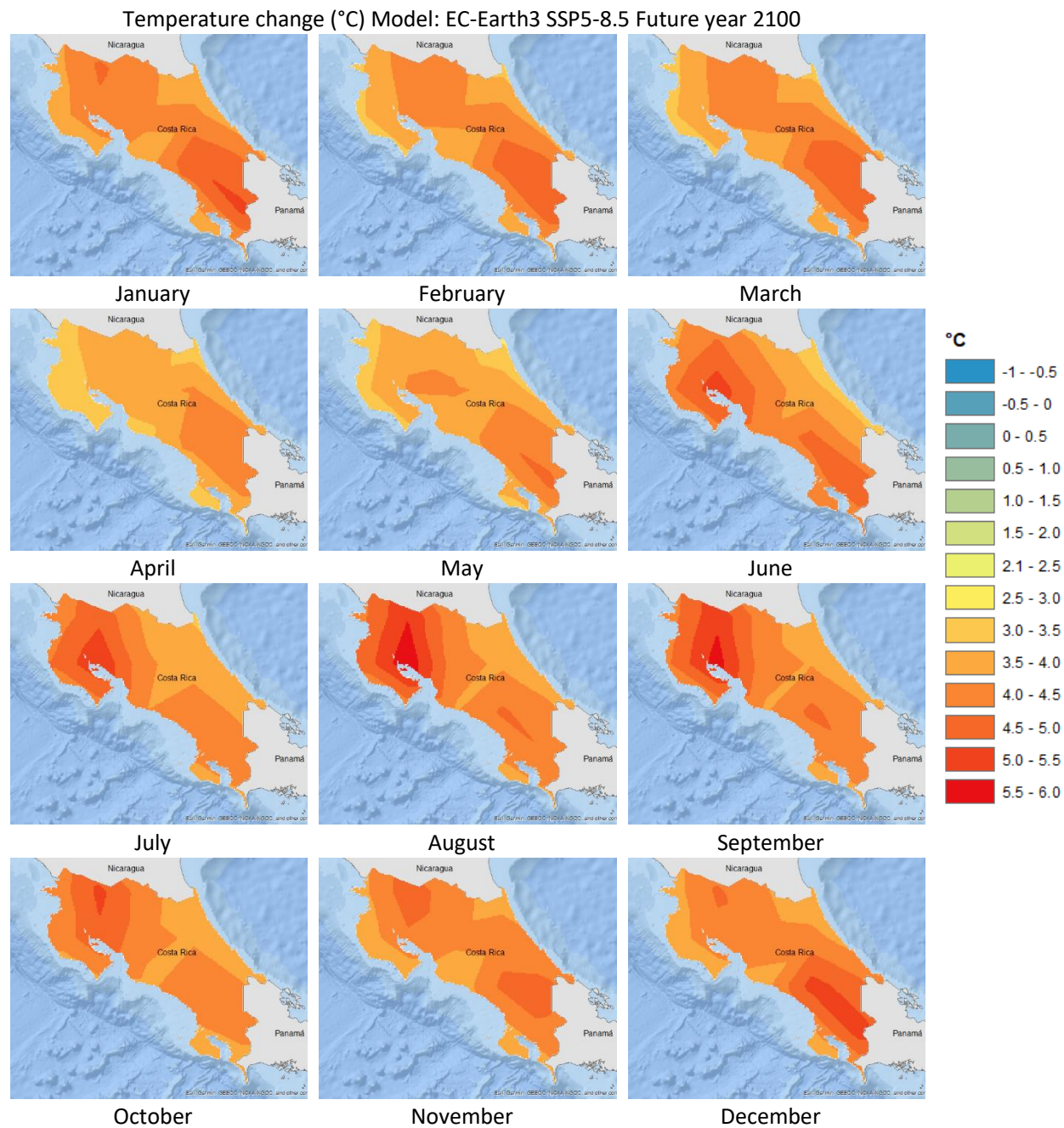












A.3 FLOOD HAZARD ASSESSMENT METHODOLOGY

The methodology presented here is also included in the Inception Report of this consultancy (Section 6.3) and is reproduced here for the reader's convenience.

Floods can occur in different forms depending on the origin of the triggering event. This section focuses on the assessment of pluvial flooding (caused by surface water accumulation) and fluvial flooding (caused by river overflow). The model for coastal flooding is presented in Annex A.5. The hazard modeling approach implemented here follows a classic structure composed of meteorological forcing modeling (i.e., rainfall events), hydrological response modeling of the watersheds, and hydraulic modeling.

Rainfall Events (Heavy Rainfall)

From the precipitation series obtained at different stations across the territory, it is possible to extract synthetically generated heavy rainfall events with total values and spatial patterns that reflect historical rainfall characteristics. These events are generated by applying simple selection criteria to the simulated precipitation series. For example:

- A minimum number of stations recording a given rainfall (e.g., 70% of stations in a watershed must record precipitation for the event).
- A minimum threshold value for a significant event, meaning the recorded precipitation must exceed this value in the defined number of stations (e.g., precipitation greater than 10 mm in 24 hours).
- A mean threshold value for the average precipitation among stations exceeding the minimum threshold (e.g., average precipitation of at least 50 mm in 24 hours).

Applying these or similar criteria makes it possible to identify heavy rainfall events from the simulated daily series. The retrieved values are spatially interpolated using the Kriging method.

Los aguaceros simulados cuentan implícitamente con patrones realistas de precipitación, obtenidos directamente de los datos de las series individuales, lo cual le confiere una ventaja especial al método al no requerirse el uso de patrones espaciales sintéticos. Así mismo, la distribución de la lluvia fuerte en la cuenca cambia considerablemente en magnitud y distribución espacial. En el conjunto de eventos no hay entonces dos eventos idénticos. Estos eventos indican la precipitación total diaria en un escenario de lluvia fuerte. Sin embargo, la precipitación no cae uniformemente a lo largo de 24 horas, por lo cual se requiere simular, adicionalmente, su distribución en el tiempo (lluvia intradiaria). Esto se realiza mediante el uso de curvas Huff (Huff, 1967).

Huff curves can be used to temporally distribute the total daily precipitation into hourly values. The time derivative of the Huff curves corresponds to the hyetograph, that is, the intensity–time function, as illustrated in Figure 121. This makes Huff curves a powerful tool, as they allow the synthesis of hyetographs. In this way, the identified rainfall events can be distributed into hourly values using Huff curves, as shown in Figure 122.

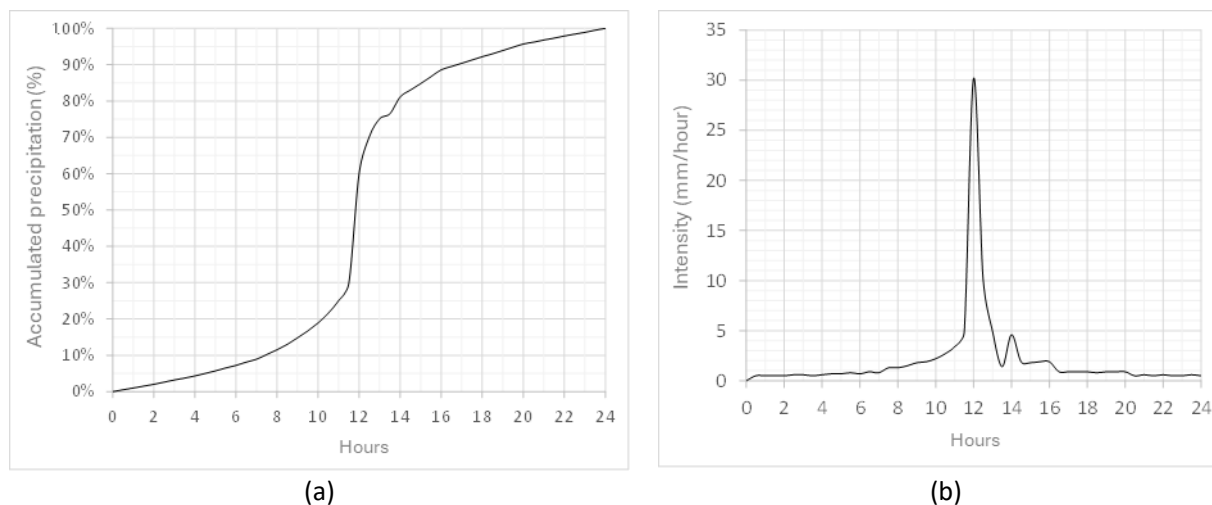


Figure 121. (a) Huff curve. (b) Time derivative of the presented Huff curve.

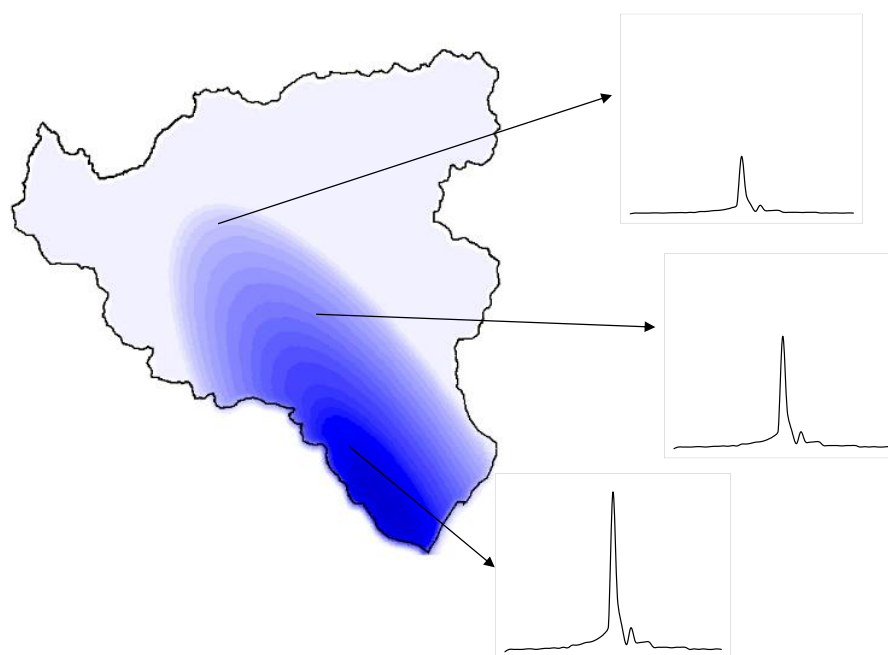


Figure 122. Illustration of the temporal distribution of daily rainfall for a simulated rainstorm.

Estimating Runoff Volume

Once rainfall events are defined, input hydrographs for hydraulic modeling must be established. These are based on the effective precipitation volume that becomes surface runoff and reaches rivers and streams. *The Soil Conservation Service Curve Number (CN)* method is used to estimate runoff volume, a standard simplified infiltration model.

Effective precipitation corresponds to the remaining rainfall after subtracting infiltration, interception, and evapotranspiration processes. It is calculated as:

$$P_e = \frac{\left[P_m - \frac{508}{CN} + 5.08 \right]^2}{P_m - \frac{2032}{CN} - 20.32} \quad \text{Equation 5}$$

Where P_e is the effective precipitation in cm, P_m is the storm precipitation in cm, and CN is the *curve number* based on land use, vegetation cover, and soil infiltration capacity. En la Table 22 lists CN values for different land covers and soil hydrologic groups (Chow et al., 1994). The application range for Equation , is:

$$P_m > \frac{508}{CN} + 5.08 \quad \text{Equation 6}$$

Outside this range, effective precipitation is considered zero. It must also not exceed the total storm precipitation.

Table 22. CN values by land use and soil type⁵. (Soil Conservation Service, 1986)

Land cover Type and Condition	A	B	C	D
Straight row crops - Good	67	78	85	89
Forest - Good	30	55	70	77
Grassland - Fair	49	69	79	84
Impervious surface	100	100	100	100
Residential district (1/8 acre)	77	85	90	92
Forest - Fair	36	60	73	79
Mixed forest and grassland - Good	32	58	72	79
Mixed forest and grassland - Fair	43	65	76	82
Residential district (1 acre)	51	68	79	84
Straight row cereals	63	75	83	87
Recently developed land	77	86	91	94
Urban district - Industrial	81	88	91	93
Paved streets with open gutters	83	89	92	93
Fallow (uncultivated)	77	86	91	94
Paved streets	98	98	98	98
Pasture	30	58	71	78

Pluvial Flooding (Surface Water Accumulation)

The issue of pluvial flooding is modeled based on the potential for surface water accumulation, which is determined by the topography in terms of a topographic water accumulation potential, along with the

⁵ The soil types mentioned correspond to the Hydrologic Soil Groups defined by the United States Soil Conservation Service.

infiltration rate at each point in the territory. The volume of water available for flooding is calculated as described in Section 0 (the infiltration model).

The topographic water accumulation potential is assessed by identifying areas of higher and lower susceptibility based on topographic features within a Digital Elevation Model (DEM), as illustrated in Figure 123.

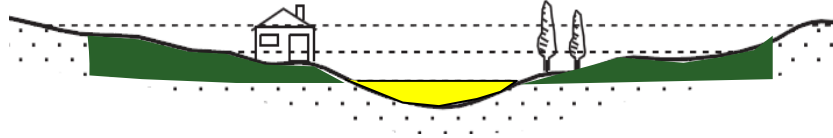


Figure 123. Illustration of areas with high (yellow), medium (green), or no (uncolored) accumulation potential.

The Topographic Accumulation Potential (TAP) is classified into three categories:

- High: Corresponds to topographic depressions.
- Medium: Corresponds to relatively flat sites.
- Low: Corresponds to steep regions or hilltops.

For each node in the Digital Elevation Model (DEM), given its geographic location (X, Y), the accumulation potential is quantified by examining the four cardinal directions (north, south, east, and west). This search is bounded by the following parameters:

- N_{max} : Maximum horizontal distance within which the accumulation potential will be evaluated relative to a fixed location.
- m : Reference slope used to assess the accumulation potential of the site in relation to adjacent terrains.

