Climate change and heatwaves in the main coastal cities of the Basque Country

In this paper we analyse the probabilistic behaviour of heatwaves (HWs) in the main coastal cities of the Basque Country (Bayonne, Bilbao and Donostia-San Sebastián) in the twenty-first century. We estimate HW behaviour using data from eight climate circulation models under two representative concentration pathways (RCP 8.5 and RCP 4.5). We model HWs according to three factors: number per annum, duration and intensity, including correlations, and find very different results for each climate model. This highlights the problem of using a single model. Under RCP 8.5, we find an expected mean excess over the 30ºC temperature threshold of 4.19ºC for Bayonne, 4.05ºC for Bilbao and 4.14ºC for Donostia-San Sebastián in 2100. These expected values are based on incomplete information, so we also calculate several risk measures.

En este artículo analizamos el comportamiento probabilístico de las olas de calor (HWs) en las capitales costeras del País Vasco (Bayona, Bilbao, Donostia- San Sebastián) en el siglo XXI. Estimamos el comportamiento futuro de las HWs utilizando ocho modelos de circulación climática bajo dos trayectorias de concentración representativas (RCP 8.5, RCP 4.5). Modelizamos las HWs conforme a tres factores: número anual, duración e intensidad, incluyendo correlaciones, encontrando resultados muy diferentes dependiendo de cada modelo climático, constatando la problemática de confiar en un solo modelo. En el escenario más desfavorable, RCP 8.5, obtenemos una temperatura media de exceso sobre el límite de 30ºC de 4,19ºC en Bayona, 4,05ºC en Bilbao y 4.14ºC en Donostia-San Sebastián en 2100. Como el valor esperado nos da una información limitada, calculamos adicionalmente varias medidas de riesgo.

XXI. mendean, bero-boladek (HW) Euskal Herriko kostaldeko hiriburuetan (Baiona, Bilbo, Donostia) izan duten portaera probabilistikoa aztertzen dugu artikulu honetan. HWen etorkizuneko portaera aurreikusteko, zortzi zirkulazio klimatiko dituen eredua erabili dugu, bi kontzentrazio-ibilbide adierazgarritan oinarritzen dena (RCP 8.5, RCP 4.5). HWak hiru faktoreren arabera modelizatu ditugu: urteko kopurua, iraupena eta intentsitatea. Korrelazioak ere hartu dira kontuan, eta emaitza oso desberdinak lortu dira klima-eredu bakoitzaren arabera. Beraz, eredu bakar batekin fidatzeak arazoak dakartzala egiaztatu dugu. Kasurik txarrenean, RCP 8.5, 30 ºC-tik gorako batez besteko tenperatura hauek lortzen ditugu 2100an: 4,19 ºC Baionan, 4,05 ºC Bilbon eta 4,14 ºC Donostian. Aurreikusitako balioak informazio mugatua ematen digunez, hainbat arrisku-neurri ere kalkulatu ditugu.

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1. INTRODUCTION

Heatwaves are one of the main impacts of climate change (CC) (Abadie *et al.*, 2019). Climate change can affect the intensity, number and duration of extreme events (IPCC 2012, 2013). The future occurrences of extreme heat modelled are a function of the RCP scenarios and the geographical factors used.

In this paper, we analyse future HW behaviour in the main coastal cities of the Basque Country (Bayonne, Bilbao and Donostia-San Sebastián). The selection of cities has been motived by data availability. Additionally, this selection complements with heatwave information a previous study by Sainz de Murieta *et al.* (2018) that assessed sea-level rise in Basque coastal cities.

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The first step is to define what is meant by «heatwave». One of the main effects of heatwaves is on health. Diaz *et al.* (2015), using epidemiological and climate data, calculated for Spain and at the regional scale, critical temperature values above which there is a significant impact on mortality. These authors define a heatwave as one or more consecutive days exceeding the trigger temperature. The same definition has been used by Diaz *et al.* (2019) and Abadie *et al.* (2019). Note that these critical temperature values calculated by Diaz *et al.* (2015) are regionally different, the values are 30ºC for Bizkaia and Gipuzkoa (see Figure 2 of Diaz *et al.*, 2015) and we assume also 30ºC for Lapurdi. For example, in Madrid the critical threshold occurs at a temperature of 34ºC.

As in Diaz *et al.* (2015), we consider for our study that there is a HW when the maximum daily temperature on one or more consecutive days exceeds 30ºC, which we take as the critical temperature. There are other standards criteria about the critical temperature, as that of the Spanish Meteorological Agency (AEMET), but we use a criterion especially adjusted to the region studied.

HWs affect health especially that of risk groups such as elderly people, children and those who work outdoors. In extreme cases, especially within the aforementioned vulnerable groups, exposure to extreme heatwave conditions can lead to premature deaths. Human adaptation is certainly possible but this aspect of future behaviour is very difficult to predict. More severe HWs will trigger increases in the use of air conditioning, affecting peak demand in electrical systems.

The World Health Organization (WHO) and the World Meteorological Organization (WMO, 2015) state that HWs are one of the most dangerous weather events. According to the WMO, HWs are likely to burden health and emergency services, affect physical infrastructures (energy, water, transport), increase demand for water and electricity (possibly resulting in power shortages or even blackouts), negatively affect crops and livestock and thus also impact other sectors such as clothing and food retailing, ecosystem services and tourism.

The impact of HWs is worse in urban areas because of the heat island effect. This is aggravated by the increasing numbers of people who live in urban areas.

This situation may worsen in the future: the IPCC (Intergovernmental Panel on Climate Change) expects an increase in the frequency, duration and magnitude of HWs over the course of this century (IPCC 2012, 2013).

Christidis *et al.* (2015) investigate how the likelihood of having another extremely hot summer in one of the worst affected parts of Europe has already changed. They find that events which in the early 2000's were expected to occur twice a century are now considered to have significantly shorter return periods and occur on average twice per decade.

Abadie *et al.* (2019) analyse the expected future mortality caused by the impact of CC in HWs in two Spanish cities (Madrid and Bilbao), using a single climate model with two RCP scenarios. Their paper calculates measures of risk such as the 95% percentile and the mean of the average of the 5% of worst cases.

Lo *et al* (2019) analyse future heat-related mortality induced by CC in 12 U.S. cities. They show that increasingly ambitious mitigation to meet the temperature goals set in the Paris Agreement can prevent substantial heat-related mortality in the cities in question. They calculate that ratcheting up mitigation ambition to meet the 2°C threshold target could prevent between 70 and 1980 heat-related deaths per city per annum during extreme events.

Díaz *et al.* (2019) analyse the mortality impact of high temperatures for 2021-2050 and 2051-2100 under RCP8.5 with and without adaptation. They conclude that in the no adaptation case overall annual mortality attributable to high temperatures in Spain could total 1414 deaths/year in the first period and as many as 12,896 deaths/year in the second.

Mitchell *et al.* (2016) quantify the role of human activity in climate and heat-related mortality by analysing the Europe-wide response to the high temperatures in 2003 (which caused up to seventy thousand excess deaths in Europe) and the localised responses in London and Paris.

Muller *et al.* (2016) find that the probability of extremely hot summers is now about ten times greater in many regions of the world than it would have been in the absence of past greenhouse gas increases due to CC.

The main contribution of this work are, first, the application of the model defined by Abadie *et al.* (2019) to the main Basque coastal cities; second, and more importantly, the analysis of results when different climate models are used, which highlights the problem of relying on results from a single model.

The rest of the paper is organised as follows. Section 2 is dedicated to material and methods, and includes a description of the data used in the paper and of the stochastic model deployed. Section 3 presents our findings and Section 4 sets out conclusions.

