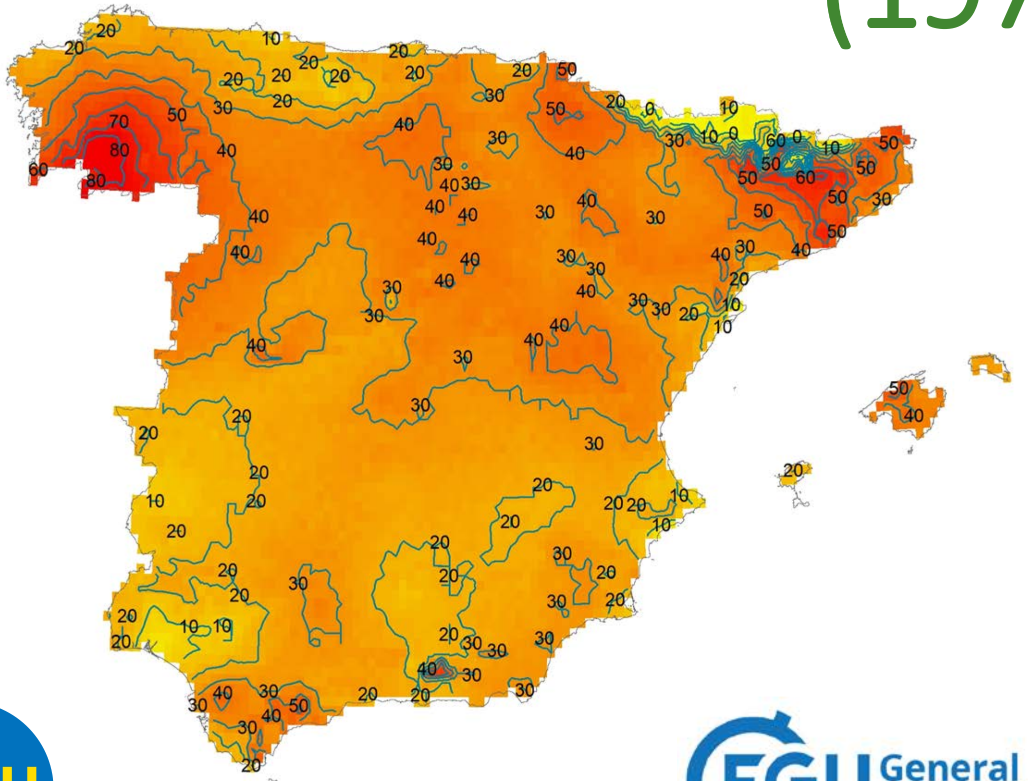
Global Warming in Spanish Cities (1971-2022)



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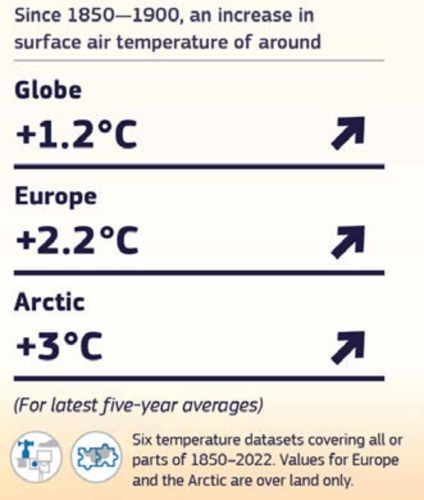
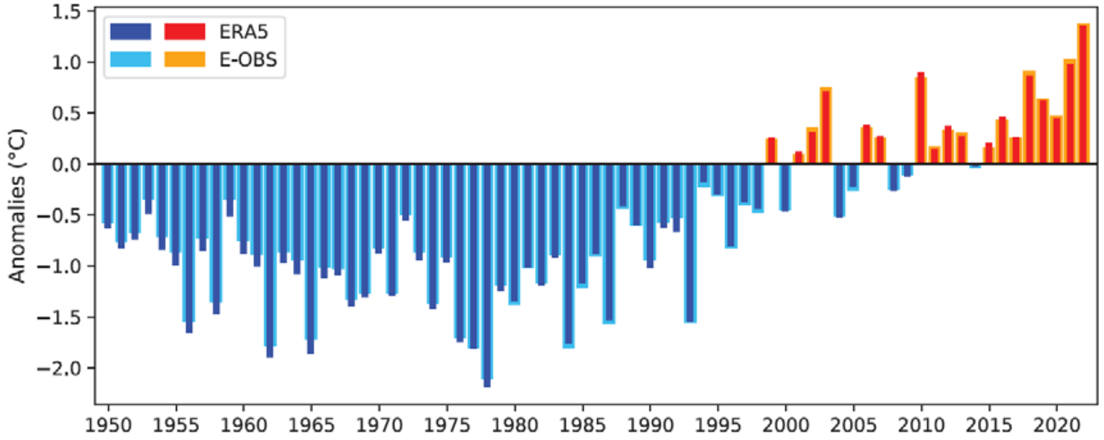
EGU General Assembly 2023

Vienna, Austria & Online | 23–28 April 2023

Global Warming

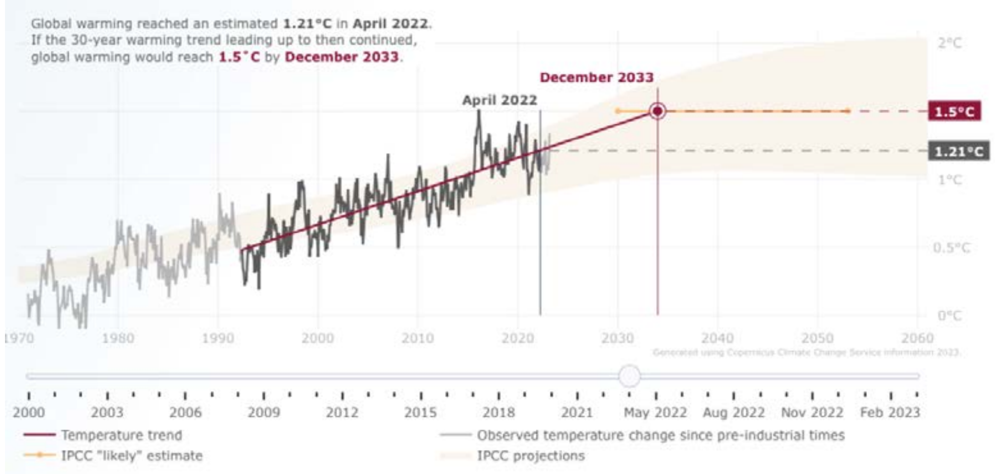
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH





European land surface air temperature anomalies for summer (JJA) 1950–2022, relative to the average for the 1991–2020 reference period. *Data source: ERA5, E-OBS. Credit: C3S/ECMWF/KNMI.*

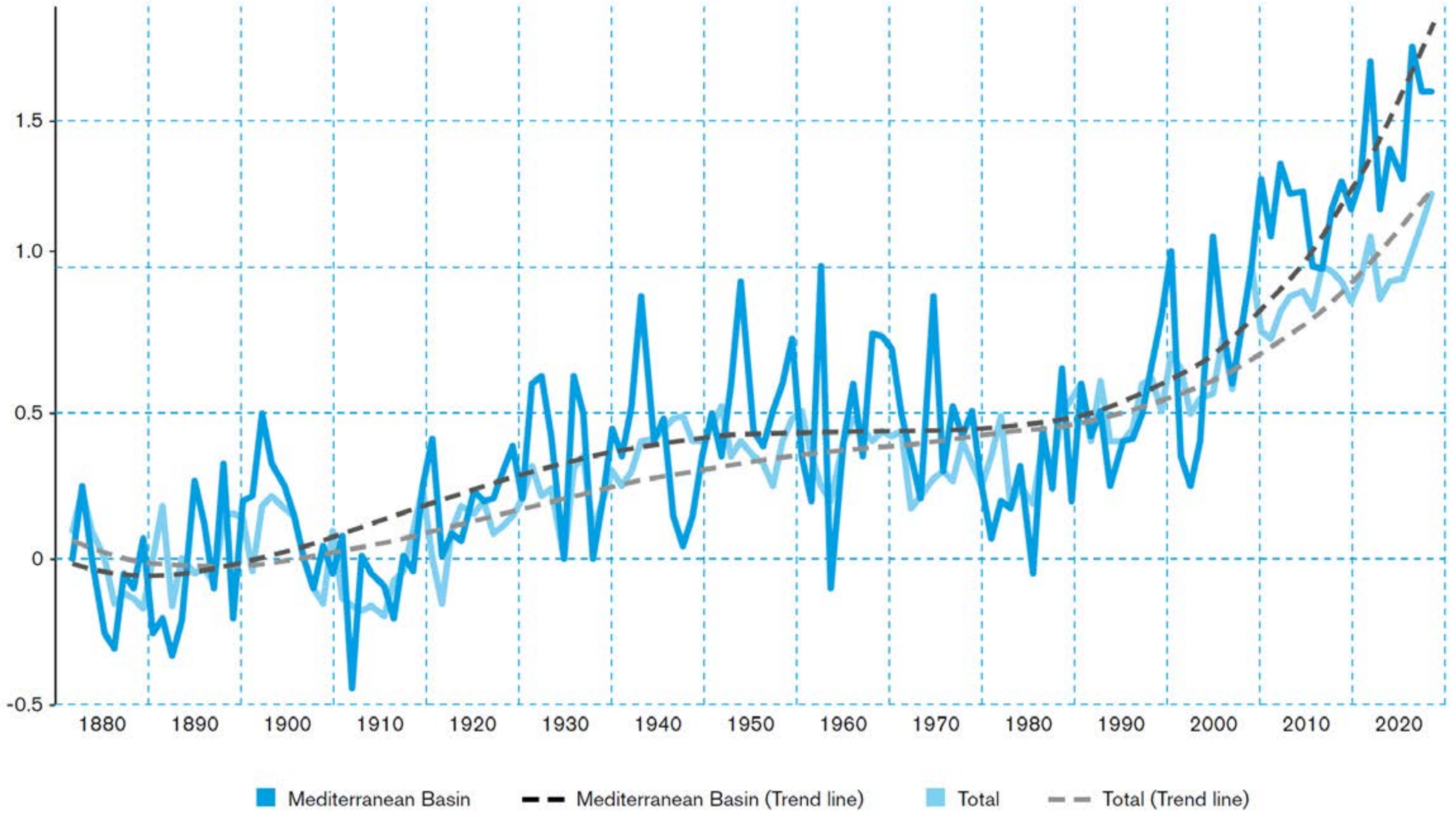
GW reached 1,21°C in April 2022. If the 30-year warming trend continued, GW would reach 1.5°C by 12/2033



2022 was the second warmest year on record for Europe, at 0.9°C warmer than average. **For many countries in southwestern Europe, the year was the warmest**. The highest anomalies in temperatures occurred in northeastern Scandinavia and those countries bordering the northwestern Mediterranean Sea (ESOTC2022)

Global Warming in Mediterranean Area:

Mean Temperature Anomalies



Lange, M. A. 2021. Climate Change in the Mediterranean: Environmental Impacts and Extreme Events. IEMed Mediterranean Yearbook 2021

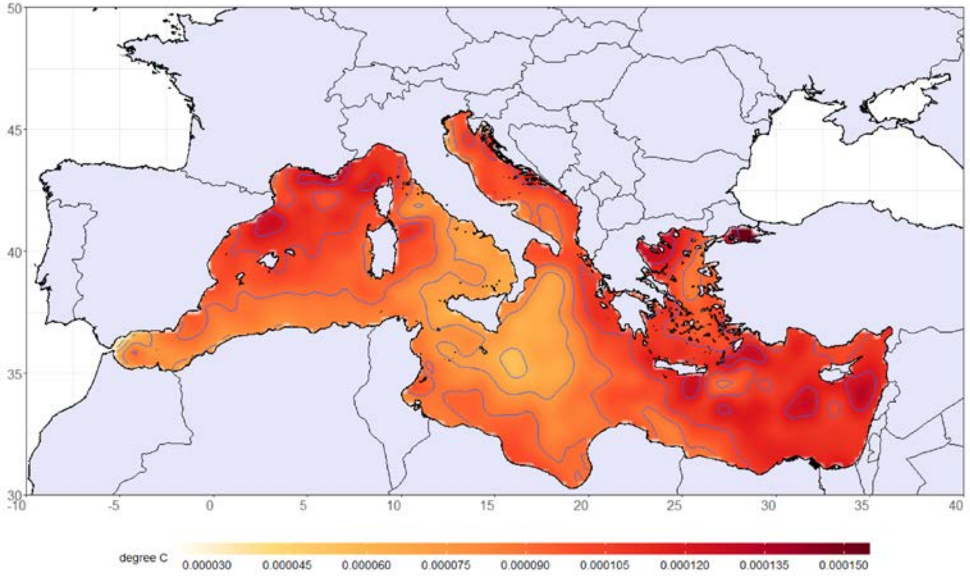
The **Mediterranean** is expected to be one of the most vulnerable climate change 'hotspots' of the 21st century

The mean temperature over the Mediterranean has higher increasing than the global average

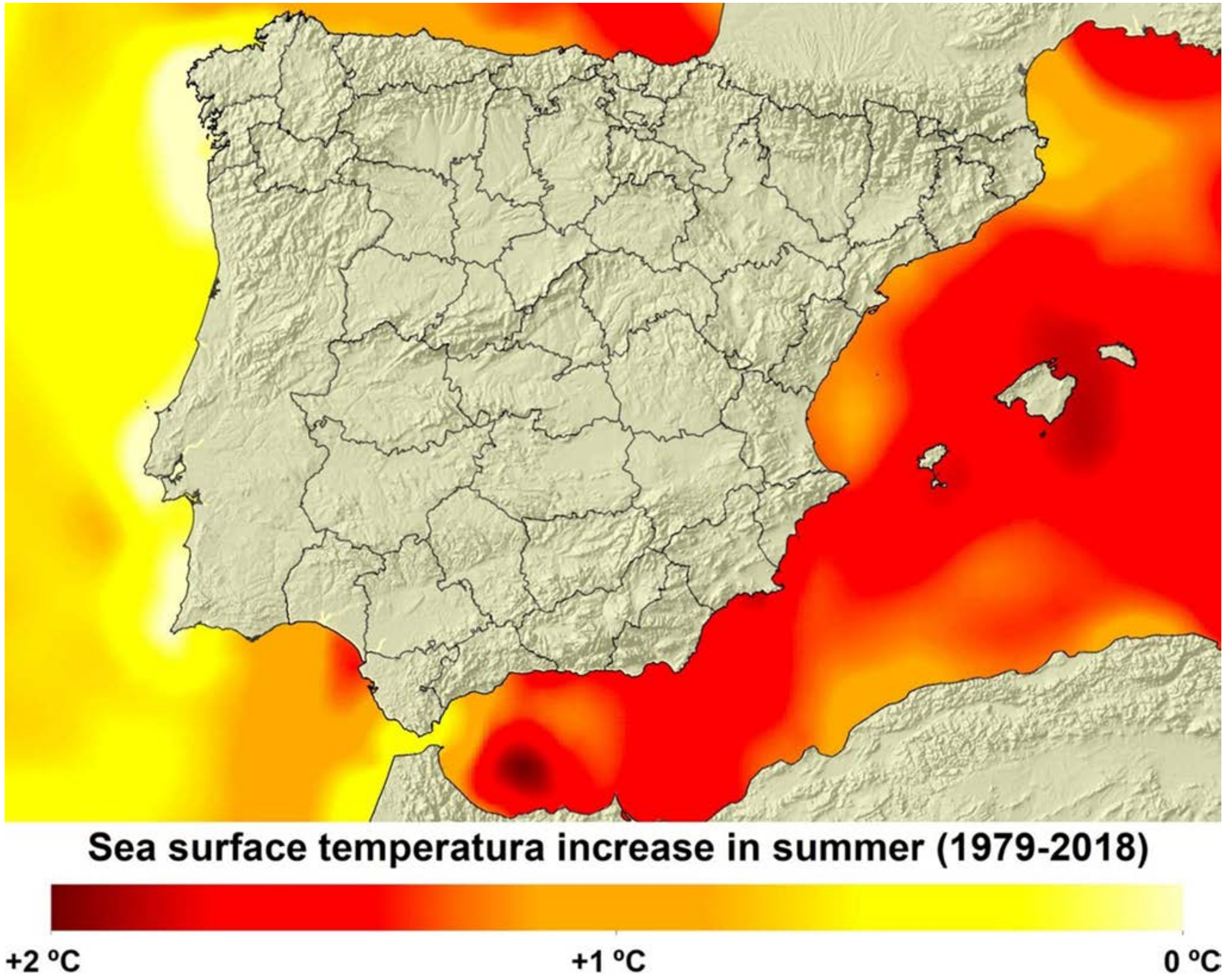
Warming in Mediterranean Sea

Warming of the Mediterranean is an important factor in explaining the increase in temperatures in Spain. Coastal zones face heightened disaster risks, including flooding, erosion, and the salinization of river deltas and aquifers.

