Science of the Total Environment 846 (2022) 157537

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Influence of atmospheric patterns on soil moisture dynamics in Europe

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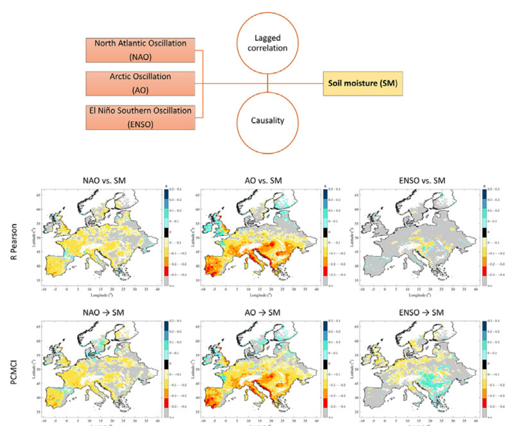
HIGHLIGHTS

- The influence of atmospheric patterns on SM dynamics in Europe is analysed.
- A correlation analysis shows a uniform response of SM to NAO and AO, mostly inverse.
- Causal relations between NAO, AO, ENSO and SM are revealed with the PCMCI method.
- A general one-to-two month lagged response of SM to atmospheric patterns was found.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paulo Pereira

Keywords:
Soil moisture
North Atlantic Oscillation
Arctic oscillation
El Niño Southern Oscillation
Causality
Lagged response

ABSTRACT

Soil moisture (SM) plays a key role in the water cycle, and its variability is intimately linked to coupled land-atmosphere processes. Having a good knowledge of soil-atmospheric interactions is thus essential to assess the impact of climate change on SM; however, many aspects of how water and energy exchanges occur in the soil-atmosphere continuum are still uncertain. In particular, it is known that atmospheric circulation patterns influence climate conditions over Europe but their impact on SM has only rarely been studied. This study provides insight into how atmospheric patterns influence soil moisture dynamics in Europe, where an increase in temperature and agricultural droughts are expected as an impact of climate change. To do so, we analysed the influence of the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), and the El Niño Southern Oscillation (ENSO) on European SM, including lagged responses, for the period 1991–2020 at a monthly scale. Two methods have been used: a lagged correlation analysis and a more sophisticated causality approach using the PCMCI (PC method combined with the momentary conditional independence (MCI) test). SM series from two different databases were considered: the hydrological model LISFLOOD and the reanalysis dataset ERA5-Land. The results from the correlation analysis showed a significant, predominantly negative relationships of SM with NAO and AO over almost all of Europe and no significant relation with ENSO. With the causality analysis, similar patterns are obtained for NAO and AO; however, the PCMCI analysis revealed clear patterns of ENSO influencing SM with a delayed response of one-to-two months in central and northwest Europe. The results obtained in this work highlight that there are causal relations between the main modes of

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http://dx.doi.org/10.1016/j.scitotenv.2022.157537
Received 21 March 2022; Received in revised form 14 July 2022; Accepted 17 July 2022
Available online 22 July 2022

interannual climate oscillations and SM variations in Europe, underlining the importance of accounting for global atmospheric circulations to study current changes in regional soil water-related processes.

1. Introduction

The study of climate change impacts on different environmental systems has motivated many works, especially on water-related systems (Arnell, 1999; Middelkoop et al., 2001). Soil moisture (SM) is a key variable involved in many climatic, geophysical and biological processes, so monitoring its dynamics and understanding its (causal) relations in these processes are crucial. In addition, SM plays a very important role in the hydrological cycle, as it modulates the water and energy exchanges within soil–atmosphere systems (Seneviratne et al., 2010). Thus, knowledge of the evolution of this variable can help to better understand the impact of climate change in these systems. SM dynamics and factors that influence its variability have been widely analysed from different perspectives (Daly and Porporato, 2005; Dorigo et al., 2012; Entekhabi et al., 1996; Martínez-Fernández et al., 2021; Piles et al., 2019). However, some issues about soil–atmosphere interactions are still uncertain (Boé, 2013).

It is well-known that different atmospheric circulation patterns highly influence climate conditions across the globe (Hurrell and Van Loon, 1997; Lau and Yang, 2003). In particular, several teleconnection patterns dominate European climate variability (Hurrell, 1995; Thompson and Wallace, 1998). Thus, changes in atmospheric circulation can be related to changes in several climatic variables and the increase in extreme events during recent decades over this continent (Horton et al., 2015; Kostopoulou and Jones, 2007; Kyselý, 2007; Moberg and Jones, 2005). The dominant modes of climate variability in the Northern Hemisphere are the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) (Simpkins, 2021). However, some other patterns also induce changes in European climate conditions, such as the El Niño Southern Oscillation (ENSO) (Fraedrich and Müller, 1992), the East Atlantic (EA) (Bastos et al., 2016) and the Scandinavian Pattern (SCAND) (Casanueva et al., 2014). They induce changes in precipitation and temperature (Hurrell et al., 2001; Ionita et al., 2020; Scaife et al., 2008; Toreti et al., 2010; Trigo et al., 2002) and, consequently, in related processes such as river flow (deCastro et al., 2006; Su et al., 2018) and vegetation growth (D'Odorico et al., 2002; Gordo and Sanz, 2010).

One of the most disturbing natural hazards is droughts, as they exert a great impact on human activities. They are complex phenomena influenced by several factors but they always have an atmospheric inception (Vicente-Serrano et al., 2011), hence understanding the atmospheric influence on droughts is crucial since it could help mitigating their damage spread. In this context, several works have focused on studying the influence of atmospheric circulation patterns on meteorological droughts in Europe (Ionita et al., 2015; Schubert et al., 2016; Vicente-Serrano et al., 2011). However, agricultural drought, defined by the SM deficit, represents a more direct and immediate impact (Almendra-Martín et al., 2021; Salvia et al., 2021; Sánchez et al., 2018); thus, as a highly meaningful topic, this work focuses on exploring the influence that atmospheric fluctuation patterns exert on SM.

In the past, little attention has been given to the effect that some atmospheric patterns exert on SM, mainly because of the scarcity of long-term spatially continuous data series (De Luca et al., 2020; Wang et al., 2011). Diverse works have modelled SM data in certain regions to perform this kind of analysis (Kurnik et al., 2015; Sheffield and Wood, 2008) or analyse the drivers of this variable to relate their dynamics (Hassan and Nayak, 2020; Ionita et al., 2015; Mühlbauer et al., 2016). Remote sensing databases have also been used to analyse this relationship. However, in such works, short study periods of only a few years were used (Bueso et al., 2020a; Piles et al., 2019) since available data are relatively recent and thus limited in time. Thus, the need for accurate long-term spatiotemporally continuous SM databases is highlighted to achieve rigorous assessments of climate change impacts (Thorne et al., 2018). Currently, there are SM databases available from modelling and reanalysis suitable for this type of analysis (Beck et al., 2020; Miralles et al., 2014).

Although relationships between atmospheric circulation patterns and general dryness or wetness conditions have been established in Europe, most are based on atmospheric teleconnections (Brönnimann, 2007; Hurrell et al., 2001). Furthermore, it is assumed that these relationships explain the variability of the different studied variables, but their causal relationships have rarely been analysed (Runge et al., 2019a). A causal relationship was found between ENSO, AO and NAO, and the streamflow of >30 % of the rivers in Europe (Su et al., 2018). Furthermore, in some regions, causality studies showed additional relationships between ENSO and climatic variables that were not detected with correlation analysis (Silva et al., 2021). Several methods have been proposed in the literature to study causality but are still rarely applied in Earth system science (Runge et al., 2019a).

Understanding the influence that atmospheric patterns exert on SM dynamics is key to assessing the impact of climate change on this variable and, therefore, on issues such as the occurrence of agricultural drought or groundwater recharge. This interest is highlighted in Europe, as the predicted changes in climatic conditions suggest an increase in temperature over all continents (Christensen et al., 2013), which can lead to an intensification of hydrological extremes such as floods (Dankers and Feyen, 2008) or agricultural droughts (Grillakis, 2019). Thus, the main objective of this work is to provide further knowledge of how SM responds to the main atmospheric patterns in Europe. The two atmospheric circulation patterns dominant in the Northern Hemisphere, the NAO and AO (Simpkins, 2021), and the phenomenon with more impact on global climate, ENSO (Brönnimann, 2007), were considered in this work. Two SM databases were used, for the period 1991–2020. We studied both the lagged influence that atmospheric patterns exert on SM and causation, i.e., whether there is a causal relationship between the climate modes and SM time series at a monthly time scale.

2. Methods and dataset

2.1. Soil moisture databases

Two SM databases were considered in this study, one from the ERA5-Land reanalysis (Muñoz-Sabater et al., 2021) and the other from the LISFLOOD hydrological model (van der Knijff et al., 2010). Both databases have been widely used for different purposes, such as flood forecasting (Wanders et al., 2014), growth vegetation studies (González-Zamora et al., 2021) and trend detection (Almendra-Martín et al., 2021). The reanalysis database used in this study is the ERA5-Land (hereafter, ERA5L) from the European Centre for Medium-Range Weather Forecasts (ECMWF). It provides a global series of different land variables. These series are given on a regular grid of 0.1° with hourly time resolution from 1981 to the present (Muñoz-Sabater et al., 2021). As the surface SM is more demonstrative of the soil-atmosphere coupling (Santanello et al., 2011), only the first layer of the product, comprising the soil top 7 cm, was used. The second database used was the hydrological rainfall-runoff model LISFLOOD (hereafter, LF), developed by the Natural Hazards Project of the Joint Research Centre (JRC) of the European Commission (van der Knijff et al., 2010). It provides SM data over Europe with a spatial resolution of 5 × 5 km every 6 h from 1991 to the present (De Roo et al., 2000). These data are estimated for 3 depth layers, but for this study, only the surface layer (5 cm) was considered. In addition, this database has been rescaled to the ERA5L grid so that the study results are comparable.