2. MATERIALS AND METHODS

2.1. The data

To investigate the impacts of extreme temperatures in the three Basque coastal cities targeted (Bayonne, Bilbao and San Sebastián) we used the recommended multi-model ensemble approach since the ensemble outperforms individual projections and provides a more reliable picture of future changes (Sillmann *et al.*, 2013b). A multi-dynamic Regional Climate Model (RCM) downscaling of individual Global Circulation Models (GCMs) is also desirable (Smid and Costa, 2017). The European branch of the CORDEX experiment currently provides the largest collection of simulations, with data at two different resolutions: 0.11° and 0.44°. These simulations have been assessed by many researchers. Projected climate variables were compared with observed values (e.g. Abiodun, *et al.*, 2017; Hofstra *et al.*, 2009; Soares and Cardoso, 2018) and indices based on simulations of daily minimum and maximum temperature CORDEX data were extensively validated against their counterparts computed on an observational dataset (Lelieveld *et al.*, 2016; Pereira, *et al.*, 2017). These validation exercises are usually performed using the Ensemble-OBS gridded observational dataset as per Haylock *et al.*, (2008). Some studies specifically assess the ability of models to project HWs (e.g. Ouzeau *et al.*, (2016), Vautard *et al.*, (2013); or Lhotka *et al.*, (2018)) and the literature in general confirms the reliability of EURO-CORDEX data (e.g. Kotlarski *et al.*, (2014)).

EURO-CORDEX models exhibit common biases in underestimating heat extremes in Scandinavia, and the contrary for Southern and Central Europe. They also show large-scale cooling over vast continental areas in simulations at increased resolution. Detailed analyses of biases can be found in Vautard *et al.* (2013). Despite these systematic biases, simulated values of temperature variables have been found to be especially reliable.

Of the two available EURO-CORDEX resolutions, we chose the finer grid projections (~ 12.5 km). Coarser simulations have been shown to project drier summer conditions (Kotlarski *et al.*, 2014) and very persistent HWs (Vautard *et al.*, 2013). These issues are improved in the higher resolution (Kotlarski *et al.*, 2014; Lhotka *et al.*, 2018): the main advantages of finer-scale projections are found in the warm season (Soares and Cardoso, 2018; Lhotka *et al.*, 2018). These improvements can be attributed to enhanced orography data and better-resolved local feedbacks, which are pronounced in some coastal regions due to more accurate representation of coastline and coastal breezes (Vautard *et al.*, 2013). The same goes for areas of complex terrain (Lhotka *et al.*, 2018). Both these factors are relevant in the context of our target cities on the coast of the Basque Country, an orographically complex region.

We excluded some models from the full EURO-CORDEX ensemble due to shortcomings in the Mediterranean area (Kotlarski *et al.*, 2014) and in their ability to estimate the intensity of extreme events (Vautard *et al.*, 2013). The resulting subset used in this work comprises 8 simulations containing different GCM/RCM combinations drawn up by seven different institutions (Table 1). The daily maximum near-surface temperature data for 1971-2100 are taken from the ESG (Earth System Grid) data repository and details on models can be found on the EURO-CORDEX website (http://www.euro-cordex.net).

Out of all the Representative Concentration Pathway (RCP) scenarios adopted by the IPCC for its 5th Assessment Report (Christensen *et al.*, 2013), we use RCP4.5 and RCP8.5 here. Unlike the SRES (Special Report on Emission Scenarios) (Nakicenovic *et al.*, 2000) scenarios, they are not associated with particular storylines and thus account for the combined uncertain influence of economic, technological, demographical and policy factors (Sillmann *et al.*, 2013b).

Table 1. **LIST OF GCM/RCM COMBINATIONS USED**

Organisation	RCM	Driving GCM
Climate Limited-area Modelling community (CLMcom)	CCLM4-8-17	CNRM-CERFACS-CNRM-CM5
Swedish Meteorological and Hydrological Institute (SMHI)	RCA4	CNRM-CERFACS-CNRM-CM5
Royal Netherlands Meteorological Institute (KNMI)	RACMO22E	ICHEC-EC-EARTH
Danish Meteorological Institute (DMI)	HIRHAM5	ICHEC-EC-EARTH
Institut Pierre Simon Laplace (IPSL-INERIS)	WRF331F	IPSL-IPSL-CM5A-MR
Swedish Meteorological and Hydrological Institute (SMHI)	RCA4	IPSL-IPSL-CM5A-MR
Climate Limited-area Modelling community (CLMcom)	CCLM4-8-17	MPI-M-MPI-ESM-LR
Max Planck Institute - CSC group (MPI - CSC)	REMO2009	MPI-M-MPI-ESM-LR

Source: http://www.euro-cordex.net http://www.euro-cordex.net

The RCP4.5 scenario was designed at the Pacific Northwest National Laboratory's Joint Change Research Institute (JGCRI) by the GCAM modelling team. It describes a future with stabilisation in which total relative forcing reaches a steady balance soon after 2100 with no overshooting of the long-term target (Smith and Wigley, 2006). RCP4.5 represents category IV from the AR4, which contains the vast majority of the scenarios assessed in that report (van Vuuren, 2011). This illustrates the importance of RCP4.5 as a plausible future scenario.

RCP8.5 assumes continued growth in energy demand and hence does not have any peak breaking point in the 21st century. This scenario assumes continuing trends in all anthropogenic activities influencing the climate, with no mitigation policies being implemented (Riahi *et al.*, 2011). We chose this scenario here because it might be more relevant in projected future heat impacts on cities given the additional influence of urbanisation on local climates. Many previous studies have found that the most severe impacts throughout the 21st century are projected under the RCP8.5 scenario (e.g. Jacob *et al.*, 2014; Lhotka *et al.*, 2018; Russo *et al.*, 2015). However, a noteworthy recent finding by Lhotka *et al.* (2018) for the near future (2020-2049) in Central Europe shows the largest increment in HW frequency in the RCP4.5 «low concentration» scenario.

Table 2. **RCP 4.5 MAXIMUM DAILY TEMPERATURE STATISTICS (2006-2100)**

Bayonne	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Maximum temperature °C	44.11	43.43	41.48	38.05	35.06	48.13	46.32	44.38
99% percentile °C	35.65	35.54	32.15	31.09	30.02	39.37	36.14	35.47
95% percentile °C	31.83	31.31	29.14	28.65	27.31	36.00	31.86	32.32
>30 °C (number of days)	2,324	1,969	1,013	685	352	5,564	2,334	2,844
Mean temperature °C	16.56	17.21	17.11	16.71	16.23	19.55	17.17	18.49
Bilbao	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
Maximum temperature °C	45.04	39.75	39.44	35.83	35.09	42.38	43.63	48.18
99% percentile °C	35.92	34.20	31.20	29.88	29.62	37.38	35.76	36.94
95% percentile °C	32.20	31.14	28.49	27.72	27.05	34.77	31.89	33.74
>30 °C (number of days)	2,504	2,069	682	311	282	5,480	2,378	4,199
Mean temperature °C	16.48	17.08	16.90	16.48	15.21	19.28	16.98	19.89
Donostia-San Sebastián	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
Maximum temperature °C	43.62	43.16	41.50	36.89	35.20	46.21	44.66	44.10
99% percentile °C	35.33	35.29	31.92	30.39	29.80	39.18	35.57	35.53
95% percentile °C	31.54	31.12	28.90	28.23	27.10	35.92	31.54	31.96
>30 °C (number of days)	2,178	1,936	912	483	303	5,525	2,164	2,635
Mean temperature °C	16.28	16.95	16.66	16.41	15.92	19.32	16.88	18.29

Source: Calculated by the authors.

In short, we use eight different GCM/RCM simulation runs under one medium stabilisation scenario (RCP4.5) and one very high emission baseline scenario (RCP8.5), thus meeting the requirement of having a multi-model and multi-scenario set up for our future climate impact experiment.

We obtain near-surface daily maximum temperatures for each central grid cell in each of our target cities. Thus 34,675 simulated values are used for each city, RCP and model. Tables 2 and 3 show some basic statistics of these time series.