- 2°C global warming will reduce precipitation by ~10 to 15%.
- An increase of 2°C to 4°C would reduce precipitation by up to 30% in Southern Europe

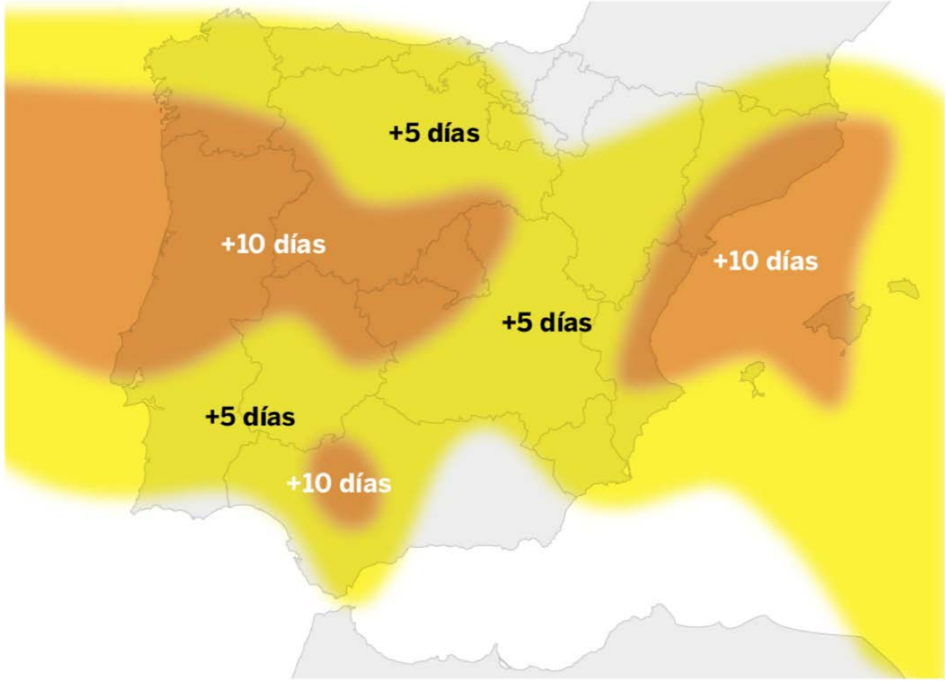


Daily warming trend in the Mediterranean basin from 1982 to 2019. Pastor *et al* 2020



Changes in sea water temperature in the last 40 years (AEMET)

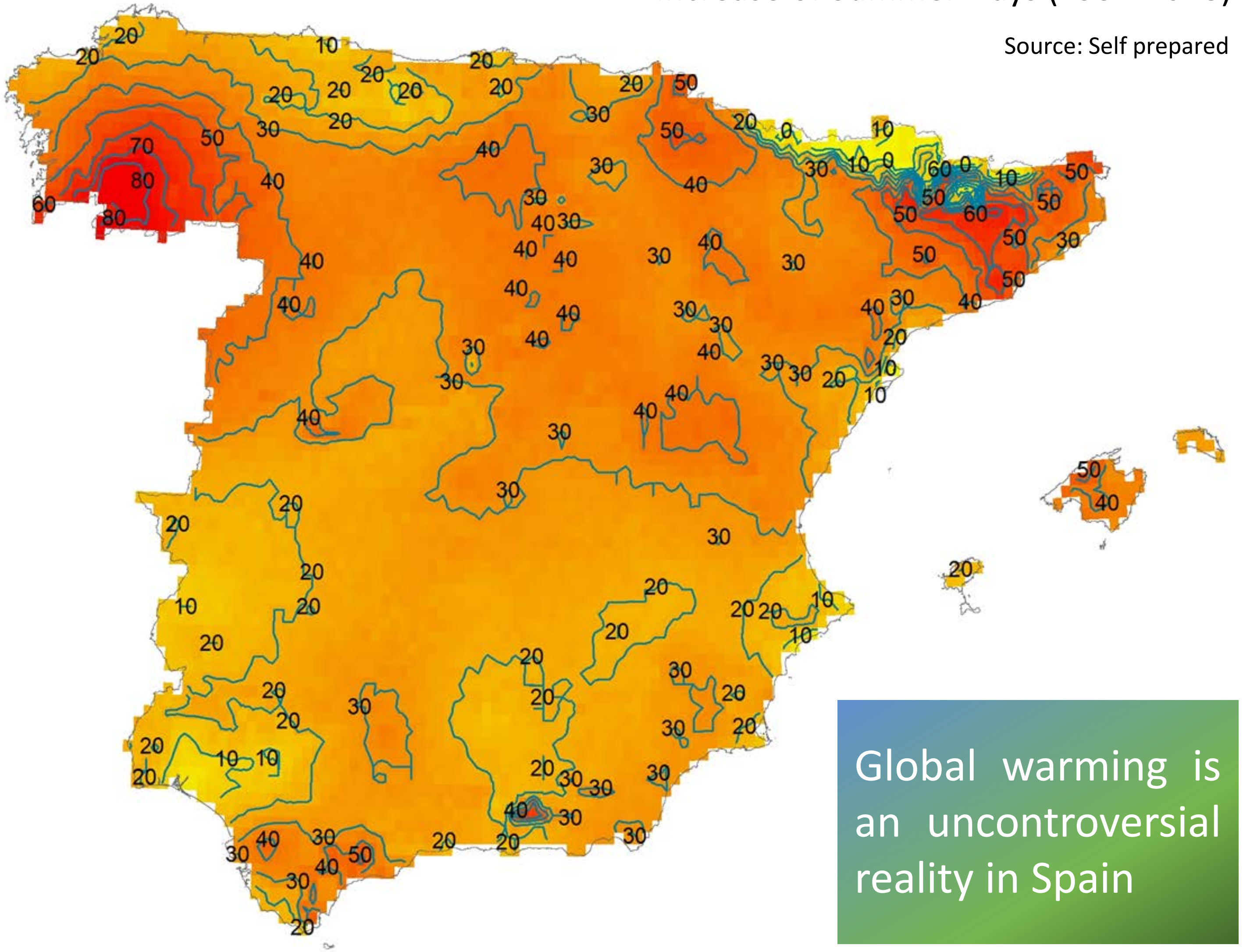
Increase of Summer days per decade due to temperature increase



Source: AEMET, 2019

Increase of Summer Days (1951-2018)

Source: Self prepared

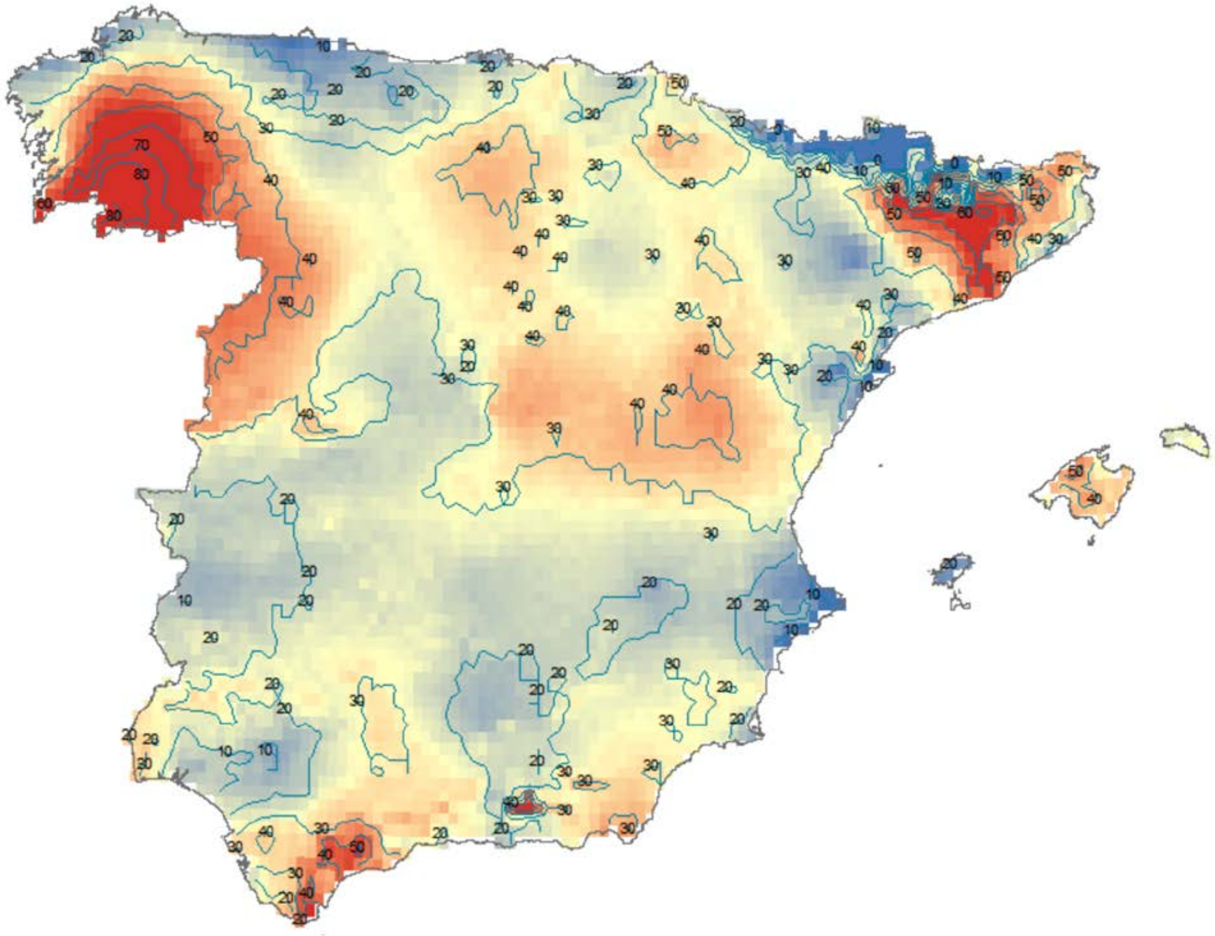


- Summer in Spain now lasts on average almost five weeks longer than in the early 80’s.
- In addition, it is hotter.

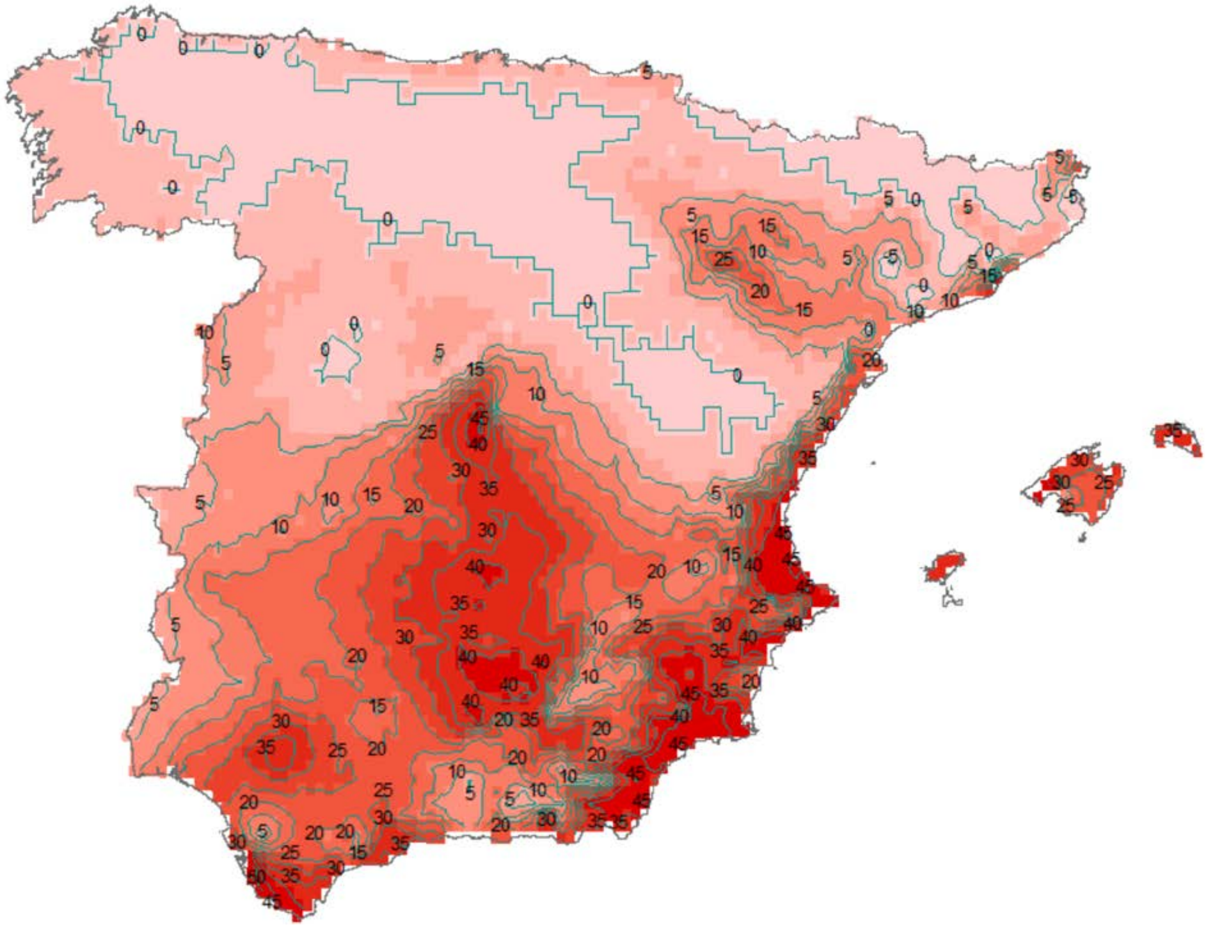
Global warming is an uncontroversial reality in Spain

