RESEARCH

Local-scale regionalisation of climate change effects on rainfall pattern: application to Alicante City (Spain)

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Abstract
Understanding the future patterns of precipitation behaviour in unique geographical areas, largely determined by their orography and local scale, can help lay the foundations for a new precipitation model for the design of the city's main urban drainage infrastructures (intensity-duration-frequency curves, mathematical functions that relate precipitation intensity to duration and frequency of occurrence, hereafter IDF, for the short-, medium- and long-term future). This will definitely contribute to the improvement of the city's resilience to the effects of climate change. In this paper, the projections of a subset of climate change models from both the sixth phase of the Coupled Model Intercomparison Project (CMIP6; with a total of 5 simulations) and Euro-CORDEX (for a set of 51 simulations) have been adjusted to the municipality of Alicante (in the southeast of Spain), using the Climadjust tool (climadjust.com). These projections contain different climatic variables. The rainfall variable has been used to derive a new framework of boundary conditions to help design more resilient infrastructure for torrential rainfall events and urban flooding. The projections corresponding to three climate change scenarios (CMIP6: SSP1-2.6, SSP2-4.5, SSP5-8.5; and Euro-CORDEX: RCP2.6, RCP4.5, RCP8.5) are considered with daily resolution and, by applying statistical techniques of temporal disaggregation (by means of a cascade model), hourly (and sub-hourly, reaching 30-min resolution) disaggregation. The results at hourly and 30-min resolutions are used to construct IDF curves of future climate, grouped into short-term (years 2015 to 2040), medium-term (years 2041 to 2070) and long-term (years 2071 to 2100) sub-scenarios. The selected future climate IDFs for an adverse climate change scenario (SSP2-4.5 and SSP5-8.5) show increases in rainfall intensities, higher the shorter the rainfall duration, for return periods greater than or equal to 25 years, whereas for return periods under 25 years the current IDFs can be representative of future scenarios. Current calculations and future projection of the torrentiality index for severe climate change scenarios, as well as the climate change factors, show an increase in the frequency and magnitude of the heaviest rainfall. This fact corroborates the hypotheses of greater general torrentiality in future rainfall in this specific area of the Spanish Mediterranean coast.

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1 Introduction

The Sixth Assessment Report (AR6) of the United Nations Intergovernmental Panel on Climate Change (IPCC) (IPCC (2021)) states that it is foreseeable, with a high level of confidence, that Mediterranean cities will experience more intense precipitation events in the coming years, combined with periods of drought aggravated by a general increase in temperatures. This means that, in general, the main extreme weather events (precipitation and temperature) will increase, particularly as the projected greenhouse gas emissions scenario becomes more unfavourable.

1.1 Background and patterns of the study area

The current process of climate change is a global problem that will have a direct impact, at regional and local level, on our cities, given that it will directly affect the integral water cycle and, in particular, urban drainage infrastructures, as precipitation patterns change (Zhou et al. (2012)).

In this context, the city of Alicante suffers very often from heavy rains that cause flooding. In recent decades, the analysis of the data provided by the Spanish Meteorological Agency (AEMET) shows that rains on 30 September 1997 (with 267 mm/24h and 101 mm/1h), 20 October 1982 (208 mm/24h and 82 mm/1h), 13 March 2017 (137 mm/24h and 45 mm/1h), 5 September 1989 (134 mm/24h and 57 mm/1h) and 27 September 2009 (125 mm/24h and 41 mm/1h) are particularly noteworthy. The rain events registered in 1982 and 1997 were particularly devastating, generating a big amount of material damages in the city and even loss of human lives.

In the report of the second IPCC working group (IPCC (2022)), future projections for precipitation in the Mediterranean region show decreases in most areas of between 4 and 22% depending on the emissions scenario considered (with medium confidence). In turn, precipitation extremes are expected to increase especially in the northern area of the region with a high level of confidence. Specific detailed studies are therefore needed to particularise the general starting assumptions to specific areas.

Normal precipitation pattern on the Spanish Mediterranean coast, the geographical area between the provinces of Girona and Malaga, including the Balearic archipelago is strongly conditioned by the atmospheric situations that bring humid winds from the Mediterranean Sea towards the Iberian peninsula (eastern component circulations), and this generates, fundamentally in the autumn and spring months, a high concentration of intense precipitation events, between the second half of September and the first half of November, with a tendency, in recent years, to

be brought forward to the end of August (Gil Olcina et al. (2004)). This Spanish Mediterranean coast is a strip with Mediterranean-type climatic features, and a direct influence of the contributions of humidity and calories from the Mediterranean Sea, which has experienced a notable temperature increase from 1980 to the present (Pastor et al. (2018)). This process is behind the origin of the increase in intense precipitation that has been recorded in recent years (Olcina-Cantos (2017), Tamayo-Carmona and Núñez Mora (2020)) and the increase in flooding episodes in this Spanish area (Ribas et al. (2020)).

On this area, annual rainfall decreases from north to south, towards the southeast of the Iberian Peninsula (south of Alicante, a large part of the region of Murcia and Almeria), to increase again on the lands of the Tropical Coast of Granada and the Costa del Sol up to the foothills of the Strait of Gibraltar, although the distribution of rainfall is clearly related to the presence and orientation of the mountain reliefs and the layout of the coastline (Olcina-Cantos & Moltó (2019)).

Climate models for this Spanish climate region predict changes in precipitation as a consequence of the continuous process of atmospheric warming that has effects here on seawater, which has been experiencing an increase in its surface temperature since the 1980s (Pastor et al. (2018)). This will entail changes in urban flooding patterns, which requires new knowledge and studies, both of possible impacts on cities and on the quality of life of citizens in this new scenario and of adaptation strategies to mitigate its effects. It is therefore imperative to predict the magnitude of the impacts of climate change on the hydrological cycle in order to design drainage systems adapted to the future, and to integrate the most recent strategies based on the implementation of green infrastructures with added positive impact on cities and their population (Kourtis et al., (2020)).

1.2 State-of-the-art of climate projections

With regard to the simulation of the factors conditioning climate change, the greater uncertainty related to precipitation with respect to other climate variables such as temperature or sea level rise requires local studies that apply techniques of temporal regionalisation and bias correction in order to obtain conclusive results (Martínez-Gomariz et al. (2019)). There are several studies and publications around the world where bias adjustment methodologies have been applied in recent years to obtain improved results in the match between real data and data simulated by climate models, adequately resolving the downscaling process between general circulation models (GCMs) and regional circulation models (RCMs) or local-scale models, as presented in Eum et al. (2020) for the specific case of Alberta (Canada), in Chen et al. (2013) for North America or in Maraun and Widmann

(2018) where a review and classification of various bias adjustment methods and downscaling processes is performed. These techniques, as stated in Kourtis et al. (2021), are essential for urban-scale studies.

Understanding the future patterns of precipitation behaviour in unique geographical areas, of a distinctly specific nature (largely determined by their orography) and local scale, as is the case of the city of Alicante (city taken as a pilot case in this study and located in south-eastern Spain), will help lay the foundations for a new precipitation model for the design of the city's main urban drainage infrastructures (intensity-duration-frequency curves, hereafter IDF, for the short-, medium- and long-term future). This will definitely contribute to the improvement of the city's resilience to the effects of climate change.

At the international level, the approach of relating the effects of climate change to an effective tool for the design of hydraulic infrastructures on a local scale, such as the IDF curves, has been addressed by several authors in various studies. In some of these cases, projections similar to those expected in this research were obtained, with increases in the design intensities associated with certain return periods, although the general trend in the study region is towards a decrease in total accumulated rainfall. Some examples can be found in Arnbjerg-Nielsen (2006) for the case of Denmark, where a clear trend of increasing 10-min precipitation intensities is obtained, both in frequency and in magnitude; Larsen et al. (2009) for a more general case in Europe, where it is stated that the main increases in extreme 1-h rainfall would occur in northern Europe versus southern Europe and where, for example in Spain, the return periods would be reduced from 20 years to 10 years for such rainfall; Peck et al. (2012) for the case of the city of London in Ontario (Canada), where the climate change scenarios analysed show increases in precipitation intensities of between 35 and 42% for short-duration, 100-year return period rainfall, with the intensities for this return period expected more frequently in the future; or Wang et al. (2013) in Florida (USA), where a study was carried out at different points in a hydrological basin, showing no significant changes in rainfall intensities for the 25-year return period in the upper and middle zones of the basin, but significant changes in the lower zone.

However, in Spain, similar studies have only been carried out in large Spanish capitals such as Madrid, Barcelona or Badalona (through their participation in the European Resccue project (https://toolkit.resccue.eu/)). For the specific case of the city of Madrid (Lastra de la Rubia et al. (2018)), a climate change coefficient related to the intensities for each duration and return period of the present and future climate (projected using the models and scenarios contained in the IPCC AR-5) was determined. The results, obtained in three time horizons of the future projection (short, medium and long term), show values above 1 in all the scenarios under analysis, which suggests that the expected future intensities will increase in the future. The averaged data from the different models used give coefficients around 1.10 or 1.15 for low return periods of between 2 and 5 years, or between 1.15 and 1.20 for higher return periods of between 10 years and 50 years.

In the case of Barcelona (Rodríguez et al. (2014)), the results showed great variability depending on the circulation model used (in this case, from the IPCC AR-4), and identified a trend of an increase in maximum daily intensity of between 1 and 4% for the year 2050 and a return period of 10 years. On the other hand, the variation obtained in the maximum hourly intensity yields values in the range of −4% and 12% for the same horizon year and return period, using this final maximum percentage (12%) as the criterion for maximising the design storm.

A recent study for the city of Badalona, also in Catalonia (Martínez-Gomariz et al. (2019)), has used the IDF curves of the neighbouring municipality of Barcelona to apply climate change models from the experiments of the European branch of the CORDEX project (http://www.cordex.org/), Euro-CORDEX. The results obtained in the short-term projections (2015–2024) found no significant changes in terms of precipitation intensity after climate change models were applied. However, the long-term projections (2051–2100) do show remarkable changes related to an increase in 24-h mean precipitation intensities for RCP 8.5 scenarios, as opposed to decreases in 24-h mean intensities for RCP 4.5 scenarios. Thus, the RCP 8.5 scenario is selected as representative for updating the climate change factor (understood as the percentage of variation between measured and projected intensities), resulting in average variation values of 15% for 2-year return period rainfall, 7% for 10-year rainfall, 2% for 100-year return period rainfall and 1% for 500-year return period rainfall.

1.3 Main objectives and contributions of the research

Given this background, the main objective of this research is to minimise the impact of climate change and to improve Alicante's resilience to extreme weather events derived therefrom, by means of a regionalised study on rainfall at a local scale and the subsequent study of urban flooding patterns. To this end, this research aims at characterising the future climate through:

- Obtaining local precipitation scenarios with daily resolution, by means of the analysis of the climate projection models contained in the "Coupled Model Intercomparison Project, 6th phase (CMIP-6)" (scenarios SSP-2.6, SSP-4.5 and SSP-8.5) and "Euro-Cordex" (scenarios RCP-2.6, RCP-4.5 and RCP-8.5).

- Obtaining local precipitation scenarios with hourly and sub-hourly resolution, aimed at descending to the hourly detail of projected future rainfall, using statistical time disaggregation techniques.

- Obtaining the characteristic IDF curve that sets the pattern of rainfall behaviour from historical data series provided by AEMET, as well as its future projection by applying climate change models.

- Obtaining the climate change factors (Larsen et al. (2009)) and the future torrentiality Index (Ministerio de Fomento de España (2019)).

This research is one of the first examples, at national and international level, of the application, in the field of urban drainage, of the new mathematical models and SSP scenarios proposed in the latest IPCC report (AR-6), CMIP-6, and their comparison with the models and scenarios proposed by the European Euro-CORDEX initiative.

A relevant aspect of this work is the use of the web tool Climadjust, which offers a reliable and scientifically validated process which allows any non-expert user to be guided through the complexities of climate projections. For easy processing, Climadjust provides access to state-of-the-art input data (such as CMIP-6 or EURO-CORDEX) coming from trusted sources like the Copernicus Climate Data Store or the Earth System Grid Federation. The tool allows combining these data with specific climate observations, to obtain climate projections (via https://climadjust.com).