Both databases have been validated in previous works, obtaining good results (Laguardia and Niemeyer, 2008; Muñoz-Sabater et al., 2021). However, in certain regions, the accuracy of their products is compromised due to constraints when estimating SM in areas with, for example, heterogeneous topography and permanent or seasonal ice cover (Laguardia and Niemeyer, 2008; Li et al., 2020). To gain a robust understanding of the similarity of these databases, a comparison was first performed between the LF and ERA5L SM products (Fig. 1a). Good correlation was generally obtained between the two except in regions where the products show lower precision, such as high latitudes or great mountain ranges (Laguardia and Niemeyer, 2008; Li et al., 2020). Due to the great differences observed between products in these areas and the consequent uncertainty, we decided to exclude them from this study; pixels showing correlation values lower than 0.5 were not considered (Fig. 1b). Similar thresholds have been used in other studies to ensure consistency in SM products and lower uncertainty (Preimesberger et al., 2021). Once these areas were masked, the SM time series were averaged to obtain monthly values for the study period, 1991–2020. Then, anomalies were computed for each pixel by subtracting the monthly mean calculated using the entire period of study.

2.2. Teleconnection indices

The influence of three different atmospheric patterns on SM dynamics was studied, namely, the NAO, AO and ENSO.

The NAO refers to a circulation of atmospheric mass over the North Atlantic Ocean. It is typically monitored with the NAO index, defined as standardized differences in the surface sea-level pressure between both poles from the dipole Icelandic Low - Azores High (Hurrell et al., 2003). It entails a relevant source of interannual variability in the atmospheric circulation (Walker and Bliss, 1932) and exerts a great impact on climate conditions over most of the Northern Hemisphere, mainly in North America and Europe (Casanueva et al., 2014; Hurrell et al., 2001; Scaife et al., 2008; Trigo et al., 2002; Wang et al., 2012), modulating patterns in wind, temperature and precipitation throughout the seasons but especially during boreal winter (Bastos et al., 2016). A positive phase of NAO is defined when low- and high-pressure anomalies exist over Iceland and Azores pressure centres, respectively (Visbeck et al., 2001). The pressure gradient over the North Atlantic during this phase is large, and an increase in west winds at midlatitudes is observed (Hurrell, 1995). This leads to colder and drier conditions in the Northwest Atlantic and Mediterranean regions and warmer and wetter conditions in northern Europe and the eastern United States (Visbeck et al., 2001). Conversely, a negative phase is defined by high- and low-pressure anomalies in Iceland and Azores, respectively, and leads to opposite climatic conditions. The NAO index has a high interseasonal variability; however, positive and negative phases can last several months (Wang et al., 2010).

The AO is defined as a fluctuation of atmospheric pressure involving an exchange of atmospheric mass between the Arctic and middle latitudes of the Northern Hemisphere (Thompson and Wallace, 1998). The AO index refers to the first empirical orthogonal function (EOF) of the atmospheric pressure anomalies between 20°N and 90°N latitudes (Thompson and Wallace, 1998). Similar to the NAO, it influences the climate conditions over most of the Northern Hemisphere, and both indices are highly correlated (Wanner et al., 2001). Two phases are also distinguished: positive and negative (Hanna et al., 2015). During AO positive phases, lower atmospheric pressure anomalies over the Arctic and higher atmospheric pressure anomalies over the northern Pacific and Atlantic Oceans are observed. The mid-latitudes jet stream is located further north, steering ocean storms northwards (Lindsey, 2009). Thus, wetter and colder conditions occur in Alaska, Scotland, and Scandinavia, and drier and warmer conditions occur in North America, Europe, Siberia, and East Asia (Daoyi and Shaowu, 2003). The opposite conditions are seen during the AO negative phase.

ENSO refers to a coupled mode of the ocean-atmosphere defined by periodic fluctuations in sea surface temperature (SST) and atmospheric circulation along the equator of the Pacific Ocean (McPhaden et al., 2006). It is the dominant mode of interannual climate variability on Earth (Brönnimann, 2007), as it directly or indirectly affects weather conditions over many regions of the planet. There are different ways of monitoring ENSO, depending on whether the atmospheric or the oceanic component is measured. On the one hand, the atmospheric part is measured by the Southern Oscillation index (SOI), a standardized index based on the difference between the sea level pressure at the Tahiti and Darwin, Australia (Ropelewski and Jones, 1987). For monitoring the oceanic component, SST is averaged over specific regions; thus, different indices and thresholds for ENSO are defined (L'Heureux et al., 2019). The NOAA CPC uses the Niño 3.4 region to define warm (El Niño) or cold (La Niña) events. This region comprises from 5°N–5°S to 120°–170°W, near the warm pool of the Pacific and main centres of convection (Trenberth, 1997). During El Niño events, SST anomalies above 0.5 °C are present in this region; thus, the ocean surface in the central and eastern tropical Pacific Ocean becomes warmer. Rainfall decreases over Indonesia and increases over the tropical Pacific (L'Heureux, 2014). Conversely, during La Niña events, SST anomalies below −0.5 °C are present. Easterly winds along the equator become stronger, and rainfall increases over Indonesia and decreases over the central tropical Pacific Ocean (L'Heureux, 2014). When the SST anomalies

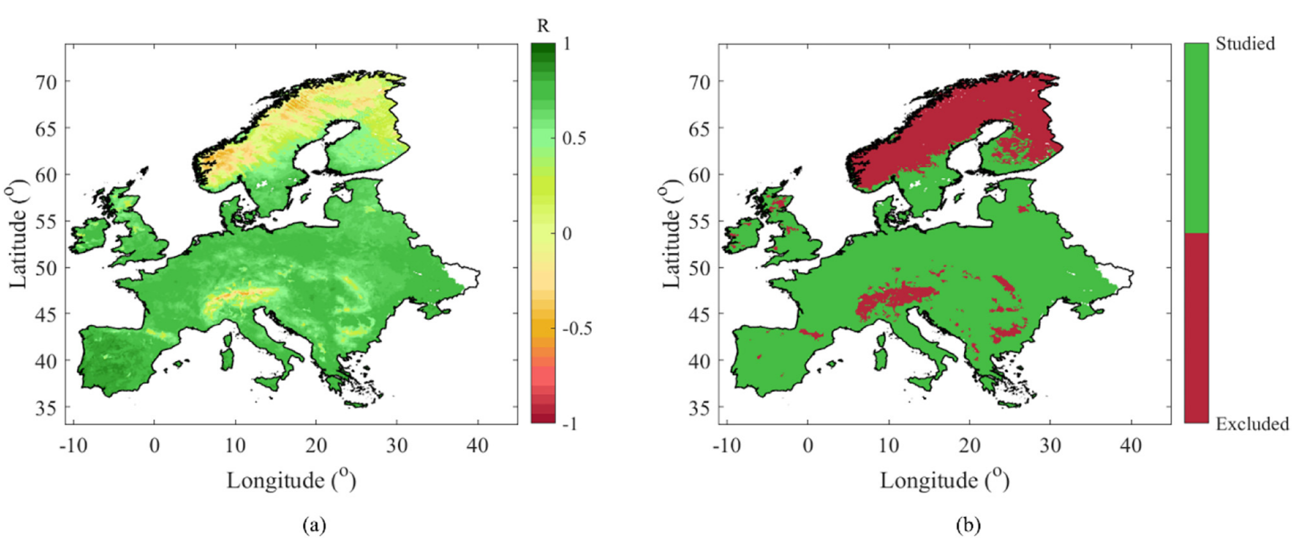

Fig. 1. (a) Pearson correlation coefficient between the LF and ERA5L SM series. (b) Mask applied to the SM products.

are between the upper and lower thresholds, ENSO is considered to be in the neutral phase.

This study used the monthly NAO, AO and Niño 3.4 teleconnection indices time series from the NOAA CPC [https://www.cpc.ncep.noaa.gov] for 1991–2020 (Fig. 2).

2.3. Lagged-correlation and causality analysis

Correlation analysis is the most commonly used tool to study teleconnections (Anderson et al., 2017; Comas-Bru and McDermott, 2014; deCastro et al., 2006; Scaife et al., 2008). This analysis provides information about the strength of the relationship between two variables and whether it is direct (positive) or indirect (negative). The correlation between atmospheric patterns and SM could have a lagged effect due to decoupling between soil–atmosphere systems even at the monthly scale. For this reason, in this study, a lagged correlation analysis was carried out by computing the Pearson correlation coefficient between teleconnection indices and SM anomaly series (Benesty et al., 2009). The significance level was set at $p < 0.05$. This correlation analysis was computed iteratively introducing a lag (τ) from 0 to 6 months. Li et al. (2022) studied up to a 2-year lag between several teleconnection patterns and terrestrial water storage and observed an approximately 5-month lag for most surface components. However, in this study, a lagged effect of teleconnection indices on SM was considered for up to 6 months, as in similar studies (Runge et al., 2019b; Silva et al., 2021; van Oldenborgh et al., 2000). Once the 7 R values were obtained for each pixel, the maximum absolute value of R (R_{max}) was obtained, considering only those with statistical significance. In this way, a significant R_{max} for a given τ can be obtained for each pixel. This kind of analysis has been widely used to study lagged effects between decoupled variables (Peng et al., 2019; Xie et al., 2020).