Global Warming in Spain

Increase in summer days (TX > 25) between 1951-54 and 2015-2018



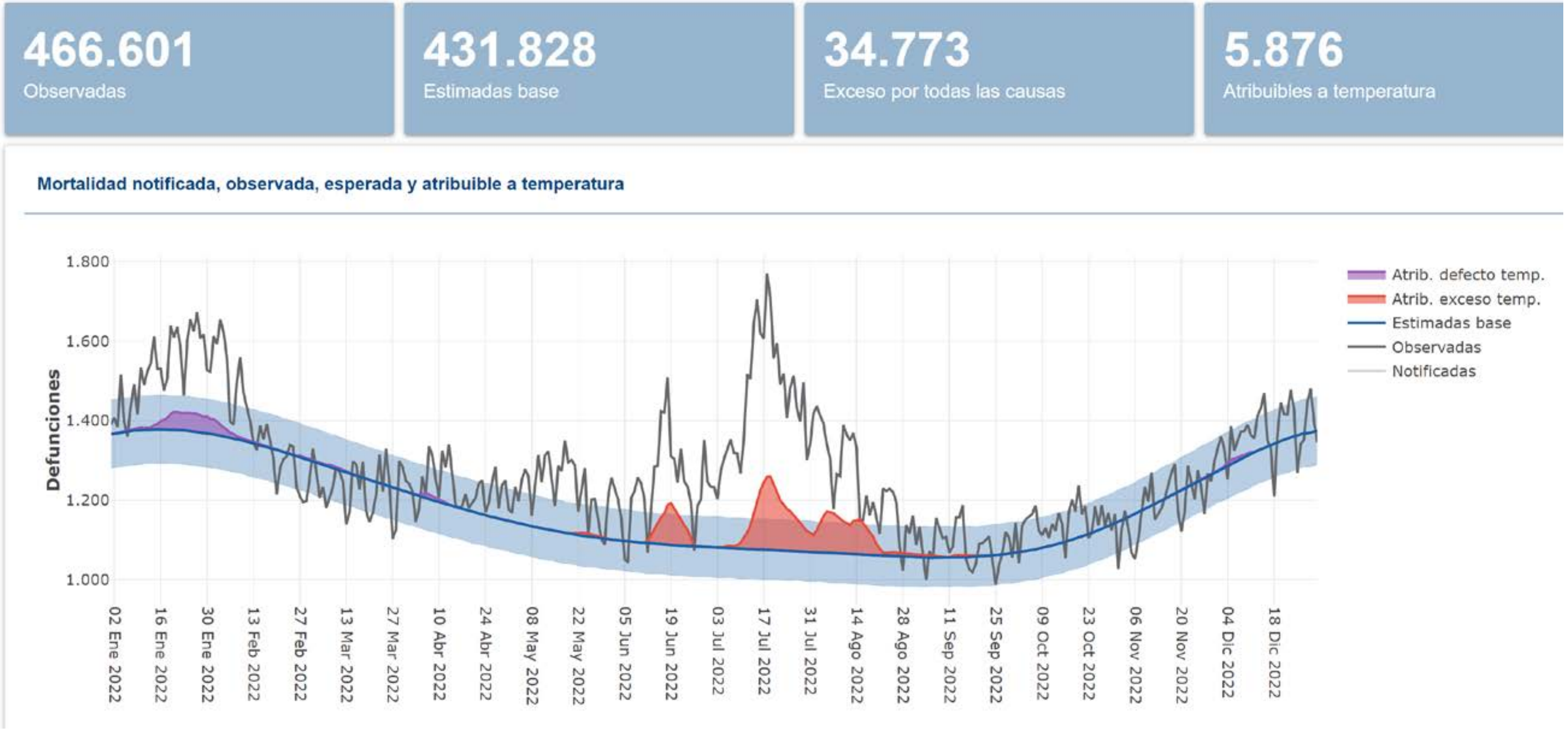
Increase in tropical nights (TN > 20)

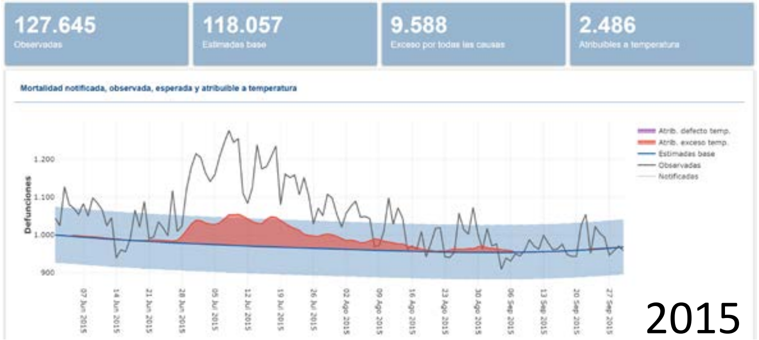


Source: Self prepared from https://surfobs.climate.copernicus.eu/dataaccess/access_eobs_indices.php

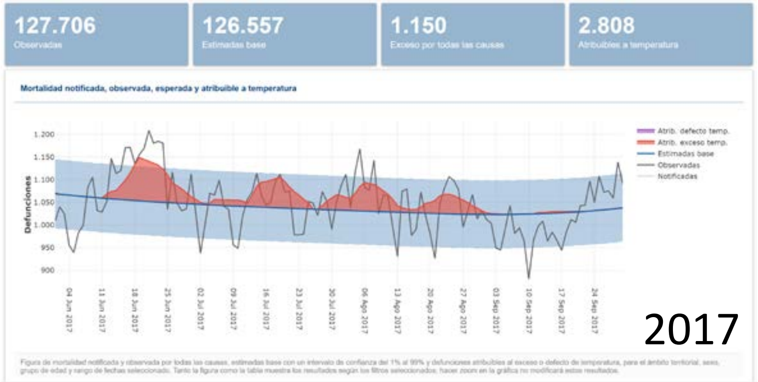
Health and Heat Waves in Spain

The extreme weather in summer affects people's health and comfort. The increase in mortality in the months of June, July and August were 22,249 additional deaths. It demonstrates the effects of the HW of 2022.

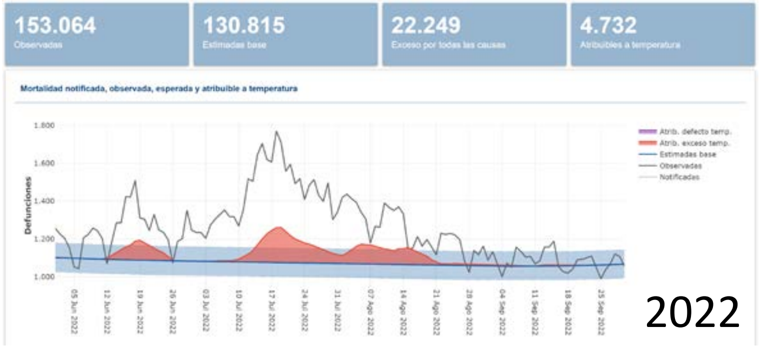




2015



2017



2022

Especially hot years

General Objective

Study of Extreme Heat Events in the Spanish Cities between 1971 and 2022

The objective is to analyze the warming process in the main Spanish urban areas since unified records in the early 1970s.

Analyzing 21 meteorological stations representative of all the Spanish Autonomous Communities

Barcelona (Catalonia)	Madrid (Community of Madrid)	Valencia (Valencian Community)	Zaragoza (Aragon)
Seville & Malaga (Andalusia)	Bilbao (Basque Country)	Valladolid (Castilla and León)	Ciudad Real (Castilla–La Mancha)
Badajoz (Extremadura)	Asturias (Asturias)	Santander (Cantabria)	Corunya & Ourense (Galicia)
Murcia (Region of Murcia)	Logroño (Rioja)	Palma de Mallorca (Balearic Islands)	Las Palmas de Gran Canaria and Santa Cruz de Tenerife (Canary Islands)

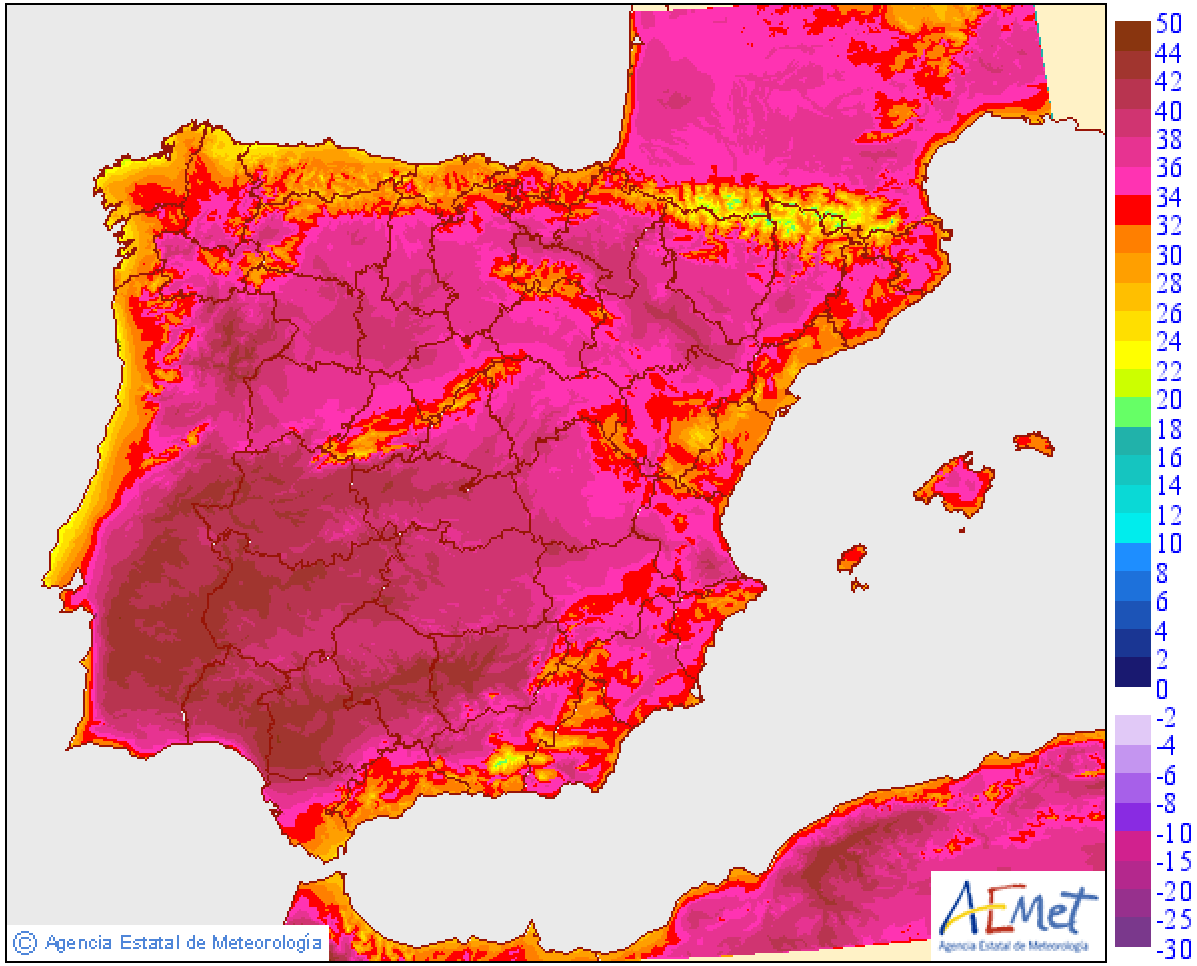
Hypothesis

It is important to differentiate Daytime Heat Wave (DHW) from those at night (NHW), since the latter are becoming more numerous and longer, affecting people's health more widely

Heat Wave

There is no universal definition of a heat wave, but such extreme events, associated with particularly hot sustained temperatures, have been known to produce notable impacts on human mortality, regional economies, and ecosystems.

The main element to define a heat wave is the presence of periods (three or more days) with extremely hot weather, in which there is no significant relief from the minimum temperatures and could have significant impacts on people's health.



Maximum temperature in the Heat Wave in July 2022

Heat Wave (Method 1)

Concept of heat wave used in the Spanish Meteorological Agency (AEMET):

A 'heat wave' is considered an episode of at least three consecutive days, in which at least 10% of the stations considered register maximums above the 95% percentile of their series of maximum daily temperatures for the months of July and August from the period 1971-2000

This definition has an important limitation: **it refers only to maximum temperatures, not minimum ones**. As indicated, it is the high minimum temperatures that mainly make the difference in health

Maximum temperatures can have serious consequences, especially "heat strokes", but health effects are more pronounced in the case of night heat, where the inability to rest (especially in homes without air conditioning as occurs mainly in Spain) can cause a significant worsening of respiratory and cardio-vascular diseases that produce premature deaths

For this reason, in this work we will differentiate Daytime Heat Waves (DHW) and Nighttime Heat Waves (NHW), **emphasizing the NHW** (Arellano & Roca, 2022)

Heat Wave (Method 2)

We assume that HW is detected when **three or more consecutive days reach temperatures above the 95 percentile on each calendar day**. These percentiles are obtained with a 15 day moving window of the maximum (TX) and minimum (TN) temperatures for each day of the year, and are calculated for the reference period 1971-2000 (Serra *et al*, 2022)

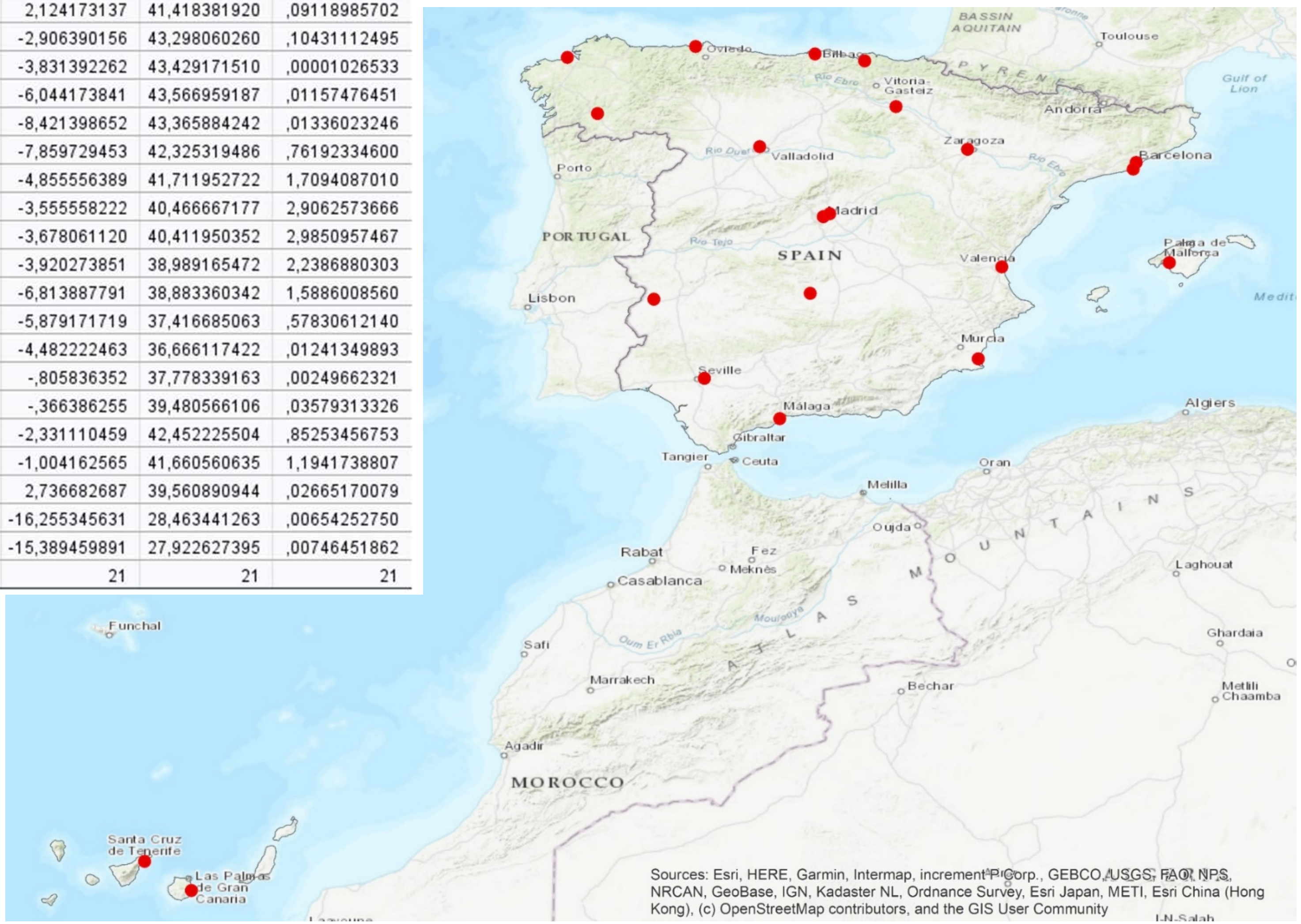
Daytime heat waves (DHW) are obtained if TX >= 95% $TX_{1971\text{-}2000}$ for 3 or more consecutive days, and at nighttime heat waves NHW) if TN >= 95% $TN_{1971\text{-}2000}$ for 3 or more consecutive nights

