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A review of large-scale climate indicators (LSCI) and their environmental and health implications in the Mediterranean region

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Abstract

Large-scale climate indicators (LSCI) refer to the intricate connections between the atmosphere, oceans, and continents in specific regions. To comprehend the relationship between these vital indicators and atmospheric and climate variability, it is crucial to explore them in detail. The objective of the present study is to gather and review relevant research on LSCI in the Mediterranean area to gain a better understanding of their impacts on atmospheric variability, climate, air quality, ecosystems, and health in the region. Numerous studies have explored LSCI and their effects in the study area, and our work aims to contribute to the existing literature in this context. Our study concludes that LSCI are linked to spatial atmospheric variability in the Mediterranean region. They influence the spatial and temporal distribution of climate and environmental variability, including temperature, rainfall, extreme events, cyclones and storms, and air pollution. Some studies have demonstrated the effects of LSCI on ecosystems, such as forests and river basins in the region. However, research on their impacts on human health is limited. Additionally, the application of LSCI involves various formulations and explanations of their potential developments, primarily explaining atmospheric complex systems and the effort required to comprehend their implications for the environment and health. This review highlights

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Climate Prediction Center of NOAA: https://www.cpc.ncep.noaa.gov/

The Climatic Research Unit (CRU) of the University of East Anglia: http://www.cru.uea.ac.uk/cru/data

Declarations

Ethics approval This is a literature review and did not require ethics approval.

Consent to participate This is a literature review and did not require a consent to participate.

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recent progress made in defining, formulating, and calculating LSCI in the Mediterranean area. The most critical functions and characteristics of LSCI are also discussed. Understanding LSCI and their applications is the first step towards developing a health warning system, starting with monitoring atmospheric dynamics and culminating in managing human health responses.

Keywords

Large-scale climate indicators (LSCI); Atmosphere; Climate; Air quality; Ecosystem; Health; Mediterranean

Introduction

The Mediterranean Sea, located at the boundary between Europe and North Africa, has drawn considerable attention from scientists, due to its strategic position and rich marine biodiversity. The sea is of great significance to millions of people who depend on its ecosystem services, particularly its fishing resources (e.g. Katsanevakis et al. 2014). The surrounding regions with a Mediterranean climate make up the Mediterranean basin. This complex and dynamic area is influenced by local air-sea interactions and the inflow of Atlantic water, resulting in the Mediterranean thermohaline circulation—a basin-scale ocean circulation driven by surface heat and freshwater exchanges that plays a vital role in the ocean by ensuring proper ventilation and facilitating the transfer of nutrients and heat (e.g. Pisacane et al. 2006; Pinardi et al. 2019). Human activities, such as urbanization, tourism, and land and sea use, have had a significant impact on the basin, with most of these activities concentrated near the coast (e.g. Depellegrin et al. 2019). The basin also supports industrial development and is home to one of the busiest shipping routes in the world (e.g. Hoballah 2006). Unfortunately, the Mediterranean region is vulnerable to climate and environmental hazards, including frequent floods and extreme rainfall events, causing significant economic losses, injuries, and casualties (e.g. Llasat et al. 2010, 2013). Additionally, the Mediterranean basin has faced several severe droughts in recent decades, affecting social and economic stability, particularly in North Africa where freshwater and surface water supplies are limited and climate variability has a major impact on food security and political stability (e.g. Touchan et al. 2017). The Mediterranean basin is influenced by both Atlantic and Mediterranean atmospheric circulations, which has been linked to over 97% of extreme 3-day precipitation events in the region (e.g. Blanchet and Creutin 2020). Moreover, recent research suggests a strong connection between localized extreme precipitation events and large-scale atmospheric flow patterns, which have far-reaching impacts on weather throughout the entire Mediterranean region (e.g. Mastrantonas et al. 2022).

The study of the large-scale atmospheric circulation in the Mediterranean basin referred to, in this paper, as large-scale climate indicators (LSCI) is crucial for understanding the variability of the region's climate and its impact on the environment and ecosystems (e.g. Luterbacher and Xoplaki 2003). The patterns of circulation have a significant effect on the transfer of heat and energy between the atmosphere and ocean. They influence weather patterns and overall climate, particularly in a region known for intense seasonal and annual climate fluctuations (e.g. Nagy et al. 2019). Over the last decade, numerous studies have focused on analyzing the extensive circulation patterns in the Mediterranean area. These studies adopt a comprehensive approach to understand the prevailing winds, ocean currents, and related phenomena in the region and their impact on local climate and ecosystems.

In the past 10 years, five reviews have been conducted that mention the relationship between large-scale atmospheric circulation and climate and environment conditions in the Mediterranean region. Among these reviews, one study found that large-scale atmospheric circulation can partially explain the occurrence of some extreme rainfall events in the Mediterranean region (Ullmann and Raymond 2017). In 2020, a comprehensive overview summarized the recent advancements in the physical understanding of climatic indices and their impact on the functioning of the Mediterranean region. The authors revisited the significance of the most critical processes of atmospheric variability in the Mediterranean region from a physical perspective. They analyzed the North Atlantic Oscillation (NAO), East Atlantic (EA) pattern, East Atlantic/West Russia (EA/WR) pattern, Mediterranean Oscillation (MO), and Scandinavian (SCA) pattern. These indicators are defined by the combination of sea-level pressure (SLP) anomalies measured at different stations or from the principal components' time series of the first empirical orthogonal function of SLP or other climate variables. The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) identifies these modes through a rotated principal component analysis of the measured monthly mean 500 hPa height anomaly fields in the area 20° N to 90° N and provides monthly index values for each mode. The authors concluded that both the positive and negative phases of the NAO are associated with basin-wide changes in precipitation regimes, with the negative phase of the EA pattern contributing to heat loss through the flow of cold, dry air. The MO has the highest correlation with the main climatic variables affecting the freshwater and heat budgets in the Mediterranean Sea (Criado-Aldeanueva and Soto-Navarro 2020). In 2021, another study reviewed the available information regarding the teleconnection between fishery resources and NAO climatic oscillation variability. The authors highlighted that not only the NAO but also other expressions of the atmosphere–ocean relationship, as measured through long-scale climatic oscillations, could better explain the fluctuations of fishing resources than local environmental variables (Báez et al. 2021). In 2022, two additional reviews were performed. One found that the large-scale atmospheric circulation, its interaction with regional synoptic systems, and the complex orographic features are the main drivers of extreme weather events such as heat-waves, droughts, heavy precipitation, cold spells, floods, and windstorms (Hochman et al. 2022), while the other confirmed the connection between Mediterranean cyclones and large-scale atmospheric circulation (Flaounas et al. 2022). The aforementioned reviews demonstrate that studying large-scale atmospheric circulation patterns contributes to a deeper understanding of the mechanisms that influence climate variability and enhances our ability to predict future changes in the region. This information is crucial for making informed decisions related to coastal management, water resources, and forest management, as well as for adapting to and mitigating the impacts of climate change. However, none of the existing reviews provides a quantitative analysis of the available studies in the region, the relevant LSCI, and their impacts. Moreover, to the best of our knowledge, there is no recent review that comprehensively examines all the LSCI in the Mediterranean area, describes their formulation methods, or summarizes their holistic impacts.

This review paper aims to provide a comprehensive and up-to-date overview of different LSCI including patterns, modes, oscillations, indices, and regimes of the atmospheric circulation in the Mediterranean region. The paper outlines their definitions, calculation methods, and impacts on climate, air quality, ecosystems, and health, counting the methods used to evaluate these impacts. The methodology used for this review is described in the “Methodology of the review” section. The “Impacts of LSCI on climate, air quality, ecosystems, and health in the Mediterranean area” section, divided into sub-sections, details the impacts of these indicators on climate, air quality, ecosystems, and health and explores the methods used to assess these impacts. The “Overview of LSCI in the Mediterranean region” section presents the various large-scale climate indicators along with their definitions and calculation methods. The paper concludes with some final remarks and suggestions for future work in the “Final remarks and future work” section. Additionally, the supplementary material provides tables summarizing all the gathered large-scale climate indicators in the Mediterranean region and their implications organized by domain of impact.

