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Review article: Towards Improved Drought Prediction in the Mediterranean Region – Modelling Approaches and Future Directions

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Abstract.

There is a scientific consensus that the Mediterranean region (MEDR) is warming and as the temperature continues to rise, extreme events such as droughts and heat waves are becoming more frequent, severe, and widespread. Given the detrimental effects of droughts, it is crucial to accelerate the development of forecasting and early warning systems to minimize their negative impact. This paper examines the current state of knowledge in drought modeling and prediction using statistical, dynamical, and hybrid statistical-dynamical models, and suggests some research prospects to further improve drought prediction in this region. The review finds that while all methods have their strengths and shortcomings, hybrid statistical-dynamical methods can perform the most skillful prediction with a long lead time. However, the application of these methods is still challenging due to the lack of high-quality observational data and the limited computational resources. Finally, the paper concludes by discussing the importance of using a combination of sophisticated methods such as data assimilation techniques, machine learning models, and copula models and integrating data from different sources (e.g., remote sensing data, in-situ measurements, and reanalysis) to improve the accuracy and efficiency of drought forecasting.

Key Words: drought, forecasting, data assimilation, machine learning, Mediterranean, review

1 Introduction

Drought is a recurrent phenomenon in the Mediterranean basin (MEDB). Throughout time, adaptation to this kind of climate events has been an important issue for the development of many countries in the region. Yet, with the disruptive accelerated impact of global warming, already reflected in more regular and intense droughts around the Mediterranean in the last few decades, building resilience to extreme weather conditions remains a true challenge (Satour et al., 2021). For these reasons among others, the region is often described as a Hotspot for climate change (Tuel and Eltahir, 2020). The Intergovernmental Panel on Climate Change (IPCC) pointed out in the Sixth Assessment Report (AR6) that global warming has been more rapid in the Mediterranean than in the rest of the world (IPCC, 2021). This report projected an increase in the frequency and/or severity of agricultural and ecological droughts across the Mediterranean and Western Africa. A global increase of 2 °C is thought to correspond to a 3 °C increase in the daily maximum temperature in the MEDB (Seneviratne et al., 2016; Vogel et al., 2021). If this increase in temperature continues at the same pace, the Mediterranean region (MEDR) is susceptible to experience fearful desertification by the end of the 21st century, driving an increase in aridity. This will surely lead to irreversible biodiversity loss and reduce the capacity of semi-arid Mediterranean ecosystems as

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a carbon sink in the forthcoming. All these conditions exacerbate water stress that enhances in turn the probability of wildfire. A phenomenon already witnessed these two last summers (2021 and 2022) in several Mediterranean countries (Turkey, Greece, Italy, Algeria, and Morocco), displacing thousands, killing hundreds, and causing irreparable damage (Rodrigues et al., 2023; Yilmaz et al., 2023; Eberle and Higuera Roa, 2022).

The Mediterranean Sea (MEDS) is the body of water that separates three continents: Africa, Europe, and Asia. Its connection to the Atlantic Ocean via the Strait of Gibraltar is only 14 km wide. The MEDS is surrounded by vegetated areas to the north and desert areas to the south and east with narrow vegetated areas around the coast (Michaelides et al., 2018). The topography of land surrounding the MEDS is varied with the existence of complex mountain ranges with high altitudes (Fig. 1). This is one of the reasons that render the dynamic characteristics of the atmospheric flow complex at various scales, playing a critical role in the regional and local climate (Michaelides et al., 2018).

The Mediterranean climate is defined as a mid-latitude temperate climate with mild rainy winters and hot, dry summers (Lionello et al., 2023). Precipitation has a marked annual cycle, with hardly any precipitation during summer. It is also unevenly distributed and characterized by a strong spatial gradient, with values decreasing toward the South (Lionello, 2012). Droughts occurring during the wet season (or during the crop growing season) can severely impact water supply, and agricultural production, especially for countries relying mostly on rain-fed agriculture (Tramblay et al., 2020).

Water availability is unevenly distributed among the Mediterranean countries with 72% in temperate countries of the North, against 5% in the South, and 23% in the East (Milano et al., 2013). Accordingly, several countries such as Algeria, Morocco, Egypt, Libya, Malta, and some countries of southern Europe such as Portugal and Spain are experiencing a structural water shortage that is likely to increase with the expected population growth. This situation is further aggravated when multi-annual droughts hit the region. Therefore, drought forecasting at a sufficient lead time is of primary importance for the proactive management of water resources and agriculture in this difficult context.

Growing concern about the drought phenomenon in the last decades has spurred the development of improved systems that predict the full cycle of drought (onset, duration, severity, and recovery) via a large number of indices and models. Common approaches to predicting drought can be subdivided into two categories of models: statistical models and dynamical models. Statistical models, also named data-driven models, rely on the estimated correlations between several predictors (large-scale climate variables) and predictands (local climate variables represented by historical observations). While dynamical drought prediction relies on the use of Global Climate Models (GCMs) to simulate the dynamical processes that govern hydroclimatic variability. Nevertheless, despite the usefulness of these models in drought prediction and early warning systems, their forecast accuracy remains limited for longer lead times (exceeding one month) (Wood et al., 2015). The post-processing and multi-model ensemble techniques are usually used to improve prediction skills by avoiding systematic bias related to the coarse resolution of GCMs (Han and Singh, 2020). Recently, drought prediction has been tackled by the hybrid statistical-dynamical models which combine the two approaches mentioned above. These models constitute a promising tool for long lead-time drought forecasting (Ribeiro and Pires, 2016).

Despite the efforts made to predict drought phenomena, it remains largely little understood due to its multiple causing mechanisms and contributing factors (Kiem et al., 2016; Hao et al., 2018). The complexity and variability

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depicted by many physical mechanisms such as Sea Surface Temperature (SST), North Atlantic Oscillation (NAO), El Niño—Southern Oscillation (ENSO), Mediterranean Oscillation (MO), and land-atmosphere feedback are also responsible for the low performance of drought monitoring and forecasting (Ayugi et al., 2022). The MEDB is positioned in a transitional band between the midlatitude and the subtropical regions rendering climate modeling very challenging (Planton et al., 2012). Understanding the synoptic conditions leading to the drought phenomenon becomes increasingly important given the upward trend in temperature in particular in the Mediterranean region. Further investigations to assimilate how large-scale teleconnections affect local weather and climate anomalies, as well as how these latter feedback into the larger context, are much needed in this context.

To address these questions, many review papers tried to bring together the scientific advances in the field of drought prediction from different regions of the world (e.g., Mishra and Singh, 2011; Hao et al., 2018; Fung et al., 2019; Han and Singh, 2020). However, drought is a region-specific phenomenon since the meteorological conditions that drive its onset (precipitation deficit, high temperature, soil moisture, evapotranspiration [ET]…) depend highly on the considered region. Consequently, solutions developed and successfully applied in one region may not necessarily be appropriate to others.

Tramblay et al., (2020) emphasized the need to develop drought modeling and forecasting tailored for the Mediterranean context. This research highlights the complexity and challenges for drought assessment in the MEDR under anthropogenic and climate change effects. This paper is intended to fill the knowledge gaps in the Mediterranean drought, reviews the recent drought forecast methods, and focus on the prospects that constitute a promising tool to overcome the actual drought prediction weaknesses. Section 2 highlights the difficulty related to the definition of drought from different perspectives. The causes of drought in MEDR are provided in section 3. Sections 4, 5, and 6 present the recent advances in drought prediction with statistical, dynamical, and hybrid statistical-dynamical models respectively. Section 7 discusses the results found in this review, providing insights into the current state of drought forecasting in the MEDR and highlighting potential areas for improvement. The challenges in drought prediction are reviewed with the prospects in section 8. Finally, the 9th section presents the conclusions of the whole paper.

Figure 1 Topography of the Mediterranean Region.

2 Drought Definitions, Classification, and Indices

Drought is a compound phenomenon of creeping nature. Establishing an accurate prediction, well describing its starting date and duration is extremely hard. The multidisciplinary and multiscale nature of drought renders the understanding of this phenomenon very challenging. As a matter of fact, literature gives numerous definitions for drought.

In the eighties, Wilhite and Glantz (1985) found more than 150 published definitions of drought that can be categorized into four broad groups: meteorological, agricultural, hydrological, and socioeconomical. This classification based on both physical and socioeconomic factors is still adopted today. As this classification is human-centered, some recent works emphasized the need to consider the ecological drought as well, which creates multiple stresses in natural ecosystems, see for example (Crausbay et al., 2017; Vicente-Serrano et al., 2020; Bradford et al., 2020; Zhang et al., 2022). Since the aim of this study is to review forecasting drought methods, we

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will focus only on the first three categories that provide direct methods to quantify drought as a physical phenomenon.

In an attempt to associate a mathematical definition with each drought type, several drought indices have emerged. These indices are typically based upon some hydroclimatic variables or parameters (indicators) such as temperature, precipitation, soil moisture, streamflow, and snowpack to describe three major characteristics of the drought event: severity, duration, and frequency. However, the lack of a universal definition of drought is also apparent in the huge variety of indices (more than 100) that have been developed for drought prediction. Unfortunately, this plethora of indices creates more confusion than clarity (Lloyd-Hughes, 2014) and makes the choice of the most suitable indices a difficult task.

2.1. Meteorological Drought

Meteorological drought is often defined based on precipitation deficit over a continuous period (dry spell). This definition is region-specific because the determination of the threshold used to state if a period is dry or wet depends on the average amount of rainfall in the study area. Hence, there is a considerable number of meteorological definitions belonging to different regions or countries (Isendahl, 2006). Therefore, coming up with a single definition of meteorological drought in the MEDR, that takes into account the complexity of its climate and the variability between the eastern and western meteorological conditions responsible for the drought, is complicated.

The Standardized Precipitation Index (SPI) (McKee et al., 1993) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) are two of the most prevalent indicators used to describe meteorological drought. They owe their popularity to the recommendation of the World Meteorological Organization (WMO) (Svoboda et al., 2012). The SPI has been extensively used in previous studies for its ease of computation, its probabilistic nature, and its ability to detect drought at multiple time scales (Madadgar and Moradkhani, 2013; Chen et al., 2013; Li et al., 2020; Mesbahzadeh et al., 2020; Das et al., 2020). However, it should be noted that the SPI considers only precipitation data and neglects the variability of temperature and potential evapotranspiration (PET), ignoring the effect of warming on droughts. Indeed, in relatively wet regions, precipitation deficit can constitute an important indicator for drought onset (Gamelin et al., 2022). Yet, in midlatitude (or extratropic) regions such as the Mediterranean where the climatological precipitation is modest or low, precipitation deficit may not be sufficient to measure extreme droughts. Furthermore, knowing the upward trend in temperature and the influence of high atmospheric evaporative demand (AED) in increasing severity of recent drought events in the MEDR (Tramblay et al., 2020; Mathbout et al., 2021; Bouabdelli et al., 2022), the choice of drought indices needs to prioritize those including these variables in their formulation such as SPEI, or Palmer Drought Severity Index (PDSI) (Palmer, 1965) and Reconnaissance Drought Index (RDI) (Tsakiris and Vangelis, 2005) to mention but a few.

The SPEI was developed by Vicente-Serrano et al. (2010) using the climatic water balance concept of climatic water supply and AED. It is based on precipitation and PET and has the advantage of combining the multi-scalar character of the SPI with the ability to include the effects of temperature variability (Vicente-Serrano et al., 2010). Bouabdelli et al. (2022) used SPI and SPEI indices and Copula theory to study the impact of temperature on agricultural drought characteristics under future climate scenarios over seven vast Algerian plains located in the

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Mediterranean region. The results of this study confirmed that the frequency of drought events is much higher using SPI while their duration and severity are more intense using SPEI. Russo et al. (2019) performed drought characterization in MEDR using both the SPEI and the SPI by considering the period 1980–2014. They concluded that SPEI is better correlated for the 3 months' time scale and SPI for the 9 months, which reflects the capacity of SPEI to capture earlier the balance between ET and precipitation (Russo et al., 2019). However, the main weakness of this index is its sensitivity to the method that estimates PET (Vicente-Serrano et al., 2010; Stagge et al., 2014).

The PDSI has also been widely used to quantify the drought characteristics for a given location and time. It includes precipitation, temperature, and soil moisture data to estimate water supply and demand and to reflect long-term drought. But it has shown some inconsistencies when used at various locations (Wells et al., 2004). A self-calibrating variant of this index (scPDSI) was proposed by Wells et al. (2004) to automatically calibrates the behavior of the index by replacing empirical constants in its computation with dynamically estimated values to account for the variability of precipitation and the climate characteristics between locations (Wells et al., 2004). Ionita and Nagavciuc (2021) evaluated the drought characteristics at the European level over the period 1901–2019 using SPI, SPEI, and scPDSI. The results based on SPEI and scPDSI show that the increase in mean air temperature and PET are making central Europe and the Mediterranean region dryer, whereas Northern Europe is getting wetter. While results based on SPI using only precipitation data did not reveal this drought variability.

The MedPDSI, which is an update of the PDSI formulation in terms of its soil water balance to consider real evapotranspiration (based on reanalysis data instead of PET) in the MEDB, has allowed an earlier identification of longer and more severe droughts (Paulo et al., 2012). (Paulo et al., 2012) compared SPI, SPEI, PDSI, and MedPDSI in detecting drought characteristics in Portugal for the period 1941 to 2006. They concluded that PDSI and MedPDSI are likely to identify better the supply-demand dynamics and that they may be of great interest for drought warning applications, aiming namely at agriculture (Paulo et al., 2012).