This methodology obtains a reference threshold for all calendar days, and therefore **obtaining daytime and nighttime heat waves throughout the year, not only in the months of July and August**

Also, the methodology allows to identify daytime (DCW) and nighttime (NCW) Cold Waves if temperatures are below the 5 percentile of each calendar day on three or more consecutive days

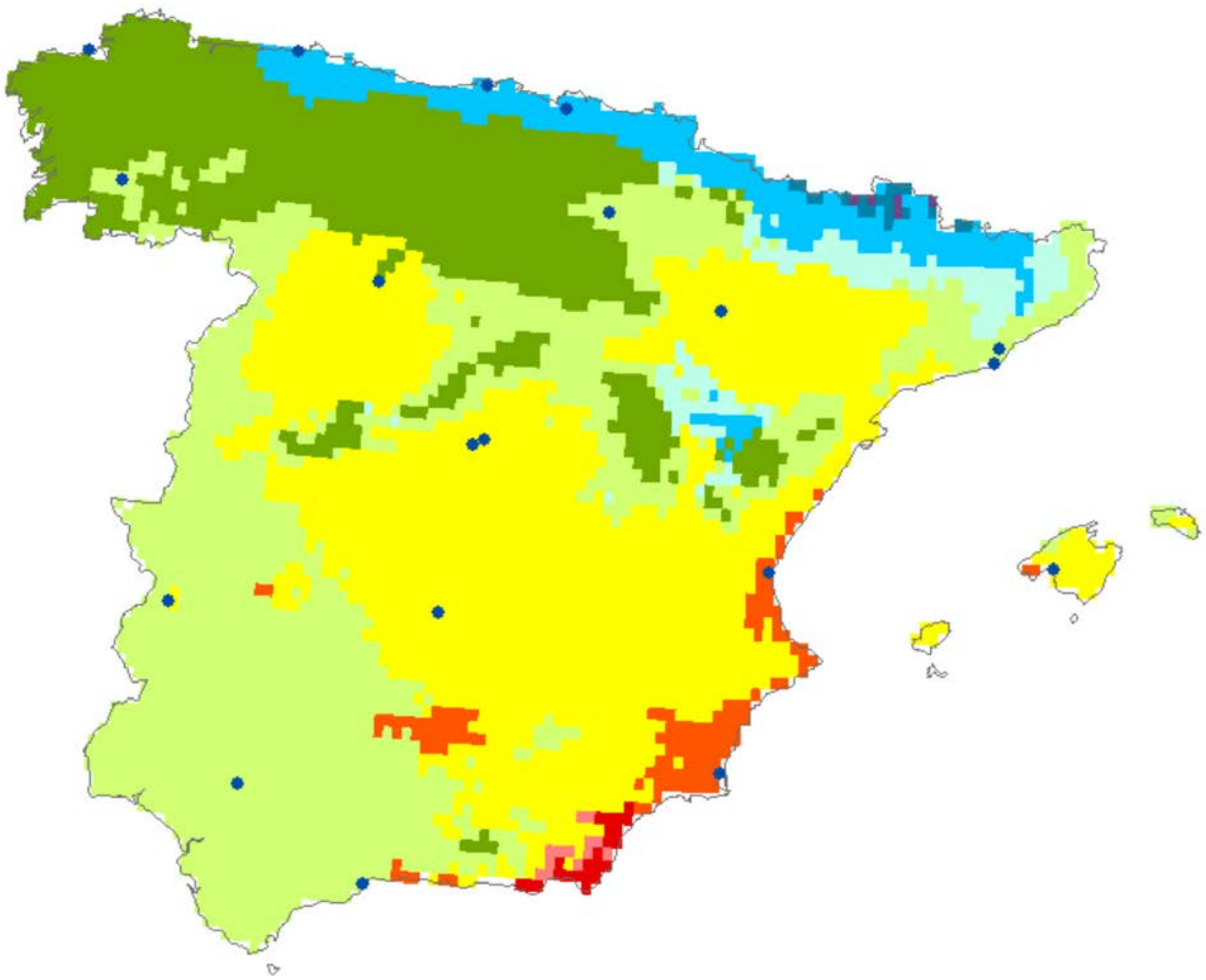
Weather Stations

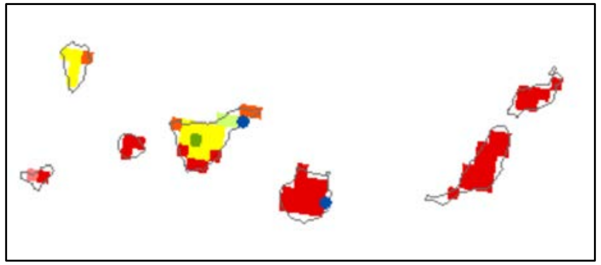
	INDICATIVO	NANE	PROVINCe	ALTITUDE	LONGITUDE	LATITUDE	Continentality
1	0076	BARCELONA/Airport	BARCELONA	4	2,070010009	41,292825367	,01313132919
2	0200E	BARCELONA (FABRA)	BARCELONA	408	2,124173137	41,418381920	,09118985702
3	1082	BILBAO/Airport	BIZKAIA	42	-2,906390156	43,298060260	,10431112495
4	1109	SANTANDER/PARAYAS	CANTABRIA	5	-3,831392262	43,429171510	,00001026533
5	1212E	ASTURIAS/AVILÉS	ASTURIAS	127	-6,044173841	43,566959187	,01157476451
6	1387	A CORUÑA	A CORUÑA	58	-8,421398652	43,365884242	,01336023246
7	1690A	OURENSE	OURENSE	143	-7,859729453	42,325319486	,76192334600
8	2539	VALLADOLID/VILLANUBLA	VALLADOLID	846	-4,855556389	41,711952722	1,7094087010
9	3129	MADRID/BARAJAS	MADRID	609	-3,555558222	40,466667177	2,9062573666
10	3195	MADRID,RETIRO	MADRID	667	-3,678061120	40,411950352	2,9850957467
11	4121	CIUDAD REAL	CIUDAD REAL	628	-3,920273851	38,989165472	2,2386880303
12	4452	BADAJOZ/TALAVERA LA REAL	BADAJOZ	185	-6,813887791	38,883360342	1,5886008560
13	5783	SEVILLA/SAN PABLO	SEVILLA	34	-5,879171719	37,416685063	,57830612140
14	6155A	MÁLAGA/Airport	MALAGA	5	-4,482222463	36,666117422	,01241349893
15	7031X	MURCIA/SAN JAVIER II	MURCIA	4	-,805836352	37,778339163	,00249662321
16	8416	VALENCIA	VALENCIA	11	-,366386255	39,480566106	,03579313326
17	9170	LOGROÑO/AGONCILLO	LA RIOJA	353	-2,331110459	42,452225504	,85253456753
18	9434	ZARAGOZA/Airport	ZARAGOZA	263	-1,004162565	41,660560635	1,1941738807
19	B278	PALMA DE MALLORCA/SON SAN JUAN	BALEARES	8	2,736682687	39,560890944	,02665170079
20	C449C	STA.CRUZ DE TENERIFE	SANTA CRUZ D	35	-16,255345631	28,463441263	,00654252750
21	C649I	GRAN CANARIA/Airport	LAS PALMAS	24	-15,389459891	27,922627395	,00746451862
Total N	21	21	21	21	21	21	21



Köppen Climate Classification & Weather Stations

- **BWh -** Warm aggregate
- **BWk** - Temperate-cold aggregate
- **BSh** - Warm semi-arid
- **BSk** - Semi-arid temperate-cold or steppe
- **Csa** - Typical Mediterranean (warm summer)
- **Csb** - Oceanic Mediterranean (mild summer)
- **Cfa** - Humid subtropical or no dry season (warm summer)
- **Cfb** - Temperate oceanic (mild summer)
- **Cfc** - Oceanic subpolar
- **Dfc** - Subpolar without dry season (short summer)





Spanish Cities Warming estimate 1971-2022

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To estimate the warming process experienced by Spanish cities, different methodologies are used.

1. Comparison of the annual mean maximum (TX) and minimum (TN) temperatures of each of the weather stations between 1971 and 2022

2. OLS model with the annual mean temperatures TX and TN of all meteorological stations as dependent variables and the year, longitude, latitude, altitude and distance to the sea (continentally) as independent variables

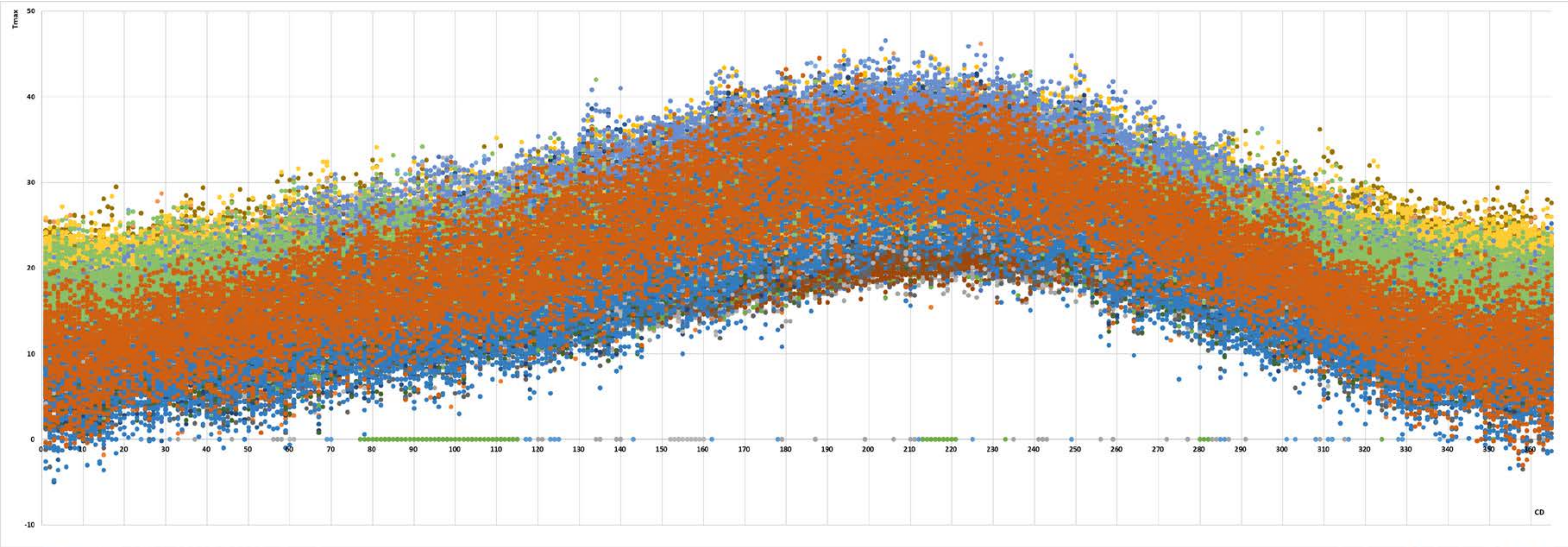
3. OLS model for each meteorological station with the maximum and minimum daily temperatures as dependent variables, and the year, the month and the calendar day (cd*), as independent variables

The calendar day (cd) is linearized by the following equation:

$$cd^* = \cos \frac{2\pi(cd - cd_{max})}{365}$$

Calendar Day Temperatures (1971-2022)

The hottest Calendar Day (Tmax) was Day 210 (August 8)



Calculation of cd*, first summarize the raw data of all weather stations and draw a scatter diagram

Global Warming in Spanish Cities (1971-2022)

The increase in temperatures between 1971 and 2022, both during the day and at night, is clearly higher than the Mediterranean average

Highlights Palma de Mallorca (day and night), Murcia and Barcelona (day), as well as Ciudad Real, Zaragoza, Barcelona and Madrid (night)

The maximum temperature (TX) increased 3.54°C between 1971 and 2022.
The minimum (Tm) increased 2.73°C

Name	Autonomous region	GW_Tmax_ Average	GW_Tmin_ Average
Barcelona Airport	Cataluña	3,12	3,23
Fabra	Cataluña	4,81	3,15
Madrid Airport	Madrid	3,71	3,11
Retiro	Madrid	4,30	3,00
Valencia	Valencia	2,67	2,65
Zaragoza Airport	Aragón	4,05	3,51
Sevilla Airport	Andalucía	3,07	2,45
Málaga Airport	Andalucía	3,00	2,60
Bilbao Airport	País Vasco	3,03	2,48
Valladolid Airport	Castilla-León	4,08	2,08
Ciudad Real	Castila La Mancha	4,02	5,32
Badajoz Airport	Extremadura	3,47	3,02
Asturias Airport	Asturias	2,67	1,55
A Coruña	Galicia	2,25	2,18
Ourense	Galicia	4,03	2,48
San Javier Airport	Murcia	4,93	2,56
Santander Airport	Cantabria	3,35	2,33
Logroño Airport	La Rioja	4,10	1,27
Gran Canaria Airport	Canarias	2,00	1,72
STA. Cruz De Tenerife	Canarias	2,19	1,90
Palma Mallorca Airport	Islas Baleares	5,42	4,71
Total		3,54	2,73

2022 An Exceptionally Warm Year

13 of the 21 Weather Stations, the year 2022 was the warmest year of the entire historical series, in both, maximum (TX) and minimum temperature (TN). Thus, the simple comparison between 1971 and 2022 can be misleading

	Indicativo	NAME	Year_TX
1	0076	BARCELONA/Airport	2022
2	0200E	BARCELONA (FABRA)	2022
3	1082	BILBAO/Airport	2022
4	1109	SANTANDER/PARAYAS	2022
5	1387	A CORUÑA	2022
6	1690A	OURENSE	2022
7	2539	VALLADOLID/VILLANUBLA	2022
8	3129	MADRID/BARAJAS	2022
9	6155A	MÁLAGA/Airport	2022
10	7031X	MURCIA/SAN JAVIER II	2022
11	9170	LOGROÑO/AGONCILLO	2022
12	9434	ZARAGOZA/Airport	2022
13	B278	PALMA DE MALLORCA/Airport	2022
14	3195	MADRID,RETIRO	2017
15	4121	CIUDAD REAL	2017
16	4452	BADAJOZ/TALAVERA LA REAL	2017
17	5783	SEVILLA/SAN PABLO	2017
18	1212E	ASTURIAS/AVILÉS	2015
19	8416	VALENCIA	2001
20	C449C	STA.CRUZ DE TENERIFE	1998
21	C649I	GRAN CANARIA/Airport	1998
Total N	21	21	21

