NEAR AND LONG-TERM CLIMATE CHANGE IN THE RESCCUE PROJECT: CLIMATE EXTREME SCENARIOS FROM DOWNSCALED CMIP5 MULTI-MODEL

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RESUMEN
El proyecto RESCCUE tiene como objetivo mejorar la resiliencia urbana de tres casos piloto, Barcelona, Lisboa y Bristol, a través de una evaluación de los impactos del cambio climático en varios sectores. En este estudio, se han obtenido proyecciones climáticas locales futuras y predicciones decadales para las tres ciudades a partir de un multi-modelo generado a escala local. Para este propósito, un método estadístico de downscaling en dos pasos se aplicó a las salidas de 10 modelos del experimento CMIP5 para simular diferentes variables climáticas, especialmente la precipitación subdiaria extrema. Se definieron eventos extremos sintéticos a partir de períodos de retorno ajustados con varias distribuciones teóricas: las distribuciones Gamma, Weibull, Gumbel y Monjo. En cuanto a los resultados, se esperan incrementos significativos en los valores de eventos extremos de temperatura máxima y precipitación subdiaria en las tres ciudades. Por otro lado, la altura de las olas extremas y la marea ciclónica disminuirían en algunos casos.

Palabras clave: Eventos extremos, escala local, multi-modelo, clima decadal.

ABSTRACT
The RESCCUE project aims to improve urban resilience of three pilot cases, Barcelona, Lisbon and Bristol, through an assessment of climate change impacts in several sectors. In this study, future local climate projections and decadal predictions have been obtained for the three cities from a multi-model generated at local scale. For this purpose, a two-step statistical downscaling method was applied to ten CMIP5 model outputs to simulate several climate drivers, focusing on extreme subdaily precipitation. Synthetic extreme events were defined for low and high return periods fitting several theoretical distributions: 2, 3 and 4-parametric versions of Gamma, Weibull, Gumbel and Monjo distributions. Regarding the results, significant increases in extreme values of maximum temperature and subdaily precipitation are expected in the three cities. Finally, extreme wave height and storm surge would decrease for some cases.

Key words: Extreme events, local scale, multi-model, decadal climate

1. INTRODUCTION

The present study is based on results from the climatic work package of the European project named RESilience to cope with Climate Change in Urban arEas (RESCCUE). In this work package, climate change drivers were identified and climate predictions/projections were generated.

The term "prediction" is used for the near-term climate or decadal simulations in contrast with the "projection" of the long-term future climate. This difference is due to the fact that the long-term simulations depend on the selected RCP scenario, which is not directly associated with a probability concept but with a political decision that is not related to numerical prediction models.

The data assimilation carried out for the initialization of both climate and decadal models causes a *drift* in the bias of the simulated variables until they are stabilized (Kim *et al.*, 2012; Doblas-Reyes *et al.*, 2013). That is, the drift is produced until the model simulates enough transitory time since the beginning of the run (around 10-year horizon). Since near-term climate models predict for 10 to 30 years (decadal models), the drift must be taken into consideration because it could extend for a half of the forecast term.

On the other hand, analysis of extremes in meteorology and climatology presents some problems that should be considered in every study. The first one is the definition of *extreme event*. The definition necessarily assumes a low occurrence probability, and in most of studies, this is combined with potential high-impacts over the studied area (WMO, 2001).

For the RESCCUE project, it is important to consider the potential impacts because, in some cases, a low-recurrent event may cause an unappreciated impact. This is the case, for instance, of the snowfall in Lisbon, where the rare snowfall events do not cause any problems in the city.

In any case, the most important element of the definition, the low occurrence, is related to the tails (extremes) of a given probability distribution (usually from the analysed climate variable). For a given distribution, the problem is to determine where each tail starts. Some authors use a threshold that splits a tail from the general distribution, but an arbitrary threshold could occur too many times or never. Therefore it is important to identify specific thresholds that cause problems in each city. Other authors use classical quantiles as 0.90, 0.95 or 0.99 to determine the extremes from a distribution. Generally, these values correspond to relatively frequent events (every year) and then they usually do not cause potential impacts.