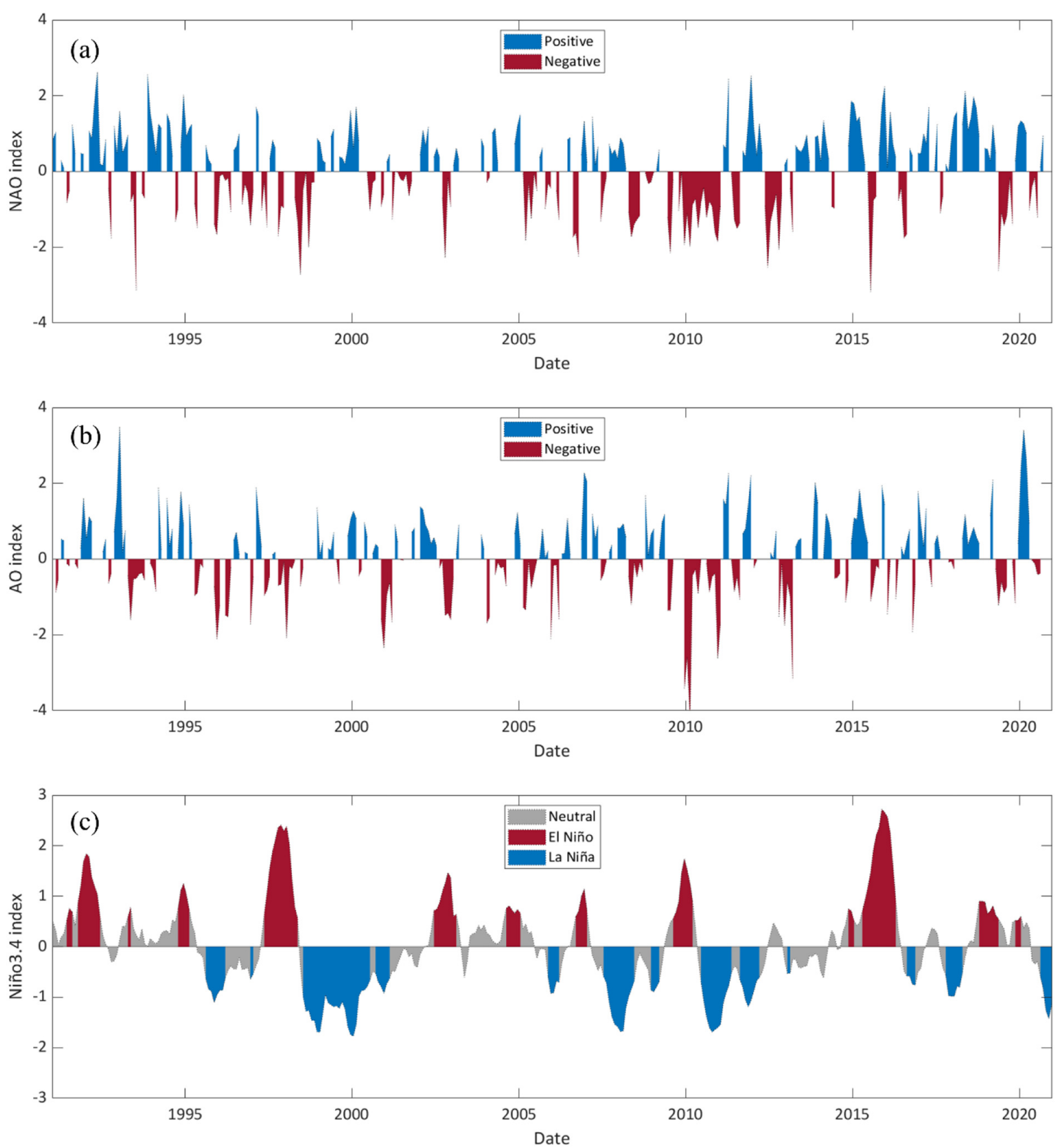

Fig. 2. Time series of (a) NAO, (b) AO and (c) Niño 3.4 indices for the study period (1991–2020).

Although lagged correlation can be a suitable tool for this kind of study, the presence of correlation between variables does not have to imply causation (Runge et al., 2019a). Additionally, note that Pearson correlation only captures linear relationships. Causal discovery consists of estimating the causal parents from a given time series data, meaning statistically significant causal dependencies, their strength and lag (Runge et al., 2019b). Identifying causal relationships between NAO, AO, ENSO and SM can help to better understand soil–atmosphere system dynamics. The Granger causality method (Granger, 1969) has probably been the most widely used approach to study causal effects on Earth dynamical systems (Bueso et al., 2020b; Gupta and Jain, 2021; Kodra et al., 2011; Morata-Dolz et al., 2020; Zolghadr-Asli et al., 2021). However, Runge et al. (2019b) recently proposed a causality method with significantly higher detection power than previous methods. This method is called PCMCI since it combines the PC method (named after its creators Peter and Clark) and the momentary conditional independence (MCI) test and enables identification of both the existence of causal links and their strength (Runge et al., 2019a). The PC method (Spirtes and Glymour, 1991) estimates the causal parents from a series. This method uses a free parameter, the significance level α_{PC}, to encompass the inclusion of both causal parents with a high probability and some false-positive links (Runge et al., 2019b). Then, the MCI test can remove irrelevant conditions even for highly autocorrelated data (Runge et al., 2019b). Both the PC and the MCI can be implemented with different conditional independence tests. In addition, to estimate time-lagged causal links, another free parameter must be chosen, the maximum time delay τ_{max} (Runge et al., 2019b). To implement this method, the Python package Tigramite v4.2 (Kretschmer et al., 2018; Nowack et al., 2020; Runge et al., 2019b) was used with the PCMCI and the partial correlation conditional independence test. The resulting coefficient obtained by this test, ranging between −1 and 1, represents the strength of the link. In this study, the free parameter α_{PC}, that ranges between 0 and 1, was chosen to be optimized for every pixel, and the time-lagged links were considered up to the previous 6 months; thus, τ_{max} was set to 6. The causal links were computed considering the teleconnection indices independently together with the SM anomaly time series for each pixel. The strength of links (climate index → SM) and their significance (set to $p < 0.05$) were tracked and, for the lagged correlation analysis, the strongest significative causal links and the associated month were recorded for each pixel.

3. Results and discussion

3.1. Correlation analysis

The correlation between SM and teleconnection indices was calculated, and only R values with statistical significance ($p < 0.05$) were considered. The results obtained with the ERA5L database (Fig. 3) showed an extensive significant relationship between SM anomalies and the NAO and AO indices over Europe. In addition, this relationship was, in general, negative, which means that drier soil conditions are given during positive phases of both NAO and AO, while wetter conditions are given during negative phases. As expected, the results obtained with both indices were quite similar, since they are highly linked patterns (Mares et al., 2002). However, there were exceptions. Direct relationships were observed with AO in some regions, such as the British Isles, south of Finland and the north coast of France, Netherlands and Germany, which are indirect with NAO. The opposite occurred in southern France and the northern coast of Spain, where direct relationships were obtained with NAO and indirect relationships were obtained with AO. In contrast to Tabari and Willems (2018), who reported a stronger influence of NAO in European precipitation than with AO, we obtained that, for SM, the strongest correlations are with AO, with R values over or around −0.3 in the Iberian Peninsula, northern Italy, the Great Hungarian Plain and the Black Sea coast. The NAO showed a more uniform pattern in the area of study with similar correlation values, between −0.2 and −0.3, and very few regions with direct relationships, mostly concentrated in areas of Scotland, around the Pyrenees, Italy and the Balkans. The positive correlation over southern France was consistent with those observed by Boé (2013). These results showed discrepancies with other studies, which detected a relationship between positive phases of NAO and wetness conditions in parts of central and northern Europe in winter (Schubert et al., 2016; Sheffield and Wood, 2008; van der Schrier et al., 2006) when NAO shows more influence on European climate.

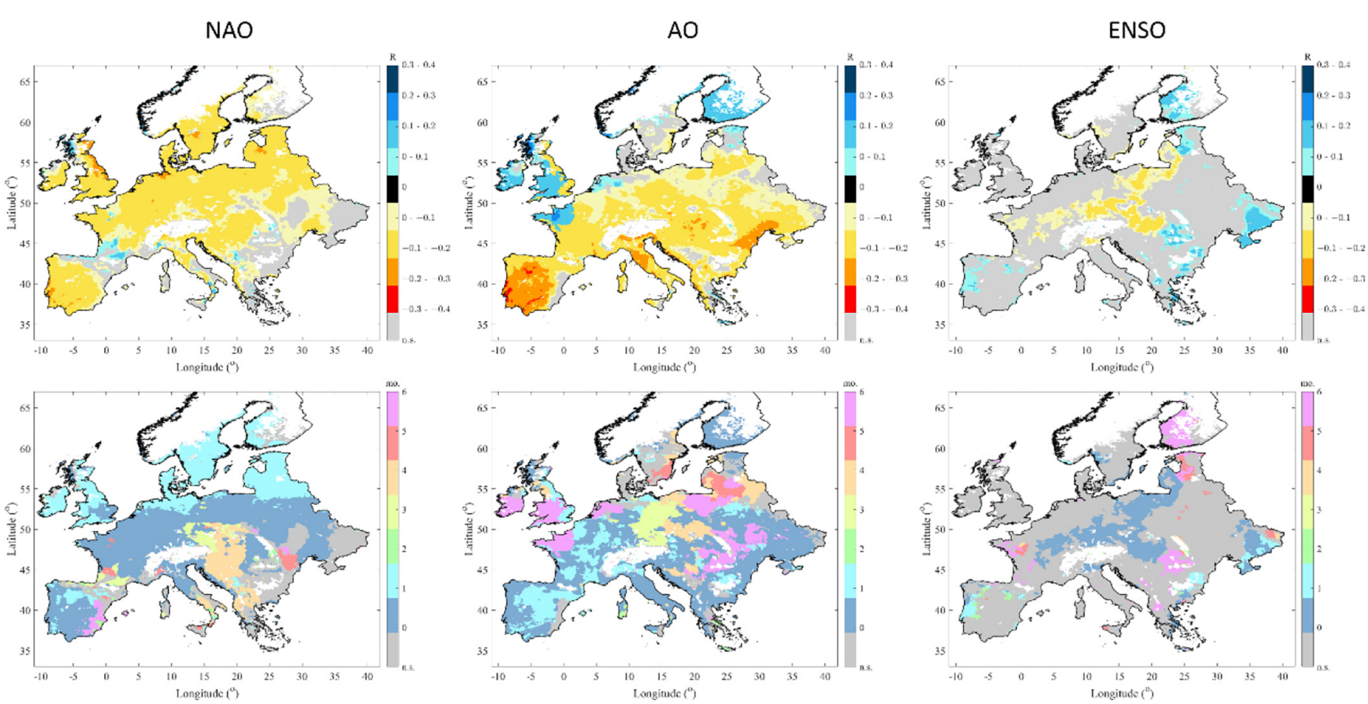

Fig. 3. Results of the lagged correlation analysis between the ERA5L SM and teleconnection indices. The maps above show the maximum R-value and those below the lag in months in which these maxima occur. The area without statistical significance (n.s., $p < 0.05$) is in grey.