The use of the torrentiality index specific to the city of Alicante, understood as the ratio between the hourly intensity and the corrected average daily intensity and the future projection of this index, is a new contribution of this paper and makes it possible to determine whether, under the various climate change scenarios considered, torrential rainfall will tend to increase. It has been possible to determine that torrentiality indices above 4 are representative of very intense (torrential) rainfall, based on observed data and real consequences in the city of Alicante. This is an important finding in this research work that defines a specific threshold for torrentiality in the city.

In addition, the use of the Wakeby probability distribution in the determination of the statistical adjustment of quantiles as a means to fit and represent extreme precipitation events is other contribution of this research work, as long as the use of statistical techniques for temporal downscaling and the evaluation of different techniques to select the most appropriate one. The calibration of the cascade method comparing precipitation distributions inferred and the observed with hourly series checking different statistical parameters is an important goal too.

2 Study area

Within the Mediterranean region, the Iberian Peninsula is, by itself, one of the regions in Europe with the greatest climate variability. The northern area with average annual rainfall of up to 2200 mm in the mountainous areas of northwest Portugal, northwest Navarre and southwest Galicia contrasts sharply with average annual values of less than 300 mm in the provinces of Almeria, Murcia and southern Alicante (Chazarra et al. (2018)).

Alicante province is located in a Mediterranean climatic context and has sub-humid (in the northern third) and semi-arid climate type (in the rest of the territory). The complex and rugged orography of this province, together with the degree of sea exposure, condition the distribution of rainfall. This fact gives rise to two main climatic areas, namely the northern area, with rainfall that can exceed 1000 mm/year (generally linked to short periods of heavy and abundant rainfall) and the central-southern area (characterised by a semi-arid environment in the lee of the Atlantic squalls, with average rainfall values of less than 300 mm/year) (https://ciclohidrico.com/recursos-hidricos/climatologia) (Fig. 1).

It is worth noting that the southern coastal area of the province, from the city of Alicante to the southern border of the province, is clearly exposed to strong easterly storms with winds of maritime origin, which are mainly linked to torrential rains in the area (Valdés & Úbeda (2021)). This is due to the layout of the coastline, which is favourable to the entry of these humid winds from the Mediterranean Sea (Martín Vide & Olcina-Cantos (2001)). These winds of maritime component are generated in cold drop atmospheric situations (500 hPa) that place cyclogenetic development on the surface that drive air from the sea towards the coast. In addition, the distribution of the mountainous reliefs allow the anchoring of the cloud systems over the reliefs and the development of abundant and intense rains in the flat areas of the province located between the mountains and the coast (Sánchez-Almodovar (2022); Khodayar et al. (2018) & Ferreira (2021)). In addition, it is in these flat areas where the highest percentage of the population living in the province and the most valuable economic activities are (tourism, logistics, intensive agriculture, etc.) (Olcina & Hernández (2021)).

The detailed study of the particular precipitation pattern of the Alicante city through the series of historical precipitation data collected at the observatory of the State Meteorological Agency (AEMET) in Ciudad Jardín (38.37°N, 0.49°W) shows that the accumulated annual precipitation in the period 1940–2020 has a perceptible tendency to be reduced over the years, from an average annual precipitation of 336.7 mm in the decade

Fig. 1 General location of the study area, Alicante City and the Spanish Meteorological Agency (AEMET) observatory in the city. Source: Own elaboration with base map extracted from IGN (National Geographical Institute of Spain)

1940–1950 to 345.2 mm in the decade 1950–1960, 322.4 mm in the decade 1960–1970, 380.1 mm in the decade 1970–1980, 372.1 mm in the decade 1980–1990, 257.3 mm in the decade 1990–2000, 303.7 mm in the decade 2000–2010 and 286.8 mm in the decade 2010–2020.

Furthermore, over the last 80 years in this local geographical context, on the one hand, there has been a trend towards a decrease in the accumulated annual rainfall, and on the other, a tendency towards an increase in heavier rainfall as opposed to moderate rainfall, which is beginning to suggest a change in the rainfall patterns typical of the municipality of Alicante (Fig. 2). However, the reduction in rainfall together with the increasingly frequent extreme events (of a heavy, very heavy or torrential nature) must be highlighted for the purposes of integrated water cycle management and planning of resilient infrastructures in the face of the increasingly common events of prolonged drought and flooding in the urban environment.

3 Materials and methods

To carry out the climate projection work regionalised to the municipality of Alicante, the Climadjust web tool (Sáenz de la Torre et al. (2021)) was used, in which a subset of climate change models from both the sixth phase of the Coupled Model Intercomparison Project (CMIP6; with a total of 5 simulations) and Euro-CORDEX (for a set of 51 simulations) were obtained. These projections contain different climate variables, the precipitation variable has been used in this study and three climate change scenarios have been considered (for CMIP-6: SSP1-2.6, SSP2-4.5, SSP5-8.5; and for Euro-CORDEX: RCP2.6, RCP4.5, RCP8.5) with daily resolution and hourly resolution by means of temporal disaggregation techniques.

The Euro-CORDEX ensemble is made with the entire combination of historical-future climate projections available in the Climate Data Store: https://cds.climate.coper
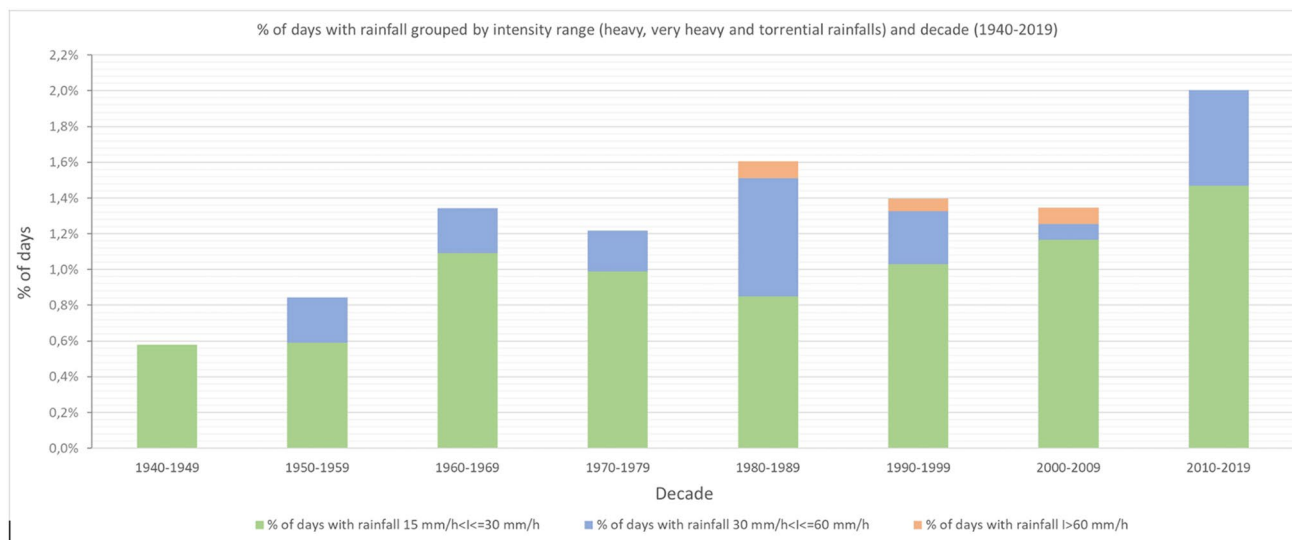
Fig. 2 Percentage of days with heavy, very heavy and torrential rainfall intensities grouped by decades, according to AEMET classification. Source: Own elaboration with AEMET (Ciudad Jardín) data

nicus.eu/cdsapp#!/dataset/projections-cordex-domains-single-levels?tab=overview

On the date when data was downloaded, 51 simulations were available for the historical and RCP8.5 scenarios, being this number reduced for the RCP2.6 and RCP4.5 scenarios. The data is provided in daily resolution with a temporal coverage which ranges, depending on the model, from 1970 to 2005. The spatial coverage covers the entire European region with a resolution of 0.11°.

For the CMIP6 data, an ensemble of 5 models was chosen based on the specifications provided by the ISIMIP3 protocol (https://protocol.isimip.org/#31-climate-related-forcing).

These are the 5 models which more properly represent the climate variability. Their temporal coverage is common and ranges from 1950 to 2015 in a daily resolution, while the spatial coverage is global with a non-common spatial resolution which depends on the model, being approximately 1° resolution for all models.

As regards the data source used for the adjustment of precipitation for the GCMs, the historical data series recorded in the official observatory belonging to the AEMET in the city of Alicante, in the period between 1938 and 2021 (83 years), have been used to build an historical scenario. Based on these historical series, bias adjustment techniques have been applied to obtain climate projections for the city.

Statistical time disaggregation techniques have been then used to obtain hourly precipitation series from the daily series and, from these, IDF curves of future climate have been designed. These IDF future climate curves are grouped into three different scenarios; short term (years 2015 to 2040), medium term (years 2041 to 2070) and long term (years 2071 to 2100).

There is a discussion on the selection of the models that best fit the climatic particularities of the municipality of Alicante, comparing the IDF curves of the present climate (historical observed series) with the analyses carried out with the regionalised GCMs under study using their so-called historical scenario.

In addition, a climate change factor and a torrential rainfall index have been calculated and projected to the future climate, which will make it possible to determine the evolution of rainfall considered as torrential, on a local scale, under the climate change hypotheses described above.

3.1 Local precipitation scenarios with daily resolution

The local precipitation scenarios are obtained by analysing the climate projections from two different sources:

- Coupled Model Intercomparison Project, 6th phase (CMIP-6), monitored under the World Climate Research Programme, for a set of 5 simulations.

  - MPI-ESM1-2-HR_r1i1p1f1 (Jungclaus et al. (2019))
  - GFDL-ESM4_r1i1p1f1 (Krasting et al. (2018))
  - MRI-ESM2-0_r1i1p1f1 (Yukimoto et al. (2019))
  - IPSL-CM6A-LR_r1i1p1f1 (Boucher et al. (2018))
  - UKESM1-0-LL_r1i1p1f2 (Tang et al. (2019))

The climate scenarios considered in the case of CMIP-6 projections will be those from the historical database, SSP1-2.6, SSP2-4.5 and SSP5-8.5, with projections up to the year 2100.

• Euro-CORDEX, sponsored by the World Climate Research Programme (WRCP), for a set of 51 simulations available online (via https://www.euro-cordex.net/imperia/md/content/csc/cordex/20180130-eurocordex-simulations.pdf).

The climate scenarios considered in the case of the Euro-CORDEX projections will be those from the historical database, RCP2.6, RCP4.5 and RCP8.5, with projections up to the year 2100.

On the basis of precise knowledge of the historical rainfall in the city of Alicante, precipitation projections are afterwards adjusted by using the following statistical bias adjustment techniques:

- Empirical quantile mapping (EQM): consists of calibrating the simulated cumulative distribution function by adding to the observed quantiles both the mean delta change and the individual delta changes in the corresponding quantiles (Maraun (2013); Déqué (2007)).

- Inter-Sectoral Impact Model Intercomparison Project, version 3 (ISIMIP3): sophisticated method where for each quantile, the simulated climate change signal of each quantile is transferred to the historical observations. In addition, it allows time series detrending to finally restore the trends. It also replaces values beyond thresholds by random numbers, adjusts marginal distributions for every variable and replaces values beyond thresholds by the respective bound. It has been the method used in the Atlas Chapter of the latest IPCC Assessment Report (Lange (2019)).

The goodness of fit using both bias adjustment techniques is obtained by determining, on the basis of the IDF curve constructed from the adjustment of historical data provided by AEMET, which of the 5 regionalised climate projection models for the municipality of Alicante extracted from the CMIP-6 experiments provides a better adjustment to the historical data. To this end, the percentage variations in intensity (mm/h) for return periods (T) of 5, 25 and 50 years and rainfall durations of 0.5, 1 and 2 h are compared for each model, with the ISIMIP3 and EQM adjustment methods (Table 1).

When comparing both bias adjustment methods, it is clearly observed that the EQM adjustment methodology tends to underestimate the intensity values for any duration and return period, whereas the adjustment values obtained by ISIMIP-3 are more precisely adapted and are mostly always on the safe side (over-adjustments). For this reason, ISIMIP3 bias adjustment methodology is determined to be better adapted to the climatic particularities observed in the municipality of Alicante.