In order to better represent the low occurrence, return periods are used in the RESCCUE project. Logically, each return period (T) is related to a quantile ($1 - 1/T$) very close to 1, which guarantees that is a real extreme.

The low recurrence of the extreme events has an additional problem: The limited number of observed extreme events leads to less robust statistical measures. To reduce the uncertainty, a multi-model ensemble strategy was used with theoretical distributions able to fit to the entire empirical distribution (Monjo *et al.*, 2016).

2. DATA

A total of 817 weather stations were selected for three studied areas around Barcelona, Lisbon and Bristol. Observed data were collected for both atmospheric and oceanic variables from the Spanish State Meteorology Agency (AEMet), the Portuguese Institute for Sea and Atmosphere (IPMA), the British MetOffice and the National Oceanic and Atmospheric Administration (NOAA). For the observed variables, the database consisted of temperature, precipitation, snowfall, wind, wave height and sea level. In order to apply the chosen statistical downscaling, it was enough to use at least 5 years of observed data (Ribalaygua *et al.*, 2013). A set of tests were applied over all time series: general consistency, outliers and inhomogeneities (Monjo *et al.*, 2013).

The studied climate variables were also collected from the ERA-Interim reanalysis and CMIP5 climate/decadal models (Table 1). Unlike the direct model outputs, reanalysis tries to reproduce the meteorological variability day-to-day. However, both kinds of simulations show important errors in their probability distributions due to physical limitations from the low spatial resolution and from the used equations or parameterizations. Therefore, it is required to apply some downscaling or correction method to adequately simulate climate variability at local scale.

AORI: Atmosphere and Ocean Research Institute (Japan)
BCC: Beijing Climate Center, China Meteorological Administration (China)
BOM Bureau of Meteorology (Australia)
CC-CMA: Canadian Centre for Climate Modelling and Analysis (Canada)
CERFACS: Centre Europeen de Rechercheet Formation Avancees en Calcul Scientifique (France)
COLA: Center for Ocean-Land-Atmosphere Studies (US)
CMCC: Centro Euro-Mediterraneo sui Cambiamenti Climatici (Italy)
CNRM: Centre National de Recherches Meteorologiques (France)
CSIRO Commonwealth Scientific and Industrial Research Organisation (Australia)
IPSL: Institut Pierre-Simon Laplace (France)
JAMSTEC: Japan Agency for Marine-Earth Science and Technology (Japan)
GFDL: Geophysical Fluid Dynamics Laboratory (USA)
MOHC: Met Office Hadley Centre (UK)
NIES: National Institute for Environmental Studies (Japan)
MPI-M: Max Planck Institute for Meteorology (Germany)
MRI: Meteorological Research Institute (Japan)
NCC: Norwegian Climate Centre (Norway)

3. METHODOLOGY

3.1. Statistical downscaling

Local climate projections for the near- and long-term trends were obtained in the RESCCUE project. The near-term simulation or decadal prediction was performed by using drift-correction of the dynamical model outputs (Doblas-Reyes *et al.*, 2013). The long-term or climate timescale was based on the two-step statistical downscaling method developed by Ribalaygua *et al.* (2013).