2.2. Agricultural Drought

Agriculture is very sensitive to climate variation especially extreme weather. Due to its dependency on water availability, this sector is strongly impacted by drought events. In the Mediterranean basin, agriculture is mainly rain-fed (wheat, barley, olive, and orange trees…). If meteorological drought lasts for a prolonged period, it can lead to a reduction in soil moisture to such a level that it harmfully affects crop production, especially during the active plant growth season. At this stage the agricultural drought sets in.

Therefore, in addition to meteorological factors, the agricultural drought definition is also related to the retention capacity of soil in the crop growth season (Kuśmierek-Tomaszewska and Żarski, 2021) which depends on crop types, soil characteristics, and soil management. All these indicators can be employed to develop relevant agricultural drought indices. Among them, we cite Crop Moisture Index (CMI) (Palmer, 1968); Soil Moisture Deficit Index (SMDI); Evapotranspiration Deficit Index (ETDI) (Narasimhan and Srinivasan, 2005); Normalized Soil Moisture index (NSMI) (Dutra et al., 2008) and Empirical Standardized Soil Moisture Index (SSMI) (Carrão et al., 2016).

All these indices include soil moisture data in their formulation. However, observed soil moisture data are still limited. Currently, the only way to obtain frequent measurements of soil moisture characteristics is through remotely sensed data (Gruber and Peng, 2022). Those have already some known limitations such as the coarse time and space resolution, low depth of penetration, and incompatible governing hydrologic principles (Mohanty et al., 2017). As an alternative, hydrological models have been commonly used to simulate and calibrate this variable in the context of agricultural drought forecasts (Hao et al., 2018). Mimeau et al., (2021) used a modeling framework to estimate soil moisture sensitivity to changes in precipitation and temperature at 10 plots located in southern France. They concluded that the current climate change scenarios may induce longer periods of depleted soil moisture content, corresponding to agricultural drought conditions.

In general, when soil moisture in the root zone reaches a critical level, farmers resort to irrigation to save crops. However, if nowadays agriculture consumes approximately 85% of global fresh water for irrigation (D'Odorico et al., 2019; Tatlhego et al., 2022), this figure tends to increase in the years to come by growing population, increasing food consumption, and rising temperatures that accelerate PET and promotes hydrological stress.

2.3. Hydrological Drought

Unlike agricultural drought which is mainly affected by the depletion of soil moisture after a dry period, a lack of precipitation impacts many components of the hydrological system in a river basin or watershed (streams, reservoirs, and lakes). These define water availability that can be used for commercial navigation, generation of hydroelectric power, irrigation of farmlands, industry, and domestic activities for several months after the deficiency in precipitation. Consequently, hydrological drought lags behind the occurrence of meteorological and agricultural droughts. This lag time is a characteristic of the watershed, which is defined based on many physical drivers such as evapotranspiration capacity, soil properties, vegetation types, snow accumulation/melt, local water management such as dams' construction and control, water supply operation rules, and irrigation strategy (Van Loon and Laaha, 2015).

A hydrological drought is generally proclaimed when the water levels in streamflow, reservoirs, lakes, aquifers, and other water storage systems fall below a specific threshold. Therefore, the hydrological drought prediction necessitates the analysis of climate variables such as precipitation and temperature and initial catchment conditions (e.g., snow cover, and soil moisture) (Hao et al., 2018).

In the Mediterranean basin, a common tendency for water levels to drop in shallow lakes and aquifers has motivated many researchers to study the hydrological drought in this region: Greece (Myronidis et al., 2012); Turkey (Akyuz et al., 2012); Tunisia (Hamdi et al., 2016); Lebanon (Al Sayah et al., 2021); Italy (Di Nunno et al., 2021); Portugal (Mendes et al., 2022); Algeria (Bouabdelli et al., 2022); Syria (Mohammed et al., 2022). The most common hydrological drought indices include Palmer Hydrologic Drought Index (PHDI) (Palmer, 1965), the Streamflow drought index (SDI) (Nalbantis, 2008), and Standardized Runoff Index (SRI) (Shukla and Wood, 2008).

As part of the effort made by Palmer in the sixties, the PHDI has been developed by using the same two-layer soil model as the PDSI, but it applies a stricter criterion for determining the ends of drought to account for long-term drought events that reduce surface and groundwater supply. (Vasiliades and Loukas, 2009) tested the Palmer indices in a Mediterranean basin (in Greece) they concluded that these indices were successful in the identification of drought severity of historical events, but they were unable to identify drought duration.

The SRI is an index that uses the same computational principles as SPI but uses monthly mean streamflow rather than precipitation only to account for the hydrologic process that determines seasonal lags in the influence of

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climate on streamflow (Shukla and Wood, 2008). Shukla and Wood (2008) compared the SRI and the SPI results during drought events in a snowmelt region. They concluded that the SRI can be used as a complement to the SPI for depicting hydrologic aspects of drought.

The SDI is also a simple index that uses the cumulative monthly streamflow volumes for a given hydrological year to predict wet and dry periods and identify the severity of a hydrological drought (Nalbantis, 2008). Bouabdelli et al., (2022) compared the SPI and the SDI and their characteristics in three watersheds in the karst area of northwestern Algeria. They found a good agreement between meteorological and hydrological drought events expressed by SPI-12 and SDI-6, respectively, which reflects the sensitivity of the response of a basin towards dry conditions.

The application of hydrological drought indices seems to be very useful. But the main problem in applying these indices is the need for a long time series of climatic data (up to 30 years of continuous rainfall data according to the WMO suggestion). This condition is not always fulfilled which makes the rainfall-runoff transformation a difficult task (De Luca et al., 2022). Modern hydrological models can offer a valuable counterpart to existing climate-based drought indices by simulating hydrologic variables such as land surface runoff (Shukla and Wood, 2008).

3 Overview of the physical mechanisms causing drought in the Mediterranean region

It is difficult to determine the physical mechanisms causing droughts in the Mediterranean basin since the region covers a complex landscape with high topographic and climatic heterogeneity, strong land-sea contrasts, and high anthropic pressure (De Luca et al., 2022).

Assuming that any type of drought starts first by being meteorological, an accurate drought prediction is automatically linked to precipitation predictability which depends on large-scale atmospheric motions (such as Walker circulations and Rossby wave), forced by SST anomaly, natural and anthropogenic changes in radiative forcing, and land surface interactions (Hao et al., 2018; Wood et al., 2015). However, because of the chaotic nature of the atmospheric circulation, this predictability became unreliable beyond a one-month lead time.

The discovery of teleconnections between SST anomalies and hydroclimatic phenomena constitutes a major advance in drought forecasting and early warning (Wood et al., 2015). Indeed, the scientific community gathers that some ocean-atmospheric teleconnections such as ENSO can have a strong correlation with drought onset in many regions of the world. Based on this correlation, a skillful seasonal drought prediction at a long lead time (>1 month) became possible. However, drought predictability is seasonally and spatially variable. In general, seasonal drought prediction skill is high over the tropics while it is still challenging over the extra-tropics (Turco et al., 2017).

In the Mediterranean region, the response of climate to ENSO is complex. It varies over time and depends on the maturity of the ENSO state, and the co-occurrence with NAO (Kim and Raible, 2021; Brönnimann et al., 2007; Mariotti et al., 2002). Although many authors have found a non-negligible correlation between ENSO and precipitation anomalies in the MEDR, it remains insignificant compared to the tropics (Mariotti et al., 2002). In contrast, many studies rather identified the NAO as an influencing factor in Mediterranean climate variability during the winter season (Ulbrich and Christoph, 1999; Vicente-Serrano et al., 2011; Kahya, 2011; Santos et al., 2014; Cook et al., 2016). The positive NAO is related to below-average precipitation rates over large parts of the

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northern and western MEDR. While in the negative phase of NAO, the climate is wetter and warmer (Lionello, 2012). Kim and Raible, (2021) analyzed the dynamics of multi-year droughts over the western and central Mediterranean for the period of 850–2099. The analysis shows that droughts occur more frequently during the positive NAO phase and La Niña-like conditions. This study also confirmed that Mediterranean droughts are mainly driven by internal variability of the climate system rather than external forcing (Kim and Raible, 2021). Paz et al., (2003) analyzed monthly mean Sea Level Pressure anomalies (SLP) from the 1958–1997 record over the Mediterranean Basin. They identified a significant anomalous SLP oscillation between North Africa (NA) and West Asia (WA) and concluded that the regional trend of the NAWA index could explain increased drought processes in the eastern Mediterranean after the late ’70s, in relation to northern hemispheric circulation.

The climate heterogeneity in the Mediterranean area may also be explained by the regional Mediterranean Oscillation (MO) characterized by the opposite precipitation patterns between the eastern and western regions (Dünkeloh and Jacobeit, 2003). More recently Redolat et al., (2019) proposed a new version of MO that uses areas instead of observatories or isolated points. The new index which is referred to as the Upper-Level Mediterranean Oscillation index (ULMOi) is based on the differences in geopotential height at 500 hPa to improve the predictability of seasonal anomalies in the Mediterranean climate (Redolat et al., 2019). According to this study, ULMOi has reported higher confidence than the MO index for rainfall predictability (Redolat et al., 2019). Other teleconnections influencing the climate of MEDR can be found in the reviews done by (Paz et al., 2003) and (Lionello, 2012).

At the regional scale, land surface interactions from various surface conditions (e.g., soil moisture, snow cover, vegetation cover, etc.) can play a prominent role in exacerbating the drought but could also contribute to their predictability on sub-seasonal time scales (Dirmeyer et al., 2021). Therefore, drought forecasting skill also depends on the accuracy in representing these land-atmosphere processes.

In addition, the Mediterranean is a hotspot region that comprises a nearly enclosed sea (source of moisture and heat) surrounded by highly urbanized littoral which results in complex interactions between ocean-atmosphere-land processes that have a high impact on the climate and hydrological cycle, including extremes weather events that frequently affect the region (Ducrocq et al., 2018).

The Mediterranean basin's climate is also shaped by the complex interaction of ocean-atmosphere-land processes, which can significantly influence the region's hydrological cycle and contribute to droughts (Lionello et al., 2012; Ducrocq et al., 2018). The nearly enclosed Mediterranean Sea serves as a substantial source of moisture and heat, affecting atmospheric circulation and weather patterns (Mariotti et al., 2008). Coastal areas in the Mediterranean basin experience land-sea breeze circulation due to temperature differences between land and sea surfaces (Drobinski et al., 2018). This daily circulation pattern can impact the distribution of precipitation, potentially leading to prolonged dry spells, especially during transitional seasons (Ducrocq et al., 2018).

The region's complex topography, featuring mountain ranges and valleys, gives rise to orographic effects that impact precipitation patterns (Ricard et al., 2012). Orographic lifting forces moist air to rise over mountains (Chaqdid et al. 2023), causing drier conditions on leeward slopes (Drobinski et al., 2016). This dynamic results in localized climate conditions and can intensify drought events. In addition, the highly urbanized littoral in the Mediterranean basin is subject to the urban heat island (UHI) effect, where urban areas exhibit significantly higher temperatures than their rural counterparts (Santamouris, 2014). This phenomenon alters local atmospheric

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circulation, intensifies heat waves, and exacerbates drought conditions, particularly in densely populated areas (Giannakopoulos et al., 2009).

Land use/cover changes driven by human activities, such as deforestation, urbanization, and agricultural expansion, further influence the regional climate and hydrological cycle (Lambin et al., 2003), affecting surface albedo, evapotranspiration rates, and soil moisture, ultimately altering the intensity and frequency of drought events (Duveiller et al., 2018).

In conclusion, several complex factors that influence the predictability of drought are not yet fully understood, especially those related to climate change. Therefore, more research on the physical mechanisms causing drought in the MEDR is needed to improve the predictability of drought forecasts.

Expanding our grasp of the physical factors causing drought in MEDR, we will now delve into drought forecasting models. By leveraging insights from these mechanisms, scientists have developed numerous approaches and techniques including statistical, dynamical, and hybrid statistical-dynamical models to boost the accuracy and trustworthiness of drought predictions.

4 Statistical Drought Prediction Methods

Once the major sources of predictability are identified, the task of the statistical models is to uncover the spatial and/or temporal relationship between a set of these potential predictors and the predictand. When a large number of predictors are identified within the same region, dimension reduction techniques like Principal Component Analysis (PCA) or Linear Discriminant Analysis (LDA) can improve model accuracy and efficiency by reducing the number of dimensions while preserving essential information. On the other hand, feature selection methods such as decision trees or Random Forests can help eliminate irrelevant predictors. These approaches can prevent overfitting, leading to enhanced model performance and interpretability (Hao et al., 2018; Ribeiro and Pires, 2016).

The next sections will present the frequently used data-driven models and how they were employed to predict different types of droughts at different spatiotemporal resolutions in the MEDR.

4.1. Time Series models

During the last few decades, several methods have been developed to analyze the stochastic characteristics of hydrologic time series (Morid et al., 2007; Rafiei-Sardooi et al., 2018; Band et al., 2022; Zarei and Mahmoudi, 2020). Moving average (MA), Autoregressive (AR), and Autoregressive Integrated Moving Average (ARIMA) are all linear models that analyze past observations of the same variable to predict its future values. Normality and stationarity of observations are two of the basic assumptions of these time-series models. Therefore, if some trends or seasonality are detected in observations, they should be removed before the modeling to avoid any drift in the concepts to be captured.