Then, for each site (X, Y) in the DEM, a site (K, L) is sought such that the following condition holds:

$$Z_{K,L} \geq Z_{X,Y} + Z_{Lim} \quad \text{Equation 7}$$

where Z_{Lim} is the required height difference between sites (X, Y) and (K, L) to obtain slope m .

If the site (K, L) exists, then site (X, Y) is classified as high accumulation, corresponding to a topographic depression. If this condition is not met, the mean topographic slope (m_T) between site (X, Y) and site (K, L) is calculated as:

$$m_T = \frac{Z_{X,Y} - Z_{K,L}}{D} \quad \text{Equation 8}$$

where D is the distance between sites (X, Y) and (K, L). If $|m_T| \leq m$, then site (X, Y) is classified as medium accumulation. Finally, if $|m_T| > m$, site (X, Y) is classified as low accumulation.

¡Error! No se encuentra el origen de la referencia. illustrates the identification of the accumulation potential along a terrain profile.

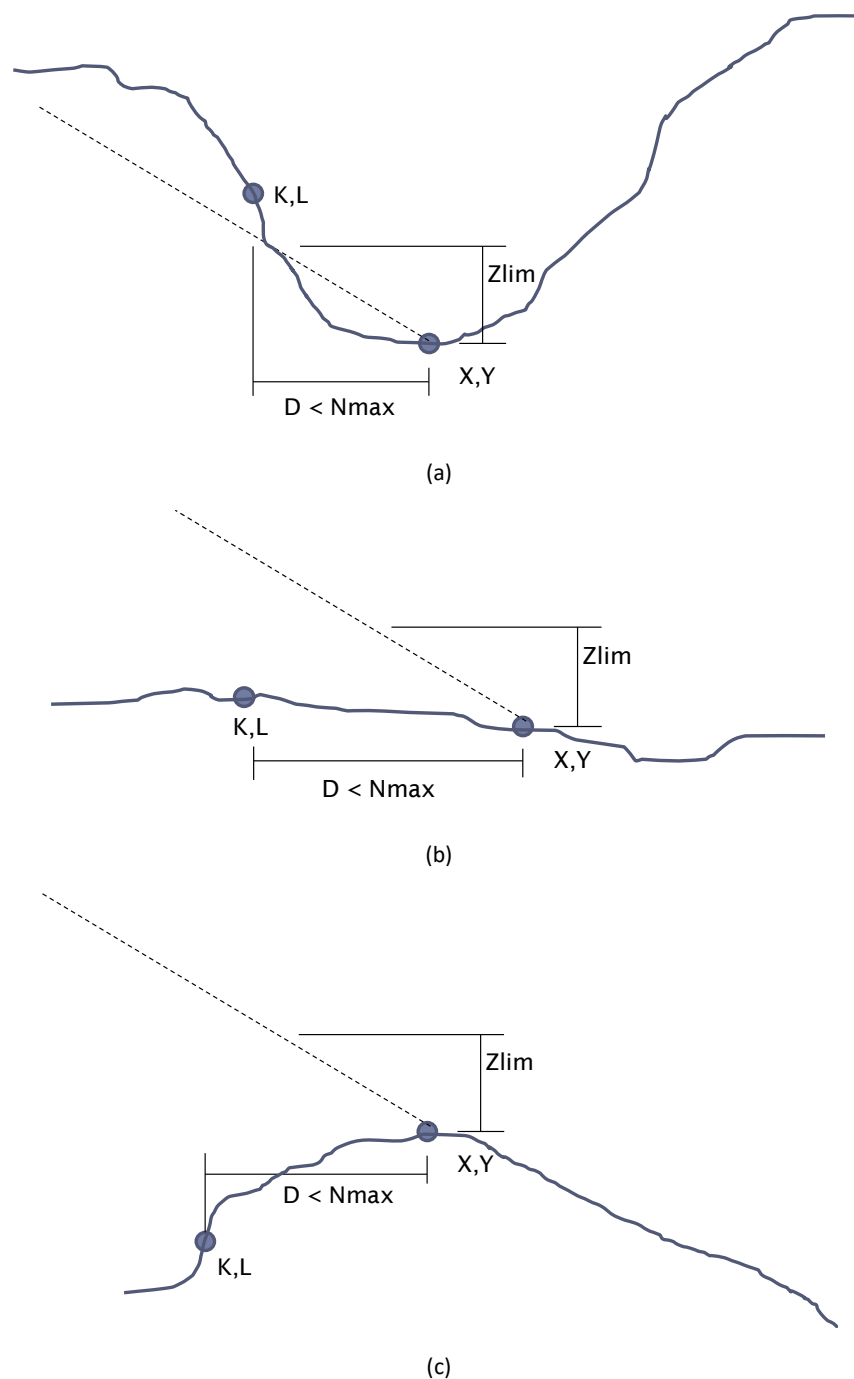


Figure 124. Illustration of TAP identification. a) Terrain with high accumulation. b) Terrain with medium accumulation. c) Terrain with low accumulation.

Once the Topographic Accumulation Potential (TAP) has been evaluated, the flood depth is calculated as a function of the effective precipitation (P_e), using the multipliers presented in Table 15.

Table 1. Multipliers of effective precipitation according to the Topographic Accumulation Potential (TAP)

TAP	Multiplier of P_e
High	1.2
Medium	1.0
Low	0.0

Watershed Hydrological Response

Hydrographs are calculated using the Modified Clark model (Mod Clark; Kull & Feldman, 1998), a distributed hydrological response model that explicitly accounts for translation (movement of excess rainfall along the drainage system) and attenuation (discharge reduction due to water storage in the soil, surface, and channels) (Brunner & Bonner, 1994). Travel time variability from all watershed points to the outlet is incorporated.

The time it takes for a water droplet to reach the outlet is modeled with a travel time grid. For each cell:

$$t_{celda} = t_c \frac{d_{celda}}{d_{máx}} \quad \text{Equation 9}$$

Where t_{cell} is the travel time from the cell, t_c is the watershed concentration time, d_{cell} is the distance from cell to outlet, and $d_{máx}$ is the maximum distance from any cell to outlet. Various empirical formulas are jointly applied to determine t_c .

Each cell's runoff volume at each time step is routed using a linear reservoir model during the attenuation process. The continuity equation is:

$$\frac{dS}{dt} = I_t - O_t \quad \text{Equation 10}$$

Where dS/dt is the change in storage over time, I_t the inflow, and O_t the outflow. In a linear reservoir, outflow is proportional to storage:

$$S = R \cdot O_t \quad \text{Equation 11}$$

Where R is the reservoir coefficient. Combining and solving the equations using a finite difference approach yields:

$$O_t = C_A I_t + C_B O_{t-1} \quad \text{Equation 12}$$

where C_A y C_B are routing coefficients, which are calculated as follows:

$$C_A = \frac{\Delta t}{R + 0.5\Delta t}$$

Equation 1

$$C_B = 1 - C_A$$

Equation 14

The average outflow at time t is:

$$\bar{O}_t = \frac{O_{t-1} + O_t}{2}$$

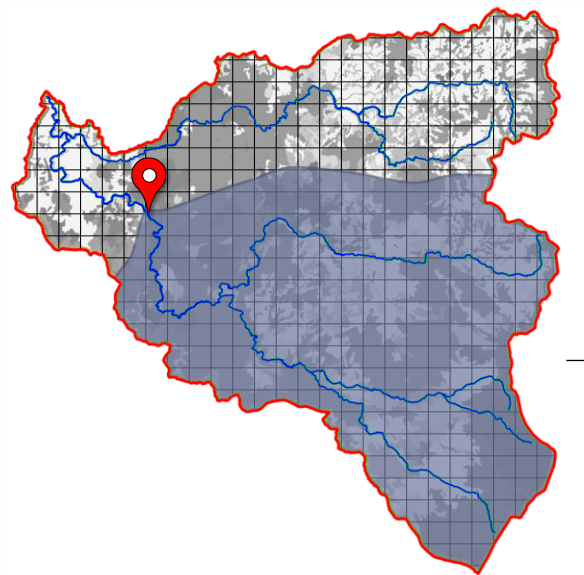
Equation 2

For each grid cell, the average outflow is calculated at every time step. The final hydrograph (Q_t) is the sum of all cell outflows:

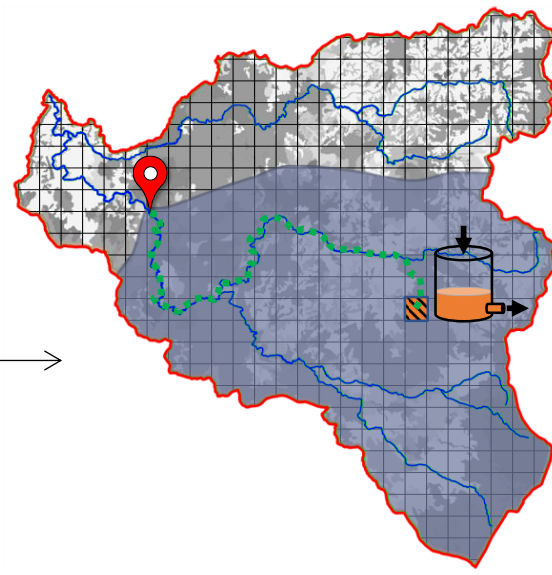
$$Q_t = \sum_{i=1}^{N_{celdas}} \bar{O}_{i,t}$$

Equation 3

¡Error! No se encuentra el origen de la referencia. illustrates the Modified Clark rainfall-runoff model.



Rasterized and characterized watershed. The contributing watershed (in blue) to the point where the hydraulic model begins is shown



Each cell within the watershed has a flow path and travel time to the outlet, and is treated as a linear reservoir.

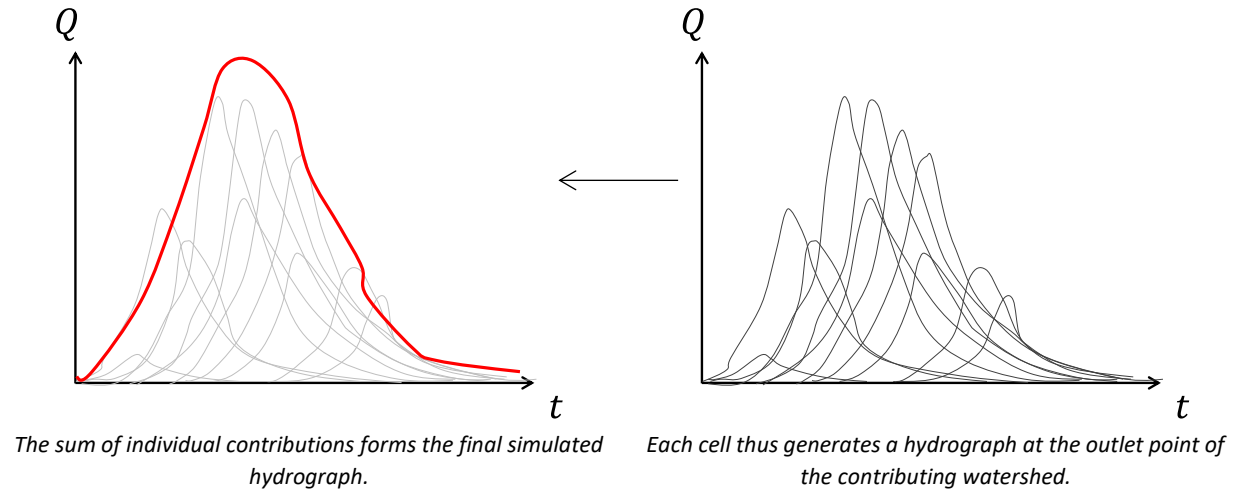


Figure 125. Illustration of the modified Clark rainfall-runoff model.

Fluvial Flooding (River Overflow)

This section describes the hydraulic modeling that allows the routing of hydrographs calculated as watershed responses through river and stream channels.

1D Model

The goal of one-dimensional analysis is to solve water depth profiles along cross-sections of a river channel. It assumes unsteady, gradually varied, one-dimensional flow. The energy equation between two adjacent cross-sections, ST_1 and ST_2 , is

$$Y_2 + Z_2 + \frac{\alpha_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \quad \text{Equation 4}$$

Where Y_1 and Y_2 are water depth at sections ST_1 and ST_2 respectively, Z_1 and Z_2 are channel bed elevation at ST_1 and ST_2 , V_1 and V_2 are average flow velocities (total discharge/total area), α_1 and α_2 are weighting coefficients, g is gravity and h_e is energy loss head. Energy loss head is defined as:

$$h_e = L\bar{S}_f + C \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \quad \text{Equation 5}$$

where L is the weighted distance between cross-sections, S_f is the representative friction slope and C is an expansion/contraction coefficient. Weighted distance and friction slope are:

$$L = \frac{L_{lob}\bar{Q}_{lob} + L_{ch}\bar{Q}_{ch} + L_{rob}\bar{Q}_{rob}}{\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}} \quad \text{Equation 6}$$

$$S_f = \left(\frac{Q_1 + Q_2}{K_1 + K_2} \right)^2 \quad \text{Equation 20}$$

Where L_{lob} , L_{ch} and L_{rob} are distances along left overbank, main channel, and right overbank. $\bar{Q}_{lob}$, $\bar{Q}_{ch}$ and $\bar{Q}_{rob}$ are average discharges across those sections, K_1 and K_2 are conveyance values at cross-sections.

Conveyance and discharge per subdivision are:

$$Q = K \sqrt{S_f} \quad \text{Equation 21}$$

$$K = \frac{1.486}{n} A R^{2/3} \quad \text{Equation 22}$$

where K is conveyance, n is the Manning's roughness coefficient, A is the flow area, and R the hydraulic radius.

