Theoretical and Applied Climatology
https://doi.org/10.1007/s00704-024-04915-9

RESEARCH

Assessing Argentina's heatwave dynamics (1950–2022): a comprehensive analysis of temporal and spatial variability using ERA5-LAND

Caterina Cimolai[1,2] · Enric Aguilar[1,2]

Received: 7 December 2023 / Accepted: 1 March 2024

Abstract

Understanding the spatial and temporal variability of heatwaves is crucial for climate change adaptation. This study examines heatwaves in Argentina from 1950 to 2022, analyzing temporal and spatial changes using four metrics: number of events (E), duration (D), mean intensity (MnI), and maximum intensity (MxI). It investigates seasonal variations (Warm and Cold Seasons—CS, WS) and the influence of different phases of the El Niño-Southern Oscillation (ENSO). Data from ERA5-LAND Reanalysis for 2 m daytime (Tx) and nighttime (Tn) temperatures are utilized. Our findings reveal regions with significantly higher heatwave intensities (Tx) in the North, east of Cuyo, west of Centro, and Southern Patagonia. Conversely, significant heatwave intensities (Tn) were observed, particularly in the north of the Litoral and Southern Patagonia. The Andes region (center and north) exhibited significant intensities for Tn. Both D and E exhibited similar significant trends for both Tn and Tx, except for the central zone. During the WS, the North-West and South Patagonia exhibit significant increasing trends for across most metrics. In contrast, during the CS, a higher number of significant increases in the studied metrics were observed in relation to Tx. El Niño amplifies heatwave intensities nationwide, except in Patagonia, where this occurs during the cold phase. In this phase, E and D of events increase in most Argentinian regions, resulting in a decoupling of intensity and duration, which increases in opposite periods. This study contributes to existing research by providing a detailed understanding of heatwave behavior with high spatial resolution.

Keywords Climate change · ERA5-LAND · Extreme events

1 Introduction

Climate change exerts its influence on many weather and climate extremes across the globe (IPCC 2023). As mean temperature rises, temperature extremes increase and their persistence in the form of heatwaves become a cause of concern. Heatwaves impact human health, economy, and the environment (Perkins-Kirkpatrick and Lewis 2020; de Araújo et al. 2022).

In South America (SA) various researchers have extensively investigated temperature extremes (Barrucand and Rusticucci 2001; Rusticucci and Barrucand 2004; Aguilar et al. 2005; Dufek et al. 2008; Tencer and Rusticucci 2012; Skansi et al. 2013; Rusticucci et al. 2014, 2016; Tencer et al. 2016; Balmaceda-Huarte et al. 2021; Seneviratne et al. 2023). The frequency of warm nights and warm days has increased, while occurrences of extremely cold nights have decreased (Skansi et al. 2013; Rusticucci et al. 2017; Olmo et al. 2020). Some authors emphasize that alrger increasing trends in minimum temperatures (Tn) compared to maximum temperatures (Tx) (Barrucand and Rusticucci 2001; Rusticucci and Barrucand 2004; Dufek et al. 2008; Rusticucci 2012; Skansi et al. 2013). On the contrary, more recent articles (Olmo et al. 2020; Balmaceda-Huarte et al. 2021) found that warming was more pronounced and uniform across different regions for Tx rather than Tn. Olmo et al. (2020) suggested that this discrepancy could be attributed

✉ Caterina Cimolai
caterina.cimolai@urv.cat

1 Center for Climate Change (C3), Universitat Rovira I Virgili (URV), Tarragona, Spain

2 Univesity Research Institute in Sustainability, Climate Change and Energy Transition (IU-RESCAT), Tarragona, Spain

Published online: 15 March 2024

to the sensitivity of trends to the study period and the the season used for constructing the indices.

In Argentina, the temporal evolution of heatwaves shows regional differences de Araújo et al. (2022), who investigated heatwaves using maximum temperatures (Tx) during the austral winter-spring transition from 1979 to 2019, demonstrated an increase in the intensity of these extreme events, particularly in the North-Central region of Argentina. Similarly, Rusticucci et al. (2016), in their analysis of trends spanning 1970–2010 in the central and northern regions of the country using daily Tx and Tn series derived from observational data, observed a significant decrease in the frequency of cold nights (Tn) and a noteworthy increase in the occurrence of warm days during the warm season months (October-January). In the North-East of Argentina, Ceccherini et al. (2016) reported an increase in the intensity and frequency of heatwaves (period 1980–2014), and Skansi et al. (2013) showed an increase in warm nights in Litoral. In Patagonia, different contributions have consistently reported significant increases in maximum temperatures (Rusticucci and Barrucand 2004; Skansi et al. 2013; Olmo et al. 2020).

However, contrasting patterns have also been identified. Rusticucci et al. (2017), working with observational data for the period 1970–2010, found reductions in the trends of warm days in the central-southern region of Argentina. Suli et al. (2023), analyzing Tx data from warm months from meteorological stations, identified negative trends in specific locations in the province of Buenos Aires, although not statistically significant. This was also corroborated by Skansi et al. (2013), who conducted a study on climate extreme indices over South America using two different periods: 1950–2010 and 1969–2009. Also, Olmo et al. (2020), who worked with Tn and Tx data from meteorological stations SA (1979–2015) encountered similar results. Both detected reductions in daily maximum temperatures (Tx90) in the central and southern coastal region.

In Argentina, heatwaves result from the combination of topographic influence and synoptic conditions associated with anomalous anticyclonic circulation patterns at medium atmospheric levels (Marengo et al. 2012). These circulation anomalies can induce the descent of adiabatically warmed air from upper atmospheric layers, leading to increased surface pressure, atmospheric desiccation (Nissan et al. 2017). The significant elevation of the Andes Mountain Range is one of the prominent topographical features of the country, influencing the region's climate (Collazo 2020). The Andes force a wide array of mesoscale and synoptic phenomena, as well as contrasted climate conditions at the eastern and western slopes and adjacent lowlands (Garreaud et al. 2009). Rusticucci et al. (2003) states the significance of the Andes Mountains in shaping atmospheric circulation by demonstrating that extreme temperature events in Argentina exhibit a stronger seasonal correlation with the Atlantic rather than the Pacific. The exception to this rule occurs during warm events in spring, for which ENSO (El Niño/Southern Oscillation) dynamics emerge as the dominant forcing mode (Rusticucci et al. 2003). The Andes prevent moisture advection from the Pacific Ocean and, to the east, the South Atlantic anticyclone dominates the lower-level atmospheric circulation (Barros and Silvestri 2002). Conversely, the prevailing North-East airflow is dominated by the South Atlantic Anticyclone (SAA) and a thermally driven low-pressure system (the Chaco Low) situated in the northwest, from Chaco to the Andes (Collazo 2020). Also, the Argentine Northwest Low is an intermittent thermal-orographic system that is an extension of the Chaco Low, with higher intensity typically observed during the summer months (Seluchi and Saulo 2012).

Different authors (Rusticucci and Vargas 2002; Kenyon and Hegerl 2008; Rusticucci et al. 2017; Collazo et al. 2019; Cai et al. 2020) mention that ENSO is strongly associated with the occurrence of extreme temperatures in South America. Moreover, ENSO stands out as the primary driver of climatic fluctuations over interannual periods and, therefore, in years characterized by ENSO neutrality, the predictability of the climatic system is reduced (Rusticucci and Vargas 2002; Collazo 2020). The understanding of the ENSO and its impact on local or regional climate is crucial because it has socio-economic, ecological, and environmental impacts (Cai et al. 2020).

ENSO also influences Argentina´s climate (as well as the rest of the world). It is a natural phenomenon characterized by the fluctuation of ocean temperatures in the central and eastern equatorial Pacific, associated with changes in the atmosphere/ocean coupling. ENSO consists of three phases: El Niño, La Niña, and a neutral phase. In general, El Niño episodes reverse the Walker Circulation and reach its maximum intensity during the period from November to January to decline in the first half of the following year. Intense and moderate El Niño episodes result in an increase in global mean surface temperatures. La Niña enhances the Walker Circulation and generates opposite effects, and during the neutral phases of the ENSO phenomenon, other climatic factors determine atmospheric conditions (Lau and Yang 2015).