3.2 Local precipitation scenarios with hourly resolution: temporal downscaling

Once the raw and bias adjusted climate projections (by means of the Climadjust tool) with daily resolution have

Table 1 Percentages of variation between the intensity data adjusted with historical data and the data provided by the models of the CMIP-6 experiments for rainfall durations of 0.5h, 1h and 2h and return periods of 5 years, 25 years and 50 years. Source: Own elaboration

Model: MPI-ESM1-2-HR_r1i1p1f1

Bias adjustment method: ISIMIP-3	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	4%	-2%	-5%
t=1h	5%	6%	4%
t=2h	14%	5%	7%

Bias adjustment method: EQM	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	-36%	-45%	-47%
t=1h	-37%	-45%	-48%
t=2h	-36%	-50%	-51%

Model: GFDL-ESM4_r1i1p1f1

Bias adjustment method: ISIMIP-3	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	27%	36%	27%
t=1h	26%	29%	37%
t=2h	36%	32%	40%

Bias adjustment method: EQM	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	-42%	-48%	-50%
t=1h	-39%	-48%	-51%
t=2h	-36%	-50%	-51%

Model: MRI-ESM2-0_r1i1p1f1

Bias adjustment method: ISIMIP-3	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	5%	0%	0%
t=1h	8%	11%	11%
t=2h	18%	16%	19%

Bias adjustment method: EQM	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	-36%	-46%	-48%
t=1h	-37%	-45%	-48%
t=2h	-36%	-50%	-51%

Model: IPSL-CM6A-LR_r1i1p1f1

Bias adjustment method: ISIMIP-3	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	22%	28%	32%
t=1h	26%	40%	44%
t=2h	23%	32%	40%

Bias adjustment method: EQM	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	-42%	-51%	-52%
t=1h	-45%	-50%	-52%
t=2h	-36%	-50%	-51%

Model: UKESM1-0-LL_r1i1p1f2

Bias adjustment method: ISIMIP-3	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	55%	74%	82%
t=1h	45%	77%	78%
t=2h	82%	58%	63%

Bias adjustment method: EQM	T5	T25	T50
diff.%	T5	T25	T50
t=0.5h	-38%	-47%	-49%
t=1h	-39%	-48%	-51%
t=2h	-36%	-50%	-51%

been obtained, it is interesting to go down to hourly and sub-hourly detail in order to relate the data obtained to hydraulic/hydrological simulation tools. To this end, statistical temporal disaggregation techniques are used to obtain hourly precipitation series, following as a reference the work proposed by Förster et al. (2016) and Breinl and Di Baldassarre (2019).

In order to choose the most appropriate temporal disaggregation technique for the characteristics of the probability distribution function corresponding to the hourly series in Alicante, an evaluation process is carried out using the daily and hourly series observed. In this way, the daily data are disaggregated and the results are compared with the original hourly data. In the evaluation of the techniques, special attention is paid to the representativeness of the high percentiles of the distribution, corresponding to heavy rainfall events.

The open-source software package MELODIST (Förster et al. (2016)) has been used to perform the temporal downscaling process, selecting the "cascade model" method (Olsson (1998)). The calibration of the cascade model method involves estimating the parameters of the statistical models used to describe the temporal structure and conditional distributions of precipitation occurrence and amount at different temporal scales. This is typically done using historical data, where both daily and hourly precipitation time series are available. The hourly observations from 2003 to 2021 were used to perform this calibration, separating 1 year of data to perform a validation study. In this brief validation study, it was checked that the different statistical parameters (mean, percentiles 75, 90, 95 and 99, maximum, etc.) of the precipitation distributions were similar between the inferred and the observed hourly series.

As a result of this study, hourly data series of the climate projection for the present and future climate and IDF curves of the climate projections for the present and future climate have been obtained for the CMIP-6 and Euro-CORDEX projects.

3.3 Methodology for statistical adjustment of quantiles associated with various durations and generalisation of IDF curves

The distribution traditionally used for the analysis of extreme events such as return periods (T) associated with maximum daily precipitation is the Gumbel distribution (Elías Castillo & Ruiz Beltrán (1979)). However, this distribution tends to underestimate the precipitation values associated with high return periods, since its adjustment is very resistant to the addition of new extreme data to the study; in other words, it results in very inflexible distributions that may pose some adjustment issues regarding

complex distributions. This is why other statistical distributions have emerged as logical alternatives to the one mentioned above, such as the general extreme value distribution based on 3 parameters or the SQRT-ETmax, Etoh and Murota (1986), which is based on 2 parameters and is relatively simple to apply.

In order to address the problem of rigidity in the adjustment, it has been decided to include in the study a much more general probability distribution based on a larger number of parameters in order to observe their validity with respect to the previous ones. The models with the greatest flexibility of adjustment include the 4-parameter Kappa distribution and the 5-parameter Wakeby distribution. The latter is known to fit any type of existing distribution (Cutillas (2015)) and responds to Eq. 1.

$$P(T) = -aT^{-b} + cT^{-d} + e \tag{1}$$

where "a", "b", "c", "d" and "e" are parameters and "T" is the return period. The value of the parameters is determined taking into account the restrictions indicated in Landwehr et al. (1987), in an iterative process.

It should be noted that this statistical adjustment proposal is contrary to the principle of statistical parsimony (which relates the robustness of a method to its simplicity of application). However, it is considered interesting since this study aims to give as much relevance as possible to extreme events and these are better represented by a more flexible (and more complex) adjustment. Looking at the correlation coefficients obtained in the five adjustment methodologies used, all of them have an adequate goodness-of-fit, although the Wakeby distribution is particularly good (Hamed & Rao (2000)).

As presented in Fig. 3, the Gumbel and SQRT-ETmáx. distributions have been fitted by the method of moments and maximum likelihood estimation and compared with the Wakeby iterative fit.

The use of the Wakeby probability distribution to fit and represent extreme events is one of the contributions of this research work.

Once the different quantiles associated with each rainfall duration were obtained, the method of adjustment and generalisation of the IDF curves used has been that proposed by Talbot (Gómez Valentín (2007)) (one of the most widely used and simple to implement), which proposes a hyperbolic adjustment based on only two parameters, as is represented in Eq. 2.

$$I = A(T)/(D + B(T)) \tag{2}$$

where "I" is the intensity in mm/h, "D" is the duration of the rainfall in minutes, "T" is the return period in years and "A" and "B" are the setting parameters determined by linear regression.
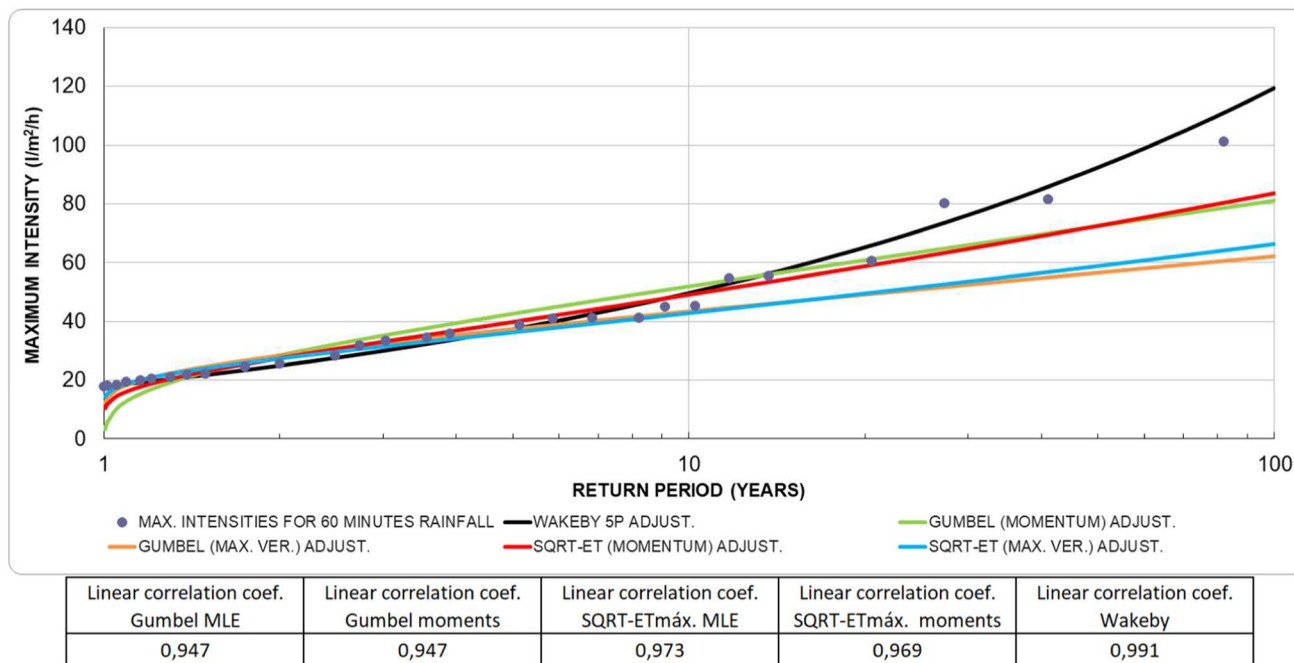
Fig. 3 Statistical adjustment for the different extreme distributions for 60-min rainfalls, in the period 1938–2020 and results of the correlation coefficient. Source: Own elaboration with AEMET meteorological data

3.4 Torrentiality index and climate change factor

The torrentiality index specific to the city of Alicante, understood as the ratio between the hourly intensity and the corrected average daily intensity, as expressed in Ministerio de Fomento de España (2019), makes it possible to characterise the frequency and intensity of extreme precipitation events. To determine this index, the average rainfall on days with values greater than 1 mm (in 30-year periods) was calculated and the hourly rainfall series was divided by the value of the constant obtained in the previous step.

The objective of this methodology is to identify hourly intervals where it rains above the normal daily value on a rainy day. The future projection of this index is a new contribution of this paper and makes it possible to determine whether, under the various climate change scenarios considered, torrential rainfall will tend to increase.

The climate change factor means the percentage variation between measured and projected intensities for the future climate as expressed in Larsen et al. (2009). If the climate change factor is above 1, the projected intensities will be higher than the intensities obtained from historical data, and the change factor will become more pronounced as it moves away from 1.

4 Results

An assessment has been performed by analysing the climate projections derived from both the CMIP-6 and Euro-COR-DEX experiments, with daily and hourly temporal resolution. The main results are shown below for the rainfall variable.

4.1 Results with daily resolution

The results obtained for the adjusted projections of the experiments derived from the CMIP-6 and Euro-CORDEX initiatives are presented below, showing the regionalised projections of the variable "mean annual precipitation" (Figs. 4 and 5) and "number of days per year with precipitation above 1 mm" (Figs. 6 and 7).

The averaged results of the different models of both experiments show similar results, somewhat more pronounced in the case of the CMIP-6 models, with a decrease in the average annual rainfall expected for the year 2100 compared to the present in the city of Alicante; the worse the climate change scenario, the greater the decrease.