Table 3. **RCP 8.5 MAXIMUM DAILY TEMPERATURE STATISTICS (2006-2100)**

Bayonne	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Maximum temperature °C	46.15	47.61	43.48	41.81	37.38	48.45	49.36	47.31
99% percentile °C	36.88	36.71	34.57	32.53	30.57	41.80	38.92	37.78
95% percentile °C	32.66	31.99	31.11	29.65	27.73	38.06	34.21	33.96
>30 °C (number of days)	2,652	2,269	1,926	1,233	477	6,654	3,421	3,882
mean temperature °C	17.26	17.87	17.95	17.42	16.82	20.52	18.16	19.37
Bilbao	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
Maximum temperature °C	45.20	44.54	40.48	37.49	38.56	45.92	46.60	47.05
99% percentile °C	36.98	35.21	33.34	31.06	30.49	40.00	37.87	39.16
95% percentile °C	32.85	31.90	30.46	28.76	27.54	36.82	33.78	35.57
>30 °C (number of days)	2,838	2,534	1,678	747	446	6,479	3,394	5,381
Mean temperature °C	17.15	17.71	17.74	17.19	15.83	20.20	17.93	20.84
Donostia - San Sebastian	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
Maximum temperature °C	46.12	47.82	44.14	42.19	37.21	48.12	48.69	53.34
99% percentile °C	36.45	36.45	34.47	31.90	30.34	41.59	38.29	37.66
95% percentile °C	32.34	31.86	30.97	29.23	27.51	37.96	33.77	33.68
>30 °C (number of days)	2,515	2,230	1,848	985	427	6,570	3,207	3,608
Mean temperature °C	16.96	17.60	17.52	17.12	16.52	20.29	17.84	19.17

Source: Calculated by the authors.

As in Diaz *et al.* (2015), we assume that there is a HW when the maximum daily temperature on one or more consecutive days exceeds 30ºC in Bizkaia and Gipuzkoa, which we take as the critical temperature. We assume 30ºC for Lapurdi as well. We apply this criterion to every day of the year, without discriminating by months.

2.2 **The stochastic model**

We consider three HW characteristics: a) the number of HWs in a given year; b) their duration in days; and c) their intensity measured by their exceedance of the critical temperature of 30ºC. We also consider two correlations: a) between the number of HWs per year and their durations; and b) between the duration of HWs and their temperature exceedances.

We use the Abadie *et al.* (2019) model with all series data, not only for the summer period. See Abadie *et al.* (2019) for a complete and detailed description of the model. However, a brief description of this model is provided in Appendix A.

The model parameters are shown in Table 4.

Table 4. **MODEL PARAMETERS**

Parameter	Units	Description
$\lambda(t)$	(-)	Number of HWs in year t
α	(y^{-1})	Exponential parameter of $\lambda(0)$
d(t)	(days)	HW duration
γ	(y^{-1})	Exponential parameter of d(0)
g(t)	(°C)	Temperature exceedance above 30°C
β	(y^{-1})	Exponential parameter of g(0)
σ	(°C)	Volatility of temperature exceedance
$\rho_{1,2}$	(-)	Correlation of duration and temperature exceedance
$\rho_{2,3}$	(-)	Correlation of number of HWs and duration
σ_d	(°C)	Volatility of duration

Source: Abadie *et al.* (2019).

The models are calibrated using nonlinear least squares.

3. RESULTS

3.1 Expected results

We use the following codes to represent cities, the model and the scenario: CCMSS.

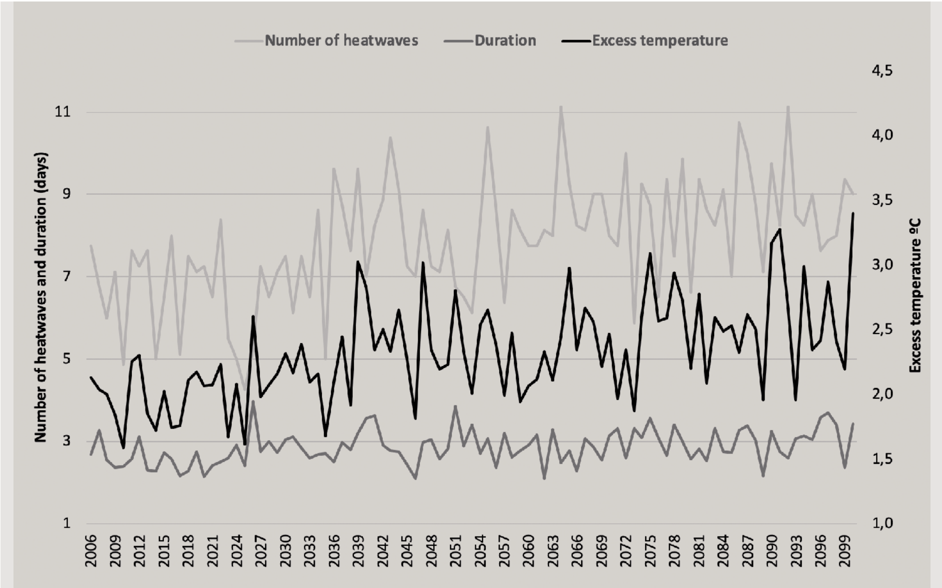
Where CC stands for the city (BA for Bayonne, BI for Bilbao and SA for Donostia–San Sebastián), M is the model M∈{1,2,….,8} and SS is the scenario (SS∈{45,85} for RCP 4.5 and RCP 8.5 respectively).

Tables 5 and 6 show the parameter values and results for Bayonne under RCP 4.5 and RCP 8.5. The different results for each model are clearly visible: the mean shows that under the RCP 4.5 scenario the mean estimation of HW occurrence for Bayonne increases overtime to 9.26 HWs in 2100. Duration also increases to a mean of 2.76 days in 2100 and a mean exceedance of 2.79ºC of the critical temperature of 30ºC in that year.

Table 5 also includes information about distribution (volatilities and correlation) that can be used to build distributions of HW components. These can be used to generate Monte Carlo distributions and calculate expected values and risk measures such as Value-at-Risk and Expected Shortfall.

Figure 1 shows the trend in the number of HWs, their duration and their temperature exceedance using the mean of the eight models under the RCP 4.5 scenario. This Figure confirms a growing trend in all three variables.

Figure 1. **MEAN NUMBER OF HWS, DURATION AND TEMPERATURE EXCEEDANCE IN BAYONNE UNDER THE RCP 4.5 SCENARIO**



Source: Calculated by the authors.

RCP 8.5 shows a mean in 2100 of 14.55 HWs with a duration of 4.19 days and a mean exceedance of 4.11ºC over the 30ºC critical temperature. These values are higher than those obtained with RCP 4.5.

Figure 2 shows the trend in the number of HWs, their duration and their temperature exceedance using the mean of the eight models under the RCP 8.5 scenario. The HW behaviour shown here is much more disturbing than in the RCP 4.5 scenario. The figure confirms the upward trends shown in Table 6.