In general, in Argentina, El Niño can be associated with hot temperatures meanwhile, La Niña with colder conditions (Garreaud et al. 2009). The El Niño phase induces warming during winter and cooler conditions in summer, in the Centre and North of Argentina (Kenyon and Hegerl 2008; Rusticucci et al. 2017). Collazo et al. (2019) also notes that El Niño favors reduction of cold extremes. During La Niña, a pattern emerges characterized by more frequent warm days and fewer cold days in summer compared to the climatic norm. Additionally, winter months experience cooling conditions, particularly in July and August (Rusticucci et al. 2016). The inter-annual variability in Patagonia is attributed to changes in the position and strength of the southeast Pacific anticyclone, mean sea-level pressure (SLP), and the El Niño-Southern Oscillation (ENSO). During El Niño events, the southeast Pacific anticyclone shifts northward and weakens, facilitating increased westerly wind flow and precipitation at mid-latitudes. Conversely, during La Niña events, the southeast Pacific anticyclone shifts southward and strengthens beyond normal levels (Daniels and Veblen 2000).

Climate projections suggests future alterations in the frequency and intensity of ENSO phases. According to (Gulizia and Pirotte 2022), projections suggest a doubling of the frequency of extreme El Niño events in the RCP4.5 and RCP8.5 scenarios, while the increases in moderate El Niño events are less pronounced. Additionally, climate models indicate, in the context of greenhouse warming, a mean pattern of rainfall change akin to the anomaly pattern associated with El Niño (Cai et al. 2020). This could signify an escalation in heatwaves due to warmer conditions in minimum temperatures and an elevated incidence of extreme warm minimum temperatures (Gulizia and Pirotte 2022).

Comprehensive and high-quality climate data networks are critical for understanding climate related hazards and their impacts (Aguilar et al. 2003). However, access to long-term and high-quality climatic records can be a challangedue not only to data scarcity, but also in relation to restrictive national policies (Skansi et al. 2013).

In Argentina, with its extensive territory and diverse topography, certain regions, such as Patagonia or mountainous areas, are monitored with a limited number of meteorological stations, making difficult a region-wide solid analysis. (Garreaud et al. 2013). TThe use of reanalyzed data helps overcoming this problem. Reanalysis are reliable sources of climatic information and are nowadays among the most used data sets (Balmaceda-Huarte et al. 2021). There are diverse types of reanalysis data, some are more suitable for certain regions than others. ERA5-Land, the latest product from the European Centre for Medium-Range Weather Forecasts (ECMWF), offers several advantages over its predecessor, ERA5. It has a higher horizontal resolution, providing more detailed and precise information (Muñoz-Sabater et al. 2021). ERA5-Land covers the period from January 1950 to the present and has a horizontal resolution of $0.1° \times 0.1°$, which better captures geographical features on each grid cell (Muñoz Sabater 2019).

Many studies have employed the ERA reanalysis family to investigate extreme temperatures and heatwaves (Rusticucci et al. 2014; Lovino et al. 2018; Collazo et al. 2018; Balmaceda-Huarte et al. 2021; de Araújo et al. 2022). Collazo et al. (2018) studied heatwaves in Argentina with ERA5-INTERIM data, for the period from 1980 to 2010 and compared them with observational data. Their analysis was limited to the warm season (October–March) and confined to the central and northern regions of the country, excluding Patagonia. They indicate that the model overestimated the summer daily Tx in most of the stations analyzed (Collazo et al. 2018). The author mentions that the probable causes of model errors may be deficiencies in representing land surface processes (Collazo et al. 2018). Furthermore, ERA-INTERIM can represent interannual variability (Rusticucci et al. 2014) and exhibits the capability to identify temperature extremes both temporally and spatially (Lovino et al. 2018).

Balmaceda-Huarte et al. (2021) studied how ERA-INTERIM and ERA5 represent spatial patterns of most of the temperature and precipitation indices. They found that, in general, this reanalysis well captures spatial characteristics but presented warmer temperatures over the region. Near the Andes Mountain range, ERA-INTERIM and ER5 underestimated the temperature indices (Balmaceda-Huarte et al. 2021) ERA5 appeared to replicate the observed spatial and temporal variations than ERA more accurately. INTERIM, likely due to its enhanced spatial resolution and improvements in the model. Additionally, (Birkel et al. 2022) discovered that the temperature warming trends in ERA5 for the central Andean region showed agreement, suggesting that ERA5 provides the most reliable and comprehensive representation of temperature and precipitation in the study area when compared to other datasets.

The performance of ERA5 across South America (SSA) exhibits satisfactory results for heatwave-related indices, albeit with a slight underestimation of the annual mean Tx (TX), notably apparent in the southernmost region and the Andes Mountain range (Balmaceda-Huarte et al. 2021). Despite acknowledged challenges in replicating observations in regions characterized by intricate topography, such as central coastal Chile, ERA5 demonstrates the capacity to capture warm extremes observed at inland Chilean weather stations (Demortier et al. 2021). Despite potential disparities between observational data and ERA5 for South America, this reanalysis has demonstrated superior performance compared to previous versions. (Balmaceda-Huarte et al. 2021; Suli et al. 2023).

Reanalysis, such as ERA5, helps understanding the behavior and distribution of heatwaves in different regions. ERA5 better replicates spatial–temporal variability compared to ERA-INTERIM due to its enhanced capacity to represent complex topographical features, as observed in certain areas of the Andes Mountain range (Balmaceda-Huarte et al. 2021). ERA5-LAND, a derivative of ERA5 and its predecessor ERA-INTERIM, offers improved global horizontal resolution at 9 km (Muñoz-Sabater et al. 2021). Significantly, ERA5-LAND provides consistent hourly temporal resolution and achieves a reduction in the global mean root mean square error of skin temperature (Muñoz-Sabater et al. 2021).

De Araújo et al. (2022) highlight the significance of this dataset collection for enhancing the characterization of heatwaves, despite the limited ERA5 validation throughout South America.

Moreover, to demonstrate the adequacy of ERA5-LAND, Wang et al. (2022) investigated the correlation between Land Surface Temperature (LST) data from NASA MODIS and Skin Temperature data from this reanalysis. These independently sourced datasets, one from satellite measurements and the other from surface modeling and observations, showed highly consistent results (Wang et al. 2022). Mihalevich et al. (2022) states that utilizing ERA5-Land for river temperature prediction yields very promising results. The study suggests that this success may be attributed to its capability to capture the spatial variability in weather conditions across extensive regions.

The objectives of this study are to investigate the geographical patterns of variations in heatwaves in Argentina for the period 1950–2022 using ERA5-LAND data, and analyze the impact of ENSO over them. To fulfill our goal, we evaluate the number (*E*), duration *(D)* and, mean and maximum intensity (*MnI, MxI*) of theatwaves, both spatially and temporally. Additionally, we aim to ascertain whether there is a variation in these parameters when considering the warm (October to March) or the cold season (April-September). Finally, we explore how La Niña and El Niño impact on the heatwave metrics in the different regions.

The paper follows the following structure: Sect. 2 outlines the data and methodology employed to analyze the evolution of Tx and Tn as well as heatwaves. Section 3 presents the obtained results. Lastly, Sect. 4 and 5 encompasses the discussion of the findings, conclusions drawn from the study, and suggestions for future research in this field.

2 Data and methodology

Our area of study, Argentina, spans across a broad range of latitudes, encompassing regions characterized by a variety of climates. Its geographical extent extends from latitude 21° 46′ 52" S and longitude 66° 13′ 17" W in the north, to latitude 55° 03′ 21" S and longitude 66° 31′ 25" W in the south (National Geographical Institute). Argentina has 23 provinces that can be grouped in North-West, North-East, Centre, Cuyo and Patagonia. The Arid Diagonal in Argentina is part of the group of dry regions distributed between middle latitudes, around 20º north and south, influenced by the Atlantic and Pacific anticyclones. It is composed of the provinces of Salta, Jujuy, Catamarca, La Rioja, San Juan, Mendoza, Neuquén, Chubut, and Santa Cruz (Martínez Carretero et al. 2013).