With regard to the results obtained in relation to days with precipitation above 1 mm per year, the three climate
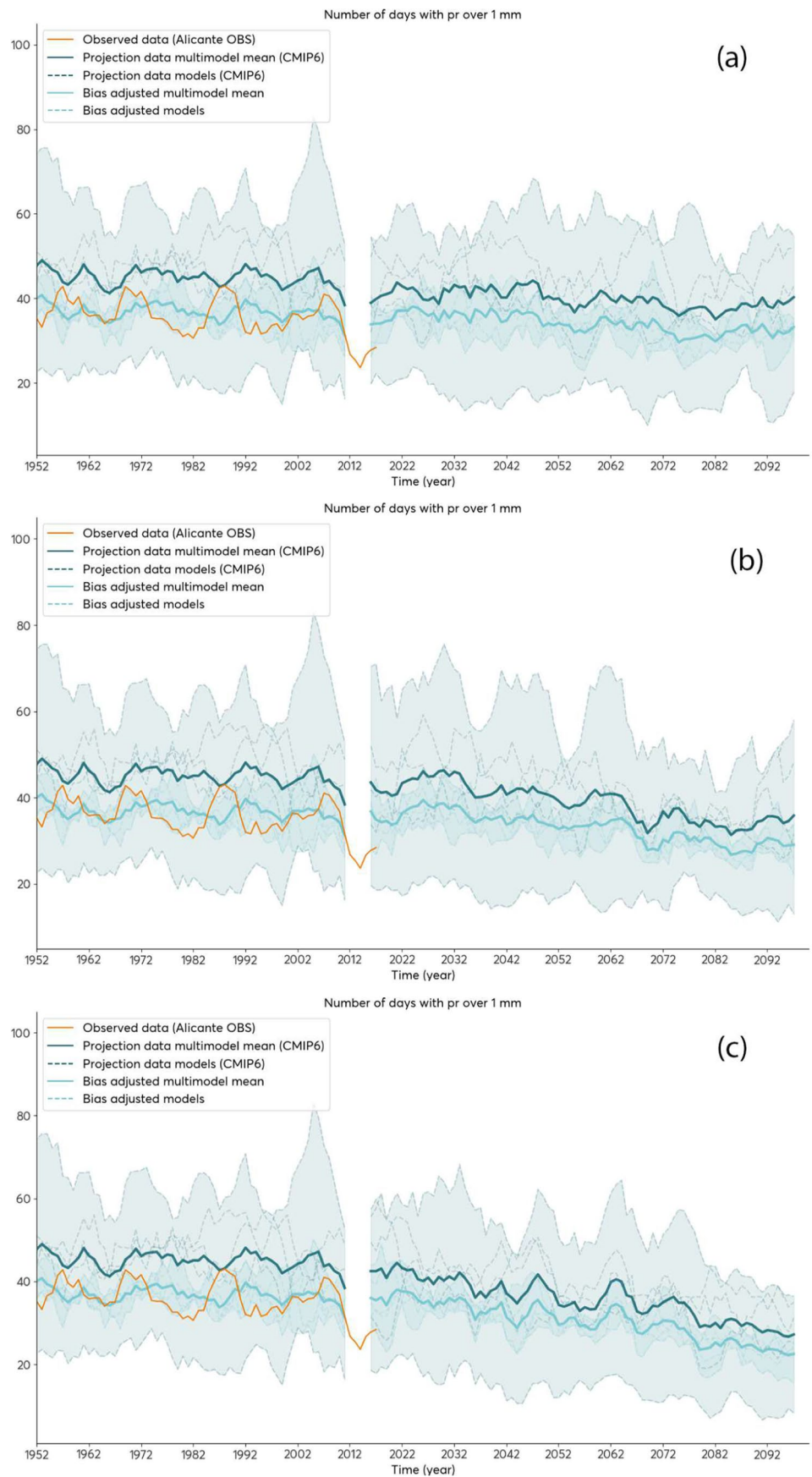
Fig. 4 Regionalised projections
of the variable "mean annual
precipitation" for each CMIP-6
model, as well as the ensem-
ble mean (dark blue line) for
the bias-adjusted results (light
blue line) and the original data
(orange line), for the historical
scenarios (1950–2015) and for
each future climate scenario, **a**
SSP1-2.6, **b** SSP2-4.5, **c** SSP5-
8.5, over the period 2015–2100.
Source: Own elaboration
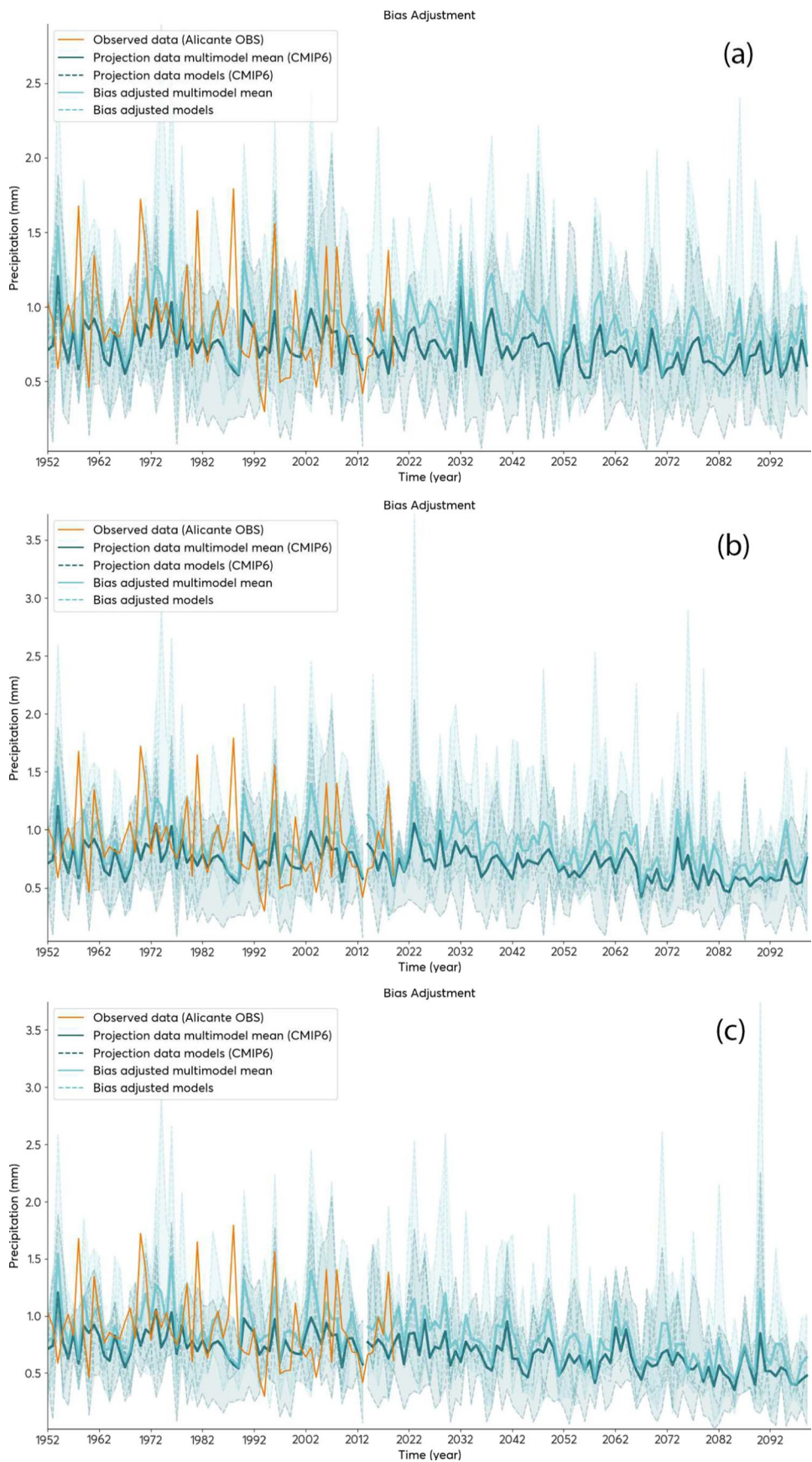
Fig. 5 Regionalised projections of the variable "mean annual precipitation" for Euro-CORDEX model, as well as the ensemble mean (dark blue line) for the bias-adjusted results (light blue line) and the original data (orange line), for the historical scenarios (1950–2015) and for each future climate scenario, **a** RCP2.6, **b** RCP4.5, **c** RCP8.5, over the period 2015–2100. Source: Own elaboration
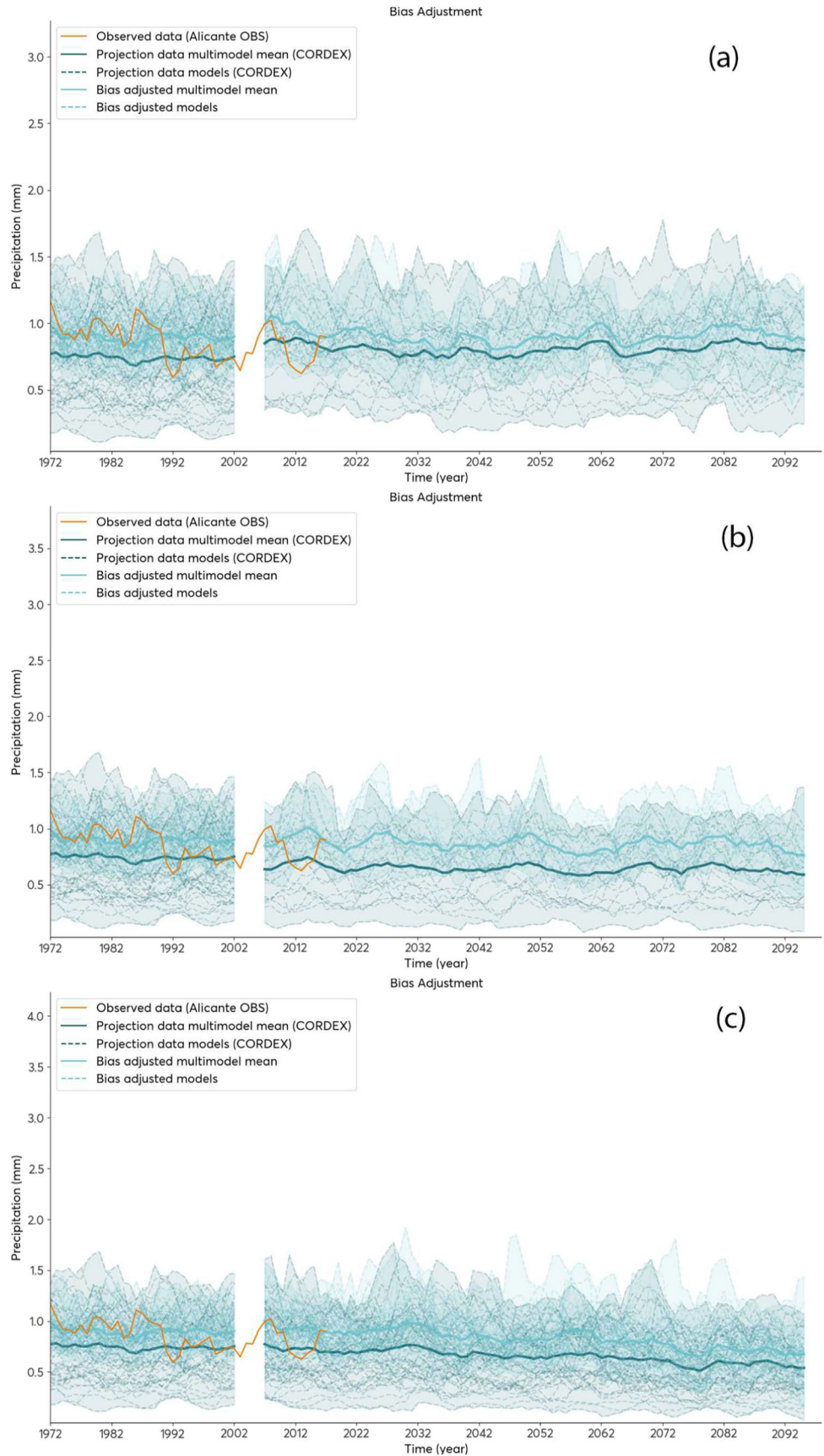
Fig. 6 Regionalised projections of the variable "number of days per year with precipitation above 1 mm" for CMIP-6 model, as well as the ensemble mean (dark blue line) for the bias-adjusted results (light blue line) and the original data (orange line), for the historical scenarios (1950–2015) and for each future climate scenario, **a** SSP1-2.6, **b** SSP2-4.5 and **c** SSP5-8.5, over the period 2015–2100. Source: Own elaboration

