

Ozone pollution in the Pyrenees: influence of heatwave events

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Introduction

The **Pyrenees mountain range** in southwestern Europe forms a natural border between Spain and France, extending approximately 430 kilometers from the Bay of Biscay in the west to the Mediterranean Sea in the east. In the Pyrenees there are only a few ground sensors which give information air pollutant concentrations although high pollution episodes can occur, specially **O₃ events** during **summer**. The origin of ozone is complex, involving **transport of anthropogenic NO_x** from populated areas combined with biogenic emissions of Volatile Organic Compounds (**VOCs**), as well as regional transport of ozone near the surface or within the lower to mid-troposphere. During **heatwaves** (HW) -persistently high temperatures typically lasting more than three consecutive days- ozone formation is increased due to higher velocity of photochemical reactions involving O₃ and precursors (VOCs and others).

Objectives of the study

- Explore and select an appropriate **heatwave detection criteria** over the Pyrenees.
- To explore the **spatial and temporal overview** of the **O₃** pollutant concentrations.
- To determine the **ozone levels** and **threshold exceedances** in the Pyrenees.
- To analyze the ozone concentrations during **heat wave** periods.

Frequency and characteristics of heatwaves in the Pyrenees

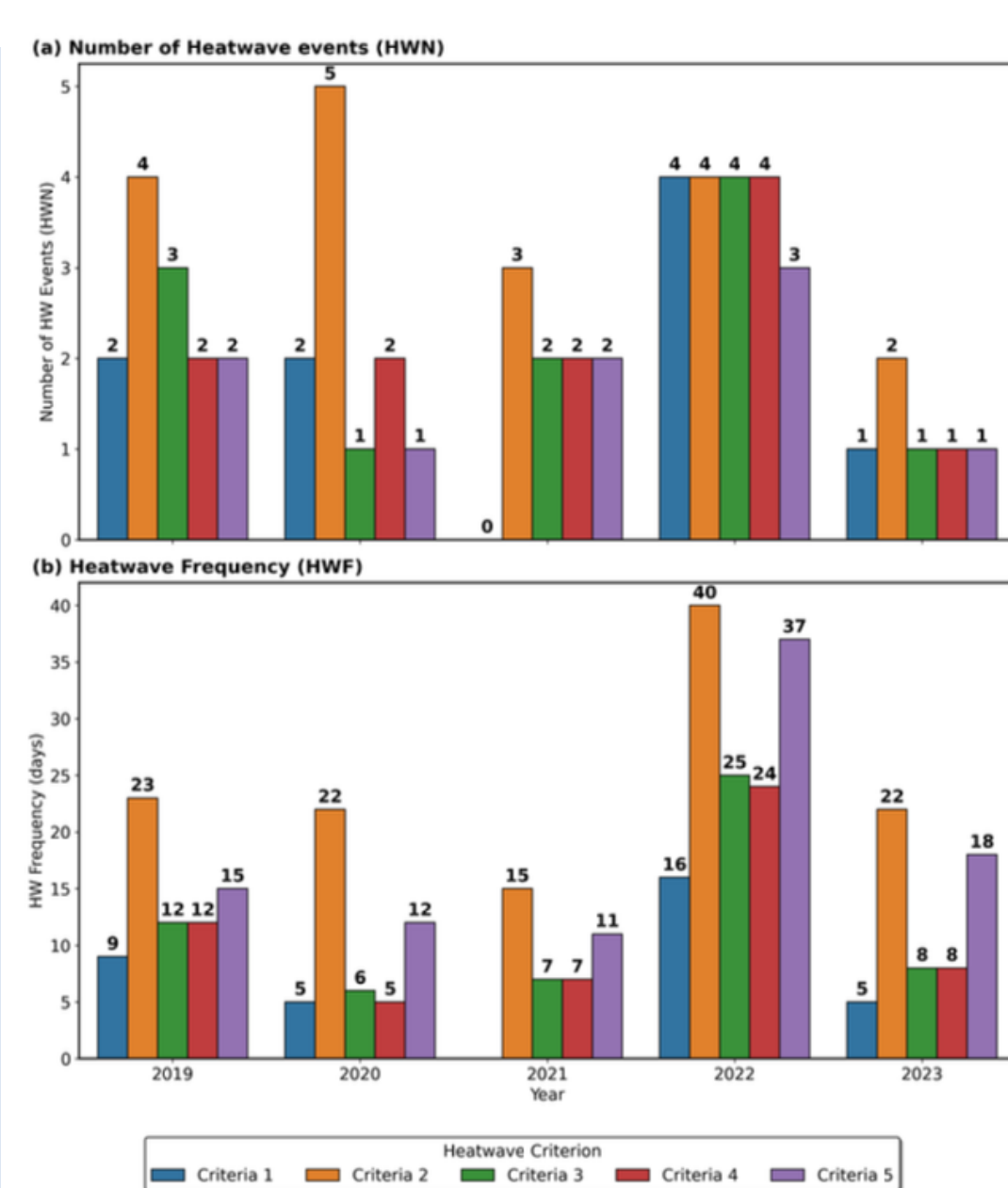
- Based on ERA5-Land data in the Pyrenees region, the number of heatwaves (HWN) and the number of days considered as heatwave or heatwave frequency (HWF) varies depending on the selected **criteria** considering percentiles and number of consecutive days from 2019 to 2023.

