Background

At the global scale, human populations are increasingly exposed to extreme heat events and are expected to be so in the future. Indeed, despite the ongoing debate around climate change, predictions of the intensification of heat wave episodes (in frequency, intensity and duration) are robust and consistent [1,2]. The vulnerability of the ecosystems to climatic fluctuations and social susceptibility of the exposed populations to the impact of extreme heat have been widely explored on its own, however the socio-ecological interactions appear to be understudied [3]. A literature review has shown that the most vulnerable to extreme heat individuals are the elderly [4]. Social isolation and low socioeconomic status are also presumed to increase the risk, because of a lower capacity to afford technological adaptations to heat (such as air conditioning), poorer housing conditions or deprived location [5].

The impact of the biophysical environmental on the health outcomes in the context of the changing patterns of warming is also significant. Population density and the scarcity of green areas are major determinants [6-8]. Dark-colored built environments absorb more heat than green areas and cool down to a lesser extent at night, while tall buildings located next to each other significantly lower the speed of winds that refresh urban air. Moreover, the concentration of human activity exacerbates meteorological phenomena through the effects of air pollution and non-efficient overly intense energy use (so called *urban heat island effect*) [9]. Overall, in a complex urban environment there are potentially millions of factors that shape the health of individuals. Therefore, it increasingly makes more sense to focus on the interactions between humans, with all the complexity and variability of its social characteristics, and diverse components of the environment, instead of tackling one aspect (e.g. plain temperature increase) taken separately.

A common approach to study the effects of extreme temperatures on mortality in Spain and elsewhere across the globe involves the use of aggregated mortality estimations for large areas. In Spain – a country that has experienced 47 heat waves in total since 1975 [10] – these effects are commonly studied using total daily mortality broken down by age and cause of death at a single or multiple city level [11, 12]. The pertinent characteristics of the studied population, as well as their social context and the environmental conditions they live in, are barely documented, which introduces biases in the analyses and interpretations. Another limitation for conducting a detailed analysis is the use of discrete meteorological measurements aggregated to province [13] or autonomous community [14] levels, which inarguably implies some ecological fallacy by creating overly generalized assumptions.

With the proposed research we aim to explore and compare the differences in mortality outcomes due to the heat waves in various settings across Andalusia combining the data on population and environment with fine spatial and temporal resolution. At the same time, this study will produce a robust and spatially continuous measurement of the urban-to-rural gradient, building it on the conceptual idea established in a prior work [15]. Here we aim to enrich our previous findings by measuring the contributions of climate change to the effects that this gradient has on mortality outcomes on its own. Furthermore, we pursue the idea to identify local populations that have been able to successfully deal with the heat waves during a turbulent period of 17 years, marked by the 2008 crisis and its socioeconomic consequences, to learn through those experiences.

Study design, data and methods

We start by creating a spatial data infrastructure based on the regular grid structure with 20X20 km resolution. First, we separate strictly urban from pronouncedly rural areas by intersecting the grid with urban functional areas as defined in the ***Urban Atlas***[1]. On the subsequent step we characterize the cells that fall into the urban category by the portions occupied by the human settlements (built-in area density), green urban areas, industrial areas, mineral extraction and dump sites. Here we aim to track

[1]Urban Atlas, a pan-European comparable land use and land cover data for Functional Urban Areas (https://land.copernicus.eu/local/urban-atlas)

the changes in the environment in time, and in case when land cover classification at the 1:15.000 as provided in the Urban Atlas is unavailable we add the ***Land Occupation***[2] data produced at the 1:25.000 reference scale and ***Corine Land Cover***[3] data at 1:100.000 scale, which allows us to create snapshots for the years 2000, 2005, 2006, 2011, 2012, 2014 and 2018. On top of this, we classify the cells according to their levels of accessibility to essential health care resources, where accessibility is estimated based on the location of resources[4], transport network configuration and traffic limitations[5]. Overall, this approach is expected to produce a fairly realistic representation of the region based on the environmental pressure and effectiveness of the infrastructure within each cell.