Fig. 7 Regionalised projections of the variable "number of days per year with precipitation above 1 mm" for Euro-CORDEX model, as well as the ensemble mean (dark blue line) for the bias-adjusted results (light blue line) and the original data (orange line), for the historical scenarios (1950–2015) and for each future climate scenario, **a** RCP2.6, **b** RCP4.5 and **c** RCP8.5, over the period 2015–2100. Source: Own elaboration
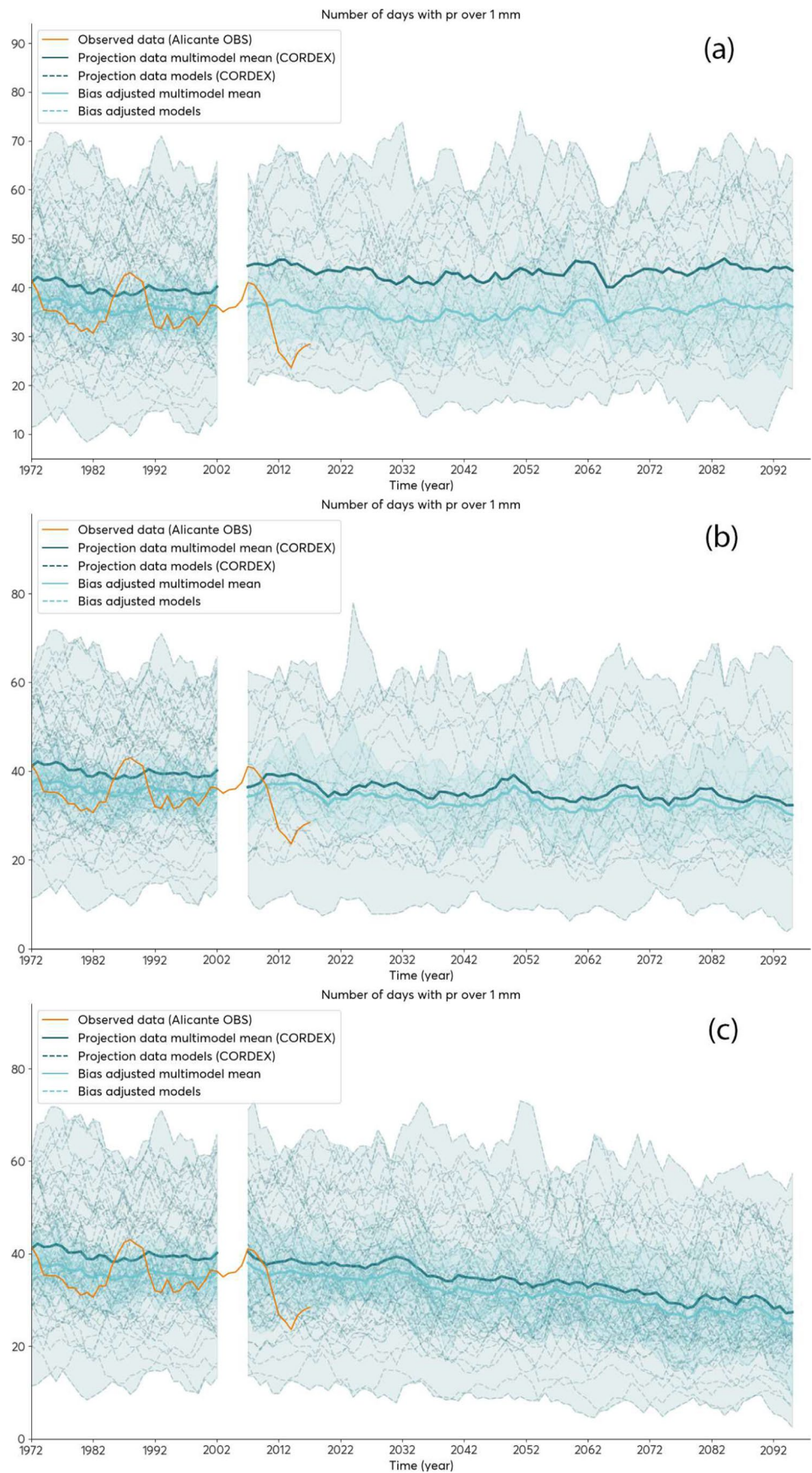
change scenarios considered in the analysis of future precipitation projections from the CMIP-6 and Euro-CORDEX experiments converge in determining a decrease in the number of days for the year 2100 compared to the average of the historical series; the worse the climate change scenario, the greater the decrease.

4.2 Results with hourly resolution: intensity-duration-frequency curves

Obtaining the intensity-duration-frequency curves requires a previous process of temporal downscaling. This new statistical treatment of the data, combined with the application of the different projection models, results in a high variability in the adjustment of IDF curve results for each of them.

For this reason, based on the IDF curve extracted from the adjustment of historical data provided by AEMET, it is studied which of the 5 climate projection models regionalised to the municipality of Alicante from the CMIP-6 initiative and which of the 51 models from the Euro-CORDEX initiative provide a better adjustment to these data, considering the historical scenario for them. For this purpose, the percentage variations in intensity (mm/h) are compared for the return periods analysed of 2, 5, 10, 25, 50 and 100 years and durations between 0.5 and 5 h (in 5-min intervals) and the error by excess and default is averaged for all rainfall durations in each return period.

Thus, it is found that the models belonging to CMIP-6 that best fit the IDF curves generated with historical data are as follows:

• MPI-ESM1-2-HR_r1i1p1f1 (Max Planck Institute for Meteorology), with an average error by excess of 13% and by default of 6%.

• MRI-ESM2-0_r1i1p1f1 (Meteorological Research Institute), with an average error by excess of 18% and by default of 5%.

Both adjusted using the ISIMIP3 method, which provides better adjustments than those provided by the EQM methodology.

Of these models, it has been used the one developed by the Max Planck Institute, since the deviations provided for high return periods are lower than those obtained in the model developed by the Japanese Meteorological Research Institute, and it is precisely these intensities associated with torrential rainfall that are of most interest in this research.

For the 51 models analysed belonging to the Euro-CORDEX initiative, the following models were selected:

• CCCma-CanESM2_r1i1p1_CLMcom-CCLM4-8-17: For return periods less than T10 (with an average error by excess of 20% and by default of 4%).

• MPI-M-MPI-ESM-LR_r1i1p1_CLMcom-ETH-COSMO-crCLIM-v1: For return periods greater than or equal to T10 (with an average error by excess of 19% and by default of 3%).

Both models were developed by the Climate Limited-area Modelling Community (CLM-Community).

Figure 8 shows the IDF curves obtained from the application of the MPI-ESM1-2-HR_r1i1p1f1 (CMIP-6) and CCCma-CanESM2_r1i1p1_CLMcom-CCLM4-8-17 for return periods lower than T10 and MPI-M-MPI-ESM-LR_r1i1p1_CLMcom-ETH-COSMO-crCLIM-v1 for return periods greater than or equal to T10 (Euro-CORDEX) in the historical scenario, and are compared with the historical IDF curves of the city of Alicante, in order to visualise their goodness of fit together.

The models selected in both the CMIP-6 and Euro-CORDEX experiments tend to slightly underestimate the intensities associated with rainfall of short duration for almost all

Fig. 8 IDFs obtained using the selected models of CMIP-6 and Euro-CORDEX in the historical scenario, compared with the historical IDF curves of the city of Alicante (AEMET). Source: Own elaboration
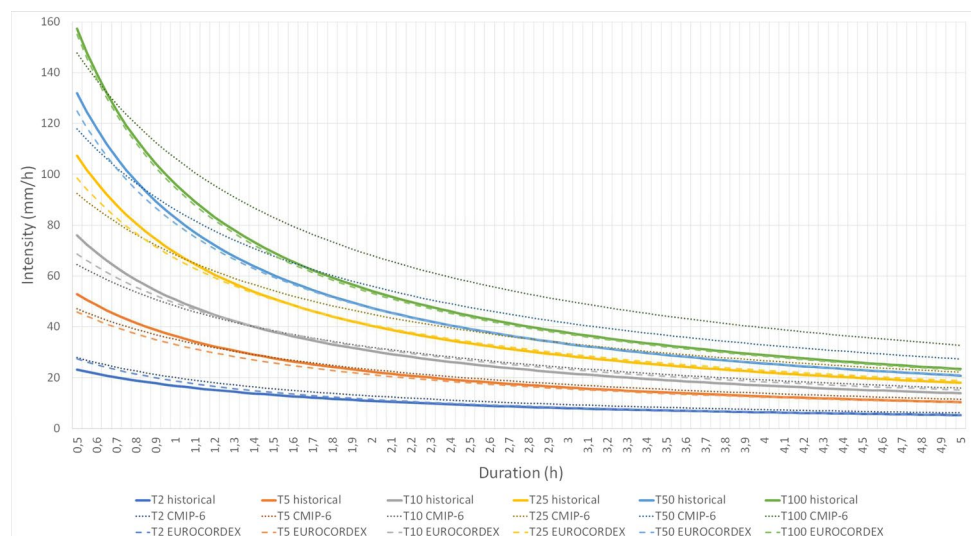
the return periods analysed (except for $T = 2$ years), whereas there is a clear tendency on the part of the selected CMIP-6 model to overestimate the intensities associated with rainfall of durations of more than 1 h for return periods greater than or equal to 25 years. However, this overestimation is maximum for $T = 100$ years and does not exceed 10 mm/h, so it is considered an adequate adjustment. In addition, the use of a combination of two Euro-CORDEX models yields very accurate adjustment values in the historical comparison for all the return periods and durations studied.

The selection of the optimal models for this study will be determined not only by their ability to adapt and reproduce historical data, but also by the results obtained in the forward projections under the different climate change scenarios.

To do this, the results of the short- (2015–2040), medium- (2040–2070) and long-term (2070–2100) climate projections for the SSP5-8.5 scenarios (shared socio-economic trajectory scenario based on social and economic development that unequivocally requires fossil fuels to be achieved (O'Neill et al. (2014))) in the case of the CMIP-6 experiments and RCP 8.5 (scenario that reflects a situation in which the population grows while economic growth is slow, with moderate rates of technological change and improvements in energy intensity, leading in the long run to high energy demand and GHG emissions in the absence of climate change policies (Riahi (2011))) for those of Euro-CORDEX have been compared with projection results obtained in other local experiences in Spain, the maximum intensities obtained in the projections have been compared with the maximum historical results and the climate change factor has been evaluated.

Given the baseline assumptions, it might be expected that, in both cases, the long-term scenarios would show an increase in the most extreme conditions. However, it is observed in the two representations that this is not necessarily the case, and statistical artefacts arise mainly due to two factors; historical data are used to train the temporal disaggregation model, which causes, in principle, the number of extreme events in the future projections to have a similar characterisation to that of past events, combined with the fact that, as seen above, the mean daily precipitation is used to train the temporal disaggregation model, which decreases as the scenario worsens and as time progresses.

Therefore, in order to assess the best adaptation model, the envelope of maximum and minimum intensity values for the short, medium and long term obtained in the SSP5-8.5 or RCP8.5 scenario has been determined, and in this way the area of probable values of future rainfall intensity for each rainfall duration has been generated and compared with the historical values, resulting in the following graphs, for the return periods of 5, 25 and 50 years (Figs. 9 and 10).

The selected models from both experiments perform a similar adjustment for low and medium return periods (up

to $T = 25$ years), with a larger range of variability in the models belonging to Euro-CORDEX. The largest differences are obtained for longer return periods (from $T = 50$ years) and lower rainfall durations, which are also the most interesting, as they represent the most extreme or torrential rainfall.

## 4.3 Results with hourly resolution: torrentiality index and climate change factor

The torrentiality index specific to the city of Alicante makes it possible to characterise the frequency and intensity of extreme (or torrential) precipitation events. To determine this index, the average rainfall on days with values greater than 1 mm (in 30-year periods) was calculated and the hourly rainfall series was divided by the value of the constant obtained in the previous step (the 1-mm threshold evaluates and compares the torrentiality index with the most common rainfall events. A higher threshold will have influence in the average daily intensity of the historical series that would increase, and subsequently the coefficient of torrentiality would decrease, since the most common rains will not be considered, but normal weather would be characterised only with intense rainfall).

The projection to the future climate has been made on the basis of the most suitable climate projection model previously selected.

However, as a preliminary step to the projection of this indicator, the amount of precipitation in the historical precipitation events of the data series between the years 2003 to 2020 (most recent data) has been evaluated. The index values show that the highest hourly rainfall intensity does not necessarily correspond to the most torrential rainfall based on this indicator; however, it is possible to determine that torrentiality indices above 4 are representative of very intense (torrential) rainfall, based on observed data and real consequences in the city of Alicante. This is an important finding in this research work that defines a specific threshold for torrentiality in the city (Fig. 11).

Once this characteristic threshold of rainfall with the highest torrential rainfall index has been identified, the future projection of this index is obtained, focusing on the month of each year with the highest probability of occurrence of torrential rainfall, that is, the month of September (according to AEMET information via https://www.aemet.es/es/serviciosclimaticos), for each of the climate change scenarios analysed in the CMIP-6 experiment. The worst-case scenarios (representing greater influence from climate change) SSP-2 4.5 and SSP-5 8.5 show, respectively, a higher frequency of occurrence of precipitation events with higher torrentiality index (value above 4) and a higher value of torrentiality index in more specific events (Fig. 12).