Methodology of the review

The identification process for LSCI and their related impacts on climate, air quality, ecosystems, and health was a three-step strategy, as illustrated in Fig. 1. Initially, a comprehensive literature exploration was performed on Scopus using an advanced search and specific keywords in the title, abstract, and keywords fields. The search included the following terms: “large AND scale OR large-scale AND climate AND indices OR index OR circulation AND Mediterranean.” Original articles published between 2017 and 2022 in either French or English were identified, resulting in a total of 172 articles.

The second step involved reviewing the relevance of each paper by examining the title and abstract and evaluating the full text in cases of uncertainty. The step involved reviewing the eligibility criteria, such as the publication date, whether the article included information on the definition and formulation of LSCI or their impact on climate, air quality, ecosystems, or health, and whether the study area included the Mediterranean region. Resulting studies that included Europe as a study area were also considered, as Europe includes a part of the Mediterranean region.

In the third step, the selected studies were grouped into four parts based on LSCI domain of impact, mainly climate, air quality, ecosystems, and health. Information extraction included details such as the authors, study area, LSCI, definition/formulation or calculation method, study period, methods for impact assessment, and main results related to the impacts. The resulting papers were compiled in Tables 1 to 4 in the supplementary material.

Some reviewed papers used the terms “index” or “circulation” interchangeably with “mode,” “pattern,” or “regime.” Therefore, in this paper, the term “indicator” encompasses all of these meanings.

Impacts of LSCI on climate, air quality, ecosystems, and health in the Mediterranean area

LSCI play a crucial role, not only in understanding the long-term changes and variability within the climate system but also in comprehending how air quality, ecosystems, and health respond to alterations in the large-scale processes. The Mediterranean region is renowned for its distinctive climate and ecosystems' characteristics. Therefore, a comprehensive overview of the environmental impacts resulting from LSCI in this region is significant for both climate researchers and policymakers. This section aims to provide a comprehensive summary of the major LSCI's influence on climate, air quality, ecosystems, and health within the Mediterranean region.

Impact of LSCI on the climate of the Mediterranean region

In recent years, a growing interest has emerged in understanding the relationship between Mediterranean region's climate and various LSCI. Numerous studies have explored the large-scale atmospheric circulation at different atmospheric levels, illuminating their impacts on climate. This includes their influence on large-scale processes and climate variables such as temperature, precipitation, and wind patterns. In the present review, a total of 27 studies are identified that assess the correlation between LSCI and the Mediterranean region's climate. Information concerning these studies and their findings is consolidated in table 1 within the supplementary material. In this section, we both share and discuss how the scientific literature pertaining to the region has perceived the association between LSCI and large-scale processes, hydroclimate variables, and climate hazards.

Interlinkage between large–scale atmospheric and oceanic processes

Several studies have explored the intricate connections between various large-scale atmospheric and oceanic processes and patterns within the Mediterranean region, with each pattern influencing climate variables. During the winter season, Alizadeh et al. (2021) revealed that the upper-tropospheric Rossby wave propagation impacts the Red Sea trough, resulting in heightened precipitation across large parts from the western North Atlantic to the Eastern Mediterranean (EM). Morales-Márquez et al. (2020) identified the EA and EA/WR patterns as dominant large-scale atmospheric modes controlling the interannual variability of extreme waves across the entire Mediterranean Sea during their negative phases. Particularly, the EA pattern was found to modulate extreme waves, mainly within the central part of the basin. Examining the North Atlantic, Mellado-Cano et al. (2019) highlighted the important role played by both the NAO and the EA in understanding the variability of the North Atlantic eddy-driven jet stream's variability and its impact on the Euro-Atlantic climate. The authors also mentioned the additional role of the EA in shaping the North Atlantic centers of action (Azores High and Icelandic Low) and the European climate responses to NAO. The EA's interference with the NAO signal is stronger in precipitation than in temperature, affecting areas with strong responses to NAO such as the Western Mediterranean. Meanwhile, Şahin et al. (2018) established that the shift of atmospheric centers of action from the subtropical mid-east Atlantic to the Northwest Atlantic shapes the Eastern and Western patterns of the Mediterranean climate variability. Investigating the Mediterranean Sea, Iona et al. (2018) analyzed the correlation between the NAO index and the Atlantic Multidecadal Oscillation (AMO) index, uncovering temporal shifts in heat and salt content patterns. They observed a cycle of approximately 40 years in ocean heat content, aligned with the AMO cycle, implying that the natural large-scale atmospheric variability overlays the warming trend. Similarly, Cusinato et al. (2018) employed a high-resolution ocean model simulation to demonstrate the significant influence of various atmospheric patterns, including NAO, EA, EA /WR, and the MO, on thermohaline properties in key Mediterranean Sea areas through diverse mechanisms. These modes induce density anomalies that persist within the upper 600 m for up to 18–24 months. Of particular note, the EA pattern triggers extensive positive density responses in the Adriatic and northern Ionian seas, with anomalies sinking to the bottom of the South Adriatic Pit within approximately 2 years. This illustrates their potential to critically impact internal, deep, and abyssal ocean dynamics and variability. Liguori et al. (2017) investigated heat flux variability over the Mediterranean Sea across interannual to decadal timescales, attributing dominant influence to the EA/WR pattern. Changes in wind associated with this pattern exert control over the dipole pattern through both direct effects on latent heat flux, such as wind speed, and indirect effects through specific humidity, such as wind advection. Finally, Zampieri et al. (2017) examined the influence of the AMO on weather regimes over Europe and the Mediterranean during spring and summer from 1871 to 2015. Their findings showcased correlations between the AMO and distinct weather patterns resembling the negative NAO and the Atlantic Ridge, accompanied by significant shifts in the frequencies of these regimes tied to AMO phase changes. These shifts aligned with the seasonal surface pressure, precipitation, and temperature anomalies corresponding to warm/positive and cold/negative AMO phases.

Impact of LSCI on hydroclimate variables in the Mediterranean region

Other studies have investigated various aspects of hydroclimate drivers and climate change signals within the Mediterranean region. At the regional scale, Suárez-Moreno et al. (2022) used the canonical correlation analysis (CCA) to examine the role of the ocean–atmosphere system and anthropogenic forcing in the hydroclimate drivers. They identified the decadal-scale NAO as the primary driver of hydroclimate variations across the Mediterranean basin in the winter, while Atlantic-Mediterranean decadal sea surface temperature (SST) variability (AMDV) acts to enhance these hydroclimate responses. Focusing on the southwestern Mediterranean region, Tuel et al. (2021) observed changes in Mediterranean atmospheric circulation leading to reduced precipitation and pronounced low-level warming. On a seasonal scale, Cusinato et al. (2021) investigated winter climate modes in the Euro-Mediterranean region using Pearson’s coefficient of correlation. Their findings highlighted the prevalence of the EA pattern, which impacts Euro-Mediterranean temperatures. The study by Barcikowska et al. (2018) examined the impact of large-scale atmospheric circulation changes in the North Atlantic sector on the current and future Mediterranean winter hydroclimate. Results indicated that the winter atmospheric circulation, including the NAO and the EA patterns, influences on the mean Mediterranean hydroclimate. At a more local scale, de la Vara et al. (2021) explored the effects of air–sea coupling on climate change over the Iberian Peninsula (IP). They revealed that changes in the Atlantic’s large-scale atmospheric circulation and in the Mediterranean Sea influence the projected temperature and precipitation changes. In Tuscany, Italy, Luppichini et al. (2021) observed a negative correlation between precipitation and NAO in winter and a positive correlation in summer throughout the year. This pattern was attributed to global atmospheric circulation, which brings moist air masses from the Atlantic Ocean to the region during winter. From December to March, varying correlations between precipitation and NAO were observed, with periods of increased anti-correlation. The trend of the NAO and precipitation correlation varies with latitude. When they extended the study to the Mediterranean basin, authors found that the correlation between NAO and precipitation in the southern Mediterranean area follows a temporal trend similar to the AMO index. The circulation of humid air masses in the Mediterranean is linked to the Atlantic Ocean's temperature represented by the AMO index. On the island of Sardinia in the Mediterranean Sea, Montaldo and Sarigu (2017) identified a decreasing trend in precipitation linked to the NAO. Using Pearson's correlation, they observed a strong correlation between winter NAO and winter precipitation, particularly along the west coast of Sardinia. The decreasing trend in winter precipitation is more pronounced on the west coast compared to the east coast, where the correlation between winter NAO index and precipitation is much weaker.