However, in summer, NAO exerts a great impact on northern Europe (Bladé et al., 2012) with an increase in temperature (Folland et al., 2009) and reduced precipitation during positive phases (Allan and Zveryaev, 2011), which agrees with the negative correlations we obtained with SM. The negative correlation we obtained in southern Europe is in line with the results of previous studies focused on the meteorological drought response in Mediterranean areas (Kim and Raible, 2021; Mariotti and Dell'Aquila, 2012; Sheffield and Wood, 2008; Vicente-Serrano et al., 2011).

The results obtained with the LF database for AO and NAO were similar (Fig. 4), although fewer significant correlation coefficients were observed. Interestingly, stronger correlation values were obtained with AO mainly in Mediterranean regions, with R values below −0.3. These results are aligned with those obtained by Hassan and Nayak (2020), who related the positive phases of AO with the appearance of droughts in the Mediterranean region.

Regarding the relationship of ENSO with both SM databases, only a few areas showed a significant correlation (Figs. 3–4). These results can be explained by the fact that atmospheric changes in the El Niño region must be strong enough for this impact to be reflected in Europe (Brönnimann, 2007), and during our study period, only two strong El Niño events (1997–1998 and 2015–2016; Fig. 2c) and no strong La Niña event occurred (Hardiman et al., 2019). Similarly, a previous study did not observe a significant relationship between modelled SM and the Southern Oscillation Index (SOI) in Europe for a similar period (Miralles et al., 2014). With ERA5L, indirect significant correlations were obtained in central Europe with R values between −0.1 and −0.2, which implies that, in that region, El Niño events lead to drier soils, while wetter conditions are given during La Niña events. Conversely, Brönnimann (2007) observed positive anomalies of precipitation during strong El Niño events and negative during strong La Niña for this region, but they only observed this during winter months. Direct correlations, meaning positive ENSO causes positive SM anomalies, were obtained in a few areas of eastern Europe, Finland and the Atlantic coast of the Iberian Peninsula. R values were, in general, lower than those obtained with AO and NAO; however, stronger correlations were obtained north of the Great Hungarian Plain, with R values below −0.2. The results obtained with the LF database matched in sign with those obtained with ERA5L, but the regions showing a significant correlation were reduced.

The R-values obtained with the three indices are relatively small in absolute value; however, it should be borne in mind that the influence of atmospheric anomalies in soil hydrology is being analysed and that there are many processes between the two systems that can dampen the strength of this relationship (Seneviratne et al., 2010). In addition, although several efforts have been made by many researchers to study teleconnections between atmospheric circulation and European climate (Brönnimann, 2007; Fraedrich and Müller, 1992), the results obtained in this study can be directly compared with only very few other results that targeted SM, either at regional or global scales (Le and Bae, 2022; Miralles et al., 2014; Sheffield and Wood, 2008). Although related variables in most cases present similar results, SM does not always behave as other water-related atmospheric variables, such as precipitation (Dai, 2011).

Some patterns could be observed when analysing the lag of maximum correlation obtained for the indices and SM anomalies (Figs. 3–4). With the NAO, few regions presented a lagged response of SM at a monthly scale for both databases. Nevertheless, more regions showed a delay in the SM anomalies with respect to teleconnection indices with ERA5L and not with LF. With ERA5L, a general one-month lag in Northern Europe was observed. A lag time of 4 months in southern Italy, the Great Hungarian Plain and the Balkans was found, while a later response (5–6 months lag) was observed in the east of the Iberian Peninsula and near the Danube mouth. For the AO, a prevalence of nonlagged effects also existed; however, the spatial distribution was less homogeneous with ERA5L. A one-month lag was mainly observed in western Europe, and a lag response of 3–4 months was observed in central Europe. In addition, it could be observed, with both products, that most regions with direct correlation presented a 6-month lag. Regarding ENSO, the lagged effects were seen mainly in regions with a direct relationship.

3.2. Causal discovery

A causality analysis was performed to investigate the existence of causal relationships between the NAO, AO and ENSO with SM anomalies. The PCMCI method was applied with a partial correlation conditional test and a maximum lag of 6 months. The results of causal link (climate index → SM)

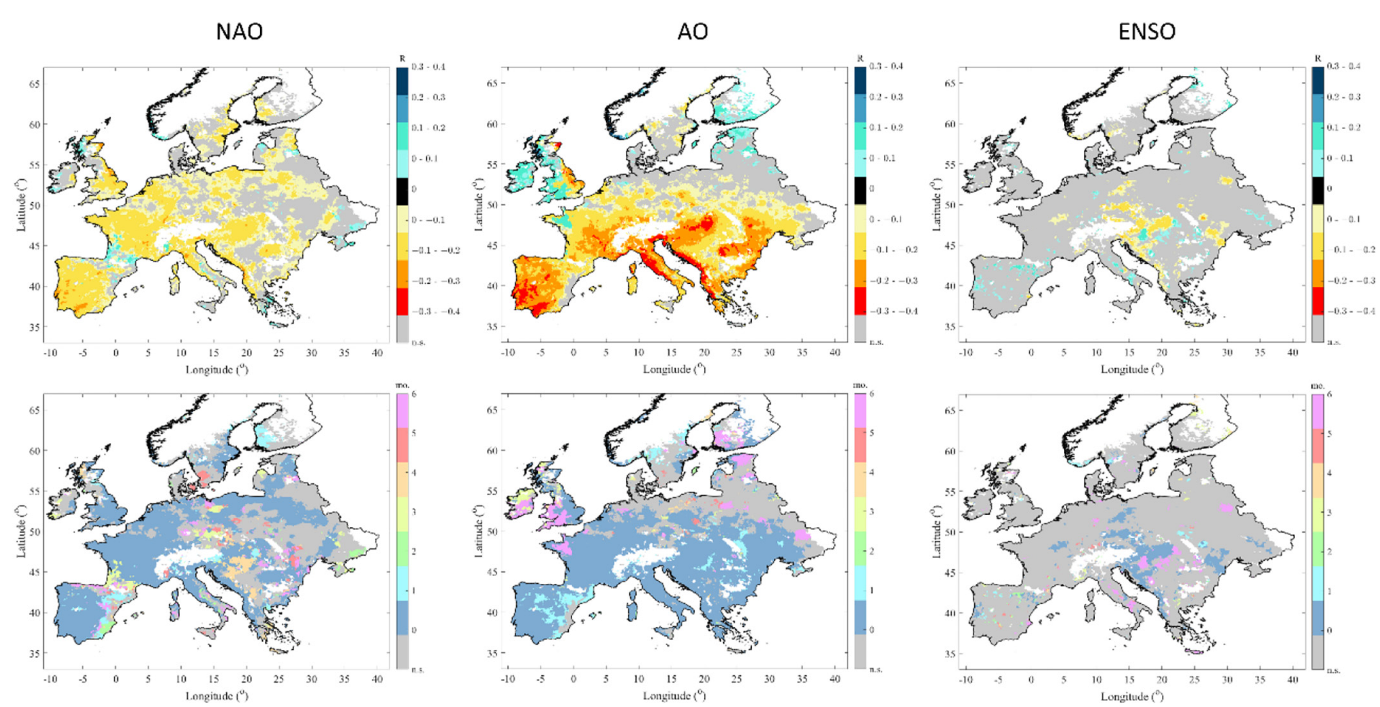

Fig. 4. Results of the lagged correlation analysis between the LF SM and teleconnection indices. The maps above show the maximum R-value and those below the lag in months in which these maxima occur. The area without statistical significance (n.s., $p < 0.05$) is in grey.

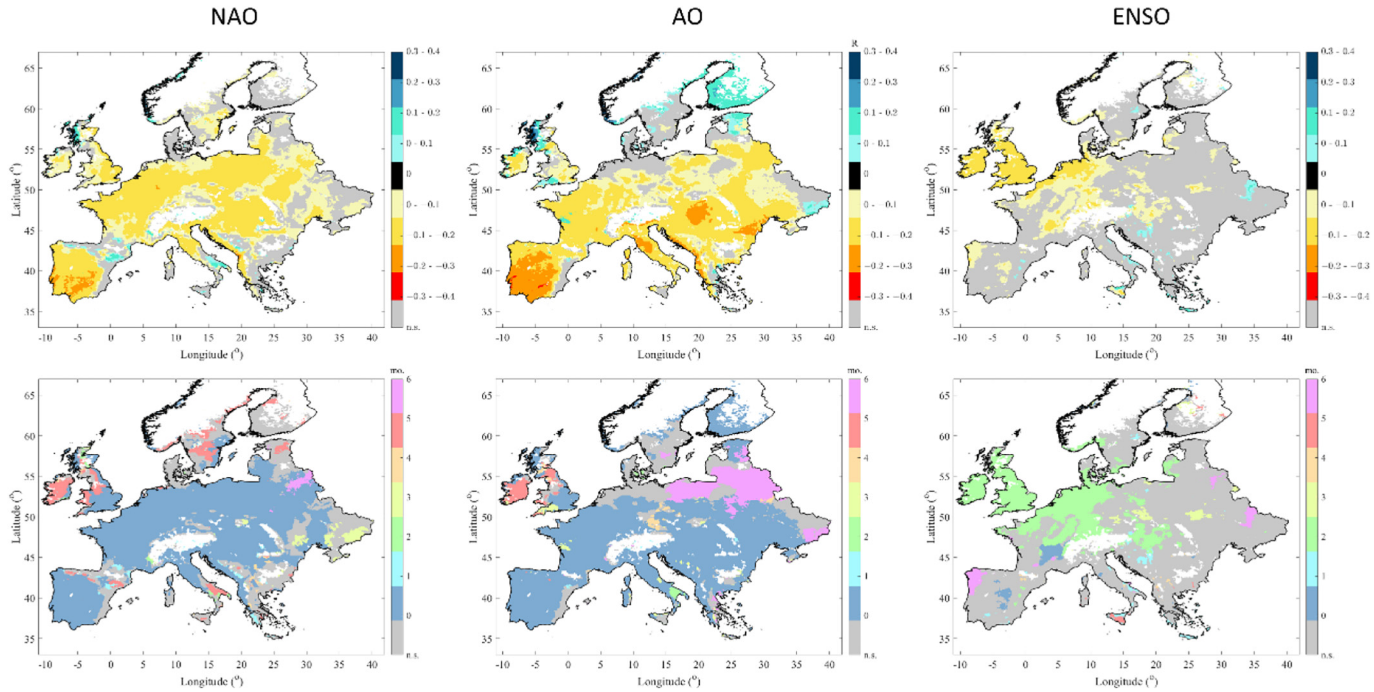

Fig. 5. Results of the causality analysis between the ERA5L SM and teleconnection indices. The maps above show the highest causal strength (teleconnection index → SM) and those below the lag of those relations. The area without statistical significance (n.s., $p < 0.05$) is in grey.