Table 5. **BAYONNE HWS RCP 4.5**

Parameters		BA1E45	BA2E45	BA3E45	BA4E45	BA5E45	BA6E45	BA7E45	BA8E45	Mean
$\lambda(0)$		8.5471	6.4043	4.3676	3.2114	1.7824	10.9392	7.7006	10.2925	6.6556
α		0.0015	0.0028	0.0044	0.0059	0.0022	0.0030	0.0055	0.0029	0.0035
d(0)		2.3092	2.7644	1.6931	1.3493	1.4014	4.2530	1.8655	2.1443	2.2225
γ		0.0026	-0.0008	0.0012	0.0030	0.0015	0.0026	0.0049	0.0034	0.0023
g(0)		2.2681	2.5409	1.4091	1.2152	0.4822	3.3627	2.4908	2.2145	1.9979
β		0.0044	0.0005	0.0015	0.0008	0.0105	0.0034	0.0037	0.0037	0.0036
σ		0.9418	1.2066	0.7967	0.6421	0.6720	0.7465	0.8863	0.7478	0.8300
$\rho_{1,2}$		0.1479	0.2680	0.3930	0.2960	0.3670	-0.3529	0.1734	0.0313	0.1655
$\rho_{2,3}$		0.4860	0.7038	0.6092	0.5286	0.5549	0.5792	0.4659	0.4685	0.5495
σ_d		0.8872	1.3427	0.7394	0.7087	1.2764	1.7789	0.8111	0.7609	1.0382
Expected Values		BA1E45	BA2E45	BA3E45	BA4E45	BA5E45	BA6E45	BA7E45	BA8E45	Mean
$\lambda(t)$	2025	8.79	6.75	4.75	3.59	1.86	11.57	8.55	10.88	7.12
$\lambda(t)$	2050	9.13	7.24	5.30	4.15	1.96	12.47	9.81	11.70	7.77
$\lambda(t)$	2075	9.48	7.77	5.92	4.81	2.07	13.43	11.26	12.59	8.48
$\lambda(t)$	2100	9.84	8.33	6.61	5.57	2.19	14.47	12.92	13.54	9.26
d(t)	2025	2.43	2.72	1.73	1.43	1.44	4.47	2.05	2.29	2.32
d(t)	2050	2.59	2.66	1.79	1.54	1.50	4.78	2.32	2.48	2.46
d(t)	2075	2.76	2.61	1.84	1.66	1.55	5.10	2.62	2.70	2.60
d(t)	2100	2.94	2.56	1.90	1.79	1.61	5.45	2.97	2.94	2.76
g(t)	2025	2.47	2.57	1.45	1.23	0.59	3.58	2.67	2.37	2.14
g(t)	2050	2.76	2.60	1.51	1.26	0.77	3.90	2.93	2.60	2.34
g(t)	2075	3.08	2.63	1.56	1.28	1.00	4.24	3.21	2.86	2.55
g(t)	2100	3.44	2.67	1.62	1.31	1.30	4.61	3.51	3.13	2.79

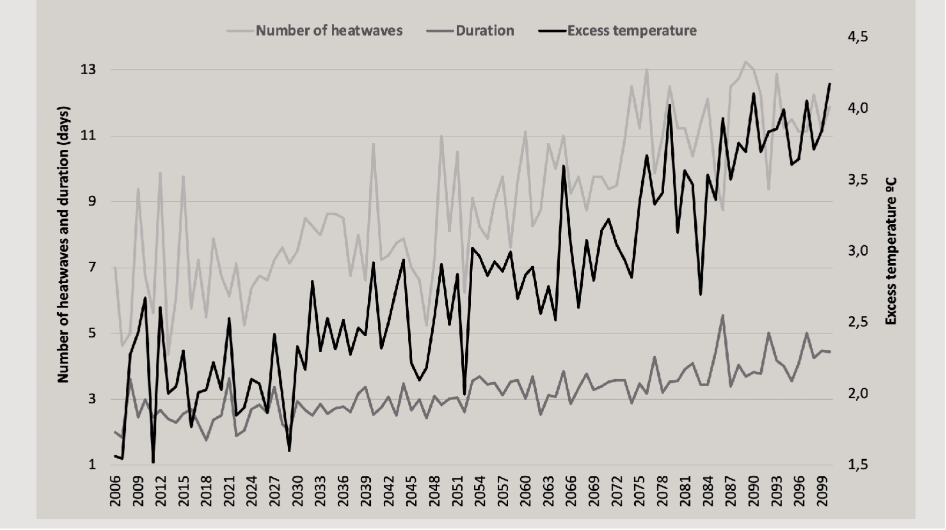
Source: Calculated by the authors.

Table 6. **BAYONNE HWS RCP 8.5**

Parameters		BA1E85	BA2E85	BA3E85	BA4E85	BA5E85	BA6E85	BA7E85	BA8E85	Mean
λ(0)		6.4921	6.3612	4.2294	2.6160	1.1135	11.6384	7.8557	10.4441	6.3438
α		0.0072	0.0052	0.0117	0.0166	0.0150	0.0013	0.0079	0.0059	0.0088
d(0)		2.2616	1.7339	1.6148	1.1968	1.0535	3.4559	1.9187	1.9577	1.8991
γ		0.0055	0.0095	0.0083	0.0080	0.0083	0.0108	0.0088	0.0080	0.0084
g(0)		2.3285	1.7160	1.4980	0.9678	0.5911	3.2610	2.4927	2.1348	1.8737
β		0.0065	0.0100	0.0079	0.0084	0.0112	0.0075	0.0077	0.0078	0.0083
σ		0.8413	1.2186	0.8471	0.7376	0.7067	0.9095	0.9327	0.7697	0.8704
$\rho_{1,2}$		0.1093	0.1415	0.3599	0.5933	0.4547	-0.4117	0.2122	0.0293	0.1860
$\rho_{2,3}$		0.5136	0.6131	0.5210	0.4541	0.5477	0.5691	0.5674	0.5666	0.5441
σ_d		0.8571	1.3597	0.8357	0.6554	1.0765	2.2805	1.1155	1.0830	1.1579
Expected Values		BA1E85	BA2E85	BA3E85	BA4E85	BA5E85	BA6E85	BA7E85	BA8E85	Mean
λ(t)	2025	7.44	7.02	5.28	3.58	1.48	11.93	9.13	11.68	7.50
λ(t)	2050	8.91	7.98	7.07	5.43	2.15	12.32	11.12	13.53	9.36
λ(t)	2075	10.67	9.08	9.46	8.21	3.13	12.73	13.55	15.68	11.67
λ(t)	2100	12.77	10.32	12.67	12.43	4.55	13.15	16.52	18.17	14.55
d(t)	2025	2.51	2.08	1.89	1.39	1.23	4.24	2.27	2.28	2.23
d(t)	2050	2.89	2.64	2.33	1.70	1.52	5.55	2.83	2.78	2.75
d(t)	2075	3.32	3.35	2.87	2.08	1.87	7.26	3.53	3.39	3.39
d(t)	2100	3.81	4.25	3.54	2.55	2.30	9.50	4.39	4.13	4.19
g(t)	2025	2.63	2.07	1.74	1.13	0.73	3.76	2.88	2.47	2.20
g(t)	2050	3.10	2.66	2.12	1.40	0.97	4.53	3.50	3.00	2.71
g(t)	2075	3.65	3.41	2.58	1.72	1.28	5.46	4.24	3.65	3.33
g(t)	2100	4.29	4.38	3.14	2.12	1.69	6.58	5.13	4.43	4.11

Source: Calculated by the authors.

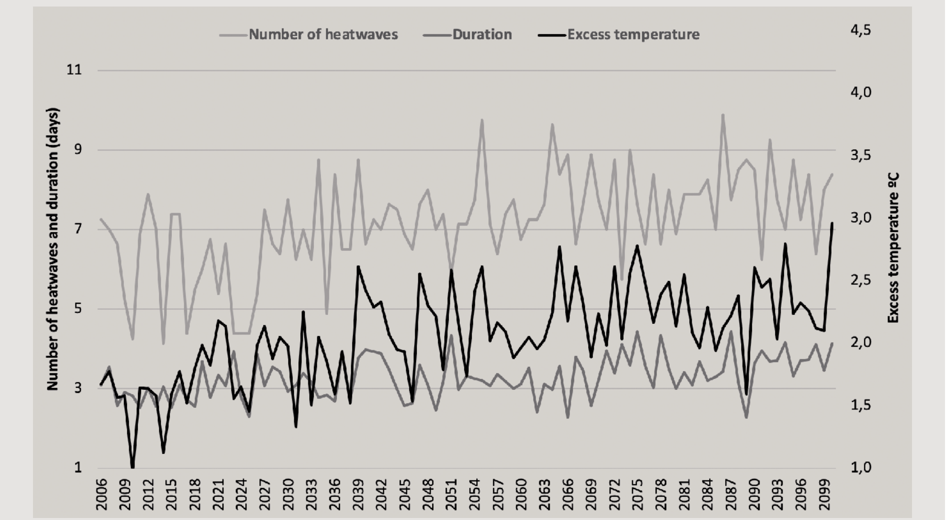
Figure 2. **MEAN NUMBER OF HWS, DURATION AND TEMPERATURE EXCEEDANCE IN BAYONNE UNDER THE RCP 8.5 SCENARIO**



Source: Calculated by the authors.

