Spatio-temporal domains of wildfire-prone teleconnection patterns in the Western Mediterranean Basin

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Key Points:

- We found three distinctive but homogeonous domains of influence of climate teleconnections patterns.
- The SCAND pattern exerts a zonal influence over the western Mediterranean basin. NAO controls the IP and WeMOi the Mediterranean coast.
- Positive moisture winter-spring anomalies coupled to short-term dry and warm conditions boost most of the wildfire activity.

Plain language summary

We synthetized the climate influence on wildfire activity over the Western Mediterranean Basin into three distinctive configurations. We applied computer-assisted statistical analysis on historical fire records from national/regional agencies and climate-related data (the so-called climate teleconnection indexes; e.g. 'El Niño' or the NAO). Burned area size over the entire basin tends to be larger under the confluence of rainy winter-spring and sudden heat waves and dry spells during summer, which is governed by the Scandinavian pattern. In the Mediterranean coast of Spain fires occur more frequently under sustained calm and warm conditions while they grow larger when winds blow from the western side of the Iberian Peninsula. These conditions depend on the North Atlantic Oscillation and Western Mediterranean Oscillation pattern (WeMOi), respectively. Fire activity in Southern France, Corsica and Sardinia seems to be linked to the lack of rainfall, which is regulated by the atmospheric conditions over the Mediterranean sea, mostly controlled by the WeMOI pattern.

Abstract

This work explores the main climate teleconnections influencing the Western Mediterranean Basin to outline homogeneous fire-prone weather domains combining cross-correlation time series and cluster analysis. We found a zonal effect of the Scandinavian pattern over the entire region with an interesting alternation of phases from positive during winter-spring (increased rainfall leading to fuel accumulation) to negative (dry conditions) modes during summer controlling burned area and fire size. The NAO dominates the number of fires over the Iberian Peninsula (IP) while the Western Mediterranean Oscillation pattern modulates fire activity over the Mediterranean coast in the IP (linked to westerly winds), Southern France, Corsica and Sardinia (rainfall regulation). These distinctive influence traits resulted in 3 different domains splitting the IP into a Mediterranean rim along the coast (from southern Spain to southwestern France) and an inland and western region (Portugal plus western Spain); and a third in southeastern France, Corsica and Sardinia.

1 Introduction

Wildfires are a key ecosystem process that modulates vegetation distribution and evolution (Bond, Woodward and Midgley, 2005) and impacts the global carbon cycle (Jones et al., 2019), whilst having substantial economic and social impacts (Moritz et al., 2014). During the last two decades, most of the extreme wildfires reported as being economically or socially catastrophic were concentrated in suburban areas intermixed with flammable forests, particularly in the western United States (Radeloff et al., 2018), southeastern Australia (Bowman et al., 2017) and the Mediterranean Basin (Modugno et al., 2016). The latter was specifically identified as a disaster-prone landscape with projections suggesting an increase of extreme fire weather of 50-100% by the end of the current century (Bowman et al., 2017). Currently, most of the total burned area in Europe occurs in this region during the summer, with an average of about 4,500 km^2/yr, an area that is expected to increase (Ganteaume et al., 2013; Turco et al., 2017).

Mediterranean Europe occupies a climatic transitional area under the alternate influence of sub-tropical and temperate climates (Lionello, 2012). In this area, ecosystems and human populations are affected by frequent weather-driven natural hazards, such as droughts (Hoerling et al., 2012; Russo et al., 2017), heat waves (Sánchez-Benítez et al., 2018; Sousa et al., 2019) and wildfires (Ruffault et al., 2020). The frequency and severity of these extreme weather-driven events are likely to increase under climate change (Dupuy et al., 2020; Lionello and Scarascia, 2020). Additionally, the compound occurrence of drought and heatwave events has recently increased (Vogel et al., 2021), a trend that will persist according to future forecasts (Zscheischler et al., 2018; AghaKouchak et al., 2020). Additionally, the summer fire activity in Mediterranean-type ecosystems is thought to be sensitive to antecedent winter rainfall pulses that could lead to an accumulation of fuels, while concurrent droughts and/or hot-dry winds are the short-term driver of wildfires (Moritz et al., 2012). Predicting future fire activity does not only hinge on understanding the short-term fire weather patterns, but also the longer-term of climate variability (Rodrigues et al., 2020; Vieira et al., 2020), particularly on biomass accumulation mediated by regional-scale drivers (Moritz et al., 2012).

Previous studies suggest that coincident drought conditions and high temperatures promote large wildfires across southern Europe (Camiá et al., 2009; Bedia et al., 2013; Urbieta et al., 2015; Gouveia et al., 2016). Nevertheless, the role of antecedent large-scale climate conditions remains a debated topic across much of the Mediterannean Europe. Previous analyses of the linkages between fire activity and meteorological variables in southern France (Ruffault et al., 2016), Greece (Koutsias et al., 2013; Gouveia et al., 2016) and the Iberian Peninsula (Turco et al., 2013; Vieira, Russo and Trigo, 2020) reveal significant correlations with both same-summer and lagged climate variables.