Model	Institution	Reference	AGCM resolution(Lon×Lat)	RCP				Decadal
				2.6	4.5	6.0	8.5	(RCP4.5)
ACCESS1-0	CSIRO, BOM	Bi *et al.* (2013)	1.87°×1.25°		X		X	T
BCC-CSM1-1	BCC	Xiao-Ge *et al.* (2013)	2.8°×2.8°	X	X	X	X	T, D
CanESM2*	CC-CMA	Chylek *et al.* (2001)	2.8°×2.8°	X	X		X	T, CanCM4
CMCC-CM	CMCC	Vichi *et al.* (2011) Bellucci *et al.*(2012)	0.75°×0.75°					D
CNRM-CM5	CNRM-CERFACS,	Voldoire *et al.* (2013)	1.4°×1.4°	X	X		X	T, D
GFDL-ESM2M	GFDL	Dunne *et al.* (2012)	2°×2.5°	X	X	X	X	T
HADGEM2-CC	MOHC	Collins *et al.* (2008)	1.87°×1.25°		X		X	T, D
IPSK-CM5A-LR	IPSL	Dufresne *et al.* (2013)	3.75°×1.89°					D
MIROC-ESM-CHEM	JAMSTEC, AORI, NIES	Watanabe *et al.* (2011)	2.8°×2.8°	X	X	X	X	T, MIROC5
MPI-ESM-MR	MPI-M	Marsland *et al.* (2003)	1.8°×1.8°	X	X		X	T, MPI-ESM-LR
MRI-CGCM3	MRI	Yukimoto *et al.* (2011)	1.2°×1.2°	X	X	X	X	T, D
NorESM1-M	NCC	Bentsen *et al.* (2012), Iversen *et al.*(2012)	2.5°×1.9°	X	X	X	X	T

Table 1: Available CMIP5 climate/decadal models. The table shows the model name, the responsible institution, the model references, their spatial resolution for the AGCM, and the available RCPs. The most basic run r1i1p1 was taken for all climate models except for CanESM2, for which it was the r2i1p1 run. For decadal outputs, T *indicates Teleconnection-combined approach,* D *indicates Drift-corrected outputs, and alternative decadal models were taken in some case to compensate the unavailability of others. Acronyms:*

The first step of Ribalaygua is common for all simulated climate variables according to an analogue stratification: the *n* most similar days to the day to be downscaled (problem day) are selected. The similarity between two days was measured using a weighted Euclidean distance according to three nested synoptic windows and four large-scale fields used as predictors: (1) speed and (2) direction of the geostrophic wind at 1000 hPa and (3) speed and (4) direction of the geostrophic wind at 500 hPa. For each predictor, the distance was calculated and standardised by substituting it by the closest percentile of a reference population of distances for that predictor. The four predictors were finally equally weighted, while the synoptic windows had different weights. In the second step, a transfer function is applied to the *n* analogous days previously selected in the first step. This function depends on the downscaled variable. For example, the final simulation of temperature is obtained by using a linear function obtained by stepwise regression for $n = 150$ analogous.

Regarding the decadal prediction, outputs from nine decadal models with four different initialization *runs* have been used (except for CMCC-CC that only has *run*1, and MPI-ESM-LR and MRI-CGCM3 that do not have *run*4).

For each initialization *run*, a total of ten *historical* experiments (the maximum for some decadal models) have been considered to estimate the bias drift. Daily output obtained for each city has been aggregated to the corresponding annual time-series. As the bias drift depends on the temporal horizon (ten years), drift was separately computed for each horizon *h* of the ten experiments. For example, if h_{ij} is the *i*-year horizon for the *j*-experiment, we jointly compute all the h_{1j} for the first year horizon (where $j = 1,\ldots,10$), and so on for each horizon.

The systematic error is obtained by comparing each simulated variable (from climate models *historical experiment*) with the observations (from reference time-series). In order to correct this systematic error, it is necessary to have long time-series of reference, because the large natural variability of climate (especially precipitation and wind) has a significant uncertainty associated. For that reason, we have extended the observed time series downscaling ERA-Interim reanalysis (1979-2015) before validation. Due to systematic found in the extreme values, we chose to correct the ECDF of each downscaled ERA-Interim output, with reference to observations in the common period. This correction is based on quantile-quantile parametric transferences (Benestad, 2010; Monjo *et al.*, 2014).