To investigate the evolution of heatwaves in Argentina, we used daily maximum (Tx) and minimum temperature (Tn) data obtained from ERA5-LAND for 1950 to 2022. We acquired 2-m air temperature data in degrees Celsius for the identification of heatwaves from The Copernicus Climate Data Store (Muñoz Sabater 2019). We downloaded Tx and Tn times series using the KrigR R-package interface (Kusch and Davy 2022), in NetCDF format. Data sets have a spatial resolution of $0.1° \times 0.1°$ (native resolution is 9 km). We conducted the assessment of heatwaves for each pixel using the function *detect.event* of the HeatwaveR R-package (Schlegel and Smit 2018) for Tx and Tn. This approach allowed us to understand how each specific location behaves, which is particularly important in regions with such diverse topographies as in the case of Argentina.

Our heatwave definition identifies as such periods consistent of a minimum of 5 consecutive days with temperatures (Tx or Tn) exceeding the 90th percentile of the 1961–1990 reference period. This definition is like the ETCCDI's Warm Spell Duration Index (see, for example, Aguilar et al. 2005). In the analysis of heatwave events, if there is a gap of fewer than two days between the conclusion of one heatwave and the commencement of another, we consolidate these periods. The total duration of the combined period is then regarded as a single continuous heatwave event.

We conducted a study focusing on four key metrics derived from the HeatwaveR R-package: duration (D), annual count of events (E), maximum intensity (MxI), and mean intensity (MnI). Duration (D) refers to the number of days for each individual heatwave event, while the annual count of events (E) represents the total number of heatwave events occurring during a specific period. Maximum intensity (MxI) denotes the highest temperature exceedance (in ºC) observed during a heatwave, whereas mean intensity (MnI) indicates the average daily exceedance in Celsius (ºC) during a heatwave. Both mean and maximum intensities are calculated by the HeatwaveR R-package as anomalies above seasonal thresholds (Schlegel and Smit 2018).

To investigate temporal variations, we incorporated relevant parameters into annual time series data. Non-parametric methods, specifically Zhang's slope and the Mann–Kendall Test, were utilized to assess slopes and their significance. The Mann–Kendall Test, also known as Kendall's tau test, is a rank-based nonparametric test for evaluating the significance of trends (Yue et al. 2002). We employed the `zyp.zhang` function from the R package "zyp" for this purpose.

The "zyp" package offers an efficient implementation of the slope method described by Sen (1968), while incorporating prewhitening. These approaches, when applied to climatic data, address temporal autocorrelation that may be present in climatic time series approaches (Bronaugh and Schoeneberg 2023). Zhang et al. (2000) and Yue et al. (2002) note that the pre-whitening approach can effectively eliminate the lag-one autoregressive component (current value of a time series is correlated with its immediate preceding value) improving the accuracy of estimation and statistical significance. However, it is important to acknowledge that pre-whitening will also eliminate a portion of the trend, potentially leading to an underestimation of a significant trend (Yue et al. 2002).

We divided Argentina into 7 regions to better understand spatial patterns and the regional characteristics of heatwave phenomena (see Fig. 1): South-Patagonia (Tierra del Fuego, Chubut, Santa Cruz, and the Malvinas Islands), North-Patagonia (Neuquén and Río Negro), Centre (Buenos Aires, La Pampa, Córdoba, and Santa Fe), Cuyo (Mendoza, San Luis, San Juan, and La Rioja), North-West (Tucumán, Catamarca, Salta, and Jujuy), North-Centre (Formosa, Santiago del Estero, Chaco), and Litoral (Entre Ríos, Corrientes, and Misiones). Within each region, we conducted a comprehensive analysis by calculating the mean values for various metrics (D = duration, E = events, MxI = Maximum Intensity, MnI = Mean Intensity) for both minimum (Tn) and maximum (Tx) temperatures. This analysis was performed for all pixels within each respective region.

Furthermore, to provide a nuanced understanding of heatwave events, we categorized the data based on three distinct temporal frames: warm season (WS = October–March), cold season (CS = April-September), and the entire year (Y). For each variable and time period, annual means were calculated for each region, and trends were subsequently assessed using the same methods described previously: Mann–Kendall test and Zhang's slope. This comprehensive approach allows us to discern the nuances of heatwave patterns across different regions and seasons, thereby facilitating a more insightful interpretation of the data.

Finally, we assessed correlations between ENSO and heatwaves in Argentina, analyzing data derived from Tx and Tn for all regions. The monthly Oceanic Niño Index (ONI) from the Climate Prediction Center (National Centers for Environmental Prediction, National Weather Service of the United States of America) was employed for this evaluation. La Niña is characterized by ONI values smaller than –0.5, while El Niño is represented by ONI values larger than 0.5. Periods with ONI values between these thresholds are considered neutral. We categorized the monthly series of heatwave parameters based on ENSO phases (El Niño or La Niña). We calculated means, independently, for each metric, region, season, and variable (Tx, Tn). Subsequently, we computed the differences between the values corresponding to the two phases (El Niño vs. La Niña).

To evaluate the significance of differences among the metrics, we opted for non-parametric tests. First, we employed the Kruskal–Wallis test, which serves as the non-parametric counterpart to one-way analysis of variance-ANOVA (Conover 1999). Subsequently, we conducted the Wilcoxon test (also called Mann–Whitney U Test) to assess whether the mean values of two or more groups differ significantly from each other (Schwaid 2017).

3 Results

In this section we present the results of our heatwave analysis, describing the temporal evolution of the *E*, *D*, *MnI* and *MxI*, both for daily Tn and Tx. Figure 2 presents the results for daily Tn, with non-white areas depicting significant trends. Both the E and *D* (Fig. 2, a-b) present a similar pattern, they have significant increasing trends (i.e., increased *E* and increased total duration of days/10 year under a heatwave) specially in North-West and Litoral region. In relation to *E*, the trend indicates an increase of between 0.01 to 0.65 events per decade. In the case of duration, we observe increases between 0 to 5 days in the duration of the heatwaves per decade. The highest values can be observed in the North-West region near the Andes and along the Litoral. It is noteworthy that in different regions of the country, especially in South Patagonia, significant positive trends are observed, even though with values close to zero.

Regarding the intensities in Tn (Fig. 2, panels c-d), both maximum and mean, significant trends are observed in Southern Patagonia, the Litoral region, and areas near the Andes. The central area of the country shows non-significant trends. Notably, we can discern significant trends specially in Litoral region, followed by Andes region in central and north areas. Southern Patagonia shows significative trends but most af them are close to zero. The variable MxI exhibits its maximum values in the Litoral, with increases of approximately 1° per decade. Additionally, it is noteworthy that negative trends have been detected in specific areas of the Province of Buenos Aires (northwest and southwest), and in a small region in the North-West of the country, with trends reaching up to -0.3° per decade. For MnI, we observe a similar pattern, with the maximum nearing 0.8° per decade in Litoral. Furthermore, this variable shows negative trends in the same regions as the previous one but, generally, the maximum values do not exceed -0.2° per decade.

We show Tx results in Fig. 3. We identify large increasing trends in the number and *D* of heatwave events, (Fig. 3, panels a-b). Regarding the number and duration of HWs, significant trends can be observed across most of the country, except in the central region (Buenos Aires province and North Patagonia) where non-significant trends are evident. In the North-West region, maximum increases of 1.2 HW/10 years and 9 days/10 years can be observed, in the Coastal region 0.5 HW/10 years and 4 days/10 years, and finally in Southern Patagonia 0.3 HW/10 years and 2 days/10 years. Additionally, negative trends were detected in areas concentrated in the south of Buenos Aires Province;