Climate teleconnections (CTs) have a synchronous influence on weather at a regional scale (sub-continental) while playing a key role in modulating temperature and precipitation patterns at both interannual and decadal scales (e.g., Ascoli et al., 2017; Harris and Lucas, 2019). These patterns can subsequently dictate plant growth (fuel amount) and its dryness, and hence modulate the occurrence and spread of wildfires (Cai et al., 2014; Mariani, Veblen and Williamson, 2018). CTs patterns are expected to become more extreme in the future (Power et al., 2013; Cai et al., 2014), potentially exacerbating their effects on wildfires (Mariani et al., 2018). Thus, the links between CTs and fire activity have been investigated in various regions (Kitzberger et al., 2007; Mariani, et al., 2018; Cardil et al., 2021; Rodrigues et al., 2021). However, the role of large-scale CTs on wildfire occurrence and spread has not yet been fully explored in the western Mediterranean region (Royé et al., 2020). Within this area, various CTs influence weather, including the North Atlantic Oscillation (NAO), the East Atlantic (EA), the Atlantic Multidecadal Oscillation (AMO), the El Niño Southern Oscillation (ENSO), the Mediterranean Oscillation (MOI), the Pacific Decadal Oscillation (PDO), the Scandinavian pattern (SCAND) and the Western Mediterranean oscillation (WeMOi). In a recent study carried out in the Iberian Peninsula, fire danger patterns were found to be significantly correlated to the WeMOi,MOI, NAO, ENSO and SCAND indexes (Rodrigues et al., 2021).

Investigating mechanisms behind climate-fire dynamics, including lagged relationships between climatic conditions and wildfire activity (i.e., fuel built-up fostered by above average antecendent moist conditions), is critical for understanding the future of Mediterranean ecosystems. Despite the clear importance of wildfires in shaping vegetation and impacting human lives under the projected climate change (Moritz et al., 2012; Bowman et al., 2017), the climatic drivers of fire activity through time remain poorly understood in many regions on Earth, including the European Mediterranean Basin (Turco et al., 2017). In this paper, we provide a new assessment of the climatic drivers of wildfire occurrence and spread within the western Mediterranean region over the period 1980-2015. We expand the spatial and temporal scales of work carried out so far in the Iberian Peninsula (IP) on the links between wildfires and CTs, while focusing on actual fire features (namely number of ignitions, burned area and fire size) rather than fire-weather indexes (Rodrigues et al., 2021). The main goal of the present work is assessing spatio-temporal climate domains reflecting the interaction of climate teleconnections and their potential influence in wildfire activity across western Mediterranean Europe. We aim to address the following research questions: 1) Which are the leading CTs over wildfire occurrence and spread across western Mediterranean Europe?; 2) Can we identify transboundary domains of CT influence?; and 3) Is biomass limitation generating a lagged relationship between CTs and wildfires? Answering these questions will provide a better understanding of the regional climate-fire linkages, which would allow a better preparation for potential future wildfires or prompt timely fuel load reduction programmes.

2 Materials and Methods

We calculated the Pearson's R correlation coefficient between monthly time series of fire features (number of fires, burned area and fire size) and CTs in each grid cell. Thus we retrieved a set of Pearson correlation coefficients for each combination of fire feature, CT and lag (0, 3, 6 and 9 months) for each grid cell. The spatial pattern of correlations was summarized in maps depicting the direction (either positive or negative) and the significance ($p<0.05$, $R=\pm0.34$) of the association.

To outline potential climatic domains resulting from the interaction of CT at multiple time scales we submitted the correlation coefficients to a cluster analysis. Identifying such domains will enable us to better understand the climatic forcing of wildfire activity. Our approach is heavily focused on identifying transnational climatic regions under the premise that homogenous patterns of both wildfire activity and climate factors do exist. We adopted a hierarchical cluster approach using *Euclidean Distance* as dissimilarity measure and *ward.D2* as agglomeration criterion, which aims to create groups such that variance is minimized within them. Clusters were trained for each fire feature separately and the optimal number of clusters (i.e., climate domains) was determined from the set of criteria available in the *nbClust* package (Charrad et al., 2014). Climate domains were then characterized according to the observed distribution of CT correlation, indicating the most influential patterns in terms of significance and direction of the relationship.

3 Data

3.1 Study region and fire data

The region under study extends over the Western Mediterranean Basin, including Portugal, Spain, Southern France, Corsica and Sardinia (Italy), which are among the most fire-affected region of Europe. Fire data were obtained from the national/regional wildfire databases of Portugal (ICNF, http://www2.icnf.pt/portal/florestas/dfci/inc/estat-sgif), Spain (EGIF; https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/incendios-forestales.aspx), France (Prométhée; https://www.promethee.com/incendies) and Sardinia (CFVA; http://www.sardegnageoportale.it/webgis2/sardegnamappe/ ?map=aree_tutelate). We retrieved all fire records in the period 1980-2015, retaining only those larger than 100 ha to prevent inhomogeneities related to fire detection and compilation. For each fire record we extracted the date and place of ignition and the final size. Fire events were aggregated into a regular grid of 0.5º resolution to prevent undesired effects due to partial/inaccurate location information. For each cell, we calculated the burned area, the total number of fires and the 95th percentile of fire size on a monthly basis. Fire features were aggregated as the sum of the number of fires and burned areas, and the 95th percentile of fire size, in the period May-to-October. Finally, we applied an unweighted moving window procedure using a bandwidth of 500 km. This procedure helps smoothing the spatial distribution of fire activity to facilitate the identification of spatial patterns of association with large-scale climate teleconnections (Koutsias et al., 2016; Andela et al., 2017). Because of the unweighted moving window, a given pixel does not represent its actual location but rather the 500km region surrounding it, increasing the average number of fire events per pixel to sufficient amount (from 0.07 to 18.16) for the investigation of extremes.