Index	Abbreviation (unit)	Definition
Heat-wave intensity	HWI (°C)	Sum of daily excesses of T_{max} above the heat-wave threshold over all heatwave days (cumulative intensity).
Peak heat-wave temperature	HWP (°C)	Maximum T_{max} reached during a heatwave event.
Heat-wave day frequency	HWF (days)	Total number of days meeting the heatwave criterion over the period considered.
Number of heatwaves	HWN	Count of distinct heatwave events in summer.
Heat-wave duration	HWD (days)	Total number of heatwave days in summer (sum of event lengths).

$$HWI = \sum_{d=1}^D (T_{max,d} - T_{threshold})$$

Heat wave description by 5 different detection criteria in the Pyrenees (2019-2023)

ID	Heatwave Definition	Tmax threshold (°C)	HWN	HWF (days)	HWD (days)	HWP (°C)	HWI (°C)
1	$T_{max} \geq P97.5$ (JJA), ≥ 2 days	29.75	9	35	3.89	33.85	5.52
2	$T_{max} \geq P95$, ≥ 3 days	31.71	18	122	6.32	32.92	18.65
3	$T_{max} \geq P97.5$, ≥ 3 days	29.33	11	58	5.18	33.86	14.92
4	$T_{max} \geq P98$, ≥ 3 days	27.91	11	56	5.18	33.63	13.15
5	$T_{max} \geq P95$, ≥ 5 days	31.71	10	93	9.30	33.76	29.62