ARIMA and Seasonal ARIMA (SARIMA) are the most frequently used time-series models. The popularity of these models is related to their ability to search systematically for an adequate model at each step of the model building (identification, parameter approximation, and diagnostic check). This method is based on the concept that nonstationary data could be made stationary by “differencing” the series (Box et al., 2015). The approach involved considering a value Y at time point t and adding/subtracting based on the Y values at previous time points and adding/subtracting error terms from previous time points. The formula can be written as:

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$$Y_t = c + \varphi_1 Y_{t-1} + \cdots + \varphi_p Y_{t-p} + \theta_1 e_{t-1} + \cdots + \theta_q e_{t-q} + e_t, \tag{1}$$

where:

Y_t is the value of the variable at time t; c is a constant term; p and q are the orders of AR and MA models, respectively; φ_i and θ_i are model parameters; $e_{t-1} \ldots . e_t$ are the error terms.

The AR component captures the impact of past values on the current value, the I component handles any non-stationarity in the data (i.e., changes in the mean or variance over time) by "differencing" the time series, and the MA component captures the impact of random shocks or errors in the data.

The ARIMA model is generally expressed with the three terms p, d, and q. The order of differencing in the I component is denoted by the value of (d) in the ARIMA(p,d,q) notation. It represents the number of times that the data must be "differenced" to produce a stationary signal. The lag order (p) represents the number of prior observations having a strong correlation with the current observation. While (q) is the size of the moving window and is identified by determining the number of lag errors that have a significant impact on the current observation.

The SARIMA is a more specific version of ARIMA that includes a seasonal component, which takes into account the repeating patterns that occur at regular intervals (e.g., daily, weekly, monthly) in the data. This makes it more appropriate for forecasting seasonal time series data.

(Bouznad et al., 2021) used ARIMA and SARIMA to assess drought in the Algerian highlands by analyzing precipitation, temperature, and ET data from 1985 to 2014, then by computing the aridity index, the SPI, and the Normalized Difference Vegetation Index (NDVI). They identified SARIMA as the best model as it returned significant p values for all the studied variables. In the same country (Achite et al., 2022) investigated the meteorological and hydrological drought in the Wadi Ouahrane basin using ARIMA and SARIMA models applied to SPI and SRI indices. A validation based on R^2 revealed high quality for SPI and SRI of 0.97 and 0.51, respectively. Additional examples of the use of the time series model in drought forecasting in MEDR can be found in Table 1.

Although time series models have shown good predictability of drought characteristics, these methods present certain limitations as they are based solely on the persistence of some drought indicators (trend, seasonality) without worrying about their interactions.

Table 1 Main studies using the Time series model to forecast drought in the MEDR.

4.2. Regression analysis

Regression models are commonly applied in drought forecasting due to their straightforwardness, interpretability, and proficiency in revealing potential connections between hydroclimatic variables. These models use various predictors (independent variables), including precipitation, temperature, and other relevant climate indices, to approximate drought indices or related target variables (dependent variables).

Simple and multivariate linear regression (MLR) models have been broadly applied for projecting extreme hydrological phenomena such as droughts (Sharma et al., 2018). These models shed light on the linear connections

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between various predictors and predictands, offering a valuable method to understand the primary factors of drought conditions and their interactions (Mishra et al., 2011).

An MLR model that predicts drought from multiples drought predictors $X_1, X_2, \dots X_n$ can be formulated as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon \qquad (2)$$

Where:

β_0 is the y-intercept or the constant term,

$\beta_{i(i=1,2,\dots,n)}$ are the regression coefficient for each independent variable $X_{i(i=1,2,\dots,n)}$,

ε is the model's error term.

On the other hand, when drought forecasts have a binary or dichotomous nature, such as drought vs. no drought, logistic regression models can be particularly useful. In these cases, the dependent variable (drought) is expressed as a probability or likelihood of occurrence. The main goal of logistic regression is to estimate the relationship between a set of predictors and the probability of the binary outcome (Rahali et al., 2021; Hosmer et al., 2013).

Some of the applications of regression analysis for drought forecasting in the MEDR are discussed below and summarized in (Table 2).

Table 2 Main studies using regression analysis to forecast drought in the MEDR.

Sousa et al., (2011) analyzed the spatiotemporal evolution of drought conditions in the MEDR during the 20th century using monthly precipitations, NAO, and SST as independent variables and scPDSI as a dependent variable of a calibrated stepwise regression model. A six-month-lead prediction of drought conditions with a high correlation between simulated and observed scPDSI time series. Tigkas and Tsakiris, (2015) used the MLR model with variables that include the minimum temperature and RDI as the main independent variable for the assessment of drought effects on wheat yield in two rural areas of Greece. The results of this analysis showed a high correlation between RDI and the wheat yield during the winter months which proves that satisfactory prediction of the drought impacts on wheat yield 2 to 3 months before the harvest can be achieved using the MLR model. Martínez-Fernández et al., (2016) investigated the agricultural drought in the REMEDHUS (Soil Moisture Measurement Stations Network) area (Spain) by computing a specific agricultural drought index (SWDI), using data from the SMOS satellite. Several computation approaches have been analyzed, and those based directly on soil attributes or parameters extracted from pedo-transfer function (PTF) [a multiple regression analysis, using the soil water parameters as dependent variables and many other soil characteristics as independent variables (texture, bulk density, and porosity)], showed the best results.

Although regression models have been valuable in drought forecasting, they exhibit certain limitations such as the linearity assumption, limited interactions between variables, sensitivity to overfitting and multicollinearity (Rafiei-Sardooi et al., 2018). Consequently, their ability to accurately represent complex real-world phenomena is often insufficient (Zhang, 2003). To address these shortcomings, more advanced models capable of capturing non-linear relationships and interactions are required, ultimately improving the forecasting of complex hydroclimatic events such as droughts.

4.3. Machine Learning and Hybrid Models

One of the big challenges in drought prediction is the random and nonlinear nature of the hydroclimatic variables. Over the last two decades, intelligent techniques such as Artificial Neural networks (ANN), Support Vector Machines (SVMs), and Fuzzy Logic (FL) have proven to be very promising tools for modeling nonlinear and dynamic time series (Mokhtarzad et al., 2017; Dikshit et al., 2022; Prodhan et al., 2022). Therefore, these algorithms have received great attention in the field of drought forecasting and modeling (Prodhan et al., 2022). Table 3 highlights the key studies utilizing intelligent models to predict drought in the Mediterranean region.

(Prodhan et al., 2022) stated in their review of machine learning methods for drought hazard monitoring and forecasting that the ANN was the most popular model in peer-reviewed literature and they suggested that higher use of the ANN model is anticipated because it has non-linear properties that make it more robust for identifying all possible interactions between predictors.

ANN is a mathematical model inspired by biological brain neural networks. It consists of an interconnected group of nodes (artificial neurons) and processes information using a connectionist computation (Fig. 2). In the case of drought forecasting, ANN architecture is usually made of three layers: an input layer which consists of the drought predictors, hidden layer(s) which comprises a function that applies weights to the input variables and passes them using a non-linear activation function, and an output layer that consists of the drought target variable or drought index (Han and Singh, 2020).

Figure 2 Drought forecasting based on a simple ANN architecture.

For the proper functioning of a neural network, the optimization of network weights (known as the learning or training process) is an essential step (Dikshit et al., 2022). Back-propagation, Feed Forward, Gradient Descent, Stochastic Gradient Descent, Adam and Levenberg–Marquardt are among the common training algorithms (Bergou et al., 2020). The role of these algorithms is to minimize the difference between predicted and observed values by adjusting the network weights and biases of the model.

Di Nunno et al., (2021) used a non-linear AutoRegressive with eXogenous inputs (NARX) neural network (a particular type of recurrent dynamic ANNs) to predict spring flows in the Umbria region (Italy). The results of this study show a good performance of the NARX model in predicting spring discharges for both short (1 month: $R2 = 0.9012–0.9842$, $RAE = 0.0933–0.2557$) and long-term lag time (12 months: $R2 = 0.9005–0.9838$, $RAE = 0.0963–0.2409$). Achour et al., (2020) also confirmed the performance of the ANN model with multi-layer perceptron networks architecture and Levenberg–Marquardt calibration algorithm in predicting drought in seven plains located in northwestern Algeria with 2 months lead time ($R^2=0.81$, $RMSE< 0.41$ and $MAE <0.23$).

SVM is also a robust supervised learning model that investigates data for classification and regression analysis. It designates the best separating line to classify the data with more safety margins. Besides, the good performance in solving linear problems, SVMs could also transfer a non-linear classification to a linear one using the kernel function and be able to solve high-dimensional problems (El Aissaoui et al., 2021).

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In drought forecasting, SVM uses a kernel function to map predictors in high dimensional hidden space and predictand to the output space (Hao et al., 2018). It can use a small data set for training and can handle many inputs. Therefore, SVM is less sensitive to data sample size and less prone to overfitting than ANN.

El Aissaoui et al., (2021) used the Support Vector Regression (SVR) model with three kernel functions (linear, sigmoid, polynomial, and radial basis function [RBF]) for the prediction of drought in the region of Upper Moulouya (Morocco) through the SPI and SPEI indices. They have demonstrated a good performance of the prediction model and the SVR with RBF was designated as the best model in predicting the weather drought index with R = 0.92 for the SPI and R = 0.89 for the SPEI. Mohammed et al., (2022) evaluated the applicability of 4 Machine Learning algorithms namely bagging (BG), random subspace (RSS), random tree (RT), and random forest (RF) in predicting agricultural and hydrological drought events in the eastern Mediterranean region based on SPI. The results of this study revealed that hydrological drought (SPI-12, −24) was more severe over the study area and BG was the best model in the validation stage with RMSE ≈ 0.62–0.83 and r ≈ 0.58–0.79.

To further improve the prediction accuracy of AI models, preprocessing of data using wavelet decomposition (WD), PCA, or empirical mode decomposition (EMD) is recommended. These techniques known as hybrid models have gained attention due to their potential to improve prediction accuracy and better capture complex relationships in the data (Yoo et al., 2015; Liu et al., 2020). The preprocessing techniques are used to extract and represent the essential features and patterns within the data and statistical methods, such as ANN, SVM, or RF, model the relationship between the input variables and the target drought index. El Ibrahimi and Baali, (2018) explored the prediction of short-term (SPI-3) and long-term (SPI-12) drought conditions using 6 models: SVR, ANN-MLP, Adaptive Neuro-Fuzzy Inference Systems (ANFIS), WA-SVR, WA-MLP, and WAANFIS in the Saïss Plain (Morocco). They argued that ANN models were more efficient than SVR models and that the use of wavelet analysis has enhanced the prediction skill of ANN models which is probably due to their capacity in detecting local discontinuities and non-stationary characteristics of the data.

Table 3 Main studies using Artificial Intelligence Models to forecast drought in the MEDR.

(Özger et al., 2020) evaluated the effect of using EMD and WD for decomposing time series data on drought prediction using the self-calibrated Palmer Drought Severity Index (sc-PDSI) and machine learning models ANN and SVM. They found that the accuracy of standalone machine learning models in mid-term sc-PDSI predictions was unsatisfactory, but it significantly improved when EMD and WD techniques were introduced, particularly for hybrid wavelet models.

In summary, machine learning and hybrid models, which combine preprocessing techniques with statistical methods, have demonstrated their efficiency in drought forecasting, as they can effectively handle intricate, nonlinear relationships and adjust to a diverse range of input data characteristics. However, the applicability of these models may be challenging when input variables exhibit strong dependence on each other. This dependency can lead to several issues such as multicollinearity, overfitting, and diminishing returns (Maloney et al., 2012). To address these limitations and improve drought forecasting performance, it is essential to consider joint probability models (Madadgar et al., 2014; Hao et al., 2018).

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4.4. Joint Probability Models

The probabilistic analysis of drought events plays a significant role in the planning and management of water resources systems, particularly in arid or semi-arid Mediterranean regions known for low annual and seasonal precipitation. Drought return periods, which estimate the frequency of drought events, can provide valuable information for responsible water management during drought conditions. The univariate frequency analysis is a common method for analyzing drought events. As mentioned above, drought is usually characterized by its severity, duration, and frequency which can be extracted using the theory of runs introduced by Yevjevich (1967). These characteristics present a dependence structure that can be ignored by the univariate approach, resulting in an under/overestimation of drought risks. As such, several joint probability theories have been recently incorporated into drought risk analysis including two or more variables. One of the most important joint probability models that have garnered increasing attention in the hydrologic community over the last decade is the copula model (Jehanzaib et al., 2021; Pontes Filho et al., 2020; Das et al., 2020; Zellou and Rahali, 2019; Mortuza et al., 2019; Ozga-Zielinski et al., 2016; Xu et al., 2015; Madadgar and Moradkhani, 2013; Chen et al., 2013).

There are numerous copula families and classes, such as elliptic, Archimedean (Clayton, Frank, Gumbel, Joe), extreme value, and Bayesian to cite but a few. The choice of the most suitable copula family depends on the specific modeling goals and the structure of the data being modeled.