Impact of LSCI on extremes and hazards in the Mediterranean region

Research into extreme weather records and hazards has demonstrated the crucial role of LSCI in forecasting and comprehending the emergence of exceptional events. In a study conducted by Mastrantonas et al. (2022), nine large-scale atmospheric patterns were defined, revealing their potential to extend the prediction window for extreme precipitation events (EPE) by over 3 days across numerous locations. Additionally, the authors demonstrated that utilizing these patterns for EPE forecasting leads to enhanced economic benefits in terms of medium to extended-range lead times. Blanc et al. (2022) investigated the impact of Atlantic and Mediterranean atmospheric circulations on extreme precipitation occurrences in the Northern French Alps, uncovering their significant contribution. In a study by Merino et al. (2018), the analysis of temperature extreme events (TEE) in relation to NAO, Western Mediterranean Oscillation (WeMO), and MO phases was performed on the data spanning from 1948 to 2009. The study unveiled that the interannual variability of extreme maximum temperatures is primarily influenced by the dominant phase of the WeMO across all seasons except winter, where NAO prevails. Similarly, Scorzini et al. (2018) examined changes in near-surface air temperature over the central Adriatic region of Italy from 1980 to 2012, focusing on extreme events at annual and seasonal scales. By analyzing temperature indices such as warm spells, frequency of warm days and warm nights, and summer days and employing Pearson correlation, the study identified noteworthy links between the selected temperature indices and the EA pattern, particularly during the warm season. In the same year, Tabari and Willems (2018) explored the lagged effects of various climate patterns on extreme precipitation in Europe, emphasizing the influence of NAO and El Niño-Southern Oscillation (ENSO) signals in both winter and subsequent seasons. The researchers discovered that Mediterranean atmospheric circulations during summer significantly impact extreme precipitation, affecting the following autumn, winter, and spring extremes. Merkenschlager et al. (2017) delved into the connection between non-stationary behavior in large-scale atmospheric circulation and heavy precipitation events in the Mediterranean region from 1950 to 2008. The study highlighted the MO's significant role in this behavior, affecting cyclone activity and Cyprus low's characteristics.

Further studies included hazards like cyclones, storm tracks, snow cover, and droughts. Caian et al. (2021) demonstrated that Mediterranean-origin storm tracks are a primary source of warm-season cyclones, with links to pressure variability modes. This connection serves as a mechanism for altering extreme storm occurrence and intensity, particularly in relation to anomalous polar jet shifts. The study employed a lag correlation analysis, spanning both one and zero years, to examine the relationship between storm track numbers and the primary modes of pressure variability. The findings highlighted that cyclone track numbers are predominantly influenced during the cold season by the NAO and Polar-European modes and in summer by the AMO and East-Asian modes. Additionally, Hofstätter and Blöschl (2019) examined the correlation between Vb cyclones[1] and various teleconnection patterns in the Northern Hemisphere. The authors considered patterns such as the Arctic Oscillation (AO), the NAO, the EA/WR pattern, the SCA, the Polar-Eurasia pattern (PEP), the eastern Atlantic pattern (EAP), the East Pacific/North Pacific pattern (EP/NOP), and the Pacific/North American pattern (P/NAP). The assessment of correlations revealed that the simultaneous presence of the polar and subtropical jet stream (STJ) over the Western Mediterranean is a predominant feature during the onset of Vb cyclones. Furthermore, the occurrence of Vb cyclones is synchronized with both the NAO and AO, and there is a concentration of Vb cyclone clusters when both NAO and AO exhibit negative phases.

Addressing dry spells and droughts, Tramblay and Hertig (2018) found that positive NAO index anomalies were linked to prolonged dry spells in the Mediterranean region. Ghazipour and Mahjouri (2022) employed a multi-model data fusion methodology for seasonal drought forecasting, integrating large-scale climate variables like the Southern Oscillation (SO) and the NAO to reduce the uncertainty in drought predictions. Using a Bayesian maximum entropy-based fusion (BMEF) model, the authors discovered that the inclusion of the SST as a predictor contributed to a reduction in the uncertainty of drought forecasts. Furthermore, Diodato et al. (2022) investigated the Atlantic Multidecadal Variability (AMV) on the duration patterns of snow cover in the Central-Southern Apennines (CSA) region of Italy. The study revealed that utilizing large-scale data input could effectively reconstruct the variability of ground-level snow cover at the national level.

Impact of LSCI on air quality at the Mediterranean region

Air quality has become an increasingly critical concern over the past few decades. This section delves into the impact of LSCI on air quality within the Mediterranean region. Several studies in the literature have explored the connection between LSCI and air quality, particularly focusing on ozone, particulate matter with a diameter of 10 μm or smaller (PM_{10}) and dust. Supplementary Table 2 summarizes the information from these diverse studies.

In a recent study, Khomsi et al. (2022) investigated the simultaneous occurrence of heat waves and ozone episodes in two cities in Morocco. Their findings revealed that the concurrence of these events is influenced by a combination of factors, including the geographical location of the cities and the prevailing large-scale atmospheric circulation. The authors identified a synoptic pattern that contributes to this concurrence, characterized by the interaction between an anticyclonic zone in the north and the Saharan trough, which extends the low pressure area centered in the south (Khomsi et al. 2022). This pattern

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[1] Vb cyclones are described as low pressure systems propagating from the Western Mediterranean Sea to the Northeast, by crossing Northern Italy and leaving the Alpine ridge on the left (Hofstätter and Blöschl 2019).

generates a warm flow that can potentially trigger photochemical pollution (Khomsi et al. 2020). In the same two cities, the same research group investigated the role of large-scale patterns in particulate pollution. The results unveiled a connection between the MO and the average P M_{10} concentrations. The study demonstrated that particulate pollution in the study area is influenced in part by a continental flow from the northeast to the southwest, triggered by the Saharan trough and influenced by a high-pressure area in the north. This investigation led to the creation of a new LSCI, the Saharan Oscillation (SaO) index. Notably, significant statistical correlations, particularly in winter, supported the links between the SaO index, average PM_{10} concentrations, and the MO and NAO indexes (Khomsi et al. 2020). Over the EM, a significant increase in fold activity and ozone concentrations occurs during intense summers. The Etesians—synoptically driven, persistent, northerly winds that blow during the summer over the Aegean and the EM—coincide with favorable factors for the formation of tropopause folds and stratosphere-troposphere transport, leading to elevated ozone levels (Dafka et al. 2021). In the Western Mediterranean Sea, the NAO index significantly explains a substantial portion of the interannual variability of POLDER-3[2] Aerosol Optical Depth Column (AODC), reflecting its influence on the frequency of Saharan dust transportation across the region (Chiapello et al. 2021).

Impact of LSCI on the ecosystems of the Mediterranean region

An ecosystem constitutes a complex network wherein living organisms interact with their physical environment engaging in energy and nutrients (Rapport et al. 1998). Forests and river basins serve as distinct ecosystems, with vegetation as a vital component. This section reviews eight studies about the influence of LSCI on the ecosystems of the Mediterranean region, including shifts in biodiversity, ecosystem services, and land use patterns. Table 3 of the supplementary material provides a summary of the diverse studies.