3.2 Climate teleconnection patterns

We investigated seven CT patterns, known to be among the most influential factors modulating wildfires in the Western Mediterranean Basin:

- The NAO computed as the Gibraltar- Reykjavik normalized Sea Level Pressure (Jones, Jonsson and Wheeler, 1997);https://crudata.uea.ac.uk/cru/data/nao/nao.dat.

- The EA teleconnection pattern index, which is structurally similar to the NAO, and consists of a north-south dipole of anomaly centers spanning the North Atlantic from east to west (Barnston and Livezey, 1987); http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml.

- The SCAND, which consists of a primary circulation center over Scandinavia, with weaker centers of opposite sign over western Europe and eastern Russia/ western Mongolia, and known there as Eurasia-1 (Barnston and Livezey, 1987);https://www.cpc.ncep.noaa.gov/data/teledoc/scand.shtml.

- The ENSO, which was calculated from the HadISST1. It is the area averaged sea surface temperature (SST) from 5S-5N and 170-120W (Rayner et al., 2003); https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/.

- The PDO, which was derived as the leading PC of monthly SST anomalies in the North Pacific Ocean, poleward of 20N (Mantua et al., 1997); https://psl.noaa.gov/data/climateindices/list/.

- The MOI, defined by Conte, Giuffrida and Tedesco (1989) as the normalized pressure difference between Algiers and Cairo; https://crudata.uea.ac.uk/cru/data/moi/moi1.output.dat.-
The WeMOi, which is an index measuring the difference between the standardized atmospheric pressure recorded at Padua in northern Italy, and San Fernando, Cádiz in Southwestern Spain (Martin-Vide and Lopez-Bustins, 2006); ttp://www.ub.edu/gc/documents/Web_WeMOi-2020.txt.

CTs were averaged into the corresponding 6-month time frame. In addition to synchronous correlation (i.e., lag =0 May-to-October), we investigated asynchronous effects in the CTs signal by exploring a lag of 3 (February-July), 6 (November-May) and 9 (September-February) months before the summertime.

4 Results

4.1 Influence of climate teleconnections on fire features

The spatial patterns of correlation between CTs and the selected fire features (burned area, number of fires and fire size) depicted varied spatial arrangements. It should also be highlighted that the statistical significance was non-stationary over space and differed among CTs (Figure 1, 2 and 3). The CT indices depicting the strongest positive or negative correlations were SCAND, WeMOI and NAO.

The SCAND index showed significant negative synchronous correlations (lag 0) with burned area almost in the entire study area. Surprisingly, we identified a sharp transition across the different time lags from positive association at lag 6 (antecedent winter), though statistically significant only in midland Spain. The NAO index was positively correlated above 40º latitude in the IP and Southern France at lag 0. NAO also denoted a significant lagged signal (6 and 9 months before summer) in Southern France, Corsica and Sardinia. The WeMOI index is correlated to increased burned area in Sardinia, Corsica, and the Mediterranean coast of Spain and France from lag 3 to 9 (Figure 1). The correlations with MOI and PDO were lower than the aforementioned indices and only significant in specific enclaves (i.e., MOI in the south of Sardinia at lag 9 and PDO in Spain at lag 9).

In terms of correlation results with the number of fires (Figure 2), NAO was clearly the dominant pattern, being positively correlated in the IP and Southern France at time lag 0 and Southern France and Sardinia at lag 9. The effect of the SCAND index differed, in spatial terms, from the burned area analysis. This index was only significant (negatively) in Corsica, the north of Sardinia, Southern France and NE Spain at lag 0. It was found to be positively correlated in Sardinia, Southern France and the Spanish Mediterranean coast at lag 3. The contribution of the persistent positive WeMOI phase (and to a lesser extent PDO) was significantly evident in the Mediterranean at all lags. The MOI was also significant in Sardinia, Corsica and some coastal Mediterranean areas of France at lag 6 and 9.

The significance of all indices explaining fire size was lower compared to burned area and fire ignitions (Figure 3). Similarly to the burned area, the SCAND index significantly explained the size of fires, transitioning as well from positive association in lag 6 to antiphase correlation at lag 0 in most of the study area. NAO shows significant correlations with fire size in Sardinia, Southern France and Corsica at lag 3 (antecedent spring) and the WeMOI index showed a positive correlation along the Spanish Mediterranean coast, though only significant at lag 3.

The other CT modes (EA and ENSO) did not show significant effects anywhere in the study region.

4.2 Spatio-temporal domains of climate teleconnections

We identified three clusters based on most influential CT indices (SCAND, WeMOI and NAO) that consistently outlined coincident domains among the three fire features considered in this work (Figure 4). These homogeneous zones reflect the climatic gradient from Atlantic (Zone 1) to Mediterranean conditions (Zones 2 and 3). Despite the geographical concordance of the patterns, we observed clear differences in the inner contribution of CTs in terms of association and significance of CTs and temporal scales of influence, which significantly varied across fire features.