2D Model

The dynamic nature of floods and the movement of water into low-lying areas requires numerical models that incorporate two horizontal flow directions. The proposed method uses a two-dimensional model based on the conservation of momentum and continuity equations. Velocities are averaged over the vertical. The dynamic equations for momentum conservation are:

$$\frac{1}{g} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{n^2 |u| u}{h^{4/3}} = - \frac{\partial h}{\partial x} - \frac{\partial z}{\partial x} \quad \text{Equation 23}$$

$$\frac{1}{g} \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{n^2 |v| v}{h^{4/3}} = - \frac{\partial h}{\partial y} - \frac{\partial z}{\partial y} \quad \text{Equation 24}$$

Where u and v are the velocity components x and y directions, n is Manning's roughness coefficient, h is the free surface elevation relative to terrain and t is time. The mass conservation (continuity) equation in two dimensions is:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (uh) + \frac{\partial}{\partial y} (vh) = 0 \quad \text{Equation 7}$$

The floodplain area is divided into rectangular cells of length ∂x and width ∂y . To calculate floodplain flows, the system of differential equations above is solved with appropriate initial and boundary conditions. Figure 110 shows an example of the 1D/2D hydraulic model configuration for the Yaguarón River, Uruguay.

A.4 DESCRIPTION OF MAIN BASINS AND MORPHOMETRIC PARAMETERS

Description of the main basins

The descriptions included here refer to the basins presented in Figure 68.

Sixaola: Located on the Caribbean slope, this watershed serves as the natural boundary between Costa Rica and Panama. Its main river, the Sixaola, is navigable and has several tributaries, including the Yorkín and the Coen. The basin is significant for biodiversity and for cross-border ecological connectivity.

La Estrella: Situated on the Pacific slope, this watershed is recognized for its mountainous topography and biodiversity. The river of the same name is of importance for local communities as well as for ecosystem conservation.

Banano: This watershed is characterized by mountainous terrain and its relevance to local agriculture. The Banano River is a tributary of the Sixaola River and plays a crucial role in the region's economic activities.

Bananito: Located on the Caribbean slope, this watershed is known for its biodiversity and ecological importance. The Bananito River is a tributary of the Sixaola River and is vital for local communities.

Moín: This watershed is located in the province of Limón and is known for its port activity at the port of Moín. The Moín River is important for transportation and the regional economy.

Matina: Situated on the Caribbean slope, this watershed is known for its biodiversity and ecological importance. The Matina River is a tributary of the Reventazón River and is vital for local communities.

Madre de Dios: This watershed is characterized by its mountainous relief and its importance for ecosystem conservation. The Madre de Dios River is a tributary of the Reventazón River and is crucial for the region's economic activities.

Pacuare: Known for its biodiversity and ecological importance, this watershed is home to the Pacuare River, famous for its rapids and widely used for rafting. It is one of the main watersheds on the Caribbean slope.

Reventazón: The third-largest watershed in the country, located on the Caribbean slope. The Reventazón River is crucial for hydroelectric power generation and for agricultural activities in the region.

Tortuguero: This watershed is recognized for its ecological importance and biodiversity. The Tortuguero River is vital for local communities and is also a major ecotourism destination.

Sarapiquí: Located on the Caribbean slope, this watershed is known for its biodiversity and ecological relevance. The Sarapiquí River is a tributary of the San Juan River and is vital for local communities.

Cureña: This watershed is characterized by mountainous terrain and its importance for ecosystem conservation. The Cureña River is a tributary of the San Carlos River and plays a crucial role in the region's economic activities.

San Carlos: The San Carlos River watershed is one of the largest in the country, encompassing a wide variety of ecosystems. The river is essential for agricultural, industrial, and urban activities in the northern region. The basin is also important for biodiversity and for hydrological regulation in the area.

Pocosol: The Pocosol River watershed is located in northern Costa Rica, near Arenal Volcano National Park. The river flows through tropical forests and agricultural areas, making it essential for irrigation and potable water supply.

Frío: The Frío River watershed is significant due to its location in northern Costa Rica, near Tortuguero National Park. The river is known for its clear waters and as a key habitat for numerous aquatic species. The basin faces challenges related to conservation and sustainable resource management.

Zapote: This watershed is characterized by mountainous terrain and its importance for ecosystem conservation. The Zapote River is a tributary of the San Carlos River and plays a crucial role in the region's economic activities.

Nicoya Peninsula: This watershed is recognized for its agricultural activity and ecological importance.

Tempisque: Located on the Pacific slope, this watershed is known for its agricultural activity and ecological significance. The Tempisque River is a tributary of the San Juan River and is vital for local communities.

Bebedero: This watershed is characterized by mountainous terrain and its relevance for ecosystem conservation. The Bebedero River is a tributary of the Tempisque River and is critical for economic activities in the region.

Abangares: Located on the Pacific slope, this watershed is known for its mining activity and ecological importance. The Abangares River is a tributary of the Tempisque River and is vital for local communities.

Barranca: This watershed is characterized by mountainous terrain and its role in ecosystem conservation. The Barranca River is a tributary of the Tempisque River. The Barranca River basin is located in northwestern Costa Rica, covering primarily the cantons of San Ramón, Naranjo, Palmares, and Esparza, in the provinces of Alajuela and Puntarenas.

Savegre: Situated on the Pacific slope, the Savegre River basin stands out for its biodiversity and natural beauty. The Savegre River is renowned for its water quality and is considered one of the cleanest rivers in Central America. The basin encompasses tropical forests and mountainous areas, making it an important resource for conservation and ecotourism.

Barú: Located in Puntarenas Province, the Barú River basin is essential for the region due to its water resources and influence on local agriculture. The Barú River flows through diverse ecological zones, from humid forests to agricultural lands, highlighting its importance for ecological connectivity and the sustainable management of water resources.

Térraba: The Térraba River basin is one of the largest in Costa Rica, encompassing a wide range of ecosystems, from mountains to coastal plains. It is vital for local communities, providing water for domestic use, irrigation, and economic activities. In addition, the Térraba River is crucial for regional biodiversity, hosting a variety of aquatic and terrestrial species in its habitats.

Esquinas: Located in the southern region of the country, the Esquinas River basin is known for its rich biodiversity and its importance in conserving tropical ecosystems. The Esquinas River flows through rainforests and is essential for water regulation and the maintenance of natural habitats. Its basin is also significant for fishing activities and ecotourism in the area.

Changuinola: Although part of this basin lies within Panama, the Changuinola River basin is relevant to Costa Rica due to its influence in the border region. The Changuinola River is vital for local communities, providing water resources and serving as a biodiversity corridor in the area. The basin encompasses tropical forests and protected areas, making it essential for transboundary conservation.

Chirripó: The Chirripó River basin is recognized for its elevation and ecological diversity. Originating in the country's highest mountains, the Chirripó River flows through diverse ecosystems, from páramo grasslands to tropical forests. It plays a crucial role in conserving endemic species and regulating water resources in the region. The basin is also important for recreational activities and ecotourism.

Tárcoles: The Grande de Tárcoles River basin is one of the most important on the central Pacific slope. The Tárcoles River is known for its discharge and as a habitat for a variety of aquatic species. The basin encompasses both urban and rural areas, making it essential for water supply and resource management in the region.

Naranjo: Located in the central region of the country, the Naranjo River basin is vital for both agricultural and urban activities. The Naranjo River flows through farmland and residential areas, serving as a key source for irrigation and potable water supply. The basin also faces challenges related to pollution and the sustainable management of water resources.

Sarapiquí: The Sarapiquí River basin is known for its biodiversity and as an important biological corridor in northern Costa Rica. The Sarapiquí River flows through tropical forests and agricultural zones, playing a critical role in ecosystem conservation and local economic activities. The basin is also significant for scientific research and ecotourism.

Jesús María: The Jesús María River basin is located on the Pacific slope of Costa Rica. Its main tributaries are the Machuca and Cuarros rivers, and its channel discharges into the Tivives Bay. The area is characterized by intensive land use with crops such as melon, sugarcane, and mango, reflecting the agricultural importance of this basin for regional economic development.

Tusubres: The Tusubres River basin also belongs to the Pacific slope and features altitudinal variations ranging from near sea level to more than 1,600 m. Its main tributaries are the Chires and Tulín rivers, forming a hydrographic system that drains into the Pacific Ocean and traverses landscapes ranging from mountain ranges to coastal plains.

Parrita: The Parrita-Pirris River basin is one of the largest on the Pacific slope. Its main channel originates in the Talamanca Mountain Range, specifically at Cerro de la Muerte, and flows until it empties into the Pacific Ocean. The basin is characterized by high sediment dynamics, which enrich the alluvial plains and enhance soil fertility in the lower basin, supporting extensive agricultural activity.

Damas: Its tributaries originate in the Chonta Range and surrounding hills, following a general northeast–southwest course until reaching the central Pacific. The basin combines mountainous areas and coastal plains, creating a varied landscape of significant ecological and productive importance.

Finally, the hydrological region of the Osa Peninsula encompasses a set of watersheds of exceptional natural richness, including the Sierpe, Agujas, Riyito rivers, and several smaller basins that drain into the Golfo Dulce and the Pacific Ocean. This territory is characterized by high biodiversity, with wetlands, mangroves, and tropical forests that form part of globally unique ecosystems. These watersheds play a

critical role in water regulation, environmental conservation, and in sustaining economic activities such as fisheries and ecotourism.

Table 23 summarizes the main physical characteristics of these watersheds. It includes data such as: Area (km²), Perimeter (P) (km), Compactness Index, Form Factor, Maximum, Minimum, and Mean Elevations (m a.s.l.), Main Channel Length (km), Mean Channel Slope (%), and Mean Basin Slope (%).

Table 23. Geomorphometric parameters (IMN, 2011)

Basin	Area km ²	P km	Compactness index	Form factor	Maximum elevation masl	Minimum elevation masl	Mean elevation masl	Channel length km	Mean channel slope %	Mean basin slope %
Sixaola	2309	-	1.97	0.41	3800	0	1249	153.4	8.16	40.97
La Estrella	1249	231	2.01	0.42	2240	0	411	65.7	14.39	27.31
Banano	207	86	1.66	0.49	2040	0	543	43.8	10.01	33.64
Bananito	225	73	1.36	0.93	980	0	150	32.3	10.37	17.99
Moín	163	61	1.34	0.66	520	0	97	25.1	4.72	11.41
Matina	1612	251	1.74	0.43	3800	0	983	112.5	16.5	36.24
Madre de Dios	255	78	1.4	0.46	620	0	55	44.0	2.89	4.32
Pacuare	573	236	2.18	0.21	3340	0	975	136.4	13.16	33.19
Reventazón	2810	1242	1.63	0.42	3460	0	1056	177.3	11.04	23.4
Tortuguero	1463	201	1.47	0.89	538	0	37	82.7	0.47	1.6
Sarapiquí	1721	219	1.48	0.54	2887	10	551	104.0	9.46	13.99
Cureña	359	92	1.39	0.98	340	10	51	32.8	1	3.69
San Carlos	3130	321	1.61	1.05	2320	20	534	142.1	5.02	17.39
Pocosol	1643	218	1.51	1.26	360	0	78	108.9	0.72	4.58
Frío	1686	192	1.27	0.57	1900	20	188	110.8	4.05	6.46
Zapote	2450	263	1.49	2.65	2020	20	308	51.8	6.77	10.47
Península de Nicoya	4165	750	3.24	-	1000	0	181	-	-	23.32
Tempisque	3382	365	1.76	0.56	1900	0	169	142.2	3.87	10.29
Bebedero	2068	652	1.38	1.14	2020	0	291	72.2	4.01	12.15
Abangares	1347	222	1.7	1.15	1840	0	374	47.2	4.32	20.91
Barranca	465	154	1.96	0.58	2180	0	792	68.8	12.43	25.7
Jesús María	377	99	1.42	0.62	1421	0	264	44.0	9.82	16.28
Grande de Tárcoles	3595	254	1.44	0.74	2960	0	1031	111.7	2.15	15.3
Tusubres	823	132	1.29	1.33	1633	0	258	53.2	20.43	25.1
Parrita	1273	207	1.61	1.29	3140	0	1167	97.5	19.11	39.76
Damas y otros	451	141	1.84	1.13	2100	0	307	17.1	12.07	25.78
Naranjo	425	122	1.9	0.49	3006	0	902	52.5	14.42	37.05
Savegre	607	129	1.46	0.48	3480	0	1327	70.6	18.88	45.28
Barú	544	145	1.75	3.46	1365	0	364	18.5	-	31.14
Térraba	5055	436	1.72	1.95	3760	0	1002	185.7	6.26	31.01
Península de Osa	1943	372	2.36	-	1320	0	131	-	-	18.32
Esquinas	1786	348	2.32	2.55	1538	0	207	39.4	8.82	18.29
Changuinola	253	80	1.4	1.43	3340	1240	2419	16.7	21.28	39.44
Chirripó	2046	329	2.02	0.26	3400	0	500	140.0	4.7	16.29

A.5. COASTAL FLOOD HAZARD ASSESSMENT METHODOLOGY

The methodology presented here is also included in the Inception Report of this consultancy (Section 6.4) and is reproduced here for the reader's convenience.

Coastal flooding events are typically triggered by extreme meteorological phenomena capable of producing sea level surges along coastlines. Events such as hurricanes, although they do not directly impact Costa Rica's coasts⁶, can generate storm surges that pose coastal flood risk. This study models coastal floods by considering hurricanes as the triggering phenomenon. Tsunamis are also considered in coastal flood evaluation, as described in Annex A.6.

Hurricane tracks consist of advisories issued every six hours indicating: date and time, geographic location of the cyclone's center, central pressure, and sustained wind speed over one minute at 10 meters above sea level. These advisories are typically issued by the U.S. National Hurricane Center for the entire North Atlantic basin. **¡Error! No se encuentra el origen de la referencia.** shows the track and advisories of Hurricane Otto (November 2016).