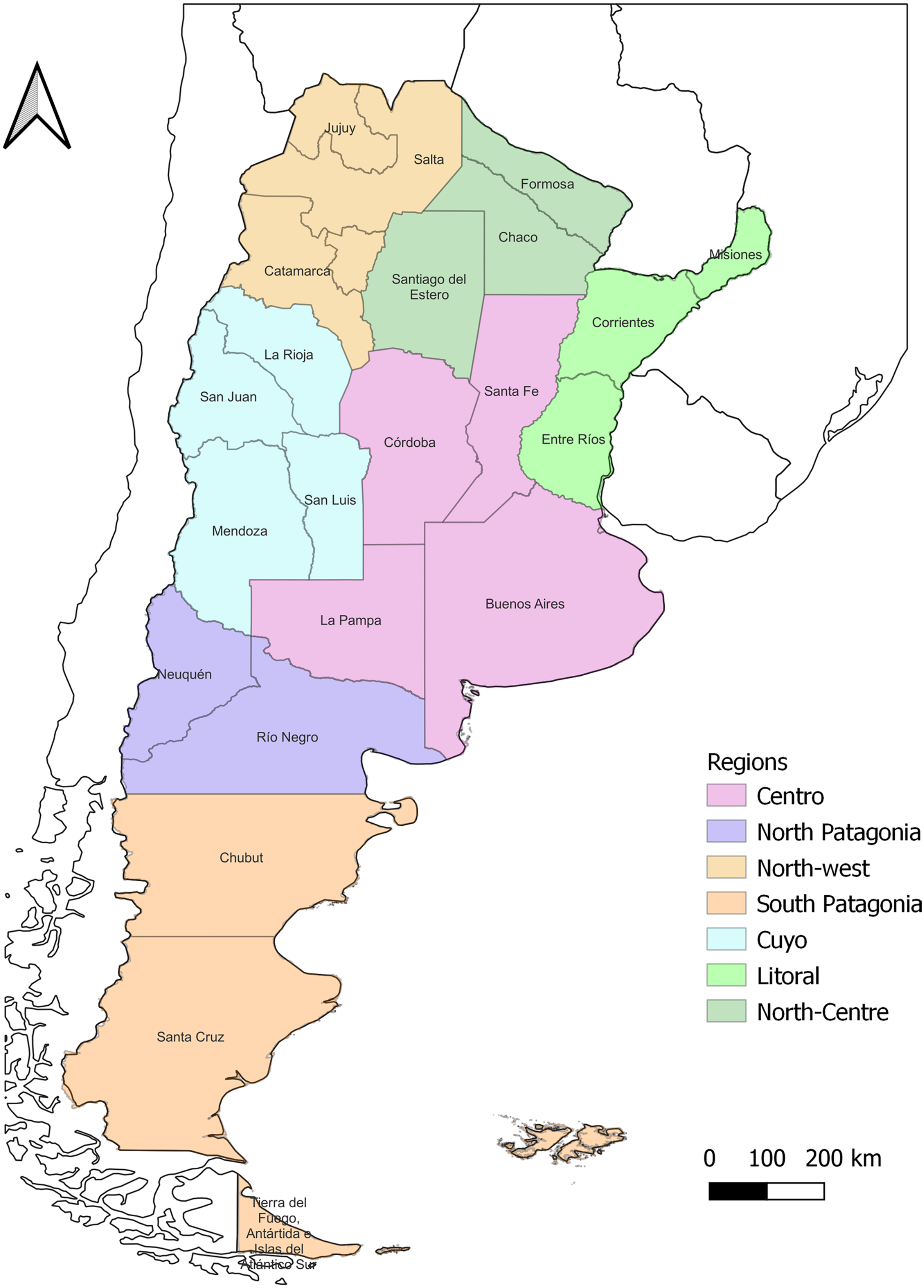

Fig. 1 Illustrates provinces of Argentina along with their corresponding regions

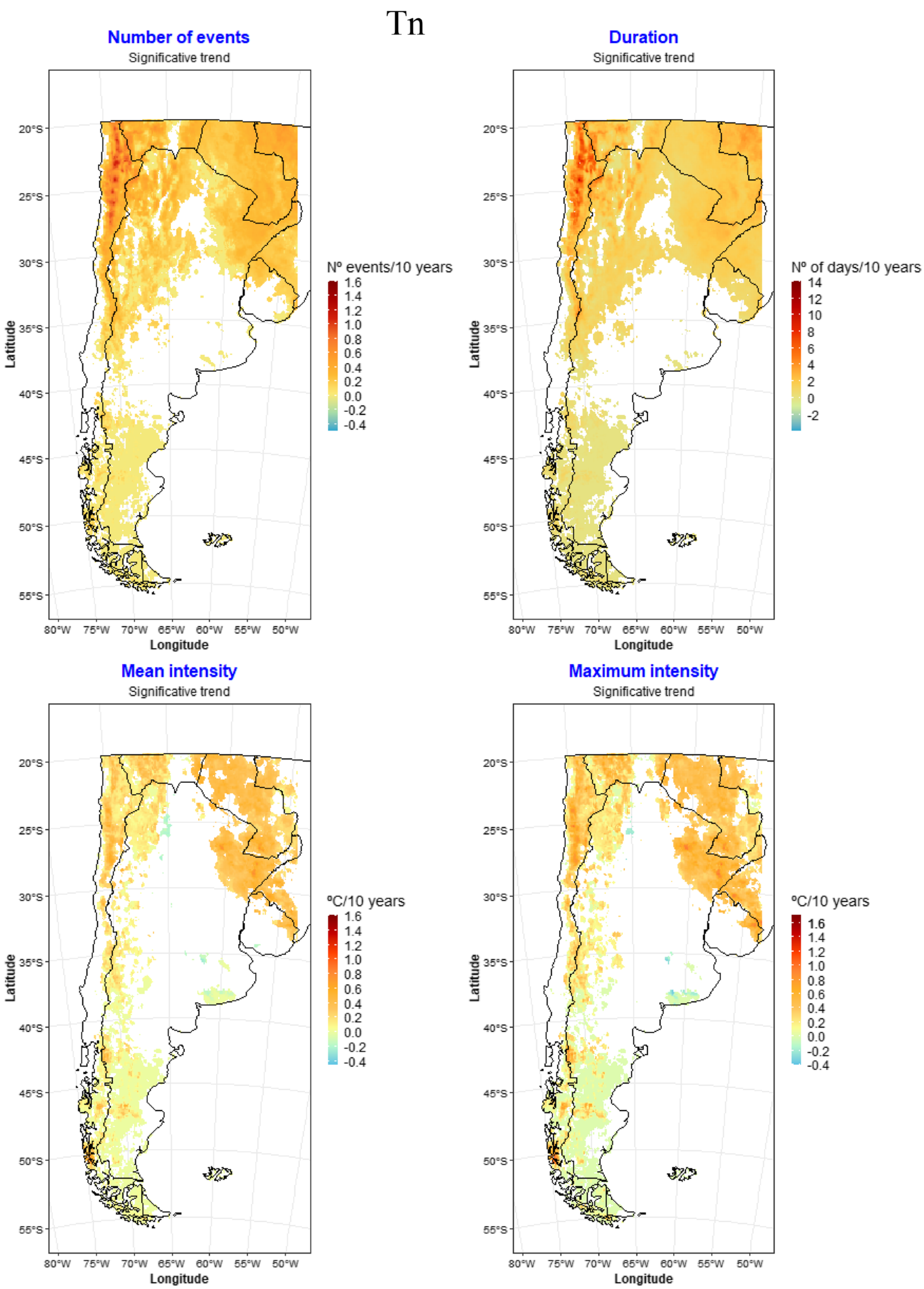

Fig. 2 Shows the trends (period 1950–2022) of different heatwave metrics for Argentina, calculated from minimum temperatures: **a** Number of HW events; **b** Duration of HW; **c** Mean Intensity of HW; **d** Maximum Intensity of HW.. Uncolored areas represent regions where no significant differences in trends were found