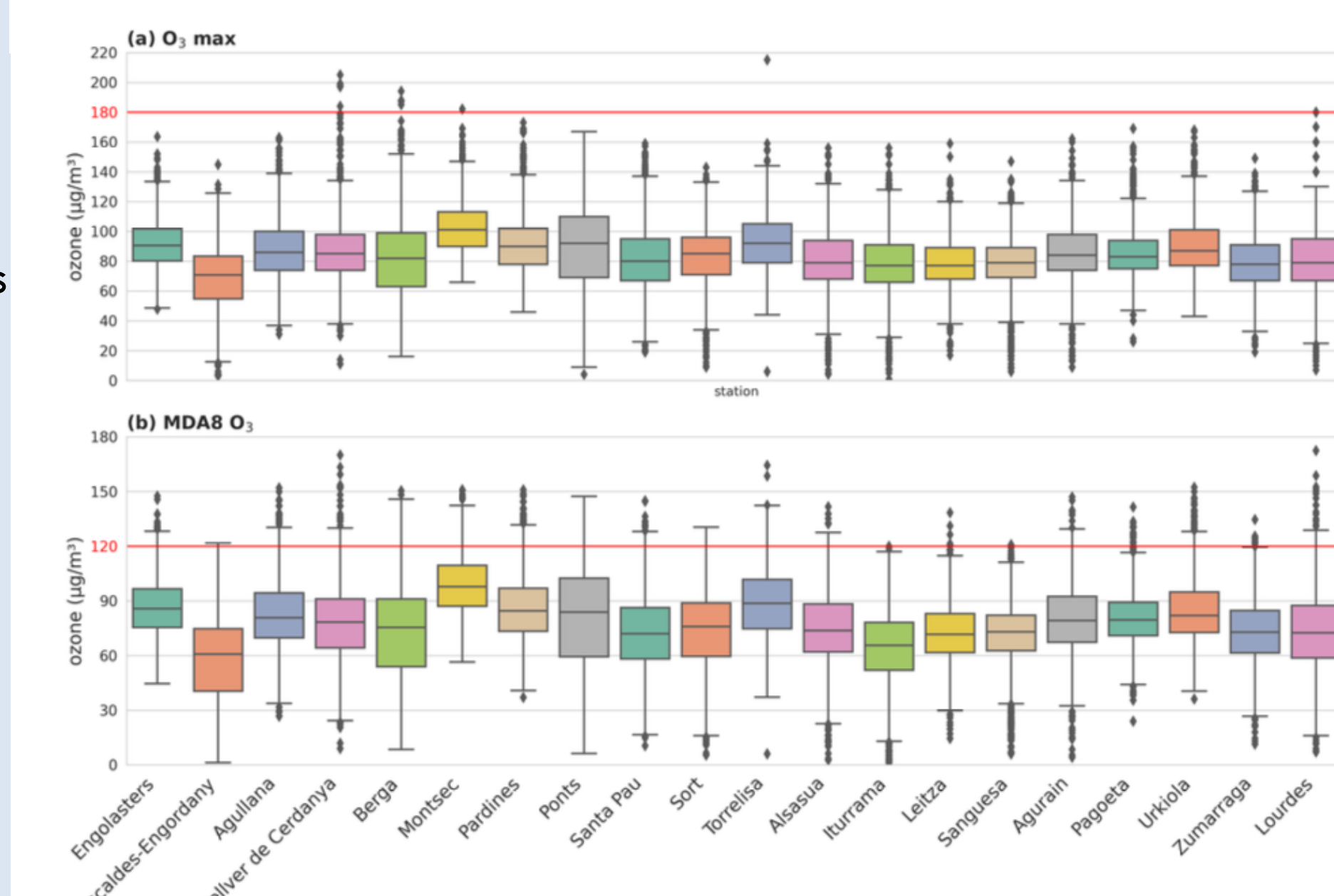
- Criterion 2 and 5 ($P95 > 3$ or 5 days) selects the highest number of heatwave days, specially in 2019 and 2022.
- Criterion 3 is selected** as the condition to capture an intermediate number of heatwave events -> **11 heatwave events** with a total of **58 heatwave days**:

Event	Start date	End date	Duration (days)	HW mean Tmax (°C)
1	2019-06-26	2019-06-30	5	33.27
2	2019-07-04	2019-07-06	3	30.48
3	2019-07-22	2019-07-25	4	32.85
4	2020-08-06	2020-08-11	6	31.49
5	2021-07-21	2021-07-23	3	31.35
6	2021-08-11	2021-08-14	4	32.09
7	2022-06-14	2022-06-18	5	33.07
8	2022-07-11	2022-07-19	9	32.69
9	2022-08-02	2022-08-04	3	31.56
10	2022-08-06	2022-08-13	8	31.03
11	2023-08-17	2023-08-24	8	33.09

Ozone levels over the Pyrenees

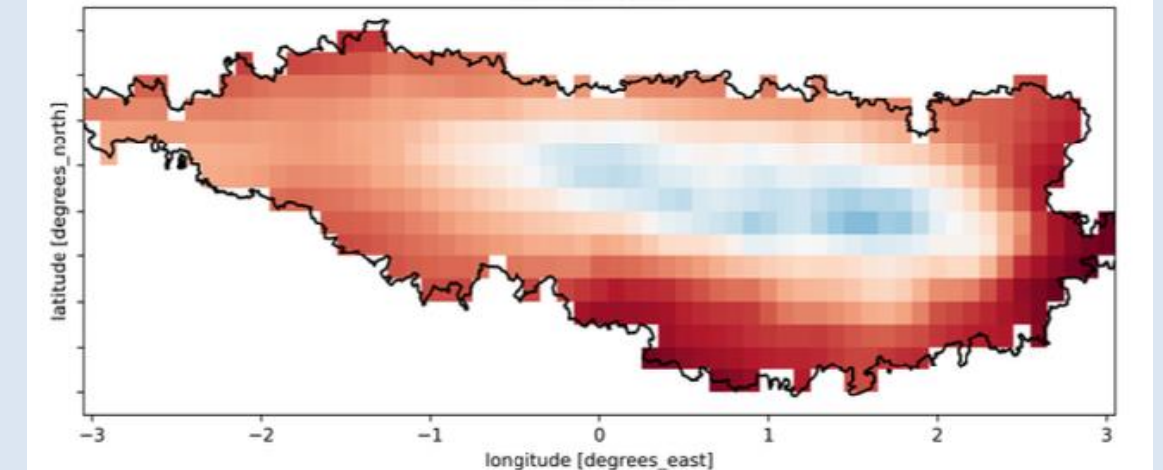
- Ozone 1-hourly daily maximum (O₃max) concentrations medians are highest in **Montsec** and **Torrelisa** which are **rural** remote stations.
- O₃max** information threshold **exceedances** ($180 \mu\text{g}/\text{m}^3$) occur occasionally in Bellver de Cerdanya, Berga, Montsec and Torrelisa and Lourdes
- 8-hourly** averaged daily maximum (MDA8) human health protection threshold ($120 \mu\text{g}/\text{m}^3$) is **exceeded** in **all stations**.
- Escaldes-Engordany in the Central valley of Andorra has the lowest mean ozone concentration -> **urban** location (high NO and NO₂ emissions).