The average torrential index values expected for the most unfavourable climate change scenarios (with a value of
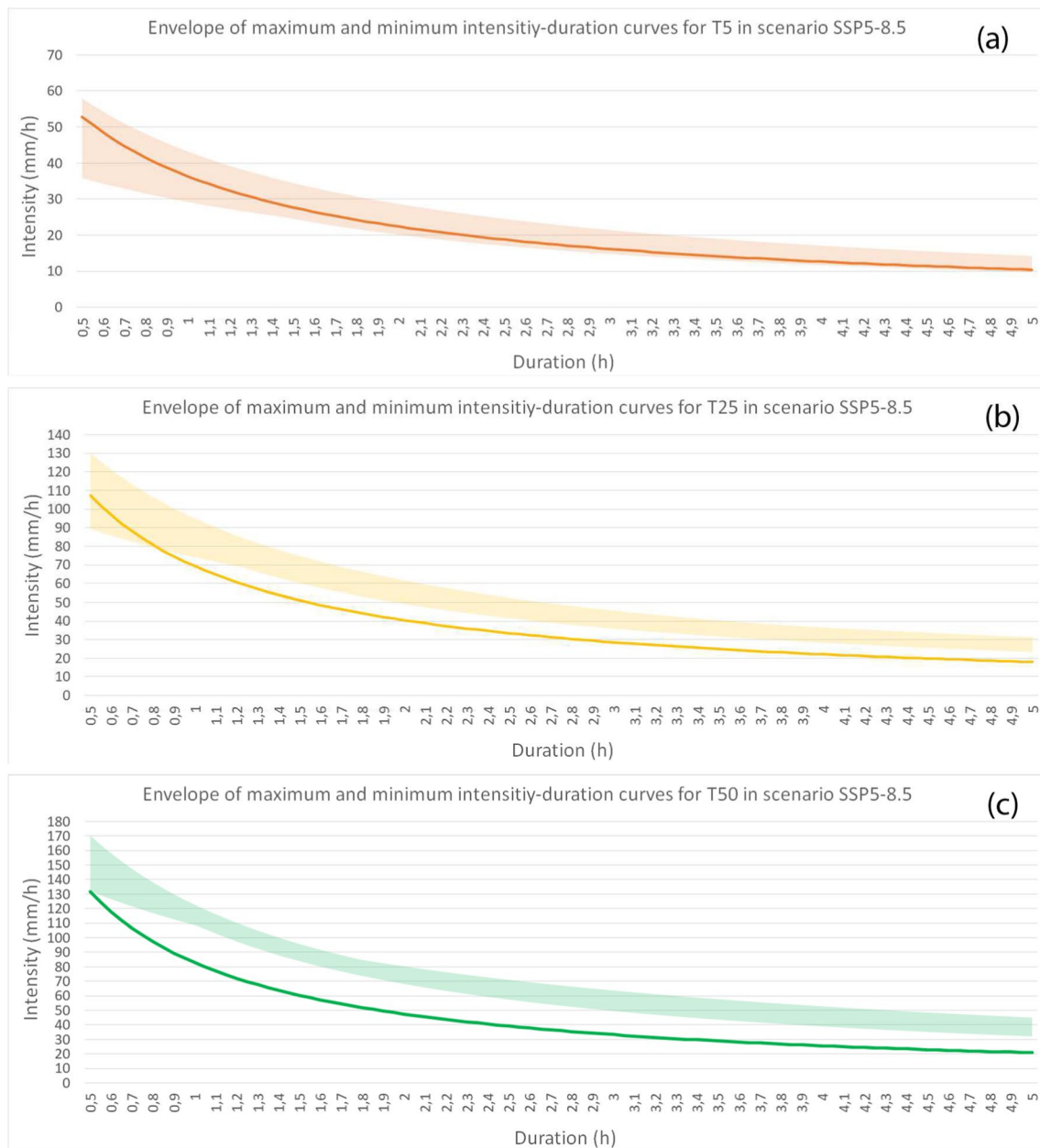
Fig. 9 Results of the projections of the intensity-duration curves between their maximum and minimum envelopes (shaded area) for the selected CMIP-6 models an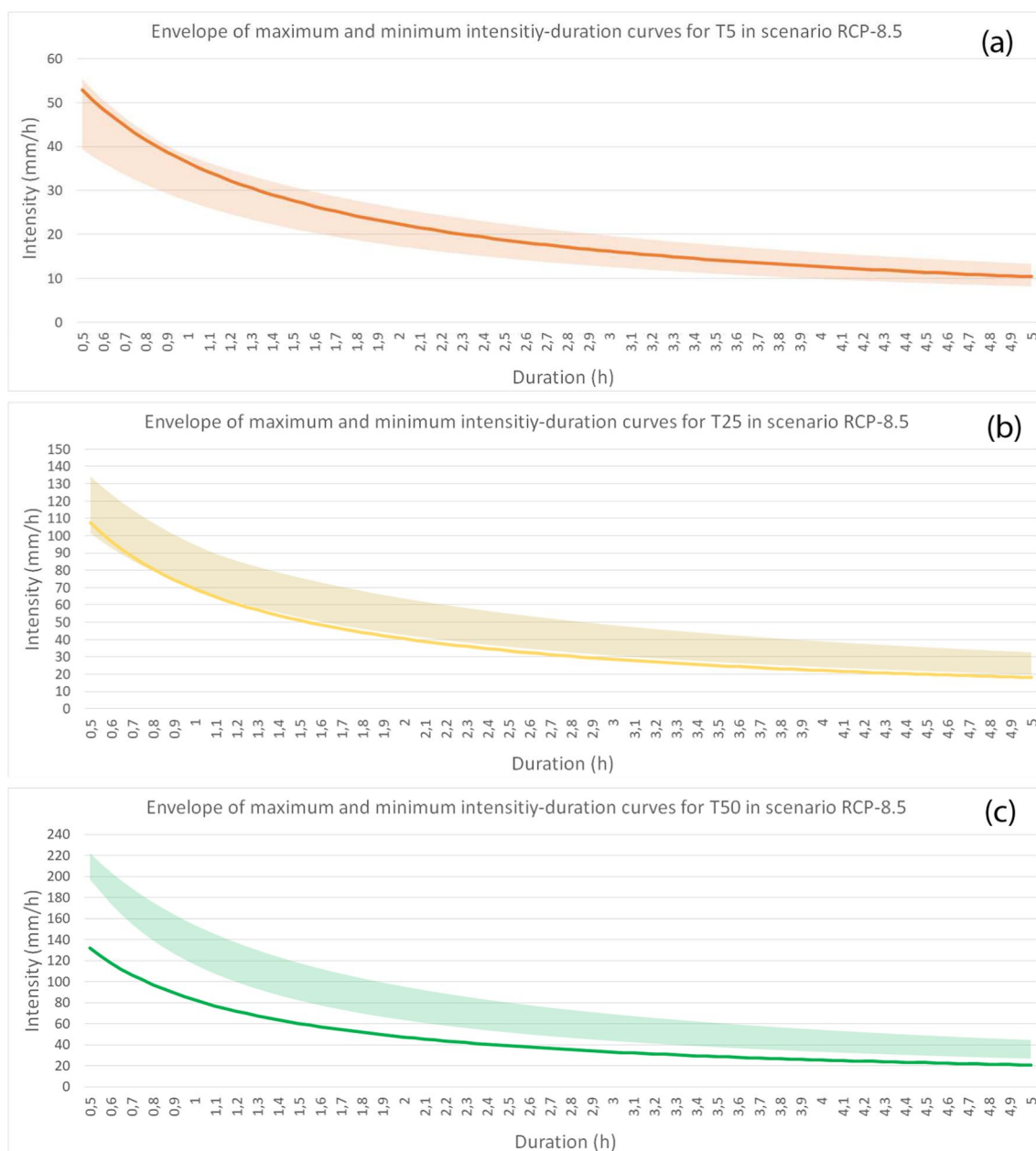d comparison with the historical IDF curves (solid line), for a return period of 5 (**a**), 25 (**b**) and 50 (**c**) years. Source: Own elaboration

3.15 for the maximum mean torrentiality index using MPI-ESM1-2-HR_r1i1p1f1 model in the period 2015-2100 for SSP 4.5 and SSP 8.5 scenarios) tend to be higher than those of the most distant historical series (with a value of 2.42 in the series 1950–1990), and aligned with the most recent historical series (with a value of 3.93 in the series 1990–2015). These values based on average rates, must be considered in qualitative terms (of increase or decrease) than merely

quantitative and, even better, combined with other study parameters such as the climate factor.

The values obtained for this index are consistent with an increase in the maximum mean intensities obtained in the projections of the IDF curves studied, and are also consistent, as presented below, with the values of climate factors (the percentage variation between measured and projected intensities for the future climate as expressed

Fig. 10 Results of the projections of the intensity-duration curves between their maximum and minimum envelopes (shaded area) for the selected Euro-CORDEX models and comparison with the histori-cal IDF curves (solid line), for a return period of 5 (**a**), 25 (**b**) and 50 (**c**) years. Source: Own elaboration

in Larsen et al. (2009)) obtained, greater than 1 as the return period increases for the short, medium and long term.

The methodology and definition of the climate change factor (CF) has been applied for its calculation in the city of Alicante for the return periods of 2, 5, 10, 25, 50 and 100 years in the CMIP-6 and Euro-CORDEX experiments in the climate change scenarios SSP5-8.5 and RCP 8.5

respectively, and projected in the short (2015–2040), medium (2041–2070) and long term (2071–2100) (Table 2).

The results show that the Euro-CORDEX experiments tend to obtain higher CF for the most return period and term analysed. Besides that, in both experiments, it is generally obtained a higher climate change factor in the near term than in the medium or long term. This may be due to the fact that historical data are used to train the temporal
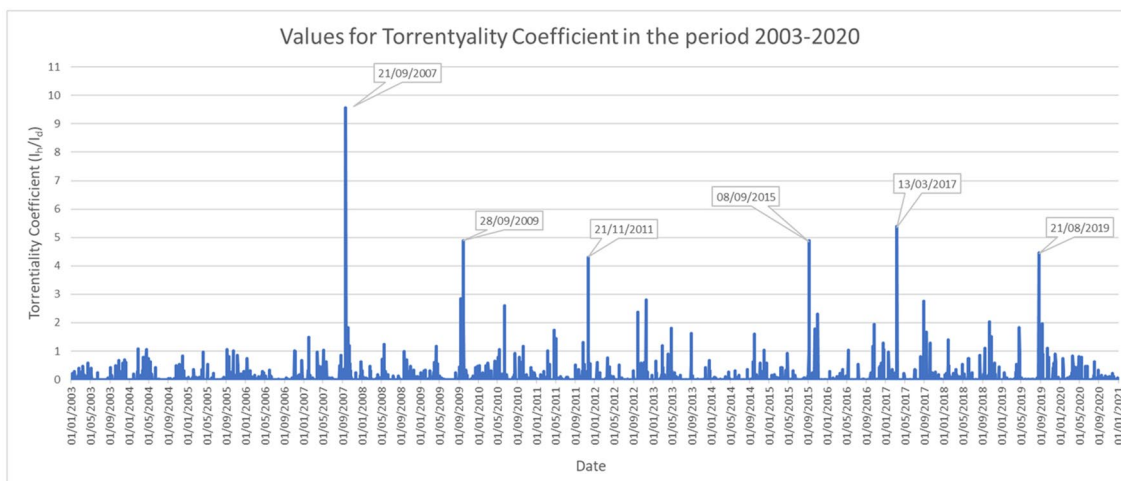
Fig. 11 Results of the Torrentiality Index for the rainfall series in the period 2003–2020 in the city of Alicante. Source: Own elaboration with AEMET data

disaggregation model, which means that, in principle, the number of extreme events in the future projections has a similar characterisation to that of past events. However, since mean daily precipitation is also used to train the model and decreases as the scenario worsens and time progresses, the most unfavourable increases in precipitation intensity occur in the short term, when the effect of the reduction in mean precipitation is not yet so noticeable.

Additionally, it is observed that the CF generally increases as the return period increases, which seems logical if the initial hypothesis of the occurrence of less but more intense rainfall in the Spanish Mediterranean coast is taken into account.

In reference to the CF value, for the CMIP-6 experiments, the CF is greater than the unit for all terms (near, medium and long) and return periods except the return periods of 2, 5 and 10 years in the medium and long term. In the case of the Euro-CORDEX experiments, the CF is greater than the unit for all terms (near, medium and long) and return periods except the return periods of 2, 5 and 10 years in the long term.

Particularly remarkable in the Euro-CORDEX experiments are the very high coefficients obtained for high return periods (50 and 100 years), which are even higher than 2 for the 100-year return period.

5 Discussion

The key findings obtained in this research work are summarised in the following paragraphs, and will be discussed in detail later on.