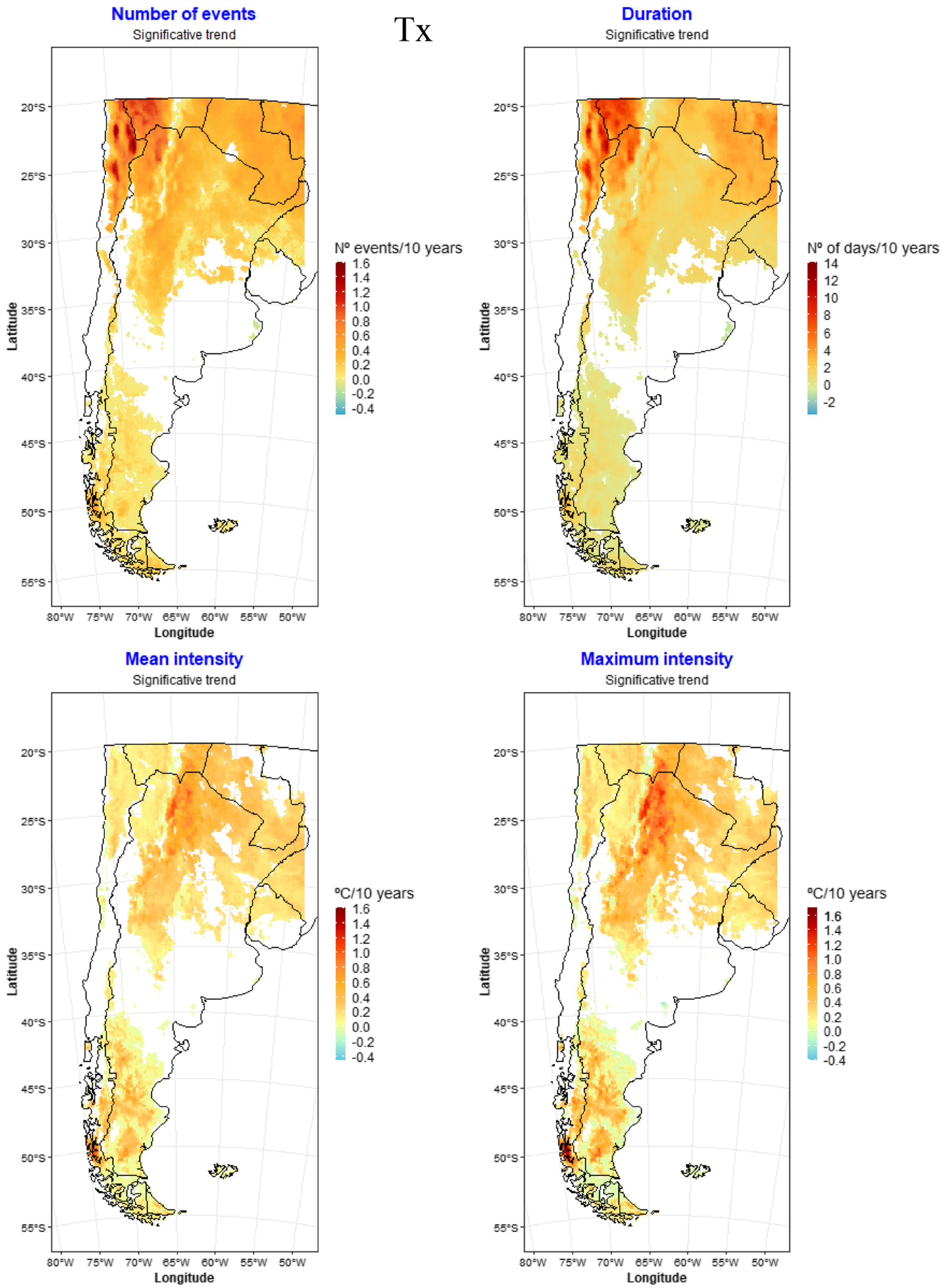

Fig. 3 Shows the trends (period 1950–2022) of different heatwave metrics for Argentina, calculated from Tx: **a** Number of HW events; **b** Duration of HW; **c** Mean Intensity of HW; **d** Maximum Intensity of HW.. Uncolored areas represent regions where no significant differences in trends were found

for E, the maximum values were -0.1 HW/10 years, and for D, -1 days/10 years.

Turning our attention to MnI and MxI (Fig. 3, panels c-d), we observe the highest values in the North-Central regions, specific areas of South Patagonia, and the Northeast. In these areas, we notice MxI maximum values increasing at rates of 1.5ºC, 1ºC, and 0.5ºC per decade, respectively. For MnI, values decrease slightly but maintain the same patterns: 1.1ºC, 0.8ºC, and 0.4ºC. Finally, significant negative trends were detected, albeit very reduced, in the south of Buenos Aires Province (MxI = -0.2; MnI = -0.06).

In our geographical analysis of heatwaves, considering both Tn and Tx (Fig. 2 and 3), we identify different impacts across the territory. It is noteworthy that the Andean regions are more profoundly affected when considering Tn. On the other hand, the Litoral region shows increases in heatwave trends for all analyzed metrics (Tx and Tn) especially in provinces like Misiones and the northern part of Corrientes. We also observe significant increasing trends in South-Patagonia region and a small portion of North-Patagonia (southern Neuquén Province). Increases in trends observed for Tn, partially affect the latter one. Finally, the North-Centre of the country, in general, shows increases in heatwave metrics associated with Tx.

Tables 1 and 2 outline the trends of heatwave metrics (*D* = duration; *E* = events; *MxI* = Maximum Intensity; *MnI* = Mean Intensity) across different regions of Argentina, during Warm Season (WS), Cold Season (CS), and the complete year (Y). During different seasons of the year, heatwave variables exhibit variations for both Tn and Tx. Correlating with what was shown in Fig. 3, for the North-Central region of Argentina, we found significant rising patterns, especially for TX. Significant positive trends were detected for MxI and MnI during all analyzed periods, while for the variable E, they were identified only during CS and Y. For TN, only increasing trends were identified for D during WS.

In the North-West region, significant increases were observed for TX, D, and E during all study periods. Significant trends for MnI were observed during Y and WS, while for MxI, they were observed during Y. For CS, significant trends were only found for D. However, it is noteworthy that Fig. 2 currently highlights significant trends, especially near the Andes. This region is one of the most impacted by increasing changes in the studied HW variables, along with South Patagonia and the Litoral region.

In Litoral, We observed positive trends in all metrics for all analyzed periods, both for TX and TN. However, for TN, we only found significant trends for E during WS. In the case of TX, we detected significant trends for MxI and MnI during CS and Y. We can attribute the lack of significance in the trends to the fact that, as depicted in Fig. 2, the significant increasing trends are concentrated in the provinces of Misiones and Northern Corrientes. Consequently, there is a sizable portion of the Litoral territory that exhibits non-significant results.

In Cuyo, for Tx, we currently observe significant trends for *MxI* and *MnI* during WS, although we find no significant trends for CS. Figure 3 currently displays significant trends in certain areas of this region, although it is worth noting that the areas near the Andes remain non-significant. For Tn, we currently find only increasing significant trends during WS for the variables *D*, *MxI*, and *MnI*. During Y, we founded significant trends in E (TN) and MnI (TX).

In the Centre of the country, negative trends are notable, especially for TX, although they are not significant. We observed increasing significant trends for Mxi and MnI during CS (TX). For Tn, we currently observe significant increasing trends for D during WS. This could help explain why specific areas of this region are non-significant in the map (Fig. 3, b).

In North Patagonia, we currently find significant rising trends for *D* (WS) and for *MxI* (CS) for Tx. Also, for Tn, we currently find increasing significant trends for *MxI* during WS and for E considering Y. We identified some decreasing trends in variables like MxI and MnI (TN) but they were not significant.

On the other hand, South Patagonia is one of the most impacted areas of Argentina, where most variables have experienced increasing significant trends for the studied HW variables. For Tx, we were able to identify that all analyzed variables exhibited significant increasing trends during WS. During CS, we currently find trends for D, and during Y, the variables E, D, and MxI showed significant increasing trends. Evaluating Tn, MxI and MnI exhibited increases during WS and Y, while D and E showed increases especially in CS and Y.

The phases of ENSO influence climate conditions across the world. Figures 4 and 5 illustrate metric disparities during El Niño and La Niña periods. Regarding Tn (Fig. 4), La Niña results in a significant increase in the *E* variable (p value < 0.05), except for the north-central region where we find no signal. The *D* of heatwaves increases in the Cuyo, Centre, and North-West regions during El Niño months, while the North Central and South Patagonia regions experience increases during La Niña. The Litoral and North Patagonia regions do not show significant differences for this metric. In all regions of the country, we observed significant increases in concerning values for maximum and mean intensities (Tn), during El Niño months, except in Patagonia, where we can notice the opposite effect.