Focusing on forests, the study by Hernández-Alonso et al. (2021) analyzed the differential growth responses of *Pinus nigra*, *P. pinaster*, and *P. sylvestris* within the Sierra de Gredos Mountain range in Spain. Using mixed-effect models spanning 1954 to 2019, they explored the influence of main climatic variability patterns in the Western Mediterranean: AMO, EA, NAO, and WeMO. Their findings supported EA and NAO as potential drivers of temperature and precipitation variability in the study site, with the EA correlating positively with temperatures and precipitation and the NAO correlating negatively with precipitation. The model selection supported both EA and NAO as significant drivers of basal area increments (BAI)[3] for *P. nigra* and *P. sylvestris*, while *P. pinaster* exhibited sensitivity to EA. The study underscored EA as the dominant climatic driver impacting tree growth in this region, suggesting the integration of large-scale climatic patterns in forest productivity models for enhanced understanding and regional planning. Touchan et al. (2017) conducted fieldwork from 2002 to 2015 across the Western Mediterranean region, spanning from Morocco to southern Italy. Their research, covering 85 chronologies from 86 sites, explored climate's

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[2] POLarization and Directionality of the Earth's Reflectances version 3 (POLDER-3)/Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) aerosol data record derived from the operational clear-sky ocean algorithm (collection 3) available from March 2005 to October 2013.

[3] Basal area increment (BAI) refers to the annual growth rate in the cross-sectional area of a tree trunk at a certain height above the ground level (Jevšenak and Skudnik 2021).

role in tree growth. The study compared ring-width chronologies against climate data and NAO index. The strongest association with the NAO was observed in Western Moroccan chronologies.

Vegetation is pivotal within ecosystems, providing habitats for other living organisms and participating in nutrient, carbon, and water cycles. It additionally furnishes sustenance and oxygen, while regulating Earth's climate through photosynthesis. Several studies investigated the impact of large-scale patterns on vegetation (Wu et al. 2015). For example, the study conducted by Wu et al. (2021) investigated the connection between climate and vegetation activity in Europe during early growing seasons. The study analyzed seven teleconnection indices, including the NAO, EA, West Pacific (WP) pattern, P/PNA, EA/WR, SCA, and PEP from 1982 to 2014. Pearson's correlation coefficient was used to assess the coupling between climatic conditions and greenness anomalies during the first 2 months of the growing season, which largely determined the full growing season. The results spotlighted NAO, SCA, and EA as the principal drivers for these coupling conditions with greenness anomalies, significantly impacting vegetation.

Turning to river basins, Peña et al. (2022) examined the impact of low-frequency atmospheric variability patterns and synoptic types on large floods in the lower Ebro River Basin in Tortosa, Spain. Their 405-year analysis (1600–2005) established links between major floods, the positive phase of the NAO, high values of solar activity, and positive temperature anomalies in the Northern Hemisphere. The study by De Santis et al. (2018) delved into the evolution of the Ofanto River delta from the "Little Ice Age" to modern times and highlighted the implications of large-scale synoptic patterns. The research found that the weather-climatic condition was the primary driver of different delta evolution phases, while anthropogenic factors had a secondary role. The study also revealed that the most favorable situations for both the Ofanto and other rivers are omega-blocking, deep low-pressure troughs, and strong meridional atmospheric circulation, creating Mediterranean low-pressure systems. The frequency of floods is guided by synoptic patterns, and a relationship can be established between delta evolution and synoptic patterns in the past. Conversely, Ogrin et al. (2022), who investigated the correlation between daily air temperatures and precipitation across the Sava River Basin and three main atmospheric circulations, the AO, the NAO, and the MO, found that from 1981 to 2010, there was no significant influence of atmospheric circulation patterns on seasonal air temperatures and precipitation in the Sava River Basin. Similarly, Ranzi et al. (2021) analysis of the impact of NAO, AMO, and WeMO on precipitation in the Adda river basin between 1845 and 2016, using wavelet spectra analyses, revealed a weak correlation between NAO and precipitation. In northern central Algeria, Zerouali et al. (2018) explored potential relationships between large-scale climatic fluctuations and rainfall over a 39-year period in the Sebaou river watershed. Using cross wavelet transform (XWT), wavelet coherence transform (WCT), and Cross multi-resolution wavelet analysis (CMRWA), the authors found significant links between rainfall variability in the watershed and large-scale atmospheric circulation phenomena, including NAO, SO, MO, and WeMO. These connections encompass dominant modes, fluctuations, and dry periods leading to more severe droughts. More recently, these same authors used the four LSCI to optimize a multilayer perceptron network to model monthly rainfalls within the same river basin. Upon assessing various input combinations, it was revealed that the NAO index was the most influential parameter in improving the artificial intelligence modeling accuracy (Zerouali et al. 2023). The influence of NAO on precipitation has been supported by additional studies that was not included in this review for eligibility criteria. For instance, Corona et al. (2018) showed that the observed declines in winter precipitation within the Flumendosa basin, located in Sardinia, a Mediterranean Sea island, exhibited a strong correlation with the NAO, between 1923 and 2007. This correlation offers a potential avenue for forecasting future winter precipitation and runoff tendencies considering the predictability of the winter NAO. In fact, understanding the influence of atmospheric circulation on the variability of hydro climatic parameters can considerably contribute to effective water management. This was confirmed by Akbas and Ozdemir (2023), who studied the atmospheric dynamics' impact on rainfall and runoff variability in Marmara sea river basins. They unveiled a strong correlation between NAO and rainfall and runoff, particularly in winter. Similarly, Hakam et al. (2022) suggested that teleconnections affect the amounts of rainfall in the Lower Sebou Basin. Negative and statistically significant correlations are observed between the NAO and MO and the amounts of rainfall falling in the basin. Spring rainfall shows significantly negative (positive) correlations in the Eastern (Western) Pacific with SST, highlighting the negative impact of El Niño (negative phase of SO) on rainfall in Northwestern Morocco.

Impact of LSCI on health in the Mediterranean region

Since LSCI can have effects on climate, air quality, and ecosystems, their impact on health should not be surprising. However, this impact has been relatively underexplored in the Mediterranean region. In the context of this review, we came across only one study conducted in Europe including the Mediterranean region. Yue and Lee (2021) conducted an investigation within this scope, delving into the delayed effects of cooling on the correlation between the NAO and outbreaks of plague in pre-industrial Europe. The authors examined the correlation between NAO patterns and the incidence of plague between 1347 and 1760 CE. Their analysis involved techniques such as moving correlation analysis and the cross-correlation function to unveil the role of temperature in mediating the NAO-plague connection, as well as the lead-lag relationship between both. The outcomes of the study highlighted a notable lag of 15–22 years between multidecadal temperature changes and the correlation between NAO and plague incidents across diverse European regions. In Mediterranean Europe specifically, the NAO-plague correlation exhibited a fluctuating pattern, alternating between positive and negative associations. Table 4 of the supplementary material summarizes information on this study.

Summary and discussion of the reviewed studies

The above-mentioned studies underscore the complexity of large-scale atmospheric systems impacting the Mediterranean region. This complexity arises from the extensive and yet-to-be-fully-understood interactions among these systems, as well as the potential consequences of these systems—along with their interactions—on external factors such as climate.

The studies investigating the relationship between large-scale atmospheric circulation and hydroclimate variables have revealed that, at a broader scale, the latter are more significantly influenced by the NAO and the Mediterranean atmospheric circulation. Winter seasons are particularly affected, as both the EA and NAO have a notable impact on the Mediterranean hydroclimate. However, on the local scale, research has been limited and focused on a modest number of areas. These local studies indicate that both the large-scale Atlantic and Mediterranean atmospheric circulations impact the regions, but the hydroclimate response varies depending on each specific region. Moreover, at the local level, several other large-scale indexes play a role, notably the AO, AMO, SO, WeMO, and MO.