Tables 7 and 8 show the results for Bilbao and Tables 9 and 10 those for Donostia-San Sebastián.

Figure 3. **MEAN NUMBER OF HWS, DURATION AND TEMPERATURE EXCEEDANCE IN BILBAO UNDER THE RCP 4.5 SCENARIO**



Source: Calculated by the authors.

Table 7: **BILBAO HWS RCP 4.5**

Parameters		BI1E45	BI2E45	BI3E45	BI4E45	BI5E45	BI6E45	BI7E45	BI8E45	Mean
$\lambda(0)$		7.7027	5.7167	2.4776	1.3464	1.4734	9.7975	7.3289	13.4202	6.1579
α		0.0028	0.0047	0.0062	0.0091	0.0029	0.0017	0.0050	0.0013	0.0042
d(0)		2.6061	3.1761	1.4266	0.8216	1.0593	5.0037	2.1181	2.5594	2.3464
γ		0.0027	-0.0011	0.0040	0.0065	0.0042	0.0038	0.0046	0.0040	0.0036
g(0)		2.4318	1.7246	0.8639	0.6528	0.4894	2.6621	2.2793	2.4959	1.7000
β		0.0036	0.0031	0.0043	0.0052	0.0070	0.0041	0.0042	0.0036	0.0044
σ		0.8620	0.8932	0.7480	0.7430	0.6120	0.8018	0.8458	0.7406	0.7808
$\rho_{1,2}$		0.0654	0.0033	0.3769	0.5903	0.4203	-0.6074	0.0806	-0.0469	0.1103
$\rho_{2,3}$		0.5729	0.7286	0.7197	0.5961	0.5920	0.5956	0.5151	0.7087	0.6286
σ_d		1.0657	1.8677	1.2663	0.7304	1.1965	3.0738	0.9211	0.8703	1.3740
Expected Values		**BI1E45**	**BI2E45**	**BI3E45**	**BI4E45**	**BI5E45**	**BI6E45**	**BI7E45**	**BI8E45**	**Mean**
$\lambda(t)$	2025	8.13	6.25	2.79	1.60	1.56	10.11	8.06	13.76	6.67
$\lambda(t)$	2050	8.72	7.04	3.26	2.01	1.68	10.54	9.13	14.23	7.41
$\lambda(t)$	2075	9.36	7.92	3.80	2.53	1.80	10.98	10.34	14.71	8.24
$\lambda(t)$	2100	10.04	8.92	4.44	3.17	1.94	11.45	11.71	15.21	9.16
d(t)	2025	2.74	3.11	1.54	0.93	1.15	5.37	2.31	2.76	2.51
d(t)	2050	2.93	3.03	1.70	1.09	1.27	5.90	2.59	3.05	2.75
d(t)	2075	3.13	2.95	1.88	1.29	1.41	6.48	2.90	3.36	3.00
d(t)	2100	3.35	2.87	2.08	1.51	1.57	7.12	3.25	3.71	3.28
g(t)	2025	2.60	1.83	0.94	0.72	0.56	2.88	2.47	2.67	1.85
g(t)	2050	2.85	1.98	1.04	0.82	0.67	3.18	2.74	2.92	2.06
g(t)	2075	3.12	2.14	1.16	0.94	0.80	3.52	3.05	3.19	2.30
g(t)	2100	3.41	2.32	1.29	1.07	0.95	3.90	3.39	3.49	2.57

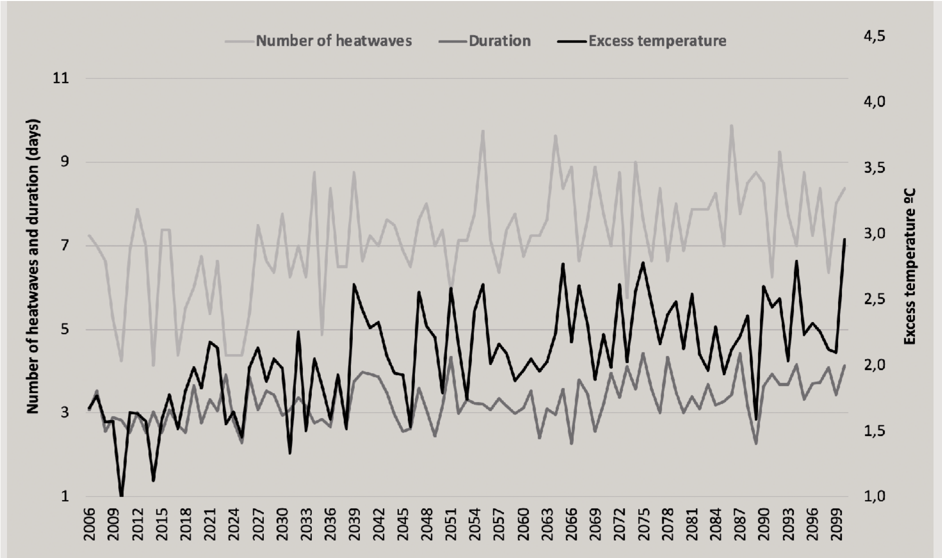
Source: Calculated by the authors.

Table 8. **BILBAO HWS RCP 8.5**

Parameters		BI1E85	BI2E85	BI3E85	BI4E85	BI5E85	BI6E85	BI7E85	BI8E85	Mean
$\lambda(0)$		6.3305	5.3640	2.4599	1.0549	0.9195	10.5684	7.3337	13.3422	5.9216
α		0.0067	0.0081	0.0167	0.0240	0.0173	0.0004	0.0072	0.0025	0.0104
d(0)		2.6448	2.2724	1.4745	0.7909	0.9007	3.8161	1.9980	2.5175	2.0519
γ		0.0050	0.0075	0.0110	0.0124	0.0103	0.0115	0.0102	0.0086	0.0095
g(0)		2.3666	1.4471	0.8299	0.5302	0.4161	2.4552	2.3269	2.3200	1.5865
β		0.0062	0.0092	0.0120	0.0105	0.0163	0.0097	0.0074	0.0086	0.0100
σ		0.8618	0.7596	0.6691	0.5890	0.6984	0.8858	0.8153	0.8343	0.7641
$\rho_{1,2}$		0.0266	0.0102	0.3992	0.5300	0.4668	-0.5468	0.0513	-0.2672	0.0838
$\rho_{2,3}$		0.5336	0.6440	0.5478	0.5870	0.5859	0.6197	0.6431	0.6683	0.6037
σ_d		1.0588	1.6791	1.2326	0.9257	1.1272	2.8158	1.4373	1.3929	1.4587
Expected Values		BI1E45	BI2E45	BI3E45	BI4E45	BI5E45	BI6E45	BI7E45	BI8E45	Mean
$\lambda(t)$	2025	7.19	6.26	3.38	1.66	1.28	10.64	8.42	14.00	7.21
$\lambda(t)$	2050	8.51	7.67	5.13	3.03	1.97	10.75	10.09	14.91	9.35
$\lambda(t)$	2075	10.07	9.39	7.79	5.52	3.04	10.85	12.09	15.89	12.11
$\lambda(t)$	2100	11.91	11.50	11.83	10.05	4.68	10.95	14.49	16.92	15.70
d(t)	2025	2.91	2.62	1.82	1.00	1.09	4.75	2.43	2.96	2.46
d(t)	2050	3.29	3.16	2.39	1.36	1.41	6.33	3.14	3.67	3.12
d(t)	2075	3.73	3.81	3.14	1.86	1.83	8.43	4.05	4.55	3.96
d(t)	2100	4.22	4.59	4.13	2.53	2.36	11.24	5.24	5.63	5.03
g(t)	2025	2.66	1.72	1.04	0.65	0.57	2.95	2.68	2.73	1.92
g(t)	2050	3.11	2.17	1.41	0.84	0.85	3.76	3.23	3.38	2.46
g(t)	2075	3.63	2.73	1.90	1.09	1.28	4.79	3.89	4.19	3.16
g(t)	2100	4.24	3.43	2.56	1.42	1.93	6.10	4.68	5.20	4.05