Figure 126. Track and advisories of Hurricane Otto

Hurricane Track Perturbation

For each hurricane track, a set of "child" tracks is generated using a two-dimensional Wiener process, whereby the historical track is artificially perturbed to create a new trajectory. This perturbation process is described in Equation 8:

$$\mathbf{x}_s(t_{k+1}) = \mathbf{x}_s(t_k) + \Delta \mathbf{X}_{k,k+1} + e \quad \text{Equation 8}$$

Where $\mathbf{x}_s(t_k)$ is the position vector at time t_k , $\mathbf{x}_s(t_{k+1})$ is the position at t_{k+1} , $\Delta \mathbf{X}_{k,k+1}$ is the delta between k and $k + 1$, and e is a normally distributed random variable with $\mu=0.0$ and $\sigma=0.5$.

⁶ With the exception of Hurricane Otto in 2016.

Simulated central pressures initially match those of the original hurricane and are then modified using the balance model proposed by Emanuel (2006), which considers atmospheric-oceanic parameters influencing a hurricane's lifecycle. This procedure allows artificial expansion of the hurricane catalog in the calculation region, enabling simulation of additional tracks not included in the original dataset. Typically, 100 child tracks are simulated per historical track.

Figure 112 illustrates perturbed tracks over a hypothetical territory.

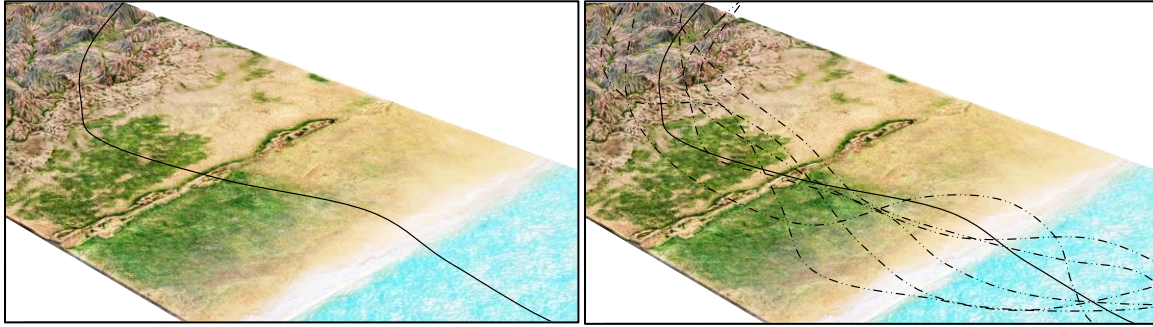


Figure 127. Illustration of trajectory perturbation over a hypothetical territory. From the original trajectory (left), a set of perturbed trajectories is generated (right)

Wind Field Modeling

Wind field modeling is crucial for evaluating storm surges, as wind shear is the main driver of sea level rise, especially at coastal zones located a moderate distance from the hurricane's center. Wind field modeling follows three steps (Vickery et al., 2009a):

1. Compute gradient wind speed from the hurricane's central pressure. This is the wind resulting from pressure gradient forces, initially neglecting surface friction and nonlinear effects.
2. Use a planetary boundary layer model to derive vertical wind speed profiles, factoring in surface roughness and average one-hour wind speed at 10 meters. Nonlinear friction effects are introduced as random perturbations.

The gradient wind speed (v_G) is calculated using Holland's model (1980):

$$v_G = \sqrt{\left(\frac{RMW}{r}\right)^B \cdot \frac{B \cdot \Delta P \cdot \exp\left(-\left(\frac{RMW}{r}\right)^B\right)}{\rho} + \frac{r^2 f^2}{4} - \frac{f \cdot r}{2}} \quad \text{Equation 9}$$

where RMW is the radius to maximum winds, r is the observation distance (i.e. the distance from the calculation site to the center of the storm), ΔP is the pressure gradient ($\Delta P = P_n - P_0$, where P_n is the nominal atmospheric pressure, set at 1005 hPa), ρ is air density, f is the Coriolis parameter ($f = 2\Omega \sin\varphi$, where Ω is the Earth's angular rotation speed, and φ is the latitude of the cyclone's eye, and B is Holland's dimensionless parameter, a constant that defines the shape of the gradient wind profile and typically ranges between 0.7 and 2.2).

The radius of maximum winds (RMW) marks the point at which the gradient wind profile reaches its peak, measured from the center of the hurricane. Multiple approaches for calculating this parameter exist in the literature. In this study, the empirical equation proposed by Vickery & Whadera (2008) is applied.,

$$RMW = 3.015 - 6.291 \cdot 10^{-5} \Delta P + 0.0337 \phi \quad \text{Equation 10}$$

To calculate Holland's parameter B , the formulation proposed by Vickery & Wadhera (2008) is used, as they found a sufficiently strong correlation between B and a dimensionless parameter A defined by them:

$$B = 1.732 - 2.237 \sqrt{A} \quad \text{Equation 11}$$

$$A = \frac{RMW \cdot f}{\sqrt{2R_d T_s \cdot \ln \left(1 + \frac{\Delta P}{P_0 \cdot e} \right)}} \quad \text{Equation 12}$$

where R_d is the gas constant for air, T_s is the sea surface temperature (given in °K), and e is Euler's constant. For illustrative purposes, Figure 113 shows a wind field calculated for a stationary hurricane (i.e., with no forward motion), using the Holland model (1980) presented here. The resulting wind speed profile is symmetrical, leading to a wind field with circular contours. The calculated gradient wind corresponds to a sustained wind over a long period of time and is therefore associated with a one-hour duration.

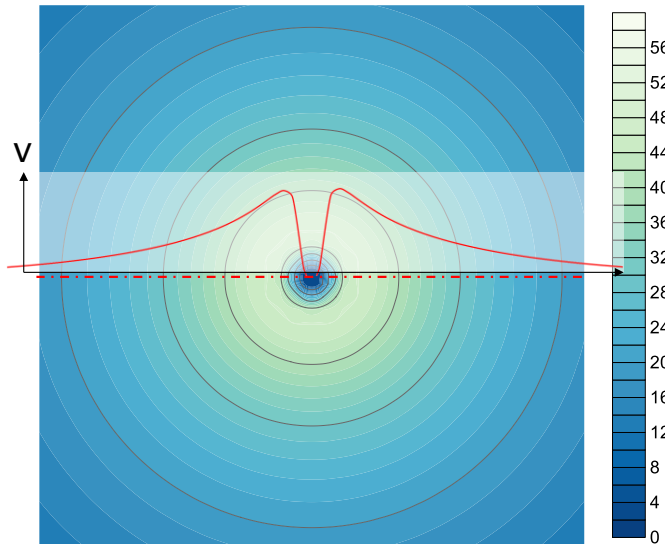


Figure 128. Gradient wind field of a stationary storm with a central pressure of 950 hPa. The wind speed profile shown is calculated using the Holland model (1980).

The gradient wind speed (v_G) is adjusted to obtain the wind speed at ground level (actually at 10 meters above the surface) using a planetary boundary layer model. Vickery et al. (2009b) propose a model for the variation of the mean wind speed (over one hour), $u(z)$, as a function of the height above the surface, z , within the boundary layer, as follows:

$$u(z) = \frac{u_*}{k} \left[\ln \left(\frac{z}{z_0} \right) - 0.4 \left(\frac{z}{H^*} \right)^2 \right] \quad \text{Equation 13}$$

where k is the von Kármán constant ($k = 0.4$), u_* is the friction velocity, z_0 is the aerodynamic roughness length, and H^* is the height of the boundary layer, which can be modeled according to Vickery et al. (2009b) as follows:

$$H^* = 343.7 + \frac{0.26}{I} \quad \text{Equation 14}$$

where I is the inertial stability, defined by Kepert (2001) as:

$$I = \sqrt{\left(f + \frac{2V_G}{r}\right) \left(f + \frac{V_G}{r} + \frac{\partial V_G}{\partial r}\right)} \quad \text{Equation 15}$$

Friction velocity u_* :

$$u_* = \sqrt{\frac{\tau}{\rho}} \quad \text{Equation 16}$$

where τ is the surface wind shear, defined as:

$$\tau = \rho \cdot C_d \cdot u^2 \quad \text{Equation 17}$$

where C_d is the drag coefficient and, u is surface wind speed. The application of this boundary layer model results in logarithmic profiles of one-minute sustained wind speed variation with height above the surface. These profiles have been extensively validated against values recorded by drop sondes deployed over tropical cyclones during reconnaissance flights (see Vickery et al., 2009b for further details). **¡Error! No se encuentra el origen de la referencia.** shows three wind speed profiles calculated for different distances from the center of a cyclone with a central pressure of 930 hPa moving over open sea.

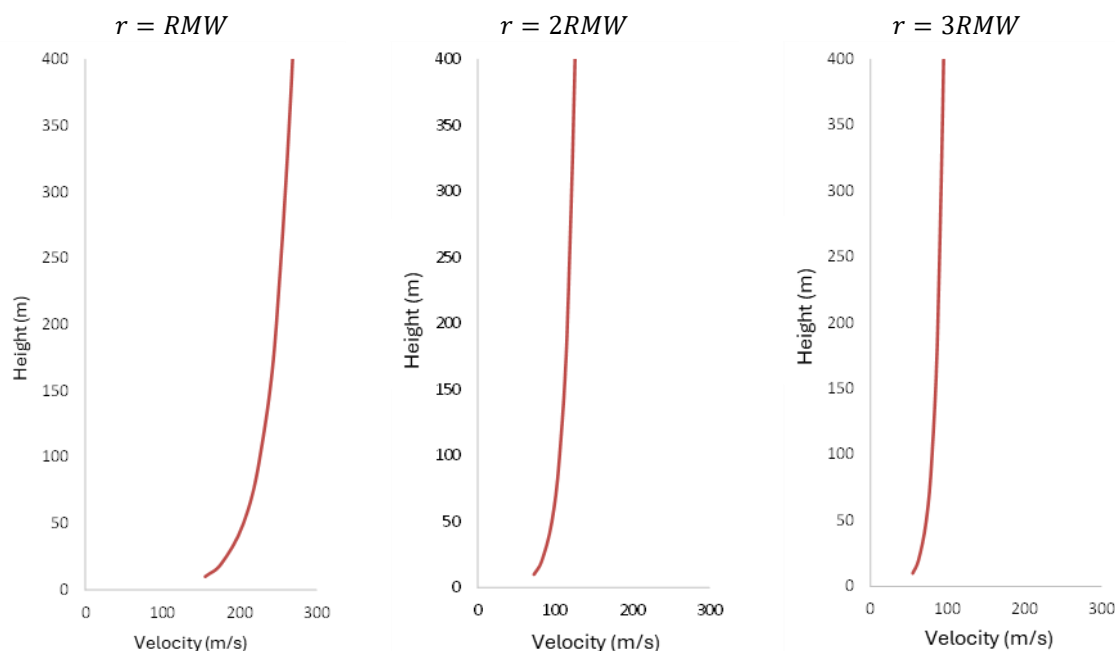


Figure 129. Logarithmic wind speed profiles calculated at different distances from the storm center for a hurricane with a central pressure of 930 hPa moving over open sea.

Surface roughness is associated with the size and density of obstacles to wind flow, which induce local turbulence and reduce surface wind speed. Surface roughness is directly incorporated into the boundary layer model through the parameters z_0 (aerodynamic roughness length) and C_d (drag coefficient). Modifying these parameters affects the logarithmic wind profile, as illustrated in **¡Error! No se encuentra el origen de la referencia..**

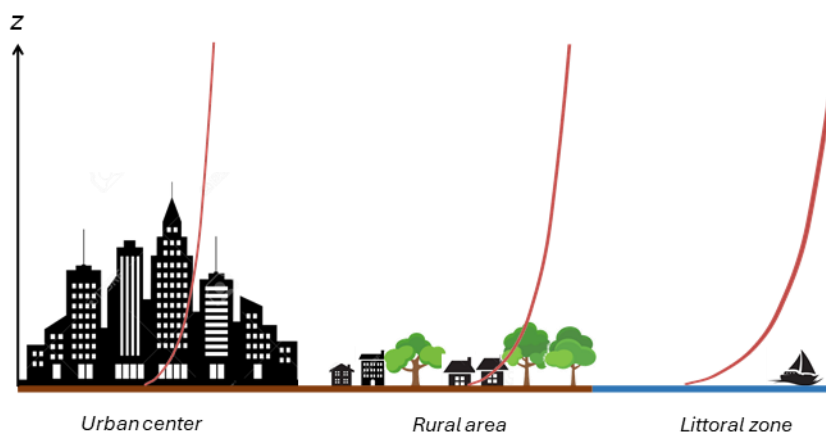


Figure 130. Illustration of the change induced in the logarithmic profile of the boundary layer model due to surface roughness.

Wind fields are defined geographically in terms of v_{10} . For each hurricane, multiple wind fields are simulated. At each grid point, probabilistic models are fitted, defining v_{10} as a random variable.