Zone 1 gathered the influence of SCAND and NAO patterns on all fire features This CT domain extends over the western IP, excluding the Mediterranean coast. Positive NAO at lag 0 and a sharp transition from positive to negative SCAND (also observed in zones 2 and 3) are the distinctive traits of the region. Zone 2 seems to act as a transition area from Atlantic to Mediterranean conditions. It covers the Spanish Mediterranean coast, extending over the western portion of southern France. The SCAND pattern is still exerting a strong influence, showing negative and synchronous associations. Zone 2 better relates to positive association with the WeMOI pattern, which boosts both burned area and fire size but showed weaker influence in fire ignitions, still strongly linked to synchronic NAO.

The third domain (Zone 3), was clearly led by the WeMOI pattern, exerting a strong positive association with burned area and number of fire ignitions. The influence of WeMOI extends from lag 9 to 0 in the case of fire ignitions, shortening in the case of burned area (3 to 9). Again, the SCAND index depicted a synchronous negative influence in the entire study region and a sharp transition. NAO significantly explained fire features at different time lags: burned area (lag 0), number of fires (lag 3), fire size (lag 9).

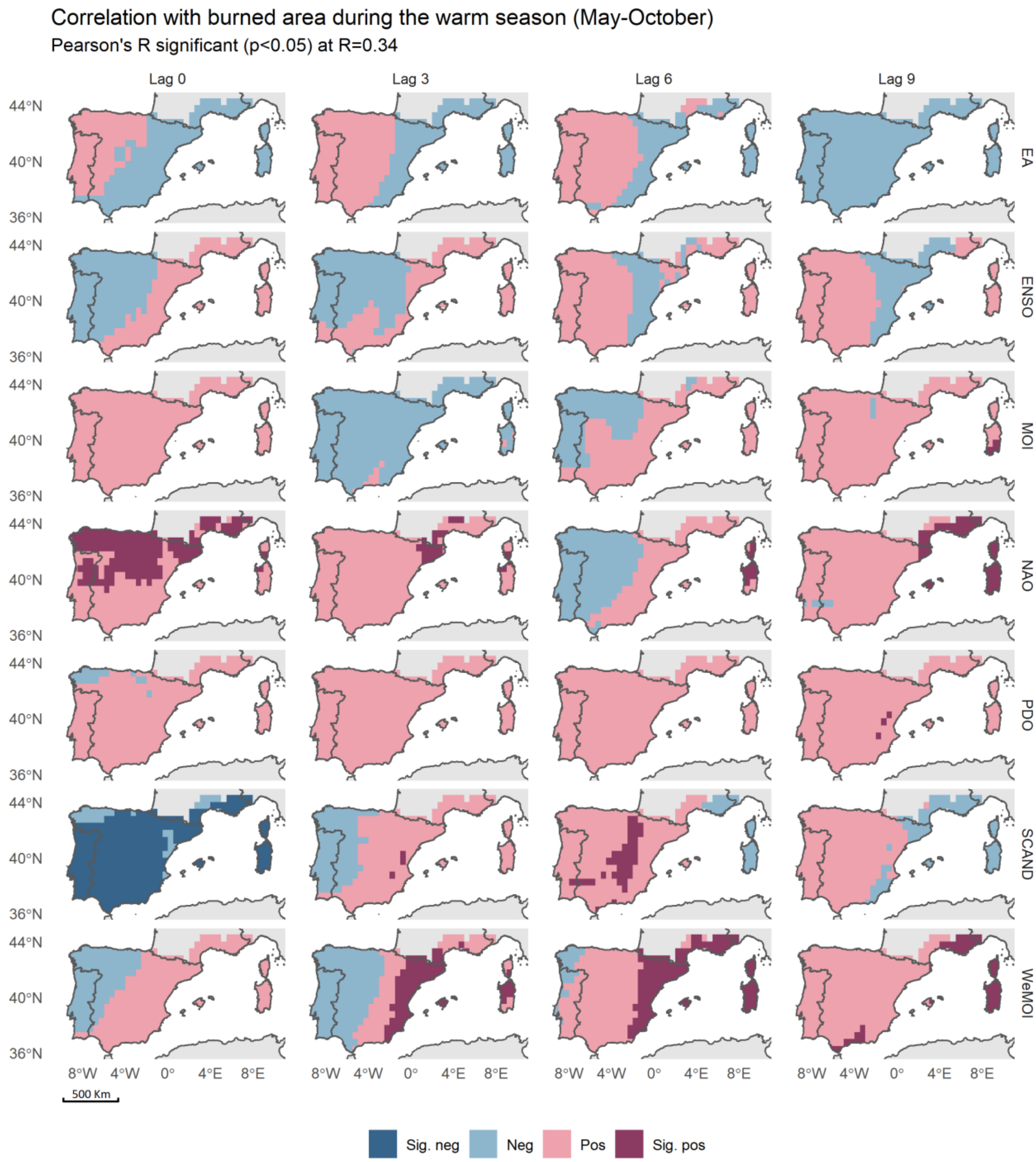

Figure 1. Spatial distribution of Pearson's R correlation coefficient between CTs and burned area (fires > 100ha), 1980-2015. Columns indicate lagged cross-correlation intervals of months before summer season.