As for extreme events and hazards, all of the reviewed studies showed that large-scale patterns including Atlantic and Mediterranean atmospheric circulations impact precipitation events and temperature extremes. Winter NAO and ENSO signals have a controlling influence on extreme precipitation in both winter and following seasons. Summer atmospheric circulations over the Mediterranean Sea had a strong impact on summer extreme precipitation, with lagged effects on the following autumn, winter, and spring extremes. MO was identified as one of the major factors for non-stationary behavior of large-scale patterns inducing extreme precipitation events. It also affects cyclone activity in the Mediterranean basin. In fact, the cyclone track number is mainly driven during the cold season by the NAO and Polar-European modes and in summer by the AMO and East-Asian modes. The superposition of the polar and the STJ over the Western Mediterranean is a main feature at the onset of Vb cyclones, and the occurrence of this type of cyclones is synchronized with the NAO and the AO, with clusters of Vb cyclones occurring when both NAO and AO were negative. At a local scale, only a modest number of studies were conducted and results cannot be generalized. For example, it has been shown that in the IP, the interannual variability of extreme maximum temperatures is largely controlled by the dominant phase of the WeMO in all seasons except wintertime where NAO is prevailing. Extreme temperature was shown to be linked to EA pattern in the Adriatic region of Italy, particularly for the warm season. Also, positive anomalies of the NAO were linked to longer extreme dry spells. Findings related to LSCI and their impacts on hydroclimate variable are expected to help in increasing the abilities to reconstruct the variability in data such us snow cover or also decrease uncertainties in model’s forecasting.

The impact of LSCI on air quality, ecosystems, and health is less investigated. The studies reviewed in this paper confirmed the impact these indicators may have on air quality mainly ozone, PM_{10}, and dust. NAO, MO, SaO, and the Etesians are more involved. Also, authors believe that the better understanding of these indicators will help in studying some more complex scientific topics such as the concurrence of extreme climate events and air pollution episodes.

The impact of LSCI on ecosystems is as diverse as the ecosystems themselves. Therefore, many studies confirm the implication of LSCI in ecosystems, mainly their correlations with tree growth, the BAI of some species, and greenness anomalies. The ENSO, Southern Annular Mode (SAM), NAO, SCA, and EA are the most cited influencing indicators for forests and vegetation. As for river basins, their response differs according to the basin. Some reviewed studies assessed the impact of LSCI on river basins through climate variables and showed that these variables, mainly precipitation extremes in some river basins, may be linked to LSCI, mainly the NAO, while others may not.

Many previous and recent studies, not covered by the criteria of this review, have confirmed the results underscored above. For example, the study by Mathbout et al. (2020) showed that both WeMO and MO can play an important role in modulating rainfall in the northwest Mediterranean. The positive EA/WR phase is mainly connected with positive precipitation mean anomalies in the EM and vice versa in the west. The high daily precipitation concentration values over south France, northeast Spain, Croatia, and Tunisia are linked to the low values of WeMO and high values of EA. Kahya (2011) showed that results for the EM countries differ from one location to another in terms of the impact of the NAO on the hydrology. In Turkey for example, the NAO during winter was found to influence precipitation and streamflow patterns. In contrast, temperature patterns appeared to be less sensitive to the NAO. In southwest Iran, the October–December season is influenced mostly by the NAO in both dry and wet spells. Positive significant correlation values were found between the NAO and the total rainfall in the center and southern Israel and with some of the rainfall categories. High correlations between the winter mode of the NAO and temperature and sea-level pressure in Israel were also noted.

Exploring the ecological impact of NAO in Mediterranean ecosystems, Gordo et al. (2011) concluded that the impacts of the NAO on Mediterranean ecosystems are still poorly understood, especially on terrestrial ecosystems. This may be due to the heterogeneity in the species and biological phenomena studied, the negligence of the potential influence of the NAO in organisms through climate patterns of the other seasons other than winter, and the luck of multidisciplinary collaborations between climatologists and ecologists to deal accurately with the complex interactions between climate and biosphere.

While the topic has been investigated previously, none of the studies reviewed addressed the relationship between rainfall erosivity and LSCI. In a study by Angulo-Martínez and Beguería (2012), the interannual variability of daily rainfall erosivity in Northeast Spain was analyzed for the period 1955–2006, along with its correlation to atmospheric circulation patterns influencing regional rainfall, specifically the NAO, the MO, and the WEMO. The authors discovered that the erosive potential of rainfall is stronger during negative phases of all three LSCI and weaker during positive conditions. Overall, the MO and WeMO exhibited the most pronounced impact on extreme daily rainfall erosivity.

Employing a novel approach known as the center of action (COA) approach, Rehman et al. (2023) investigated the spatiotemporal relationship between winter precipitation in Spain and SLP fields. They focused on the COAs comprising the NAO, the Azores High (AH), and the Icelandic Low (IL). The study revealed that the correlation between AH properties and winter precipitation is most pronounced in the northwestern region of the country. Authors found that the positive extreme values of AH indices are related to droughts and negative extremes to heavy rain. The westward and southward shifts of the AH contribute to the presence of low-pressure system over the IP leading to elevated precipitation levels in Spain. This phenomenon arises from the moisture transport originating in the North Atlantic and affecting both the Spanish Peninsula and France.

Overview of LSCI in the Mediterranean region

LSCI are defined using atmospheric or oceanic variables within specific regions and timescales such as SLP, Z500 hPa, winds, and SST. Different techniques, such as principal component analysis, empirical orthogonal function (EOF) analysis, and cluster analysis, are frequently employed to identify patterns and isolate dominant modes of variability in the climate system. These modes of variability are essential for understanding climate dynamics and their effects. Developing knowledge of LSCI variation is an important step towards efficient management processes. The preceding sections of this review have explored the impact of LSCI on climate and atmospheric processes, air quality, ecosystems, and health within the Mediterranean region. This section provides an overview of these LSCI covered by this review, including the NAO, EA, EA/WR, MO, SCA, WeMO, AMO, ENSO, and other above-mentioned large-scale processes. It is worth noting that various spatial patterns can describe these LSCI, and several accepted definitions of each indicator are available in the literature. These definitions are provided by organizations such as NOAA/CPC, the Climatic Research Unit (CRU) of the University of East Anglia, and the Climate Analysis Section of the US National Center for Atmospheric Research (NCAR). Information on the different reviewed LSCI is summarized in Table 5.

The North Atlantic Oscillation (NAO)

In the 1920s, Sir Gilbert Walker identified the NAO as a dominant climate pattern in the Atlantic (Zerouali et al. 2018). The NAO describes the persistence of two opposite north–south pressure centers of action over the Azores and the Iceland (Morales-Márquez et al. 2020). The NAO comprises two phases: positive and negative. However, an appreciable asymmetry exists between these phases in terms of amplitude, duration, and meridional shift (Luppichini et al. 2021). The occurrence of a negative (positive) phase of the NAO is associated with a decrease (increase) in SLP and a southward (northward) shift of the Icelandic Low and the Azores High. Additionally, the NAO is a non-stationary signal affected by changes over the North Atlantic surface boundary conditions, such as sea surface temperature and the radiative variation caused by greenhouse gas concentrations (Montaldo and Sarigu 2017). This complex and dynamic atmospheric behavior poses serious challenges in defining the NAO with high precision.