A brief overview of the bivariate copula theory is given here to initiate readers about their concept and application. However, for additional details on the theory and concepts of the copula, readers may refer to the monographs by Joe (1997) and Nelsen (2007). For the construction of high-dimensional copulas, such as pair copula construction (PCC) and nested Archimedean construction (NAC), readers may refer to Aas and Berg (2009) and Savu and Trede (2010).

Let F be a 2-dimensional distribution function, with univariate margins $\mathrm{F_1}$and $\mathrm{F_2}$ for random variables U and V, respectively. According to Sklar's theorem (Sklar, 1959), there exists a copula C such that:

$$\mathrm{F(U,V)} = \mathrm{C}\big(\mathrm{F_1(U)}, \mathrm{F_2}(V)\big)\ \mathrm{U,V} \in R \qquad (3)$$

with C unique when $\mathrm{F_1(U)}$ and $\mathrm{F_2(V)}$ are continuous marginal distributions, so that

$C{:}\,[0,1]^2 \rightarrow [0,1]$ that satisfies the boundary conditions $C(u,0) = C(0,v) = 0$

and $C(u,1) = C(1,u) = u$ (Uniform margins) for any $u \in [0,1]$ and the so-called 2-increasing property (Papaioannou et al., 2016).

The main advantage of the copula over the traditional multivariate distributions is its ability to model the nonlinear dependence structure between variables independently from the choice of their marginal distributions (Salvadori and De Michele, 2004). This concept simplifies the joint probability analysis and its application in high dimensions (with a large number of variables or predictors) becomes possible.

Serinaldi et al. (2009) constructed a four-dimensional joint distribution using the copula approach and SPI to model the stochastic structure of drought variables in Sicily (Italy). Drought return periods were next computed as mean interarrival time, taking into account two drought characteristics at a time by means of the corresponding bivariate

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marginals of the fitted four-dimensional distribution. Bouabdelli et al. (2020) investigated the joint probability and joint return period of drought severity and duration using copula theory to assess the hydrological drought risk in the reference period and its probability of occurrence in the future under two climate change scenarios in three basins located in northern Algeria. Bonaccorso et al. (2015) evaluated the conditional probability of future SPI classes under the hypothesis of multivariate normal distribution of NAO and SPI series in Sicily (Italy). The results of this study indicated that transition probabilities toward equal or worse drought conditions increase as NAO tends toward extremely positive values. Table 4 displays additional examples of the application of the Joint Probability Models to forecast drought in the MEDR.

Table 4 Main studies using Joint Probability Models to forecast drought in the MEDR.

All the above-mentioned studies confirm that copulas can accurately capture the joint distribution and dependence structure between multiple drought predictors without making strong assumptions about their marginal distributions. By combining the strengths of machine learning models with the flexibility of copulas, researchers can develop more accurate and reliable hybrid methods that better represent the intricacies of hydrological processes and climatic variables, even in the presence of strong dependence among the input variables (Jiang et al., 2023; Li et al., 2022; Wu et al., 2022; Zhu et al., 2020).

4.5. Markov Chain Models

Unlike some regions of the world, subjected to well-known phenomena like ENSO (e.g., tropical regions), the governing factors of drought are not clearly identified in the MEDR. Consequently, drought prediction becomes a challenging task, particularly on seasonal and longer-time scales. The stochastic analysis of drought episodes may then be a promising alternative to handle this issue. Markov chains are effective tools to understand the stochastic characteristics of drought events and their temporal dependency. These models are based on the assumption that future states depend only on the current state.

Mathematically, Markov chain is a stochastic process X, such as at any time t, X_{t+1} is conditionally independent from X_0, X_1, X_2, ..., X_{t-1}, given X_t; the probability that X_{t+1} takes a particular value j depends on the past only through its most recent value X_t:

$$P\{X_{t+1} = j | X_0, X_1, \ldots\ldots, X_t\} = P\{X_{t+1} = j | X_t = i\} \forall i, j \in S, t \in T \qquad (4)$$

A Markov chain is characterized by a set of states, S, and by the transition probability, P_{ij}, between states. The transition probability P_{ij} is the probability that the Markov chain is at the next time point in state j, given that it is at the present time point in state i.

The drought prediction using this concept can be expressed as the transition from wet or normal state to dry state (or the other way around) or the transition from one drought severity state to another (e.g., no drought, mild drought, moderate drought, extreme drought). Habibi et al. (2018) studied meteorological drought in North Algeria's Chéliff–Zahrez basin, employing both localized and spatially-distributed probabilities for temporal transitions using Markov Chains, and recurrence probabilities using an optimal time series model, the APARCH approach. Paulo and Pereira (2007) used Markov chains, incorporating homogeneous and non-homogeneous formulations, to predict drought transitions up to three months ahead, based on the SPI derived from 67 years of data in Southern Portugal. The non-homogeneous Markov model outperformed its counterpart by considering the initial month and seasonal rainfall variations. Table 5 lists additional studies that apply Markov chain models for MEDR drought forecasting.

Table 5 Main studies using Markov Chains Model to forecast drought in the MEDR.

These studies generally support the effectiveness of Markov chain models in providing valuable drought insights. However, it is essential to consider the challenges associated with applying Markov chains within the MEDR, as the region's complex topography, considerable interannual climate fluctuations, limited data availability, and the non-stationarity resulting from climate change can adversely affect the models' core assumptions and constrain their long-term forecasting accuracy. Addressing these challenges calls for the adoption of more sophisticated techniques that encompass both stochastic and physically-based approaches, ultimately enhancing the accuracy and reliability of drought predictions in this region (Paulo and Pereira, 2007).

5 Dynamical Drought Prediction Methods

Future drought projections and near-real-time prediction are challenging since several relevant variables and complex processes contribute to the occurrence and severity of this phenomenon (Balting et al., 2021). The dynamical drought prediction is frequently based on GCMs. These models can represent the physical processes in the atmosphere, ocean, and land surface and project future climate changes under different scenarios to provide estimates of climate variables such as precipitation, temperature, surface pressure, and winds on a global scale. However, GCMs have generally quite coarse resolution relative to the scale of exposure units in most impact assessments with a horizontal resolution varying between 150 and 300 km, 10 to 20 vertical layers in the atmosphere, and up to 30 layers in the oceans. Therefore, post-processing including downscaling and bias correction is often an essential step before using GCM forecasts in practice (Tuel et al. 2021). The goal of this step is to provide high-resolution climate projections for impact studies on the regional and local scales.

The most common approaches to downscale GCM forecasts include statistical models, dynamic or nested models, and hybrid statistical–dynamical models (Wilby et al., 2004). In statistical downscaling, large-scale variables are used as the predictors and desired near-surface climate variables are the predictands (Gutiérrez et al., 2019). The role of statistical models is then to measure the correlations between predictors and predictands. Whereas dynamical downscaling refers to the use of high-resolution regional simulations to dynamically extrapolate the effects of large-scale climate processes to regional or local scales based on a nesting approach between GCMs and Regional Climate Models (RCMs) (Giorgi and Gutowski, 2015). However, it is known that GCMs contain significant systematic biases that may propagate into RCMs through the lateral and lower boundary conditions and thus degrade the dynamically downscaled simulations and lead to large uncertainties (Maraun, 2016). Besides, climate predictions from a single climate model simulation are sensitive to initial oceanic and atmospheric states and can represent only one of the possible pathways the climate system might follow. To allow probabilistic estimates of climate variables with uncertainties in quantification, it is necessary to carry out an ensemble of simulations with different initial conditions from each model and to combine various models as ensemble members. The frequently used Multi-Model Ensemble (MME) and bias correction methods include quantile mapping (Wood et al., 2002) and Bayesian Model Averaging (Krishnamurti et al., 1999; Seifi et al., 2022). These methods proceed by adjusting the modeled mean, variance, and/or higher moments of the distribution of climate variables, to match the observations. However, such MME simulations can be very computationally demanding.

Therefore, some international dynamical downscaling intercomparison projects were carried out such as the Coordinated Regional Downscaling Experiment (CORDEX, Wilby et al., 1998) and its Mediterranean initiative MEdCORDEX (Ruti et al., 2016) to provide present and future climate simulations with a high spatial resolution (~12km). Baronetti et al. (2022) analyzed the expected characteristics of drought episodes in the near (2021–2050) and far (2071–2100) future compared to the baseline conditions (1971–2000) for northern Italy using EURO-CORDEX and MedCORDEX GCMs/RCMs pairs at a spatial resolution of 0.11 degrees for the Representative Concentration Pathways (RCPs) (4.5 and8.5) scenarios. The results indicated that the GCM/RCM pairs performed generally well, while in complex environments such as coastal areas and mountain regions, the simulations were affected by considerable uncertainty. Dubrovský et al. (2014) used an ensemble of 16 GCMs to map future drought and climate variability in the Mediterranean region. Bağçaci et al. (2021) compared the capacity of the latest release Coupled Model Intercomparison Project Phase 6 (CMIP6) model ensembles in representing near-surface temperature and precipitation of Turkey in comparison with its predecessor CMIP5 to better understand the vulnerability degree of the country to climate change. All these studies confirmed the good performance of MME methods in providing probabilistic drought forecasts for 1 to 2 months of lead time. However, much effort should be made in selecting the most skilled GCM ensembles in reproducing the large and synoptic scale atmospheric and land-surface conditions associated with drought development in the MEDR.

On the other hand, some drought-relevant variables such as soil moisture, streamflow, groundwater level, and PET, which are integral parts of the hydrological cycle, are not necessarily well represented in the GCMs (Balting et al., 2021). So, to dynamically forecast agricultural and hydrological droughts, the water balance should be correctly simulated by hydrological models forced by climate forecasts (Wanders and Wood, 2016). Among the most used models to forecast hydrological drought, we cite, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), the Variable Infiltration Capacity (VIC) (Liang et al., 1994), and the Community Land Model (CLM) (Oleson et al., 2004). These models can incorporate data on soil moisture, vegetation, snow water equivalent, groundwater level, and other initial hydrologic conditions with climate forecasts to simulate the movement of water through the hydrological cycle, including the processes of precipitation, evaporation, infiltration, and runoff. Crop growth models can also be coupled with hydrological models to make an accurate prediction of agricultural drought and its impact on crop yields.

Coupled hydroclimatic models can improve drought forecasting by allowing for the consideration of feedback between the hydrological and climatological components of the Earth system. Indeed, drought conditions can affect the availability of water for evapotranspiration, which in turn can affect the amount of moisture in the atmosphere and the likelihood of precipitation. By incorporating this feedback into the model, it is possible to produce more accurate forecasts of drought conditions.

In a recent study, Brouziyne et al. (2020) combined meteorological and hydrological drought indices (SPI and SDI) with a SWAT model forced by bias-corrected CNRM-CM5 data to predict future droughts under two RCPs (4.5 & 8.5) in Bouregreg watershed, Morocco. They confirmed that using multiple drought indices and a comprehensive water budget indicator such as Total Water Yield provided a valid approach to evaluate drought conditions in a Mediterranean context. Marx et al. (2018) analyzed a multi-model ensemble of 45 hydrological simulations based on three RCPs (2.6, 6.0, and 8.5), five GCMs (CMIP5), and three state-of-the-art hydrological models (mHM, Noah-MP, and PCR-GLOBWB) to investigate how hydrological low flows are affected under

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different levels of future global warming. Based on the analysis of the results, the authors recommended using multiple hydrological models in climate impact studies and to embrace uncertain information on the multi-model ensemble as well as its single members in the adaptation process.

Table 6 Main studies using dynamical models to forecast drought in the MEDR.

In summary, significant advancements in recent years have led to improvements in the accuracy and reliability of dynamical drought forecasting. Key developments include higher-resolution climate models, enhanced process representation through advanced land surface and hydrological models, and the implementation of data assimilation techniques to better incorporate observed data (Liu et al., 2020). Additionally, the adoption of ensemble forecasting methods has improved the assessment of forecast uncertainty (Wanders and Wood, 2016; Seker and Gumus, 2022), while the integration of coupled climate models has captured the influence of large-scale climate patterns on regional drought conditions (Guion et al., 2022). However, they still have some limitations related to computational complexity, data requirements, and reduced skill at longer lead times.

6 Hybrid statistical-dynamical methods

As mentioned above the major limitations of statistical models are related to the non-stationary relationship between the predictands and predictors used to forecast drought. Statistical models do not consider climate changes, which means that they may not be able to adequately forecast drought events that have not occurred in the past. While dynamical models can integrate climate change signals through some Shared Socioeconomic Pathways (SSPs) scenarios and can capture the nonlinear interactions in the atmosphere, land, and ocean, their forecast skill is still limited for a long lead time due to the inherent uncertainty in predicting future events. To address the shortcomings associated with seasonal forecasting skills, hybrid models employ statistical or machine learning methods to merge a broad variety of forecasts from statistical and dynamical models into a final probabilistic prediction product (Slater et al., 2022). The frequently used merging methods include the regression analysis, BMA, and Bayesian post-processing method (Hao et al., 2018; Strazzo et al., 2019; Han and Singh, 2020; Xu et al., 2018). The BMA method involves the estimation of the posterior probability density function (PDF) of model parameters based on the observed data and using this PDF to weight each individual model forecast (Tian et al., 2023). The hybrid forecast is then generated as the weighted average of the individual forecasts from statistical and dynamical models. The BMA weights estimation with simultaneous model uncertainty quantification can also be used in selecting the best-performing ensemble members to reduce the cost of running large ensembles (Raftery et al., 2005). There is also an opportunity to enhance the probabilistic seasonal forecast skill through Bayesian post-processing methods such as the Calibration, Bridging, and Merging (CBaM) technique (Schepen et al., 2014; Schepen et al., 2016; Strazzo et al., 2019). The calibration step consists in optimizing the dynamical forecasts from multiple GCMs by analyzing their correlation to observed data through a statistical model. In the bridging step, the dynamical forecasts from GCMs are calibrated using some large-scale climate indices (e.g., ENSO, NAO, PDO, AO), and finally, the merging component combines the forecasts of the two previous steps.