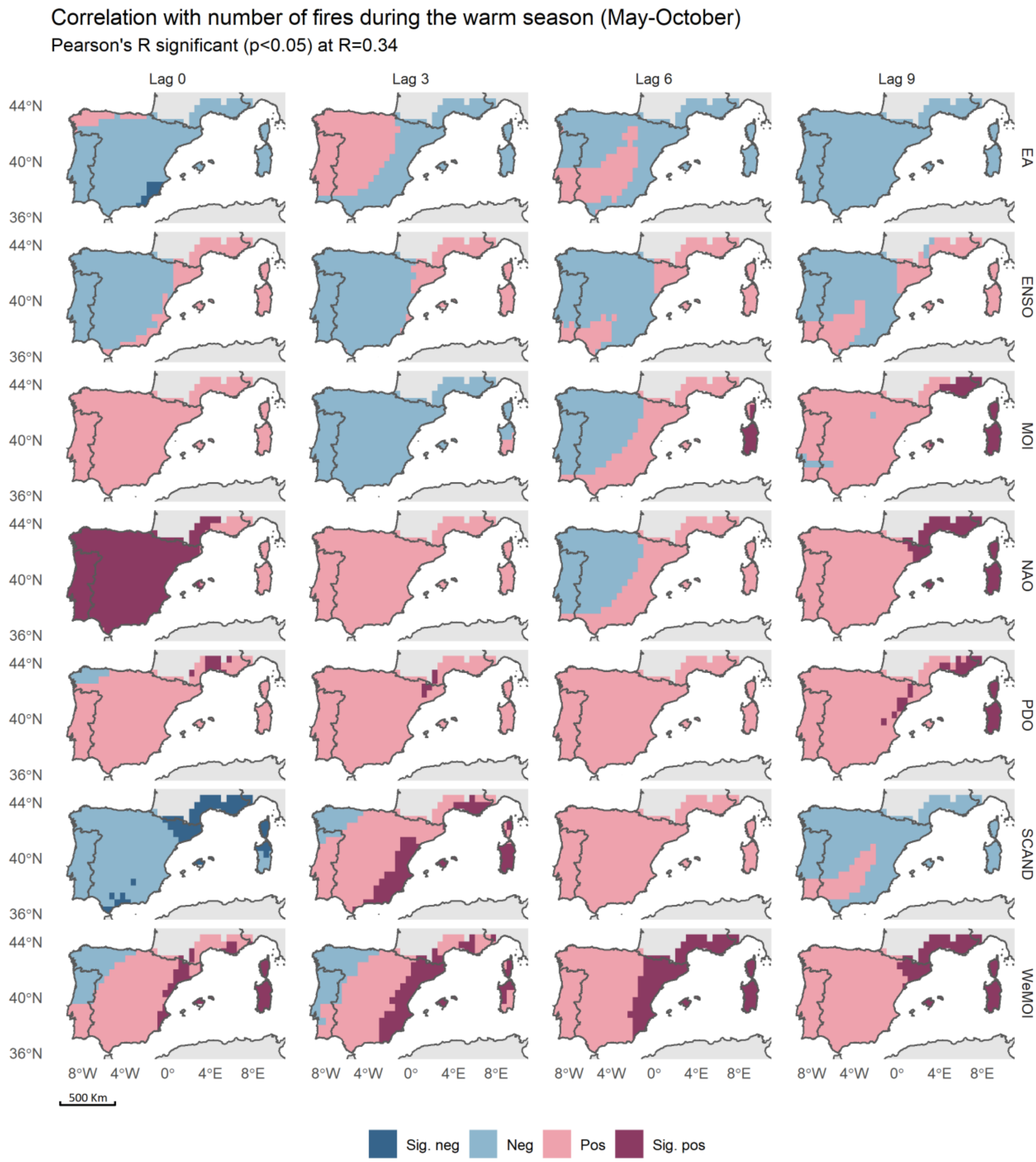

Figure 2. Spatial distribution of Pearson's R correlation coefficient between CTs and number of fires (fires > 100ha), 1980-2015. Columns indicate lagged cross-correlation intervals of months before summer season.