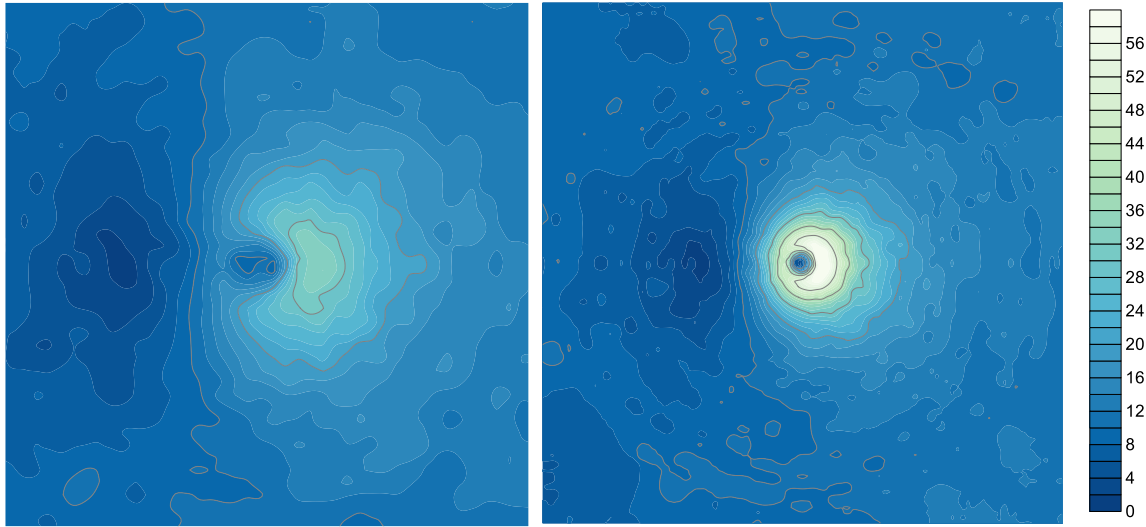


Figure 131. Examples of surface wind fields for hurricanes with a forward speed of 10 m/s moving northward and central pressures of 950 hPa (left) and 920 hPa (right).

Storm Surge Modeling

Storm surge is one of the most significant impacts of tropical cyclones on coastal zones. The rise in sea level is mainly caused by hurricane-induced wind shear, which pushes the ocean surface and generates an oceanic current that changes direction with depth due to Ekman spirals from the Coriolis effect. An additional contribution comes from the low atmospheric pressure at the storm center, which causes further sea level elevation. As the surge approaches the coast, local bathymetry amplifies the sea level rise, leading to flooding of extensive coastal areas. The total surge (η) is the sum of the wind-induced surge (η_C) and the pressure-induced surge (η_P).

$$\eta = \eta_C + \eta_P \quad \text{Equation 18}$$

The maximum wind-induced surge can be estimated using the model proposed by Tilburg and Garvine (2003), based on Ekman ocean circulation equations. The surge is computed at a specific coastal point, with the x -direction aligned parallel to the continental shelf and the y -direction perpendicular:

$$\eta_C = \int_0^L -\frac{fU_x}{g} \sqrt{\frac{\rho_a c_a U}{\rho \cdot c_b |U_x|}} + \frac{\rho_a c_a U_y U}{\rho g D(y)} dy \quad \text{Equation 19}$$

Where L is the width of the continental shelf, ρ_a is air density, c_a is the surface drag coefficient, U is wind speed, ρ is seawater density, c_b is seabed drag coefficient, $|U_x|$ is the component of wind parallel to the shelf, U_y is the perpendicular component, and $D(y)$ is the bathymetric profile.

The pressure-induced surge is modeled using the inverse barometric effect, where sea level rises approximately 1 cm for every 1 hPa drop in pressure:

$$\eta_P = \frac{\Delta P}{\rho \cdot g} \quad \text{Equation 20}$$

The pressure field associated with the cyclone is assumed symmetric and is defined as a function of central pressure and the radius to maximum winds.

$$P(r) = P_0 + (P_n - P_0) \exp\left(-\frac{RMW}{r}\right) \quad \text{Equation 21}$$

Hydraulic modeling of tidal flooding along the coasts is commonly addressed through computational simulation, which—even in the two-dimensional case—requires very high computational costs as well as complex data preparation processes, such as continuous layers of topography and bathymetry or meshes generated over the terrain to be evaluated. For this reason, in this case, an approximate model has been implemented based on an algorithm that classifies cells as wet or dry, solving a simplified version of the two-dimensional flow equation in which the contribution of the inertia of the water volume in each terrain cell is neglected (see Gao et al., 2024):

$$\frac{\partial}{\partial x} \left(\eta + \frac{v^2}{2g} \right) = \frac{\tau_a - \tau_b}{\rho g d} \quad \text{Equation 22}$$

where v is the flow velocity onshore, τ_a is the wind friction shear stress, τ_b is the bottom friction shear stress, and d is the flood depth in the cell. Using a finite difference approach, the partial derivative shown can be simplified and evaluated discretely over a digital elevation model. **¡Error! No se encuentra el origen de la referencia.** illustrates the proposed iterative evaluation procedure for tidal flooding.

The proposed model has been compared with field observations as well as with simulations from hydrodynamic modeling systems, demonstrating a very good fit and high computational efficiency, making it the preferred solution for modeling multiple events within the catastrophic risk assessment framework.

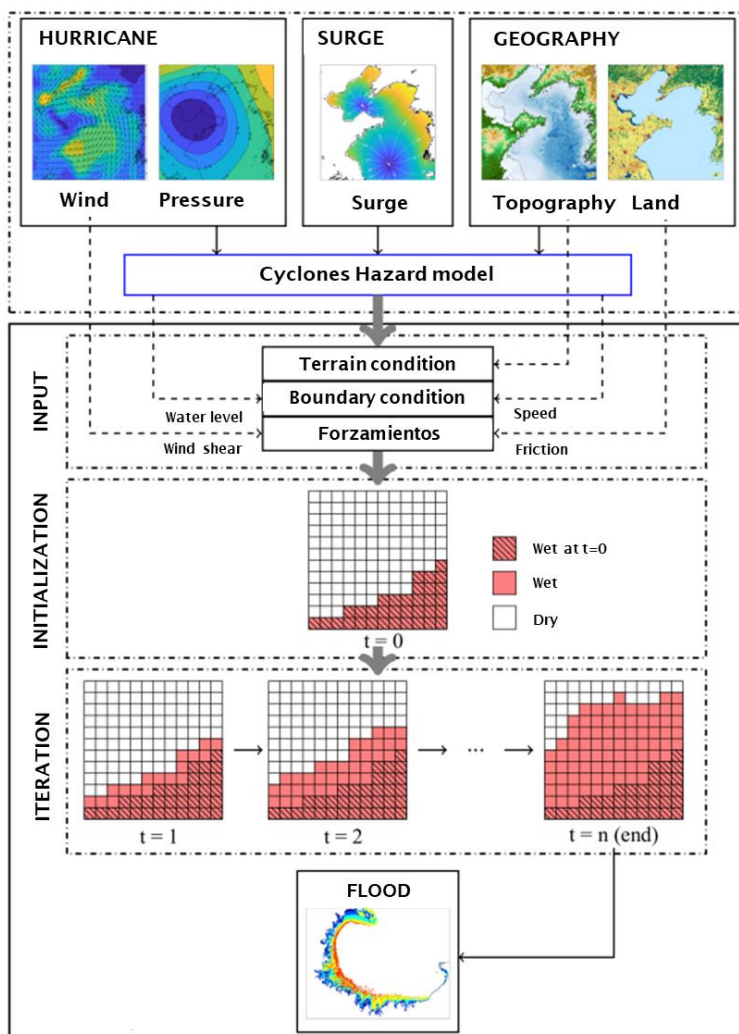


Figure 132. Conceptual framework of the tidal flooding model. Adapted from Gao et al., 2024.

A.6. TSUNAMI HAZARD ASSESSMENT METHODOLOGY

The methodology presented here is also included in the Inception Report of this consultancy (Section 7.2) and is reproduced here for the reader's convenience.

Tsunamis are gravity waves generated in the ocean when a triggering phenomenon causes the vertical displacement of a large water mass. These waves can travel thousands of kilometers and impact coastlines across multiple continents. There are different types of tsunamis, mainly classified by their triggering mechanism. In this study, only those associated with tectonic processes of the Earth's crust—commonly referred to as tectonic tsunamis—are considered.

Three key processes are involved in tsunami hazard: (i) generation, (ii) propagation, and (iii) run-up. Generation refers to the conditions under which vertical displacement of ocean water initiates gravity waves. Propagation describes how these waves travel across the ocean basin. Run-up involves the amplification of tsunami wave heights as they approach shallow coastal waters due to bathymetric effects

Generation

Modeling the generation mechanism of tectonic tsunamis requires considering two essential aspects: (i) the coupling between the elastic solid medium of the Earth's crust and the liquid medium of the ocean, and (ii) the relationship between vertical displacements of the ocean surface and the seabed.

Earth-Ocean Coupling

Tsunami generation is associated with the behavior of the water–seabed system, specifically how seismic waves influence the hydrodynamic waves that result. This can be approached through two different frameworks:

In a coupled system, seismic waves traveling through the crust influence the behavior of the overlying water column. This approach requires considering the variations in seabed shape within the tsunami propagation analysis.

In a decoupled system, there is no direct interaction between crustal deformation and water movement. Elastic deformations of the seabed due to seismic waves are considered negligible. When the coseismic seabed displacement is significant, it is commonly modeled as a rigid seabed with a shape matching the maximum elastic deformation induced by the earthquake.

These approaches have been evaluated by several authors using formulations based on Rayleigh wave theory. Ward (1980) and Okal (1988) extended the free spherical oscillation framework of Rayleigh to address tsunami generation and propagation in spherical coordinates.

Seabed and Ocean Surface Displacement

The standard assumption for determining the initial displacement of the ocean surface is that it matches the vertical displacement of the seabed. In this study, the seabed deformation resulting from crustal rupture is calculated using the formulation developed by Odaka (1985). Okada (1985), building on Volterra's dislocation theory, developed an analytical solution to compute displacement in an elastic

medium due to a fault rupture. This formulation has been widely adopted for tsunami propagation modeling. The vertical deformation field ζ is calculated as follows:

$$\zeta = \left(-\frac{U_\phi}{2\pi} \left[\frac{3xdq}{R^5} + I_\phi \sin \delta \right] - \frac{U_\delta}{2\pi} \left[\frac{3dpq}{R^5} + I_\delta \sin \delta \cos \delta \right] \right) \Delta\Sigma \quad \text{Equation 23}$$

Where U_ϕ is the strike-slip displacement, U_δ is the dip-slip displacement, d is the source depth, p and q are functions of the dip angle, I_ϕ and I_δ are functions dependent on the site location and Lamé constants, and $\Delta\Sigma$ is the rupture area. **Error! No se encuentra el origen de la referencia.** shows an example of a vertical seabed deformation field computed using Odaka's (1985) formulation for a Mw 7.0 earthquake with eastward strike and a focal depth of 5 km.

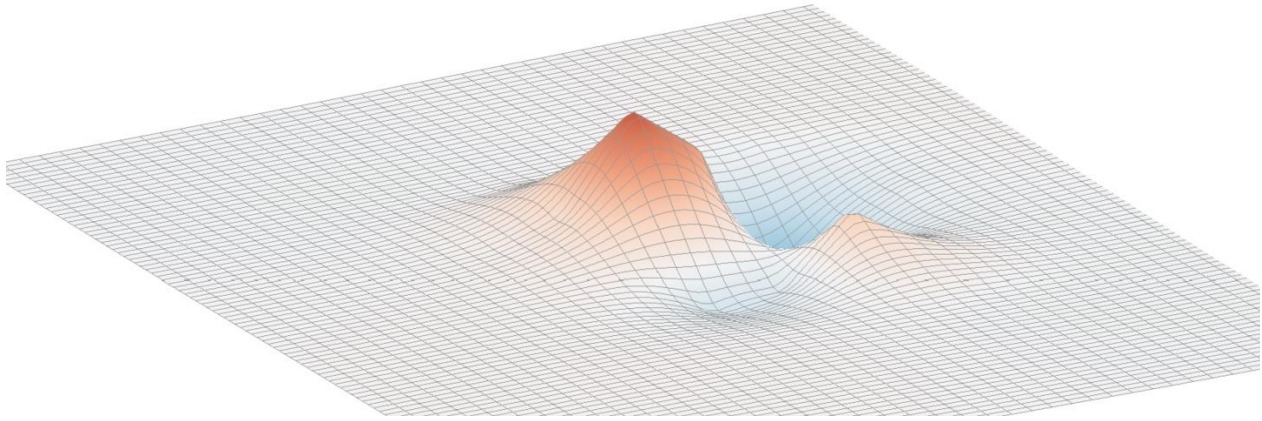


Figure 133. Vertical seabed deformation for a Mw 7.0 earthquake with eastward strike and 5 km depth.

Propagation

The propagation of tsunami waves across the ocean is generally modeled using shallow water wave theory. These are also known as gravity waves, since gravity acts as the restoring force in the medium. When gravity waves travel in a medium where the wavelength is much greater than the depth, the resulting vertical acceleration is negligible compared to gravity. This means the horizontal velocity of the water column is nearly constant from the seafloor to the surface—this is the defining characteristic of long waves or shallow-water waves.

In the case of tsunamis, ocean depths are typically around 5 km, while tsunami wavelengths can span several hundred kilometers. As a result, the long wave approximation is sufficiently valid to characterize tsunami energy propagation in the open ocean.

The mathematical development of shallow water wave theory is based on Stokes' formulation, which describes the one-dimensional motion of an inviscid fluid subject to constant gravitational force, bounded by a rigid bottom and a free surface. Although Stokes' equations have been known for over 150 years, no general analytical solution exists. Therefore, specialized formulations have been developed under simplifying assumptions for specific cases. For tsunami modeling, the relevant scenario involves long waves with small amplitudes, propagating in one direction in an incompressible medium with constant shallow depth.

Several mathematical models have been proposed under these conditions, including those by Boussinesq (1871), Korteweg and de Vries (1895), Kadomtsev and Petviashvili (1970), and Camassa and Holm (1993).