strength are shown in Figs. 5 and 6 for ERA5L and LF, respectively. Both the AO and NAO results were quite similar to those obtained in the lagged correlation with both products, with similar strength magnitudes and signs, which indicates that the two indices are not only correlated to SM anomalies but are actually causing them. Thus, our obtained results reveal that negative phases of NAO and AO cause a general annual decrease in SM, beyond the broad presumption that winter (summer) positive NAO favours an increase (decrease) in precipitation and subsequently SM over central and northern Europe. According to this, the impact of climate change on atmospheric circulation patterns may ultimately induce changes in SM interannual variability. In this regard, an upwards trend in the AO has been reported since the 1960s

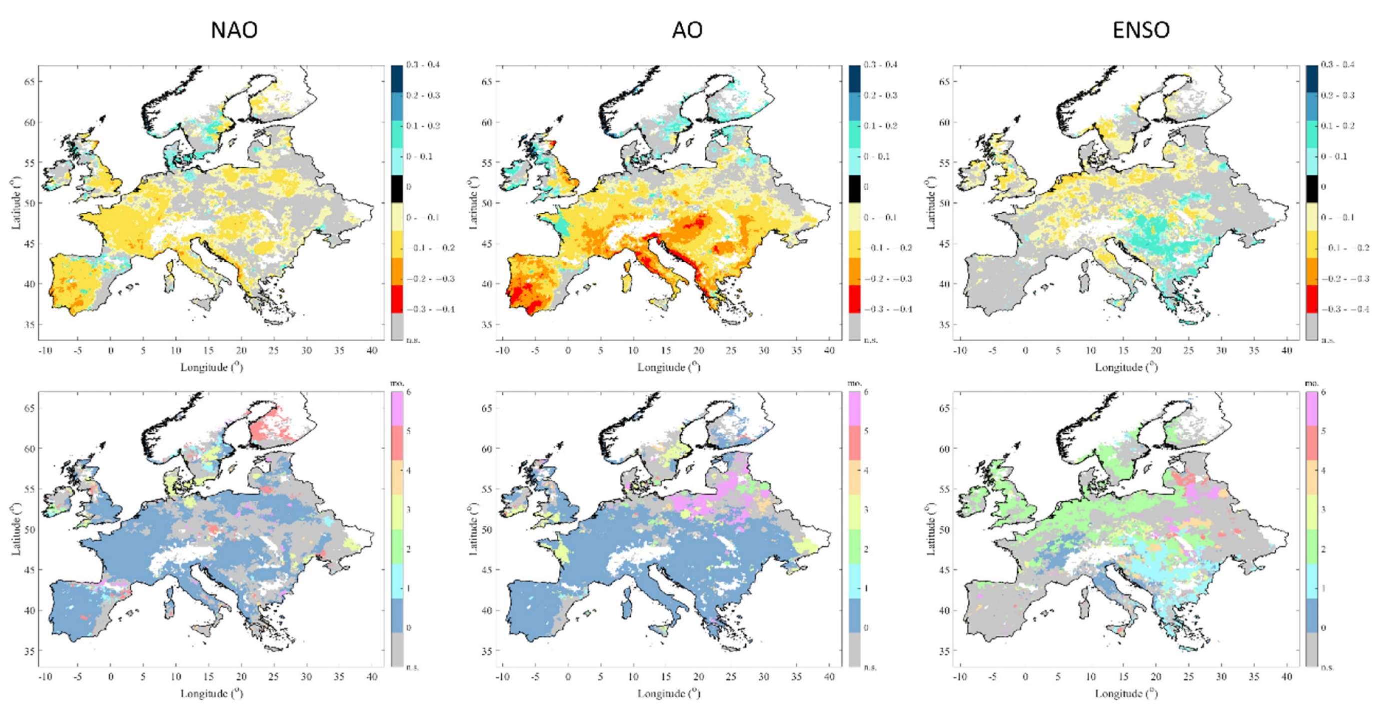

Fig. 6. Results of the causality analysis between the LF SM and teleconnection indices. The maps above show the highest causal strength (teleconnection index → SM) and those below the lag of those relations. The area without statistical significance (n.s., $p < 0.05$) is in grey.

(Delworth and Dixon, 2000) as well as a trend towards more positive NAO winters in the 1990s (Hurrell et al., 2003). Additionally, Hanna et al. (2015) reported a significant downwards trend in the summer NAO and an increase in variability in winter.

Causality and correlation do not necessarily have to coexist (Runge et al., 2019b), and this is precisely what we observed with ENSO and SM anomalies. Larger areas showed a significant causal relationship than in the lagged correlation analysis, especially with LF (see Figs. 5 and 6). Silva et al. (2021) also identified more response areas to ENSO with a causal method than with the correlation analysis. Negative causal relations appeared in the British Isles and the Atlantic coast, implying that an increase (decrease) in SST in the El Niño 3.4 region causes drier (wetter) soil conditions in these regions. This agrees with results found by Brönnimann (2007) during strong El Niño and La Niña events; he reported anomalies of low precipitation in those areas starting in Ireland during late autumn and extending to the continent in late winter, when they are combined with high temperature anomalies during El Niño and opposite conditions during La Niña. Positive causal relations were obtained (only with LF) in the Balkan region and the Great Hungarian Plain, which is also in agreement with that observed by Brönnimann (2007).

Regarding the lag of maximum causal strength, a similar pattern to that obtained with the lagged correlation analysis was observed. There is a predominance of nonlagged effects with the NAO and AO. Very few regions present a lagged response, especially with LF. For the NAO, lags were mainly observed when the relationships were positive, while for the AO, 6-month lagged causal relationships were located in the Baltic areas. With ENSO, a clear pattern was observed, consistent with both SM products: negative causal relationships showed a lag of 2 months, while positive ones showed a lag of 1 month. Longer lagged responses were obtained with this phenomenon than with AO and NAO, as could be expected, since different mechanisms occur between the equator of the Pacific Ocean and North Atlantic regions before seeing the impact in Europe (Brönnimann, 2007). Bulić and Kucharski (2012) observed a lagged spring precipitation response to winter ENSO in Europe but also a contemporaneous response in spring, which agrees with the 1–2 month lag found here.

Causal discovery can help to better understand the processes interacting in the soil–atmosphere continuum. This methodology has shown that the correlations obtained with NAO and AO are indeed causal relationships and have allowed for a more in-depth analysis of the SM response to ENSO, which is probably nonlinear and hence was not fully captured by the correlation analysis. Nevertheless, the strength of the links obtained in this analysis refers to the evaluation of only two variables (teleconnection index and SM). These causal relationships could be analysed more precisely if more variables were incorporated, without increasing the dimensions of the analysis too much for the detection power to be affected (Runge et al., 2019b). However, performing this type of multivariable analysis would require a spatial aggregation of the information, and the spatial patterns would depend on the selected area and the method (Bueso et al., 2020a).

4. Conclusions

In this study, the influences that the NAO, AO and ENSO exert on European SM have been analysed. Monthly SM series were obtained from two different databases, one from the LF model and the other from reanalysis ERA5L. The results showed that both AO and NAO have a significant influence on European SM over almost the entire continent. The relationship was predominantly negative and maximum with no lag, which implies drier soil conditions in the positive phases and wetter conditions in the negative phases. The strongest correlations were obtained with AO in the Mediterranean regions. Whereas a direct relationship was expected with the NAO in Northern Europe, as NAO is traditionally assumed to increase precipitation and colder conditions in the north, this region only showed a direct relationship with AO with a lag of 6 months, while NAO showed a uniformly indirect response over almost the entire continent. With ENSO, hardly any correlation was observed, probably because ENSO influences the European climate indirectly and nonlinearly. Although the spatial patterns observed for SM were, in general, in line with those obtained in other works for water-related atmospheric variables, some differences have been observed, which highlights the need for focusing studies specifically on the SM response to atmospheric circulation patterns.

The analysis of causality between the teleconnection indices and SM was the second objective of this study. This type of analysis has been applied in only a few studies of Earth science. In this work, a novel method has been used, the PCMCI, which allows the incorporation of conditional independence tests such as partial correlation. In the causality study carried out, for AO and NAO, the results obtained have been very similar in strength, sign and lag to those obtained in the correlation study. This result showed the causal effect that both atmospheric patterns have on the SM dynamics, i.e., negative phases of NAO and AO will cause a decrease in SM. Stronger causal relations were obtained with AO in Mediterranean regions, which is important to consider due to the increasing risk of drought occurrence in this region. For ENSO, the causality analysis allowed finding SM response areas that were undetected by the correlation analysis. Direct links were observed in central and northwestern Europe with a delayed effect of two months, and indirect links were observed in the Balkan region with a delayed effect of 1 month.