Various formulations and methods are utilized to calculate the NAO index, with varying inputs depending on the source and methodology. Common methods include pressure-based, wind-based, and hybrid-based approaches. Data for the NAO index is obtained from various sources, fields, domains, and methodologies. Among the most prevalent techniques for computing the NAO index are the principal component analysis (PCA) (Mellado-Cano et al. 2019), the rotated principal component analysis (RPCA) (Şahin et al. 2018), the EOF (Suárez-Moreno et al. 2022), the station-based (Zerouali et al. 2018; Mellado-Cano et al. 2019; Luppichini et al. 2021), and the box-based methods (Wallace and Gutzler 1981; Stephenson et al. 2006; Cusinato et al. 2021). The station-based method represents the traditional approach as a simple difference of some climate variable between two locations. Within the PCA approach, the NOAA/CPC constructs the NAO index by applying RPCA to the monthly mean standardized 500 hPa height anomalies in the Northern Hemisphere (Morales-Márquez et al. 2020). In this context, the NAO represents the primary leading mode of low-frequency variability over the North Atlantic. Regarding the box-based definition, numerous versions of NAO index are documented in the literature. One such definition employs SLP information, encompassing a substantial portion of the Atlantic region from the tropics to the North Pole (Stephenson et al. 2006). This definition helps avoiding ambiguity and interpretation issues associated with more complex definitions like those relying on PCA. Nevertheless, the determination of the box size remains a subject of investigation, although certain studies highlight a consistent response irrespective of box size (Stephenson et al. 2006). In relation to box size considerations, an updated definition is presented in a selected study, which identifies centers of action and seed boxes through regression of the gridded Z500 anomalies or SLP on the target index provided by the NOAA CPC (Cusinato et al. 2021). To conclude, a variety of criteria and procedures are available for defining the NAO index. However, the commonly used NAO index is provided by the NOAA/CPC.

The eastern Atlantic pattern

The EA pattern is primarily described as a dipole in the pressure field with shifted centers of action that are southeastward and more zonally oriented than the NAO (Hernández-Alonso et al. 2021). However, recent studies have identified EA as a sea-level pressure monopole, with an extensive low-pressure weather system centered to the west of the British Isles, positioned about halfway between the two centers of action associated with the NAO system (Liguori et al. 2017). EA has two phases: during the negative phase, identified as high pressure over the northern Atlantic and a relatively strong pressure gradient over the Western Mediterranean, a northerly flow of cold, dry air induces ocean heat loss in the Mediterranean area (Josey et al. 2011; Liguori et al. 2017). Conversely, negative anomalies in sea-level pressure during the positive phase lead to the emergence of potent cyclonic winds in the North Atlantic.

Studies have focused on the coupled impact of the EA-NAO patterns, showing that the combined phases affect various aspects (Hernández-Alonso et al. 2021). By decadal timescales, some works indicate that EA significantly impacts the NAO dipoles' strength and location and can modify the surface reactions to NAO (Abrantes et al. 2017; Mellado-Cano et al. 2019).

Various studies retrieved EA data, with different time-frames, from the Earth System Research Laboratory (ESRL)[4] (Hernández-Alonso et al. 2021) and NOAA/CPC[5] (Josey et al. 2011; Abrantes et al. 2017; Liguori et al. 2017; Cusinato et al. 2018; Scorzini et al. 2018; Morales-Márquez et al. 2020; Wu et al. 2021). The latter defines the EA based on the RPCA of the monthly mean standardized 500 hPa height anomalies in the Northern Hemisphere. Consequently, it guarantees independence between modes due to orthogonality (Morales-Márquez et al. 2020). The EA constitutes the second leading teleconnection pattern that interplays with the NAO and contributes to the Northern Hemisphere's climatic evolution (Abrantes et al. 2017). Other definitions of EA patterns are used in the literature, for instance, the box-based definition mentioned earlier (Cusinato et al. 2021).

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[4] www.esrl.noaa.gov/
[5] http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents

East Atlantic/West Russia (EA/WR)

The EA/WR pattern is identified by three centers of action alternating in signs over the northern Atlantic, Central Europe, and Western Russia (Liguori et al. 2017). The EA/WR mode also refers to an intense anomaly center over the British Isles and Central Europe, coupling with an anomaly of an opposite sign over the Caspian Sea (Cusinato et al. 2018). The EA/WR exhibits interannual and decadal fluctuations in sea-level variability in the Mediterranean Sea (Cusinato et al. 2018). Positive values of the EA/WR index indicate higher pressure over the Eastern Atlantic and lower pressure over Western Russia. The negative values indicate the opposite. One of the reviewed studies defines the EA/ WR index by box-based strategy (Cusinato et al. 2021). The authors extract EA/WR mode from Z500/SLP data and calculate the corresponding index through the best combination of boxes (Cusinato et al. 2021). EA/WR index is often gathered from the NOAA/CPC, where RPCA is applied to monthly mean standardized 500 hPa height anomalies (Josey et al. 2011; Liguori et al. 2017; Scorzini et al. 2018; Morales-Márquez et al. 2020; Caian et al. 2021).

The Mediterranean Oscillation (MO)

The Mediterranean Oscillation (MO) is first discussed by Conte et al. (1989). MO characterizes atmospheric circulation at the scale of the Mediterranean basin. MO is identified as an atmospheric dipole oscillation between the Eastern and Western Mediterranean regions (Cusinato et al. 2018). The MO index is firstly proposed as the difference in geopotential height anomalies between Algiers (Algeria) (36.4° N, 3.1° E) and Cairo (Egypt) (30.1° N, 31.4° E) at Z500 hPa (Zerouali et al. 2018). Another station-based definition considers this index value as the difference between the SLP at Gibraltar (35° N, 5° W) and Lod, Israel (30° N, 35° E). Other definition based on the PCA approach is presented in the literature, in which the index is obtained as the time series of the first mode of normalized SLP anomalies across the extended Mediterranean region (Criado-aldeanueva and Soto-navarro 2013). It is noteworthy that while NAO, EA, and EA/WR can be seen as independent modes originating from the same PCA or EOF analysis, the same principle does not apply to MO. Both NAO and MO exhibit meaningful similarities; during their positive (negative) phases, they share the characteristic of having higher (lower) SPL anomalies over the Mediterranean region. Subsequently, both are significantly influenced by low-pressure systems in the Northeast Atlantic, which play a crucial role in driving cyclogenesis within the Mediterranean area. MO time series may be obtained from the CRU website.[6]

The Western Mediterranean Oscillation (WeMO)

The WeMO is a newly defined large-scale climatic fluctuation that depicts atmospheric circulation in the Mediterranean basin (Zerouali et al. 2018). The WeMO index, which is defined using monthly SLP values from Padua (45° 24′ N–11° 52′ E) and San Fernando (Cádiz) (36° 28′ N–6° 12′ W), reflects cyclogenesis in the Western Mediterranean basin and drives rainfall in the IP region, which is less connected to the NAO (Merino et al. 2018; Hernández-Alonso et al. 2021). The WeMO data is available from the Group of Climatology,

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[6] http://www.cru.uea.ac.uk/cru/data

University of Barcelona, at http://www.ub.edu/gc/en/wemo/(Scorzini et al. 2018; Zerouali et al. 2018; Hernández-Alonso et al. 2021; Ranzi et al. 2021).

The Etesians regime

During the summertime, the strong northerly winds that blow across the Aegean Sea and the EM are called Etesian. The intense Etesian winds commonly span around 40 days (Dafka et al. 2021). This regime is linked to increasing pollution over the EM. It is marked by well-defined large-scale atmospheric circulation systems that cover the troposphere and extend across the region from Central Europe to the EM. The northerly winds result from a pronounced pressure gradient created by the interaction of the Anatolian thermal low over the EM and the high-pressure system over Central Europe and the Western Mediterranean (Dafka et al. 2021). The Etesian winds usually coincide with the position of the STJ on the western side of the upper-level trough system. This synoptic scenario usually leads to the creation of tropopause folds along the jet stream’s track. These associated conditions conduct to the intrusion of stratospheric dry air into the upper and mid-troposphere over the cyclogenesis region (Dafka et al. 2021) consequently influencing air quality in the region. In this review, the only found paper covering this topic uses a classification strategy to identify the Etesian regime based on the methodology of Dafka et al. (2021), which relies on the pressure gradient over the Aegean sea, where the third quartile is selected as a filtering strategy.