Once the area is classified according to the urban-to-rural gradient, we add the data on meteorological conditions for the same period. Here we work with the ***ground point meteorological observations*** of temperature, humidity, precipitations and many more[6], which are interpolated to the 20X20 km grid using the kriging regression prediction considering the differences in the relief and distance to the coastline. In case when the interpolation seems to be an inappropriate method to create continuous surfaces, we turn to ***pre-modelled data based on the global air circulation models***[7]. Having the hourly series of all basic meteorological variables enables us to analyze the daily, monthly and yearly variations of the temperatures and temperature-derived indices (e.g. *Heat Index*, which indicates the effect of humidity on the body subjected to high temperatures and involves temperature and relative humidity measurements, or *Apparent Temperature*, which represents a complex index based on the elaborated series of expressions which consider the effects of the thermal resistance such as exercise, the respective effects of clothing on moisture loss and heat loss, ambient temperatures, atmospheric vapor pressure, direct solar radiation, diffuse solar radiation, the fraction of the body covered by clothing, the degree of wind penetration into the clothing) over the period of 17 years. We identify the episodes of heat waves by analyzing the reference period of time and setting up an individual threshold value for each cell of the grid. Furthermore, we identify the cells that experienced the most intense pressure in terms of heat stress during the study period (fig.1).

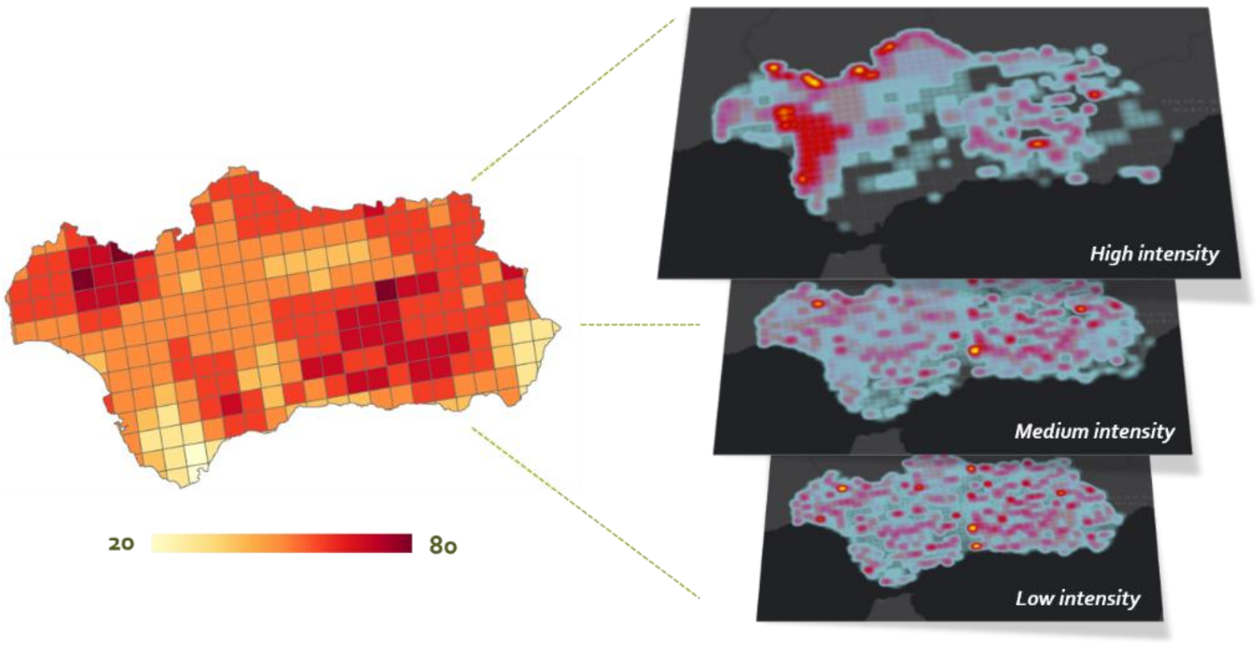

Figure 1. Cumulative number of days with extreme heat during the period from 2000 to 2017