Regarding both SM databases, the results obtained were very similar. However, slightly stronger correlations and causal relationships were observed with the LF database. Conversely, more surface area with significant correlations and more spatial patterns of delayed response of SM were observed with the ERA5L data.

From the results of the present study, causal discovery methods are powerful methods to help better understand soil–atmosphere interactions. However, the way of applying this methodology in this work shows some limitations, and the results should be taken with caution. In particular, only linear relationships and just two variables were considered here, the teleconnection index and SM, while incorporating more variables and apply no linear methods would probably enable a more precise evaluation of the causal relationships. Additionally, we are treating time series separately, while spatiotemporal methods could also be considered. However, with a spatiotemporal approach, the spatial patterns would depend on the spatially aggregated area or the method used to analyse all information together.

This work highlights the importance of studies focused on SM dynamics and interactions, since most studies are centred on precipitation, but the atmosphere does not always impact all water-related variables in the same way, and SM is key to understanding its impact on issues such as agricultural drought, runoff yield, groundwater recharge and many other water-related processes. Undoubtedly, there is still work to be done to properly define the causal relationships between soil–atmosphere systems, but advances in this field are paramount to better understand the impact of climate change on SM dynamics and consequently on agricultural drought.

CRediT authorship contribution statement

Laura Almendra-Martín: Conceptualization, Formal analysis, Writing – review & editing. **José Martínez-Fernández:** Conceptualization, Supervision, Writing – review & editing. **María Piles:** Conceptualization, Supervision, Writing – review & editing. **Ángel González-Zamora:** Formal analysis, Writing – review & editing. **Pilar Benito-Verdugo:** Writing – review & editing. **Jaime Gaona:** Writing – review & editing.

Data availability

Data are available online

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by MCIN/AEI/10.13039/501100011033/ (projects ESP2017-89463-C3-3-R, RTI2018-096765-A-I00 and PID2020-114623RB-C33), the Castilla y León Government (projects SA112P20 and CLU-2018-04) and the European Regional Development Fund (ERDF). The research of Laura Almendra-Martín was funded by a pre-doctoral grant (Castilla y León Government and ERDF).

References

Allan, R.P., Zveryaev, I.I., 2011. Variability in the summer season hydrological cycle over the Atlantic-Europe region 1979–2007. Int. J. Climatol. 31, 337–348. https://doi.org/10.1002/joc.2070.

Almendra-Martín, L., Martínez-Fernández, J., González-Zamora, Á., Benito-Verdugo, P., Herrero-Jiménez, C.M., 2021. Agricultural drought trends on the Iberian Peninsula: an analysis using modeled and reanalysis soil moisture products. Atmosphere (Basel) 12. https://doi.org/10.3390/atmos12020236.

Anderson, W., Seager, R., Baethgen, W., Cane, M., 2017. Life cycles of agriculturally relevant ENSO teleconnections in north and South America. Int. J. Climatol. 37, 3297–3318. https://doi.org/10.1002/joc.4916.

Arnell, N.W., 1999. The effect of climate change on hydrological regimes in Europe: a continental perspective. Glob. Environ. Change 9 (1), 5–23. https://doi.org/10.1016/S0959-3780(98)00015-6.

Bastos, A., Janssens, I.A., Gouveia, C.M., Trigo, R.M., Ciais, P., Chevallier, F., Peñuelas, J., Rödenbeck, C., Piao, S., Friedlingstein, P., Running, S.W., 2016. European land CO2 sink influenced by NAO and East-Atlantic pattern coupling. Nat. Commun. 7. https://doi.org/10.1038/ncomms10315.

Beck, H.E., Pan, M., Miralles, D.G., Reichle, R.H., Dorigo, W.A., Hahn, S., Sheffield, J., Karthikeyan, L., Balsamo, G., Parinussa, R.M., van Dijk, A.I.J.M., Du, J., Kimball, J.S., Vergopolan, N., Wood, E.F., 2020. Evaluation of 18 satellite- and model-based soil moisture products using in situ measurements from 826 sensors. Hydrol. Earth Syst. Sci. Discuss. 1–35. https://doi.org/10.5194/hess-2020-184.

Benesty, J., Chen, J., Huang, Y., Cohen, I., 2009. Pearson Correlation Coefficient, pp. 1–4 https://doi.org/10.1007/978-3-642-00296-0_5.

Bladé, I., Liebmann, B., Fortuny, D., van Oldenborgh, G.J., 2012. Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the Mediterranean region. Clim. Dyn. 39, 709–727. https://doi.org/10.1007/s00382-011-1195-x.

Boé, J., 2013. Modulation of soil moisture-precipitation interactions over France by large scale circulation. Clim. Dyn. 40, 875–892. https://doi.org/10.1007/s00382-012-1380-6.

Brönnimann, S., 2007. Impact of El Niño-southern oscillation on European climate. Rev. Geophys. 45. https://doi.org/10.1029/2006RG000199.

Bueso, D., Piles, M., Camps-Valls, G., 2020a. Nonlinear PCA for spatio-temporal analysis of earth observation data. IEEE Trans. Geosci. Remote Sens. 58, 5752–5763. https://doi.org/10.1109/TGRS.2020.2969813.

Bueso, D., Piles, M., Camps-Valls, G., 2020b. Explicit granger causality in kernel hilbert spaces. Phys. Rev. E 102, 062201. https://doi.org/10.1103/PhysRevE.102.062201.

Bulić, I.H., Kucharski, F., 2012. Delayed ENSO impact on spring precipitation over North/Atlantic European region. Clim. Dyn. 38, 2593–2612. https://doi.org/10.1007/s00382-011-1151-9.

Casanueva, A., Rodríguez-Puebla, C., Frías, M.D., González-Reviriego, N., 2014. Variability of extreme precipitation over Europe and its relationships with teleconnection patterns. Hydrol. Earth Syst. Sci. 18, 709–725. https://doi.org/10.5194/hess-18-709-2014.

Christensen, J.H., Krishna Kumar, K., Aldrian, E., An, S.-I., Cavalcanti, I.F.A., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, J., Lau, N.-C., Renwick, J., Stephenson, D.B., Xie, S.-P., Zhou, T., 2013. Climate Phenomena and their Relevance for Future Regional Climate Change, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Comas-Bru, L., McDermott, F., 2014. Impacts of the EA and SCA patterns on the European twentieth century NAO-winter climate relationship. Q. J. R. Meteorol. Soc. 140, 354–363. https://doi.org/10.1002/qj.2158.

D'Odorico, P., Yoo, J.C., Jaeger, S., 2002. Changing seasons: an effect of the North Atlantic Oscillation? J. Clim. 15, 435–445. https://doi.org/10.1175/1520-0442(2002)015<0435:CSAEOT>2.0.CO;2.

Dai, A., 2011. Drought under global warming: a review. Wiley Interdiscip. Rev. Clim. Chang. 2, 45–65. https://doi.org/10.1002/wcc.81.

Daly, E., Porporato, A., 2005. A review of soil moisture dynamics: from rainfall infiltration to ecosystem response. Environ. Eng. Sci. 22, 9–24. https://doi.org/10.1089/ees.2005.22.9.

Dankers, R., Feyen, L., 2008. Climate change impact on flood hazard in Europe: an assessment based on high-resolution climate simulations. J. Geophys. Res. Atmos. 113, 1–17. https://doi.org/10.1029/2007JD009719.

Daoyi, G., Shaowu, W., 2003. Influence of Arctic oscillation on winter climate over China. J. Geogr. Sci. 13, 208–216. https://doi.org/10.1007/BF02837460.

De Luca, P., Messori, G., Wilby, R.L., Mazzoleni, M., Di Baldassarre, G., 2020. Concurrent wet and dry hydrological extremes at the global scale. Earth Syst. Dyn. 11, 251–266. https://doi.org/10.5194/esd-11-251-2020.

De Roo, A.P.J., Wesseling, C.G., Van Deursen, W.P.A., 2000. Physically based river basin modelling within a GIS: the LISFLOOD model. Hydrol. Process. 14, 1981–1992. https://doi.org/10.1002/1099-1085(20000815/30)14:11/12<1981::aid-hyp49>3.0.co;2-f.

deCastro, M., Lorenzo, N., Taboada, J.J., Sarmiento, M., Alvarez, I., Gomez-Gesteira, M., 2006. Influence of teleconnection patterns on precipitation variability and on river flow regimes in the Miño River basin (NW Iberian Peninsula). Handb. Environ. Chem. Water Pollut. 5 (32), 63–73. https://doi.org/10.3354/cr032063.

Delworth, T.L., Dixon, K.W., 2000. Implications of the recent trend in the Arctic/North Atlantic oscillation for the North Atlantic thermohaline circulation. J. Clim. 13, 3721–3727. https://doi.org/10.1175/1520-0442(2000)013<3721:IOTRTI>2.0.CO;2.

Dorigo, W., De Jeu, R., Chung, D., Parinussa, R., Liu, Y., Wagner, W., Fernández-Prieto, D., 2012. Evaluating global trends (1988–2010) in harmonized multi-satellite surface soil moisture. Geophys. Res. Lett. 39, 3–9. https://doi.org/10.1029/2012GL052988.

Entekhabi, D., Rodriguez-Iturbe, I., Castelli, F., 1996. Mutual interaction of soil moisture state and atmospheric processes. J. Hydrol. 184, 3–17. https://doi.org/10.1016/0022-1694(95)02965-6.

Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S., Hurrel, J.W., 2009. The summer North Atlantic oscillation: past, present, and future. J. Clim. 22, 1082–1103. https://doi.org/10.1175/2008JCLI2459.1.

Fraedrich, K., Müller, K., 1992. Climate anomalies in Europe associated with ENSO extremes. Int. J. Climatol. 12, 25–31. https://doi.org/10.1002/joc.3370120104.

González-Zamora, Á., Almendra-Martín, L., de Luis, M., Martínez-Fernández, J., 2021. Influence of soil moisture vs. climatic factors in Pinus halepensis growth variability in Spain: a study with remote sensing and modeled data. Remote Sens. 13, 1–20. https://doi.org/10.3390/rs13040757.