The Scandinavian pattern (SCA)

The SCA pattern consists of three opposite centers sign over Scandinavia and the Mediterranean Sea (Liguori et al. 2017; Morales-Márquez et al. 2020). The SCA displays during its positive phase a low-pressure area situated over the IP and a high-pressure area over northwestern Russia (Liguori et al. 2017). This phase tends to create a weak low-pressure system and southerly wind over the entire Mediterranean Sea and a blocking high-pressure over Scandinavia. This blocking situation is associated with a southerly shift of moisture fluxes. Thus, precipitations (temperatures) are higher (lower) than average over the Mediterranean region (Abrantes et al. 2017). NOAA provides SCA time series; thereby, it is often used in the literature (Abrantes et al. 2017; Morales-Márquez et al. 2020; Caian et al. 2021; Wu et al. 2021). However, one selected paper in this review defined a new SCA box-based index with one positive Z500 anomaly and two opposing center signs (Cusinato et al. 2021).

The Atlantic Multidecadal Oscillation (AMO)

The AMO is a low-frequency large-scale pattern characterized by periodic changes in sea surface temperatures (SST). It is linked to the strength of summers and heat waves in the Atlantic regions (Hernández-Alonso et al. 2021; Luppichini et al. 2021). This phenomenon displays a cycle of warming (positive phase) and cooling phases (negative phase), between the Equator and Greenland, with a frequency of 60 to 80 years (Zampieri et al. 2017; Luppichini et al. 2021). Instead of AMO, the general term AMV is also used to refer to Atlantic decadal-to-multidecadal phenomena of SST variability in the North Atlantic (Diodato et al. 2022; Suárez-Moreno et al. 2022). Concerning large-scale patterns interplay, it is found that NAO oscillation follows the AMO shift after 10 to 15 years (Zampieri et al. 2017). AMO pattern could be identified using EOF analysis applied to Atlantic SST where the principal component associated with the leading EOF represents the AMO (Suárez-Moreno et al. 2022). The AMO index which is available at the NOAA website is primarily used (Luppichini et al. 2021; Ranzi et al. 2021). However, one filtered research in this review defines the AMO index using the Trenberth and Shea (2006) approach, which involves calculating the average SST anomaly for the North Atlantic over the area (0–60° N).

El Niño–Southern Oscillation (ENSO)

The interplay between the atmospheric and oceanic processes on a broad scale in the Equatorial Pacific region defines the ENSO phenomenon. The significant association between the ENSO event and the rainfall in the world is investigated by many studies, particularly over the Mediterranean sector (Zerouali et al. 2018; Benassi et al. 2022). In order to understand ENSO, different pacific SST and pressure patterns and their relative indices' definitions are used in the literature, for instance, among others, the SST, the Interdecadal Pacific Oscillation (IPO), Pacific Decadal Oscillation (PDO), SST-Niño-3.4, and SO indices (Zerouali et al. 2018).

IPO index quantifies the low-frequency change in the SST over the Pacific Ocean and across several decades. It is characterized as the leading EOF applied to the entire Pacific basin (Benassi et al. 2022). IPO index is computed as the difference between the sea surface temperature anomaly (SSTA) in the central equatorial Pacific and the average SSTA in the Northwest and Southwest Pacific. While IPO's positive phase enhances the occurrence of El Niño events, the negative phase enhances the occurrence of El Niña.

As part of the Pacific low-frequency variability, in the extratropical Pacific region, the PDO represents the primary pattern of low-frequency climate variability. It is determined by the leading EOF of SSTs (Benassi et al. 2022). PDO has a double effect on climate variability, directly affecting local and global decadal patterns and indirectly modulating interannual climate variability (Benassi et al. 2022). The PDO signal depicts changes in precipitation, temperature, and marine ecosystems, including shifts in fish populations and ocean productivity.

Another index called the SST-Niño-3.4 is also used to identify the presence of El Niño and La Niña events. SST-Niño-3.4 index uses SST variations over the east-central tropical Pacific at 5° N–5° S and 170°–120° W to quantify ENSO events (Venegas-González et al. 2022). During El Niño, convection prevails in the central and eastern tropical Pacific, leading to increased rainfall in those regions. Meanwhile, the western tropical Pacific experiences a reduction in precipitation due to changes in atmospheric circulation patterns caused by El Niño (Benassi et al. 2022).

Regarding the SO index, Walker and Bliss (1932) initially proposed this term as a seesaw pattern of atmospheric pressure variability. SO index is based on the difference in atmospheric pressure between the Eastern (Tahiti) and Western (Drawin) tropical Pacific (Zerouali et al. 2018). This measure reflects a large-scale fluctuation in air pressure and gives basic information on the current state of ENSO and its trends in development. It is mainly an indicator of the intensity of the Walker circulation. The positive phase of the SO index signal depicts the above-normal trade winds that alleviate the development of El Niño events. The negative phase instead reflects the adequate condition for El Niño events to develop. Hence, during La Niña (positive phase), the pressure difference led to air masses' circulation towards the west. Conversely, during El Niño (negative phase), the opposite condition prevails (Zerouali et al. 2018).

These indices are typically calculated and reported by various organizations, including the NOA and the CRU (Zerouali et al. 2018). To identify ENSO patterns, EOF analysis is mainly applied.

The atmospheric Rossby wave

Rossby waves are large-scale atmospheric waves characterized by regions of alternating vorticity, with areas of strong vorticity associated with troughs in the wave pattern and areas of weak vorticity associated with ridges. This large-scale configuration is generated mainly due to temperature gradient and the rotation of the Earth. The propagation of Rossby waves in the upper troposphere can alter the atmospheric circulation patterns in the lower troposphere, subsequently impacting the surface weather conditions in northeast Africa. Winter is typically associated with a stronger connection to the North Atlantic and Mediterranean storm tracks due to significant differences in potential vorticity gradients between the poles and the equator. This creates conditions that are more conducive to the propagation of Rossby waves. The propagation of Rossby waves occurs in a southwest-to-northeast direction. As a result, wave activity that enters the Mediterranean region is received from higher latitudes in a north–south direction (meridional) and from the west in an east–west direction (zonal). The Rossby wave is only examined in one reviewed paper. It covers the upper-level Rossby wave and its interaction with the atmospheric circulation in the lower-level troposphere over the Mediterranean. Authors highlighted the impact of Rossby wave breaking on the Red Sea trough development and highlighted the importance of upper-tropospheric Rossby waves as an indicator of the atmospheric circulation in the Mediterranean region (Alizadeh et al. 2021).

The Saharan Oscillation (SaO)

Khomsi et al. (2020, 2022) developed the SaO index to capture the flow of the Saharan desert and its impact on climate and air pollution. The index is constructed by calculating the difference between the normalized pressures at the Azores (37.79° N, − 25.5° E) and Niamey (13.51° N, 2.10° E). Data of the SaO index are available in the CRU website.

The Vb cyclones

Vb cyclones are low-pressure systems that typically form in the Western Mediterranean and move towards the Northeast, passing through Northern Italy while avoiding the Alpine ridge on the left. These cyclones are mainly caused by the convergence of the polar and STJ over the Western Mediterranean. The eddy-driven polar jet stream over the North Atlantic induces clustering of cyclones, and the appearance of Vb cyclones seems to be associated with the phases of the NAO and AO. During the negative phase of NAO, the southern position of the jet stream over the Western Mediterranean is favored due to the weakening of the center of pressure, resulting in strengthened cyclogenesis and clustering in the region. Only one study addresses Vb cyclones in this review. According to the findings, the NAO and AO exhibit significantly more negative values during months when Vb cyclones occur than during months without them. This phenomenon is explained by the shift of the polar jet stream position towards southern latitudes during negative NAO conditions, which corresponds with high-latitude blocking and pushes cyclone formation towards the Western Mediterranean (Hofstätter and Blöschl 2019).

The Arctic Oscillation (AO)

The AO is a weather phenomenon over the arctic pole. Various studies have indicated that the NAO is closely related to the AO. Their coupled impact over the Mediterranean is investigated in the literature, particularly on Vb cyclone formation (Hofstätter and Blöschl 2019). The inquiry into which atmospheric index, including NAO or AO, best reflects the dynamics of the atmosphere remains an active area of study and exploration. During the negative phase of the AO, over the Western Mediterranean, there is a dominant zonal circulation (Kotsias and Lolis 2018). Conversely, during the positive phase, dry and clear weather conditions prevail (Kotsias and Lolis 2018). The latter is due to the displacement of the high-pressure center over the Azores to the south of France (Şahin et al. 2018). One study in this review sheds the light on the AO as the best indicator of variability in the driest/wettest conditions (Şahin et al. 2018). The website of NOAA provides AO time series data (Kotsias and Lolis 2018; Şahin et al. 2018; Hofstätter and Blöschl 2019).