The analysis of the data with daily resolution shows that, in both the CMIP-6 and Euro-CORDEX experiments,

reduction values are obtained both in the amount of average annual rainfall and in the number of days with significant precipitation (greater than 1 mm), for the year 2100, in the three scenarios of climate change considered. Thus, if we average the reduction values obtained in the two experiments, we obtain that:

• For the best-case scenario (SSP-1 2.6/RCP2.6), the average reduction in average annual rainfall would be approximately 5%, while the reduction in the number of days with significant rainfall would be 7%;

• For the intermediate scenario (SSP-2 4.5/RCP4.5), the average reduction in average annual rainfall would be approximately 16%, while the reduction in the number of days with significant rainfall would be 21%; and

• For the worst-case scenario (SSP-5 8.5/RCP8.5), the average reduction in average annual rainfall would be approximately 28%, while the reduction in the number of days with significant rainfall would be 35%.

The analysis of the data with hourly resolution shows the following:

• The models selected in both the CMIP-6 and Euro-CORDEX experiments tend to slightly underestimate the intensities associated with rainfall of short duration for almost all the return periods analysed (except for $T = 2$ years), whereas there is a clear tendency on the part of the selected CMIP-6 model to overestimate the intensities associated with rainfall of durations of more than 1 h for return periods greater than or equal to 25 years. However, this overestimation is maximum for $T = 100$ years and does not exceed 10 mm/h.

• The selected models from both experiments perform a similar adjustment for low and medium return periods (up to $T=25$ years), with a larger range of variability in the models belonging to Euro-CORDEX. The largest differences are

Fig. 12 Regionalised projections of the "Torrentiality Index" for the mean of the CMIP-6 models in the month of September for every climate change scenario, SSP-1 2.6 (**a**), SSP-2 4.5 (**b**), SSP-5 8.5 (**c**), in the period 2015–2100 with indication of the 4 value threshold (red line). Source: Own elaboration
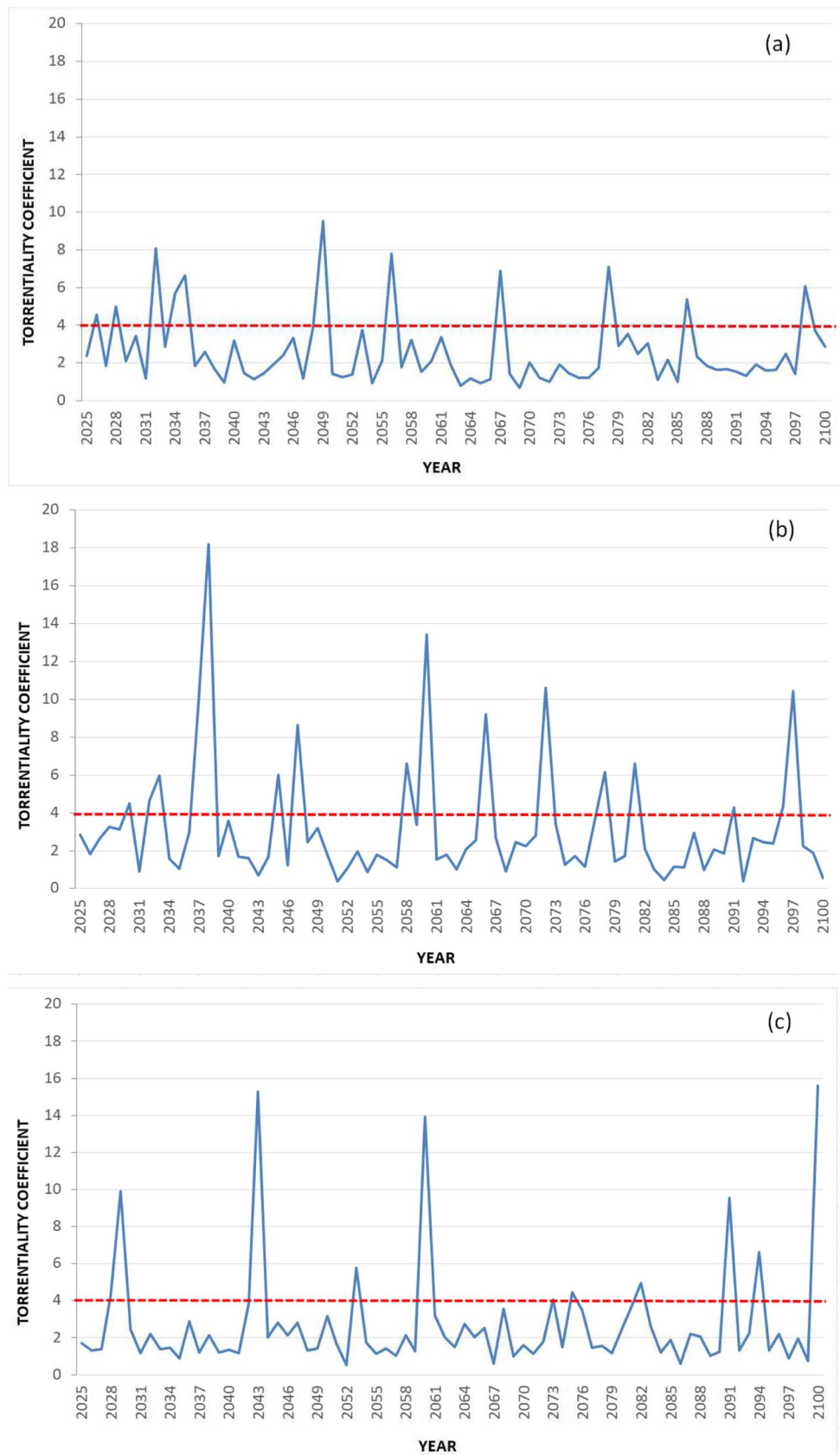
Table 2 Climate change factors according to CMIP-6 and Euro-Cordex experiments for SSP5-8.5/RCP8.5 scenarios and different return periods. Source: Own elaboration

CMIP-6 experiments						
Near term	Return period (years)					
	2	5	10	25	50	100
Climate factor	1.19	1.19	1.25	1.37	1.48	1.60
Medium term	Return period (years)					
	2	5	10	25	50	100
Climate factor	0.97	0.80	0.87	1.07	1.31	1.65
Long term	Return period (years)					
	2	5	10	25	50	100
Climate factor	0.93	0.86	0.94	1.12	1.32	1.57
Euro-CORDEX experiments						
Near term	Return period (years)					
	2	5	10	25	50	100
Climate factor	1.33	1.05	1.06	1.35	1.73	2.29
Medium term	Return period (years)					
	2	5	10	25	50	100
Climate factor	1.16	1.04	1.03	1.37	1.86	2.67
Long term	Return period (years)					
	2	5	10	25	50	100
Climate factor	0.81	0.76	0.77	1.00	1.41	2.11

obtained for longer return periods (from $T=50$ years) and lower rainfall durations, which are also the most interesting, as they represent the most extreme or torrential rainfall.

- The CMIP-6 experiments for projections of the IDF curves show increases in the occurrence of extreme precipitation events, with increases in precipitation intensity in 30-minute rainfall of up to 6% for T25, 17% for T50 or 36% for T100, compared to the intensities extracted from the IDF curves obtained with historical data.

- The worst-case scenarios (representing greater influence from climate change) SSP-2 4.5 and SSP-5 8.5 show, respectively, a higher frequency of occurrence of precipitation events with higher torrentiality index (value above 4) and a higher value of torrentiality index in more specific events.

- In reference to the CF value, for the CMIP-6 experiments, the CF is greater than the unit for all terms (near, medium and long) and return periods except the return periods of 2, 5 and 10 years in the medium and long term. In the case of the Euro-CORDEX experiments, the CF is greater than the unit for all terms (near, medium and long) and return periods except the return periods of 2, 5 and 10 years in the long term. Particularly remarkable in the Euro-CORDEX experiments are the very high coefficients obtained for high return periods (50 and 100 years), which are even higher than 2 for the 100-year return period.

The data with daily resolution are consistent with those presented in Amblar Francés et al. (2017), which suggest a decrease in mean annual precipitation, although it is indicated that, for the scenario with the highest emissions (RCP

8.5) and for the final period of the century, neither the agreement in the sign of the precipitation change between the projections nor its magnitude are identical in all Spanish regions. Focusing on the Mediterranean area and more specifically on the Valencian Community, it is indicated that the decrease in precipitation in winter will be more pronounced (between 6 and 28% reduction) with a high concordance in the change, whereas in the spring months this reduction ranges between 0 and 30%. However, the data obtained for the summer period in the Valencian Community show ranges between +5% (slight increase in summer rainfall) and −30% (sharp decrease in rainfall), as would be the case in autumn, with variations between +1% (increase) and −22% (decrease).

Along the same lines, Fernández et al. (2017) point to a consensus that the projections derived from the CMIP-5 (set out in the fifth IPCC report) show a decrease in average annual precipitation in all seasons of the year, although the agreement in the change is only complete in the summer period, reaching an average decrease of 30% in the estimates of the regional models studied.

Additionally, the data published by the Ministry for the Ecological Transition and Demographic Challenge of Spain through its digital platform AdapteCCa (which uses as data sources the point projections of the State Meteorological Agency and grid projections from the international Euro-CORDEX initiative, via https://escenarios.adaptecca.es) show, for the grid that encompasses the municipality of Alicante and for the RCP8.5 climate change scenario projected until 2100, an annual precipitation of 168 mm (0.46 mm/

day), which represents a reduction of approximately 30% compared to current rainfall levels. However, the data from this platform shows that there is hardly any reduction in the RCP4.5 scenario, compared to the 16% obtained as an average of the experiments carried out in this paper.

The results obtained with the hourly and sub-hourly resolution data, expressed as the relationship between precipitation intensity, duration and return period (IDF curves), will be contextualised in relation to the results obtained in other studies on the regionalisation of precipitation in municipalities on the Spanish Mediterranean coast, such as Barcelona and Badalona (located 520 km and 535 km north of the city of Alicante, respectively). These two cities suffer the same rainfall intensification process than Alicante or other cities in the Spanish Mediterranean coast like Valencia, Cartagena, Almería or Málaga. The entire territory of this area, with its climatic varieties, within the general context of rooted Mediterranean climates, is being affected by this process of intensification of precipitation, which is closely related to the global warming that is experiencing the water of the Mediterranean Sea in front of the Spanish coast (Miro et al. (2022)) and the development, more frequent, of situations of instability that favour the maritime component winds towards this geographical area (Muñoz et al. (2019)).

The results obtained for the city of Barcelona identified in Rodríguez et al. (2014) show, as indicated in the introductory section, a variation in the maximum intensity in 1 h in the range of −4% and 12% (depending on the climate change scenarios considered) for the horizon year 2050 and a return period of 10 years, with this final maximum percentage (12%, obtained for scenario A1B) being used as a criterion for maximising the design storm.

A comparison of these results with those obtained after the analysis carried out in the CMIP-6 and Euro-CORDEX experiments in the municipality of Alicante shows that, for the same return period and horizon year, in the medium term (period 2041–2070), we obtain that the percentage variation of the intensity in a projected hour with respect to the intensity obtained with historical data rises to 37% in the case of the CMIP-6 experiment and up to 94% in the case of Euro-CORDEX.

On the other hand, in the most recent case studied in the city of Badalona (Martínez-Gomariz et al. (2019)), the results obtained in the short-term forecasts (2015–2024) found no significant changes in terms of precipitation intensity after climate change models were applied. However, the long-term projections (2051–2100) do show remarkable changes related to an increase in 24-h mean precipitation intensities for CPR 8.5 scenarios. The percentages of intensity variation with time resolution in 24-h historical and future projection were applied directly on the historical IDF curves of Badalona (based on those of Barcelona), on

the basis of sub-daily durations, to obtain the future IDFs, and the corresponding climate change factors were obtained.

This methodology yields climate change factors for 1-h rainfall durations and for each return period considered of 15% for 2-year return period rainfall, 7% for 10-year return period rainfall, 2% for 100-year return period rainfall and 1% for 500-year return period rainfall.

Compared with the results obtained in the city of Badalona, the values of the climate change factor are higher in the case of Alicante, with an increase over 1, in the worst case scenarios, of 19% for rainfall with a 2-year return period, 25% for rainfall with a 10-year return period and 48% for rainfall with a 100-year return period for the data obtained from CMIP-6, and, in the case of data obtained from Euro-CORDEX, 33% for 2-year return period rainfall, 6% for 10-year return period rainfall or up to 129% for 100-year return period rainfall.