3.2. Extreme events

Common criteria have been established regarding extreme meteorological events for the three cities considered in the RESCCUE project. After considering the different characteristics of each city's climate and the already known trends obtained for future climate projections of each variable (temperature, rainfall, snowfall, wind, wave height and storm surge), we have designed synthetic extreme (SE) events to represent the most interesting events. Each SE is defined according to a particular *return period***:** Eight SEs were defined according to 1, 2, 5, 10, 20, 50, 100 and 500 years of *point return period*. Different (theoretical) probability distributions were used to find the best fit to the variability of each station: 2, 3 and 4-parametric versions of Gamma, Weibull, Classical Gumbel, Reverse Gumbel and Modified Log-logistic distributions (Monjo *et al.*, 2014, 2016). In addition to the return

periods, extreme values were also estimated by using indicators as the Standardised Precipitation Evapotranspiration Index (SPEI) for hydrological drought, the *n*-index for the rainfall concentration (Monjo, 2016) and some heat indexes such as heat wave days per year, duration and intensity (WMO, 2017).
The study of changes in future extreme values was performed considering several periods in both historical and future years. A baseline was required to compare the simulated and observed past periods, while three future horizons were defined from the near-term (prediction) to the long-term (projection) climate simulations.
Historical experiments (1950-2005) have been considered for validating the downscaled model outputs according to the extended observations (combined with ERA-Interim, 1979-2017) in the common period, usually 1979-2005.
Regarding the projection of the climate variables, mainly RCP4.5 and RCP8.5 were considered. Within those RCPs, three thirty-year climate periods are selected to analyse the progression of the changes along the century: 2011-2040, 2041-2070 and 2071-2100, with respect to the 1976-2005 baseline. For the near-term climate predictions, the period 2016-2035 was considered with respect to the baseline period 1986-2015. The 30-year period of 1986-2015 was considered as the most recent period for the reference climate (baseline).

3.3. Uncertainty analysis

Uncertainty cascade in the extreme events simulation was analysed according to several contributions: (1) The method-model performance [validation process], (2) the RCP scenarios considered, and (3) the climate natural variability.
Regarding to the first uncertainty source, all used methods were validated to be applied in the extreme events simulations obtained from the downscaled climate models. As a reference, observations extended with the corrected downscaled ERA-Interim (1979-2015).
The main statistic for a validation process is the bias of the analysed model output. To check the spatial distribution of the simulated climate (average values), the study analysed the bias of extreme events given by the selected return periods. Historical trends of the extreme indicators were analysed too. Systematic errors up to ±3°C and ±30% were accepted to be corrected. The models that passed the tests were used to analyse the absolute and relative changes in the main climate variables.
The last two uncertainty sources are commonly represented using the ensemble strategy. In particular, we used multi-model statistics. That is, once bias-correction is applied to all validated models, combination (ensemble) of the outputs provides an estimation of the uncertainty caused by the (past and future) climate variability. The ensemble also combines the main RCP scenarios to obtain representatives from the smallest to the greatest change. Projections are performed for extreme indices using a continuous temporal evolution, while the changes in return periods were mapped to represent the spatial distribution in each future period.
The multi-model spread is represented by using uncertainty areas. Particularly, it is considered as the 10th–90th percentile values and the median value for each year-horizon, calculated from all stations and models validated for each climate variable.

4. RESULTS AND DISCUSSION

4.1. Results of validation

For high return periods before correction, simulation of extreme temperature was only acceptable in a few climate models applied to Lisbon and Bristol, while most of the downscaled models passed the tests for Barcelona (Table 2). Wind gust extremes presented problems to be simulated properly in the Barcelona area, and the rest of variables perform correctly under most of downscaled models for the climate timescale.

Regarding the near-term predictions, temperature is well simulated by most of the drift-corrected decadal models considering low and high return periods. Precipitation is better simulated by decadal teleconnections combined with climate models. Wind gust extremes are not correctly simulated for Lisbon, and snowfall presented problems in Barcelona for the highest return periods.