Using the theoretical framework of Korteweg and de Vries (1895), the dislocation model by Okada (1985), and nonlinear shallow water wave equations, Dutykh & Dias (2007) proposed an integral solution for the combined problem of tsunami generation and propagation. This formulation allows the calculation of water surface elevation, wave velocity, and seabed pressure at different times and locations, as a function of the seismic source geometry, average ocean depth, and a dislocation function that characterizes the coseismic seabed displacement.

$$\eta(x, y, t) = \frac{1}{(2\pi)^2} \iint_{\mathbb{R}^2} \frac{e^{i(kx+ly)}}{\cosh(mH)} \int_0^t (1 - \omega \sin \omega \tau) \bar{\zeta}(k, l, t - \tau) d\tau dk dl \quad \text{Equation 24}$$

Where k and l are wave numbers in the x and y directions, $m = \sqrt{k^2 + l^2}$, $\omega = \sqrt{gm \tanh(mH)}$, H is ocean depth, and $\bar{\zeta}$ is the combined Fourier-Laplace transform of the seabed deformation function. **Error! No se encuentra el origen de la referencia.** illustrates wave elevation propagation computed using the Dutykh & Dias (2007) model for the earthquake previously described in Figure 120.

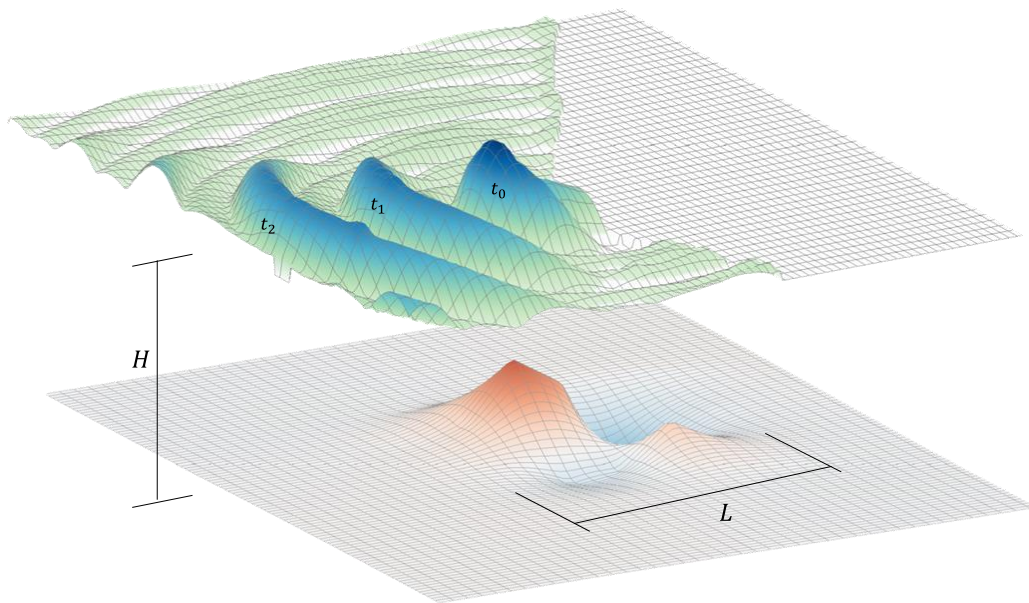


Figure 134. Simulation of tsunami wave elevation η at three time steps (t_0 , t_1 , t_2), for the earthquake in **Error! No se encuentra el origen de la referencia.**, using the model by Dutykh & Dias (2007).

Run-Up

In deep ocean waters, tsunami wave amplitudes are low and practically imperceptible. However, as the waves approach the shore, their amplitude increases dramatically, resulting in large and destructive coastal waves. This amplification is due to the decreasing water depth near the coast.

In deep water, gravity waves travel at a speed equal to $\sqrt{gH}$, where H is ocean depth and g is gravitational acceleration. As long waves, their speed remains nearly constant in the deep ocean. As the tsunami wave enters shallower regions, the front slows down due to reduced depth, while the rear of the wave—still in deeper water—continues at a faster speed. This causes the wavelength to compress horizontally. Because of water's near-incompressibility, this compression results in a rapid increase in wave amplitude at the front, generating powerful surges upon landfall.

Several analytical models exist to solve the run-up problem. These are widely used to estimate coastal wave heights due to tsunamis and are based on the following assumptions:

- Wave breaking effects at the shoreline are neglected.
- Energy dissipation at the seabed is ignored.
- Total wave reflection at the shoreline is assumed; the shoreline remains fixed.
- The waves are treated as periodic gravity waves, neglecting the transient nature of tsunamis.
- The seabed slope is assumed to be constant.

Based on these premises, Madsen & Fuhrman (2007) proposed a method to estimate wave height at the shoreline and its onshore velocity:

$$\frac{R}{a_0} = 2\pi^{3/4} \left(\frac{a_0}{h_0}\right)^{-1/4} \xi^{-1/2} \quad \text{Equation 25}$$

$$\frac{U}{\sqrt{g \cdot a_0}} = \frac{\sqrt{\pi}}{\xi} \left(\frac{R}{a_0}\right) \quad \text{Equation 26}$$

Where R is the run-up amplitude at the coast, U is the onshore velocity, a_0 is the offshore wave amplitude, h_0 is the offshore water depth, and ξ is the *surf parameter*, also known as the *Iribarren number*, defined by Iribarren & Nogales (1948) as,

$$\xi \equiv \frac{s}{\sqrt{\frac{h_0}{L}}} \quad \text{Equation 27}$$

Where L is the offshore tsunami wavelength and s is the mean bathymetric slope. When s is very small, the equations tend toward infinity. This means that extremely steep bathymetric profiles make the solution invalid, as wave amplitudes cannot increase indefinitely. This constraint, known as the breaking criterion, was described by Carrier and Greenspan (1958). Madsen and Fuhrman (2007) expressed it in terms of the Iribarren number:

$$\frac{R}{a_0} \leq \frac{R_{max}}{a_0} = \frac{1}{\pi} \xi^2 \quad \text{Equation 28}$$

Where R_{max} is the maximum amplitude the wave can reach under the conditions defined by ξ . **Error! No se encuentra el origen de la referencia.** shows the variation in wave run-up R and onshore velocity U with the Iribarren number, and how the breaking criterion defines the model's limit of validity.

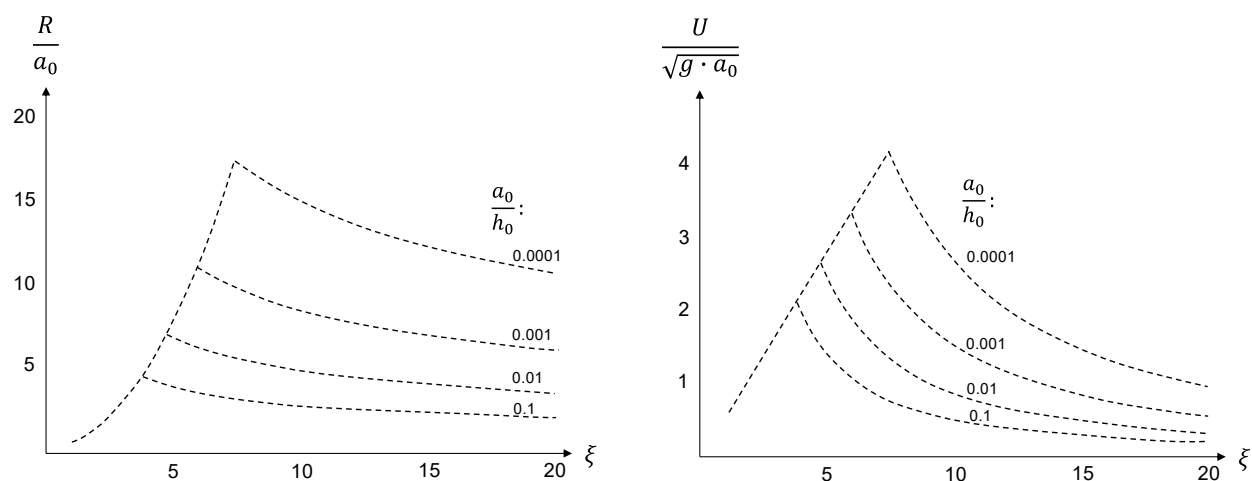


Figure 135. Variation of run-up amplitude R and onshore velocity U with the Iribarren number, including the breaking criterion as a limit of validity. Adapted from Madsen & Fuhrman (2007)

The hydraulic flow of wave amplitude will be modeled using the conceptual framework of the iterative wet and dry cell classification model presented in Annex A.5, omitting the term related to surface wind shear, which does not apply in this context.

A.7. CONSIDERATIONS ON THE VALIDATION OF HAZARD RESULTS

Limitations To the Validation Process

The validation of probabilistic hazard models, such as those developed in this work, faces inherent and widely recognized limitations, particularly when conducted at the national scale. These limitations are not specific to this study, but rather reflect structural constraints in the availability, quality, and consistency of data, which affect most large-scale hazard modeling efforts worldwide. In many countries the observation infrastructure and historical records required to support a rigorous and statistically robust validation of hazard intensity fields are incomplete, fragmented, or nonexistent. Consequently, the direct validation of probabilistic hazard results, understood as the systematic comparison between modeled and observed intensities in space and time, is not feasible in practice.

A robust validation process would first require the availability of georeferenced measurements of hazard intensity, expressed in the same metric used in the model. In the case of floods, this typically corresponds to variables such as water depth, flow velocity, or flood extent; for droughts, to standardized indicators such as SPI or SPEI. These observations should be available across multiple locations throughout the territory and for multiple independent events. However, in practice, such information rarely exists with the spatial density and temporal continuity required. Hydrometric networks are often limited and concentrated in specific regions, while post-event surveys of flood depth or extent are not conducted systematically. Similarly, drought indicators are often derived at coarse spatial resolutions or through indirect approaches, making direct comparison with model results difficult.

Additionally, a consistent and spatially detailed characterization of the meteorological forcing associated with triggering events is required. This includes, for example, high-resolution precipitation fields, tropical cyclone tracks and wind fields, or temperature anomalies during prolonged periods. These datasets must be consistent with the spatial and temporal scales of the modeled phenomena. However, in many contexts, the available meteorological information does not reach the required resolution or presents significant levels of uncertainty, especially for historical events prior to the availability of modern observation systems or satellite records. This limitation makes it difficult to establish a reliable relationship between observed forcing and resulting hazard intensities.

Another fundamental requirement for validation is the existence of a sufficiently large and diverse set of historical events for which both intensity and forcing information are available. These events must provide adequate spatial coverage of the study area, encompassing all relevant geographic and climatic contexts represented in the model. For example, the validation of coastal flooding would require observations along the entire coastline, while fluvial flood validation should cover all major river basins and hydrological regimes. In reality, historical records tend to be concentrated in areas with higher population density or economic importance, leaving large regions without reliable information. This lack of spatial coverage introduces additional uncertainties and limits the possibility of comprehensive validation.

Equally important is the need for a sufficiently large number of events to validate the probabilistic characteristics of the hazard, and not only individual events. Probabilistic models aim to reproduce the statistical distribution of intensity at each location, including its mean value, variability, and behavior in the extremes. The validation of these statistical moments requires long and consistent time series of

observations, which are rarely available. Even in contexts with greater data availability, the number of observed extreme events is usually insufficient to adequately characterize the tails of the distribution, which are precisely the most relevant for risk assessment.

Given this reality, a purely visual comparison was carried out between the existing cartographic information published by the CNE and the hazard results obtained in this consultancy, noting that the information provided by the CNE does not correspond to probabilistic assessments, and therefore both results are not truly comparable. No comparison is performed for pluvial flooding, as no existing cartography was found for this hazard.

Fluvial Flooding

The CNE has fluvial flood hazard maps for all cantons of Costa Rica, in which areas with flood potential are presented, essentially corresponding to buffer zones around main river channels. These maps were compared with the probabilistic flood hazard assessment developed in this consultancy. Figure 136 shows the comparison between the CNE's map of areas with flood potential⁷ and the fluvial flood hazard map for a 1,000-year return period.

The map of areas with flood potential shows a broad and continuous delineation of areas susceptible to flooding, mainly following the hydrographic network and its associated floodplains, with a qualitative coverage. In contrast, the probabilistic hazard map presents a distribution in which the extent and severity of flooding respond to explicitly modeled hydrological and hydraulic processes. This is reflected in spatial patterns that are consistent with basin dynamics, including areas where the hazard is more intense or extensive, and others where, despite proximity to river channels, flooding does not occur under that level of probability. Consequently, the two maps are not expected to match in their spatial patterns and, therefore, comparing them as if they were equivalent may lead to misleading interpretations regarding the actual extent or severity of flood hazard.

Despite their methodological differences, both maps show clear agreement in identifying the main spatial patterns of flooding in Costa Rica. There is consistency in the location of extensive affected areas in regions known for recurrent events, such as the Caribbean lowlands and certain sectors of the Pacific, suggesting that both approaches coherently capture the areas where physical conditions favor water accumulation and overflow.