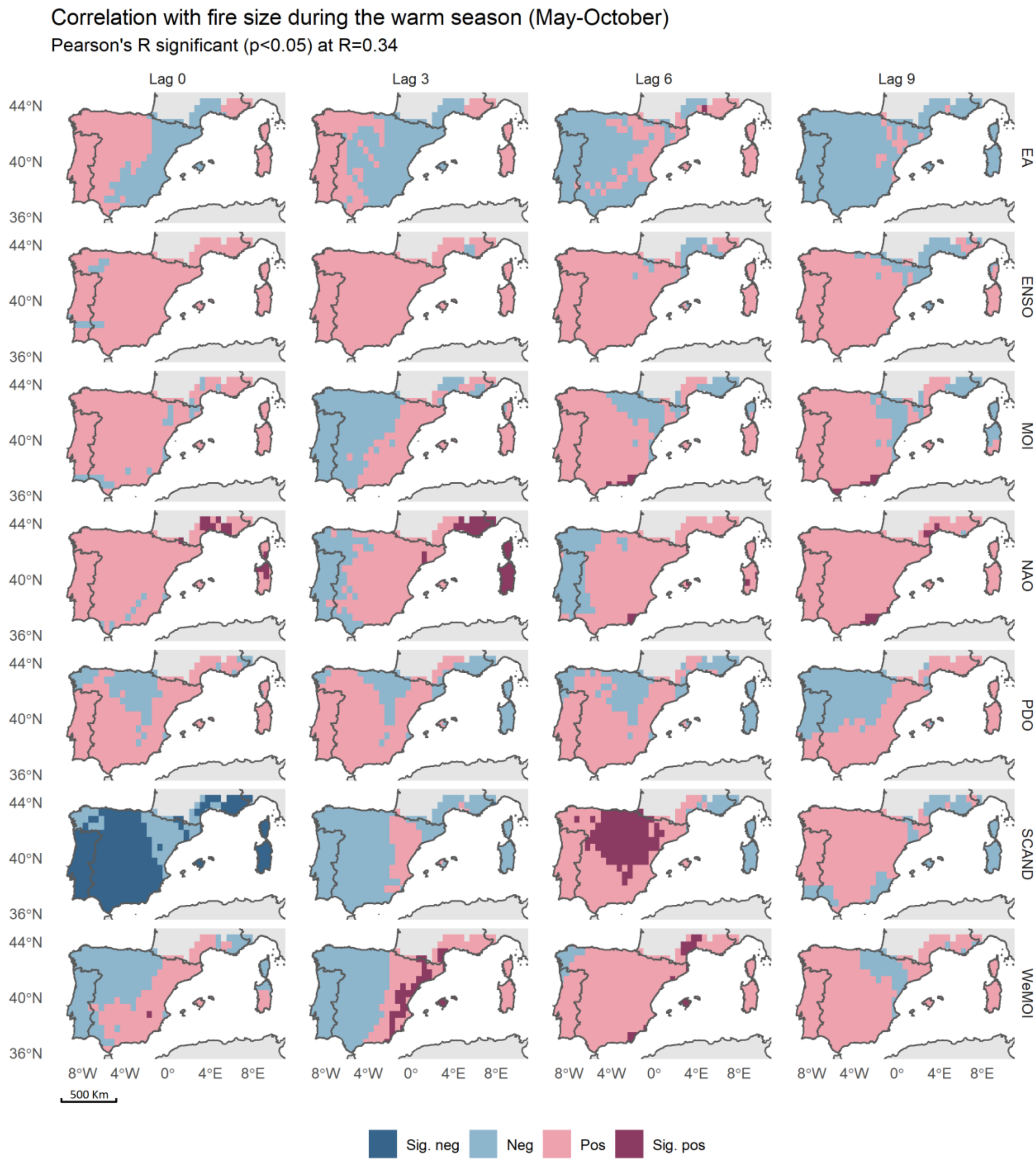

Figure 3. Spatial distribution of Pearson's R correlation coefficient between CTs and 95th percentile of fire size (fires > 100ha), 1980-2015. Columns indicate lagged cross-correlation intervals of months before summer season.