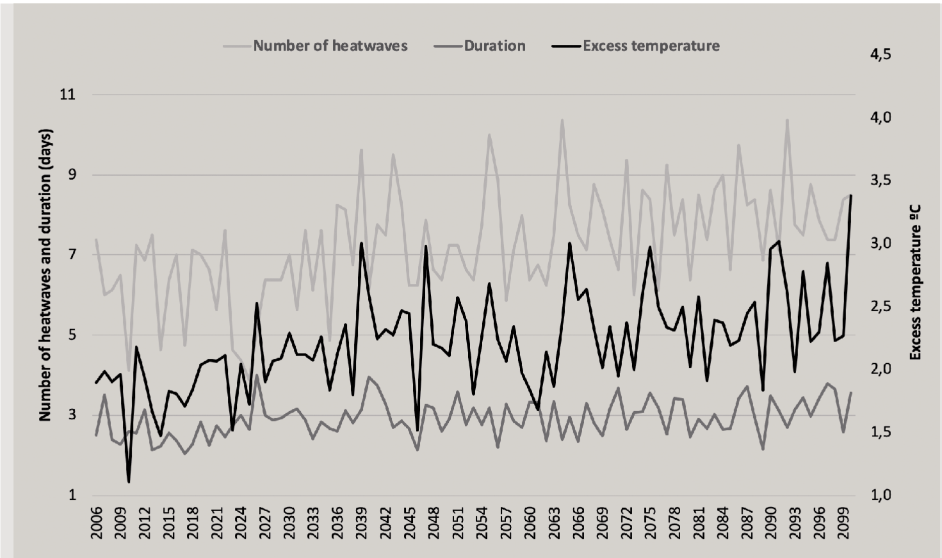
Source: Calculated by the authors.

Figure 4. **MEAN NUMBER OF HWS, DURATION AND TEMPERATURE EXCEEDANCE IN BILBAO UNDER THE RCP 8.5 SCENARIO**



Source: Calculated by the authors.

Figure 5. **MEAN NUMBER OF HWS, DURATION AND TEMPERATURE EXCEEDANCE IN DONOSTIA-SAN SEBASTIÁN UNDER THE RCP 4.5 SCENARIO**



Source: Calculated by the authors.

Table 9. **DONOSTIA-SAN SEBASTIÁN HWS RCP 4.5**

Parameters		SA1E45	SA2E45	SA3E45	SA4E45	SA5E45	SA6E45	SA7E45	SA8E45	Mean
$\lambda(0)$		7.9673	5.9170	3.7493	2.2182	1.6064	11.4845	6.9468	9.3017	6.1489
α		0.0020	0.0033	0.0040	0.0072	0.0025	0.0013	0.0057	0.0042	0.0038
d(0)		2.2083	2.8949	1.6537	1.2751	1.2166	4.1951	1.8453	2.1967	2.1857
γ		0.0030	-0.0011	0.0018	0.0023	0.0020	0.0039	0.0054	0.0021	0.0024
g(0)		2.2835	2.3567	1.3083	0.8673	0.5119	3.3160	2.3153	2.2388	1.8997
β		0.0036	0.0008	0.0026	0.0023	0.0086	0.0034	0.0039	0.0032	0.0036
σ		0.9155	1.1682	0.8883	0.6228	0.6743	0.7372	0.8838	0.7780	0.8335
$\rho_{1,2}$		0.1773	0.2430	0.4565	0.3239	0.4806	-0.4797	0.2078	-0.0109	0.1748
$\rho_{2,3}$		0.5032	0.7360	0.7114	0.4135	0.5714	0.5159	0.4383	0.4816	0.5464
σ_d		0.8440	1.5830	0.9739	0.7833	1.0473	2.2158	0.8302	0.7802	1.1322
Expected Values		SA1E45	SA2E45	SA3E45	SA4E45	SA5E45	SA6E45	SA7E45	SA8E45	Mean
$\lambda(t)$	2025	8.28	6.30	4.04	2.55	1.68	11.76	7.74	10.08	6.61
$\lambda(t)$	2050	8.70	6.83	4.47	3.05	1.79	12.14	8.92	11.19	7.26
$\lambda(t)$	2075	9.15	7.41	4.94	3.65	1.91	12.52	10.28	12.44	7.97
$\lambda(t)$	2100	9.62	8.04	5.46	4.38	2.03	12.92	11.85	13.82	8.76
d(t)	2025	2.34	2.83	1.71	1.33	1.26	4.52	2.04	2.29	2.29
d(t)	2050	2.52	2.75	1.79	1.41	1.33	4.98	2.34	2.41	2.43
d(t)	2075	2.72	2.68	1.87	1.49	1.40	5.50	2.67	2.55	2.58
d(t)	2100	2.93	2.60	1.95	1.58	1.47	6.06	3.06	2.69	2.74
g(t)	2025	2.45	2.39	1.37	0.91	0.60	3.54	2.49	2.38	2.03
g(t)	2050	2.68	2.44	1.47	0.96	0.75	3.85	2.75	2.58	2.22
g(t)	2075	2.93	2.49	1.56	1.01	0.93	4.19	3.03	2.80	2.43
g(t)	2100	3.20	2.54	1.67	1.07	1.15	4.57	3.34	3.03	2.65

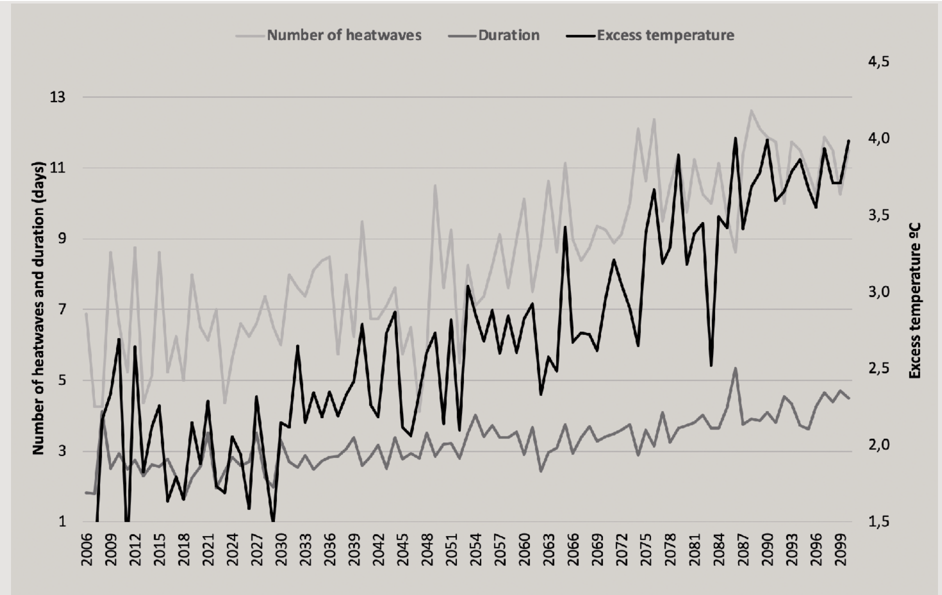
Source: Calculated by the authors.