⁷ Taken from: <https://cne.cr/maps.arcgis.com/>

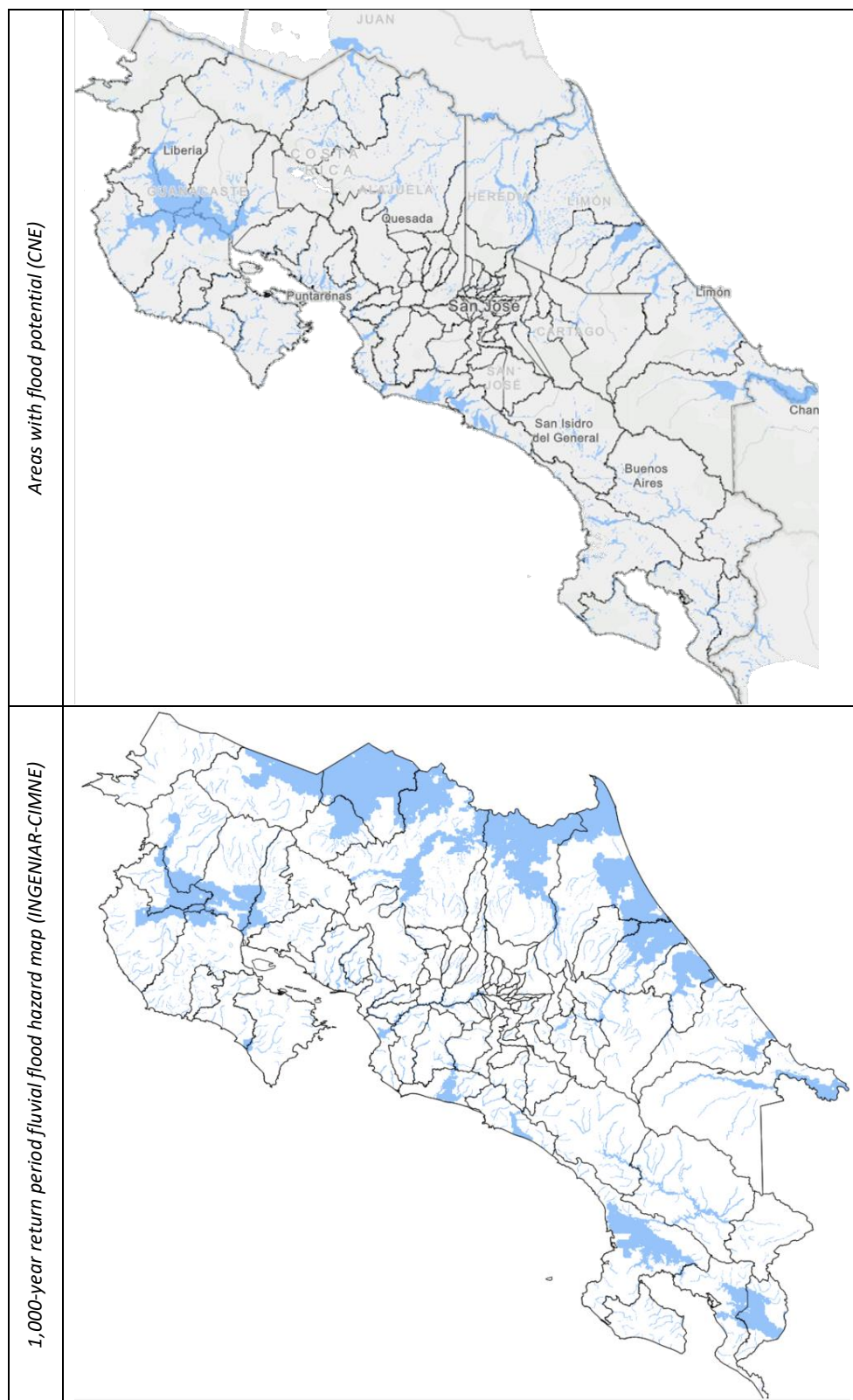


Figure 136. Comparison between the map of areas with flood potential (CNE) and the 1,000-year return period fluvial flood hazard map (INGENIAR-CIMNE)

Coastal Flooding

In the case of coastal flooding, the available information from previous hazard assessments or recognized historical events is much more limited. Although there have been significant events with known coastal impacts, such as those caused by Hurricane Otto or Tropical Storm Nate, there are no field records of flood extent.

The CNE has a map of flood-prone coastal areas in Costa Rica⁸, which is compared with the 1,000-year return period coastal flood hazard map developed in this consultancy. The comparisons are presented in Figures 137 and 138 for two arbitrarily selected sectors along the Pacific and Caribbean coasts. As can be observed, the results of the probabilistic assessment complement the pre-existing flood-prone area maps by considering the potential occurrence of multiple events not observed in historical records. Geographically, the agreement between both maps is notable for obvious reasons, as these are inundations constrained to the coastal zone.

Similarly to what is observed for fluvial flooding, the two maps are not expected to exhibit matching spatial patterns; therefore, treating them as equivalent may lead to incorrect interpretations regarding the actual extent or intensity of coastal flood hazard.



Figure 137. Comparison between the map of flood-prone coastal areas (CNE) and the 1,000-year return period coastal flood hazard map (INGENIAR-CIMNE), in an arbitrarily selected sector of the Pacific coast.

⁸ Taken from: <https://cne.cr/maps.arcgis.com/>

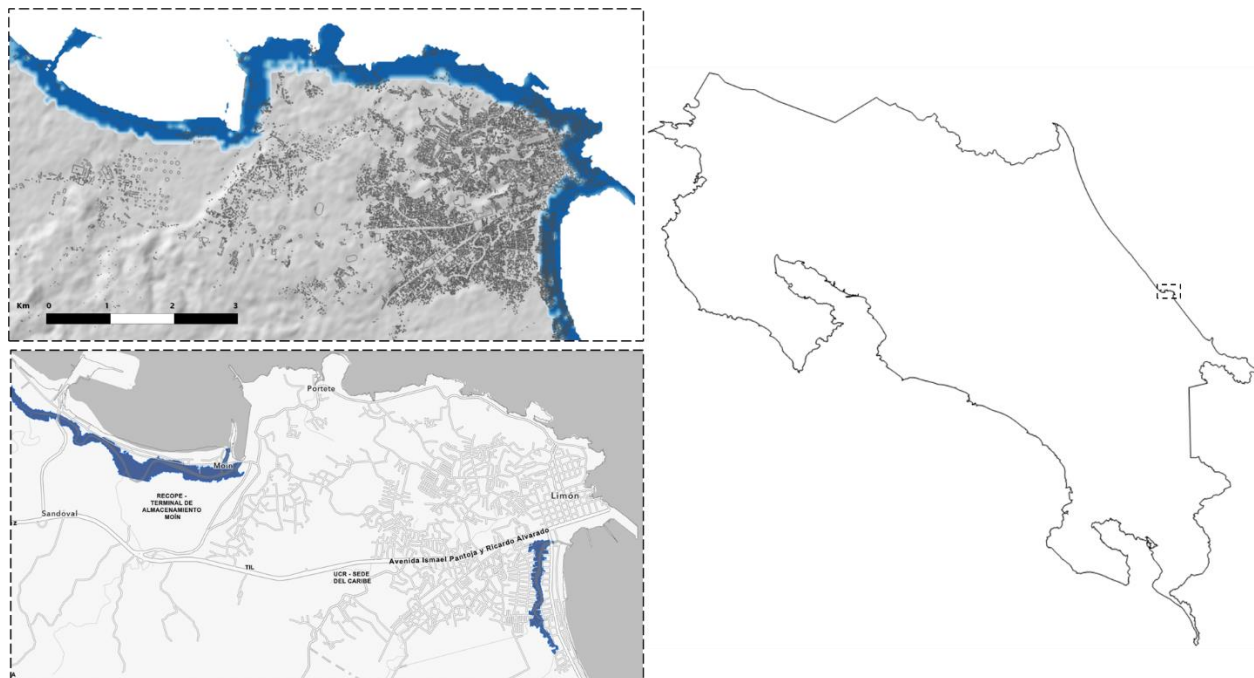


Figure 138. Comparison between the map of flood-prone coastal areas (CNE) and the 1,000-year return period coastal flood hazard map (INGENIAR-CIMNE), in an arbitrarily selected sector of the Caribbean coast.

Drought

In the case of drought, no equivalent official cartography was identified that would allow for a direct comparison with maps of indicators such as SPI or SPEI. Consequently, validation was approached indirectly by contrasting the spatial patterns of average annual losses (AAL) at the cantonal level with the cantons included in the 2019 drought emergency declarations (Executive Decrees 41852 and 41944), as illustrated in Figure 139.

This exercise does not constitute a strict or equivalent comparison, as it relates modeled risk results with administrative records of impacts; however, it does provide a qualitative reference regarding the spatial coherence of the results. It is important to emphasize that, in this case, the comparison is no longer of hazard, but rather of consequences and, therefore, risk, which introduces additional conceptual differences that must be considered in the interpretation.

The risk assessment results presented here correspond to those obtained for Operational Project 2: *Flood and Drought Risk for Small and Medium Agricultural Producers*. Relative AAL values are presented specifically for drought. Further details on the modeling process, as well as the complete set of risk results, can be found in the document: *Probabilistic estimation of climate risk in coffee, sugarcane, and extensive cattle production* (INGENIAR-CIMNE, 2026, for GRMA).

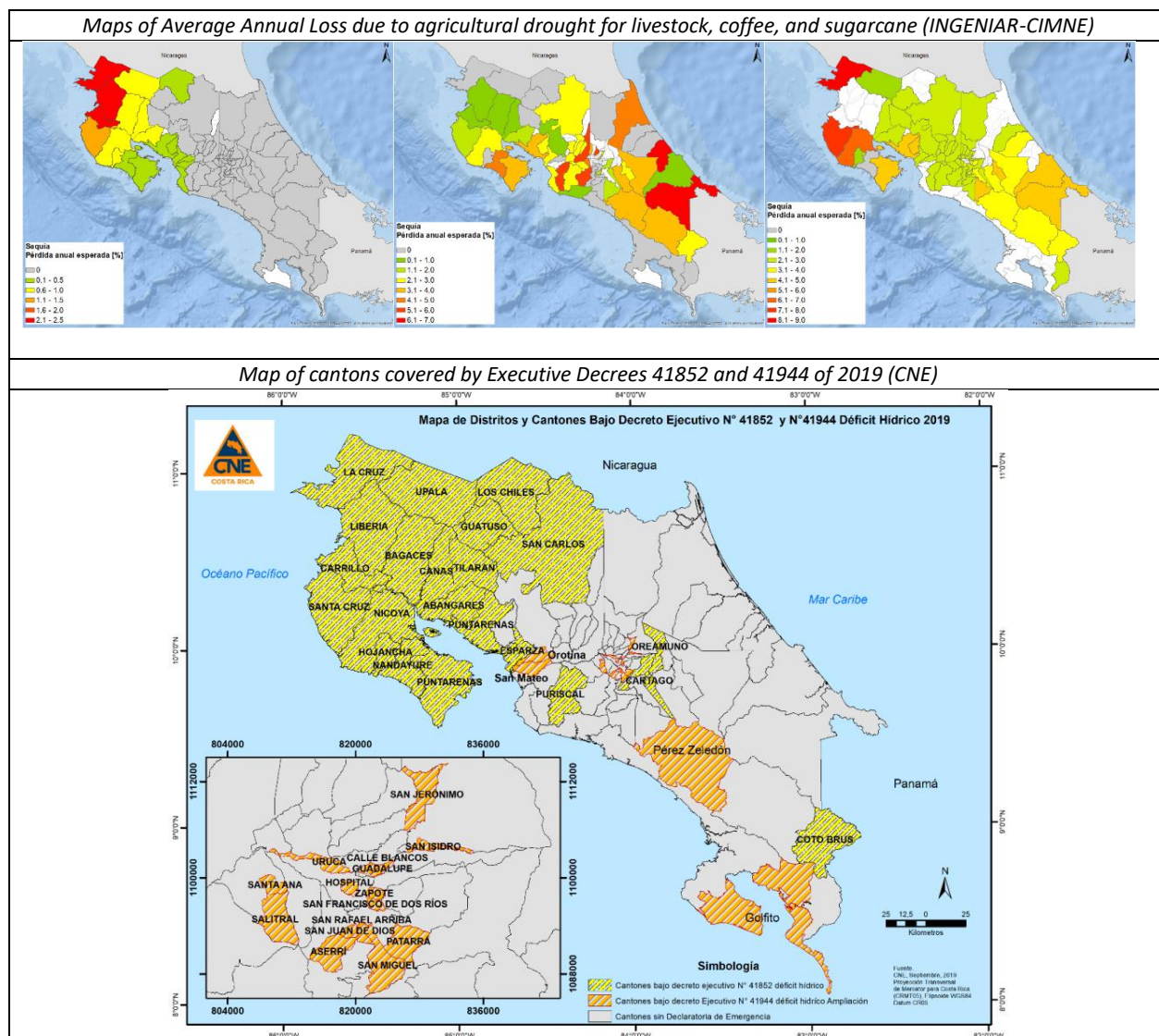


Figure 139. Comparison between AAL maps in the agricultural sector (INGENIAR-CIMNE) and the map of cantons affected by drought in 2019 (CNE).

When comparing the AAL maps for livestock, coffee, and sugarcane with the map of cantons included in the 2019 drought emergency declarations, it can be observed that, in general terms, the probabilistic results are able to reproduce spatial patterns consistent with the areas actually affected during that event. In particular, there is a notable correspondence in regions of the Northern Pacific and parts of the Central Pacific, where both high AAL values and inclusion in the emergency decrees reflect a greater susceptibility to drought impacts. Likewise, some areas in the southern part of the country show consistent signals across both approaches, although with variations depending on the productive sector analyzed, which is expected given the different sensitivities of each activity to water deficit.

However, this comparison must be interpreted with caution, as AAL maps do not represent a specific event, but rather the result of simulating thousands of plausible droughts, integrating their frequency and expected impact over time. In contrast, the map of cantons covered by emergency decrees corresponds

to a single specific episode—the 2019 event—and is conditioned by the climatic, social, and productive conditions of that moment. For this reason, although the observed spatial agreement provides confidence in the model’s ability to capture structural patterns of risk, the two products are not directly comparable, as one reflects long-term average risk while the other represents a specific realization of that risk.

Use of Risk Results as Validation Mechanism

The comparisons presented illustrate the inherent difficulty in implementing validation processes for probabilistic hazard estimates. While it is possible to identify similarities between existing sources of information, typically associated with past events, and hazard results, such comparisons are not direct and, therefore, are not sufficient to assess the adequacy of a probabilistic hazard modeling approach. Moreover, much of the available information generally refers to consequences rather than to the physical intensities of the phenomena, which makes it more appropriate to conduct comparisons in terms of risk rather than hazard. This is consistent with the approach presented in this document for the case of drought, although not through comparison with a specific event, but rather by evaluating the fit of the modeled severity–frequency relationship of losses against observed losses.