Boxplots of: (a) 1-hourly daily O₃max ($\mu\text{g}/\text{m}^3$) and (b) 8-hourly averaged daily maximum (MDA8) ozone concentrations ($\mu\text{g}/\text{m}^3$) measured between 2019–2023 in each station. Red lines indicate: (a) Information and recommendation threshold at $180 \mu\text{g}/\text{m}^3$ (hourly average); (b) air quality objective for human health protection at $120 \mu\text{g}/\text{m}^3$ (daily max 8-hour average).



Heatwave events detection criteria

- Data sources: 2 m air temperature from ERA5-Land reanalysis (C3S, 2019) and calculation of the daily maximum temperature (Tmax) for each grid.
- Area: from a rectangle (-3° to 3° E, 41.75 to 43.50 °N) and a mask is applied for selection only the OPCC region.
- Heatwave **criteria**: different percentile and number of consecutive days are explored for the extensive period 1981-2023.
- Period of heatwave study: from 2019 to 2023 a heatwave period is identified when the **Tmax** spatial mean **exceeded** the threshold for **3 days or more**

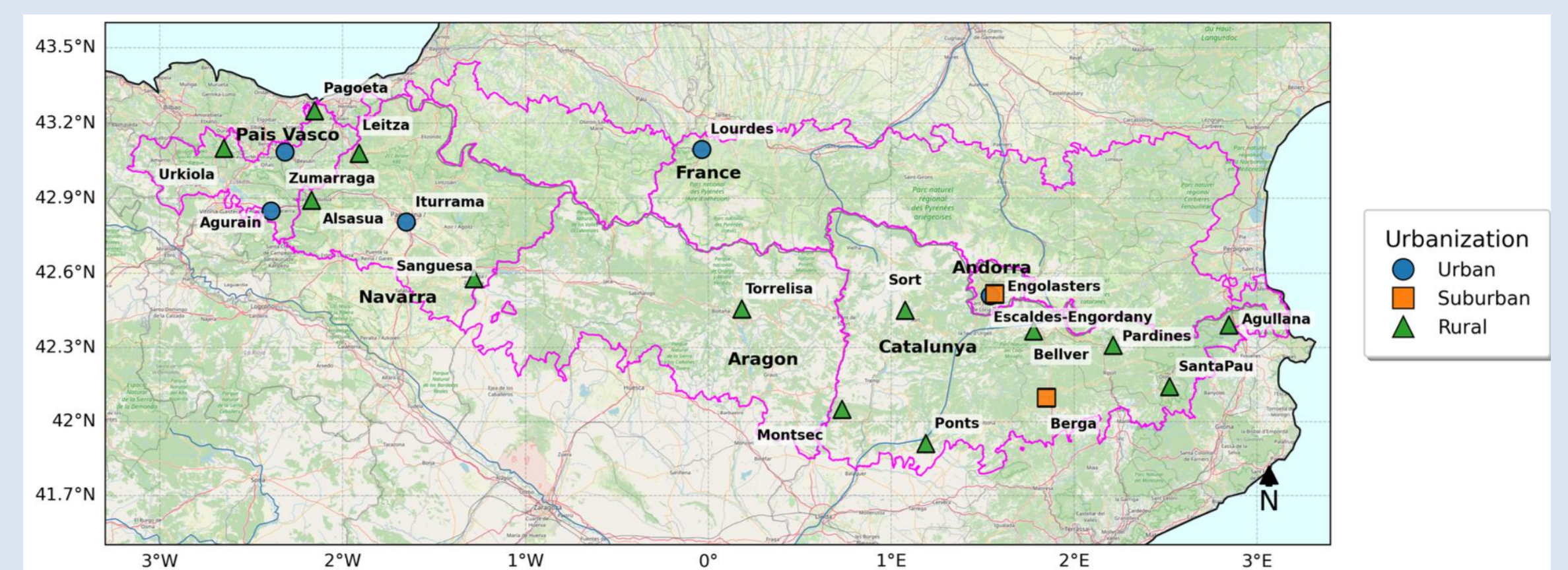