	Indicativo	NAME	Year_TN
1	0076	BARCELONA/Airport	2022
2	0200E	BARCELONA (FABRA)	2022
3	1109	SANTANDER/PARAYAS	2022
4	1212E	ASTURIAS/AVILÉS	2022
5	1387	A CORUÑA	2022
6	1690A	OURENSE	2022
7	3129	MADRID/BARAJAS	2022
8	3195	MADRID,RETIRO	2022
9	4121	CIUDAD REAL	2022
10	6155A	MÁLAGA/Airport	2022
11	8416	VALENCIA	2022
12	9434	ZARAGOZA/Airport	2022
13	B278	PALMA DE MALLORCA/Airoort	2022
14	C449C	STA.CRUZ DE TENERIFE	2017
15	7031X	MURCIA/SAN JAVIER II	2016
16	4452	BADAJOZ/TALAVERA LA REAL	2014
17	1082	BILBAO/Airport	2011
18	2539	VALLADOLID/VILLANUBLA	2011
19	5783	SEVILLA/SAN PABLO	2010
20	9170	LOGROÑO/AGONCILLO	2003
21	C649I	GRAN CANARIA/Airport	1998
Total N	21	21	21

2022, an exceptionally warm year

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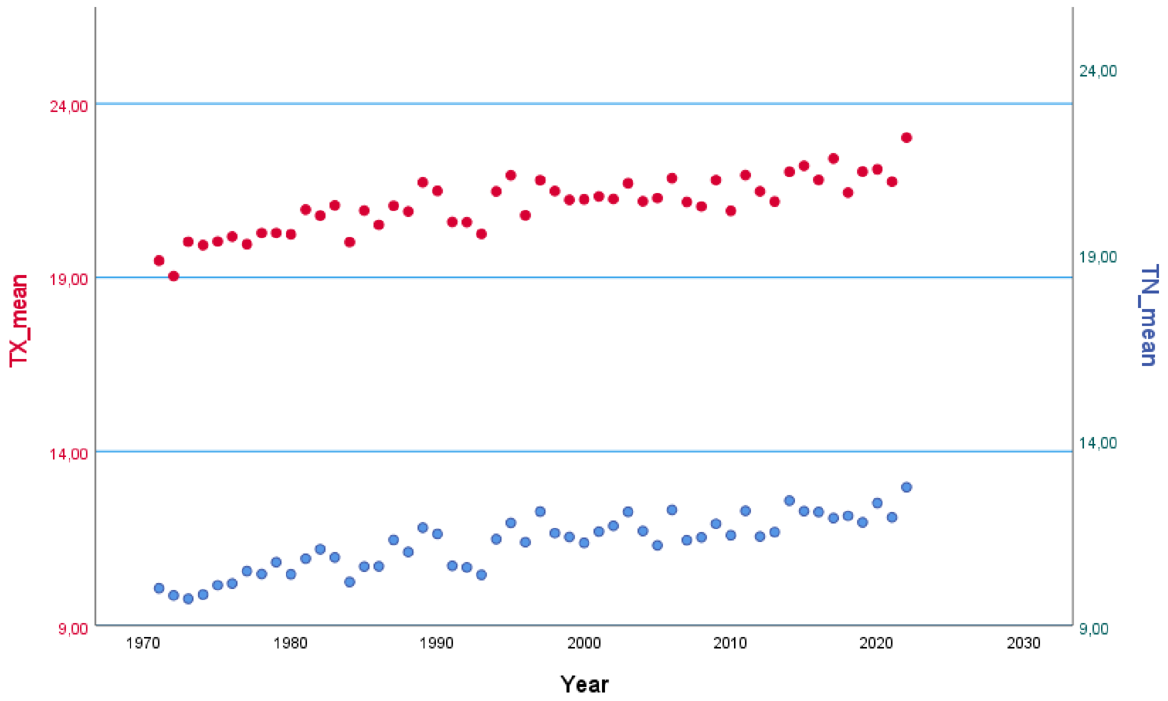
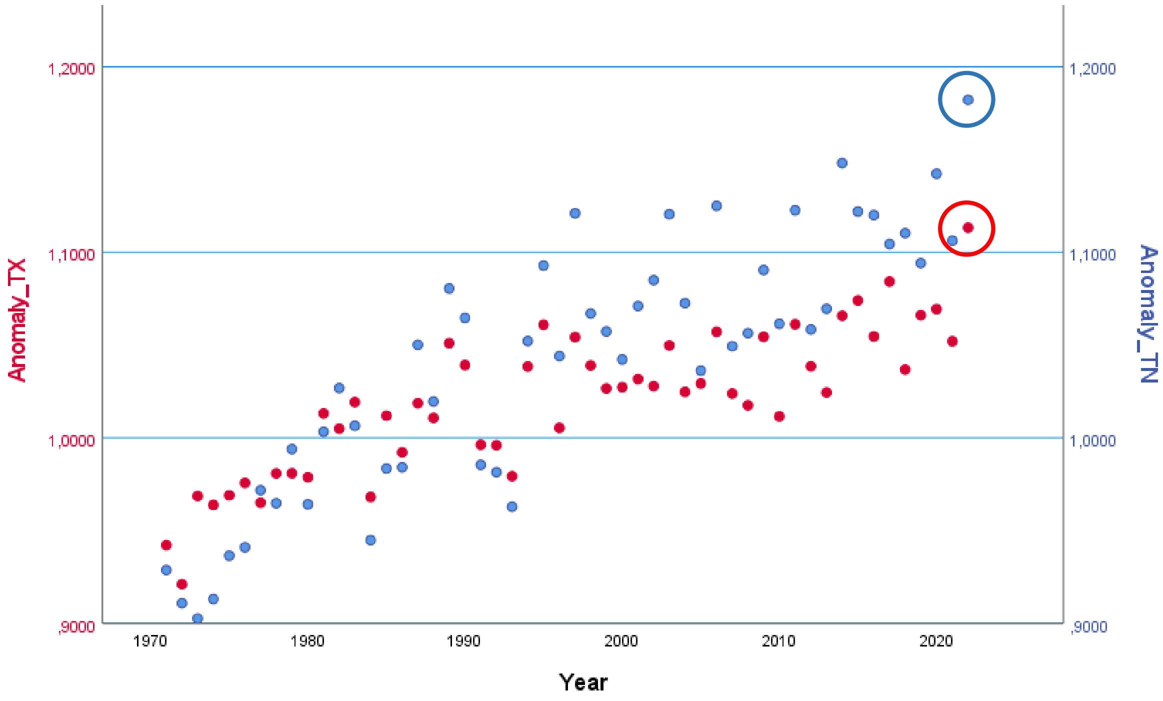
The exceptionality of the year 2022 is evidenced by presenting an anomaly in maximum temperatures (TX) of 1.13 times higher than the average for the period 1971-2000

In relation to the minimums, the anomaly of 2022 was even more pronounced: a 1.18





Global Warming (OLS Model, Annual Means)

The exceptionality of 2022 means that the simple comparison 1971/2022 is not appropriate to estimate the GW, so an OLS model is tested, with all the weather stations, and with the year, longitude, latitude, altitude and continentally (distance to the sea) as explanatory variables, and with TX and TN (**annual means**) as dependent variables. The R^2 reaches 0.796 in the TX and 0.849 in the TN

This means that the maximums would have increased 2.21 °C, and the minimums 2.16 °C, between 1971 and 2022

Resumen del modelo

Modelo	R	R cuadrado	R cuadrado ajustado	Error estándar de la estimación
1	,893[a]	,797	,796	1,12753

a. Predictores: (Constante), Continentability, Year, Longitude, Latitude, Altitude

Coeficientes[a]

Modelo		Coeficientes no estandarizados B	Coeficientes no estandarizados Desv. Error	Coeficientes estandarizados Beta	t	Sig.
1	(Constante)	-46,294	4,561		-10,149	<,001
	Year	,044	,002	,266	19,473	<,001
	Altitude	-,007	,000	-,764	-29,563	<,001
	Longitude	,169	,009	,326	18,233	<,001
	Latitude	-,506	,011	-,847	-46,552	<,001
	Continentability	1,805	,065	,705	27,695	<,001

a. Variable dependiente: TX

Resumen del modelo

Modelo	R	R cuadrado	R cuadrado ajustado	Error estándar de la estimación
1	,922[a]	,849	,849	1,22285

a. Predictores: (Constante), Continentability, Year, Longitude, Latitude, Altitude

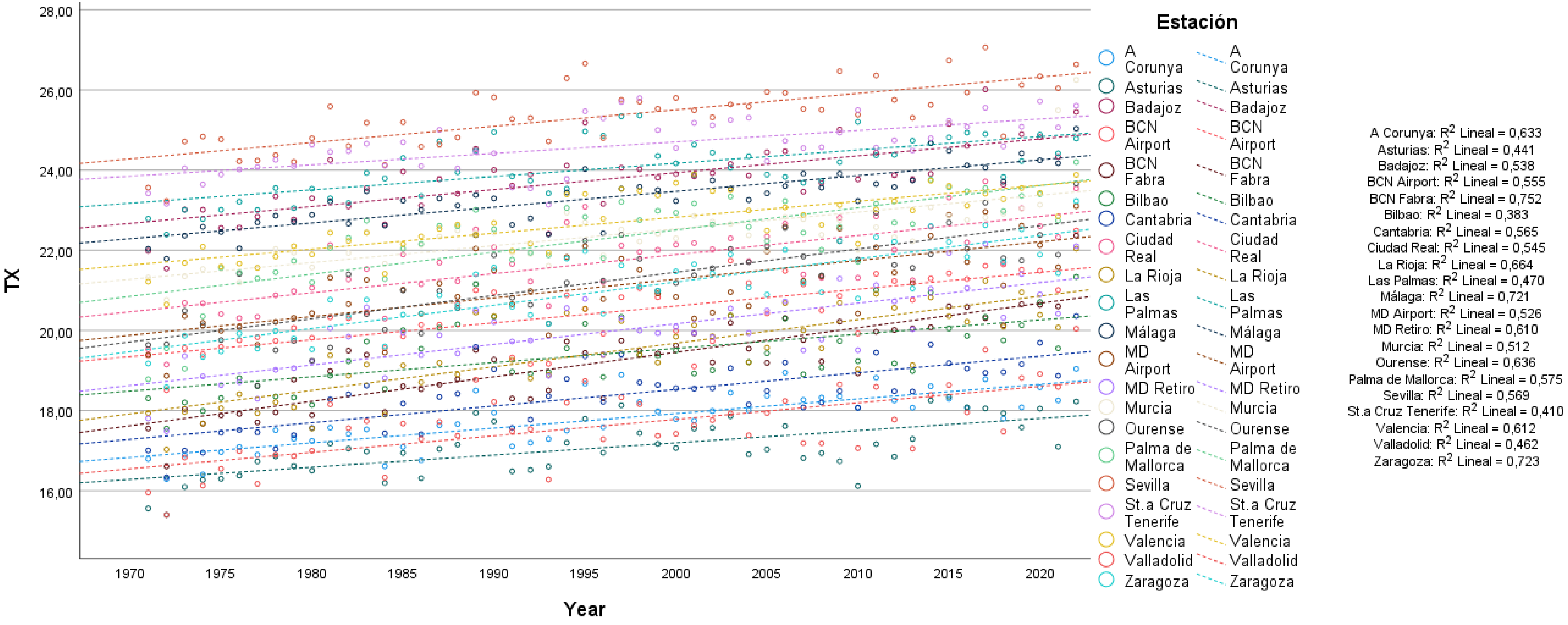
Coeficientes[a]

Modelo		Coeficientes no estandarizados B	Coeficientes no estandarizados Desv. Error	Coeficientes estandarizados Beta	t	Sig.
1	(Constante)	-53,017	4,947		-10,717	<,001
	Year	,043	,002	,206	17,519	<,001
	Altitude	-,004	,000	-,327	-14,673	<,001
	Longitude	,023	,010	,035	2,274	,023
	Latitude	-,524	,012	-,698	-44,479	<,001
	Continentability	-,489	,071	-,152	-6,917	<,001

a. Variable dependiente: TN

Global Warming in Spanish Cities (1971-2022)

The increase has been widespread in all the cities studied



Global Warming in Spanish Cities (1971-2022)

OLS Model, Daily Temperatures

The realization of an OLS model, with the maximum and minimum **daily temperatures** of the last 50 years, of the different studied weather stations, with year, month and calendar day (cd*) as independent variables allows modeling the increase in temperatures between 1971 and 2022

This approximation, more precise than the one previously carried out in the OLS model of the annual means, allows us to estimate that between 1971 and 2022, **the increase in the maximum temperature has been 2.30°C and in the minimum, 2.26°C.**

Name	Autonomous region	GW_Tmax_Regression	GW_Tmin_Regression
Barcelona Airport	Cataluña	2,187520548	3,935475943
Fabra	Cataluña	3,178041755	2,554076566
Madrid Airport	Madrid	2,42447823	1,95236333
Retiro	Madrid	2,669320424	2,126795615
Valencia	Valencia	2,068729557	2,158112385
Zaragoza Airport	Aragón	3,015532883	2,31571854
Sevilla Airport	Andalucía	2,123469709	2,685954168
Málaga Airport	Andalucía	2,047390542	2,853774
Bilbao Airport	País Vasco	1,844870218	1,976284105
Valladolid Airport	Castilla-León	2,136460516	1,249645296
Ciudad Real	Castila La Mancha	2,473439523	4,342824982
Badajoz Airport	Extremadura	2,191947887	1,900631015
Asturias Airport	Asturias	1,582940916	1,574580185
A Coruña	Galicia	1,896217182	1,66776096
Ourense	Galicia	3,014989341	1,522320797
San Javier Airport	Murcia	2,181488428	2,780202174
Santander Airport	Cantabria	2,157636403	2,180503064
Logroño Airport	La Rioja	3,056707368	0,591155193
Gran Canaria Airport	Canarias	1,727218145	1,665493595
STA. Cruz De Tenerife	Canarias	1,48418646	1,60845035
Palma De Mallorca Airport	Islas Baleares	2,874500725	3,521863736
Total		2,301766036	2,245904095

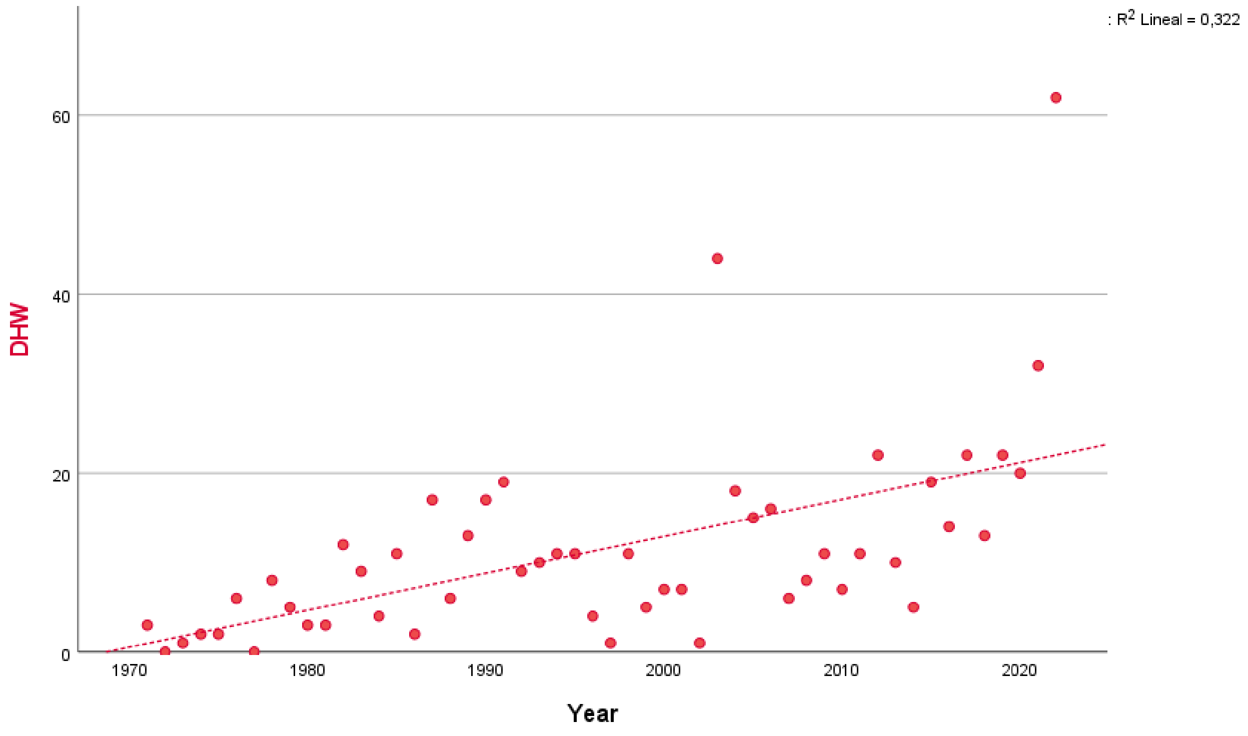
Daytime Heat Waves (Approach 1)