Concerning Tx (Fig. 5), La Niña produces significant increases in the *D* and the *E* throughout the country, except in the Northwest, where the most significant increases occur during El Niño for the *D* variable. It is important to note that the *E* variables does not exhibit significant differences in the North-West region. Like Tn, El Niño primarily affects

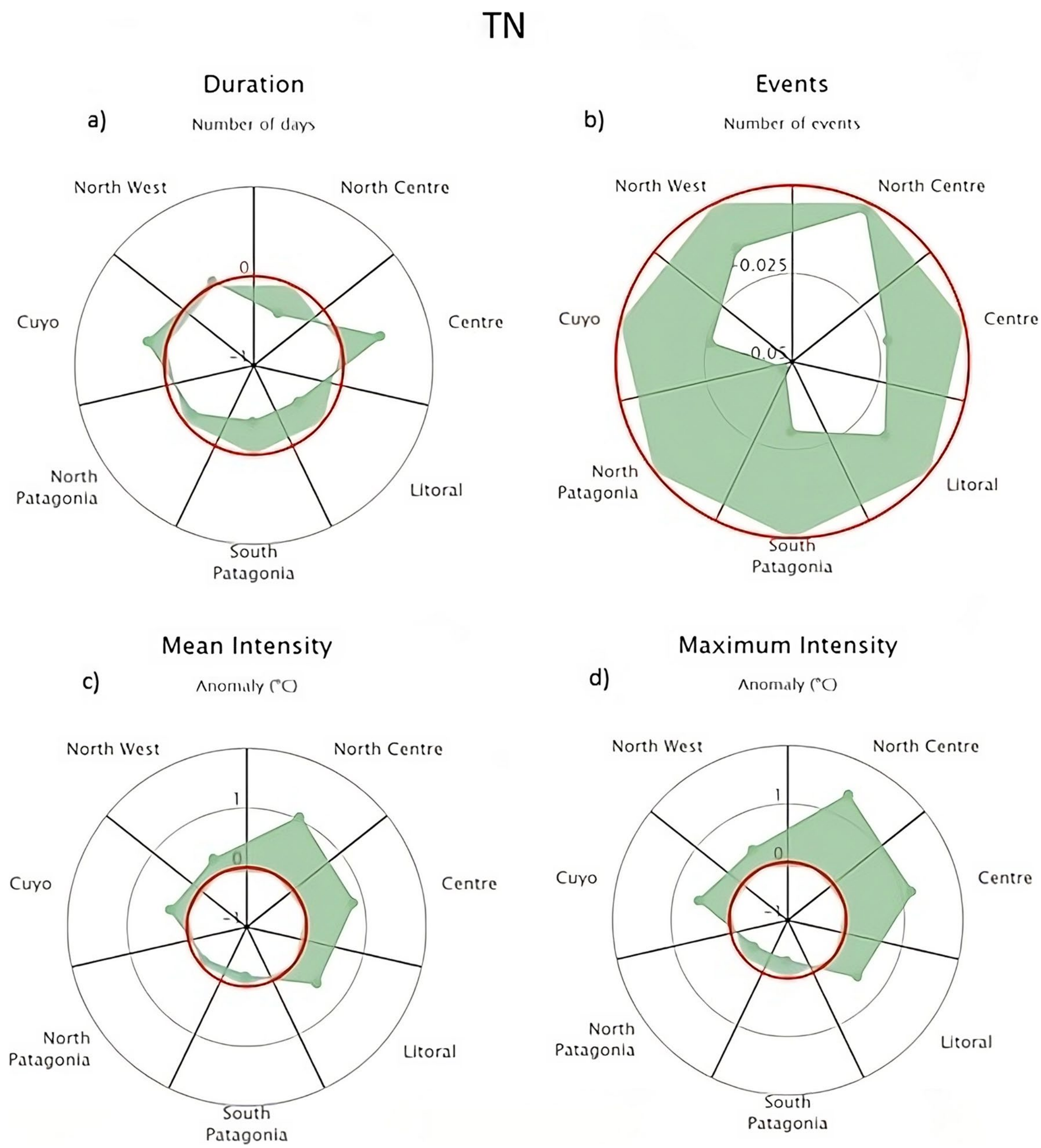

Fig. 4 Differences in heatwave metrics during El Niño and La Niña events calculated based on minimum temperatures (Tn). Positive differences (> 0) indicate higher values for these variables during El Niño, while negative values suggest greater impacts during La Niña. (*) Means no significant differences exist in the region. The variables presented include: **a** *D*: differences of the mean number of days for heatwave events; **b** *E*: differences of the number of heatwave events; **c** *MnI*: differences of the average amount of Celsius degrees (ºC) exceeded daily during a heatwave; **d** *MxI*: differences of the averaged maximum exceedance (ºC) during a heatwave

maximum and mean intensities in the whole country, except in Patagonia (North and South), where La Niña enhances heatwave metrics.

Figure 4 and Fig. 5 depict the spatial differences in ENSO's effect over Argentina, and the central and northern regions of the country (Centre, North-Centre, Litoral, Northwest, and Cuyo) experience similar impacts from ENSO. Mean and maximum intensities increase during El Niño months. The most significant increases for Tn are in the Litoral, Centre, and North-Centre regions, with respective increases of 10.5% and 7.3%, 7.4% and 7.7%, and 8.6% and 7.6%. Meanwhile, for Tx, the most substantial increases are in the Centre and North-Centre regions, with respective increases of 13.5% and 14.5%, and 15.6% and 16.6%.

In Northwest Argentina, it seems that El Niño influences an increase in the number of events, particularly noticeable

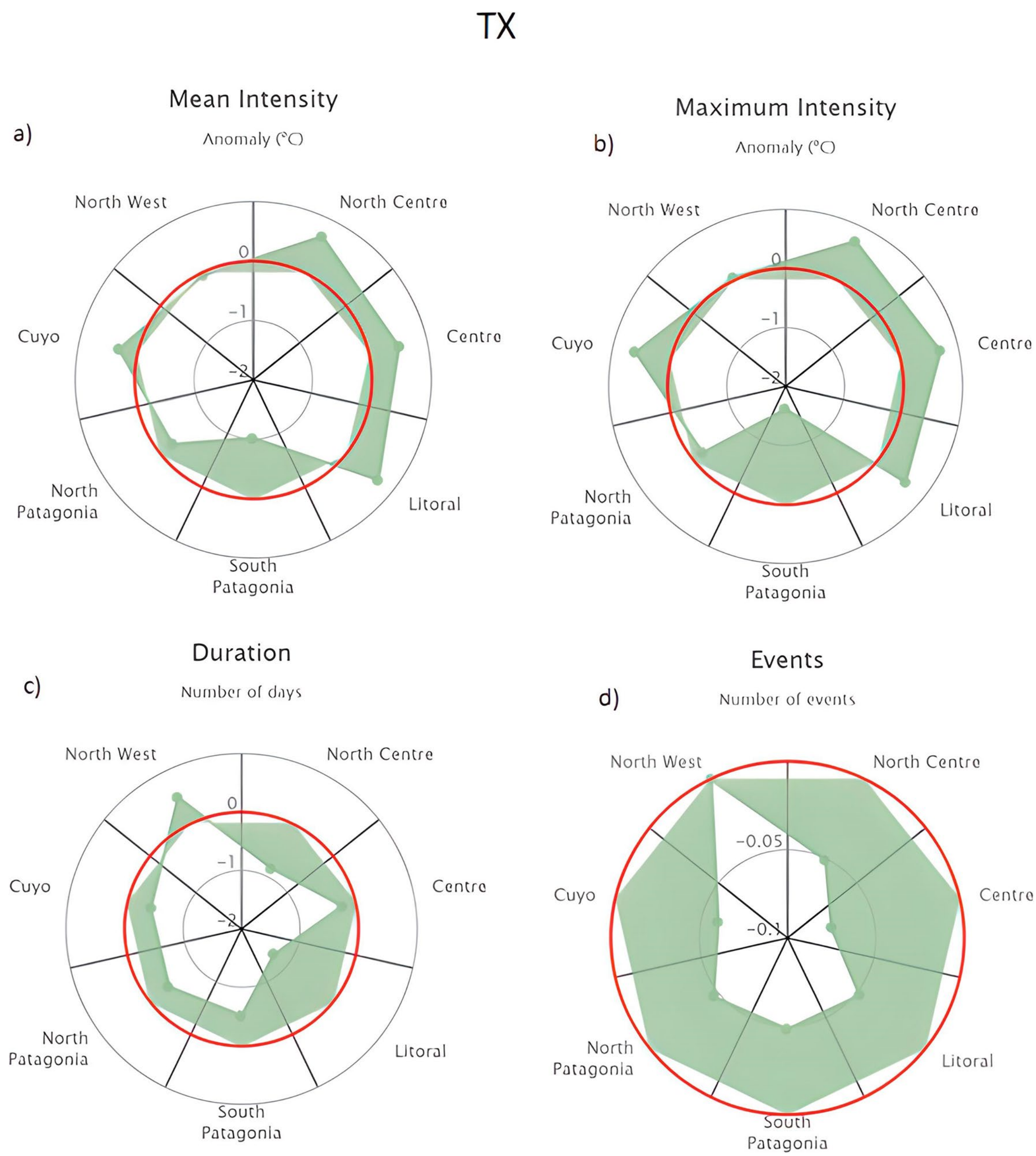

Fig. 5 Differences in heatwave metrics during El Niño and La Niña events calculated based on maximum temperatures (Tx). Positive differences (>0) indicate higher values for these variables during El Niño, while negative values suggest greater impacts during La Niña. (*) Means no significant differences exist in the region. The variables presented include: **a** *D*: differences of the mean number of days for heatwave events; **b** *E*: differences of the number of heatwave events; **c** *MnI*: differences of the average amount of Celsius degrees (ºC) exceeded daily during a heatwave; **d** *MxI*: differences of the averaged maximum exceedance (ºC) during a heatwave