For its part, the results obtained for the specific case of the city of Madrid presented in Lastra de la Rubia et al. (2018) determine a climate change factor (projected using the models and scenarios contained in the IPCC AR-5) in three time horizons of the future projection (short, medium and long term), with values above 1 in all the scenarios considered, which implies that the expected future intensities will increase in the future. The averaged data from the different models used give coefficients around 1.10 or 1.15 for low return periods of between 2 and 5 years, or between 1.15 and 1.20 for higher return periods of between 10 years and 50 years. These data show more consistency with those obtained for the city of Alicante from the CMIP-6 experiments than the data obtained from the Euro-CORDEX models.

In turn, the analysis of the intensities linked to future climate for the highest return periods, $T=50$ and $T=100$ years and for 1-h duration rainfall in both experiments, makes it possible to contextualise these results in relation to the most extreme intensities recorded in the city in the historical database.

The rains of September 1997, with a 1-h intensity of 101.2 mm/h, and October 1982, with an 1-h intensity of 81.5 mm/h, can be regarded as the most catastrophic in the last 83 years, followed by September 2007, with an intensity of 80.2 mm/h (these extreme rainfalls have been taken into account for the statistical adjustment necessary for the elaboration of the historical IDF curves).

The range of minimum and maximum 1-h intensity values projected from the selected CMIP-6 model for the SSP5-8.5 scenario is as follows:

• Intensity for $T=50$ years and duration of 1 h: 110–125 mm/h

• Intensity for $T=100$ years and duration of 1 h: 120–160 mm/h

The range of minimum and maximum 1-h intensity values projected from the selected Euro-CORDEX models for the RCP 8.5 scenario is as follows:

- Intensity for T=50 years and duration of 1 h: 150–160 mm/h
- Intensity for T=100 years and duration of 1 h: 200–260 mm/h

The maximum 1-h intensity value recorded in the 83-year series analysed is 101 mm/h (therefore associated with a return period of approximately 100 years). The increases obtained in the CMIP-6 projections are valued at between 20 and 60%, while those obtained in the Euro-CORDEX projections reach 100 and 160%.

In view of the congruence of the data obtained by adjusting the CMIP-6 models with respect to other local experiences in Spain, and also with the data of maximum historical precipitation intensities (the current 100-year return period rainfall would be classified approximately in the 50-year return period in the future projections), the model selected from the CMIP-6 experiment (MPI-ESM1-2-HR_r1i1p1f1; Max Planck Institute for Meteorology) is adopted as representative of the future precipitation projection for the city of Alicante.

Finally, with regard to the torrential nature of precipitation in the Mediterranean basin, as stated in the document published by the IPCC (IPCC (2022)), precipitation is expected to become more intense as global warming increases (SSP 4.5 and SSP 8.5 scenarios). For warming increases of about 4 °C above pre-industrial levels, events linked to return periods of 10 years or longer are expected to become frequent. Increases in frequency and intensity are very likely for most continents and very likely for most AR6 regions.

A similar conclusion, although more regionalised, is reached by Monjo et al. (2015) who find, by applying 9 climate models from CMIP-5 for the RCP4.5 and RCP 8.5 scenarios, that for the southern coastal area of Valencia and northern Alicante (region close to the city of Alicante), the projections show an increase (statistically not significant) of extreme events, which could exceed 20% in both scenarios, for the 100-year return period precipitation, with a certain tendency to move from inland areas towards the coast. The results obtained for return periods of 50 years are similar, although with a lower degree of significance.

However, the conclusions drawn from Amblar Francés et al. (2017) regarding intense rainfall do not show conclusive results since clear differences are observed in the three regionalisation methods used. The study indicates that, for the Valencian Community, the percentage of change in intense rainfall may vary between −3% (decrease) and +4% (increase).

The results obtained for the regionalisation carried out in the municipality of Alicante are in line with what is described in Pörtner, H.O. et al. (IPCC 2022) and in Olcina-Cantos et al. (2018) showing a trend of increased torrentiality for higher emission scenarios (SSP2-4.5 and SSP5-8.5).

5.1 Uncertainties associated with climate change projections

There are many sources of uncertainty associated with climate change projections. Maybe the most important ones can be classified, according to Tebaldi and Knutti (2007), in initial conditions uncertainty (like internal variability, different GCM or RCM models, spatial or temporal downscaling), boundary conditions uncertainty (like climate scenarios) and parameter uncertainty (parameter estimation method).

Related to the initial conditions, for daily results, it has been proposed the use a multi-model ensemble with various initial conditions, different GCMs and RCMs and various climate scenarios. This solution combining several models can reduce uncertainties and biases associated with any individual model that, as can be seen in the figures presented in this article, have a big variability. Regarding the spatial downscaling uncertainty, the resolution of the models used is significant to be applied to the area of Alicante varying between 1° and 0.11°.

The uncertainty due to boundary conditions appears when defining the future socio-economic and GHG scenarios. To try to minimise this uncertainty, three RCP or SSP scenarios have been taken into account, an optimistic one, a "business as usual" one and a pessimistic one, in order to compare the results of their projections.

Finally, parameter uncertainties are referred to small-scale processes in all components of the climate system that cannot be resolved specifically, and their effect on the large-scale climate response must be parameterised with general formulas that depend on large-scale variables available in each model. Using the ISIMIP-3 methodology described in the article to make bias correction based on large series of real data available is possible to statistically reduce these uncertainties.

Regarding the uncertainty inherent to the hourly resolution data, the methodology used to construct the IDF curves has some limitations; the first one is related to the scale of the data used. In the case of this study, the data provided by the AEMET, despite covering a historical series of 83 years, have a level of detail in the duration of the precipitation of 1 h and 24 h; therefore, the temporal downscaling process has been executed descending to 30 min in duration, using the hourly data to calibrate the downscaling models of the daily data. The detail of the minute adjustment data to hours can be done, effectively, from statistical methods, but

there is a limitation of the methodology for short durations, appearing some statistical artefacts. The estimation of IDF curves for short durations with historical information has systematically presented problems of this nature. This has been confirmed in Kourtis and Tsihrintzis (2021), where it is indicated that the majority of the studies examined developed future IDF curves based on hourly (43%) daily (14%) time scales, being the main reason the need for long-term observations with high temporal resolution from a dense network of stations.

An improvement in the determination of the IDF curves for short durations involves the detailed analysis of the specific historical series of short duration storms with high monitoring frequency (5-min or 10-min) (Gutierrez & Barragán (2019)).

In addition, updating IDF curves considering climate change encompasses various sources of uncertainty. In terms of hourly resolution and IDF curves construction, the most important uncertainties are related to, in addition to those indicated in the daily resolution, the associated to the temporal downscaling method. To solve this problem, as commented before, the calibration of the downscaling method has been done using historical data with hourly resolution from years 2003 to 2021, separating 1 year of data to perform a validation study. In this study, it was checked that the different statistical parameters (mean, percentiles 75, 90, 95 and 99, maximum, etc.) of the precipitation distributions were similar between the inferred and the observed hourly series.

On the other hand, when defining the IDF curves representative of the future climate, it has been decided to select the climate projection models most adjusted to IDF curves constructed from the historical data.

Obtaining the intensity-duration-frequency curves requires a previous process of temporal downscaling. This new statistical treatment of the data, combined with the application of the different projection models, results in a high variability in the adjustment of IDF curve for each of them and the ensemble of the models is highly influenced by this variability, not adjusting adequately to the historical curve. For this reason, it has been studied which of the 5 climate projection models regionalised to the municipality of Alicante from the CMIP-6 initiative and which of the 51 models from the Euro-CORDEX initiative provides a better adjustment to these data, compared to this historical scenario.

6 Conclusions

Climate change is the main challenge faced by humanity in this century due to the magnitude of its expected effects in urban areas where most of the population is concentrated.

It is therefore imperative to predict the magnitude of the impacts of climate change on the hydrological cycle in order to design drainage systems adapted to the future, and to integrate the most recent strategies based on the implementation of green infrastructures with added positive impact on cities and their population.

This paper presents a methodology for the regionalisation at the local scale in a pilot city (Alicante, SE of Spain) of the latest and main climate projection models endorsed by the scientific community, and obtains the future evolution of one of the main key hydrometeorological variables for assessing the city's resilience to possible extreme events: precipitation.

The comparison of the models that best fit the climate of the city of Alicante indicates that there are models from both the CMIP-6 and Euro-CORDEX initiatives that closely approximate the general precipitation conditions; however, the model developed at Max Planck Institute for Meteorology for the CMIP-6 experiment offers a very close approximation based in past episodes and is congruent with other studies analysed, so it is selected to represent future projections of precipitation in the city.

The results obtained for the coming years (the projections have been made up to the year 2100, but the tangible effects of these projections may occur in the short, medium or long term) show a local climate for the city of Alicante characterised by a decrease in average annual precipitation (up to 16% in the period 2022–2100 and in the most likely scenario SSP2-4.5/RCP4.5 or up to 28% in the worst-case scenario SSP5-8.5/RCP8.5), but an increase in the occurrence of extreme precipitation events (with increases in precipitation intensity in 30-min rainfall of up to 6% for T25, 17% for T50 or 36% for T100, compared to the intensities extracted from the IDF curves obtained with historical data). This fact requires us to reflect on the importance of optimising water resources and the correct management of hydrometeorological risks. Additionally, there is a clear trend towards an increase in frequency and/or magnitude of the rainfall torrentiality index depending on the climate change scenario studied, which tends to increase in the scenarios that include an increase in GHG emissions, as well as in the climate change factor, which also increases, in general, as the return period analysed increases.

The changes in the extreme rainfall regime will force a paradigm shift in the design hypotheses of the main drainage infrastructures of the city, generally designed for return periods of between 10 and 50 years, depending on their hydraulic responsibility.

As indicated, the increase in the precipitation intensities obtained will have a direct influence on the reduction in the capacity of the preexisting hydraulic networks and installations in the city, causing an increase in the risk of both flooding problems and environmental problems derived from discharges into the environment. On the other hand, the

increases in the intensities projected for the new synthetic rainfalls that will serve as the basis for the design of new drainage infrastructures will imply an increase in their useful section or capacity, being necessary greater economic resources to minimise the aforementioned flood and environmental risks. As an alternative for these "grey" infrastructure issues, Nature-based Solutions (NbS) (www.iucn.org), as a means of restoring natural watershed conditions prior to urban development in the city, which allows runoff control, flood abatement, storage or infiltration of flows, at a lower cost per cubic metre managed than the implementation of traditional infrastructures, are presented as an effective means to combat the effects of climate change, allowing to improve the resilience of ecosystems, helping societies to adapt to climatic hazards such as floods, rising levels of the sea, droughts, heat waves and more frequent and intense forest fires.

Applied specifically to urban drainage, the NbS have the aforementioned advantages, with a cost per managed cubic metre lower, as a general rule, than the implementation of traditional infrastructures, improving urban resilience and providing social and biodiversity benefits.

Additionally, the decrease in the rainfall regime will also irremediably modify the way urban drainage networks are managed, with more periods of dry weather and less self-cleaning effect of networks caused by rainfall, which will imply greater accumulations of dirt inside the network that will be mobilised at specific moments of precipitation (lesser, but more intense). This will imply a greater susceptibility to the occurrence of obstructions if the preventive cleaning tasks are not correctly carried out and a worsening of the quality parameters of the discharges from the sewer networks to the environment during rainfall episodes, parameters strongly controlled by European and Spanish legislation. In this case, the NbS are also emerging as runoff control systems and improvement of the quality of circulating or discharges that will greatly help to achieve environmental goals in the medium and long term.

For all these reasons, in order to adapt to climate change and evolve towards a resilient city model, it is essential that local climate projections can be considered in urban planning tools, with local administrations coordinating efforts between themselves, management companies of the integral water cycle and climate service companies.

Future research will focus on reducing the time scale of future projections (to durations of 5–10 min) in order to adequately simulate the hydrological and hydraulic phenomena that characterise the behaviour of urban catchments and sewer networks, as well as the use of NbS to improve urban resilience and provide social, citizen welfare and biodiversity benefits.

Finally, the interrelationship between the new hydrometeorological boundary conditions conditioned by climate change and regionalised at the local scale in the city of Alicante, the construction of a digital twin of the drainage network and its relationship with the environment (sea and ravines) adjacent to the city, as well as the effectiveness of the NbSs for the improvement of the resilience of the urban environment, will also be the subject matter of future research.

Declarations

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