Therefore, the validation strategy adopted in this consultancy, and presented in detail in the risk assessment products of the projects that make up the GRMA program in Costa Rica, follows an approach focused on evaluating model performance at the level of risk results. The proposed validation is carried out using the method of hybrid Loss Exceedance Curves (LEC). This approach uses available historical loss data to assess the ability of the risk model to reproduce the observed relationship between loss magnitude and frequency of occurrence.

The hybrid LEC method allows for comparison between modeled and observed loss behavior within the range where empirical data exist, typically associated with high-frequency, low-to-moderate loss events. Achieving consistency in this domain strengthens confidence in the representation of the underlying processes within the model. Based on this foundation, the approach provides a structured framework to extrapolate the frequency–loss relationship into the domain of low-frequency, high-impact events, that is, extreme or catastrophic events that are not represented in historical records.

It is important to highlight that validation at the risk level implicitly captures the combined behavior of all model components. The loss exceedance curve reflects not only the quality of the hazard model, but also the adequacy of the exposure characterization and the realism of the vulnerability functions. Although this approach does not allow for isolating specific conditions within individual components, it ensures that the model is evaluated in terms of its ultimate objective: risk estimation.

A.8. CLIMATE HAZARDS DATASET

Como parte de los productos incluidos en este entregable, se estableció un repositorio web (Drive) para alojar todos los archivos de amenazas climáticas para Costa Rica, incluyendo sequía, inundación fluvial y pluvial, e inundación costera (por ciclones y tsunamis). Este repositorio compila los entregables D2.1a, D2.1b, D2.1c, D2.1d, D2.1e, D2.1f, D2.1g, D2.2a, D2.2b, D2.2c, D2.2d, D2.2e y D2.2f.

A continuación, se presenta la lista de los archivos que componen este conjunto de datos.

El enlace para acceder al dataset es:

<https://onedrive.live.com/?redeem=aHR0cHM6Ly8xZHJ2Lm1zL2YvYy85ZjZmNTQ4ZGFkMDc1MzQzL0VyTWNDRIkV3psTmdaZ0k2YTk5eWdNQIBINERfYThVTFV4QnN3Y2RFZi1ta3c%5FZT1qQ2RIZzU&id=9F6F548DAD075343%21s1a0ebc5a7f4a47f5abb1fa31022ed9ba&cid=9F6F548DAD075343&sb=name&sd=1>

Amenaza de inundación

Inundación Fluvial

Este directorio contiene archivos que representan la profundidad del agua, expresada en metros, para diferentes períodos de retorno.

File	Format	
Fluvial 100	.grd	.tif
Fluvial 1000	.grd	.tif
Fluvial 200	.grd	.tif
Fluvial 25	.grd	.tif
Fluvial 50	.grd	.tif
Fluvial 500	.grd	.tif

Los archivos con extensión *.grd son archivos de datos ráster generados y utilizados por el software Surfer, desarrollado por Golden Software. Estos archivos contienen una malla regular de valores numéricos que representan una variable continua en el espacio, típicamente utilizada para modelar superficies topográficas, distribuciones geofísicas o resultados de interpolaciones espaciales.

Los archivos *.tif representan la misma información espacial y los mismos valores que los archivos *.grd y se proporcionan en dos sistemas de referencia espacial: WGS 84 y CR-SIRGAS / CRTM05.

Inundación Heredia

Cauces

Los archivos incluidos corresponden a datos espaciales en formato shapefile (*.shp), georreferenciados en dos sistemas de coordenadas, que representan los cauces principales de Heredia.

File	Format
QuebradaSeca	.shp
QuebradaSeca_CRTM05	.shp

File	Format
RíoBermudez	.shp
RíoBermudez_CRTM05	.shp
RíoBurio	.shp
RíoBurio_CRTM05	.shp
RíoPirro	.shp
RíoPirro_CRTM05	.shp

Cuencas

Los archivos corresponden a datos espaciales en formato shapefile (*.shp), georreferenciados en dos sistemas de coordenadas, que representan las cuencas de los cauces principales de Heredia.

File	Format
Quebrada_Seca	.shp
QuebradaSeca_CRTM05	.shp
Río_Bermudez	.shp
Río_Bermudez_CRTM05	.shp
Río_Burio	.shp
Río_Burio_CRTM05	.shp
Río_Pirro	.shp
Río_Pirro_CRTM05	.shp

DEM

Estos archivos representan la elevación del terreno, expresada en metros sobre el nivel del mar, con una resolución espacial de 5 m.

File	Format
DEM_Heredia	.grd .tif

Los archivos se proporcionan en dos sistemas de referencia espacial: WGS 84 y CR-SIRGAS / CRTM05.

Inundación

Este directorio contiene archivos que representan la profundidad del agua, expresada en metros, para diferentes períodos de retorno.

File	Format
Tr100	.grd .tif
Tr1000	.grd .tif
Tr250	.grd .tif
Tr50	.grd .tif
Tr500	.grd .tif

Inundación Pluvial

Este directorio contiene archivos que representan la profundidad del agua, expresada en metros, para diferentes períodos de retorno.

File	Format	
Pluvial 100	.grd	.tif
Pluvial 1000	.grd	.tif
Pluvial 20	.grd	.tif
Pluvial 200	.grd	.tif
Pluvial 50	.grd	.tif
Pluvial 500	.grd	.tif

Modelo de elevación digital (DEM)

Estos archivos representan la elevación del terreno, expresada en metros sobre el nivel del mar, con una resolución espacial de 12.5 m.

File	Format
demCR	.tif
Dem_CR-SIRGAS	.tif

Amenaza de Inundación Costera

Amenaza

File	Format
Marea_CC	.shp
Marea_CC_CRTM05	.shp
Marea_Clima_base	.shp
Marea_Clima_base_CRTM05	.shp
Tsunami CR	.shp
Tsunami CR_CRTM05	.shp

Marea

Este directorio contiene los mapas de amenaza uniforme de altura de *run-up* generados por marejada ciclónica a lo largo de la costa de Costa Rica, para períodos de retorno de 50, 100, 250, 500 y 1000 años, bajo el escenario de clima base.

File	Format
Coastal 100 East	.grd
Coastal 100 West	.grd
Coastal 1000 East	.grd
Coastal 1000 West	.grd
Coastal 250 East	.grd
Coastal 250 West	.grd
Coastal 500 East	.grd
Coastal 500 West	.grd
CRTM05_Coastal 100 East	.tif
CRTM05_Coastal 100 West	.tif
CRTM05_Coastal 1000 East	.tif
CRTM05_Coastal 1000 West	.tif

File	Format
CRTM05_Coastal 250 East	.tif
CRTM05_Coastal 250 West	.tif
CRTM05_Coastal 500 East	.tif
CRTM05_Coastal 500 West	.tif
WGS84_Coastal 100 East	.tif
WGS84_Coastal 100 West	.tif
WGS84_Coastal 1000 East	.tif
WGS84_Coastal 1000 West	.tif
WGS84_Coastal 250 East	.tif
WGS84_Coastal 250 West	.tif
WGS84_Coastal 500 East	.tif
WGS84_Coastal 500 West	.tif

Batimetría

Este directorio contiene los datos batimétricos utilizados en el proyecto. El dataset corresponde a la versión 2024 de GEBCO (General Bathymetric Chart of the Oceans), que proporciona un modelo batimétrico global continuo con una resolución espacial de 15 segundos de arco, equivalente a aproximadamente 500 metros en el ecuador.

File	Format
Batimetria_CRI	.grd
gebco_2024_CRTM05	.tif
Gebco_2024_n12.0_s8.0_w-86.0_w-82.0	.tif

Topografía

Este directorio contiene los datos topográficos utilizados en el proyecto. La topografía corresponde a un dataset ráster con una resolución espacial de 12.5 m.

File	Format
DEM_CR_30m	.tif
DEM_CR_30m_CRTM05	.tif

Trayectorias

Este directorio contiene las trayectorias para las condiciones de clima base y los escenarios de cambio climático.

Amenaza de sequía

Indicadores de sequía

El presente dataset incluye dos archivos *.csv que contienen las series temporales de los indicadores de sequía meteorológica SPI-12 ("SPI 12 Simulated") y SPEI-12 ("SPEI 12 Simulated"), calculados bajo condiciones de clima base.

File	Format
SPEI 12 Simulated	.csv

SPI 12 Simulated	.csv
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Mapas de amenaza uniforme

El dataset incluye mapas de amenaza uniforme asociados a los indicadores de sequía SPI-12 y SPEI-12, calculados a una escala temporal de 12 meses. Los archivos se presentan en formato ráster GeoTIFF (*.tif) y contienen la representación espacial de los valores del índice correspondientes a diferentes períodos de retorno.

SPEI 12 Clima base

File	Format
speiTR10	.tif
speiTR10_CR-SIRGAS	.tif
speiTR100	.tif
speiTR100_CR-SIRGAS	.tif
speiTR1000	.tif
speiTR1000_CR-SIRGAS	.tif
speiTR2	.tif
speiTR2_CR-SIRGAS	.tif
speiTR25	.tif
speiTR25_CR-SIRGAS	.tif
speiTR250	.tif
speiTR250_CR-SIRGAS	.tif
speiTR5	.tif
speiTR5_CR-SIRGAS	.tif
speiTR50	.tif
speiTR50_CR-SIRGAS	.tif
speiTR500	.tif
speiTR500_CR-SIRGAS	.tif

SPI 12 Clima base

File	Format
spiTR10	.tif
spiTR10_CR-SIRGAS	.tif
spiTR100	.tif
spiTR100_CR-SIRGAS	.tif
spiTR1000	.tif
spiTR1000_CR-SIRGAS	.tif
spiTR2	.tif
spiTR2_CR-SIRGAS	.tif
spiTR25	.tif
spiTR25_CR-SIRGAS	.tif

File	Format
spiTR250	.tif
spiTR250_CR-SIRGAS	.tif
spiTR5	.tif
spiTR5_CR-SIRGAS	.tif
spiTR50	.tif
spiTR50_CR-SIRGAS	.tif
spiTR500	.tif
spiTR500_CR-SIRGAS	.tif

Modelación del Forzamiento Meteorológico

File	Format
Stations	.csv
Stations	.shp
BaseSimulations	.rar
CCSimulations	.rar

La carpeta comprimida *.rar contiene archivos correspondientes a 1.000 años de simulaciones climáticas diarias tanto para condiciones de clima base como para escenarios de cambio climático.

Anexo 2

Cada archivo contiene la comparación estadística diaria, mensual y anual entre la estación de tierra más cercana y el punto correspondiente en la malla climática para precipitación y temperatura.

File	Format
ppt_AEROPJUANSANTAMARIA_vs_P66	.xlsx
ppt_AEROPLIBERIAOESTE_vs_P30	.xlsx
ppt_AEROPLIMON_vs_P71	.xlsx
ppt_ALTAMIRA_vs_97	.xlsx
ppt_CANTAGALLO_vs_P48	.xlsx
ppt_CHIRRIPO_vs_P86	.xlsx
ppt_CIGEFI_vs_P67	.xlsx
ppt_COMANDOLOSCHILES_vs_P16	.xlsx
ppt_FABIOAUDRIT_vs_P66	.xlsx
ppt_FINCALACEIBA_vs_P52	.xlsx
ppt_HDAMOJICA_vs_P42	.xlsx
ppt_HITOYCERERE_vs_P80	.xlsx
ppt_IMNARANJUEZ_vs_P67	.xlsx
ppt_ITCRCARTAGO_vs_P68	.xlsx
ppt_LAREBUSCA_vs_P46	.xlsx
ppt_LASBRISSASSABALITO_vs_P98	.xlsx
ppt_PINDECO_vs_P91	.xlsx

File	Format
ppt_RECOPELAGARITA_vs_P66	.xlsx
ppt_RECOPEOCHOMOGO_vs_P68	.xlsx
ppt_SANTACRUZ_vs_P40	.xlsx
ppt_SIXAOLA_vs_P82	.xlsx
ppt_UPALA_vs_P23	.xlsx
tmed_AEROPJUANSANTAMARIA_vs_P66	.xlsx
tmed_AEROLIBERIAOESTE_vs_P30	.xlsx
tmed_AEROLIMON_vs_P71	.xlsx
tmed_ALTAMIRA_vs_97	.xlsx
tmed_CANTAGALLO_vs_P48	.xlsx
tmed_CHIRRIPO_vs_P86	.xlsx
tmed_CIGEFL_vs_P67	.xlsx
tmed_COMANDOLOSCHILES_vs_P16	.xlsx
tmed_FABIOAUDRIT_vs_P66	.xlsx
tmed_FINCALACEIBA_vs_P52	.xlsx
tmed_HDAMOJICA_vs_P42	.xlsx
tmed_HITOYCERERE_vs_P80	.xlsx
tmed_IMNARANJUEZ_vs_P67	.xlsx
tmed_ITCRCARTAGO_vs_P68	.xlsx
tmed_LAREBUSCA_vs_P46	.xlsx
tmed_LASBRISSASSABALITO_vs_P98	.xlsx
tmed_PINDECO_vs_P91	.xlsx
tmed_RECOPELAGARITA_vs_P66	.xlsx
tmed_RECOPEOCHOMOGO_vs_P68	.xlsx
tmed_SANTACRUZ_vs_P40	.xlsx
tmed_SIXAOLA_vs_P82	.xlsx
tmed_UPALA_vs_P23	.xlsx

Metadatos RDLS

Este directorio contiene los metadatos siguiendo el estándar Risk Data Library, proporcionando información estructurada para describir, organizar y asegurar la consistencia de los conjuntos de datos utilizados en el proyecto.

File	Format
Haz_CoastalFlood	.json
Haz_Drought	.json
Haz_Flood_fluvial	.json
Haz_Flood_Heredia	.json
Haz_Flood_pluvial	.json

El archivo *.json puede contener información relacionada con amenaza, exposición, vulnerabilidad o pérdidas, dependiendo del tipo de datos representados dentro del proyecto.