Gordo, O., Sanz, J.J., 2010. Impact of climate change on plant phenology in Mediterranean ecosystems. Glob. Chang. Biol. 16, 1082–1106. https://doi.org/10.1111/j.1365-2486.2009.02084.x.

Granger, C.W.J., 1969. Investigating causal relations by econometric models and cross-spectral methods. Econom. J. Econom. Soc. 37, 424–438.

Grillakis, M.G., 2019. Increase in severe and extreme soil moisture droughts for Europe under climate change. Sci. Total Environ. 660, 1245–1255. https://doi.org/10.1016/j.scitotenv.2019.01.001.

Gupta, V., Jain, M.K., 2021. Unravelling the teleconnections between ENSO and dry/wet conditions over India using nonlinear Granger causality. Atmos. Res. 247, 105168. https://doi.org/10.1016/j.atmosres.2020.105168.

Hanna, E., Cropper, T.E., Jones, P.D., Scaife, A.A., Allan, R., 2015. Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland blocking index. Int. J. Climatol. 35, 2540–2554. https://doi.org/10.1002/joc.4157.

Hardiman, S.C., Dunstone, N.J., Scaife, A.A., Smith, D.M., Ineson, S., Lim, J., Fereday, D., 2019. The impact of strong El Niño and La Niña events on the North Atlantic. Geophys. Res. Lett. 46, 2874–2883. https://doi.org/10.1029/2018GL081776.

Hassan, W.U., Nayak, M.A., 2020. Global teleconnections in droughts caused by oceanic and atmospheric circulation patterns. Environ. Res. Lett. 16. https://doi.org/10.1088/1748-9326/abc9e2.

Horton, D.E., Johnson, N.C., Singh, D., Swain, D.L., Rajaratnam, B., Diffenbaugh, N.S., 2015. Contribution of changes in atmospheric circulation patterns to extreme temperature trends. Nature 522, 465–469. https://doi.org/10.1038/nature14550.

Hurrell, J.W., 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. Science 269, 676–679. https://doi.org/10.1126/science.269.5224.676.

Hurrell, J.W., Van Loon, H., 1997. Decadal variations in climate associated with the North Atlantic oscillation. Clim. Chang. High Elev. Sites 69–94. https://doi.org/10.1007/978-94-015-8905-5_4.

Hurrell, J.W., Kushnir, Y., Visbeck, M., 2001. The North Atlantic oscillation. Science 291, 603–605. https://doi.org/10.1126/science.1058761.

Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M., 2003. An overview of the North Atlantic oscillation. Geophys. Monogr. Ser. 134, 1–35. https://doi.org/10.1029/134GM01.

Ionita, M., Boroneanț, C., Chelcea, S., 2015. Seasonal modes of dryness and wetness variability over Europe and their connections with large scale atmospheric circulation and global sea surface temperature. Clim. Dyn. 45, 2803–2829. https://doi.org/10.1007/s00382-015-2508-2.

Ionita, M., Nagavciuc, V., Kumar, R., Rakovec, O., 2020. On the curious case of the recent decade, mid-spring precipitation deficit in Central Europe. Npj Clim. Atmos. Sci. 3, 1–10. https://doi.org/10.1038/s41612-020-00153-8.

Kim, W.M., Raible, C.C., 2021. Dynamics of the Mediterranean droughts from 850 to 2099 CE in the community earth system model. Clim. Past 17, 887–911. https://doi.org/10.5194/cp-17-887-2021.

Kodra, E., Chatterjee, S., Ganguly, A.R., 2011. Exploring granger causality between global average observed time series of carbon dioxide and temperature. Theor. Appl. Climatol. 104, 325–335. https://doi.org/10.1007/s00704-010-0342-3.

Kostopoulou, E., Jones, P.D., 2007. Comprehensive analysis of the climate variability in the eastern Mediterranean. Part II: relationships between atmospheric circulation patterns and surface climatic elements. Int. J. Climatol. 27, 1351–1371. https://doi.org/10.1002/joc.1466.

Kretschmer, M., Cohen, J., Matthias, V., Runge, J., Coumou, D., 2018. The different stratospheric influence on cold-extremes in Eurasia and North America. Npj Clim. Atmos. Sci. 1, 1–10. https://doi.org/10.1038/s41612-018-0054-4.

Kurnik, B., Kajfež-Bogataj, L., Horion, S., 2015. An assessment of actual evapotranspiration and soil water deficit in agricultural regions in Europe. Int. J. Climatol. 35, 2451–2471. https://doi.org/10.1002/joc.4154.

Kyselý, J., 2007. Implications of enhanced persistence of atmospheric circulation for the occurrence and severity of temperature extremes. Int. J. Climatol. 27, 689–695. https://doi.org/10.1002/joc.1478.

L'Heureux, M.L., Tippett, M.K., Takahashi, K., Barnston, A.G., Becker, E.J., Bell, G.D., Di Liberto, T.E., Gottschalck, J., Halpert, M.S., Hu, Z.Z., Johnson, N.C., Xue, Y., Wang, W., 2019. Strength outlooks for the El Niño-southern oscillation. Weather Forecast. 34, 165–175. https://doi.org/10.1175/WAF-D-18-0126.1.

Laguardia, G., Niemeyer, S., 2008. On the comparison between the LISFLOOD modelled and the ERS/SCAT derived soil moisture estimates. Hydrol. Earth Syst. Sci. 12, 1339–1351. https://doi.org/10.5194/hess-12-1339-2008.