ID	Percentile Threshold	Duration	Heatwave Criteria	Studies
1	97.5 th	2	$T_{max} \geq 97.5^{\text{th}}$ percentile (JJA) for ≥ 2 days	Tong et al. (2010) [39]
2	95 th	3	$T_{max} \geq 95^{\text{th}}$ percentile for ≥ 3 days	Xu et al. (2013) [40], Tong et al. (2010) [39], Basagala et al. (2011) [41]
3	97.5 th	3	$T_{max} \geq 97.5^{\text{th}}$ percentile for ≥ 3 days	Tong et al. (2010) [39]
4	98 th	3	$T_{max} \geq 98^{\text{th}}$ percentile for ≥ 3 days	Lan et al. (2012) [42]
5	95 th	5	$T_{max} \geq 95^{\text{th}}$ percentile for ≥ 5 days	Tong et al. (2010) [39]

Ozone data (O₃)

The ozone formation and accumulation is particularly relevant during **summer**, when there is enough solar irradiance and when high temperatures intensify photochemical reactions. Thus, it is a critical pollutant in the context of climate change.

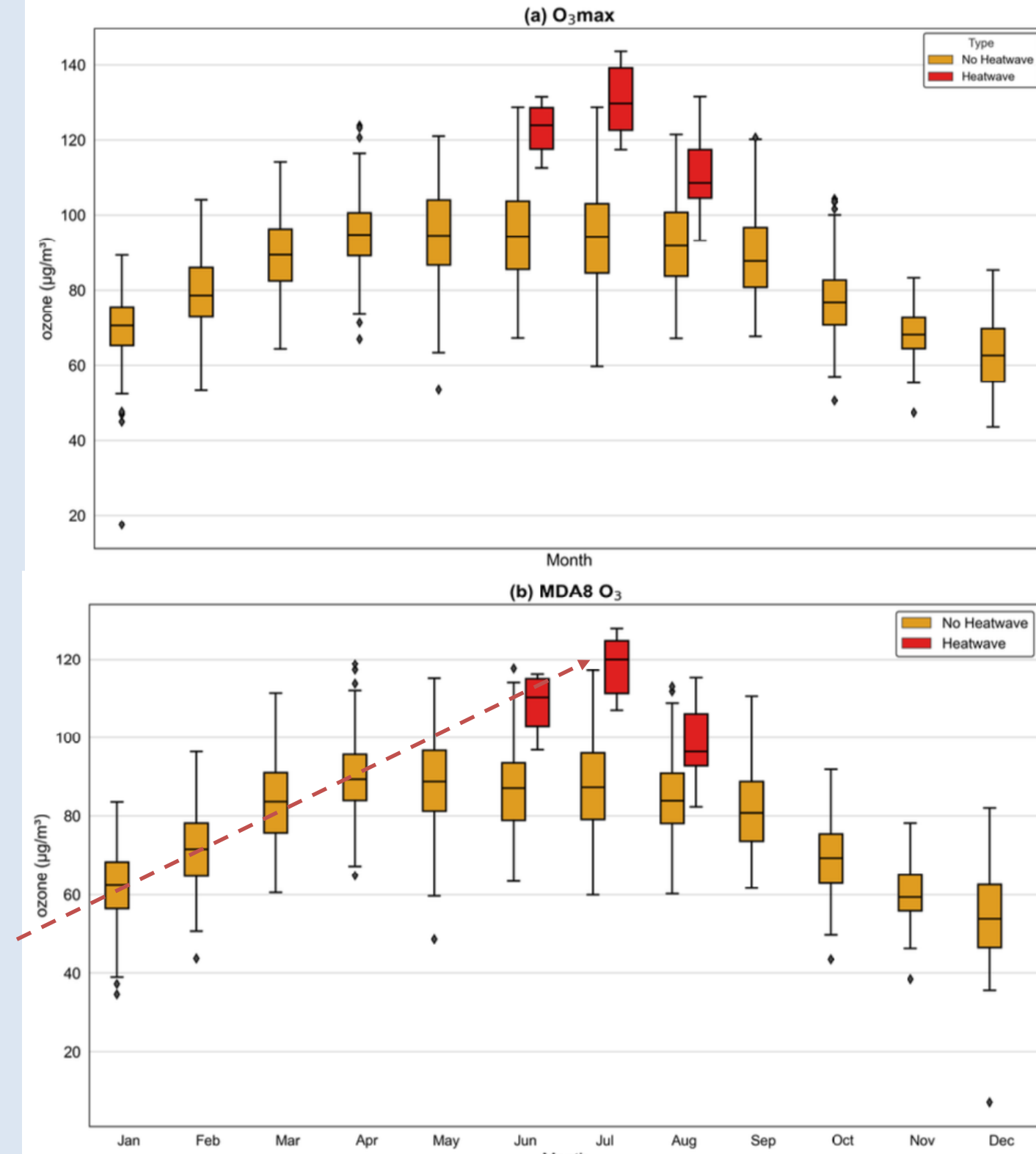
There are **20 air quality monitoring stations** for ozone from 2019 to 2023 distributed in 6 areas: Andorra (2), Catalonia (8), Aragon (1), Navarra (4), Basque Country (4), France (1).