In detail for extreme temperature, it is correctly simulated by all the downscaled models for Barcelona, except in two cases: NorESM1 for high return periods and MIROC-ESM-CHEM for low return periods. For Bristol and Lisbon, half of the downscaled model outputs presented a systematic error about 3 or 4°C. The heat wave features, such as duration, mean intensity and maximum intensity, were adequately reproduced by the downscaling method. The validation process for Barcelona only presented remarkable biases in a few models. For instance, GFDL-ESM2M outputs overestimate mean and maximum intensities up to +2.5°C, while MRI-ESM-CHEM and ACCES1-0 overestimate the heat duration about +2 days (+50%). These biases are within the common error interval of the climate simulations and therefore they were corrected.

Maximum daily precipitation accumulated in Barcelona is correctly estimated by every model for all return periods except by HADGEM2-CC in Barcelona and BCC-CSM1 in Bristol, with bias about 50%. Regarding the validation of the hydrological drought simulation, the historical trend (significantly decreasing about -0.5 dec^{-1}) is well simulated by all downscaled models in Barcelona, but three downscaled models did not pass the tests for Lisbon and five for Bristol.

4.2. Extreme events prediction

For Barcelona, 100y-return extreme temperature could rise about +5.1°C with uncertainty going from +2.3°C up to +8.9°C in the worst-case scenario. Meanwhile, heat wave days will suffer a great increase of 400%, with little uncertainty below median but high above it with the worst-case scenario pointing to an increase of up to 1500%. This increase in both temperature and heat waves will have associated an increase in hydrological drought (from SPEI), with values rising from +50% up to +100% with an expected value of +75% by 2100 (Figure 1).

Return period	CMIP5 climatic models	Max. Temp.			Rainfall			Snowfall			Wind gust			Storm surge			Wave height		
		Barcelona	Bristol	Lisbon	Barcelona	Bristol	Lisbon	Barcelona	Bristol	Lisbon	Barcelona	Bristol	Lisbon	Barcelona	Bristol	Lisbon	Barcelona	Bristol	Lisbon
2 years	ACCESS1-0	Green	Red	Green	Green	Green	Green	Green	Green	Grey	Green	Green	Green	Green	Green	Green	Green	Grey	Green
	BCC-CSM1-1	Green	Yellow	Green	Green	Red	Green	Green	Green	Grey	Green	Green	Green	Green	Green	Green	Green	Grey	Green
	CanESM2	Green	Green	Yellow	Green	Green	Green	Green	Green	Grey	Yellow	Green	Green	Green	Green	Green	Green	Grey	Green
	CNRM-CM5	Green	Green	Green	Green	Green	Green	Red	Green	Grey	Green	Green	Green	Green	Green	Green	Green	Grey	Green
	GFDL-ESM2M	Green	Red	Red	Green	Green	Green	Green	Green	Grey	Green	Green	Green	Green	Green	Green	Green	Grey	Green
	HADGEM2-CC	Green	Yellow	Red	Red	Green	Green	Green	Green	Grey	Green	Green	Green	Green	Green	Green	Green	Grey	Green
	MIROC-ESM-CHEM	Red	Yellow	Green	Green	Green	Green	Green	Green	Grey	Yellow	Green	Green	Green	Green	Green	Green	Grey	Green
	MPI-ESM-MR	Green	Red	Yellow	Green	Green	Green	Green	Green	Grey	Yellow	Green	Green	Green	Green	Green	Green	Grey	Green
	MRI-CGCM3	Green	Green	Yellow	Green	Green	Green	Green	Green	Grey	Green	Green	Green	Green	Green	Green	Green	Grey	Green
	NorESM1	Green	Red	Green	Green	Green	Green	Green	Green	Grey	Green	Green	Green	Green	Green	Green	Green	Grey	Green
100 years	ACCESS1-0	Yellow	Red	Red	Green	Green	Green	Yellow	Green	Grey	Yellow	Green	Green	Green	Green	Green	Green	Grey	Green
	BCC-CSM1-1	Green	Red	Green	Green	Red	Green	Green	Green	Grey	Yellow	Green	Yellow	Green	Green	Green	Green	Grey	Red
	CanESM2	Green	Red	Red	Green	Green	Green	Green	Green	Grey	Red	Yellow	Yellow	Green	Yellow	Green	Green	Grey	Red
	CNRM-CM5	Red	Yellow	Yellow	Green	Green	Green	Green	Green	Grey	Red	Green	Yellow	Green	Green	Green	Green	Grey	Yellow
	GFDL-ESM2M	Green	Red	Red	Green	Green	Green	Green	Green	Grey	Yellow	Green	Green	Green	Green	Green	Green	Grey	Red
	HADGEM2-CC	Green	Yellow	Red	Red	Green	Green	Red	Green	Grey	Red	Green	Yellow	Green	Yellow	Green	Green	Grey	Yellow
	MIROC-ESM-CHEM	Red	Green	Green	Green	Green	Green	Green	Green	Grey	Red	Green	Green	Green	Green	Yellow	Green	Grey	Red
	MPI-ESM-MR	Green	Red	Green	Green	Green	Green	Green	Green	Grey	Yellow	Green	Yellow	Green	Green	Green	Green	Grey	Green
	MRI-CGCM3	Green	Yellow	Yellow	Green	Green	Green	Green	Green	Grey	Yellow	Green	Green	Green	Green	Green	Green	Grey	Green
	NorESM1	Red	Red	Yellow	Green	Green	Green	Green	Green	Grey	Red	Green	Green	Green	Green	Green	Green	Grey	Green