The increase in daytime Heat Waves has been constant throughout the period studied.
The years 2003 (great HW in Europe) and the exceptional year of 2022 stand out as outliers

Highlighted, with more than 35 DHW between 1971 and 2022,

- Barcelona Airport (49 DHW, 260 days),
- Zaragoza Airport (42, 170),
- Madrid-Retiro (39, 199),
- BCN-Fabra Obs. (38, 177)
- Gran Canaria Airport (38, 137)

Time period	DHW	Number of days
1971-1980	3	10,6
1981-1990	9,4	36,5
1991-2000	8,8	34,2
2001-2010	13,7	59,8
2011-2020	15,8	62,1
2013-2022	21,9	105,7



In total, 597 DHW at 21 weather stations, with a total of 2,570 days

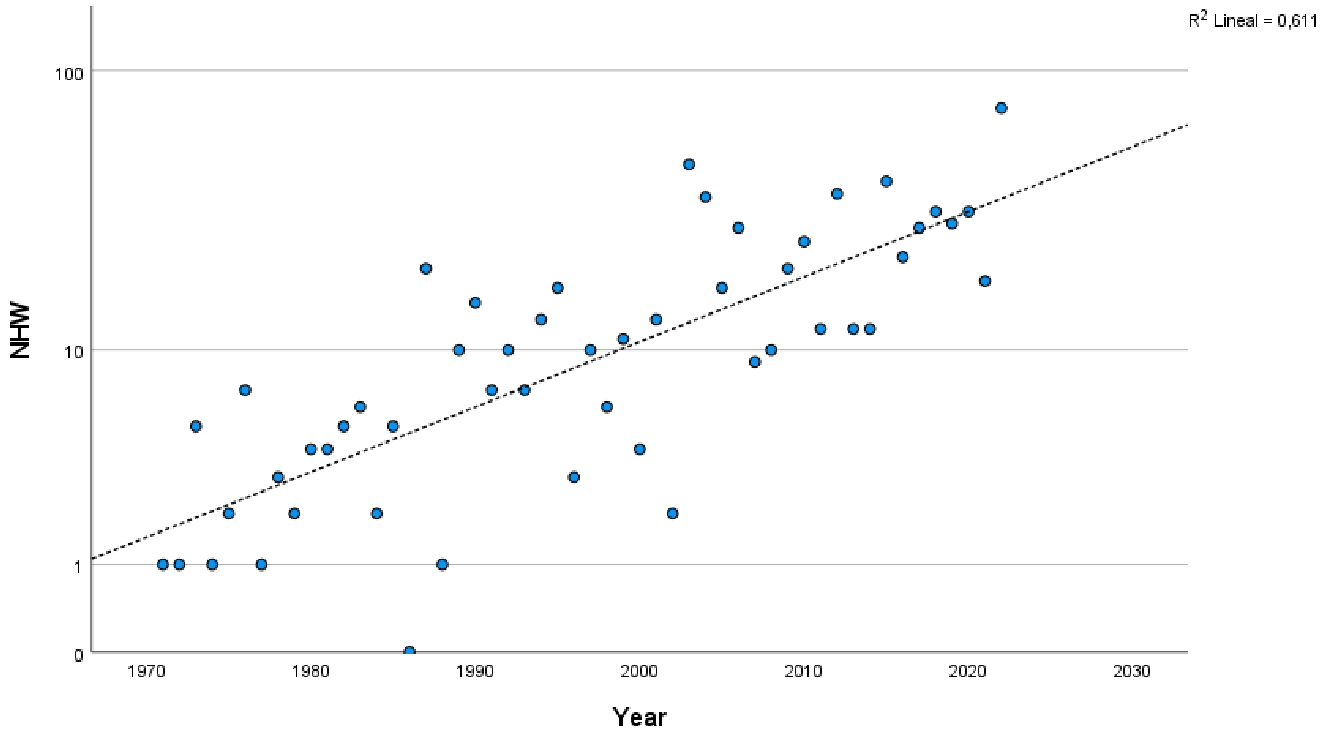
Nighttime Heat Waves (Approach 1)

The evolution of Nighttime Heat Waves (NHW) shows an **exponential increase**

Stand out, with more than 40 NHW between 1971 and 2022

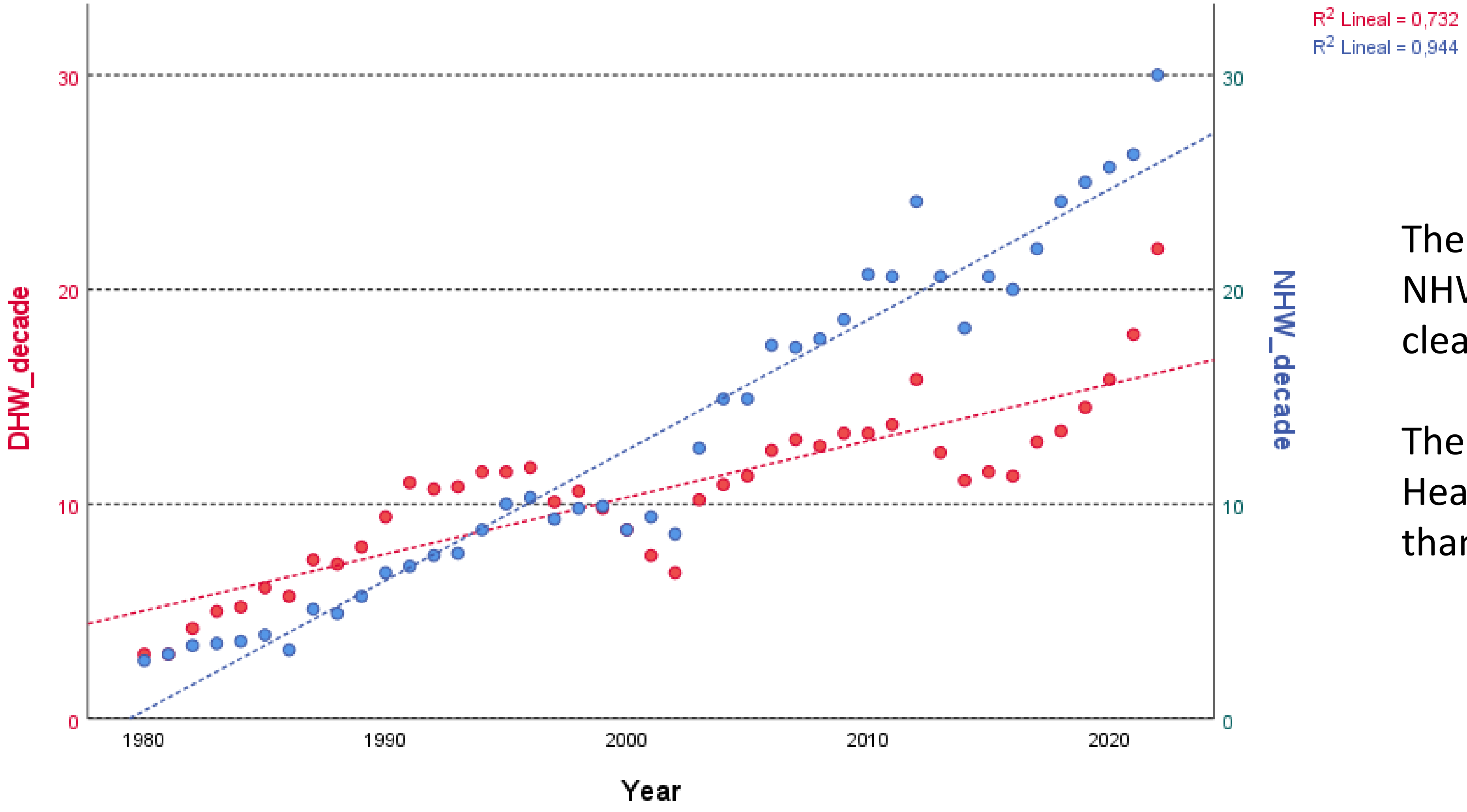
- Barcelona Airport (82 NHW, 459 days)
- BCN Fabra Obs. (47, 211)
- Sevilla Airport (46, 255)
- Tenerife (44, 178)
- Bilbao Airport (43 173)
- A Corunya (41, 158)
- Gran Canaria Airport (40 NHW, 151 days)

Time period	NHW	Number of days
1971-1980	**2,7**	**9**
1981-1990	**6,8**	**25,1**
1991-2000	**8,8**	**33,6**
2001-2010	**20,7**	**94,4**
2011-2020	**25,7**	**113,6**
2013-2022	**30**	**140,6**



In total, 739 NHW at 21 weather stations, with a total of 3,204 nights

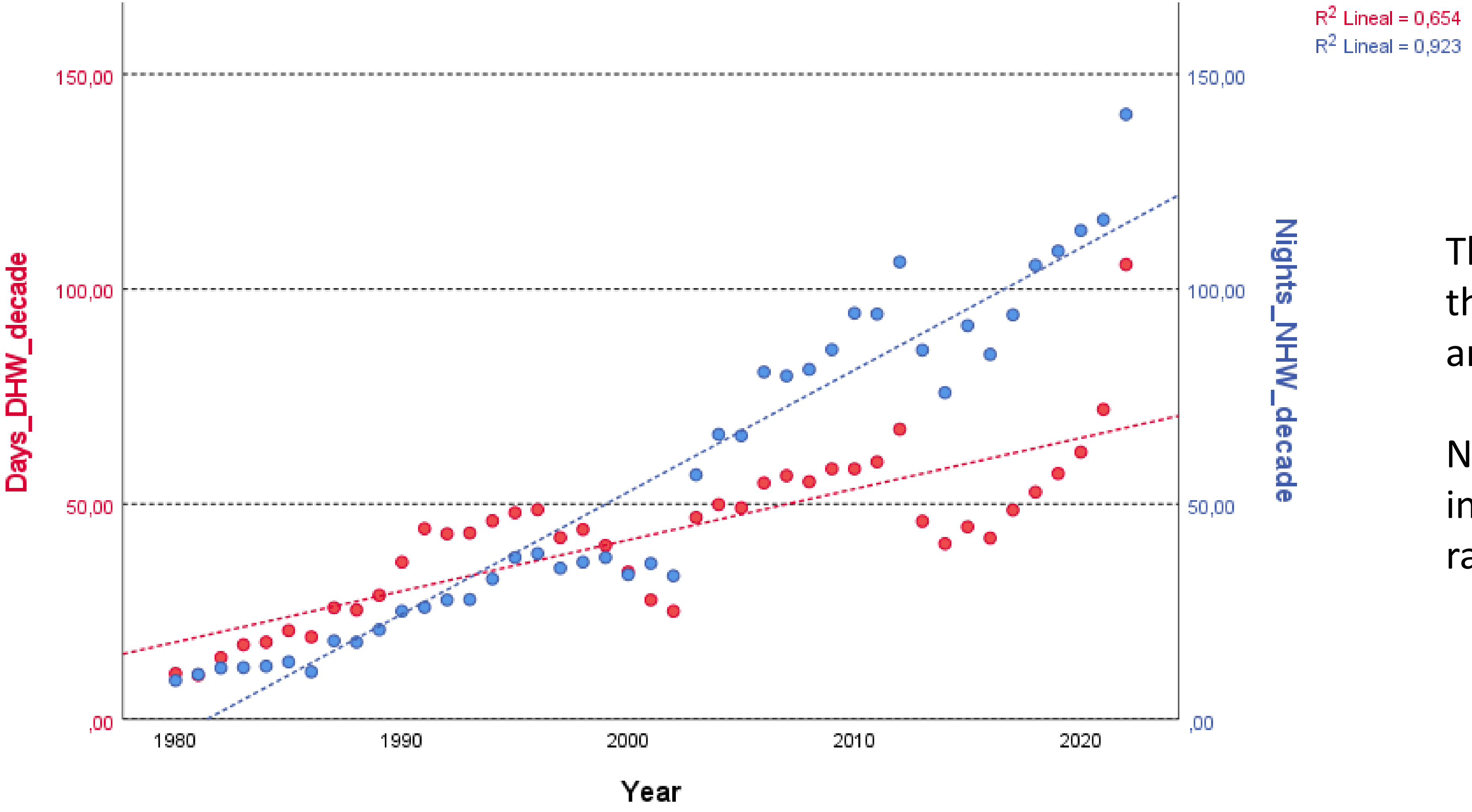
Daytime & Nighttime Heat Waves per Decade (Approach 1)



The evolution of DHW and NHW for decades shows a clear increase

The increase in Nighttime Heat Waves is clearly higher than Daytime HW.