[2]Information System on Land Occupation of Spain, integrated into the National Land Observation Plan (http://www.siose.es/)
[3]CORINE Land Cover inventory (https://land.copernicus.eu/pan-european/corine-land-cover)
[4]National catalogues of hospitals and health centers by the Ministry of Health, Consumption and Social Welfare of Spain (https://www.mscbs.gob.es/), data on social and sanitary facilities for elderly care by the Spanish National Research Council (http://envejecimientoenred.es/)
[5]StreetMap Premium for ArcGIS, based on the HERE data (https://enterprise.arcgis.com/en/streetmap-premium/latest/get-started/overview.htm)
[6]Hourly and daily ground point measurements by the State Meteorological Agency (www.aemet.es)
[7]ERA-Interim/ERA5 datasets by the European Centre for Medium-Range Weather Forecasts (www.ecmwf.int)

The ***core data on population*** is derived from the ***Longitudinal Database of Population of Andalusia***, developed and maintained by the Institute of Statistics and Cartography of Andalusia[8]. This population register follows all the individuals residing in Andalusia since 2000 onwards (approximately 10 million individuals) and represents a unique systematic data collection initiative which offers geocoded information within small area settings (continuous grid with minimal spatial resolution of 250m^2). This comprehensive database contains administratively collected information on individuals who were registered in the autonomous community of Andalusia at the time of the Spanish Population and Housing Census of 2001. Linked by a personal identifier, it adds up the 2011 Census data on the same individuals and combines it with additional data coming from multiple routinely updated registers. The linkage to the annually updated Vital Statistics and Population Register (*Spanish: Padrón*) allows to follow up births, deaths, migration and residential movements in combination with a series of other socioeconomic indicators. Furthermore, all the events, like births and deaths, socioeconomic and demographic information are geo-referenced. This enables us to represent the data stratified by basic demographic characteristics (e.g. sex, date, place of birth, place of residence, educational attainment) spatially at 20X20 km resolution. We use the daily mortality estimates produced on the basis of the Population Register described above, urban-to-rural gradient and heat wave episodes measurements to create a multilevel model using the integrated nested Laplace approximation.).

As one of the research questions in this study is related to the processes of human adaptation to extreme heat over time and potential determining factors resulting in successful outcomes, we design this study in the manner that allows us to compare different phases. The numerous hot spells registered after the most harmful heat wave of 2003 (fig.2), which provoked a total excess mortality of almost 80.000 deaths across Europe and significantly impacted the population of Spain as well, have not resulted in the mortality responses of the same intensity, even when accounting for destabilizing factors like the severe economic crisis that Spain has suffered since 2008.

Figure 2. Episodes of heat waves of different intensity registered in Andalusia between 2002 and 2016

[8]Institute of Statistics and Cartography of Andalusia (www.juntadeandalucia.es/institutodeestadisticaycartografia)

In this study, we contrast the periods of 2000-2003, 2004-2008 and 2009-2017 in order to explore the factors defining more or less successful adaptations to climate change in this area. We analyze the evolution of both mortality levels and heat wave mortality responses as the measure of "success", considering the related changes in demographic and socioeconomic composition of the Andalusian population and transformation of the local environmental context. Besides, we believe that public health preventive measures provide an important contribution to successful adaptation, and thus we consider this factor at the regional and local (city) levels.

Research questions and expected results

A plethora of studies have described the social and demographic profiles of the most susceptible to extreme heat individuals, highlighting that the elderly are at the higher risk, however other aspects were studied less. In this contribution we ask if there is any difference in mortality response to heat waves according to the urban-to-rural gradient? Is this gradient persistent through time? Where these unfavorable outcomes (i.e. mortality responses) are more pronounced? How this spatial pattern changes over time? Where are the "hot" and "cold" spots of the successful adaptation to extreme heat seen through persistent trends in mortality? What are the underlying socio-economic and environmental conditions in these areas, and how these are changing over time?

When asking all these questions, we expect that individual and societal adaptation to heat waves takes place earlier in urban areas, despite the potentially harmful urban heat island effect, as the density of social and public health institutions is much higher than in rural settings. We also suspect that the socioeconomic gradient reflects on the process of adaptation to extreme heat, putting those with higher education and socioeconomic status in a more favorable position for surviving and coping with heat stress. By applying the comprehensive approach described earlier we expect to reveal the growing disparities in mortality and depict the vulnerabilities within the society.

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