Grey	Not available
Green	Valid for > 70% of the analysed stations
Yellow	Valid for >50% and <70% of the analysed stations
Red	Valid for <50% of the analysed stations

Table 2: Summary of the validation process for long-term climate simulations downscaled.

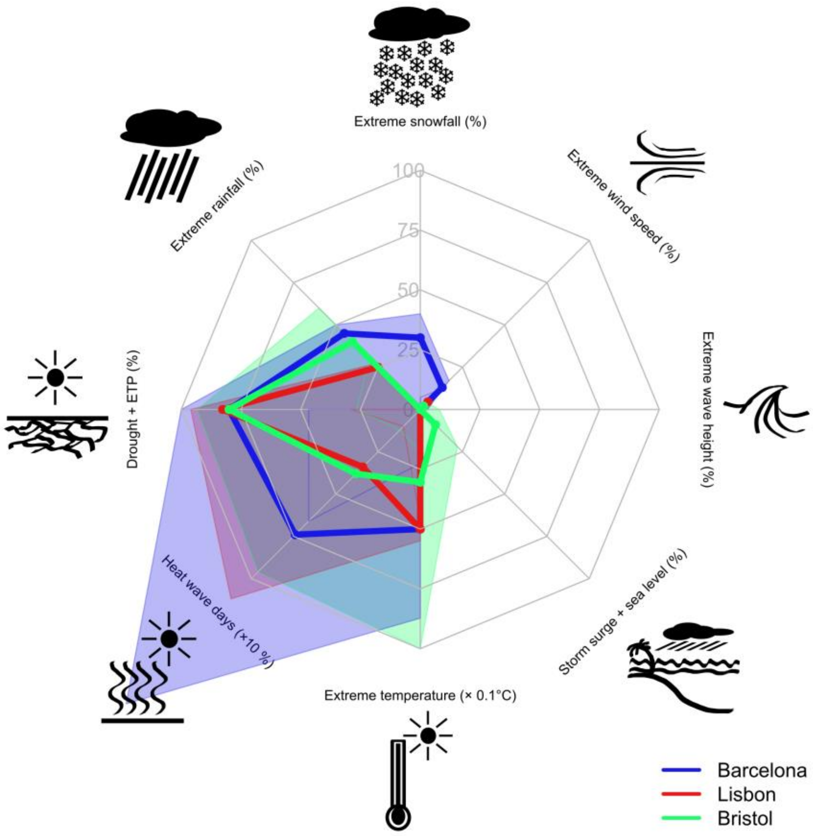

Fig. 1: *Extremes Compass Rose for Barcelona, Lisbon and Bristol: Maximum point change in climate extreme events along the century taking into account return periods between 2 and 100 years. The centre represents no changes and the edge corresponds to an increase of 100% for every variable except for heat wave days (border is +1000%) and extreme temperature (border is +10°C). Thick lines represent the median scenario and the shaded area is the uncertainty region (95%).*