Daytime & Nighttime Heat Waves Duration per decade (Approach 1)

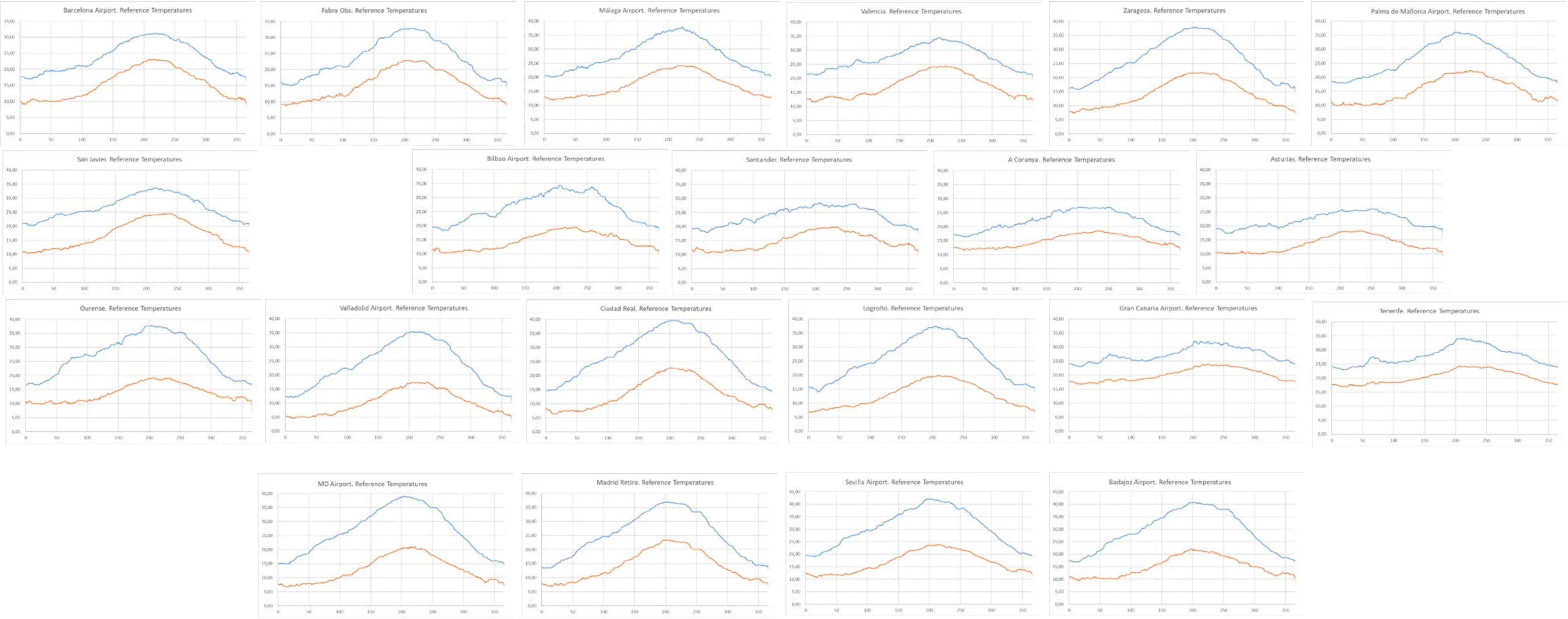


The same happens with the number of nights and days in a heat wave

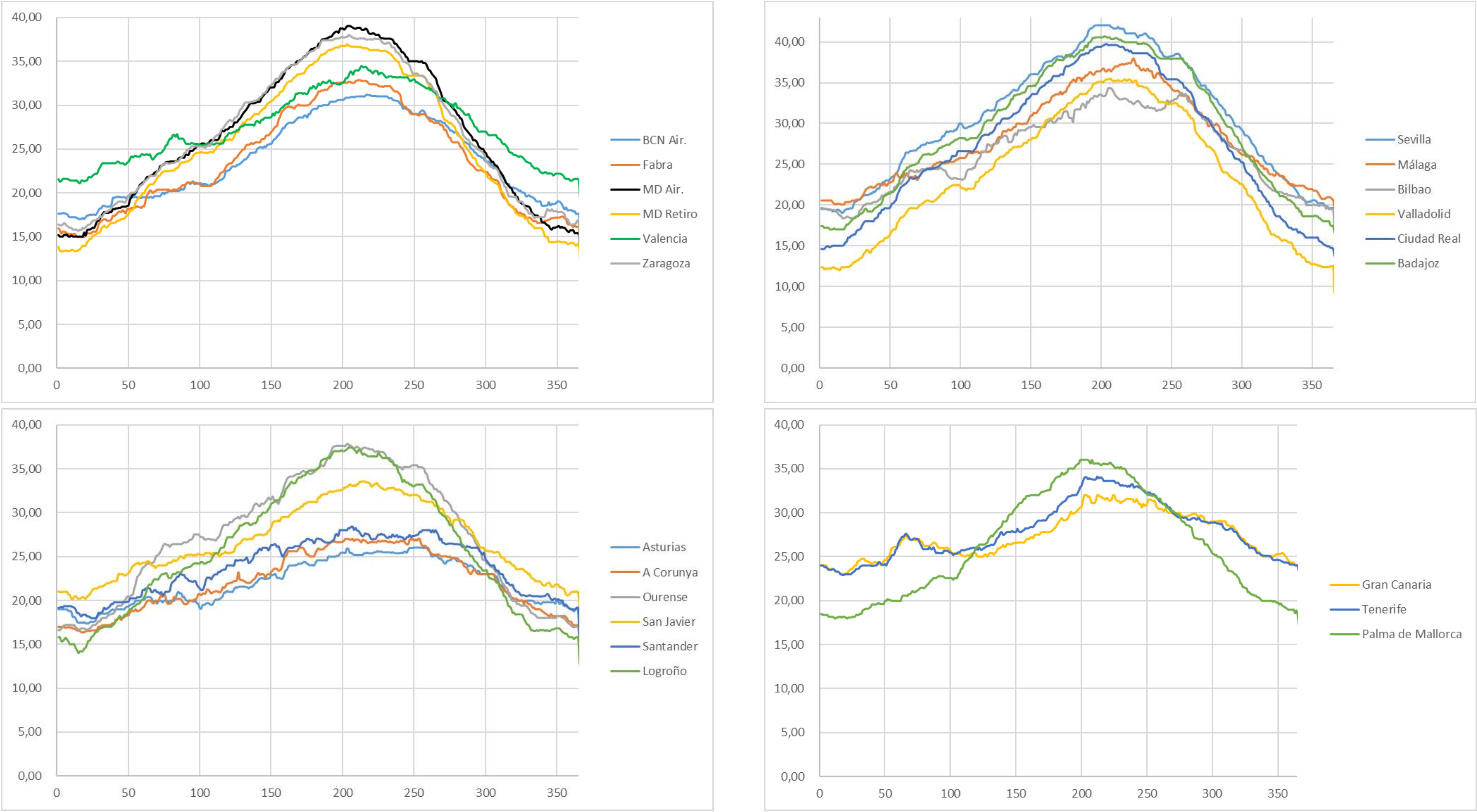
Nights in NHW are increasing at a faster rate than days in DHW

95th percentile reference temperatures (Approach 2)

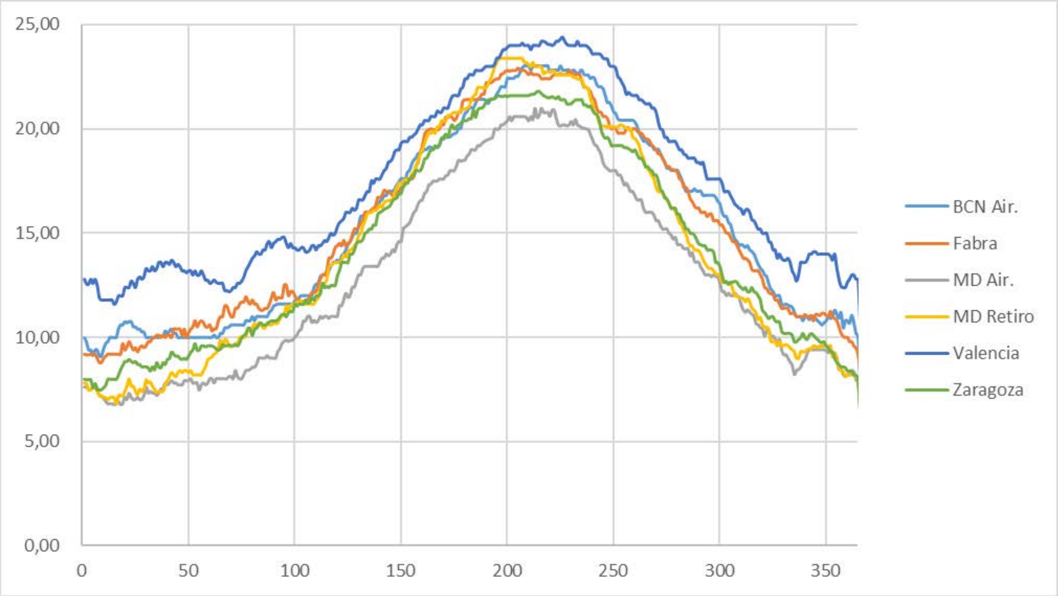
Moving windows of 15 days for each calendar day in the period 1971-2000 for stablish the thresholdsfor the DHW & NHW of each of the 21 meteorological stations

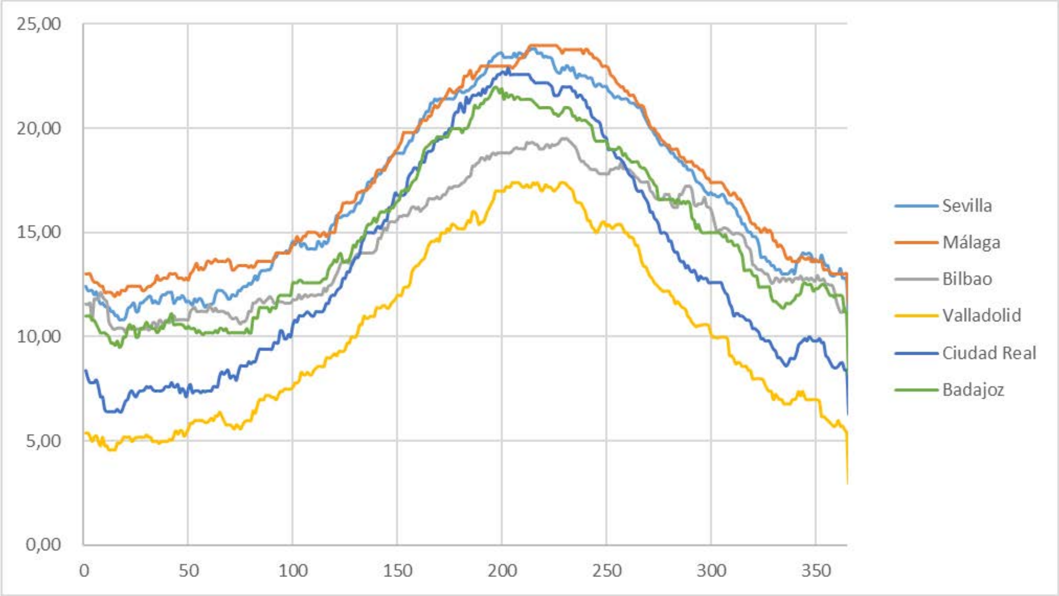


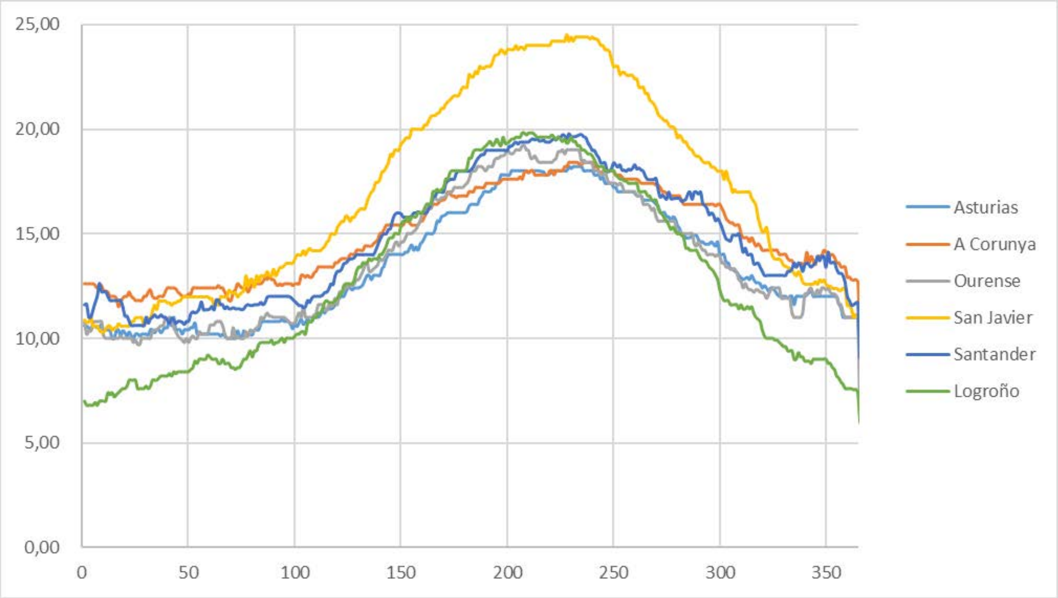
Daytime HW thresholds (Approach 2)

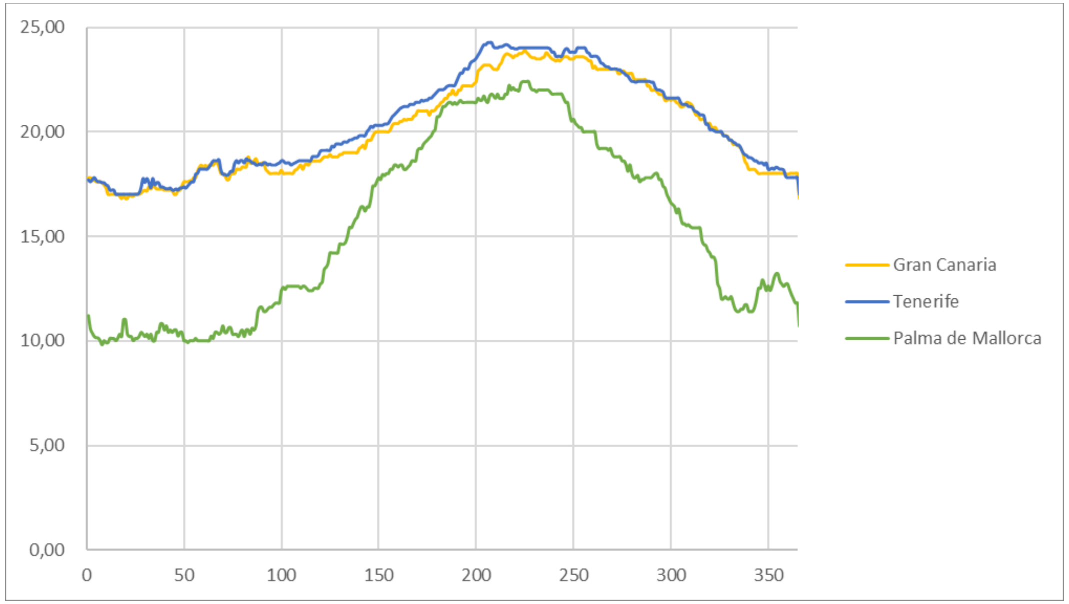


Nighttime HW thresholds (Approach 2)









Daytime Heat Waves (Approach 2)

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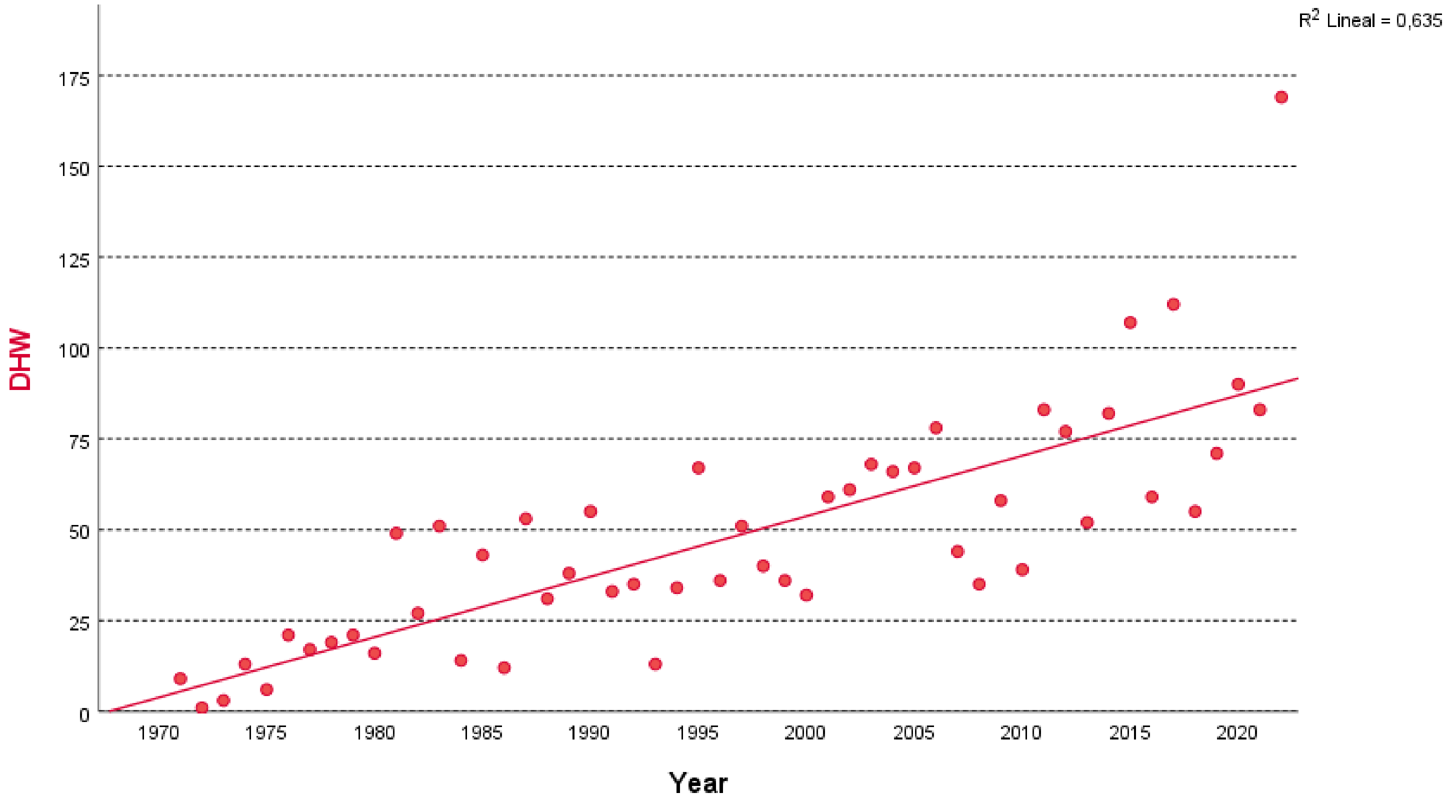
The increase in DHW has been constant throughout the period studied. The year 2022 stands out very sharply, truly exceptional in what corresponds to the maximum temperatures