These hybrid statistical-dynamical models combine the strengths of both modeling approaches and offer several advantages compared to either statistical or dynamical models alone. Thereby, drought forecasting using hybrid models has recently become an active area of research (Madadgar et al., 2016; Strazzo et al., 2019; AghaKouchak et al., 2022). In the MEDR, Ribeiro, and Pires, (2016) proposed a two-step hybrid scheme combining dynamical model forecasts from the UK Met Office (UKMO) operational forecasting system and past observations as predictors on a statistical downscaling approach based on MLR models to forecast long-range regional drought index SPI in Portugal (Table 7). They concluded that hybridization improves drought forecasting skills in comparison to purely dynamical forecasts.

Table 7 Main studies using hybrid statistical-dynamical models to forecast drought in the MEDR.

Moreover, the hybrid statistical-dynamical models make the prediction of flash droughts possible. Indeed, these events can develop rapidly by a quick decline in soil moisture and streamflow that may cause devastating economic and ecological impacts in a short period (from a few days to 1–2 months) (Mo and Lettenmaier, 2015) which makes them, particularly challenging to forecast. By providing a more nuanced understanding of the drought contributing factors, hybrid statistical-dynamical models help to identify potential warning signs of an imminent drought event, improve drought early warning system, and reduce false alarm rate of drought onset (Xu et al., 2018).

7 Discussion

7.1. Drought types and indices

The indices adopted by the surveyed studies were grouped according to three distinct drought categories: meteorological, agricultural, and hydrological. Figure 3 illustrates the percentage of usage for each index by category. Meteorological droughts were the most common, appearing in 63% of the examined studies, followed by agricultural droughts with approximately 22.2%, whereas hydrological droughts were the least prevalent, making up only 14.8%.

The SPI was the primary indicator, used in 70.59% of meteorological drought studies. But it also served as an indicator for hydrological and agricultural droughts, with usage rates of around 25% and 8.33%, respectively. By fitting a probability distribution to observed precipitation data, the SPI is calculated and subsequently transformed into a standard normal distribution with a mean of 0 and a standard deviation of 1 (Livada and Assimakopoulos, 2007). Consequently, SPI values can be compared across various regions and timeframes (e.g., 1, 3, 6, 12, or 24 months). This multiscale nature of SPI enables it to capture diverse aspects of drought depending on the selected time scale. The shorter time scales (1-3 months) are suitable for monitoring agricultural drought, while longer time scales (6-12 months or more) are better suited for evaluating hydrological drought. It is important to recognize, however, that the SPI does not consider other factors influencing drought, such as evapotranspiration, soil moisture, land use, and water management practices. In regions with high temperatures and evapotranspiration rates like the Mediterranean, the SPI may not offer a comprehensive assessment of drought conditions.

Using multivariate drought indices like the SPEI, PDSI, and sc-PDSI, or a combination of multiple indices, can help account for regional feedback in the forecast process and better assess the impact of global warming on drought severity and intensity in MEDR (Marcos-Garcia et al., 2017; Gouveia et al., 2017).

Figure 3 Pie chart showing the proportion of use of indices in the MEDR for different drought types.

On the other hand, SDI was the most applied index in hydrological drought studies in the MEDR (37.5%). It is calculated by comparing the current streamflow to the long-term average or median streamflow for a specific location and time of year (Nalbantis & Tsakiris, 2009). Despite its usefulness, there are some limits to using SDI in MEDR. Indeed, this region is known for highly variable climates with strong seasonality (wet winters and dry summers) and the presence of transient streams or intermittent rivers that flow only during and after rainfall events, especially in sub-humid and semi-arid areas. Groundwater recharge principally occurs during the wet season, when precipitation infiltrates the soil and replenishes aquifers (Scanlon et al., 2002). In these regions, the SDI may not provide an accurate representation of the hydrological drought as it relies solely on streamflow data. Therefore, the use of SDI should be done in combination with other drought indices that consider variables such as groundwater, soil moisture, runoff, and regional variations in precipitation and streamflow patterns for accurate hydrological drought assessment.

One can notice from Fig. 3 that the agricultural drought studies are characterized by more diversity of indices. This diversity can be explained by the varied range of agro-climatic conditions that characterize the MEDR, including a wide range of soil types, topography, and vegetation cover. These diverse conditions can result in varying impacts of drought on agricultural production, which require different drought indices to accurately capture the extent and severity of the drought. In addition, the MEDR is also home to a diverse range of crops, each with different sensitivities to drought (Fereres & Soriano, 2007). This diversity of crops can require different indices to assess the impact of drought on each crop.

Overall, a suitable index should be able to capture the impacts of drought, detect changes over time, and differentiate between different levels of severity, while also being accurate and easily interpretable by stakeholders.

7.2. Drought forecasting accuracy

Key obstacles in drought modeling include the absence of a one-size-fits-all model, choosing suitable inputs, determining an index that accurately represents drought tracking in various regions, and the uneven geographical influence that leads to discrepancies in model accuracy (Mishra & Desai, 2005; IPCC, 2012). Consequently, contrasting different methodologies is crucial for developing a reliable prediction model.

The accuracy of drought prediction depends on various factors such as the quality and availability of data, spatial and temporal scales, prediction lead time, and model complexity, to cite but a few (Wilhite et al., 2014; Mishra & Singh, 2010). For consistency, this analysis only includes studies that use R^2 as evaluation criteria of the forecast with a lead time of 1 month. Joint probability models were excluded from this analysis since the accuracy evaluation criteria were different. Moreover, the concept of lead time is not addressed in the majority of the surveyed studies. It is also important to note that this analysis does not include hybrid statistical-dynamical models, as the number of studies applying this approach in the MEDR was quite limited. Consequently, the available research is insufficient to offer a comprehensive understanding of the applicability and effectiveness of these models in the region.

Figure 4 Box and whiskers plot showing the performance of drought prediction models denoted by the coefficient of determination (R^2) for the surveyed studies in MEDR.

Figure 4 shows a box and whisker plot of drought forecasting model accuracy based on R^2 in the surveyed studies in the MEDR. The lower box shows the 25 percentile, the upper box shows the 75 percentile and the median (50th percentile) is represented by the black line inside the box. The whiskers show the extent to the minimum and maximum values within 1.5 times the interquartile range (IQR) from the box.

According to the graph, hybrid models appear to be the most accurate and consistent, with the highest median and shortest box height. Markov chains and AI models also have relatively short box heights, indicating high agreement and accuracy across studies. Meanwhile, dynamical and regression models exhibit moderate to high accuracy (both have median equal to 0.79), but the height of the dynamical model box is shorter than that of the regression models, suggesting greater consistency. Time series models also show moderate to high accuracy, with a median equal to 0.82.

Nonetheless, Fig. 4 provides valuable information about the relative performance of different models across multiple studies in the MEDR. The consistently high median of hybrid models suggests that they are particularly effective for drought forecasting in the region. Similarly, the consistent performance of the AI and Markov chain models, suggests that these models also show promise. The variability in the performance of the regression, and the time series, as indicated by their taller boxplots, suggests that there may be more variability in the effectiveness of these models across different studies and regions. The results also show that dynamical models can provide valuable insights into drought conditions. However, the high variability in their performance, suggests that there may be room for improvement in the development and implementation of these models in MEDR.

This analysis concludes that simple statistical models such as Markov chains, regression, and time series can still be useful in some situations and are generally more transparent and easier to interpret. For example, when focusing on a single variable to forecast drought (e.g., precipitation using SPI), simple models like ARIMA can effectively capture the temporal patterns and provide reasonable forecasts. Or, when drought conditions can be effectively represented by discrete states or categories, Markov chains can be employed to model the transition probabilities between these states and forecast future drought conditions (Habibi et al., 2018; Nalbantis and Tsakiris, 2009; Paulo and Pereira, 2007). Also, when working with a limited number of variables and moderate interactions, simple regression models like linear or logistic regression can provide adequate predictions of drought conditions (Sharma et al., 2017). The effectiveness of simple models in these situations depends on the specific context and the data quality and quantity. When more complex relationships or high-dimensional data are involved, it may be necessary to employ more advanced models like dynamical models or combine simple models with techniques like machine learning, copulas, or hybrid approaches to improve forecasting performance. Hybrid statistical-dynamical models present a promising avenue for enhancing forecast accuracy, particularly for extended lead times and in situations where intricate processes and interactions are critical (AghaKouchak et al., 2021; Mehran et al., 2020; Madadgar et al., 2016). The relatively nascent emergence of these hybrid techniques has resulted in a limited number of studies applying them in the MEDR. This can be ascribed to factors such as data constraints, computational complexity, and model uncertainty. Moreover, proficiency in both statistical and dynamical modeling is needed, and interdisciplinary cooperation is frequently deficient. Notwithstanding these challenges, there is an increasing interest in refining drought forecasting abilities, with the prospect of wider adoption of hybrid models as research advances and resources become more accessible.

7.3. Spatial and Temporal Scales of Drought

Figure 5 displays the spatial and temporal scales of drought forecasting studies in the MEDR with a pie chart indicating the percentage of use of drought forecasting method: statistical, dynamical, and hybrid statistical models for each spatiotemporal scale. This figure shows that the number of droughts forecasting studies tends to decrease as the spatial scale increases and increases as the time scale increases. We can also notice from this figure that the majority of studies in the MEDR focused on the local scales (e.g., city or catchment), particularly at annual and seasonal time scales. In contrast, very few studies were conducted at the MEDR scale, and only a few studies were conducted at the country scale.

Figure 5 Spatial and temporal scales of drought forecasting studies in the Mediterranean region with pie chart indicating the percentage of use of drought forecasting method: statistical, dynamical, and hybrid statistical models for each spatiotemporal scale.

When considering the spatial scale, drought forecasting becomes more challenging at larger scales due to various factors. One of the major challenges is the complexity of the interactions between different factors that contribute to droughts, such as precipitation, temperature, soil moisture, and vegetation cover (Sheffield & Wood, 2011). These interactions are nonlinear and difficult to capture accurately, especially at larger scales where there are more variability and heterogeneity (AghaKouchak et al., 2015). For instance, at the country scale, there could be different microclimates, topography, and land use practices that affect these factors differently (Vicente-Serrano et al., 2010). This heterogeneity tends to increase as the spatial scale increases, making it harder to calibrate and validate drought forecasting models. On the other hand, the small number of studies that focused on large geographic areas is probably due to the challenge of data availability and homogeneity, which arises due to limitations in data collection and standardization, particularly at larger spatial scales (Dai, 2011). This can lead to incomplete or inconsistent datasets, which in turn can impact the accuracy of drought forecasting models. Remote sensing technologies can provide a solution to this problem by allowing for the collection of large-scale, high-resolution data that can improve the accuracy of forecasting models (Gouveia et al., 2017). The role of remote sensing data in improving drought prediction will be further discussed in sect. 8.2.

When considering the time scale, the number of droughts forecasting studies tends to increase as the scale increases. Drought research often emphasizes seasonal, annual, or decadal scales due to various factors. The slow-onset nature of droughts necessitates studying their progression and recovery over extended periods (Mishra & Singh, 2010). Investigating longer time scales also allows researchers to analyze the impact of large-scale climate drivers, such as ENSO or NAO, on drought events (Dai, 2011). Moreover, focusing on these time scales enables a better assessment of drought consequences on water resources, agriculture, and ecosystems, which are more pronounced over extended periods (Wilhite & Pulwarty, 2017). Additionally, data availability and reliability tend to be higher for longer time scales, facilitating more robust analyses. Long-term trends and climate change impacts on droughts can also be better understood at longer time scales (Trenberth et al., 2014).

Notably, only one study focused on the weekly time scale. Drought forecasting at small scales or weekly time scales offers several advantages, including early warning and improved water management (Pulwarty & Sivakumar, 2014), quick response to flash droughts (Mo & Lettenmaier, 2015), support for agricultural decision-making (Hansen et al., 2011), improved accuracy of longer-term forecasts (Yuan et al., 2015), and model improvement and validation (Wood et al., 2016). However, drought forecasting at such a small scale may be more challenging due to the chaotic nature of the atmosphere, making it difficult to accurately model complex interactions between atmospheric conditions, land surface characteristics, and water management practices over short periods (Lorenz, 1963; Seneviratne et al., 2012).

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On the other hand, the most commonly used forecasting methods were statistical and hybrid statistical models, with only a few studies applying dynamical models and the percentage of studies applying this last approach increases with an increase in the temporal scale. There could be several reasons for these findings. Dynamical models require large amounts of high-quality input data, which may not be readily available for the MEDR due to limitations in historical data and spatial coverage (Giorgi & Lionello, 2008). Statistical and hybrid statistical models often have lower data requirements and are generally computationally more efficient than dynamical models, making them more suitable for regions with limited data availability and computational constraints. Furthermore, the percentage of studies applying dynamical models increases with an increase in the temporal scale because these models are better suited for capturing long-term climate variability and the influence of large-scale climate drivers (Dai, 2011; Sheffield et al., 2012). Statistical and hybrid statistical models, conversely, are more effective at capturing short-term variability and local-scale processes, which are often more relevant for drought forecasting in the Mediterranean region (Mehran et al., 2014). Lastly, data availability at shorter temporal scales can be a limiting factor for developing and validating dynamical models (Shah et al., 2018).