Table 10. **DONOSTIA-SAN SEBASTIÁN HWS RCP 8.5**

Parameters		SA1E85	SA2E85	SA3E85	SA4E85	SA5E85	SA6E85	SA7E85	SA8E85	Mean
$\lambda(0)$		5.8548	5.8098	3.7688	1.6352	0.9873	11.2263	7.1728	9.9195	5.7968
α		0.0081	0.0057	0.0122	0.0207	0.0159	0.0012	0.0084	0.0065	0.0098
d(0)		2.4024	1.8435	1.6162	0.9213	1.0283	3.4393	1.9061	1.8682	1.8782
γ		0.0047	0.0094	0.0089	0.0112	0.0078	0.0116	0.0088	0.0075	0.0087
g(0)		2.1170	1.5396	1.4425	0.7473	0.5063	3.2203	2.3247	2.0650	1.7453
β		0.0074	0.0113	0.0083	0.0100	0.0128	0.0076	0.0081	0.0080	0.0092
σ		0.8207	1.1962	0.9319	0.7511	0.7247	0.9522	0.8963	0.7898	0.8829
$\rho_{1,2}$		-0.0268	0.1158	0.3918	0.6297	0.4324	-0.4571	0.2632	0.1602	0.1887
$\rho_{2,3}$		0.4035	0.5510	0.5113	0.5196	0.5160	0.5287	0.5787	0.6039	0.5266
σ_d		1.0364	1.5040	1.0007	0.7196	1.0650	2.4695	1.0931	0.8884	1.2221
Expected Values		SA1E45	SA2E45	SA3E45	SA4E45	SA5E45	SA6E45	SA7E45	SA8E45	Mean
$\lambda(t)$	2025	6.83	6.47	4.75	2.42	1.34	11.49	8.41	11.23	6.99
$\lambda(t)$	2050	8.37	7.46	6.43	4.06	1.99	11.85	10.38	13.22	8.94
$\lambda(t)$	2075	10.25	8.60	8.72	6.80	2.96	12.21	12.81	15.57	11.43
$\lambda(t)$	2100	12.56	9.91	11.81	11.40	4.41	12.59	15.80	18.33	14.61
d(t)	2025	2.63	2.20	1.91	1.14	1.19	4.29	2.25	2.15	2.22
d(t)	2050	2.96	2.78	2.39	1.51	1.45	5.73	2.80	2.60	2.76
d(t)	2075	3.32	3.52	2.98	2.00	1.77	7.65	3.49	3.14	3.43
d(t)	2100	3.74	4.45	3.73	2.64	2.15	10.22	4.34	3.78	4.27
g(t)	2025	2.44	1.91	1.69	0.90	0.65	3.72	2.71	2.41	2.08
g(t)	2050	2.94	2.53	2.08	1.16	0.89	4.50	3.32	2.94	2.62
g(t)	2075	3.53	3.36	2.56	1.49	1.23	5.43	4.06	3.59	3.29
g(t)	2100	4.25	4.47	3.14	1.91	1.69	6.57	4.97	4.39	4.14

Source: Calculated by the authors.

Figure 6. **MEAN NUMBER OF HWS, DURATION AND TEMPERATURE EXCEEDANCE IN DONOSTIA-SAN SEBASTIÁN UNDER THE RCP 8.5 SCENARIO**



Source: Calculated by the authors.

3.2 **Risk measures**

We calculated risk measures using 50,000 simulations of correlated values. Table 11 shows these risk measures for the year 2100, where VaR (95%)[1] is the 95% percentile and ES (95%)[2] is the mean of values above the 95% percentile. These are standard finance risk measures (see Hull, 2012). The ES(95%) is a better risk measure as it represents the tail of the distribution better. As in financial & economic cases, this paper takes into account two risk measures (VaR and ES). We consider the expected mean to be an incorrect measurement since risk measures should capture the worst cases, which are less likely but possible.

Table 11 shows that under RCP 8.5 temperature exceedances in HWs in 2100 may exceed 5.53ºC in Bayonne, 5.32ºC Bilbao and 5.60ºC in Donostia-San Sebastián in 5% of cases. Furthermore, the 95% percentile exceeds the expected mean temperature exceedance and shows values of 5.88ºC, 5.62ºC and 5.96ºC respectively for the cities analysed.

[1] Value at Risk with 95% confidence level.

[2] Expected Shortfall with 95% confidence level.

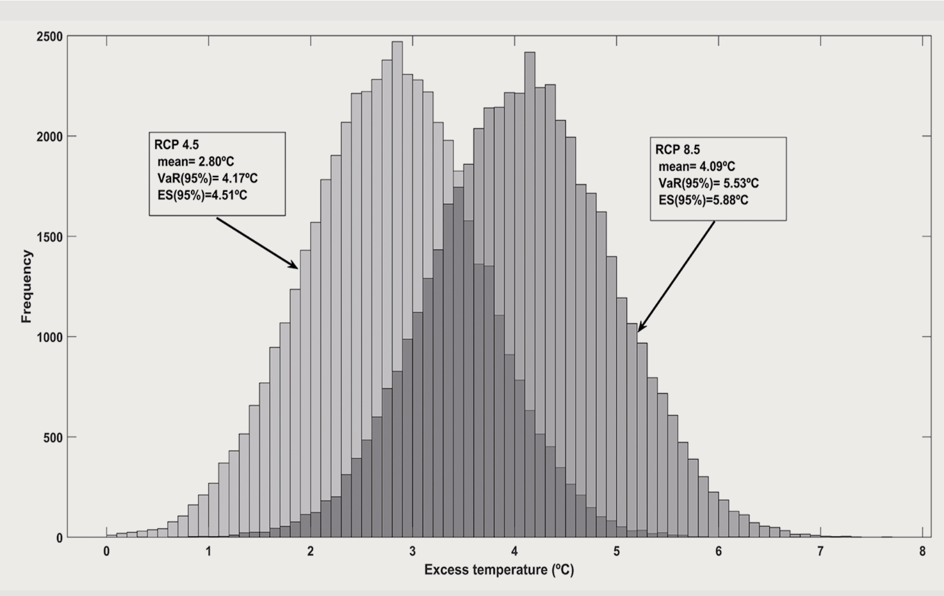
Table 11. **TEMPERATURE EXCEEDANCES ABOVE THE CRITICAL THRESHOLD FOR 2100 (ºC). EXPECTED VALUES AND TWO RISK MEASURES**

City	Scenario	Mean	VaR(95%)	ES(95%)
Bayonne	RCP 4.5	2.80	4.17	4.51
	RCP 8.5	4.09	5.53	5.88
Bilbao	RCP 4.5	2.57	3.86	4.18
	RCP 8.5	4.06	5.32	5.62
Donostia San-Sebastián	RCP 4.5	2.66	4.04	4.39
	RCP 8.5	4.15	5.60	5.96

Source: Calculated by the authors.

Figure 7 illustrates the distributions for Bayonne under the RCP 4.5 and RCP 8.5 scenarios.

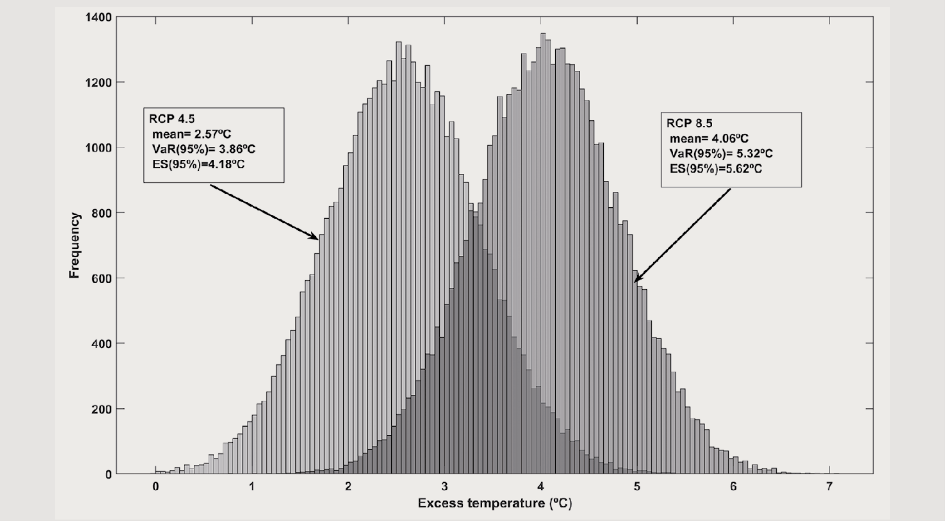
Figure 7. **DISTRIBUTION FOR BAYONNE TEMPERATURE EXCEEDANCE IN 2100**



Source: Calculated by the authors.