for Tx with a close to 7% increase. The events (E) variable appears to significantly increase during La Niña months, specifically during the night. In the Patagonia region, La Niña exerts a significant impact on heatwaves, both for Tx and Tn, representing the clearest effect on heatwaves in Argentina. The largest increases are observed in South Patagonia, with approximately 9% for *D*, 5% for the *E*, 15% for *MnI*, and 18% for *MxI*.

Table 1 Trend values derived from minimum temperatures (Tn) for all regions of Argentina and each variable during the warm season (WS = October–March), cold season (CS = April-September), and the entire year (Y). Variables are *D* = duration (nº days/10 years); E = events (nº events/10 years); *MxI* = Maximum Intensity (ºC); *MnI* = Mean Intensity (ºC) Colored cells show significant trends

TMIN	CS				WS				YEAR			
Region	**D**	**E**	**MxI**	**MnI**	**D**	**E**	**MxI**	**MnI**	**D**	**E**	**MxI**	**MnI**
North-Centre	-0.014	0.000	0.159	0.087	0.121	0.000	0.092	0.043	0.076	0.000	0.092	0.015
North-West	0.044	0.003	-0.004	-0.062	0.187	0.005	0.135	0.067	0.139	0.006	-0.044	-0.082
Litoral	0.020	0.000	0.131	0.065	0.081	0.000	0.037	0.021	0.065	0.000	0.094	0.047
Cuyo	-0.017	0.000	0.035	0.019	0.155	0.004	0.168	0.086	0.076	0.003	0.025	-0.013
Centre	-0.091	0.000	0.067	0.023	0.104	0.000	0.027	0.010	0.024	0.000	-0.073	-0.092
North Patagonia	0.000	0.000	-0.092	-0.063	0.055	0.000	0.140	0.085	0.043	0.001	0.087	0.031
South Patagonia	0.037	0.000	0.084	0.036	0.053	0.000	0.205	0.114	0.046	0.001	0.193	0.109

Table 2 Trend values derived from Tx for all regions of Argentina and each variable during the warm season (WS = October–March), cold season (CS = April-September), and the entire year (Y). Variables are *D* = duration (nº days/10 years); E = events (nº events/10 years); *MxI* = Maximum Intensity (ºC); *MnI* = Mean Intensity (ºC) Colored cells show significant trends

TMAX	CS				WS				YEAR			
Region	**D**	**E**	**MxI**	**MnI**	**D**	**E**	**MxI**	**MnI**	**D**	**E**	**MxI**	**MnI**
North-Centre	0.092	0.000	0.251	0.167	0.059	0.000	0.206	0.146	0.113	0.001	0.273	0.181
North-West	0.235	0.010	0.124	0.045	0.304	0.010	0.326	0.215	0.307	0.012	0.218	0.130
Litoral	0.132	0.000	0.243	0.182	0.115	0.000	0.062	0.060	0.058	0.003	0.128	0.105
Cuyo	-0.073	0.000	0.067	0.026	0.127	0.001	0.250	0.164	0.037	0.001	0.121	0.076
Centre	-0.044	0.000	0.191	0.146	0.092	0.000	-0.015	-0.006	0.062	-0.001	0.085	0.062
North Patagonia	-0.023	0.000	0.128	0.067	0.118	0.000	0.025	0.009	0.068	0.000	0.067	0.040
South Patagonia	0.098	0.000	-0.015	-0.014	0.084	0.000	0.343	0.185	0.118	0.001	0.165	0.076

4 Discussion

Our study has demonstrated the escalation of heatwaves across most regions of Argentina during the period from 1950 to 2022, calculated from daily minimum temperatures (Tn) and maximum temperatures (Tx). It's worth mentioning that studying heatwaves using Tn is important because it represents a key factor, particularly when considering its implications for human health. Additionally, investigating prolonged heatwaves is crucial for addressing the issues related to the risks associated with these extreme events, as it enables the identification of severely affected areas.

Our findings are consistent with the conclusions drawn by previous researchers regarding the augmentation of heatwave metrics in Argentina (Rusticucci et al. 2016; de Araújo et al. 2022; Suli et al. 2023; among others). The northern region of Argentina (comprising the North-West, North Centre, and Litoral regions) exhibits increasing trends in daily temperatures (TX) across a significant portion of its territory (refer to Fig. 3). Conversely, concerning nocturnal temperatures (TN), the Litoral region shows the most substantial significant increases in slopes. Additionally, we observed that the Andean regions in the central area display more pronounced trends (in comparison to TX) in the rise of heatwaves associated with TN (refer to Fig. 2). According to our results, the regions experiencing significant increases in all their metrics for both TX and TN are the North-West, Litoral, and South-Patagonia.

According to our results (see Fig. 3), the North-Centre region of Argentina is primarily affected by increases in trends related to HW intensity, calculated from Tx. De Araújo et al. (2022) presented similar findings, indicating pronounced intensities in the central-northern regions of the country and an increased incidence of heatwaves during the cold season in Southern Patagonia. Consistent with this, Table 2 indicates that, for Tx, there are significant rising trends for MxI, MnI, and E during CS. This significant increase is consistent when comparing regional trends for the entire year (Y). Regarding trends calculated from Tn, this region only showed increases in trends related to the variable D during the warm season (WS).

The Northwest region demonstrates the most pronounced upward trends in the assessed heatwave (HW) metrics. Specifically, we have identified notable rises in heatwave intensities for daily temperatures (TX). Furthermore, significant increases in intensity metrics have been observed across all analyzed periods. Moreover, this trend is also apparent during the warm season (WS) for nocturnal temperatures (TN), where we observe significant upward trends in all analyzed metrics. The South-Patagonia region exhibits similar significant trends, albeit with lower values. In this regard, it is noteworthy to highlight that this region displays increasing (significant) trends in all analyzed metrics, with this effect particularly prominent during the warm season (WS) and throughout the entire year. During the cold season (CS), the only metric that increases for both TN and TX is the duration of heatwaves.

These findings concur with Skansi et al. (2013), who detected increases in warm nights and decrease in cold nights in South Patagonia and North-West of Argentina. Furthermore, Rusticucci et al. (2016), in their examination of trends spanning 1970–2010 in the central and northern regions of the country, using daily Tx and Tn series derived from observational data, observed a noteworthy decrease in the frequency of cold nights (Tn) and a significant increase in the occurrence of warm days during the warm season months (October-January). Olmo et al. (2020) suggested that changes in atmospheric circulation could contribute to the observed warming during the warm season.

For CS, some authors exhibited a significant decrease in the frequency of cold days (Rusticucci et al. 2016) and increasing in warm nights (Olmo et al. 2020), indicating an increase in mean day temperatures. Our results have also observed temperature increases during the cold period, except for the central region, where negative trends are evident (although not significant at the regional level), especially concerning Tn (nights). This analysis will continue in further paragraphs.

Litoral showed significant rising trends for all the metrics (for Tn and Tx) evaluated in those areas corresponding with Misiones province and the north of Corrientes (Fig. 2 and 3). This concentrated behavior could be the reason we only found significant increases in the trends on *MxI* and *MnI* calculated using Tx during CS and Y (Table 1 and 2). For Tn, we only found significative trends for E during WS, but this was close to zero. Ceccherini et al. (2016) also states increase in intensity and frequency of HW in the North-East of Argentina (period 1980–2014) and Skansi et al. (2013) also show increases in warm nights in Litoral.