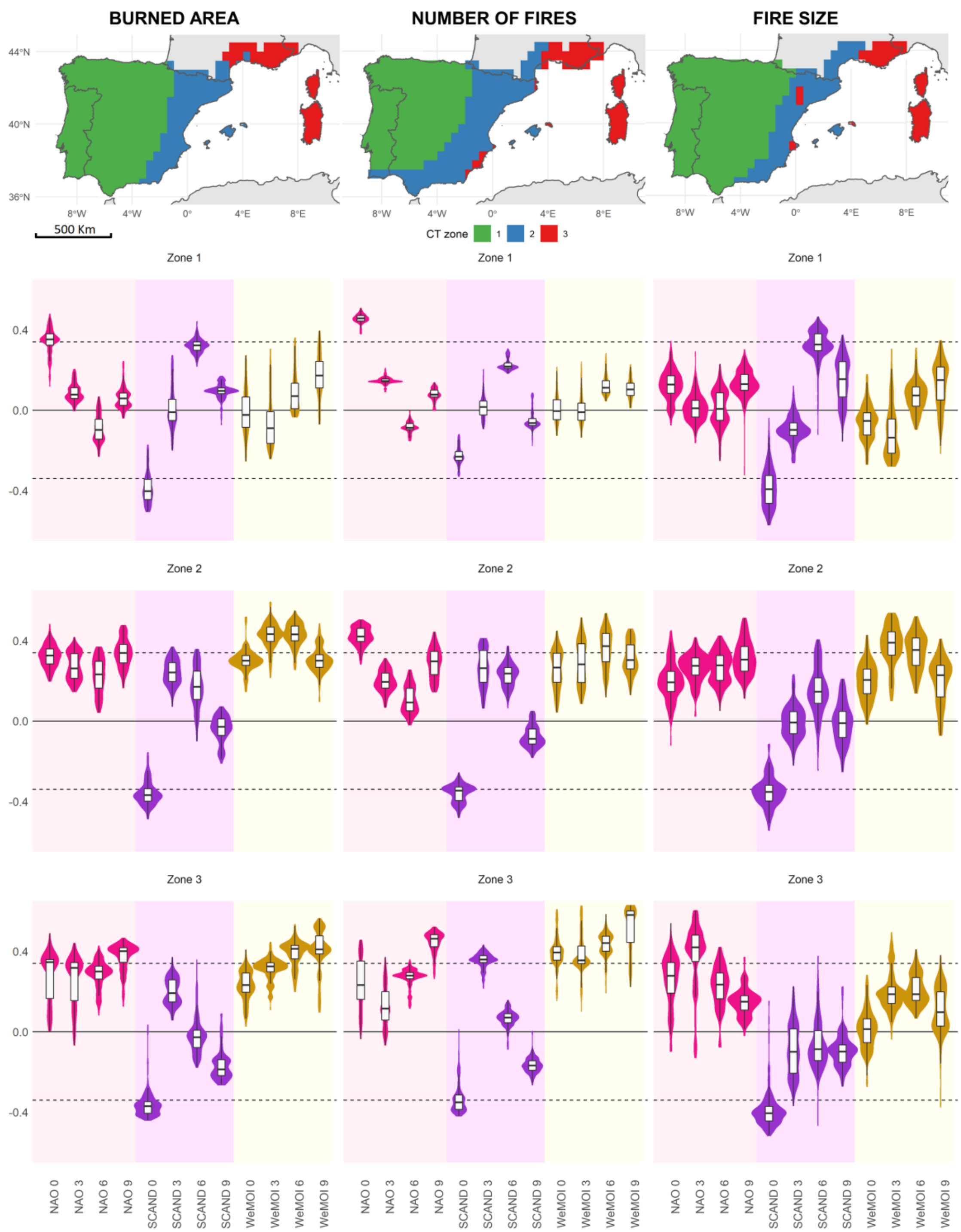

Figure 4. Climate teleconnection domains. Maps show the spatial distribution of CTs' domains for burned area (left), number of fires (middle) and fire size (right). violin plots display the correlation strength (Pearsons' R) between NAO, SCAND and WeMOi per feature and lag. The solid black line indicates the 0 correlation threshold. Inner and outer dashed lines indicate the significance threshold $p<0.05$.

5 Discussion and conclusions

Several studies already prompt the importance of anticipating the pernicious effects of future shifts in fire regimes, with a wide consensus about the growing impacts of climate warming cascading into increased extreme wildfire events (Bedia et al., 2015, 2014; Ruffault et al., 2020; Turco et al., 2018). In this paper we provide insights into the dominant CT patterns modulating wildfire activity in the Western Mediterranean basin.

In line with Royé et al. (2020), we identified three CT domains spanning west-to-east and being mainly associated with the SCAND, the NAO and the WeMOi climate modes. From a spatial standpoint, the mediterranean coast CT domain (zone 2) largely matches fire regime zones delineated in the region (Rodrigues et al., 2020; Rodrigues et al., 2019a; Trigo et al., 2016) Vieira, Russo and Trigo, 2018). According to Calheiros, Pereira and Nunes (2021), this region is likely to persist over time and the frequency of days experiencing extreme fire-weather conditions will increase; an analysis that should consider the aforementioned CT modes influencing this domain in future analysis. Our domain delimitation assigns the rest of the IP into a single cluster (zone 1), despite the known variety of driving forces and different fire regimes (Nunes et al., 2016; Rodrigues et al., 2018). However, from a climate perspective, large fires in the region (>100 ha) seem to respond to similar spatial (Rodrigues et al., 2020) and temporal (Silva et al., 2019) patterns. The domains observed in France span from zone 3 in the East, to zone 2 in the west. They match to a certain degree the 'pyroclimate' delimitation by (Curt et al., 2014). However, the coarse spatial resolution of our fire data (50x50 km compared to the 2x2 km resolution of the French database) precluded us from detecting the fine-grained mosaic of local regions.

These CTs differently interacted across space and time (time lags between the CT and fire season), thus leading to different driving weather patterns described below. The negative relationship with the SCAND observed 0-3 months before summer involves reduced precipitation, suggesting drought spells influencing dead fuel moisture content as the main climate driver of wildfires (Ruffault et al., 2018). One of the most striking results was the observed phase transition of the SCAND (from positive to negative, i.e., wet to dry conditions) related to increased fire activity. This sharp shift suggests fuel build-up during +SCAND (increased rainfall) coupled to dry spells (-SCAND) fostering the accumulation of low dead fuel moisture content in the months leading up to summer. This indicates a certain limiting effect of dead biomass/fuel availability (herbaceous fuel load) in the ultimate dimensions of the burning (Gouveia et al., 2016; Littell et al., 2018) while supporting the notion that wildfires in the western Mediterranean are usually events fostered by short-term fire-prone conditions modulated by the moisture status and abundance of herbaceous dead fuels. This is in line also with the results of (Russo et al., 2017) for the IP, which highlight the relationship between wildfires and drought is better explained by the influence of spring precipitation on the central sector, and by the influence of temperature and precipitation during summer on most of the Portuguese provinces. Thus we should not overlook antecedent positive water balance anomalies (+SCAND), which may play an equally important role as dry spells or heat waves do (Pausas and Fernández-Muñoz, 2012; Pausas and Paula, 2012).