Other LSCI

The reviewed articles on the framework of this review study mention other LSCI, including the PEP (Hofstätter and Blöschl 2019; Wu et al. 2021), the North Sea-Caspian pattern (Kotsias and Lolis 2018), the P/NAP (Wu et al. 2021), the WP pattern (Wu et al. 2021), and the SAM (Venegas-González et al. 2022). However, these papers do not provide sufficient explanations regarding the underlying mechanisms of these indices, and there have been few investigations into their impacts on the Mediterranean region. It is worth noting that these indices are available on the NOAA website for further information.

Final remarks and future work

The Mediterranean region is vulnerable to climate and environmental hazards, including frequent floods, severe droughts, and extreme rainfall events. Large-scale atmospheric circulation plays a significant role in the transfer of heat and energy between the atmosphere and ocean, influencing weather patterns and overall climate and activities in the region. This review is now one of the several reviews that have been conducted on the relationship between large-scale atmospheric circulation, climate, and environmental conditions in the Mediterranean region. Our main findings are as follows:

1. Definition and computation methods of LSCI:
2. LSCI utilize atmospheric or oceanic variables over a specific region and timescale to identify dominant modes of variability in the climate system, essential for understanding climate dynamics and their effects.

3. Various spatial patterns can describe these LSCI, and several accepted definitions of each indicator are available in the literature.
4. Various formulations and methods are utilized to calculate LSCI, with varying inputs depending on the source and methodology.
5. Data for these indices are obtained from various sources, fields, domains, and methodologies.
6. Impacts of LSCI on the Mediterranean region:
7. The Mediterranean region is influenced by several LSCI, including NAO, EA, EA/WR, MO, SCA, WeMO, AMO, ENSO, and other large-scale processes.
8. NAO and EA are the main LSCI highlighted by the literature as strongly impacting the Mediterranean region.
9. The EA pattern is primarily described as a dipole in the pressure field with shifted centers of action that can affect climatic conditions and primary productivity in the Mediterranean area and across Europe.
10. Large-scale atmospheric circulation and hydroclimate variables in the Mediterranean region are more impacted by the NAO and the Mediterranean atmospheric circulation, especially in winter.
11. The NAO significantly affects the trajectory of storms originating from the Atlantic and moving towards the Mediterranean, impacting atmospheric circulation and precipitation patterns in various regions.
12. Various patterns, mainly NAO, EA, and MO, impact extreme waves and ocean dynamics in the Mediterranean region. Additionally, the AMO influences the heat and salt content of the Mediterranean Sea and affects the frequency of certain weather patterns.
13. Extreme events and hazards in the Mediterranean region are affected by large-scale patterns, including Atlantic and Mediterranean atmospheric circulations.
14. LSCI have an impact on air quality, ecosystems, and health, with NAO, MO, SaO, and Etesians being the most involved indicators.
15. The impact of LSCI on ecosystems is diverse, with many studies confirming its implication in ecosystems, mainly its correlations with tree growth, species BAI, and greenness anomalies.
16. The response of river basins to LSCI differs according to the studied basin, with some studies linking LSCI to climate variables such as precipitation extremes in the river.

The present review on the relationship between large-scale atmospheric circulation, climate, and environmental conditions in the Mediterranean region provides valuable insights into the various indicators that impact weather and overall climate activities in the region. As the region is vulnerable to climate and environmental hazards, it is crucial to further understand and monitor the natural large-scale atmospheric variability that may superimposes onto the warming trend. Further research on LSCI and its impact on different variables is essential to better predict and manage the impacts of these large-scale systems on the Mediterranean region. The importance of considering these LSCI in modeling and analytic studies is highly recommended as they may explain regional and local variations from the Mediterranean and surrounding regions. Ultimately, this review highlights the need for efficient management processes and improving climate predictions through a better understanding of LSCI variation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

As already mentioned in the text, the LSCI datasets analyzed during the current study are available in the websites of the following:

Abbreviations

AH	Azores High
AMDV	Atlantic-Mediterranean decadal SST variability
AMO	Atlantic Multidecadal Oscillation
AMV	Atlantic Multidecadal Variability
AO	Arctic Oscillation
AODC	Aerosol Optical Depth Column
BAI	Basal area increments
BMEF	Bayesian maximum entropy-based fusion
CCA	Canonical correlation analysis
COA	Center of action
CPC	Climate Prediction Center
CSA	Central-Southern Apennines
CRU	Climatic Research Unit
EA	East Atlantic

EAP	Eastern Atlantic pattern
EA/WR	East Atlantic/West Russia
EM	Eastern Mediterranean
EOF	Empirical orthogonal functions
EPE	Extreme precipitation events
EP/NOP	East Pacific/North Pacific pattern
ENSO	ElNiño-Southern Oscillation
ESRL	Earth System Research Laboratory
IL	Icelandic Low
IP	Iberian Peninsula
IPO	Interdecadal Pacific Oscillation
LSCI	Large-scale climate indicators
MO	Mediterranean Oscillation
CMRWA	Cross Multi-Resolution Wavelet Analysis
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
P/NAP	Pacific/North American pattern
PDO	Pacific Decadal Oscillation
PEP	Polar-Eurasia pattern
PCA	Principal Component Analysis
PM	Particulate Matter
RPCA	Rotated principal component analysis
SaO	Saharan Oscillation
SAM	Southern Annular Mode
SCA	SCAndinavian pattern
SLP	Sea-Level Pressure
SO	Southern Oscillation
SST	Sea Surface Temperature

SSTA	Sea Surface Temperature Anomaly
STJ	SubTropical Jet stream
TEE	Temperature Extreme Events
WeMO	Western Mediterranean Oscillation
WCT	Wavelet Coherence Transform
WP	West Pacific
XWT	Cross Wavelet Analysis
Z500 hPa	500 Hectopascal Geopotential Height

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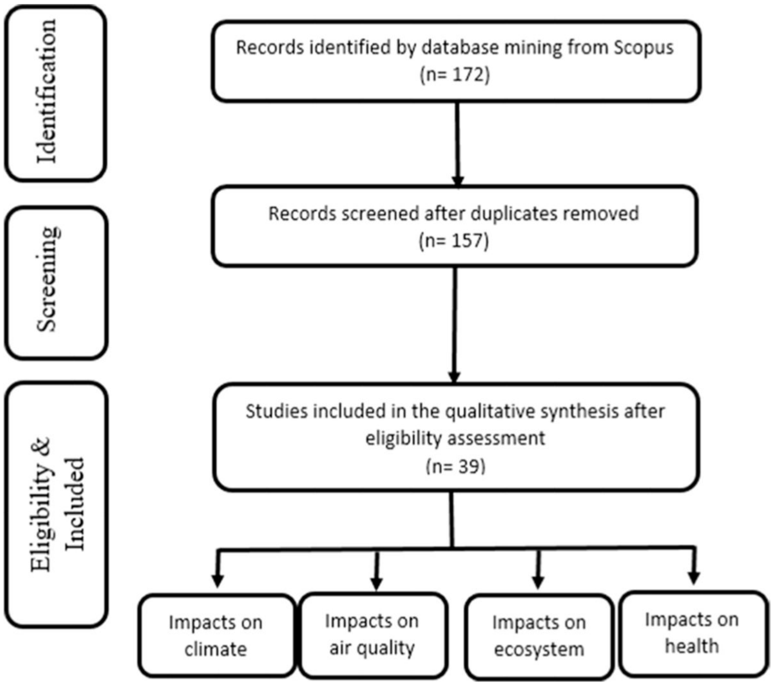

Fig. 1.

The search strategy for the current review