In summary, while increasing the spatial scale can decrease the accuracy of drought forecasting studies, increasing the time scale can improve the accuracy by allowing for a more comprehensive understanding of the various factors that contribute to drought conditions. It is essential to consider both spatial and temporal scales when conducting drought forecasting studies to ensure the most accurate predictions possible.

8 Challenges and Future Prospects

In the earlier discussion, we analyzed drought indices, factors affecting the accuracy of drought forecasts, and the significance of spatial and temporal scales in drought predictions within the MEDR context. Building on this understanding, the following sections will focus on the challenges and prospects within the realm of drought forecasting, which will help to pinpoint potential avenues for progress and innovation in this area.

8.1. Data Assimilation

The lack of in-situ measurement networks and coarse global seasonal forecast skills has hindered drought forecasting facilities, especially in data-poor regions (Pozzi et al., 2013; Haile et al. 2020). In this regard, Data Assimilation (DA) provides a powerful approach to enhancing drought forecasting accuracy by incorporating different observations and climate forecasts into a hydrologic model to generate more precise initial conditions (Hao et al., 2018; Tang et al., 2016). Therefore, many studies have referred to this method to better forecast hydroclimatic variables (e.g., Bazrkar and Chu, 2021; Peng, 2021; Xu et al., 2020; Liu et al., 2019; Steiger et al., 2018; Steiger and Smerdon, 2017). The ensemble Kalman Filter (EnKF) (Evensen, 1994) algorithm is one of the most popular DA techniques applied by the hydrologic community. However, this assimilation method is subject to some inherent drawbacks especially in nonlinear dynamic systems thus resulting in suboptimal performance and violation of water balance (Abbaszadeh et al., 2018). Given these limitations, emphasis should be placed on the development of improved DA algorithms better adapted to hydrologic models, which allow the modeling of different temporal and spatial scales and the improvement of water balance. This can be achieved by modifying the standard approaches such as the ensemble Kalman filter or variational algorithms so that, accurate predictions can be obtained at a reasonable computational cost. These include among others hybrid EnKF-Var methods (Bannister, 2017; Bergou et al., 2016; Mandel et al., 2016) and AI algorithms for ensemble

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post-processing (Grönquist et al., 2021). One recent advance in data assimilation techniques for drought forecasting is the use of machine learning algorithms to improve the accuracy of predictions. For example, researchers have used machine learning techniques to develop models that can analyze large amounts of data from a variety of sources and generate more accurate forecasts of drought conditions (Aghelpour et al., 2020; Rhee and Im, 2017; Feng et al., 2019). These models can also be updated in real-time as new data becomes available, allowing for more accurate and up-to-date forecasts. Another advance in data assimilation techniques for drought forecasting is the use of remote sensing data and reanalysis to improve the accuracy of predictions, which may be particularly beneficial in areas where ground-based observations are limited (Shahzaman et al., 2021b; Shi et al., 2011).

8.2. Remote Sensing and Reanalysis

Various challenges in drought modeling in the MEDR are related to data availability. The lack of climatic and hydrological observations in ungauged catchments, low station density, short data records, data gaps, and limited data access in some Mediterranean countries. All these challenges can limit the accuracy and reliability of drought predictions. Finding alternative data sources and modeling techniques is essential to tackle these challenges.

Remote sensing data can provide real-time information about the Earth's surface facilitating effective drought forecasting, monitoring, and early warning (Zhang et al., 2016). Agricultural drought can be assessed by analyzing changes in vegetation cover over time. Indeed, drought can lead to marked changes in the health and vigor of vegetation, and these changes can be detected using remote sensing data (Belal et al., 2014). By analyzing changes in vegetation greenness over time, it is possible to identify areas that are experiencing or are at risk of experiencing drought stress. Moreover, drought conditions related to vegetation or evapotranspiration can also be monitored with drought indices from remote sensing products, such as NDVI or Evaporation Stress Index (ESI) (Shahzaman et al., 2021a). Microwave satellite data can also be used to estimate soil moisture levels during crop growing season, which can be used to predict and monitor potential agricultural droughts (Le Page and Zribi, 2019; Yuan et al., 2015).

In addition, satellite observations of precipitation and soil moisture such as IMERG (Huffman et al., 2015), PERSIANN-CCS (Sadeghi et al., 2021), CHIRPS (Funk et al., 2015), and SMAP (Entekhabi et al., 2010) can be used in conjunction with the in-situ observations and ground-based radar observations data to fill observational gaps.

Moreover, data from numerical weather forecasting reanalysis such as ERA5-land were used instead or along with direct observations to forecast drought in many studies (Babre et al., 2020; Junqueira et al., 2022; Parker et al., 2021). ERA5-land is a state-of-the-art global reanalysis dataset that can provide a consistent view of the evolution of land variables (e.g., precipitation, temperature) over several decades at an enhanced resolution (~10km). This product obtained by assimilating observations through a 4D-VAR data assimilation technique can be used as ground truth in data-poor regions. For example, ERA5-land can be used to calibrate and validate climate forecasts and to choose an ensemble of the most skilled GCMs in reproducing the actual observed climate in a specific region.

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Finally, remote sensing data and reanalysis remain valuable tools for drought forecasting and monitoring, as it provides timely land surface information that can fill the observational gaps, help to identify areas at risk of potential drought conditions and to monitor the progression of drought over time.

8.3. Uncertainty analysis in drought forecasting

In spite of the large number of studies that have been carried out on the probabilistic characterization of drought, the quantification of uncertainty of these forecasts is still ignored in major studies. Uncertainty analysis is an important aspect of probabilistic drought forecast, as it allows users to understand the degree of confidence associated with the forecasted probabilities (Hao et al., 2016; Dehghani et al., 2014). Therefore, more efforts should focus on quantifying the uncertainty beyond just an ensemble of model simulations (AghaKouchak et al., 2022).

Drought forecasting is subject to epistemic and aleatory uncertainties. The first one arises from incomplete knowledge of drought processes and can be reduced with improved understanding, more data, and good models' calibration and validation. The second one is related to the inherent variability and randomness in natural systems and is often difficult to reduce (Pappenberger & Beven, 2006). In addition, uncertainties in drought forecasting can vary by region, spatial scale, and temporal scale. As we discussed in sect. 7.3, even well calibrated and validated, the drought forecasting model will not necessarily perform equally well in all periods or locations. By considering the uncertainty of the drought model as a nonstationary process in space and time, researchers can gain new insights into the variability of uncertainty and its underlying causes (AghaKouchak et al., 2022). This perspective can help identify regions or periods where the uncertainties are particularly high, which can guide further research, data collection, and model development efforts. Additionally, understanding the space-time variability of uncertainty can inform the development of more robust and reliable forecasting and decision-making approaches that account for the changing nature of uncertainty.

Various techniques can be employed to quantify drought forecast uncertainty, including ensemble forecasting (Palmer et al., 2004), Bayesian methods (Vrugt et al., 2008), sensitivity analysis (Saltelli et al., 2008) and probabilistic forecasting (Gneiting et al., 2005). Probabilistic drought prediction can also involve the use of data assimilation techniques to integrate different data sources, including remote sensing data, ground-based observations, and output from meteorological and hydrological models. Lately, hybrid statistical-dynamical models have shown their potential in reducing uncertainties associated with both statistical and dynamical methods (Yuan et al., 2015; Madadgar et al., 2016). For example, shortcomings in dynamical model physics or data can be counterbalanced by the empirical associations in statistical models. While, uncertainties in statistical models resulting from shifting climate conditions can be tackled by the physically-based dynamical models (Yuan et al., 2015).

In summary, probabilistic drought prediction with uncertainty analysis can be useful tools for decision-makers, as they provide a more comprehensive view of the potential impacts of drought and allow for more informed risk management decisions. However, what is missing in the current drought forecasting models is not just the uncertainty quantification, but also a lack of awareness of it (AghaKouchak et al., 2022).

8.4. Drought Information Systems

A critical component of proactive approaches to drought preparedness is providing timely and reliable climate information, including seasonal forecasts, that helps decision-makers prepare management policies (Manatsa et al., 2017). Identifying drought risk timely depends on our ability to monitor and forecast its physical causing mechanisms at the relevant spatiotemporal scale. An integrated national drought monitoring and early warning system has been implemented in many regions and countries such as the United States, New Zealand, South Asia, India, and Europe (Prabhakar and Rama, 2022) but has not taken place until recently in developing countries (e.g., the Southern and Eastern Mediterranean countries). This is probably due to the lack of a drought information system, the sparse observation networks, and the low predictability of seasonal precipitation in these countries. To overcome these limitations, there is a need for developing a Drought Information System with a complete approach allowing data collection and preprocessing, accurate probabilistic drought risk prediction using a combination of ensemble climate seasonal forecasts, ground-based observations, reanalysis, conventional and remote-sensing observations, Artificial Intelligence, Data Assimilation and hydrological models and drought information dissemination through a web-based Drought Early Warning System (DEWS).

9 Conclusions

This study reviewed the recent statistical, dynamical, and hybrid statistical-dynamical methods used to forecast droughts and their application on the MEDR. Drought definitions, classification, indices, and causative physical mechanisms were also presented in the context of the MEDR. The main conclusions of this review are:

1. There are only a few studies on the analysis of physical mechanisms causing droughts in the MEDR. The review of these studies confirmed that seasonal drought predictability skills are still very limited over the region due to its relatively poor teleconnection with ENSO compared to the tropical and subtropical regions. Besides, MEDR is strongly influenced by other climate patterns, such as the NAO, regional MO, ULMOi, and NAWA which can also affect the region's weather and climate but their relationship to drought onset is rather weak and could not explain major droughts in the region. Land surface memory can also contribute to the predictability of seasonal and sub-seasonal droughts. Thereby, an accurate representation of these land-atmosphere processes is needed to improve drought forecasting skills in mid-latitude regions such as the Mediterranean.
2. Statistical models were largely used to forecast droughts in the MEDR. One of the major limitations of these models is that they often assume a stationary relationship between the predictors and the predictands which can lead to potentially inaccurate forecasts. In this regard, AI models such as SVR, SVM, and ANN have proven good capacity in detecting local discontinuities and non-stationary characteristics of the data and show satisfactory forecasting skills at less than 6 months lead time. Moreover, sophisticated statistical models, incorporating a data pre-processing technique such as wavelet analysis, EMD, or PCA with AI models have proven to be more efficient than using a single model and can extend the lead time of the drought forecast up to 12 months. The copulas can also provide valuable insights into the complex relationships between different drought predictors. The use of copulas enables a more in-depth analysis of the nonlinear dependencies between variables such as temperature, precipitation, and soil moisture, yielding a more comprehensive understanding of the factors that contribute to drought risk in a specific region. This

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leads to a more sophisticated and reliable forecast of drought probability. Thus, copulas are a highly useful resource in the ongoing effort to understand and manage the consequences of drought.

3. Dynamical models can capture the nonlinear interactions in the atmosphere, land, and ocean, but their forecast skill is still limited for a long lead time due to the chaotic nature of the atmosphere. In addition, the reliability of the dynamical models is related to the quality of data used to drive hydrological models (e.g., initial hydrologic condition and downscaled climate forecasts) and the quality of the model calibration and validation which also depends on the quantity and quality of observations used in these processes. On the other hand, climate predictions from a single GCM cannot represent all the climate pathways. Therefore, more efforts should focus on the probabilistic estimation of climate variables, which involves uncertainty quantification on various GCMs as ensemble members.
4. Hybrid statistical-dynamical models can be promising tools to potentially enhance the accuracy and reliability of drought forecasting in the MEDR. By merging a broad variety of forecasts from statistical and dynamical models into a final probabilistic prediction, hybrid models benefit from the strengths of both modeling approaches and improve the forecast skill compared to an individual model. But their applicability remains challenging due to several constraints. Indeed, the hybrid model may require careful calibration and validation to ensure that they are performing optimally which can be time-consuming, requiring a large amount of data, specialized expertise, and high computational resources.
5. One of the major challenges in drought forecasting in the MEDR is the lack of long-term, high-quality hydroclimatic observations to convey the nonstationary patterns and the variability of the climate. In addition, hydrologic model predictions are often poor, due to model initialization, parametrization, and physical errors. To address these challenges, it is important to improve the availability and quality of data for drought forecasting in this region. This could involve implementing better monitoring systems and increasing the number of weather stations in the region. In addition, efforts should be made to improve the performance of drought forecasting models by using more advanced data assimilation and machine learning techniques and to incorporate data from other sources such as state-of-art satellite observations and reanalysis with relatively high spatiotemporal analysis to provide a superior hydrologic and climate states estimate and consequently a skillful agricultural and hydrological drought forecasting.
6. Drought mapping is the final stage in which drought risk information is disseminated and communicated to end users. Major studies in the Mediterranean region analyze drought risk using some drought indices without applying a visualization via maps or presenting the risk on a single map showing the overall risk situation. An informative visualization of results via probabilistic drought risk maps with regard to cartographic rigor is recommended. Uncertainties related to drought modeling and prediction also need to be perspicuously defined, discussed and communicated to increase the intelligibility and comprehensibility of decision-makers, farmers, and other end users.
7. Finally, much effort should be done to improve the communication and dissemination of drought forecasts which can help in extending their lead time by ensuring that decision-makers and stakeholders have access to the most up-to-date information.