The arid diagonal in Argentina extends from the northwest to the south of the country and exhibits distinct bioclimatic characteristics (Martínez Carretero et al. 2013). While this study did not identify significant trends across the entire area, it did observe increasing trends throughout the region. Metrics studied from TX showed significant increases in trends for all metrics across the entire area except in the North Patagonia and central Andes region, where the observed increasing trends were not statistically significant. In relation to TN, E, and D, similar patterns were observed, although MxI and MnI only showed significant increases in trends (though largely close to zero) in areas near the Andes and Southern Patagonia. This is consistent with other authors who have noted intense warming in the arid diagonal (Skansi et al. 2013; Balmaceda-Huarte et al. 2021). Rusticucci et al. (2016) observed that the arid diagonal experiences drier conditions, as evidenced by significant increasing trends in dry spells and negative trends in total annual precipitation. Changes in precipitation observed in the area can exacerbate warming temperature trends.

As mentioned previously, adverse trends have been identified in certain areas of the Central region in the southern province of Buenos Aires, as illustrated in Figs. 2 and 3. It is worth noting that in the regional analysis (Table 1 and 2), no significant negative trends are evident. While negative trends were observed, they did not reach statistical significance due to the relatively small size of the areas with significant trends compared to the overall size of the regions under consideration.

Similar to our findings, several authors have detected reductions in temperatures in the Central region of Argentina. Of particular note is the reduction in trends (not always significant) related to daytime maximum temperatures (Tx90) (Skansi et al. 2013; Rusticucci et al. 2017; Olmo et al. 2020). Additionally, Suli et al. (2023) identified isolated trends in the frequency of local heatwaves (days with heatwaves) during the warm season in the southern and central areas of the province of Buenos Aires, although these trends were not statistically significant.

Seneviratne et al. (2023) mention medium confidence in their assessment that warm extremes have decreased in the last decades over the central region of Southeastern South America (SES) during the austral summer.

Global climatic phenomena such as ENSO can influence extreme temperatures. Some authors (Hurtado et al. 2010; Rusticucci et al. 2016; Collazo 2020) highlights the strong association between the El Niño/Southern Oscillation (ENSO) and extreme temperature occurrences in Argentina. Our findings confirm this and shows difference in these impacts related to the different regions of the country.

Our results indicate significant differences in the studied metrics during El Niño and La Niña events (p value < 0.05). However, the effects of both ENSO phases are not uniform across all regions of the country. La Niña causes increases in the variable *E* in all regions, for metrics calculated from both Tn and Tx. Furthermore, during El Niño months, we observe increases in the intensities (means and maxima) of heatwaves (Tn and Tx) throughout the country, except for Patagonia. This aligns with Rusticucci et al. (2017), who showed that El Niño events impact extreme temperatures, favoring warmer nights during winter in the Centre and north of the country. Furthermore, Collazo et al. (2019) demonstrated that the El Niño phase is associated with a decrease in the occurrence of cold extremes, and Hurtado et al. (2010) found an increase in temperatures during El Niño years. We expect to observe these temperature increases in the central and northern regions of Argentina, especially during winter months (Rusticucci et al. 2016; Cai et al. 2020).

This study reveals that in Patagonia, for both Tn and Tx, La Niña favors increases in all studied HW metrics. In the same vein, Rusticucci et al. (2016) discovered that the El Niño phase induces cooling effects in the country during the summer, particularly in southern Patagonia and Tierra del Fuego. Other authors (Hurtado et al. 2010; Cai et al. 2020) have also identified specific regions of Patagonia with temperature decreases during El Niño, especially during spring (Cai et al. 2020). Moreover, in the Argentine Andes, drought events coincide with La Niña (Poveda et al. 2020), contributing to the observed impact on heatwaves by generating positive feedback. These findings align with the climatological process detailed before (see Introduction). These findings align with the climatological process detailed before (see Introduction). During El Niño, the weakening and northward shift of the southeast Pacific anticyclone favor westerly winds and precipitation in mid-latitudes, whereas during La Niña, the southeast Pacific anticyclone strengthens (Daniels and Veblen 2000).

Our results were generated using ERA5-LAND data. While we acknowledge the importance of validating reanalysis data with observational data, we see them as an opportunity when there is not enough information available for conducing analyses with high spatial resolution. Several studies have underscored the reliability and utility of the ERA5 dataset for climate research in South America. Birkel et al. (2022) emphasized ERA5's robust depiction of temperature and precipitation in the Andes region, particularly its back-extension to 1950. Balmaceda-Huarte et al. (2021) explored various temperature and precipitation indices focused on extreme events and concluded that the climatic patterns observed in South America are well represented by ERA5. Similarly, De Araújo et al. (2022) advocated for ERA5's use in characterizing heatwaves, citing its reliability despite not being fully validated. Additionally, Baker et al. (2021) highlighted ERA5-Land's role in bridging the gap between observations and simulations, providing valuable insights in regions with limited observational data.

Given the enhancements presented by ERA5-LAND, there is potential for its utilization in the study of heatwaves in Argentina. Nevertheless, it is imperative to explore the correlation between ERA5-LAND and observational data in future research. It leaves the door open for future assessments that can lead to a better understanding of the spatiotemporal variability of these phenomena in the country. The use of reanalysis data for the study of heatwaves in Argentina should be further explored in the future, particularly with the aim of assessing performance in different regions of the country. Additionally, it would be crucial to gain a deeper understanding of the limitations and their implications in the data provided.

5 Conclusions

Using ERA5-LAND data (Tx and Tn), our study has demonstrated how heatwaves have increased across most regions of Argentina during the 1950–2022 period. This finding aligns with previous research that has also reported increases in heatwave metrics in Argentina. When considering all the metrics, Southern Patagonia and Northwest regions exhibit the most significant upward trends in the evaluated heatwave (HW) metrics. The Litoral region (Northeast) also shows notable increases, especially in the north during WS.

We have found differences in the occurrence of heatwave events during the El Niño and La Niña phases of the ENSO. During La Niña events, we observe an increase in variable E in all regions, as calculated from both Tn and Tx metrics. In Patagonia, La Niña favors increases in all studied heatwave metrics for both minimum (Tn) and maximum (Tx) temperatures. During El Niño months, we observe increases in the intensities (MnI and MxI) of heatwaves (Tn and Tx) throughout the country, except for Patagonia.

ERA5-LAND is a database that enables working with high spatial and temporal resolutions, allowing for regional analyses in countries with vast extents, such as Argentina. This information would provide valuable insights for developing adaptation plans to extreme temperature events, such as heatwaves. Nevertheless, it is crucial to continue working to validate these results through comparisons with analyses conducted using observational data.

This study enables the identification of regions experiencing increases in the trends of heatwaves calculated from Tn and Tx. It is noteworthy to determine areas with rises in trends of nocturnal heatwaves (Tn) due to their implications for human health, as well as those with increases in the trends of heatwaves derived from both maximum and minimum temperatures, as they can be particularly vulnerable to these extreme events.

The advancement of scientific and technological research in climatology, particularly in the realm of temperature-related studies, holds paramount importance for countries seeking to formulate effective and precise climate change adaptation policies. Gaining an understanding of the frequency, intensity, and spatial distribution of phenomena like heatwaves facilitates the implementation of measures to mitigate adverse effects on individuals, productive systems, infrastructure, and more. Moreover, it enhances the efficiency of public spending by assisting decision-making aligned with future regional needs.

Acknowledgements We would like to thank Alberto Hueso Alonso for the assistance provided in computer-related matters.

Author contributions All authors contributed to the study conception and design. Caterina Cimolai: formal analysis, investigation, data curation, writing and editing, visualization. Enric Aguilar: writing, review and editing. All authors read and approved the final manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. Caterina Cimolai is supported by the PMF-PIPF—Martí i Franquès Research Grants Program, Grant No. 2021PMF-PIPF-25.

Data availability The scripts generated during the current study are available in the GitHub repository: https://github.com/ccimolai/HW_ARG. The intermediate results are available, to request them, you can send an email to the author of this study.

Declarations

Competing interests The authors declare no competing interests.

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