Ozone concentrations and heat wave events

- Seasonal cycle** in ozone concentrations, with minimums during winter (DJF) and maximums in summer (JJA) due to the acceleration of precursor reactions with strong solar radiation and high temperatures, but also because of air stagnation and recirculation during summer HWs (Jaen et al. 2021).
- Spatial averaged O₃max MDA8 distributions show much **higher** median and percentiles during **heatwave** days.
- 50% of MDA8** concentrations in July during HWs **exceed** the human health protection **threshold** ($120 \mu\text{g}/\text{m}^3$).
- Bellver** and **Berga** located in eastern Pyrenees have the highest number of O₃max exceedances and almost all during HW days.
- Years **2019** and **2022** recorded the highest O₃max and MDA8 exceedances during the intense heatwaves of 26-30 of June 2019 and July 2022.

Ozone concentrations for 20 averaged stations (2019-2023)



Date	Station	O ₃ max ($\mu\text{g}/\text{m}^3$)	HW day	Tmax (°C)
18/07/2022	Bellver	199	TRUE	34.64
17/07/2022	Bellver	198	TRUE	34.80
04/07/2019	Bellver	197	TRUE	30.34
30/06/2019	Bellver	184	TRUE	32.38
29/06/2019	Bellver	205	TRUE	34.31
16/06/2022	Berga	185	TRUE	33.20
31/07/2020	Berga	188	FALSE	32.16
22/07/2019	Berga	194	TRUE	32.48
04/07/2019	Berga	187	TRUE	30.34
22/08/2023	Montsec	182	TRUE	33.73
27/06/2019	Torrelisa	215	TRUE	34.31

Conclusions

- Heatwave events were identified using percentile-based thresholds from ERA-Land dataset with a total of **11 heatwave events** and **58 heatwave days** for the 5-year period 2019-2023.
- 8-hourly** averaged daily maximum (MDA8) human health protection threshold ($120 \mu\text{g}/\text{m}^3$) is **exceeded** in **all stations** at some point.
- Hourly** daily maximum (O₃max) information threshold **exceedances** ($180 \mu\text{g}/\text{m}^3$) occur occasionally in Bellver, Berga, Montsec, Torrelisa and Lourdes and almost always during heatwave days.
- MDA8 is exceeded in **50%** of time during **heatwaves** in **July**.
- In 2019 and 2022 have large number of HW and HW days with maximum concentrations of O₃max and MDA8 as well.

References

- Copernicus Climate Change Service (C3S)(2019): ERA5-Land hourly data from 1950 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: [10.24381/cds.e2161bac](https://doi.org/10.24381/cds.e2161bac) (Accessed on DD-MMM-YYYY)(Accessed on May 2025).
- Jaén, C., Udina, M., & Bech, J. (2021). Analysis of two heat wave driven ozone episodes in Barcelona and surrounding region: Meteorological and photochemical modeling. Atmospheric Environment, 246, 118037.

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