Index of Acronyms

Adaptive neuro-fuzzy inference systems (ANFIS)

Akaike's Information Criterion (AIC)
Anderson-Darling (AD)

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Artificial neural network of multilayered perceptron (ANN-MLP)
Asymmetric Power Autoregressive Conditional Heteroskedasticity (APARCH)
Atmospheric water deficit (AWD)
Automated Statistical Downscaling (ASD)
AutoRegressive (AR)
Autoregressive Conditional Heteroskedasticity time series of order 1 (ARCH)
Autoregressive integrated moving average (ARIMA)
Autoregressive moving average (ARMA)
Autoregressive moving average time series of order (11) (ARMA)
Autoregressive moving average time series of order 1 (MA1)
Autoregressive moving average time series of order 2 (MA2)
Autoregressive time series of order 1 (AR1)
Autoregressive time series of order 2 (AR2)
Bagging (BG)
Bagnouls-Gaussen aridity index (BGI)
Bayesian Information Criterion (BIC)
Breaks for Additive Season and Trend (BFAST)
Coefficient of efficiency (CE)
Convolutional neural network long short-term memory (CNN-LSTM)
Co-ordinated regional climate downscaling experiment for the Mediterranean area (MedCORDEX)
Corrected and unbiased trend-free-pre-whitening (TFPWcu)
Coupled Model Intercomparison Project (CMIP)
Cramers-von Mises (CvM)
Crop moisture index (CMI)
Drought class transition probabilities (DCTP)
Empirical Mode Decomposition (EMD)
Exponential General Autoregressive Conditional Heteroskedasticity time series of order (11)) (EGARCH)
False alarm ratio (FAR)
Frequency bias (FB)
Generalized Autoregressive Conditional Heteroskedasticity time series of order (11) (GARCH)
Geometric Brownian Motion (GMB)
Geometric Brownian Motion time series model with asymmetric Jumps (GBMAJ)
Global Historical Climatology Network-Monthly (GHCN)
Global Land Data Assimilation System (GLDAS)
Groundwater Resource Index (GRI)
Growing season minimum and maximum values (gsmm)
Hadley Centre Coupled Model version 3(HadCM3)
Kolmogorov-Smirnov (K-S)
Land Surface Temperature (LST)
Maximum likelihood methods (MLIKE)
Mean absolute error (MAE)
Mean error (ME)
Model output statistics (MOS)
Moderate Resolution Imaging Spectroradiometer (MODIS)
Modified Fournier Index (MFI)
Monthly average relative humidity (MARH)
Monthly mean solar radiation (MMSR)
Moving average (MA)
Multiple Linear Regression (MLR)
National Center for Atmospheric Research (NCAR)
National Centers for Atmospheric Prediction (NCEP)
National Oceanic and Atmospheric Administration (NOAA)
NDVI anomaly index (NDVIA)
Non-linear AutoRegressive with eXogenous inputs (NARX)
Normalized Difference Vegetation Index (NDVI)
Normalized Difference Water Index (NDWI)
North Atlantic Oscillation (NAO)
Pedotransfer functions (PTF)
Periodic autoregressive (PAR)
Periodic autoregressive moving average (PARMA)
Principal component analysis (PCA)
Probability of detection (POD)
Probability of false detection (POFD)
Proportion of correct predictions (PC)
Random forest (RF)
Random subspace (RSS)
Random tree (RT)
Reconnaissance Drought Index (RDI)
Root mean squared error (RMSE)
Sea Surface Temperature (SST)
Seasonal-ARIMA (SARIMA)
Soil and Terrain Database (SOTER)
Soil Moisture (SM)
Soil Moisture Agricultural Drought Index (SMADI)
Soil Moisture and Ocean Salinity (SMOS)
Soil moisture anomaly index (SMAI)
Soil Moisture Deficit Index (SMDI)
Soil moisture percentiles (Wp)
Soil Water Deficit Index (SWDI)
Soil Wetness Deficit Index (SWetDI)
Standardized Water-Level Index (SWI)
Streamflow drought index (SDI)
Support vector Regression (SVR)
Temperature Condition Index (TCI)
The Second Generation of Canadian Coupled General Circulation Model (CGCM2)
Vegetation Condition Index (VCI)
Vegetation Health Index (VHI)
Wavelet Analysis (WA)

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Wavelet decomposition (WD)

Competing Interests

The authors declare that they have no conflict of interest.

Author contribution

Each author has made substantial contributions to the creation of this manuscript. BZ was responsible for conceptualization, methodology, investigation, analysis, drafting the manuscript, and reviewing and editing. NEM contributed to the methodology, analysis, writing, reviewing, and editing processes. EHB was involved in the methodology, analysis, review, and editing stages.

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1643 **Table 1** Main studies using the Time series model to forecast drought in the MEDR

Reference	Inputs	Outputs	Methods	Time scale	Study area	Drought type	Study period
(Bouznad et al., 2021)	Precipitation, temperature, and ET	Aridity index, SPI, NDVI	ARIMA, SARIMA	Monthly, annual	Algeria	Meteorological	Baseline 1985–2014 Future 2015–2024
(Achite et al., 2022)	Monthly precipitation	SPI12, SRI12	ARIMA, SARIMA	Annual	Algeria	Meteorological, hydrological	1972–2018
(Al Sayah et al., 2021)	LANDSAT imageries at a 3-year interval, and meteorological indicators	MFI, BGI, VHI, VCI, TCI, NDWI, NDVI	ARIMA/SARIMA	Annual	Lebanon	Meteorological, hydrological and agricultural	1990–2018
(Tatli, 2015)	IPCC observed precipitation	PDSI	Hurst exponent, Mann - Kendall test	Monthly	Turkey	Meteorological	1966–2010
(Pablos et al., 2017)	LST, NDVI Satellite SM data (SMOS BEC L4 and MODIS SR) and In Situ SM Data	SWDI, SMADI, SMDI, SWetDI, AWD CMI	POD; POFD; FAR; FB	Weekly	Spain	Agricultural	2010- 2016
(Hadri et al., 2021)	NDVI ; Rainfall	SPI, SWI	The Mann-Kendall and Sen's slope	Seasonal	Morocco	Meteorological, agricultural	2008-2017
(Ben Abdelmalek and Nouiri, 2020)	Monthly rainfall series in 16 main meteorological stations	SPI, RDI, Annual PET	Mann - Kendall test, Weighted Inverse Distance interpolation	Annual	Tunisia	Meteorological, agricultural	1973–2016
(Karabulut, 2015)	Precipitation	SPI	Cumulative Deviation Curve	Monthly, seasonal, annual	Turkey	Meteorological	1975–2010
(Jiménez-Donaire et al., 2020)	Rainfall, soil moisture, and vegetation (NDVI)	SPI, NDVIA SMAI	Combined Drought Indicator	Monthly, seasonal, annual	Spain	Agricultural	2003–2013
(Ben Mhenni et al., 2021)	SM (SOTER); MedCORDEX daily grided reanalysis of meteorological data; NOAA weekly NDVI	SPI, SPEI, PDSI, and Wp	Lag-correlation analysis	Seasonal, annual	Tunisia	Meteorological, agricultural	1982–2011
(Derdous et al., 2021)	Rainfall	SPI	the Mann–Kendal, Sen's slope estimator, and the Pettitt test;	Monthly, seasonal, annual	Algeria	Meteorological	1936 –2008

(Mendes et al., 2022)	Precipitation, water level in reservoirs	SPI14	BFAST	Seasonal	Portugal	Hydrological	1978-2020

Table 2 Main studies using regression analysis to forecast drought in the MEDR

Reference	Inputs	Outputs	Methods	Time scale	Study area	Drought type	Study period
(Sousa et al., 2011)	Monthly rainfall SST, NAO	PDSI, scPDSI	Calibrated Stepwise Regression	Monthly, seasonal, annual	MEDR	Meteorological	1901–2000
(Papadopoulos et al., 2021)	Monthly precipitation	SPI, RDI	Fuzzy linear regression analysis	Monthly, seasonal, annual	Greece	Meteorological	1996–2016
(Martínez-Fernández et al., 2016)	In situ hourly SM, daily rainfall, daily PET, and SMOS data	SWDI	PTF; linear regression	Seasonal	Spain	Agricultural	2010–2014
(Tigkas and Tsakiris, 2015)	Monthly rainfall; average monthly mean, max, and min temperature	PET, RDI	Multiple regression models	Monthly, seasonal, annual	Greece	Agricultural	47-50 years

Table 3 Main studies using Artificial Intelligence Models to forecast drought in the MEDR

Reference	Inputs	Outputs	Methods	Time scale	Study area	Drought type	Study period
(Mohammed et al., 2022)	Precipitation	SPI	BG, RSS, RT, and RF	Monthly, seasonal, annual	Syria	Agricultural, Hydrological	1946-2005
(Di Nunno et al., 2021)	Precipitation and discharge		NARX neural networks	Seasonal	Italy	Hydrological	1997-2020
(El Aissaoui et al., 2021)	Monthly average precipitation; Monthly min/max air temperature; MARH; MMSR	SPI, SPEI	SVR1: linear; SVR2: Polynomial; SVR3: RBF; SVR4: sigmoid	Monthly	Morocco	Meteorological	1979–2013
(Achour et al., 2020)	Monthly rainfall data	SPI	TFPWcu; ANN	Monthly, seasonal and annual	Algeria	Meteorological	1960–2010

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(El Alaoui El Fels et al., 2020)	Monthly rainfall amount	SPI	PCA, Frequency analysis, ANN	Monthly, annual	Morocco	Meteorological	1970–2017
(El Ibrahimi and Baali, 2018)	Observed SPI	Predicted SPI	ANFIS; ANN-MLP; SVR, ANN, WA-ANFIS WA-SVR, WA-ANN-MLP	Monthly, seasonal, annual	Morocco	Meteorological	1978–2014
(Djerbouai and Souag-Gamane, 2016)	Historical monthly rainfall	SPI	ARIMA, SARIMA, WA-ANN	Monthly, seasonal, annual	Algeria	Meteorological	1936–2008
(Myronidis et al., 2012)	Monthly precipitation Monthly in-situ measurements of water lake levels	SPI	ARIMA-ANN	Annual and seasonal	Greece	Meteorological	1973–2008
(Danandeh Mehr et al., 2022)	Rainfall and temperature time series	SPEI-3 and SPEI-6	CNN-LSTM, genetic programming, ANN, LSTM and CNN	Monthly	Turkey	Meteorological	1971–2016
(Başakın et al., 2021)	Monthly sc-PDSI	Predicted sc-PDSI	ANFIS, EMD-ANFIS	Monthly, seasonal,	Turkey	Meteorological	1900–2016
(Özger et al., 2020)	Monthly sc-PDSI	Predicted sc-PDSI	EMD, WD, ANFIS, SVM, WD-ANFIS, EMD-ANFIS, WD-SVM,	Monthly, seasonal	Turkey	Meteorological	1900–2016

Table 4 Main studies using Joint Probability Models to forecast drought in the MEDR.

Reference	**Inputs**	**Outputs**	**Methods**	**Time scale**	**Study area**	**Drought type**	**Study period**
(Bouabdelli et al., 2020)	Monthly precipitation, temperature 9 GCMs of CMIP5	SPI12, SDI6	Copula theory, Hydrological modeling using GR2M	Seasonal, annual	Algeria	Meteorological, Hydrological	Baseline: 1941–2011, Future: 2021–2100
(Bonaccorso et al., 2015)	NAO; areal monthly precipitation series;	SPI	DCTP (SPI, NAO)	Monthly, seasonal	Sicily, Italy	Meteorological	1921–2008
(Serinaldi et al., 2009)	Mean areal precipitation, aggregated at 6 months	SPI; joint return periods of drought	Probabilistic analysis of drought characteristics using Copula	Seasonal	Italy	Meteorological	1921–2003
(Hamdi et al., 2016)	Daily streamflow data,	The joint probabilities and bivariate	Two-dimensional copula model;	Annual	Tunisia	Hydrological	1966–2008

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		return periods	the threshold level method				
(Esit and YUCE, 2022)	Monthly precipitation	SPI	Two-dimensional copula model	Seasonal	Turkey	Meteorological	1963–2016
(Tosunoglu and Can, 2016)	Monthly rainfall series	SPI; probabilistic properties of droughts	Two-dimensional copula model	Monthly	Turkey	Meteorological	1966–2006

Table 5 Main studies using Markov Chains Model to forecast drought in the MEDR.