Stand out, with more than 150 DHW between 1971 and 2022:

- Fabra Observatory (177 DHW, 781 hot days)
- Ourense (165, 709)
- MD-Retiro (162, 720)

Time period	DHW	Number of days
1971-1980	126	421
1981-1990	373	1453
1991-2000	377	1415
2001-2010	575	2393
2011-2020	788	3305
2013-2022	880	3990



In total, 2,491 DHW at 21 weather stations, with a total of 10,348 hot days

Nighttime Heat Waves (Approach 2)

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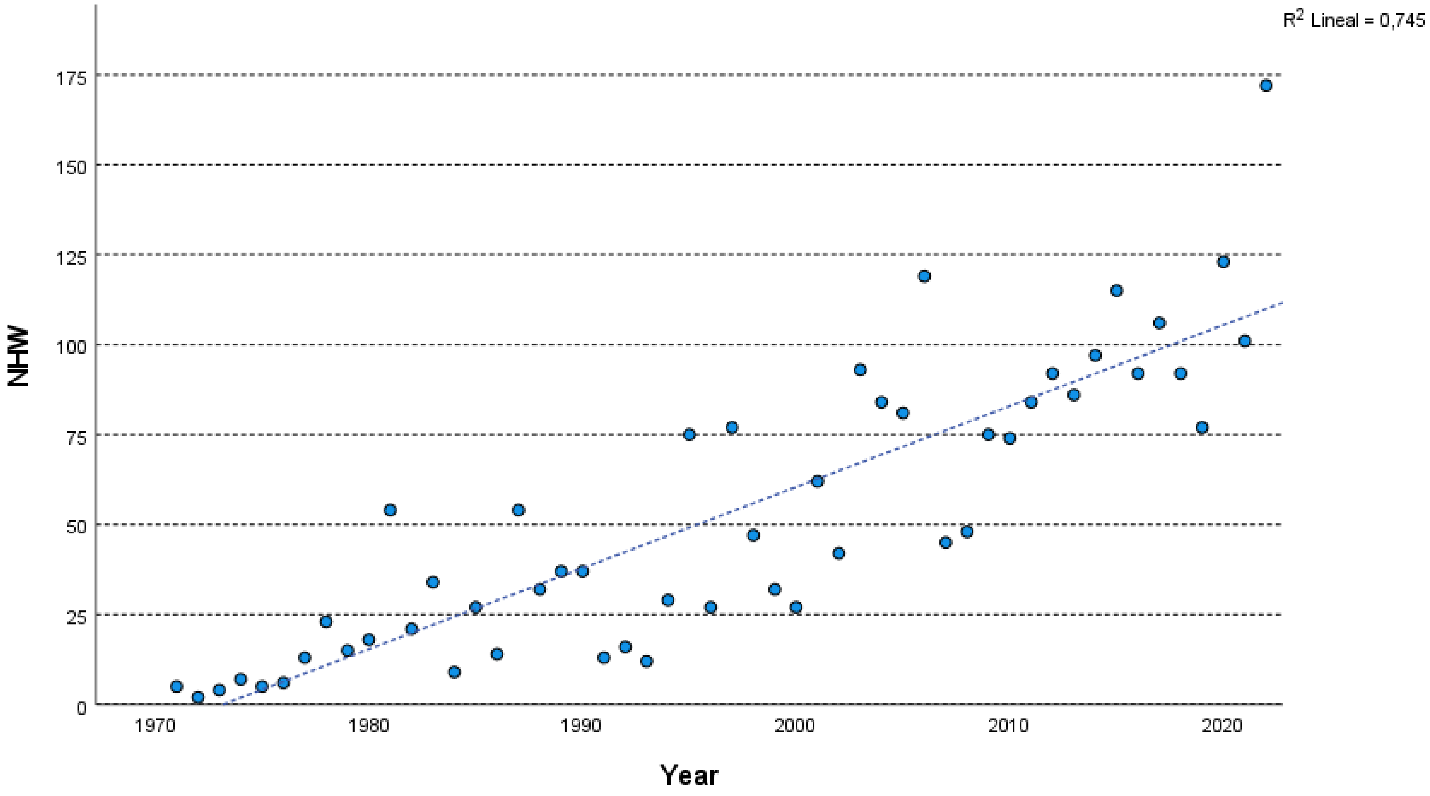
The evolution of the NHW is constant throughout the period 1971-2022. 2022 appears as an outlier, although less pronounced than the DHW. The R2 of the linear model is higher than in Approach 1

Stand out, with more than 150 NHW between 1971 and 2022:

- Barcelona Airport (238 NHW, 1336 hot nights)
- Fabra Observatory (180, 817)
- Sevilla Airport (159, 713)
- MD Retiro (153, 667)

Time period	DHW	Number of days
1971-1980	98	371
1981-1990	319	1133
1991-2000	355	1269
2001-2010	723	3170
2011-2020	964	4187
2013-2022	1061	4801



In total, 2,732 NHW at 21 weather stations, with a total of 11,469 nights

Increase of Summer Days and Tropical Nights (1971-2022)

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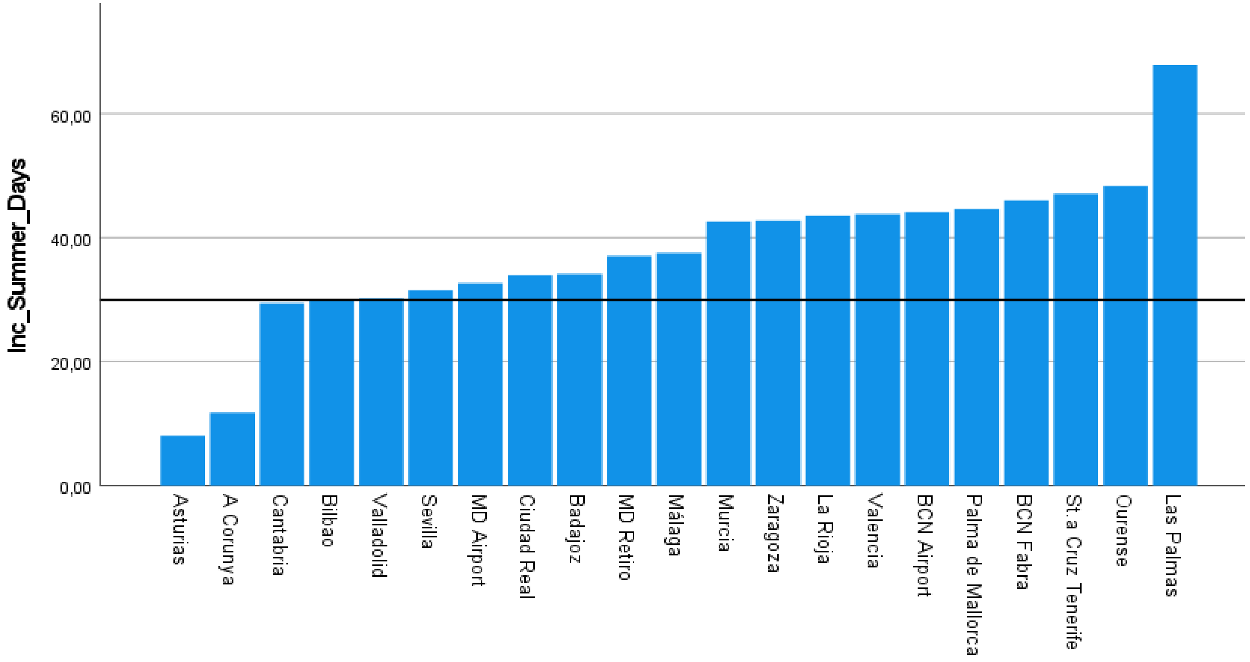
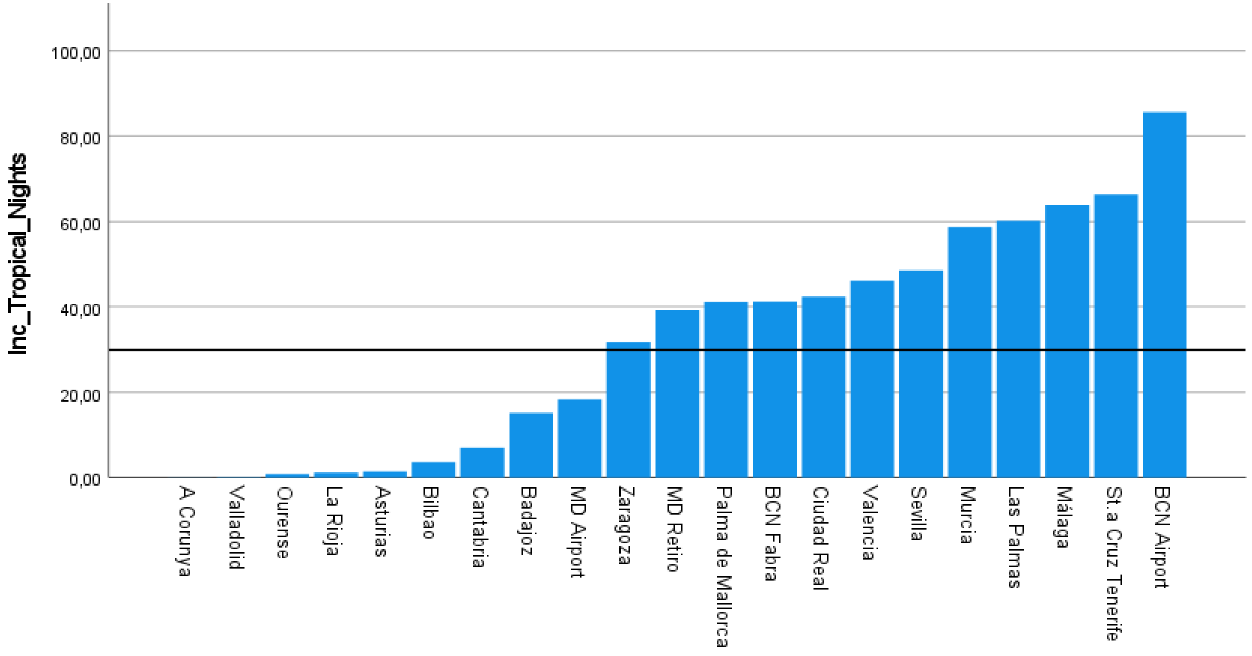
- Most of the meteorological stations have more than 1 month of increase in summer days

- The same happens with tropical nights; the weather stations near to the sea stand out for its larger increases





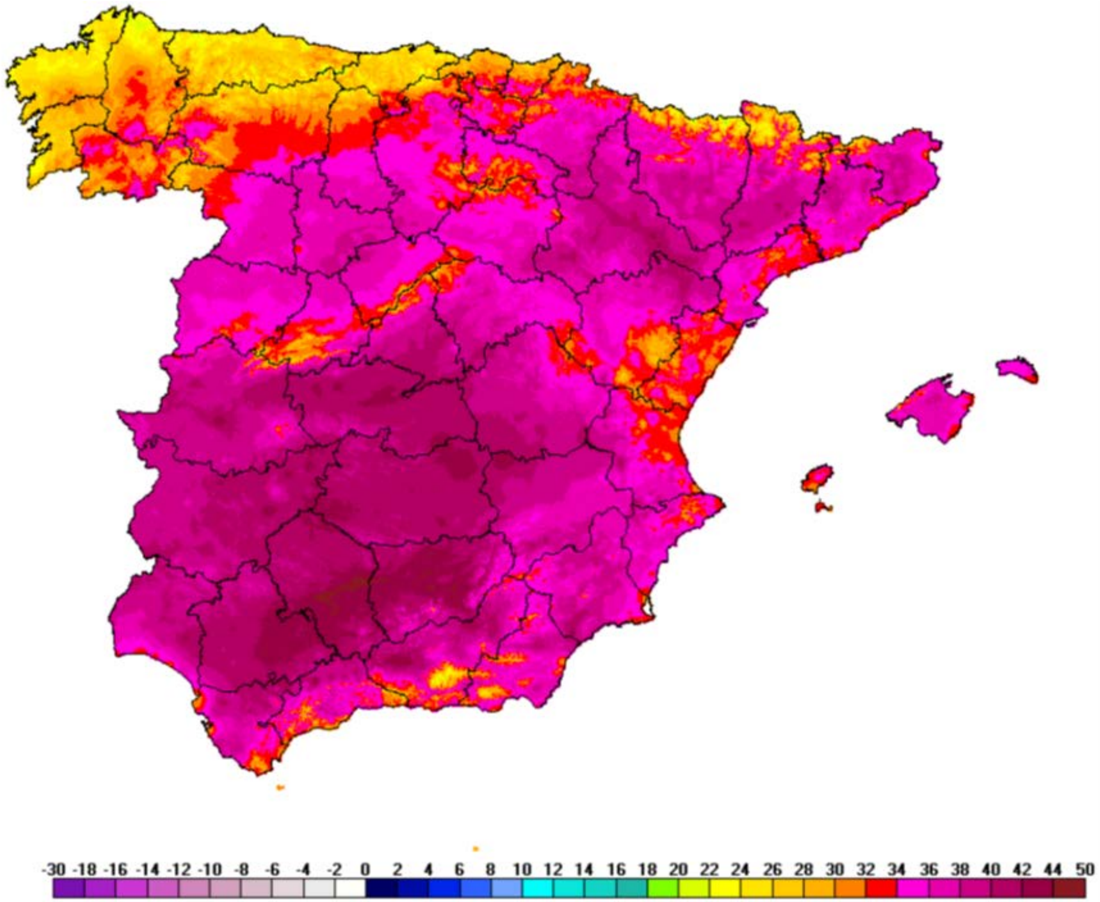
Conclusions

- The study of 21 representative meteorological stations in all Spanish regions between 1971 and 2022, confirms that the increase in temperatures is greater in Spain than in the Mediterranean basin, and of course, than Global Warming

- With the development of the Calendar Day methodology (Approach 2), we have been able to prove not only the greater importance of the nighttime heat waves, but we were also able to specify in greater detail the heat related extreme events in quantity and extent.

- This methodology propose a model for all seasons, not only summer, to explain the annual variation in temperatures for each weather station

- The trend in the evolution of daytime and nighttime heat waves between 1971 and 2022 seems to indicate a strong increase in extreme weather events in the coming decades



Thanks for your attention and take care!

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