Lau, K.M., Yang, S., 2003. Walker circulation. Encyclopedia of Atmospheric Sciences, pp. 2505–2510.
Le, T., Bae, D., 2022. Causal impacts of El Niño-southern oscillation on global soil moisture over the period 2015–2100. Earths Futur. 10. https://doi.org/10.1029/2021EF002522.
L'Heureux, M., 2014. What is the El Niño–Southern Oscillation (ENSO) in a nutshell? ENSO Blog. https://www.climate.gov/news-features/blogs/enso/what-el-ni%C3%B1o%E2%80%93southern-oscillation-enso-nutshell (accessed 4 February 2022).
Li, M., Wu, P., Ma, Z., 2020. A comprehensive evaluation of soil moisture and soil temperature from third-generation atmospheric and land reanalysis data sets. Int. J. Climatol. 40, 5744–5766. https://doi.org/10.1002/joc.6549.
Li, P., Zha, Y., Shi, L., Zhong, H., Tso, C.H.M., Wu, M., 2022. Assessing the global relationships between teleconnection factors and terrestrial water storage components. Water Resour. Manag. 36, 119–133. https://doi.org/10.1007/s11269-021-03015-x.
Lindsey, 2009. Climate Variability: Arctic Oscillation. https://www.climate.gov/news-features/understanding-climate/climate-variability-arctic-oscillation (accessed 4 February 2022).
Mares, I., Mares, C., Mihailescu, M., 2002. NAO impact on the summer moisture variability across Europe. Phys. Chem. Earth 27, 1013–1017. https://doi.org/10.1016/S1474-7065(02)00135-3.
Mariotti, A., Dell'Aquila, A., 2012. Decadal climate variability in the Mediterranean region: roles of large-scale forcings and regional processes. Clim. Dyn. 38, 1129–1145. https://doi.org/10.1007/s00382-011-1056-7.
Martínez-Fernández, J., González-Zamora, A., Almendra-Martín, L., 2021. Soil moisture memory and soil properties: an analysis with the stored precipitation fraction. J. Hydrol. 593. https://doi.org/10.1016/j.jhydrol.2020.125622.
McPhaden, M.J., Zebiak, S.E., Glantz, M.H., 2006. ENSO as an integrating concept in earth science. Science (80-.) 314, 1740–1745. https://doi.org/10.1126/science.1132588.
Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H., Schädler, B., Schulla, J., Wilke, K., 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. Clim. Chang. 49, 105–128. https://doi.org/10.1023/A:1010784727448.
Miralles, D.G., Van Den Berg, M.J., Gash, J.H., Parinussa, R.M., De Jeu, R.A.M., Beck, H.E., Holmes, T.R.H., Jiménez, C., Verhoest, N.E.C., Dorigo, W.A., Teuling, A.J., Johannes Dolman, A., 2014. El Niño-La Niña cycle and recent trends in continental evaporation. Nat. Clim. Chang. 4, 122–126. https://doi.org/10.1038/nclimate2068.
Moberg, A., Jones, P.D., 2005. Trends in indices for extremes in daily temperature and precipitation in central and western Europe, 1901–99. Int. J. Climatol. 25, 1149–1171. https://doi.org/10.1002/joc.1163.
Morata-Dolz, M., Bueso, D., Piles, M., Camps-Valls, G., 2020. Understanding Climate Impacts on Vegetation with Gaussian Processes in Granger Causality.
Mühlbauer, S., Costa, A.C., Caetano, M., 2016. A spatiotemporal analysis of droughts and the influence of North Atlantic oscillation in the Iberian Peninsula based on MODIS imagery. Theor. Appl. Climatol. 124, 703–721. https://doi.org/10.1007/s00704-015-1451-9.
Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D., Piles, M., Rodríguez-Fernández, N., Zsoter, E., Buontempo, C., Thépaut, J.-N., 2021. ERA5-land: a state-of-the-art global reanalysis dataset for land applications. Earth Syst. Sci. Data Discuss. 1–50. https://doi.org/10.5194/essd-2021-82.
Nowack, P., Runge, J., Eyring, V., Haigh, J.D., 2020. Causal networks for climate model evaluation and constrained projections. Nat. Commun. 11 (1), 1–11. https://doi.org/10.1038/s41467-020-15195-y.
Peng, J., Wu, C., Zhang, X., Wang, X., Gonsamo, A., 2019. Satellite detection of cumulative and lagged effects of drought on autumn leaf senescence over the northern hemisphere. Glob. Chang. Biol. 25, 2174–2188. https://doi.org/10.1111/gcb.14627.
Piles, M., Ballabrera-Poy, J., Muñoz-Sabater, J., 2019. Dominant features of global surface soil moisture variability observed by the SMOS satellite. Remote Sens. 11, 1–21. https://doi.org/10.3390/rs11010095.
Preimesberger, W., Scanlon, T., Su, C.H., Gruber, A., Dorigo, W., 2021. Homogenization of structural breaks in the global ESA CCI soil moisture multisatellite climate data record. IEEE Trans. Geosci. Remote Sens. 59, 2845–2862. https://doi.org/10.1109/TGRS.2020.3012896.
Ropelewski, C.F., Jones, P.D., 1987. An extension of the Tahiti-Darwin southern oscillation index. Mon. Weather Rev. 115 (9), 2161–2165.
Runge, J., Bathiany, S., Bollt, E., Camps-Valls, G., Coumou, D., Deyle, E., Glymour, C., Kretschmer, M., Mahecha, M.D., Muñoz-Marí, J., van Nes, E.H., Peters, J., Quax, R., Reichstein, M., Scheffer, M., Schölkopf, B., Spirtes, P., Sugihara, G., Sun, J., Zhang, K., Zscheischler, J., 2019a. Inferring causation from time series in earth system sciences. Nat. Commun. 10, 1–13. https://doi.org/10.1038/s41467-019-10105-3.
Runge, J., Nowack, P., Kretschmer, M., Flaxman, S., Sejdinovic, D., 2019b. Detecting and quantifying causal associations in large nonlinear time series datasets. Sci. Adv. 5. https://doi.org/10.1126/sciadv.aau4996.
Salvia, M., Sanchez, N., Piles, M., Ruscica, R., Gonzalez-Zamora, A., Roitberg, E., Martinez-Fernandez, J., 2021. The added-value of remotely-sensed soil moisture data for agricultural drought detection in Argentina. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 14, 6487–6500. https://doi.org/10.1109/JSTARS.2021.3084849.
Sánchez, N., González-Zamora, Á., Martínez-Fernández, J., Piles, M., Pablos, M., 2018. Integrated remote sensing approach to global agricultural drought monitoring. Agric. For. Meteorol. 259, 141–153. https://doi.org/10.1016/j.agrformet.2018.04.022.
Santanello Jr., J.A., Peters-Lidard, C.D., Kumar, S.V., 2011. Diagnosing the sensitivity of local land–atmosphere coupling via the soil moisture–boundary layer interaction. J. Hydrometeorol. 12 (5), 766–786.
Scaife, A.A., Folland, C.K., Alexander, L.V., Moberg, A., Knight, J.R., 2008. European climate extremes and the North Atlantic oscillation. J. Clim. 21, 72–83. https://doi.org/10.1175/2007JCLI1631.1.
Schubert, S.D., Stewart, R.E., Wang, H., Barlow, M., Berbery, E.H., Cai, W., Hoerling, M.P., Kanikicharla, K.K., Koster, R.D., Lyon, B., Mariotti, A., Mechoso, C.R., Müller, O.V., Rodriguez-Fonseca, B., Seager, R., Senevirante, S.I., Zhang, L., Zhou, T., 2016. Global meteorological drought: a synthesis of current understanding with a focus on sst drivers of precipitation deficits. J. Clim. 29, 3989–4019. https://doi.org/10.1175/JCLI-D-15-0452.1.
Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture–climate interactions in a changing climate: a review. Earth Sci. Rev. 99, 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004.
Sheffield, J., Wood, E.F., 2008. Global trends and variability in soil moisture and drought characteristics, 1950–2000, from observation-driven simulations of the terrestrial hydrologic cycle. J. Clim. 21, 432–458. https://doi.org/10.1175/2007JCLI1822.1.
Silva, F.N., Vega-Oliveros, D.A., Yan, X., Flammini, A., Menczer, F., Radicchi, F., Kravitz, B., Fortunato, S., 2021. Detecting climate teleconnections with Granger causality. Geophys. Res. Lett. 48, 1–10. https://doi.org/10.1029/2021GL094707.
Simpkins, G., 2021. Breaking down the NAO–AO connection. Nat. Rev. Earth Environ. 2, 88. https://doi.org/10.1038/s43017-021-00139-x.
Spirtes, P., Glymour, C., 1991. An algorithm for fast recovery of sparse causal graphs. Soc. Sci. Comput. Rev. 9, 62–72. https://doi.org/10.1177/089443939100900106.
Su, L., Miao, C., Kong, D., Duan, Q., Lei, X., Hou, Q., Li, H., 2018. Long-term trends in global river flow and the causal relationships between river flow and ocean signals. J. Hydrol. 563, 818–833. https://doi.org/10.1016/j.jhydrol.2018.06.058.
Tabari, H., Willems, P., 2018. Lagged influence of Atlantic and Pacific climate patterns on European extreme precipitation. Sci. Rep. 8, 1–10. https://doi.org/10.1038/s41598-018-24069-9.
Thompson, D.W.J., Wallace, J.M., 1998. The Arctic oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett. 25, 1297–1300. https://doi.org/10.1029/98GL00950.
Thorne, P.W., Diamond, H.J., Goodison, B., Harrigan, S., Hausfather, Z., Ingleby, N.B., Jones, P.D., Lawrimore, J.H., Lister, D.H., Merlone, A., Oakley, T., Palecki, M., Peterson, T.C., de Podesta, M., Tassone, C., Venema, V., Willett, K.M., 2018. Towards a global land surface climate fiducial reference measurements network. Int. J. Climatol. 38, 2760–2774. https://doi.org/10.1002/joc.5458.
Toreti, A., Desiato, F., Fioravanti, G., Perconti, W., 2010. Seasonal temperatures over Italy and their relationship with low-frequency atmospheric circulation patterns. Clim. Chang. 99, 211–227. https://doi.org/10.1007/s10584-009-9640-0.
Trenberth, K.E., 1997. The definition of El Niño. Bull. Am. Meteorol. Soc. 78, 2771–2777. https://doi.org/10.1175/1520-0477(1997)078<2771:TDOENO>2.0.CO;2.
Trigo, R.M., Osborn, T.J., Corte-Real, J.M., 2002. The North Atlantic oscillation influence on Europe: climate impacts and associated physical mechanisms. Clim. Res. 20, 9–17. https://doi.org/10.3354/cr020009.
van der Knijff, J.M., Younis, J., de Roo, A.P.J., 2010. LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. Int. J. Geogr. Inf. Sci. 24, 189–212. https://doi.org/10.1080/13658810802549154.
van der Schrier, G., Briffa, K.R., Jones, P.D., Osborn, T.J., 2006. Summer moisture variability across Europe. J. Clim. 19, 2818–2834. https://doi.org/10.1175/JCLI3734.1.
van Oldenborgh, G.J., Burgers, G., Tank, A.K., 2000. On the El Niño teleconnection to spring precipitation in Europe. Int. J. Climatol. 20, 565–574. https://doi.org/10.1002/(SICI)1097-0088(200004)20:5<565::AID-JOC488>3.0.CO;2-5.
Vicente-Serrano, S.M., López-Moreno, J.I., Lorenzo-Lacruz, J., Kenawy, A.El, Azorin-Molina, C., Morán-Tejeda, E., Pasho, E., Zabalza, J., Beguería, S., Angulo-Martínez, M., 2011. The NAO impact on droughts in the Mediterranean region. In: Vicente-Serrano, S.M., Trigo, R.M. (Eds.), Hydrological, Socioeconomic and Ecological Impacts of the North Atlantic Oscillation in the Mediterranean Region, Advances in Global Change Research. Springer, Netherlands, Dordrecht, pp. 23–40 https://doi.org/10.1007/978-94-007-1372-7_3.
Visbeck, M.H., Hurrell, J.W., Polvani, L., Cullen, H.M., 2001. The North Atlantic oscillation: past, present, and future. Proc. Natl. Acad. Sci. U. S. A. 98, 12876–12877. https://doi.org/10.1073/pnas.231391598.
Walker, G.T., Bliss, E.W., 1932. Memoirs of the royal meteorological society. World Weather V 4, 53–84.
Wanders, N., Karssenberg, D., De Roo, A., De Jong, S.M., Bierkens, M.F.P., 2014. The suitability of remotely sensed soil moisture for improving operational flood forecasting. Hydrol. Earth Syst. Sci. 18, 2343–2357. https://doi.org/10.5194/hess-18-2343-2014.
Wang, C., Liu, H., Lee, S.K., 2010. The record-breaking cold temperatures during the winter of 2009/2010 in the northern hemisphere. Atmos. Sci. Lett. 11, 161–168. https://doi.org/10.1002/asl.278.
Wang, G., Dolman, A.J., Alessandri, A., 2011. A summer climate regime over Europe modulated by the North Atlantic oscillation. Hydrol. Earth Syst. Sci. 15, 57–64. https://doi.org/10.5194/hess-15-57-2011.
Wang, Y.H., Magnusdottir, G., Stern, H., Tian, X., Yu, Y., 2012. Decadal variability of the NAO: introducing an augmented NAO index. Geophys. Res. Lett. 39, 1–5. https://doi.org/10.1029/2012GL053413.
Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B., Xoplaki, E., 2001. North Atlantic oscillation – concepts and studies. Surv. Geophys. 22, 321–382. https://doi.org/10.1023/A:1014217317898.
Xie, X., Li, A., Tan, J., Lei, G., Jin, H., Zhang, Z., 2020. Uncertainty analysis of multiple global GPP datasets in characterizing the lagged effect of drought on photosynthesis. Ecol. Indic. 113. https://doi.org/10.1016/j.ecolind.2020.106224.
Zolghadr-Asli, B., Enayati, M., Pourghasemi, H.R., Naghdyzadegan Jahromi, M., Tiefenbacher, J.P., 2021. Application of granger-causality to study the climate change impacts on depletion patterns of inland water bodies. Hydrol. Sci. J. 66, 1767–1776. https://doi.org/10.1080/02626667.2021.1944633.