Figure 8 shows the temperature exceedance distributions for Bilbao.

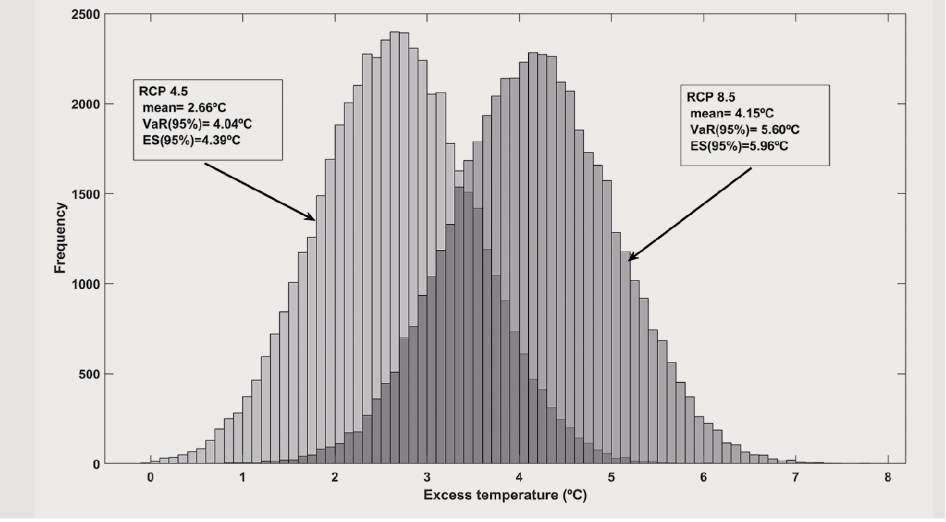
Figure 8. **DISTRIBUTION FOR BILBAO TEMPERATURE EXCEEDANCE IN 2100**



Source: Calculated by the authors.

Figure 9 shows the temperature exceedance distributions for Donostia-San Sebastián.

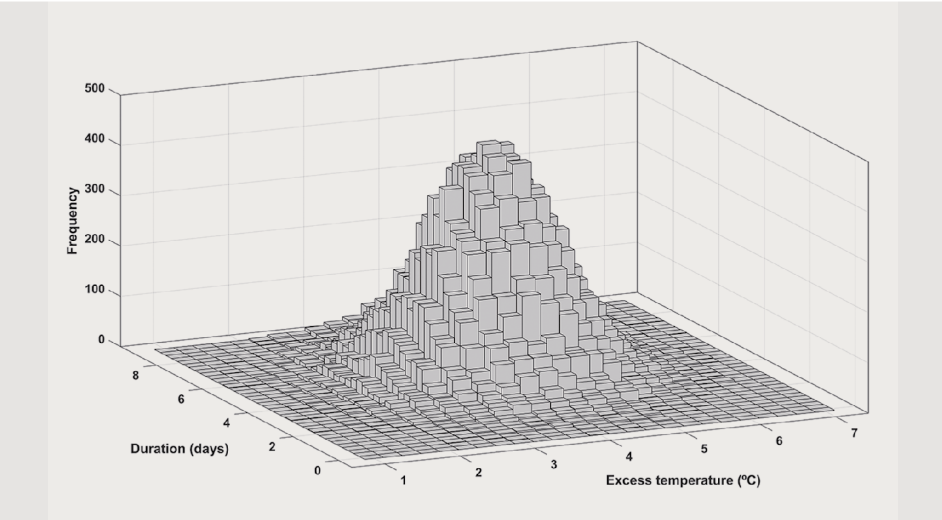
Figure 9. **DISTRIBUTION FOR DONOSTIA-SAN SEBASTIÁN TEMPERATURE EXCEEDANCE IN 2100**



Source: Calculated by the authors.

Figure 10 shows the joint distribution of temperature exceedance and duration for Bilbao in 2100 under RCP 8.5. Note that these variables are correlated.

Figure 10. **BILBAO TEMPERATURE EXCEEDANCE AND HW DURATION IN 2100 UNDER RCP 8.5**



Source: Calculated by the authors.

4. DISCUSSION AND CONCLUSIONS

In this paper, we analyse the expected impacts of HWs under CC for the main Basque coastal cities. Three HW characteristics (number, duration and intensity) are considered and eight climate models are used under RCP 4.5 and RCP 8.5 scenarios. The time series of climate models present very different behaviours. For example, if we look at the number of HWs under RCP 8.5, we obtain a number of days above the critical temperature for the time series that ranges between 747 and 6,654 for Bayonne, 446 and 6,479 for Bilbao and 427 and 6,570 for Donostia-San Sebastian. In all cases, the Model 5 (IPSL-INERIES) has the least impact and the Model 6 (SMHI) the largest one. These different behaviours generate very different future distributions (HWs number, duration and intensity).

In all cases, we find expected increases over time in all three factors. Under RCP 8.5 our calculations show mean expected exceedances of the 30ºC critical level of 4.19ºC, for Bayonne, 4.05ºC for Bilbao and 4.14ºC for Donostia-San Sebastián by the end of the century. Minor but significant impacts are obtained using RCP 4.5, with expected mean temperature exceedances in 2100 of 2.79ºC, 2.57ºC and 2.65ºC in the aforementioned cities. We obtain different results depending on which climate model is used and in this work we give more importance at the mean of eight models. Nonetheless, the data of each model are shown in Tables 5 to 10 for both RCP 4.5 and RCP 8.5.

The expected number, duration and intensity of heatwaves are important information, but it must be kept in mind that there are correlated stochastic processes, so there is a risk that impacts may be higher than average. We, therefore, include some temperature exceedance risk measures, which are VaR(95%) and ES(95%). These risk measures provide information about the shape of the distribution tail. These values are very relevant because we should be prepared for the worst cases, that although less likely, are possible and their impact could be very dramatic.

Our calculations show that under RCP 8.5 and considering 5% worst of cases, the temperature exceedance in HWs in 2100 may be greater than 5.53ºC in Bayonne, 5.32ºC in Bilbao and 5.60ºC in Donostia-San Sebastián. When the 95% percentile is exceeded, the expected mean temperature exceedances for these cities are 5.88ºC, 5.62ºC and 5.96ºC. We obtain lower values under RCP 4.5, but these values are still important when we look at risk measures, VaR(95%) and ES(95%). We argue that we should be prepared for the most harmful cases using these risk measures and do not rely too much on the expected value since it is an average value under uncertainty.

As mentioned previously, the contributions of this work are twofold. First, the application of the model developed by Abadie *et al.* (2019) to the main Basque coastal cities. Second and more importantly, the analysis of different results when we use different climate models, because these results show that relying on the results from a single model, as done by Abadie *et al.* (2019) for Bilbao and Madrid, might be problematic.

APPENDIX
THE STOCHASTIC MODEL

There is assumed to be a Poisson process that generates HWs. The mean number of HWs at time *t* is estimated using Equation 1:

$$\lambda(t) = \lambda(0)e^{\alpha t} \tag{1}$$

The duration of a HW cannot be zero days, so there is also assumed to be a gamma process that determines the duration in days of an HW when it occurs. The mean duration of HWs at time ***t*** is estimated using Equation 2:

$$d(t) = d(0)e^{\gamma t} \tag{2}$$

In the gamma process their volatility is callibrated.

The temperature exceedance above 30ºC is obtained from a zero-truncated normal distribution correlated with the HW duration. The mean temperature exceedance over 30ºC at time *t* is estimated using Equation 3:

$$g(t) = g(0)e^{\beta t} \tag{3}$$

Correlation between temperature exceedance and duration can be simulated by obtaining random samples correlated for temperature exceedance using Equation 4:

$$\rho x_1 + x_2\sqrt{1-\rho^2} \tag{4}$$

where x_1 y x_2 are two independent, normalised samples of duration and temperature exceedance.

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