The NAO is linked to a higher number of fires in the entire region. Positive NAO is linked to anticyclonic conditions boosting temperature and limiting precipitation potentially leading to extreme drought episodes (García-Herrera et al., 2007; Vicente-serrano and Cuadrat, 2007). Eventually, this situation may evolve into thermal lows and thunderstorms fostering lightning strikes and fires (Pineda and Rigo, 2017). Likewise, NAO may connect also with sub saharan intrusions due to Atlantic blocking (Sousa et al., 2019, 2018), boosting temperatures in the Mediterranean area. In fact, the largest fires in the Mediterranean side of the IP seem to be associated with southeastern advections conducive to extreme heat waves (Rodrigues et al., 2020; Rodrigues et al., 2019b). Likewise, fires are known to be concomitant with thermal anomalies in the northeastern end of the IP (Cardil et al., 2015; Duane and Brotons, 2018) or Sardinia and Corsica (Ager et al., 2014; Salis et al., 2021). Though weaker than NAO's, the WeMOI also exerts moderate influence in the Mediterranean rim of the IP. During the +WeMOI the prevailing winds on the IP are typically from the West and Northwest. These winds, by the time they reach the Mediterranean sea, have crossed the peninsular continental areas reaching the leeward side of the coastal mountain systems, thus becoming warm and dry westerly winds (Rodrigues et al., 2019b) or cool but equally dry northwesterly winds (Duane and Brotons, 2018; Ruffault et al., 2017).

Nonetheless, while fires in the IP seem to be modulated by NAO, fire activity in southern France, Corsica and Sardinia (zone 3) is better associated with the WeMOI pattern. For instance, in the period 1998-2016, Sardinia presented the most relevant wildfire spread conditions in days with southern and southwestern winds. Slightly more than 50% of the area burned by very large wildfires (>200 ha) during these wind regimes (Salis et al., 2021). Moreover, the advection of hot and dry air masses from the south through the inner parts and the north end of the island resulted in an evident increasing gradient in wildfire size and risk from southern to inner and northern Sardinia. On the other hand, strong mistral winds from the west and north-west (dominant during the positive phase of the WeMOI) promoted an increase in wildfire size and area burned in eastern and southern zones of Sardinia (Salis et al., 2021).

By identifying the key CT patterns boosting wildfire activity and its spatial-temporal domains of influence we can leverage operational climate services to provide seasonal forecasts that can be used to complement early warning systems (Lledó et al., 2020). While early warning systems based on short-term forecasted weather conditions are useful to anticipate hazardous fire behavior and danger in operational environments, CTs modulate weather patterns at monthly scales with lagged effects as shown in this manuscript, facilitating the identification of adverse fire windows during the fire season. Furthermore, it is possible to produce long-term (up to 3-months) predictions of CT patterns (Świerczyńska-Chlaściak and Niedzielski, 2020; Wang et al., 2017) which can allow for some predictability and therefore contributing to the improvement of alert systems. Finally, the ultimate effects of CTs on key weather parameters influencing fire behavior such as fuel loading, dead and live fuel moisture content or wind fields should be further analyzed.

Acknowledgments

This work was partially supported by national funds through FCT (Fundação para a Ciência e a Tecnologia, Portugal) through projects IMPECAF (PTDC/CTA − CLI/28902/2017) and UIDB/50019/2020 - Instituto Dom Luiz.

Data Availability Statement

Data used in the study are available at Zenodo via DOI 10.5281/zenodo.5138095 (https://zenodo.org/record/5138095) with Creative Commons Attribution 4.0 International license. Fire data were obtained from the following national/regional wildfire databases:

- Portugal (ICNF, http://www2.icnf.pt/portal/florestas/dfci/inc/estat-sgif)

- Spain (EGIF; https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/incendios-forestales.aspx)

- France (Prométhée; https://www.promethee.com/incendies)

- Sardinia (CFVA; http://www.sardegnageoportale.it/webgis2/sardegnamappe/?map=aree_tutelate).

Data for climate teleconnection patterns were provided by the Climatic Research Unit from the University of East Anglia, the Climatology Group from the Universitat de Barcelona, and the US's Climate Prediction Center. Individual datasets and calculations can be accessed as follows:

- The NAO computed as the Gibraltar- Reykjavik normalized Sea Level Pressure (Jones, Jonsson and Wheeler, 1997); https://crudata.uea.ac.uk/cru/data/nao/nao.dat.

- The EA teleconnection pattern index, which is structurally similar to the NAO, and consists of a north-south dipole of anomaly centers spanning the North Atlantic from east to west (Barnston and Livezey, 1987). http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml

- The SCAND, which consists of a primary circulation center over Scandinavia, with weaker centers of opposite sign over western Europe and eastern Russia/ western Mongolia, and known there as Eurasia-1 (Barnston and Livezey, 1987). https://www.cpc.ncep.noaa.gov/data/teledoc/scand.shtml

- The ENSO, which was calculated from the HadISST1. It is the area averaged sea surface temperature (SST) from 5S-5N and 170-120W (Rayner et al., 2003). https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/

- The PDO, which was derived as the leading PC of monthly SST anomalies in the North Pacific Ocean, poleward of 20N (Mantua et al., 1997). https://psl.noaa.gov/data/climateindices/list/

- The MOI, defined by Conte, Giuffrida and Tedesco (1989) as the normalized pressure difference between Algiers and Cairo; https://crudata.uea.ac.uk/cru/data/moi/moi1.output.dat.

- The WeMOi, which is an index measuring the difference between the standardized atmospheric pressure recorded at Padua in northern Italy, and San Fernando, Cádiz in Southwestern Spain (Martin-Vide and Lopez-Bustins, 2006); http://www.ub.edu/gc/documents/Web_WeMOi-2020.txt.

All analyses, maps and plots were conducted using the R's framework for stastistical computing, Version 4.1.0, available via https://cran.r-project.org/ (R Core Team, 2021).

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