Extreme rainfall events, which are common in the Mediterranean climate of Barcelona, are presumed to notably increase 30% at subdaily scale and 45% in the maximum daily precipitation with remarkable little uncertainty, ranging from 30 to 50%. These results are also reached by 2071-2100 period regarding 100-year return period events. Most frequent events also present increases in extreme values, although less pronounced. In the case of snowfall only an increase in these events is expected for long return-period events (100 years), being only significant for 2011-2040 period, with a median in the change of 40% ranging values from 5% to 50% in the amount of surface snow measured. For more frequent return periods a decrease in snowfall is expected.

For Lisbon, extreme temperature peak values are presumed to significantly increase for all time periods of the century and all return periods. Highest increases are expected by the end of the century, with a median increase of +5.1°C and little uncertainty for 100-year events (from +4.7°C to 5.6°C), although the biggest increase is expected for 2-year events, with a median of +5.0°C and a spread ranging from 1.9°C up to 7.2°C. Heat wave days are also presumed to suffer from a great increase in extreme values, with a median of 250% increase but an uncertainty that makes change non-significant (from 0% up to 1000%). Hydrological drought values behave the same, with a great median increase of +80% but incertitude ranging from 0% up to +90%. However, pluviometric drought (only-dependent of the rainfall or SPI) is not expected to change. On the other hand, extreme hourly rainfall could rise up to +30%, but the extreme daily precipitation does not show significant changes.
For Bristol, extreme temperature values are presumed to raise about +3.1°C by 2100, with an uncertainty level between +1.8°C to a remarkable +10.2°C under the worst-case scenario, showing thus a huge spread. These values are practically identical for all return periods considered (2, 10 and 100 years). Great variations are also expected for heat wave days, ranging the increase from +50% to up to +800% having a median of 280%, also by 2071-2100 period. As a result of this, hydrological drought is also expected to rise noticeably with high uncertainty, being the median an increase in 80% with an uncertainty interval from 25% to 90%. Extreme rainfall could increment about 30% at subdaily scale and 40% at daily scale. Considering oceanic variables, little change in extreme wave height is observed, being in all case a decrease, with a peak change of -25% in expected maximum height in waves by 2041-2070 period for most extreme events (especially for 100-year return ones). However, storm surge is presumed to increase (considering too sea level rise) with a maximum of a 9% increase by 2071-2100 for most frequent events (2-year).

4.3. Discussion

Generally, systematic errors were small for most of the models and therefore they could be corrected, especially in the case of climate timescale. However, some nuances can stand out for the closest time horizons: Seasonal and decadal simulations are adequate for extreme precipitation if the teleconnection-based approach is used, while temperature is best simulated using drift-corrected dynamical outputs. Extreme wind speed cannot be adequately simulated for Lisbon at decadal horizons and, therefore, only the climate timescale is available for this city.
Regarding the projections, climate change leads to a more extreme heat in the three RESCCUE cities, with a tendency towards more extreme rainfall behaviour according to a more energetic atmosphere (faster physical processes). In terms of relative values, the greatest increase is expected in heat wave days. This is because an increase of 2°C degrees in the average temperature causes that the days per year with heat wave pass from 5 days in the reference time period to more than 20 days in the future projections. For the evolution of the extreme dryness, it is necessary to distinguish between two types of drought: pluviometric drought (related with the recorded rainfall) and hydrological drought (availability of the ground or surface

water). The first type will not change significantly (i.e. SPI will not decrease), but the water shortages (hydrological drought) will increment due to a greater evapotranspiration (decrease in the SPEI).

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