Reference	Inputs	Outputs	Methods	Time scale	Study area	Drought type	Study period
(Habibi et al., 2018)	Annual precipitation from 65 meteorological stations	SPI	Markov chain models, DI and 11 time series models (GMB, GBMAJ, APARCH, AR1, AR2, ARCH, ARMA, EGARCH, GARCH, MA1, MA2)	Annual	Algeria	Meteorological	1960–2010
(Paulo and Pereira, 2007)	67-year averages of monthly precipitation	SPI	Non-homogeneous and homogeneous Markovian modeling	Monthly, seasonal, annual	Portugal	Meteorological	1931/32 – 1998/99
(Lazri et al., 2015)	Annual precipitation maps from meteorological satellite data; 219 rain gauges and radar precipitation	SPI	Markov chain model; Transition probability matrix	Annual	Algeria	Meteorological	2005–2010
(Nalbantis and Tsakiris, 2009)	Monthly Precipitation, monthly streamflow	SPI, SDI	Non-stationary Markov chain	Monthly, seasonal, annual	Greece	Hydrological	1970–71 to 1999–2000.
(Akyuz et al., 2012)	Observed annual streamflow	Probabilities and return periods of droughts	First-order Markov chain model, second-order Markov chain model	Annual	Turkey, New work, Sweden	Hydrological	1938–2005
(Cancelliere et al., 2007)	Monthly Precipitation in 43 precipitation stations	SPI	Markov chain model	Seasonal, annual	Sicily, Italy	Meteorological	1921–2003

Table 6 Main studies using dynamical models to forecast drought in the MEDR.

Reference	Inputs	Outputs	Methods	Time scale	Study area	Drought type	Study period

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(Elkharrim and Bahi, 2014)	Historical precipitation; HadCM3(monthly precipitation and temperature); Observed GHCN v3; NCEP and NCAR reanalysis	SPI	ASD	Seasonal and annual	Morocco	Meteorological	Baseline 1961-2010 Future 2014-2099
(Marx et al., 2018)	GCMs: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M		Hydrological models: mHM, Noah-MP, and PCR-GLOBWB	Annual	Europe	Meteorological and hydrological	Baseline 1971–2000
(Vasiliades and Loukas, 2009)	Observed runoff	PDSI, Weighted PDSI, PHDI and the moisture anomaly Z-index; runoff and soil moisture	monthly UTHBAL conceptual water balance model	Monthly	Greece	Meteorological and hydrological	1960–2002
(Brouziyne et al., 2020)	CNRM-CM5 (RCP4.5, RCP8.5); GLDAS 25 km reanalysis data; Observed daily rainfall and temperature (max and min) series	SPI-12; SDI-12; Monthly runoff, rainfall; Future water yield.	Hydrological model SWAT;	Annual	Morocco	Meteorological, Hydrological	Baseline 1985-2005; Future 2030–2050 and 2080–2100
(Mendicino et al., 2008)	Monthly precipitation, temperature, SPI, NDVI	GRI	A water balance model	Seasonal, annual	Italy	Meteorological and Hydrological	1959–2006
(Dubrovský et al., 2014)	Monthly and daily precipitation and temperature outputs from 16 GCMs simulations (IPCC-AR4)	PDSI, Z-index	Multi-GCM forecast	Seasonal	MEDR	Meteorological	Baseline 1961–1990; Future 2070–2100
(Ruffault et al., 2014)	Daily precipitation, temperature and global radiation from ARPEGE-Climate model Version 4; Historical observations from SAFRAN dataset	Maps of summer precipitations, number of wet days in summer and drought intensity	Water balance model, quantile mapping/ anomaly method	Annual seasonal	France	Agricultural, Hydrological	Baseline 1961–1990 Future 2071–2100

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Table 7 Main studies using hybrid statistical-dynamical models to forecast drought in the MEDR

Reference	Inputs	Outputs	Methods	Time scale	Study area	Drought type	Study period
(Ribeiro and Pires, 2016)	UKMO operational forecasting system	SPI3	MLR	Seasonal, annual	Portugal	Meteorological, agricultural, and hydrological	1987–2003

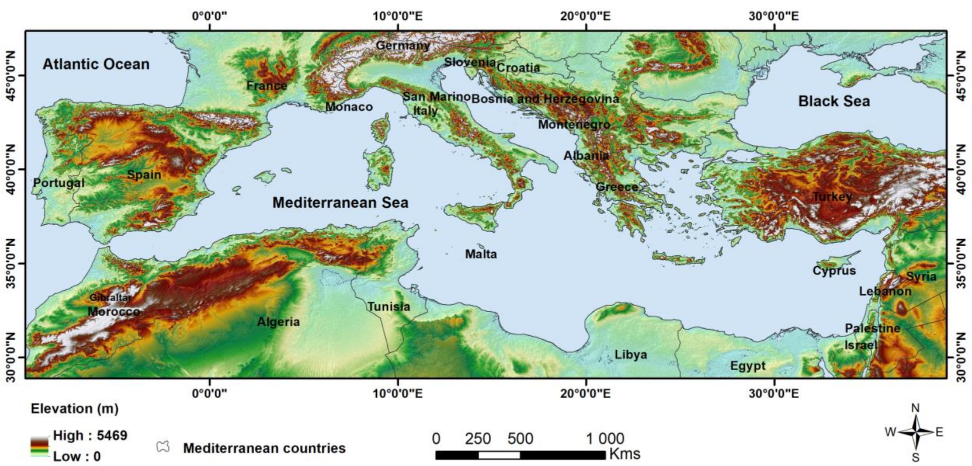

Figure 1 Topography of the Mediterranean Region.

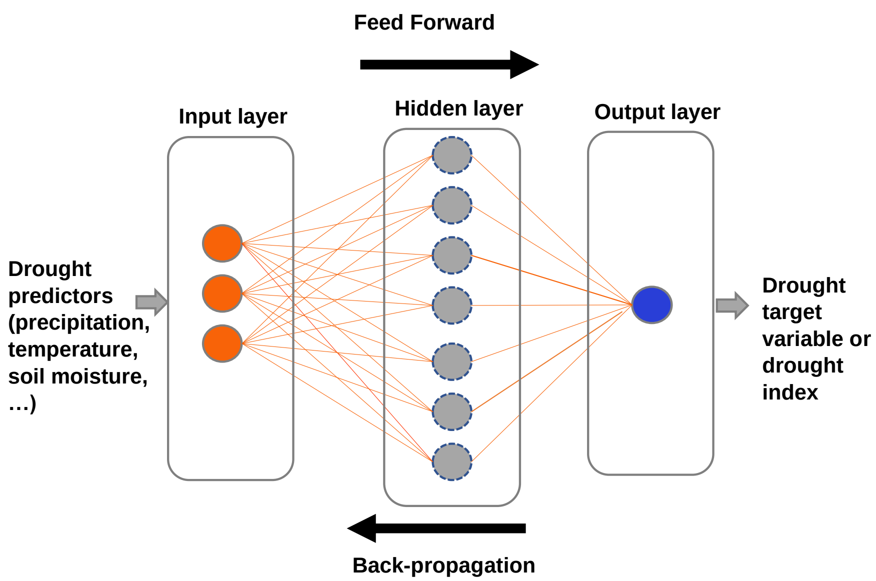

Figure 2 Drought forecasting based on a simple ANN architecture.

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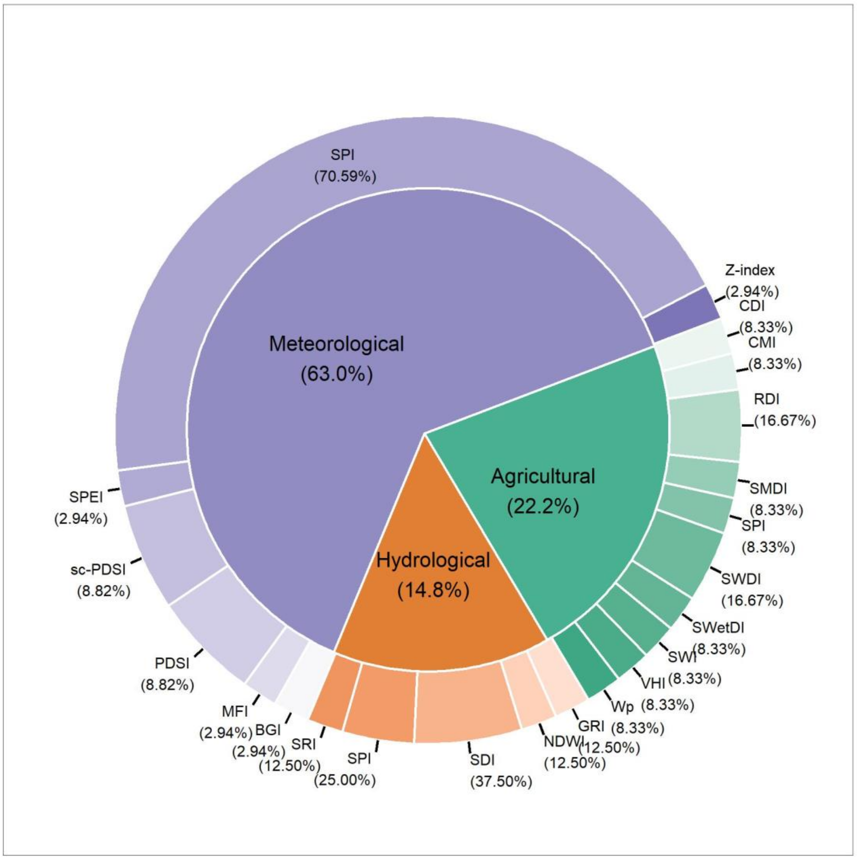

Figure 3 Pie chart showing the proportion of use of indices in the MEDR for different drought types.

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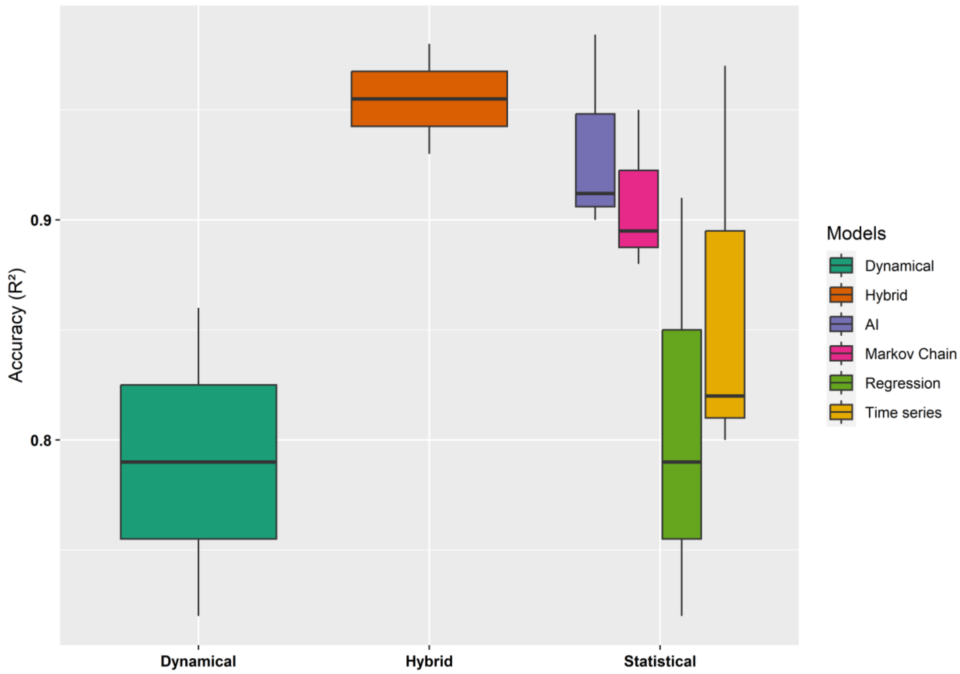

Figure 4 Box and whiskers plot showing the performance of drought prediction models denoted by the coefficient of determination (R^2) for the surveyed studies in MEDR.

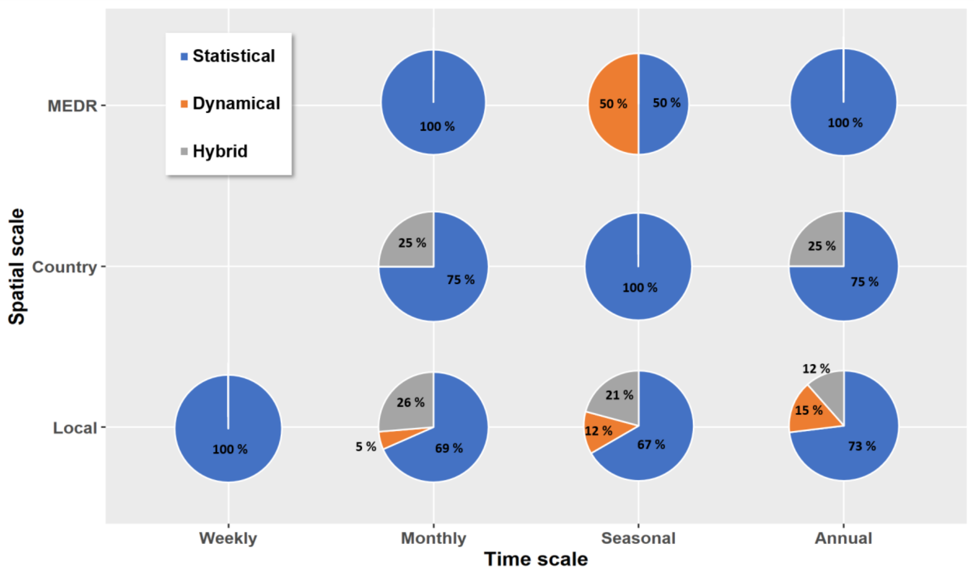

Figure 5 Spatial and temporal scales of drought forecasting studies in the Mediterranean region with pie chart indicating the percentage of use of drought forecasting method: statistical, dynamical and hybrid statistical models for each spatio-temporal scale.